Moving Towards a More Electric Aircraft

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ABSTRACT

The latest advances in electric and electronic aircraft technologies from the point of view of an "all-electric" aircraft are presented herein. Specifically, we describe the concept of a "More Electric Aircraft" (MEA), which involves removing the need for on-engine hydraulic power generation and bleed air off-takes, and the increasing use of power electronics in the starter/generation system of the main engine. Removal of the engine hydraulic pumps requires fully-operative electrical power actuators and mastery of the flight control architecture. The paper presents a general overview of the electrical power generation system and electric drives for the MEA, with special regard to the flight controls. Some discussion regarding the interconnection of nodes and safety of buses and protocols in distributed systems is also presented.

INTRODUCTION

Conventional aircraft architectures used for civil aircraft embody a combination of systems dependent on mechanical, hydraulic, pneumatic, and electrical sources. The resulting conventional equipment is the product of decades of development by system suppliers.

In a conventional architecture (Figure 1 is a basic schematic) fuel is converted into power by the engines. Most of this power is used as propulsive power to move the aircraft. The remainder is converted into four main forms of non-propulsive power [1]:

- *Pneumatic power*, obtained from the engines' high-pressure compressors. This kind of energy is conventionally used to power the Environmental Control System (ECS) and supply hot air for Wing Anti-Icing (WAI) systems. Its drawbacks are low efficiency and a difficulty in detecting leaks.

- *Mechanical power*, which is transferred (by means of the mechanical gearboxes) from the engines to central hydraulic pumps, to local pumps for engine equipment and other mechanically driven subsystems, and to the main electrical generator.

- *Hydraulic power*, which is transferred from the central hydraulic pump to the actuation systems for primary and secondary flight control; to landing gear for deployment, retraction, and braking; to engine actuation; and to numerous ancillary systems. Hydraulic systems have a high power density and are very robust. Their drawbacks are a heavy and inflexible infrastructure (piping) and the potential leakage of dangerous and corrosive fluids.

- *Electrical power*, which is obtained from the main generator in order to power the avionics, cabin and aircraft lighting, galleys, and other commercial loads (such as entertainment systems). Electrical power does not require a heavy infrastructure and is very flexible. Its main drawbacks are that conventionally it has a lower power density than hydraulic power, and results in a higher risk of fire (in the case of a short circuit).

Each system has become more and more complex, and interactions between different pieces of equipment reduce the efficiency of the whole system. A simple leak in the pneumatic or hydraulic system may lead to the outage of every user of that network, resulting in a grounded aircraft and flight delays. The leak is generally difficult to locate and once located it cannot be accessed easily.

The trend is to move towards "all-electric" aircraft, which means that all power off-takes from the aircraft are electrical in nature, thus removing the need for on-engine hydraulic

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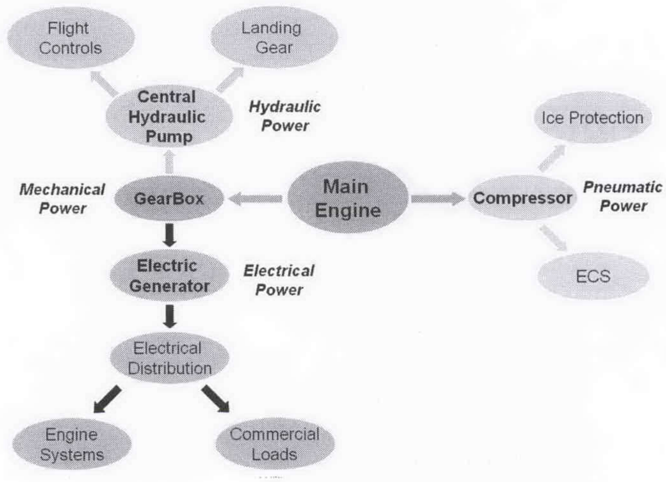

Fig. 1. Schematic of conventional power distribution

power generation and bleed air off-takes. The removal of bleed air off-takes requires new high-voltage electrical networks and new solutions, such as air-conditioning, wing ice protection, or electric engine start-up. Removal of the engine hydraulic pumps requires fully-operative electrical power actuators and a mastery of flight control architecture.

