ELECTRICAL GENERATION AND DISTRIBUTION FOR THE MORE ELECTRIC AIRCRAFT

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ABSTRACT

The aircraft industry is developing the More Electric Aircraft (MEA) with an ultimate goal of distributing only electrical power across the airframe. The replacement of existing systems with electric equivalents has, and will continue to, significantly increase the electrical power requirement. This has created a need for the enhancement of generation capacity and changes to distribution systems. The higher powers will push distribution voltages higher in order to limit conduction losses and reduce cable size, and hence weight. A power electronic interface may be required to regulate generator output into the distributed power form.

Keywords: More Electric Aircraft, Aircraft Generation, Aircraft Distribution

1 INTRODUCTION

The All Electric Aircraft (AEA) concept, distributes only electric power across the airframe, replacing the existing range of secondary power distribution systems. Secondary power on aircraft is provided from engine driven systems in four forms: mechanical, hydraulic, pneumatic and electrical [1-4].

- The mechanical system provides power for engine mounted accessories such as oil, fuel and hydraulic pumps; and electric generators.
- Hydraulic systems primarily provide actuation of flight surfaces, landing gear and doors.
- The pneumatic system derives pressure from a gas turbine off-take and provides heat and pressure for anti-ice protection engine start and cabin environmental control.
- The electric system provides power for: avionics, lighting and galleys etc.

It is expected that significant cost and performance improvements can be achieved by consolidating power distribution into a single all electric system [1-5]. A reduction in complexity and an improvement in maintainability are the anticipated benefits, summarised in Table 1. The electrical system is the only system that has the potential to perform the tasks of all the other power systems.

The goal of the AEA is to be gradually achieved through a series of progressively MEA [1, 3]. Each evolution of MEA will have increased electric power demand and a significant increase in generation capacity is required to supply the additional loads [1, 2, 6, 7]. The magnitude of the increase is illustrated in Figure 1 by the location of the A380 and B787 forthcoming MEA.

Table 1: Comparison of aircraft secondary power distribution systems

System	Complexity	Maintainence	Technological Maturity
Electrical	Complex	Simple	System (Mature), New Technologies (Immature)
Hydraulic	Simple	Complex & Hazardous	Mature
Mechanical	Very Complex	Frequent & Slow	Very Mature
Pneumatic	Simple	Complex	Very Mature

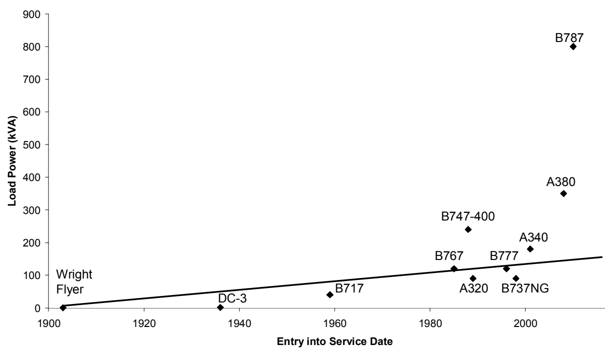


Figure 1 Electrical load power demand trend on civil aircraft. The step change in capacity of the MEA is visible as the deviation of forthcoming aircraft from the trend line.

The trend towards the MEA requires changes to the conventional electric system architecture. The increased power demand of additional loads requires an increase in generation capacity and may necessitate multiple generators per engine particularly on twin engine aircraft [8]. The power requirement of electric environmental control is expected to be approximately 500 kW [9], significantly greater than can be supplied by a single generator. Conventional electric system designs typically do not permit a single load to be supplied from more than one bus, neither are multiple generators allowed to supply a single bus. A MEA with electric environmental control will have to employ a distribution system capable of supplying a single load with power from multiple sources [8].

The electrical system will evolve to meet the MEA requirements: this will be achieved by enhancing generation and distribution capabilities. The remainder of this paper reviews the expected changes to these segments of the electric system and explains the need for a power electronics interface between the generator and distribution channel. Power electronics will be needed to supply a large number of system loads that are sensitive to the form of power which they are supplied.

