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Power Electronics for More Electric Aircraft

Kaushik Rajashekara
Department of Electrical Engineering, University of Texas at Dallas, Texas, USA

12.1 Introduction

Transportation as a whole is estimated to be responsible for over 20% of the world's CO_2 discharges. According to the Intergovernmental Panel on Climate Change, global aviation contributes about 2% of the global CO_2 emissions caused by human activities [1]. This estimate includes emissions from all global aviation, including commercial and military. Global commercial aviation, including cargo, accounts for over 80% of this estimate. When other emissions such as nitrogen oxide and water vapor are considered, the estimated share of aviation's global emissions increases from 2 to 3%. In the United States, according to Environmental Protection Agency data, domestic aviation contributes about 3% of total CO_2 emissions. Although aviation is a relatively small source of the emissions contributing to global warming, it is of significance because it is probable that high-altitude emissions are disproportionately damaging to the environment.

The Advisory Council for Aeronautics Research in Europe has set several goals to be achieved by 2020 for air transportation [2]. These include a 50% reduction of CO_2 emissions through drastic reduction of fuel consumption; an 80% reduction of NO_X emissions; a 50% reduction of external noise; and a green product life cycle in terms of design, manufacturing, maintenance and disposal. The goals set by the International Civil Aviation Organization are to improve fuel efficiency by an average 2% per year until 2050 and to keep the global net carbon emissions from international aviation at the same level beyond 2020 [3]. Thus, the aerospace industry is facing challenges similar to those faced by the automotive industry in terms of improving emissions and fuel economy. Another similarity is the move toward replacing mechanical and pneumatic systems with electrical systems, thus transitioning toward "more electric" architectures.

To meet the above challenges in the automotive industry, significant work has been done by developing and commercializing the electric and hybrid vehicles. In the case of airplanes, more electric architecture is the emerging trend. The intention is to move as many aircraft loads as possible to electrical

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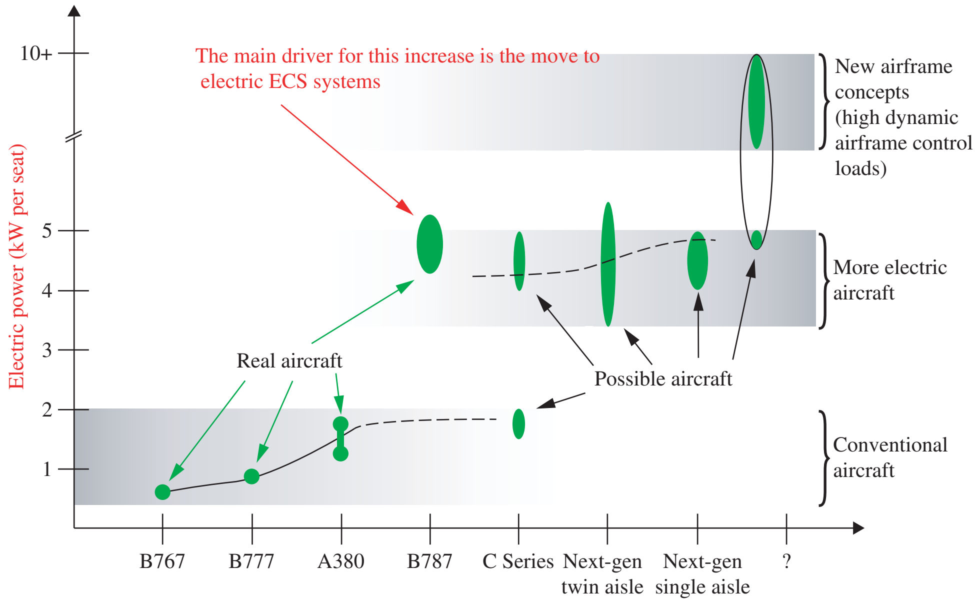

Figure 12.1 Increasing electrical power demand in civil aerospace market [4]

power resulting in simpler and efficient aircraft systems. This leads to lower fuel consumption, reduced emissions, reduced maintenance and possibly lower costs. The examples of aircraft loads under consideration are electric-powered environmental control systems (ECSs), electrical actuators and electric deicing. Electric starting of the engine and the conversion of all pneumatic and hydraulic units on the accessory gearbox (AGB) to an electrical system are also being investigated.