The "all-electric" aircraft is not a new concept: the concept of an electric aircraft has been considered by military aircraft designers since World War II [2], although until recently the lack of electrical power generation capability, together with the volume of the power conditioning equipment and the advanced control required, rendered the approach unfeasible – especially for commercial and civil transport applications.

Since the early 1990s, research into aircraft power system technologies has advanced with the aim of reducing or eliminating centralized hydraulics aboard aircraft and replacing them with electrical power. Several programs have been started with the aim of driving the research on this field [3], such as Totally Integrated More Electric Systems (TIMES), devoted to use previously developed systems into electrical aircraft, US Air Force MEA Program that investigates for providing more electrical capability for fighter aircrafts, and Power Optimized Aircraft (POA), which tries to optimize the management of electrical power on aircraft in order to reduce non-propulsive power and reduce fuel consumption, while increasing the reliability and safety of onboard systems and reducing maintenance costs.

Nowadays, novel ways of generating, distributing, and using power onboard are examined at the aircraft level. Hybrid or bleed-less air conditioning systems, "More Electric Engines" (MEEs), fuel cells, variable frequency generators, complex embedded digital systems and distributed system architectures are just a few of the technologies vying for space on forthcoming aircraft; the concept is known as "More Electric Aircraft" (MEA) as presented in Figure 2.

Recently, worldwide research into the future development of commercial aircraft has given rise to more advanced approaches to on-board energy power management and drive systems (Figure 3). These are now being carefully considered, and it is believed that electrical systems have far more potential for future improvement than conventional ones regarding energy efficiency.

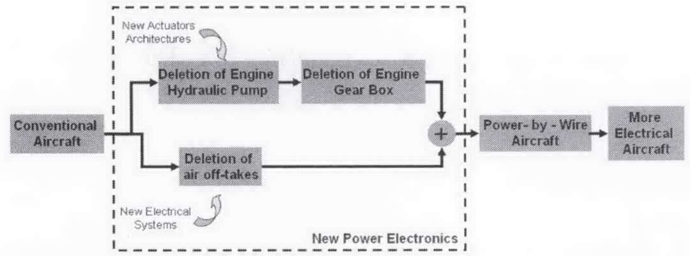

Fig. 2. Current trends toward the MEA

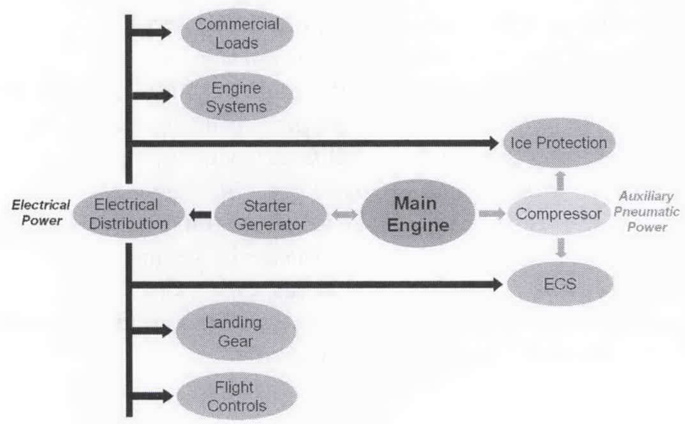

Fig. 3. Schematic of MEA Power Distribution

Steps toward a MEA are being taken in two different ways:

- Removing current air and hydraulic engines and further increasing electrical power generation capability. This requires significant changes in electrical generation and network techniques, and in fault protection.
- Substituting hydraulic actuators for electromechanical actuators. This reduces weight and decreases maintenance and production costs.

The MEA initiative emphasizes the utilization of electrical power in place of hydraulic, pneumatic, and mechanical power to optimize the performance and life cycle cost of the aircraft. The MEA requires a highly reliable, fault tolerant, autonomously controlled electrical power system to deliver higher quality power and electrical levels to the aircraft's loads. Also, reliable high integration and safety of the electrical power system leads to the use of distributed generation and control architecture.

The advantages of More Electric systems are not confined to aircraft. Other transport systems, such as marine propulsion, are also moving in this direction [4].

The next sections briefly discuss a general overview of the electrical power generation system and electric drives on the MEA, especially with regard to the flight controls. A brief introduction to the safety aspects of the flight controls has also been included.