2 MEA GENERATOR TECHNOLOGIES

On conventional civil aircraft, the generator is driven from an accessory gearbox mounted on the gas turbine. A Constant Velocity Gearbox (CVG) connects the accessory gearbox with the generator and maintains the fundamental electric frequency at 400 Hz [3, 10]. Civil aircraft generators are three stage Permanent Magnet (PM) excited wound field synchronous machines; a Generator Control Unit (GCU) performs field control of the generator's second stage [10, 11] regulating the terminal voltage, from which it is distributed directly. Figure 2 illustrates a three stage wound field aircraft generator.

The Airbus A380 is a first generation MEA [11] which has optimised the electric system by removing the CVG, permitting the fundamental electric frequency to vary over the range of engine speeds between 360-720 Hz [6, 11]. As part of MEA development, engine manufacturers intend to produce a progressively More Electric Engine (MEE) to improve efficiency, simplify the system and meet the needs of the MEA [1, 4]. The MEE goals change the way generators are driven and the location of the generator within the engine. It is anticipated that generators will be driven from multiple engine shafts [4, 7, 12-14], as power levels are perceived as too great to take from a single shaft. It has also been proposed that control of these generators could potentially enhance engine control during transient operating points [4]. Each generator is thus operating at a different speed, some of which may possess significantly higher electrical frequencies than implemented previously on aircraf [15]. These generators may eventually be embedded on their respective engine shaft, placing them in higher temperature operating environments. Alternative machine types such as PM and Switched Reluctance (SR) are likely to be used in such situations [11, 14, 16] as they can tolerate higher temperatures than wound field machines. Power electronics is essential to combine and regulate this power for distribution [4, 7].

2.1 Additional Applications

The AEA and all electric engine may use engine mounted generators to perform additional tasks. One proposal is that an AEA omits the Ram Air Turbine (RAT), instead using the windmilling action of the gas turbine to generate emergency power from the low pressure shaft mounted generator [12, 15-18]. This implies the generator will be operated over a speed range of around 12-14:1 [11, 15-19] far greater than the 2:1 operating region of the A380. The provision of emergency power at low speed means a constant power