The electrical power being used by both civil and military aircraft is also growing [4–6]. As can be seen from Figure 12.1, the civil aerospace market is seeing rapidly increasing demands for electric power. Future trends in this market sector are not known exactly, but they could move toward ~10 kW per passenger seat, which represents a significant growth from today's level. In order to meet these requirements, a major re-evaluation of aircraft electrical generation and power distribution systems is being undertaken. The requirement for electrical power onboard aircraft is forecasted to rise dramatically in the future because of the following reasons:

- Additional electrical loads because of an increased use of electrical actuators and landing gear
- Increased cabin loads for better in-flight entertainment
- Information services and passenger comfort electrically operated ECSs
- Anti-icing of the wings
- Flight controls and other electrical loads

Passenger aircraft, such as the Boeing 787 and Airbus 380, employ a number of new electrical technologies including bleedless ECSs (in the Boeing 787). These loads are creating a substantial increase in the total electrical power drawn from the aircraft's engine-driven generators. For example, in the Boeing 787, each engine drives two generators each rated at 250 kVA producing a total power of 500 kVA. It is estimated that future electrical power requirements will exceed 500 kVA per engine. The available power generation capability of some aircraft is listed in Table 12.1.

Table 12.1 Power generation capability of some selected aircraft [6]

B717	2 × 40 kVA
B737NG	2 × 90 kVA
B767-400	2 × 120 kVA
B777	2 × 120 kVA and 2 × 20 kVA backup
A340	4 × 90 kVA
B747-X	4 × 120 kVA
A380	4 × 150 kVA and 2 × 120 kVA APU
B787	4 × 250 kVA and 2 × 225 kVA APU

12.2 More Electric Aircraft

In a traditional airplane, the jet engine is designed to produce thrust and to power the pneumatic, hydraulic and electrical systems, as shown in Figure 12.2. The pneumatic power is used for pressurization and cooling of the cabin, the starting of the main engines and for deicing the wings. The hydraulic power is used mainly for flight control actuators. The electrical power is used for supplying the power to all the electrical loads, including the computers and avionics systems. In addition, the engines drive the gearbox-mounted units, such as fuel, oil and hydraulic pumps. In a More Electric Aircraft (MEA) system, the jet engine is optimized to produce the thrust and the electric power, as shown in Figure 12.3. An electric machine is used for starting the engine and for generating electric power. Most of the loads are electrical, including the deicing and ECSs. The fuel, hydraulic and oil pumps are all driven by the electric motors.

