More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft

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(Invited Paper)

***Abstract*—Similar to the efforts to move toward electric vehicles, much research has focused on the idea of a more electric aircraft (MEA). The motivations for this research are similar to that for vehicles and include goals to reduce emissions and decrease fuel consumption. In traditional aircraft, multiple systems may use one type or a combination of types of energy, including electrical, hydraulic, mechanical, and pneumatic energy. However, all energy types have different drawbacks, including the sacrifice of total engine efficiency in the process of harvesting a particular energy, as with hydraulic and pneumatic systems. The goal for future aircraft is to replace most of the major systems currently utilizing nonelectric power, such as environmental controls and engine start, with new electrical systems to improve a variety of aircraft characteristics, such as efficiency, emissions, reliability, and maintenance costs. This paper provides an in-depth look into how the systems have—or will be—changed. Future aircraft capabilities such as electric taxi and gas–electric propulsion for aircraft are also included for discussion. Most recent commercial transport aircrafts are described as the current state-of-the-art electric aircraft system. Future goals, including those of NASA, are presented for future advances in MEA.**

***Index Terms*—Aircraft power systems, auxiliary power unit (APU), environmental control system (ECS), main engine start (MES), more electric aircraft (MEA).**

I. Introduction

OVER the last few decades, there has been tremendous progress in the efforts to move toward more electric aircraft (MEA). Many subsystems that previously used hydraulic, mechanical, and pneumatic power have been fully or partially replaced with electrical systems. One of the evolutionary changes in newer commercial transport aircraft has been the elimination of the integrated drive generator (IDG). The IDG had been used to change the variable speed of the jet engine to constant speed via mechanical means. This system provided constant voltage and constant frequency power to the aircraft's electric bus. In some of the most recent commercial transport aircraft, including the Boeing 787 and Airbus A380, the main engine generator is directly coupled to the jet engine via a gearbox. Hence, the frequency of the electrical power in the aircraft's power busses is proportional to engine speed. The engine characteristic and gearbox ratio determine the variation of electrical frequency. For example, the electric frequency on these more recent aircraft may range from 350 to 800 Hz. The ac voltage produced by the generator is regulated at a fixed value, such as 115 or 230 Vac, using a generator control unit. This paves the way for a constant voltage and variable frequency power bus. The constant voltage and variable frequency power bus has been standardized for use in modern aircraft as described in MIL-STD-704 and DO-160. Hence, many loads that have run at a constant 400 Hz in the traditional aircraft with an IDG would now require additional provisions to convert power from one form to another, i.e., ac–dc and dc–ac. This trend makes power electronics and electric machines very important for the aircraft industry. The weight, volume, reliability, and performance of power electronic converters and electric machines have the utmost importance for the overall aircraft industry.

A further example of the expanding use of electrical systems includes the elimination of the use of bleed air for ECSs. ECSs are used to achieve passenger comfort by regulating the cabin temperature and pressure. Bleed air had been obtained from one of the compressor stages of the main engine; however, in the Boeing 787, instead of tapping to the bleed air from the engine, a set of compressors utilizing electric power is used to regulate the temperature and pressure in the cabin, eliminating the pneumatic system and air ducts from the engine. However, because the regulation of cabin temperature and pressure requires a large amount of electric power, the on-board power generation had to be significantly increased for the main engine generators. An additional example of electrification is the use of electrical power to start the main engine, as opposed to the use of compressed air from the auxiliary power unit (APU), ground cart, or the other main engine. The electric start of the main engine further eliminates pneumatic systems in the aircraft as well. These are just a few examples of the transitioning to pure electric systems from various other systems in newer aircrafts.

The goal of this paper is to provide an overview of the state-of-the-art technology for power conversion in large commercial transport aircraft. Challenges, trends, and research and development opportunities will be discussed in detail. NASA's goals are included to show the expected increase in fuel and energy efficiency and the reduction in noise and NOx emissions. Future technologies such as hybrid electric gas propulsion aircraft and electric taxiing for commercial transport aircraft will be presented. The technologies required for these future systems, including superconducting and nonsuperconducting machines

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and wide bandgap devices are discussed to show how to meet the efficiency, weight, and volume targets.

II. Overview of Major Subsystems and Trends of MEA

A. Electric Power System

Conventional commercial transport aircraft typically use a 115-V line-to-neutral ac voltage with a line frequency of 400 Hz. In this architecture, the generator is connected to the main engine via a mechanical drive, which keeps the mechanical speed, and hence the electrical frequency, constant on the aircraft's electric bus. Because many important functions in this aircraft, including main engine start (MES), ECSs, deicing, and hydraulics, are not powered by electrical energy, the required electric power generation per engine is lower than the most recent MEA. In traditional constant voltage and constant frequency architecture, electric power is primarily used to power the fans that circulate the air in the aircraft. Electrical power is also used by avionics equipment, hotel loads (TVs and entertainment system), lighting, and the galley loads (refrigerator, oven, and coffee maker) [1]–[4]. Most of the fans were typically run directly at 400 Hz without a power electronic converter [5]. Hence, during start-up of induction motors, a large inrush current as high as six to ten times the nominal current is possible under this electrical system [6]. The conventional electrical system also has a 28-Vdc bus. The 28 V was obtained by converting the 115 Vac, 400 Hz using transformer rectifier units (TRUs) [7]. Further reduction of dc voltage is done in each line replaceable unit (LRU), such as the avionic equipment, to obtain lower voltages such as 5 V and 3.3 V, which are used to power integrated circuits, microprocessors, and signal-level electronics [8].