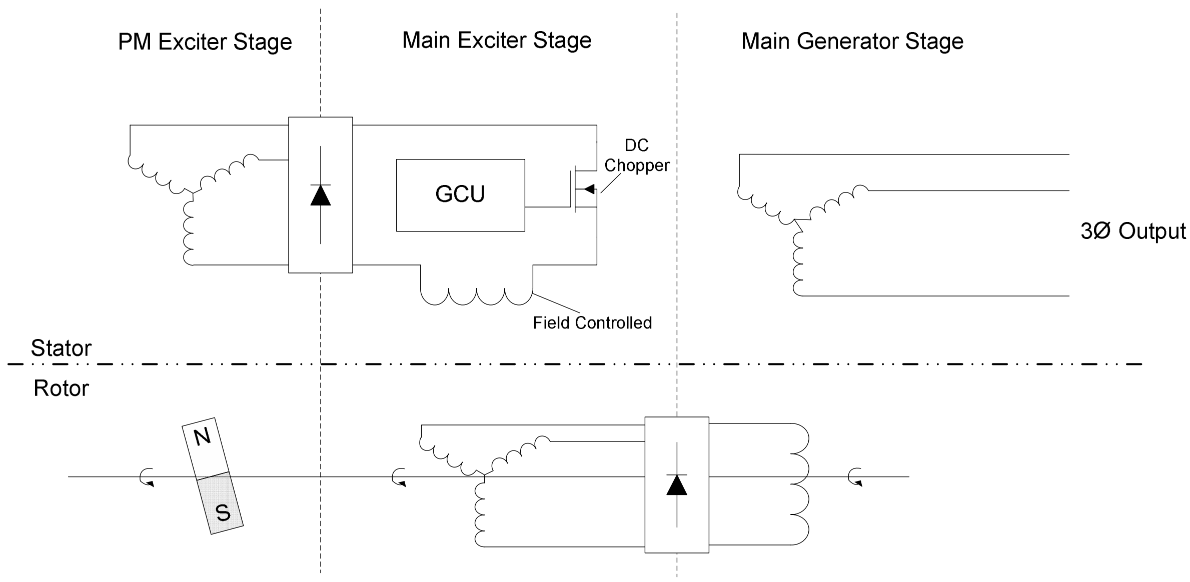


Figure 2 Three-stage wound field aircraft generator. A PM exciter stage generates sufficient energy to induce a magnetic field on the main portion of the rotor. Field control of the main exciter stage is used to regulate main rotor field strength so that a constant voltage output is produced.

is not required over the whole speed range.

Engine start is normally provided by the pneumatic system, so will be replaced by an electric equivalent in the MEA. A reduction in mass is to be achieved by operating the electric generator as a starter motor rather than adding additional system components [1, 4, 12, 13, 20, 21]. Gas turbines have high inertia so large torque capability is required from zero speed this is not an inherent capability of conventional wound field generators. For starting the main and the exciter stators need to be externally powered by a power electronic converter as the PM stage is unlikely to provide sufficient excitation power.

2.2 The PM Option

A PM generator satisfies a large number of the criteria for a MEA generator. Achievable power densities are high [22, 23], and maximum torque is available from zero speed. In comparison with a wound field machine the rotor is mechanically simple, however difficulties are associated with magnet retention during high speed operation. High generator operating speed is anticipated in MEEs so a high strength magnet retention method will have to be utilised. The machine is fully excited at all speeds so in the windmilling condition sufficient power can be generated to power the emergency bus in the critical fault condition. This is in contrast to the wound field machine where the speed of the rotor determines the power provided to the main exciter stage and thus the main rotor field strength.

Operating temperature significantly affects the field strength of PMs; Samarium Cobalt (SmCo) based compounds exhibit the highest tolerances to heat with grades available with a temperature co-efficient of -0.03%/ºC [24-26] that can be used in environments up to 350ºC [26]. This is the current operating environment ceiling to which PM machines can be employed.

Voltage regulation of PM generators has to be achieved with power electronics, which have considerable mass and volume [1, 27, 28]. Advantageously the use of a power electronic converter stage allows ac or dc distribution bus requirements to be achieved.

Being permanently excited, the field in a PM machine cannot be disabled as with a wound field machine. This can result in undesirable torque ripple [29] and elevated temperatures due to excessive current flow during fault operation. Fault tolerant PM machines have been developed with an increased number of phases and separated phase windings to mitigate these issues [22-24, 30].

2.3 SR Option

SR machines are inherently fault tolerant [22, 31] and mechanically sound as the rotor is a single laminated component [32]. The lack of electric and magnetic components on the rotor reduces the need for rotor cooling permitting operation in high ambient temperature environments in the region of 400ºC [31]. The salient shape of the rotor causes windage losses [31] which become significant at high speed; the gaps may be filled with a non magnetically permeable material to prevent this loss [31] but a mass penalty is incurred. Achievable power densities in a SR machine are lower than those possible with PM designs [22].

A power electronic drive is needed to operate a SR machine. Such a drive is similar in size and weight to those used in conjunction with PM machines. The power electronics allow the machine to provide constant power over a speed range [31, 32].