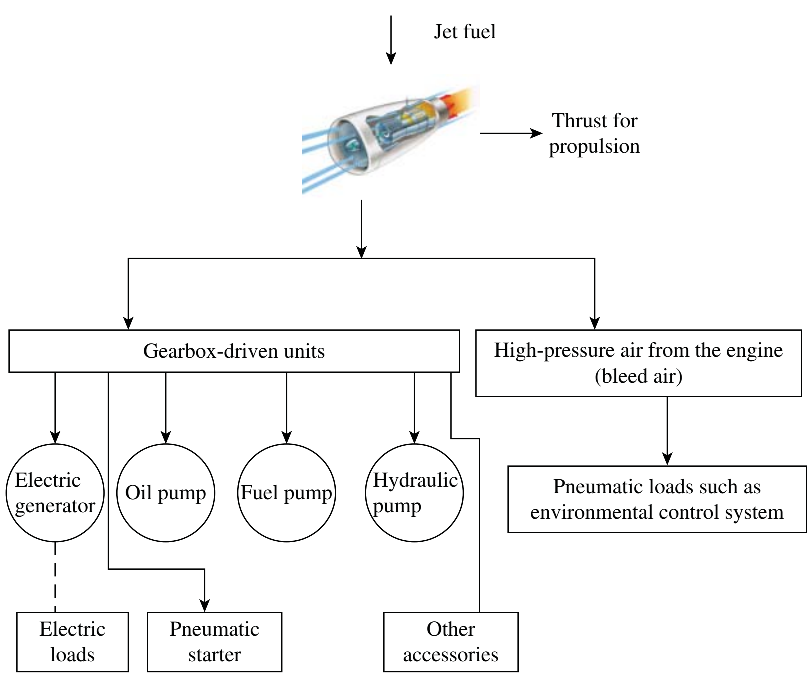

Figure 12.2 Traditional aircraft system

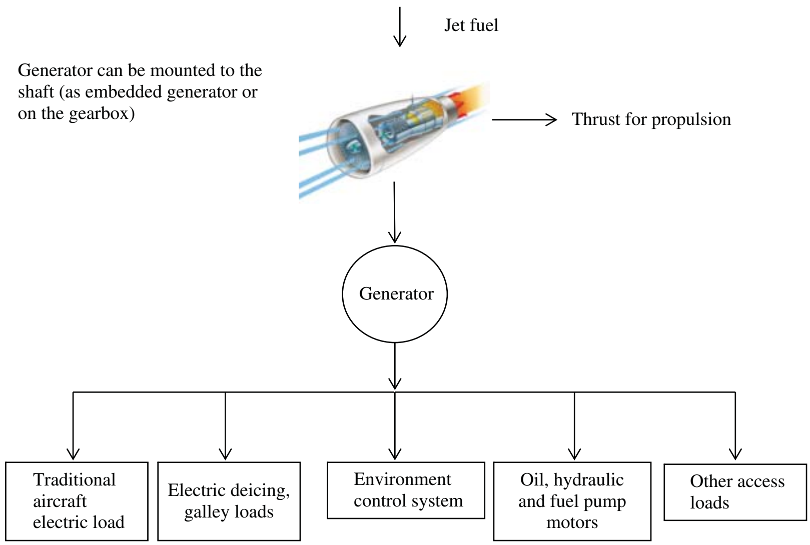

Figure 12.3 Typical more electric aircraft system

The benefits of the MEA are [5, 6] as follows:

- Better power availability throughout the flight envelope owing to the possible shift of power extraction from high spool to low spool, thus improving engine operability
- Availability of more electric power that enables the design of systems for sophisticated entertainment systems, seating comfort and so on
- Fewer constraints regarding certification of aircraft for commercial use
- Reliability and maintenance of aircraft is improved because electrical systems are easier to monitor and observe performance trends
- Enables faster diagnostics and better prediction of potential failures resulting in less downtime
- Reduction/elimination of bleed air to improve the overall performance of the engine
- Possibility of removal of engine accessory gearbox, thus reducing complexity and weight
- Increased overall performance and reduced fuel consumption and energy usage
- Eliminates high-temperature ducts and flammable fluids required in a traditional aircraft
- Reduced maintenance and ground support

More electric architecture and the associated components/subsystems are of significant interest to air framers, suppliers and the military. One of the primary motives behind the technology is the replacement of most (if not all) of the pneumatic and hydraulic systems in the aircraft by electrical systems. This has been reinforced further by the successful deployment of the Airbus 380 and Boeing 787 in the commercial arena. The MEA architecture offers significant overall system benefits in improving fuel efficiency, reducing emissions and enhancing reliability. On the other hand, the MEA concept imposes increasing demands on the generation, conversion and distribution of electrical power within the aircraft. MEA technologies are evolving continually, and there is great opportunity for improvement as systems continue to be refined and enhanced. The MEA concept is widely recognized as the future technology for the aerospace industry. The Airbus 380 and Boeing 787 systems are the two major aircraft programs that illustrate how the electric power generation and the increased use of power electronics in an aircraft are being achieved.

12.2.1 Airbus 380 Electrical System

The A380 was the first large civil aircraft to incorporate more electric architecture systems with variable-frequency (VF) power generation [6–8]. The A380 electrical system has the following:

- Four 150 kVA VF generators (370–770 Hz)
- Two constant frequency (CF) auxiliary power unit (APU) generators (nominal 400 Hz)
- One 70 kVA ram air turbine (RAT) for emergency purposes
- Four external power connections (400 Hz) for ground power

The major electrical system components of the A380 are shown in Figure 12.4. Each of the main 150 kVA AC generators is driven by the associated engine. The two APU generators are driven by their respective APUs. The main generator supplies power to the appropriate AC bus. The main AC buses cannot be paralleled because the output frequency of the generator depends on the speed of the engine driving the generator. Each output voltage of the generator is controlled by the respective generator