In large commercial aircraft, one generator per engine typically performs electrical generation. Depending on the aircraft type, there could be more than one generator connected to each engine, such as back-up generators, in order to meet redundancy and extended range twin operations (ETOPS) requirements. An additional source of electric power on an aircraft is the APU, which typically provides power when the aircraft is on the ground. APUs can also provide power while in the air under certain operating conditions, including emergencies; however, an APU's power capability is limited at very high altitudes due to the reduced air density. Additionally, a ram air turbine (RAT) can be used to provide electric and/or hydraulic power under emergency conditions. The RAT resembles a small wind turbine and is deployed by the pilot under emergency conditions. Various batteries exist in the aircraft to start the APU and to provide back-up power for critical equipment in the cockpit as well as other important functions such as the emergency lighting for the aisles [9].

There are multiple busses in the aircraft to accommodate the redundancies required for emergencies. A tie-breaker is used to tie the busses together as needed. Many switches are utilized to disconnect generators, loads, and busses from the aircraft power system. Both the primary and the secondary power distribution systems monitor, control, and protect the network busses [10].

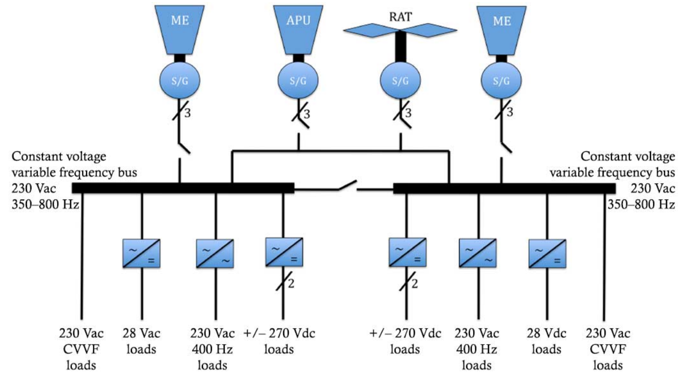


Fig. 1. Constant voltage variable frequency bus power system for MEA.

These protections as well as the above-mentioned electrical sources are shown in Fig. 1: an example of the electric power system in MEA.

In new aircraft such as Boeing 787 and Airbus A380 and A350, the conventional constant voltage constant frequency is replaced by the constant voltage and variable frequency bus. In this scenario, while the voltage is regulated at either 115 or 230 Vac, the bus frequency changes proportionally to engine speed, and depending upon engine and aircraft type, the frequency can vary between 350 and 800 Hz [11]. This change in paradigm requires power conversion for many loads, including motor drives and, as a result, power electronic converters are needed to convert ac–dc and dc–ac power. Specifically, in [12], the control of a multilevel active filter is investigated in applications related to the MEA grid architecture. DC–DC power conversion is also needed for many systems, including the battery chargers [13].

As in all applications, power quality is of great importance in the modern aircraft. With the introduction of variable frequency generation, new challenges are presented for power converters to maintain a high power quality and reliability. In [14], the modeling of nonlinear loads is performed to investigate the effects that the harmonic and changing power demands have on the electrical systems of aircraft. Reference [15] provides analytical and numerical simuations of potential problems caused by harmonics in converters with active power factor correction. Reference [16] is an in-depth analysis and comparison of the different solutions for high power factor in ac–dc converters in MEA applications.

An additional advantage that the move to MEA brings is the flexibility to generate and distribute power efficiently near to where it is being consumed. In the traditional aircraft model, all of the power is generated on the wings near the main engines and in the aft near the APU before being routed to the front of the aircraft for protection and control. This traditional architecture is shown in Fig. 2(a) and is referred to as a centralized power system distribution. In a more electric paradigm, the new solid-state power controllers and contactors with advanced communication allow for the possibility to eliminate this network configuration in favor of remote distribution. This results in increased efficiency of the power distribution system, as line losses are decreased due to shorter distances between generation and consumption. Moreover, significant weight and volume savings may be realized, as the power rating of the main

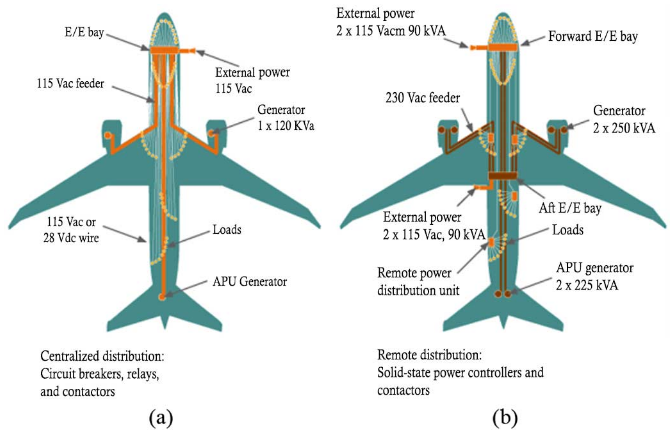


Fig. 2. The 787's electrical system uses a remote distribution system that saves weight and is expected to reduce maintenance costs [10]. (a) Traditional aircraft. (b) Boeing 787. (Courtesy of Boeing.)

conductors may be reduced. These weight savings and rating reductions contribute both to improved fuel efficiency of the aircraft and a lower total cost, as the lower rated equipment may be provided at a reduced price. Additionally, the distributed power system configuration realizes maintenance cost savings. The Boeing 787 is an example of this modern network configuration and is shown in Fig. 2(b).