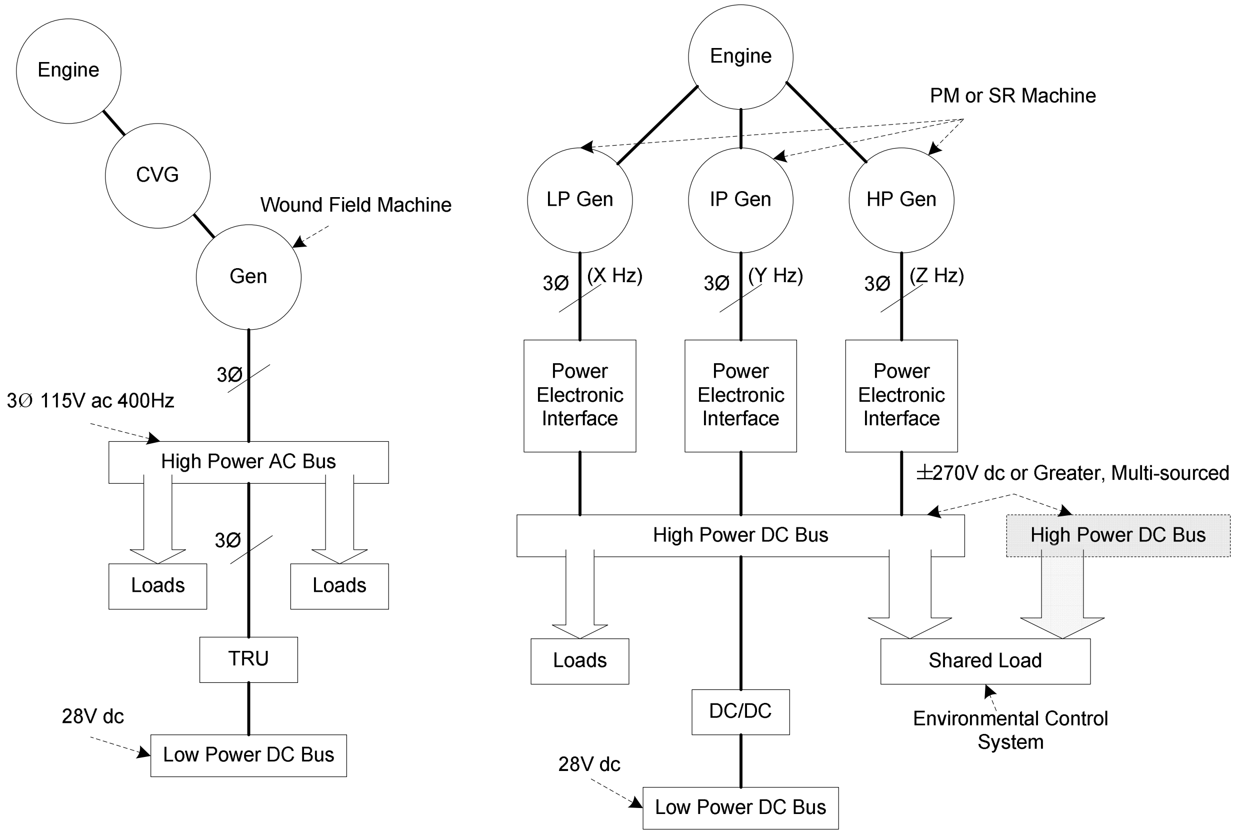
3 DISTRIBUTION FOR THE MEA

In the electric system configuration of a typical pre-MEA, power is primarily generated by a single generator driven from the accessory gear box on each engine. The Auxiliary Power Unit (APU) exists as backup in case an engine or generator fails; additionally it provides power when the engines are turned off pre-flight. Alternatively, pre-flight power is provided from an external connection where one is available. If all main generators and the APU fail in flight the RAT is deployed to supply essential loads [3].

In pre MEA power is distributed at two power levels; high power buses distribute 115 V 400 Hz three phase ac [3, 4, 11] and low power buses 28 V dc. Each engine mounted generator supplies a single high power bus; in turn each high power bus supplies a corresponding low power bus as in Figure 3a. Conversion between the two power forms is accomplished by a Transformer Rectifier Unit (TRU). Further description of possible configurations can be found in references [3, 10]. The remainder of this document focuses on the high power portion of the system.

Distribution voltages on next generation MEA (e.g. B787 and A350) will double to 230V three-phase ac [12] to reduce conduction losses as the system power level increases; to maintain efficiency this trend may continue in line with power level rises. Future architectures will additionally rectify the 230V ac bus deriving a ±270 V dc (540 V dc) sub-bus.