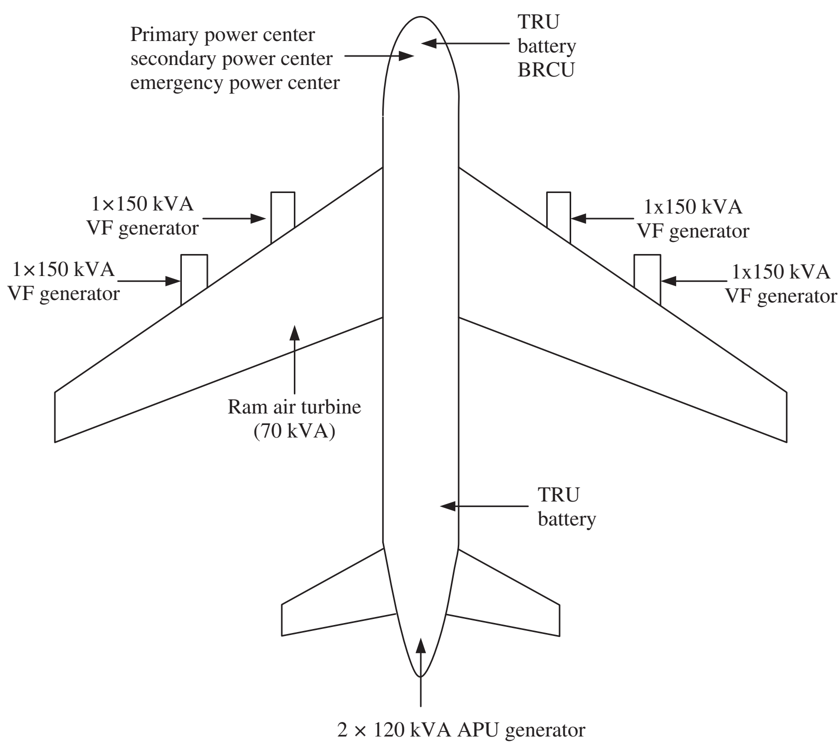

Figure 12.4 A380 Electrical power system components [6]

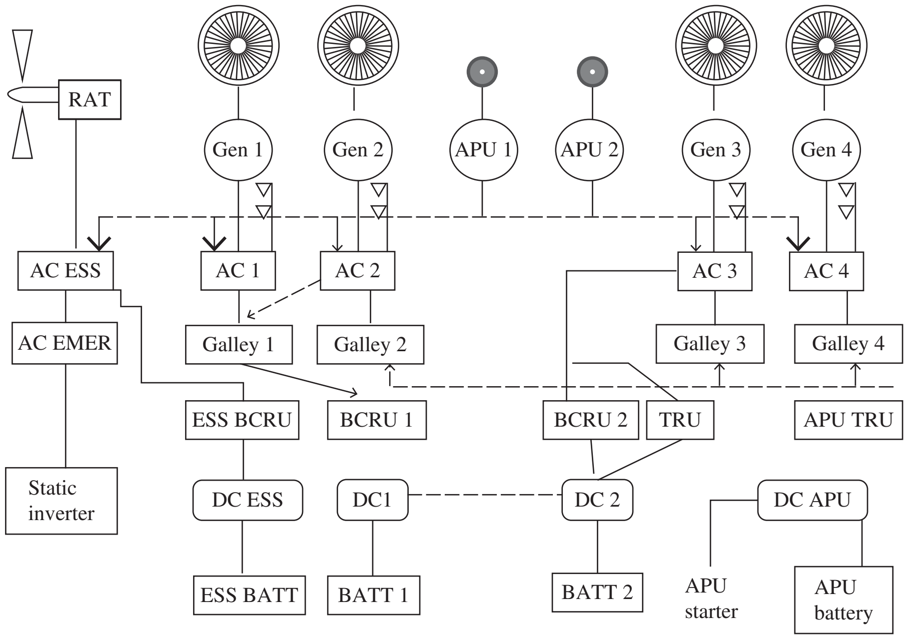

Figure 12.5 A380 DC electrical power architecture

excitation control unit (GCU). The main AC buses can also accept ground power input for servicing and support activities on the ground.

The main characteristics of the Airbus 380 power conversion and energy storage system are shown in Figure 12.5. AC1–AC4 are the AC buses at the output of the four generators, each driven by one of the four engines. There are three Battery Charge Regulator Units (BCRUs), which are based on regulated Transformer Rectifier Units (TRUs) connected to the AC bus. The AC bus also provides power to the galley loads. The DC system provides uninterrupted power capability to power the aircraft's electrical loads, including the control computers or IMA (Integrated Modular Avionics) cabinets, without power interruption during changes in system configuration.

The first A380 maiden flight took place on 27 April 2005. This plane, equipped with Rolls-Royce Trent 900 engines, flew from Toulouse Blagnac International Airport with a flight crew of six and landed successfully after 3 h and 54 min. Presently, the A380 is operating on scheduled flights by different airlines.