ELECTRONIC POWER SYSTEMS

The first factor to take into account is the large amount of power electronics for power conversions and power users that MEA will involve: at least 1.6 MW for a next-generation 300 pax aircraft. The development of efficient and secure power electronics technologies is a great challenge. However, not only are power electronics necessary, but also efficient control of the electronics must be developed.

One major evolutionary technological advance that has contributed greatly to the feasibility of an electric aircraft non-propulsive power system has been the development of reliable, solid-state, high power-density, power-related electronics. Generator power control units, inverters, converters, and motor controllers consist of state-of-the-art silicon-based power semiconductor switching devices that include integrated gate bipolar transistors (IGBTs). It is expected that advanced composition, high-performance multi-layer ceramic capacitors will dramatically improve the power density of future inverters, converters, and motor controllers. Improved, high-efficiency electric circuit topologies are also the subject of on-going research.

Some of the higher power level equipment is actively cooled through the use of oil circulation or forced air convection. The extent of the use of active, fluid-based cooling systems is extremely application-specific and is yet to be determined. Lightweight, simplified, passive (non-pumped fluid-based) thermal management techniques are also a focus of research and will be used, wherever feasible, to maintain high reliability.

Power Distribution and Management Systems (PDMS) provide fully automatic monitoring, control, protection, and switching of aircraft electrical loads under normal and emergency conditions with load management, including automatic load shedding and restoration, to make best use of available power. These systems comprise the Primary Power Buses, located close to the generators, with high power contactors and circuit breakers, and the Secondary Power Distribution Buses, located in the avionics bay, which provide the monitoring and control of the system, and contain some same circuit breakers and remote power switches.

The use of programmable solid-state devices and switching power devices in place of traditional electromechanical circuit breaker technology provides benefits to the aircraft in terms of load management, fault isolation, diagnostic health monitoring, and improved flexibility to accommodate modifications and system upgrades.

With these advancing technologies, it will be feasible to use high power-density electrical power components to drive the majority of aircraft subsystems. These will become easier to maintain (supported by less equipment and manpower), more durable, lower in cost, and higher in performance.

The engine primarily provides thrust, but it also produces all other power (Figure 1). In a MEA, current engine accessories that derive power form gearbox mounted pumps will be replaced with electronically-driven electrical machines. Vibration resistance, electromagnetic compatibility, and size constraints are key design challengers of embedding electrical machines into the engine. The integration into a harsh environment of engine off-takes for aircraft system needs without significantly affecting engine performance is also a difficult task.

By deleting air off-takes, virtually the only requirement the engines have to satisfy is to provide electrical power. Whilst the hot-air bleed ducts and the pre-cooler are removed, several other integration issues arise, such as generator thermal management, mechanical integration, new electric starting requirements, and electrical power conversion, (whether the chosen solution is a conventional gearbox-mounted generator or an embedded power-optimized generator).

Conceptually, electrical power for an MEA would be produced by a starter/generator directly driven by the gas generator spool of the main engine. Power is transferred out of the engine through wires that feed into a fault-tolerant electrical network to drive the aircraft subsystems. Electronic power converters would transform the electrical power and no accessory gearboxes would be necessary. Elimination of gearing and associated gear separation forces enhances the use of advanced magnetic bearing systems [5], which could be integrated into the internal starter/generator for both the main engine and auxiliary power units.

For many years, electrical power for aerospace applications has been generated using a variable ratio gearbox-mounted wound-field synchronous machine to obtain a three-phase 115 V AC system at a constant frequency of 400 Hz. This machine is known as a Constant Frequency Integrated Drive Generator (IDG), and today it is still the most commonly used. However, operating experiences under the new requirements of lower cost, increased reliability, easier maintenance, and higher operating speed and temperatures have shown that a replacement for the gearbox using power electronics has obvious advantages. A high quality three-phase AC-DC conversion plus subsequent DC-AC conversion is one of the steps involved in achieving these objectives. The resulting system is known as variable speed constant frequency (VSCF) system, and it results in promising technology that meets these requirements.

Figure 4 shows a typical block diagram of a VSCF system. In the motoring mode, the constant frequency system supplies the machine through the power converter, and the system acts as a starter for the aircraft engine. In the generating mode, the main engine moves the machine, providing electrical power at a variable frequency which is transformed into a constant frequency by the power converter.