Work by Rolls Royce on generation from multiple shafts and consequentially different fundamental electric frequencies has determined that combination of these power sources is best achieved by power electronic regulation onto a dc bus [4]. This and other work [11, 19, 33] predicts the AEA will have a primarily dc electric distribution system. Power electronics will enable a generator to be interfaced with a dc distribution channel [4, 7, 11]. Figure 3b contrasts a conventional civil aircraft electrical generation and distribution channel with the described AEA/MEA topology, illustrating the off-take of power from several turbine shafts and load sharing between buses.



(a) pre-MEA electric distribution channel (Constant Frequency)

(b) Potential AEA electric distribution Channel

Figure 3 Comparison between aircraft electric system channel topologies. (a) Pre-MEA electrical system channel, main power is distributed as three-phase at a constant 400 Hz produced by a three stage wound field generator driven via a CVG. (b) Potential AEA electric system channel, main power is distributed as high voltage dc, with some loads powered simultaneously by multiple buses. PM and/or SR machines generate electrical power from different engine shafts operating at different (variable) electrical frequesncies.

4 POWER ELECTRONICS IN THE MEA

A need has been identified for a power electronic interface between the generator and the distribution bus. The interface is required to facilitate a multitude of tasks:

- Regulation of the distribution bus from a variable voltage and frequency source.
- Efficient operation over a wide speed and power range i.e. from full-throttle to emergency power provision.
- Operation at very high fundamental electrical frequencies e.g. over 1 kHz when the engine is at full-throttle.
- Bi-directional power flow to allow engine start.
- Combine power from multiple generators operating at different frequency and voltage levels.
- Be physically distant from the generator i.e. a long cable length is present between the generator and the power electronic interface with possible EMC implications.
- Stable and rapid response to load changes

In addition to satisfying these requirements, as this is an aerospace application the system must be small and light weight.

4.1 Fault Tolerance

The need for fault tolerance in aerospace generator applications has been described in section 2.2. For an electric machine to be fault tolerant requires the machine drive also possesses fault tolerance characteristics [22, 23]. The primary failure modes of a power electronic converter are switching device failure open/short circuit, and dc-link capacitor failure [22, 23]. Fault tolerant drives provide complete electrical isolation of phases, this maintains operation of fault-free phases should a switching device failure occur. Most solutions realise this by connecting each phase to separate H-bridges [22, 24, 29, 30], thus the complexity increase associated with phase number is large, causing reliability issues for machines with 6 phases or more [30]. The use of the H-bridge connection requires a small device rating increase from the line voltage to the dc-link voltage, a small extra volume penalty [22] in addition to the need for four switching devices per phase [30]. Control strategies are being developed at the University of Sheffield that compensate for torque imbalances within faulted brushless permanent magnet machines which utilise such drives [29, 30, 34]. A suggested application of this technique is for embedded aircraft generators where the application of significant torque ripple to the gas turbine is undesirable.

5 CONCLUSIONS

To meet generation capacity demands new generator technology has to be considered, especially for embedded generation systems. Mechanical integrity is set to become more important as generators will be operated at higher speeds and may in due course be an integrated part of the gas turbine. The generator will become multifunctional additionally providing engine starting torque and emergency electrical power in the engine out condition. The use of new machine types as well as changes to the distribution system and new roles for the generator all call for a power electronic converter to interface the generator with the distribution channel.

The features described have significant implications upon the converter in addition to the obvious high voltage and current handling capabilities. The use of the generator as a motor to provide engine start requires that the converter can regulate bidirectional power flow. Efficient operation over a large speed range is needed as the generator is operated from full throttle to provision of emergency power in the windmilling condition after a flame out. Full throttle operation will result in a fundamental electrical frequency in excess of 1 kHz. This in combination with a long cable run is likely to exacerbate EMC problems.

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