12.2.2 Boeing 787 Electrical Power System

The Boeing 787 has most of the features of an MEA system [6, 9, 10]. The electrical power system architecture is shown in Figure 12.6a and b. The electrical power generation system comprises the following:

- Two 250 kVA starter/generators driven by each engine. This results in 500 kVA of generated power per engine

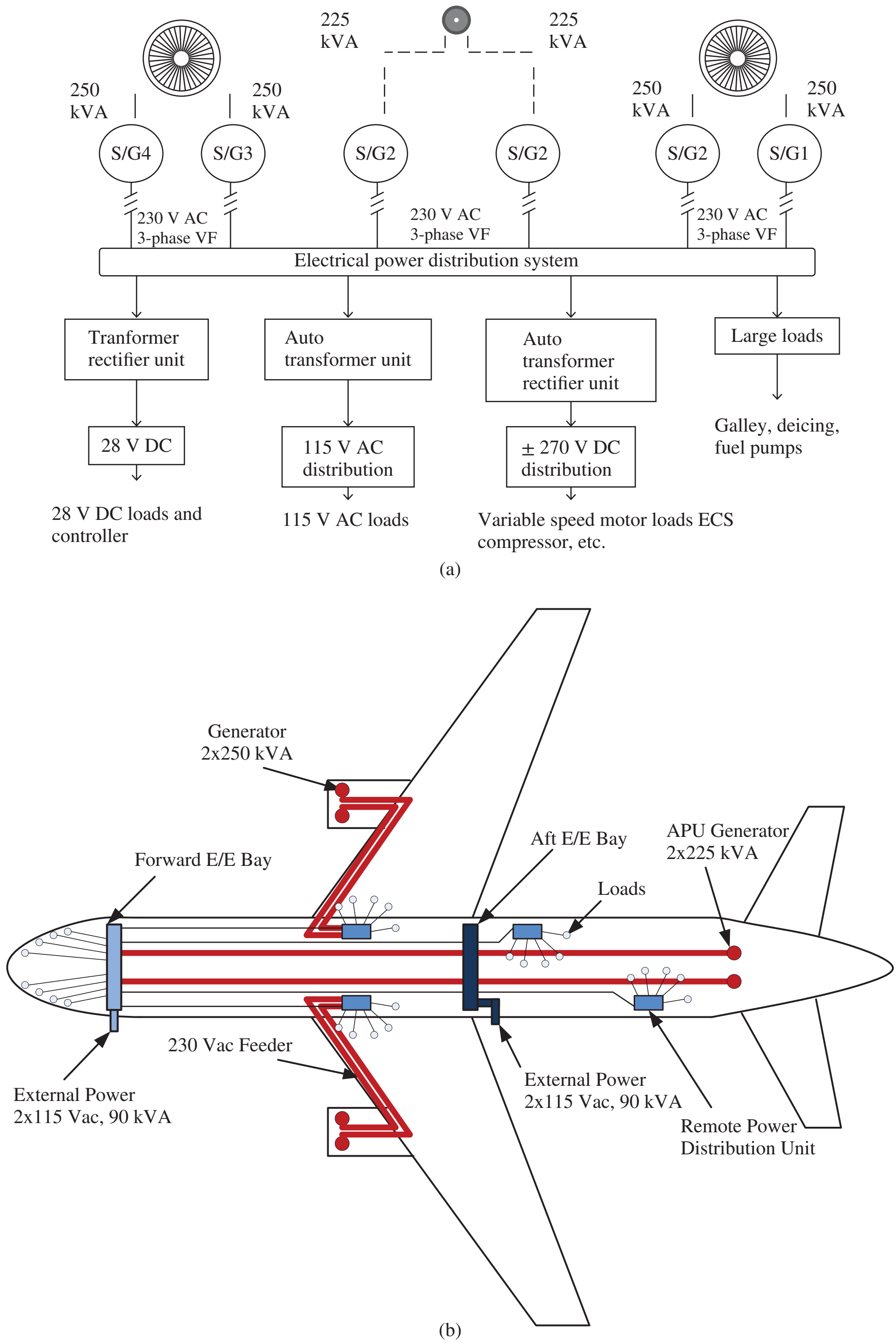

Figure 12.6 (a) Boeing 787 electrical distribution system. (b) Boeing 787 electrical power distribution system (physical locations) [10]

- Two 225 kVA APU starter/generators, each starter/generator driven by the APU engine
- Three-phase 230 V AC electric power generation with VF (380–760 Hz) compared with that of the conventional three-phase 115 V AC at 400 Hz arrangement. The increase in voltage from 115 to 230 V AC decreases losses in the cabled electrical distribution system