The bidirectional power converter can be built using a DC link in a back-to-back topology – a mature technology in use in civil aircraft (Boeing, MacDouglas, etc.) or by using a direct AC-to-AC converter. This is a new technology that is increasingly used in military fighter aircraft.

The matrix converter [6] is a clear alternative to any other AC-to-AC converter for aerospace applications. The converter consists of nine bi-directional switches arranged as three sets of three so that any of the three input phases can be connected to any of the three output lines. The switches are then controlled in such a way that the average output voltages are a three-phase set of sinusoids of the required frequency and magnitude. Some of the advantages of the converter that make it a promising technology for the near future are as follows:

- A higher power ratio with a lower size and weight.
- Unity power factor control.
- It is free from bulky reactive components (especially large electrolytic capacitors).

Electromagnetic interferences due to large currents and voltages high frequency switching are the main disadvantage of power electronics supplying actuation systems. These interferences can be alleviated by reducing the length of electrical cables supplying power and even more by integrating the matrix converter into de motor-actuator system. Moreover, the ability of matrix converter to supply almost sinusoidal currents helps to reduce these interferences as well.

Application of higher voltages is also investigated, which allows reducing the weight for the power used. 230/400 VAC 400 Hz could be relevant for some electrical subsystems because of its lighter weight generator system. 270 VDC is commonly used as DC link bus voltage, whereas the motor controllers can use even higher level, 540 VDC.

Another solution to generate electrical power for the aircraft consists in variable-frequency (VF) power generation, which allows designers to discard the complex and difficult-to-maintain equipment necessary to convert variable-speed mechanical power produced by the engines to constant-frequency electrical power traditionally used by aircraft systems. By this way, variable-frequency power generation increases reliability of the whole system. Of course, aircraft's systems such as fuel and hydraulic pumps and EHA/EMA actuators have to be designed to be compatible with VF generation and distribution.

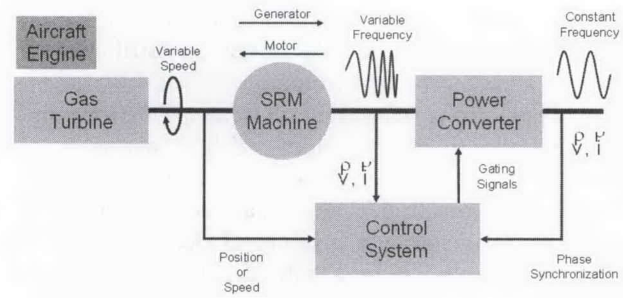

Fig. 4 VSCF Starter/Generator System

Variable-frequency power generation is now coming for large aircrafts, and it is expected that power generation reliability will be increase by about 50 percent, although the challenges related to advanced electromagnetic technology, high-speed electronic voltage regulation and system protection to maintain high-level power quality over the wide output range have to be solved.

The switched reluctance machine is very promising as an integral starter/generator system in future aircraft integral engines. The simple rotor construction and high power density of the machine permit high speed and high temperature environment operation. The possibility of direct-driving and, hence, the elimination of gear boxes and hydraulic accessories in the aircraft may give it in an advantage over the classical synchronous and induction machine technologies.

Reduction of an aircraft's multiple secondary power subsystems to a single electric subsystem is another challenge under development. There are numerous generator and distribution choices to be made for this architecture, such as ECS and Electro-Thermal WAI, but careful application of the necessary system integration must be done, and analysis tools to design and verify the integrity of the new hardware- and software-based systems are necessary.

Apart from generators and loads, other elements are needed for the control and management of high-power electrical energy. Power electronics and control are seen as the major and most crucial technologies for an MEA, which faces the challenges of reduced package size, higher power capability, reduced acquisition cost, and high efficiency.

ELECTROMECHANICAL ACTUATORS

Subsystems of the MEA include power electronics, power controllers, converters, inverters, and associated components, which have a direct impact on the viability of the MEA, especially in the case of control actuators. The basic building blocks for control actuators are solid-state power electronics and variable speed motor drives. Fully fault-tolerant Control Management and communications for decentralized systems are also required to link and control the wide range of variables used.