An additional advantage of power electronic converters in MEA is the freedom to operate the motor at varying speeds, which allows for the motor to be run at its optimum operating point depending on the load. In theory, higher mechanical-speed electric machines are preferable because as the mechanical speed increases, the weight and volume of the electrical machine decreases for a desired power capability. In addition, the more electric architecture introduces the need for power electronics to drive the electric motor, and as a result, the opportunity to replace current induction machines with permanent magnet (PM) motors is presented. PM machines are preferable, as they have inherently higher power density and efficiency compared to induction motors [17]. Although there is an increase in component cost and complexity with the addition of individual power electronic converters for electric machines, the positive tradeoffs include the ability to choose higher operating speeds of the motors, which reduces the weight and volume of the motor [18].

The IDG in conventional aircraft is a mechanical device that is susceptible to wearing out, and therefore, it must be replaced or maintained at predefined times in order to prevent failures. The elimination of the IDG with the MEA architecture leads to improved dispatch reliability, as the mechanical and less reliable subsystem has been replaced with higher reliability electrical system. This increased reliability is a major factor for revenue, especially for commercial aircraft. Further considerations for the electrification of the aircraft are the maintenance costs associated with the different systems. This is important because any unexpected "grounded" time leads to significant cost increase for airlines. Thus, even in the case where the electrification does not improve the weight, volume, and initial cost of the aircraft, the potential savings via increased dispatch reliability and reduced maintenance may make financial sense [19]. These benefits of electrification have led to the current trend of eliminating the IDG in large dual isle commercial transport aircraft [20]. The fuel savings and environmental impact of the continued electrification of the aircraft have been examined in [21].

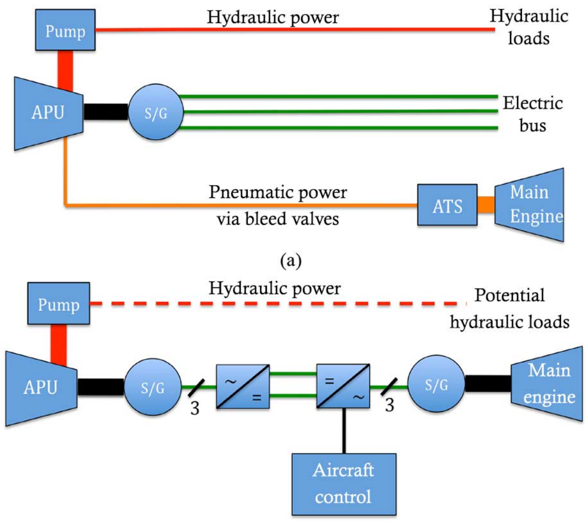
Other active research topics considering the electric power system of modern and future aircraft include reliability. In [22], a software tool is proposed to evaluate the reliability of different design architectures. The stability of the electric power systems is examined in [23]–[25], which investigate and model the small or large signal stabilities. In particular, Reference [24] presents simulations and experimental results regarding the stability of hybrid MEA power systems. Furthermore, the protection of the MEA power grid is investigated in [26] and [27]. In [26], reliability models were proposed for all critical components, and Reference [27] simulates the design of a high-voltage dc connection with hybrid power on MEA.

B. Main Engine Start

The exploration for the electrification of future aircraft has affected the MES subsystem, which on a traditional commercial transport aircraft has been done using pneumatic power. To summarize the traditional methods, the APU generates compressed air, which is then routed typically from the aft of the aircraft, where the APU resides, to the main engines, and this is done via air ducts [28]. Inside the engine nacelle, there is an accessory called the air turbine starter (ATS). The ATS acts as a pneumatic motor to spin the engine. Once the engine reaches a certain speed, the fuel and air mixture is burned in the combustion chamber of the engine to start the engine. There is also typically a provisional system in which a pneumatic connection, i.e., air ducts, between multiple main engines, is used to start the other engines [29]. This provisional system is needed to supply the compressed air to start the other engines while in flight because at high altitudes, the APU may not function properly with the reduced air density or it may not have enough power generation to supply such compressed air [30]. An alternative to the APU for MES is the use of ground carts, which provide compressed air to the main engine while on the ground.

In Airbus A350 and A380, pneumatic air start turbine system is used; however, more recently on the Boeing 787, the pneumatic system has been eliminated, including the air ducts and ATS. In lieu of this, main engine generators are operated as motors to achieve the MES. Hence, they are called main engine starter generators. Electrical wires provide the necessary power to start the main engines [10]. This new system requires converting ac power from APU generators to dc power and then back from dc to ac in order to achieve variable voltage and variable frequency control of the main engine starter/generators; hence, rectifiers and inverters are needed. Fig. 3 shows a diagram of the MES system with both traditional and electric APUs.

In this scenario, it is necessary that electrical, magnetic, and thermal sizing of the starter/generator be a part of the new system analysis that needs to be performed. It is preferable that the electrical MES maximum torque requirement



(b)

Fig. 3. (a) Traditional APU with electrical, pneumatic, and hydraulic power. (b) Electric APU illustrating MES.

does not exceed the maximum torque required for generation to prevent any additional weight and volume penalty for the MES/generators. Issues surrounding the addition of the electric start for engines are a current research field, including potential control strategies for this new system [31].