The maximum capability of combined power generation from the main engines and APUs is 1450 kVA. In addition to powering 230 V AC loads, a portion of the electrical power is converted into three-phase 115 V AC and 28 V DC power, in order to power many of the legacy subsystems that require conventional power supplies. As the bleed air is not used within the airframe, the ECS, cabin pressurization system, wing anti-icing system and other conventionally air-powered subsystems are all electrically powered. The only bleed air that is used from the engine is low-pressure fan air used for anti-icing the engine cowl. The main electrical loads are as follows:

- ECS and pressurization. Four electric compressors are used for cabin pressurization
- Electrically heated cargo bay
- Four electrical motor pumps, each of 100 kVA for the cooling loop of high-power motor controllers and galley refrigerators
- Wing deicing, which requires electrical power of the order of 100 kVA
- Flight controls
- Four electric motor pumps driven by 88 HP motor
- Electric brakes
- Landing gear, which is raised electrically

The maiden flight of the Boeing 787 took place on 15 December 2009, and flight testing was completed in mid-2011. The aircraft entered into commercial service on 26 October 2011.

12.3 More Electric Engine (MEE)

The embedded generation system, together with the use of electric pumps, will lead to a More Electric Engine (MEE) system [11–13]. The MEE replaces the current hydraulic, pneumatic and lubrication systems with electrical systems. This results in a lighter, more efficient, better performing, more reliable and less costly engine that can be more easily integrated into airframe systems.

A typical MEE architecture is shown in Figure 12.7. An electric machine with starter/generator capability is mounted on the high-pressure (HP) shaft of a two-spool engine and a generator is mounted on the low-pressure (LP) shaft of the engine. In addition, the oil, fuel and hydraulic pumps are driven electrically by their respective electric motors. The LP- and HP-shaft-mounted electric machines could be traditional wound-field synchronous machines or permanent magnet (PM) or switched reluctance machines. The motors driving the pumps could be PM brushless DC motors or induction machines. These motors are controlled using pulse-width modulation (PWM) inverters. The 28 V DC required for FADEC (Full Authority Digital Electronic Controller) and other flight controls are derived using a DC–DC converter operating from the 270 V DC supply. This 270 V DC power is obtained from the aircraft's APU or from a battery. For ground starting of the engine, the 270 V could also be derived from a ground-based APU.

12.3.1 Power Optimized Aircraft (POA)

The Power optimized aircraft (POA) is an MEE program that was demonstrated with the support of European funding [14–16]. POA was initiated in 2002 and was aimed to address and integrate technologies for a more efficient aircraft. The principal objective was to validate at an aircraft level, both qualitatively