In the area of Actuation Systems, alternative architectures incorporating electro-hydrostatic, hybrid and electromechanical actuation for primary and secondary flight control (as well as new landing gear, braking, nacelle actuation, and horizontal stabilizer architectures) are being examined. A large number of actuators have been studied, most of them electromechanical except flight control actuators due to the showstopper jamming case.

In the last decade, a lot of research has allowed Electro-Hydrostatic Actuator (EHA) technology to be mastered. One result of this on new aircraft such as the Airbus A380 or Boeing B7E7 is the replacement of the hydraulic circuits by EHA networks. These are used as a back-up for other hydraulic systems, although there is increasing interest in the use of electric drives to substitute hydraulics and electro-hydraulic systems in aircraft. In such systems, an electric motor directly drives a pump, a fan, or an actuator.

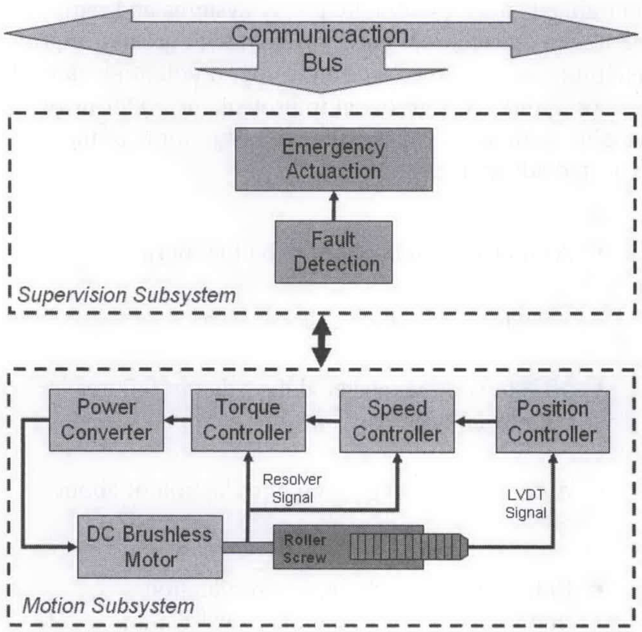

Fig. 5. Direct Drive architecture for EMA

In fact, the next step from the present hydraulic or electro-hydraulic actuation (EHA) in a centralized system, to the use of Electromechanical Actuators (EMAs) in de-centralized systems (while maintaining the same level of safety) is today of major importance for aeronautics. The objective is to reduce production and maintenance costs. Furthermore, these highly safe and reliable EMA technologies, which are jamming free, will help to satisfy the social demand for sustainable transport.

EMA technologies are already being used in aeronautics, but for safety reasons they are limited to Secondary Flight Controls or military aircraft [7]. Their application to Primary Flight Controls will allow reductions in the weight of drives, gas consumption, and polluting emissions. The major step in moving from EHAs to jam-free EMAs is the prevention of potential jamming cases by appropriate technology and monitoring, thus giving the system aircraft availability for dispatch and failure sizing cases.

Electromechanical Actuator drives for flight controls are based on a Direct Drive architecture built up by an electric motor, (usually a Permanent Magnet Synchronous Motor, PMSM) directly connected to the roller-screw that moves the actuator (Figure 5). The power stage can be built up either by standard inverters or by new matrix converter architectures. The complete control block diagram for an EMA drive includes the position, speed, torque and flux controls, and also the supervisory and communication systems.

From the previous statements, it is clear that not only power electronics, but also electric machines, are becoming more and more important in the general electric aircraft power system, both for generation and load control. Specifically, the PMSM is increasingly being used for actuator drives, due to its high efficiency throughout the full speed range, high power ratio, and ease of refrigeration, compared to classical wound machines [8].

The drive operating the flight control must ensure continuity in operation even in the case of a fault. Dual redundant power drive electronics providing motor drive, speed closed-loop, and control management can help to overcome this issue. With more electronics in the actuators, it is also possible to predict how long an actuator will last, introducing the predictive maintenance instead of preventive maintenance today used by airlines.