The challenge of starting the main engine lies in the ability to size properly the ratings of the main engine and APU generators as well as the power electronic converters. Hence, the required rating analysis of MES is critical to size the APU, APU generator, ac–dc converter, dc–ac converter, and MES/generator. To minimize the weight impact of the power electronic converter used to achieve dc–ac conversion to run the start/generator for MES, it is possible to use that same power electronic converter for another function in the aircraft after MES. This approach will relieve the burden of carrying the unnecessary weight of additional converters, thus helping to improve fuel efficiency.

C. Auxiliary Power Units

Traditional APUs, shown in Fig. 3(a), have generally been gas turbine engines that typically provide both pneumatic and electric power to the aircraft while it is on the ground and/or in the air. Traditional APUs may also be connected to a hydraulic pump that provides backup hydraulic power in case of a failure of the main hydraulic system of the aircraft. The APU typically resides at the aft of the aircraft. While on the ground, the traditional APU is typically used to provide compressed air to start the main engines, provide cabin air conditioning, and power the aircraft loads [32]. While in the air, APUs can be used under emergency conditions to provide compressed air and hydraulic and electric power. APUs conventionally operate at constant frequency, 400 Hz, and provide electricity at either 115 or 230 Vac. This type of traditional APU is used in both Airbus A350 and A380.

With electric starting of the engine and de-icing in some of the recent aircraft, it is now possible to eliminate the pneumatic and hydraulic function of the APUs [33], thus allowing for electric-only APUs, shown in Fig. 3(b). This type of more electric APU is used in Boeing 787. One of the main differences between the conventional and the electric-only APUs is that the electric APU requires a very large generator and as a result, the overall system design considerations may require that two APUs be used for total power needed and/or redundancy reasons. Historically, in traditional commercial transport aircraft, the APU was connected to only one generator; however, in Boeing 787, two generators connected to the APU are used due to the increased electric loads in the architecture of the aircraft. There may be also complex requirements for redundancy and ETOPS for critical safety equipment [10]. In Table I, a comparison of the electrical specifications of some of the more recent, and more electric, aircraft is provided as reference.

TABLE I
COMPARISON OF THE KEY ELECTRICAL SYSTEMS OF RECENT LARGE COMMERCIAL TRANSPORT AIRCRAFT [10], [34]

Aircraft	Boeing 787	Airbus 380	Airbus 350
No. engines	2	4	2
No. generator per engine	2	1	2
Gen. rating per engine	250 kVA	150 kVA	100 kVA
Gen. output voltage	235 V	115 V	230 V
No. gen. per APU	2	1	1
Gen. rating per APU	225 kVA	120 kVA	150 kVA
RAT rating	Unavailable	150 kVA	100 kVA
ECS method	Electric- 4×100 kW compressors	Bleed air	Bleed air
Brake system	Electric	Hydraulic	Hydraulic
Actuation system	EHA	conventional and EHA	convention al and EHA

Other interesting research efforts in the advancement of APUs have been the exploration of potential hybrid sources for the APU, including both a gas turbine as well as fuel cells. Analysis and feasibility considerations for these types of architectures have been done in [35]. Modeling of such a hybrid system is done in [9] and performance evaluations are examined in [36].

D. Environmental Control Systems

The expanding use of electrical systems has also been implemented through the elimination of the use of bleed air for the ECSs. ECSs are used to achieve passenger comfort by regulating the cabin temperature and air pressure. Conventionally, bleed air had been obtained from one or two of the compressor stages of the main engine [37]. The Airbus A350 and A380 ECS are based on a bleed air architecture. However, in the Boeing 787, instead of tapping bleed air from the engine, a set of compressors utilizing electric power is used to regulate the temperature and pressure in the cabin. Thus, the pneumatic system and air ducts from the engine have been eliminated for this system.

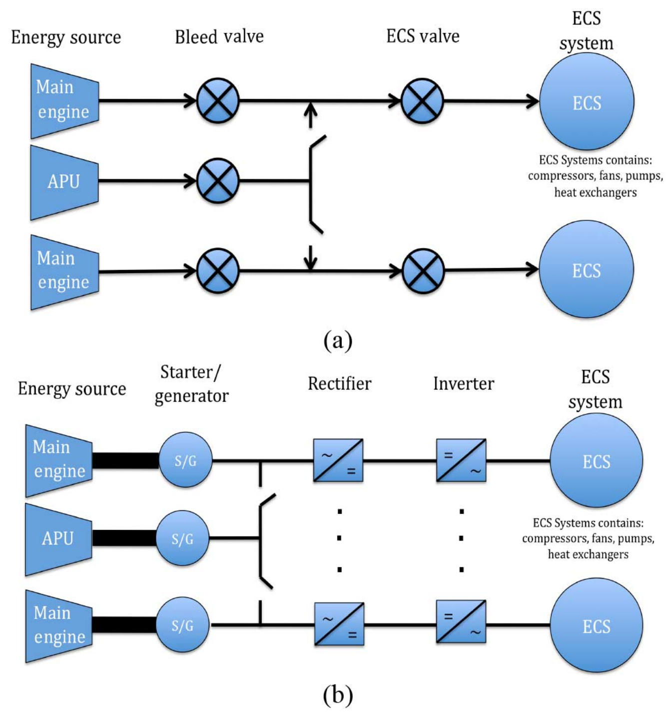


Fig. 4. (a) ECS with bleed air. (b) Electric ECS with no bleed air.