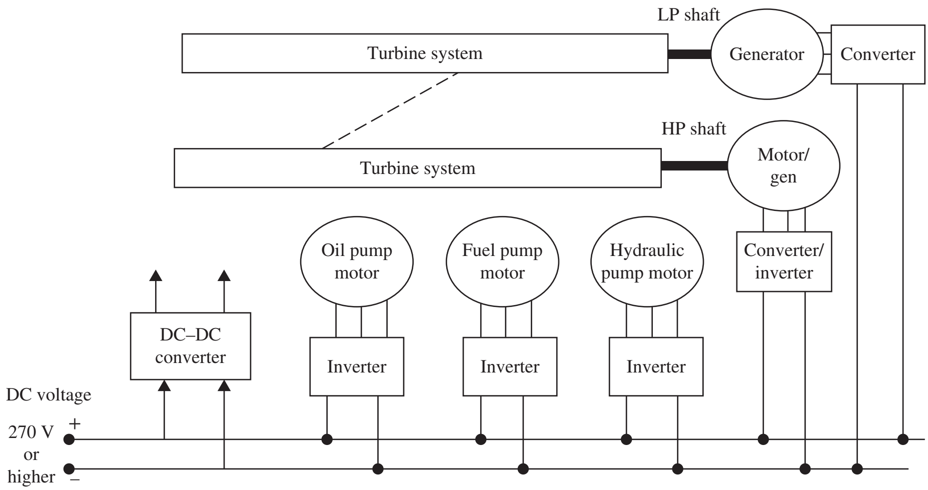

Figure 12.7 More electric engine system

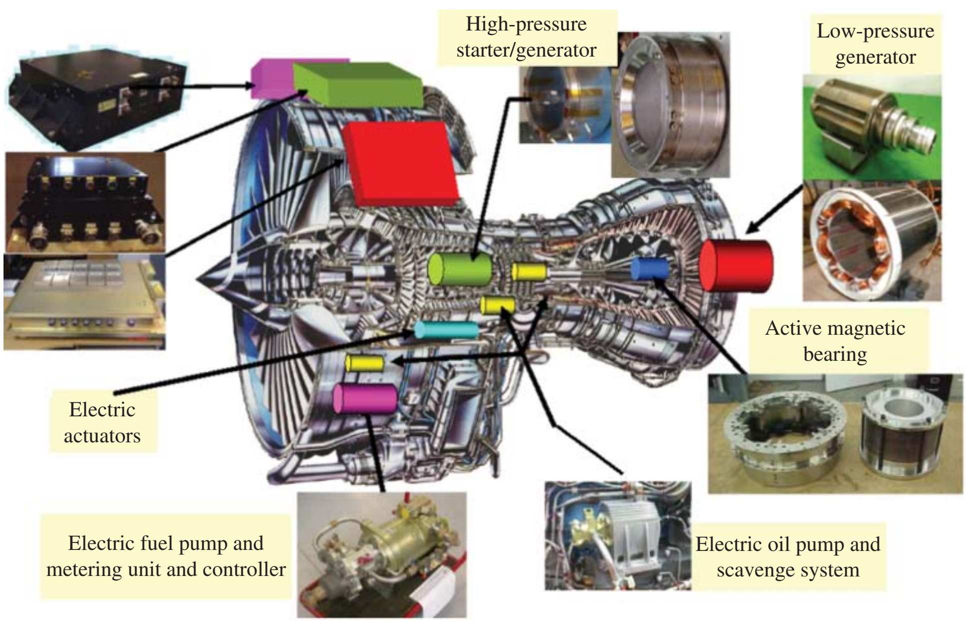

Figure 12.8 POA engine [16] (Reproduced by permission of Rolls Royce)

and quantitatively, the potential of the next-generation systems' equipment for effective reduction in consumption of non-propulsive power. The features of the POA system, as shown in Figure 12.8, are as follows:

- No external gearbox
- Electric-driven fuel pump

- Electric vane actuation
- Integral starter/generator on HP spool
- Fan shaft generator on LP spool
- Integrated power system
- Flight weight power electronics
- Oil-less LP turbine sump via active magnetic bearing

In 2008, the POA engine was tested successfully in both starting and generating modes, and a series of engine tests were conducted. Although most of the objectives were accomplished, but the reduction of aircraft total equipment weight and the reduction of aircraft fuel consumption by 5% appear too ambitious in hindsight. The embedded generation still needs significant development to ensure a viable whole engine solution. The POA project provided valuable insight into a very complex system and highlighted trends for future research and development.

12.4 Electric Power Generation Strategies

Since the beginning of the jet age, aircraft have become increasingly complex and they operate a vast array of electrical devices [17–19]. Modern military aircraft are equipped with powerful radars, sensors, weapon systems and sophisticated cockpit displays that require large amounts of electricity to operate. Commercial airliners need to provide power for environmental systems, galley equipment, cockpit displays, communication systems, weather radar, flight instruments and in-flight entertainment systems. Hence, the primary function of an aircraft's electrical system is to generate, regulate and distribute electrical power throughout the aircraft, and provide the required power to all the electrical loads. In the past, airplanes used small generators that supplied DC power only, typically at 28 V, to meet the electrical power requirements. The trend in the aircraft industry is to operate electrical components on many different voltages, both DC and VF AC, as in the Boeing 787. However, most present aircraft systems still use 115 V AC at 400 Hz and/or 28 V DC.

Aircraft are equipped with a number of power generation systems, including both primary and redundant backup systems, to supply power to critical equipment in an emergency. Primary power is usually provided by AC generators driven by the jet engines. Commercial and many military aircraft are equipped with an APU, which is essentially a mini jet engine being used as an additional power source. Many aircraft carry a RAT that can be deployed when needed to provide emergency power. If the main engine and the APU both fail, the RAT is generally deployed. The purpose of the RAT is to keep critical systems operating long enough for the aircraft to land safely. Different types of electrical power generation systems, currently being considered for aircraft, are shown in Figure 12.9 [6].