The drive should also be able to diagnose and report the nature of the fault. The system must also have the following general characteristics [9]:

- *Testability*, to make verification and real-time check-out easier.
- *Reduced complexity and low maintenance costs*, by the decomposition of the main CPU into smaller distributed controls for every EMA, many of them consisting of identical hardware.
- *Intelligent software* running in every control node, which must be able to exchange information by means of standard interfaces.

To achieve the above specifications, control and diagnosis of the EMA needs to rely on modern electronics. As in other fields, digital computer control systems have been incorporated into aircraft avionics system design. Digital systems are more reliable, lighter and more adaptable to change or modifications, as well as providing self-test capability. For these reasons, embedded digital control systems are going to be extensively used in the aeronautical industry.

The growth of electronics has also led to drive-by-wire control systems in which there are no physical connections (mechanical, pneumatic, or hydraulic) between sensors, controls, and actuators. Similarly, a fly-by-wire (FBW) aircraft has no physical connections between the pilot's stick and the aircraft's control surfaces, including the Primary Flight Controls. Moreover, advanced digital systems make automatic checking for faulty signals easier, which allows damaged channels to be identified and disconnected before they can jeopardize the safety of the whole aircraft – although control redundancy is needed to ensure sensor and actuator control even under fault conditions.

Additional advantages concern redundant equipment. In current systems, general flight controls are usually implemented by fault tolerant centralized redundant systems, which are built up by complex and expensive Central Power Units. The new distributed EMA architectures allow us to work on a completely different basis by enabling the isolation of any faulty equipment from the full actuator network by means of a simple switch. The benefits of such an arrangement include power source redundancy and an increased margin of safety, resulting from the introduction of the electric dissimilarity in the power sources.

Finally, we should make mention of the interconnection of nodes in such a distributed system. The topology for the interconnection may be a physical broadcast bus, a star-coupled system, a ring system, or any combination of these. As is easily seen, the backbone comprising the communication subsystem is a critical component for distributed control systems.

As regards flight controls, the actuator nodes are connected via a communication bus to which sensor and cockpit nodes are also connected. Actuators alone need at least half of the total communication bandwidth of the bus. For safe operation, the physical architecture of the bus must not affect the interconnected system in the case of a failure, either in the bus itself or in the node. The damage to the bus must also be immediately detected and a redundant system must be turned on.

Redundant channels are often used for protocols aimed at achieving fault tolerance against more bus failures. If these redundant channels are combined with redundant nodes, it is possible to increase the reliability of the whole system. Currently, new buses and protocols are being validated and verified for these purposes [10], and there are significant on-going efforts to establish standards for future safe communication protocols, particularly for fly-by-wire

CONCLUSIONS

Historically, there has been a desire to use electrical power as the single motive force for all non-propulsive onboard aircraft functions. Due to recent advances in solid-state power-related electronics and reductions in the weight and volume of controls for high-speed electric machines, an MEA is now considered feasible.

By generally reducing hydraulic parts and the weight of the power systems in aircrafts, the MEA concept aims to bring about significant changes in power management and use, which up to now have not been technologically possible. However, a variety of mature technologies are in use today. The common goal is low-cost, high-performance and safe electrical power components.

Based on rapidly evolving technology in ultra-reliable, miniaturized, high-efficiency, and affordable power electronic components, embedded control electronics, fault tolerant electrical power distribution systems, and electric primary flight control actuator systems, the "more electric" focus will also permit us to reduce the number of power transfer system functions and use the potential of ultra-reliable miniaturized power electronics, fault tolerant electrical distribution systems and electric generators/motors and drives/actuators to increase performance, and reduce Ground Support Equipment (GSE) and Operation and Support (O&S) costs.

For the first time in aeronautics history, the MEA approach may dramatically reduce or eliminate the need for centralized aircraft hydraulic power systems and replace them with an electrical power system with greatly improved reliability, and maintenance and support potential, as well as the possibility for significant improvements in terms of weight, volume, and system complexity. Some of the expected advantages are:

- A significant reduction in the fuel burn.
- A reduction of maintenance costs.
- 50% fewer unexpected delays due to failures in the power systems.
- A power electronics weight reduction of about 50%.
- Enhanced competitiveness, production improvement, and technology validation.

The advantages of More Electric Systems are not confined to aircraft. Other sustainable transport systems can also take advantage of the advances in this area.

ACKNOWLEDGMENTS

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