One of the challenges of an electric ECS is the sizing of the overall system and the calculation of required electric power for all phases of the flight. The largest motors and power electronic converters are for the compressors. Reliability and redundancy are two other important considerations of the ECS and contribute to the design of total electric power system architecture. However, as the regulation of cabin temperature and air pressure requires a large amount of electric power, the on-board power generation has to be significantly increased for the main engine generators [38]. As a result, recent research has also been performed in nonelectric ECSs, including [39], which simulates and experimentally tests a new control system configuration with reduced ram air usage. Diagrams comparing the bleed-type systems and nonbleed electric systems are shown in Fig. 4. In this simplified figure, ECS contains various compressors, fans, pumps, heat exchanges, valves, and pipes.

The fans required to move the air in the aircraft are a major component of the ECSs. There may be many fans to circulate the air in the cabin, cockpit, and cargo area. In addition, avionics ventilation provides forced air ventilation to the electronic equipment and cockpit equipment. Other components in the ECS are various pumps. All of these compressors, pumps, and fans in the constant voltage variable frequency aircraft require power conversion from ac to dc and dc to ac to run their individual electric motors [40]. In addition, the motor controllers have complex functions as they not only convert power, but they also contain built-in self-test and achieve power factor and electromagnetic interference/compliance (EMI/EMC) compliance, while also performing communication, health monitoring, and prognostics. All of this functionality requires advanced communication protocols, such as CAN bus, to enable to communication of various controllers in the aircraft [41].

E. On-Board Inert Gas Generation System

An on-board inert gas generation system (OBIGGS) is used to infuse the gas tank of the aircraft with nitrogen to prevent any kind of explosion that might result from a static build-up in the tank, leading to accidental electrical arcing in the various systems in the tank, and causing catastrophic consequences. In conventional architectures, the OBIGGS function has been implemented using a pneumatic system [42]. In the MEA case, bleed air from the engine would be processed and regulated to a predetermined temperature and pressure, and then the system would separate the nitrogen from other gasses in the air, including oxygen, using a separation module. A separation module generally consists of specially designed membranes. Nitrogen is separated and used to fill the empty space in the tank to prevent the presence of an oxygen content level in the tank that could, in the event of an arc, result in potential fires and explosions.

In modern MEA, it is possible to eliminate the use of bleed air for OBIGGS by implementing a compressor driven by electric motors and power electronic drives. This compressor can then be used to increase the temperature and pressure of ambient air to prepare it for the separation module [43]. However, one important challenge added is the variation in ambient pressure and temperature as a function of altitude, and this requires that the new electric system includes active control to maintain the pressure and temperature required for separation module. As an alternative solution, nitrogen for the OBIGGS may be provided through an H_2 air fuel cell (Section III-D), whose exhaust is already at a higher temperature and pressure compared to the ambient air [44].

F. Electrification of Hydraulic Systems

In the traditional aircraft, hydraulic systems are used in aircraft for primary and secondary surface control, braking, landing gear, and many other important functions. These hydraulic systems are dependent on mechanically driven actuators, but the current trend is to replace them with electro-hydraulic actuators (EHAs) or electromechanical actuators (EMAs) [45]. Both EMAs and EHAs require an electric motor and an inverter. In a self-contained unit, EHAs include a reversible hydraulic pump, a cylinder, and a reservoir of hydraulic fluid. EHAs are attractive in future aircraft, as they eliminate the external hydraulic source and piping systems. Hence, EHAs are considered advantageous because of weight, volume, dispatch reliability, and cost advantages. Conversely, EMAs do not use any hydraulic power, but instead use a gearbox and mechanical system to translate rotary motion to linear motion, similar to a jack screw [46]. This allows the EMA motors to run a reversible hydraulic pump directly. As a result, EMAs are more efficient than EHAs and are a better option for leak-free operation and reliability [47]. However, a major drawback of EMAs is the potential of mechanical jamming. This is a major challenge that needs to be addressed if EMAs are to become a viable option for critical safety applications, such as primary surfaces and landing gear deployment [48]. Other issues currently being researched related to EHAs and EMAs are the power quality

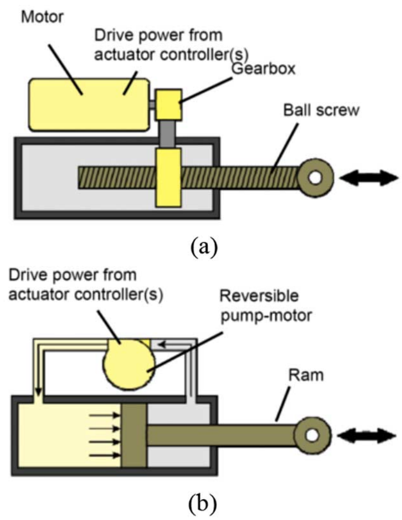


Fig. 5. (a) EMA system. (b) EHA system [45].

TABLE II
NASA FUTURE AIRCRAFT GOALS [53]

Generation	Noise goal (dB)	LTO NO_x emission goal (%)	Cruise NO_x emission goal (%)	Energy consumption
N+1 (2015)	–32	–60	–55	–33
N+2 (2020)	–42	–75	–70	–50
N+3 (2025)	–52	–80	–80	–60

Note: Projected benefits once technologies are matured and implemented by industry. Benefits may vary by vehicle size and mission. $N + 1$ and $N + 3$ values are referenced to a 737–800 while $N + 2$ is referenced to a 777.

and control implications. Reference [46] is an example of this, as it illustrates that methods of one aerospace company have taken to investigate the potential effects. Thermal modeling of these systems is done in [49], which simulates the lumped thermal circuits of an EMA system. Fast reduced-order models of EMAs are developed and simulated in [50]. Fig. 5 shows a comparison of the EMA and EHA systems.

Also, related to the research efforts for the electrification of hydraulics, both fault-tolerant PM motors and inverter design are interesting for use in the EHA or EMA systems [51]. The accommodation of regenerative power in the aircraft bus instead of using a resistor to dissipate energy is another futuristic consideration for a more efficient use of power. Additionally, it has the potential to improve the thermal management of the different systems using regenerative braking power [52]. Currently, EHAs are used in Boeing 787 for main hydraulic functionality and EMAs are used for braking [45].

III. FUTURE TRENDS AND OPPORTUNITIES

A. Hybrid Gas–Electric Propulsion Aircraft

NASA has developed goals for future generation subsonic fixed wing aircraft in which the audible noise, NOx emissions, and fuel and energy consumptions are reduced. The goals of the programs are defined for 2020 (or $N + 2$ as NASA refers to the generation) and 2025 ($N + 3$); a comparison of these goals is shown in Table II.

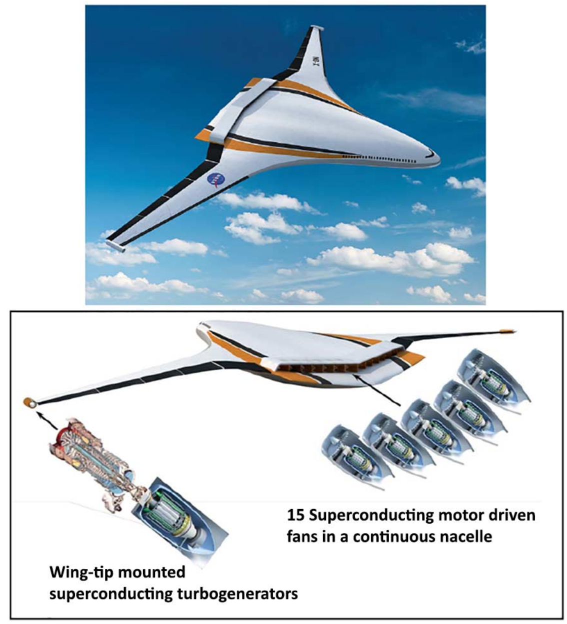


Fig. 6. N3-X HWB aircraft with a TeDP system [54].

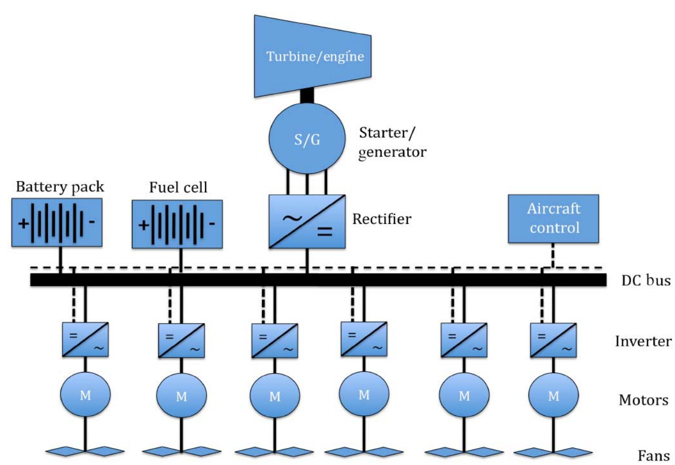


Fig. 7. Generic MEA power system architecture for hybrid gas electric propulsion aircraft.

There are at least two architectural considerations for these goals. The first idea is a hybrid wing body (HWB) aircraft with a turboelectric distributed propulsion (TeDP) concept. The other idea under consideration is a combination of a gas turbine engine and stored electric power sources driving a single propulsor. In this case, the propulsor fan is mechanically run by the turbine and/or electric motor.

The HWB with TeDP concept utilizes two gas turbine engines with enormous generators (22.4 MVA each) to produce electricity [55]. This generated power is used to drive a total of 15 propulsor 2–3 MW motors to propel the aircraft. The shafts of the gas turbine and fans are run at their optimum speed, as they are decoupled for maximum efficiency [56]. Fig. 6 shows a futuristic sketch of the TeDP concept. Fig. 7 shows an example of the MEA architecture for TeDP system.

Superconducting motors and generators are also considered machines for the HWB with TeDP concept. In this example, the dc-field winding of the electric machine is made of superconductive wire. Both stator and rotor windings can be cooled even though current technology uses nonsuperconductive wires for stator. There is further research to achieve ac powered stators to be made of superconductive materials. DC transmission power between generators and motors is envisioned to use superconducting cable. The liquefied gases, such as liquid nitrogen and liquid helium, can be used for cooling the rotor. Recently, NASA solicited proposals to investigate the applicability of the noncryogenic electric machines for hybrid gas–electric propulsion aircraft. The challenge with noncryogenic motors, however, is to achieve high efficiency with volume and weight constraints [53]. Tradeoff studies for weight, volume, and efficiency between the superconductive and nonsuperconductive machines are very complex because superconductive machine requires additional cryogenic systems to provide the cooling. Hence, total balance of systems must be considered for the superconductive machines.

Recent research solicitations from NASA include high efficiency (>96%) and high power density (~8 hp/lb or better) MW-class noncryogenic motors for hybrid gas–electric aircraft propulsion [57]. As a result, opportunities and challenges exist for developing and applying new technologies, including the new high energy density magnets, new machine topologies, conductors with better resistivity than copper, and fault redundancy. Topologies that reduce the weight and volume of machines are of interest. Additionally, new opportunities for research are the development of lightweight and high strength composite materials, new cooling techniques and materials, structural advances, and better insulation materials with high thermal conductivity [54].

B. Wide Bandgap Devices for MEA

Advances in power electronics are also desired to achieve high temperature capabilities, reductions in weight and volume, and improvements in efficiency. Silicon carbide (SiC) technology is a promising candidate to replace the Si technology in this aspect. The efficiency of SiC active rectifiers and inverters is significantly better than their Si counterparts due to the inherently lower conduction and switching losses of SiC MOSFETs compared to Si insulated gate bipolar transistors (IGBTs) [58]. Due to the high switching capability of SiC MOSFETs, higher speed machines or a higher number of pole machines are feasible. This technology will open the door for more efficient systems in any aircraft power conversion application in the near future. Additionally, the high temperature capability of the SiC is an advantage [59]. Gallium nitride (GaN) devices, another wide bandgap device technology such as SiC, are also a promising technology; however, the voltage and current ratings of GaN devices are currently lower than that of SiC devices [60]. However, GaN devices are currently appropriate for many applications in aircraft for other systems such as fans, actuators, and TRUs.

C. Electric Taxi

One of the more futuristic technologies for MEA is an electric taxi capability. Currently, the aircraft is transported from the terminal gate to the tarmac via the use of a tug vehicle. Once out of the gate, aircraft taxi using their main engine thrust to navigate the runways of the airport. This is undesirable because the main engines burn significant amounts of fuel during this taxi period, which requires a combination of mostly idle power and minimal thrust [61]. Certainly, the taxiing operation is not the most optimized operation condition for the engine. Because of the size and traffic of some of the major airports, taxiing requires significant amounts of distance and time. To solve this problem, it has been proposed to use electric motors integrated into the nose wheel and/or the main gears of the aircraft to enable taxiing [62]. This would allow the main engines to remain off until shortly before takeoff. After landing, these direct drive electric motors would allow the main engines to be shut-off and allow electric taxiing to the gate. To achieve electric taxiing, an electric motor, power electronic converter, controls, communication with the cockpit, and APU power are needed. Power from the APU would need to be conditioned for the traction motor using power electronic converters [63]. This technology integrated to the aircraft is commonly referred to as e-taxi or green taxi [64]. This architecture is shown in Fig. 8, with potential additional energy sources shown with dashed lines.

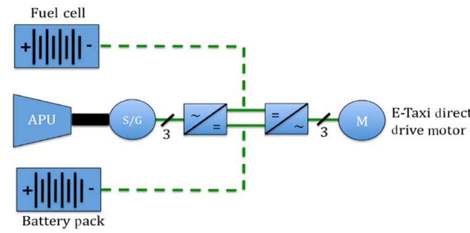


Fig. 8. Electric taxi architecture. Solid lines indicate current energy source with APU. Dashed lines show potential future energy storage implementations of electric taxi.

TABLE III
BENEFITS OF E-TAXI [65]

	E-Taxi
Fuel consumption	4% savings of total fuel
NO_2 emissions*	50% reduction
CO emissions*	40% reduction
CO_2 emissions*	25% reduction

Note: *Savings relative to tug vehicle method.

The benefit of this emerging subsystem is the ability to achieve lower emissions, reduce fuel use, and increase operational capability. An added benefit is the elimination of tug vehicles in the airports, as well as the simplification of airport logistics and operations, ultimately reducing the risk of accidents. Table III quantitatively shows a comparison of the current and electric taxi methods.

This technology can be improved even further if fuel cells or batteries are used as an alternative power source to the APU for electric taxi, entirely eliminating emissions during aircraft taxiing. This approach requires power dense and reliable motors that can be integrated inside the aircraft wheels. For this concept to become a reality, many safety critical and system

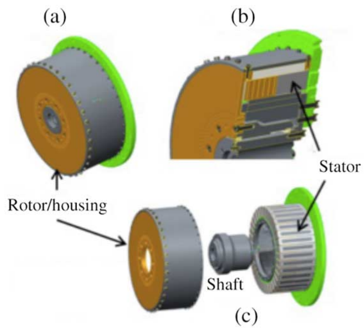


Fig. 9. Direct drive PM machine for e-taxi for aircraft [67]. (a) Overview. (b) Cross section. (c) Exploded view.

Fig. 10. Electric taxi demonstration [68].

level requirements, including reliability, fault tolerance, efficiency, cost, weight and volume, need to be considered. Recent research endeavors in this topic include the design of direct wheel actuators [66] and the thermal considerations for potential direct wheel PM machines [67]. An example of a direct drive wheel with a mounted PM motor (Figs. 9 and 10) shows the physical implementation of the electric taxi system for the Airbus A320.

D. Fuel Cell Technology for MEA

A technology of interest that has been explored for applications in MEA is the fuel cell. While the concept of fuel cells was conceived in the 1800s, research into this topic did not ramp up until the late 20th century. Since this time, fuel cells have been thought to be the next step for lightweight energy storage applications. Sponsored through research agencies such as NASA and the Office of Naval Research, fuel cells have been demonstrated in aerospace systems. In the last 10 years, one passenger and unmanned aircraft have been flown using fuel cells as the main, or sole, type of energy [69].

Fuel cells are attractive energy sources for MEA because they do not release any harmful emission and are lightweight. Although they have been demonstrated in smaller aircraft, more research and further technological maturation are needed before fuel cells become a main source of energy in the commercial aircraft. As a part of this maturation process, the use of fuel cells for specialized applications in commercial aircraft is currently being explored. The trend for fuel cells in MEA is to augment the supplies of current APUs. This would help reduce the size and weight of the APUs, making the aircraft more efficient, while continuing to meet energy demands. Eventually, fuel cells or battery and fuel cell hybrid systems are targeted to replace APUs altogether.

As mentioned, further research is needed before these trends become viable; past and current research has set the foundation to make this a reality. For instance, Reference [70] is a thorough study of different strategies for a fuel cell hybrid energy system under emergency situations. The authors model and measure various elements of the system, from device stress, lifetime, efficiency, etc. Reference [71] investigates how to integrate the fuel cell with other sources of energy in MEA, with special attention given to the dynamics of the cell. The optimization of the hydrogen use in hybrid energy aircraft systems is modeled in [72]. Additionally, in [73], a control strategy of a fuel cell and battery hybrid propulsion system has been proposed and is simulated under certain conditions.

As the trend continues to replace large and heavy turbines with smaller and lighter energy storage, the opportunities for the electrification of all systems will continue to be demonstrated. Further advances in MEA technology and concepts, not just fuel cells, are required to achieve the ultimate goal for commercial aircraft: high efficiency and extremely low emissions. Thus, the utilization of fuel cells will continue to be an intriguing and vibrant area of research for MEA.

E. Use of Low-Pressure and High-Pressure Spools for Power Extraction

Jet engines not only provide power for propulsion, but they also provide electrical, pneumatic, and hydraulic power. Due to the increased electrification of various systems on the MEA, there is an increase in the electric loading of engines. Aircraft jet engines have typically more than one spool or shaft. The propulsion fan, low-pressure compressor stages and low-pressure turbine stages can be coupled to a low-pressure spool, while the high-pressure compressor and high-pressure turbine stages can be coupled to the high-pressure spool [74]. This constitutes a two-spool engine. Some manufacturers have three spool engines where an intermediate spool is added. The two-spool engine is shown in Fig. 11.

The low-pressure and high-pressure spools rotate independently from each other. The high-pressure spool ratio is typically 2:1 speed range, for example from 10 000 rpm to 20 000 between idle and full thrust setting. The low-pressure spool may have between a 1:3 and 1:5 speed range, e.g., 1000–5000 rpm.

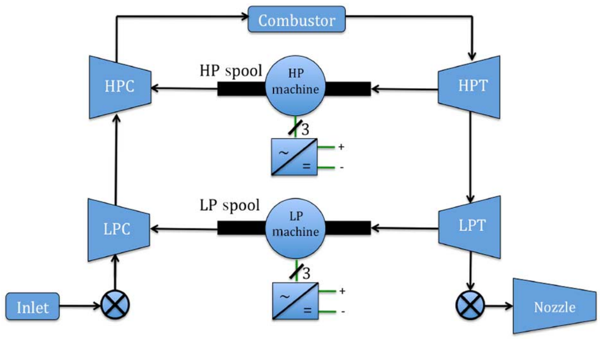


Fig. 11. Diagram of a two-spool engine.

Traditionally, the high-pressure spool is used to provide electrical, pneumatic, and hydraulic loads. Many accessories such as generators and hydraulic pumps are traditionally designed for this 2:1 speed range. Using only the high-pressure spool can negatively impact the performance of the engine with increased shaft power extraction. For example, the compressor surge margin can become a concern if too much high shaft power is extracted from high-pressure spool. The increase in engine speed and bleed air can mitigate this problem; however, this solution increases fuel burn [75].

This challenge pushes engine manufacturers to look at using low-pressure spool as an additional means of power extraction. For example, an additional generator could be coupled to low spool shaft by a gearbox. The 5:1 shaft speed variation makes the electrical machine design challenging, particularly for obtaining constant power [76]. Mechanical solutions are possible by extracting power from spools in various combinations and operating regimes including clutches and differential shafts. Enabling power extraction from the low-pressure spool will have positive impacts on engine performance and eliminate the increased fuel burn of the current actions. Overcoming the high shaft speed variation of the low-pressure spool via an MEA paradigm could be a rich area for research.

IV. Conclusion

In this paper, the trends and opportunities for MEA have been reviewed with close examination given to the large transport aircraft. Power systems, MES, APUs, ECSs for cabin pressurization and temperature control, OBIGGSs, electric taxiing, and hydraulic systems are reviewed from the perspective of electrification. NASA's future goals for civilian transport aircraft reveals that there are opportunities to employ multimegawatt machines for generation and propulsion to achieve aircraft with less noise, high fuel and energy efficiency, and reduced emissions. Efficiency, weight, volume, reliability, fault-tolerant capability and cost of these electric machines, power electronics, and energy storage systems (batteries and fuel cells) are all critical research opportunities. Importantly, wide bandgap devices will play a key role for power electronics to achieve very high efficiencies and the higher temperature capabilities desired for MEA implementations. These new semiconductor devices will also open the door for higher speed or higher pole count machines. As a result of the advances discussed throughout this paper, research will continue to explore methods to confront today's technological limitations and achieve the goals to reduce the size and weight of current machines, and, in turn, improve aircraft efficiency even further.

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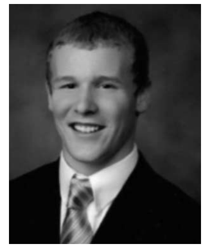

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