- CF 115 V AC, three phase, 400 Hz generation types integrated drive generator (IDG)
- Variable speed constant frequency (VSCF) cycloconverter
- VSCF with intermediate DC link
- VF 115 and 230 V, three-phase power generation (380–760 Hz)
- VF at 115 V and then converted to 270 V DC bus voltage
- Permanent magnet generators (PMGs) used for generating 28 V DC emergency electrical power for high integrity systems

The IDG is used for powering the majority of civil transport aircraft today. The constant speed drive (CSD) works like an automatic gearbox maintaining the shaft speed of the generator at a constant rpm to provide a CF output of 400 Hz, usually within 10 Hz or less. This has to cater for a 2:1 ratio in engine speed between maximum power and ground idle. The drawback of the hydromechanical CSD is that it needs to be maintained correctly in terms of oil cleanliness and level.

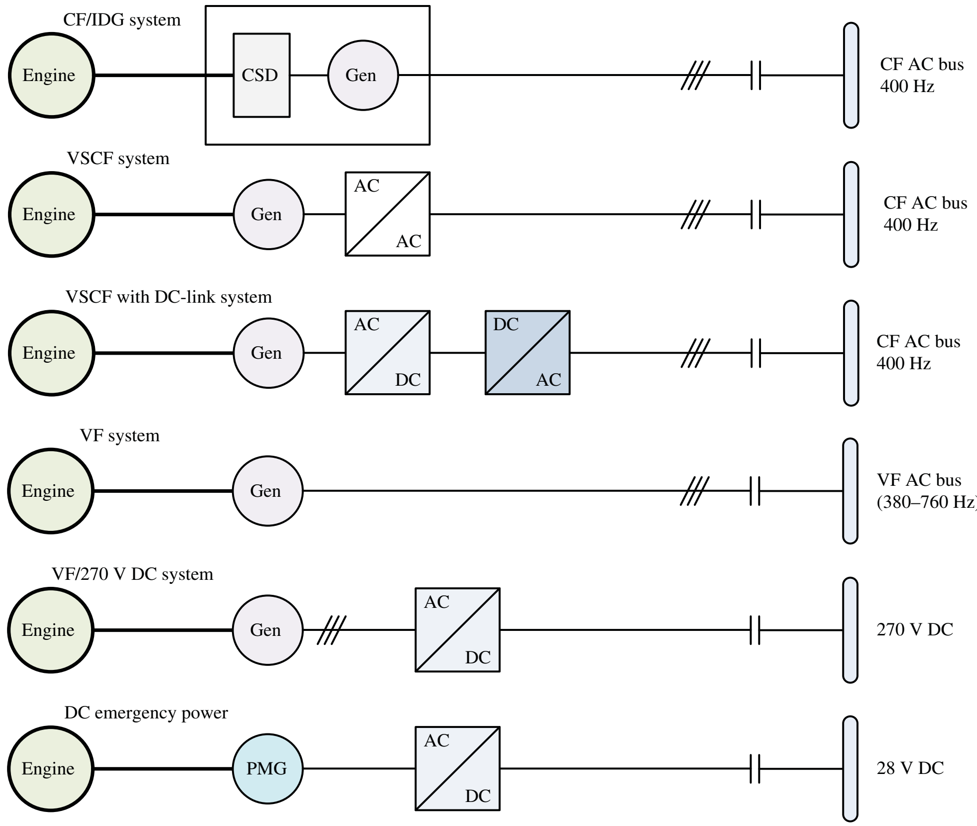

Figure 12.9 Electrical power generation strategies

In the case of variable speed generators, the VF power produced by the generator is converted electronically by the DC-link converters or cycloconverters to CF at 400 Hz with 115 V AC power. In the DC-link converters, the VF voltage of the generator is first converted to an intermediate DC power using AC–DC converters, before being converted (using inverters) to three-phase AC power at 400 Hz with 115 V. The AC–DC converters have been used on the B737, MD-90 and B777 airplanes. The cycloconverter converts directly the VF input voltage to a fixed frequency AC output. In this system, six phases are generated at relatively high frequencies in excess of 3000 Hz, and semiconductor power devices such as insulated-gate bipolar transistors switch between these multiple phases to electronically commutate the input and provide three phases of CF 400 Hz power. Cycloconverter systems have been used successfully deployed in military aircraft in the United States; the F-18, U-2 and the F-117 stealth fighter are a few examples. To date, no civil applications have used cycloconverters because the topology requires a large number of switches and a complex control system.

Due to limited availability of space in the aircraft and as weight is critical to aircraft engine thrust and fuel burn (and thus, the aircraft's range and engine horsepower per pound) three-phase 115 V, 400 Hz power has been the main system power in aircraft. It offers a distinct advantage over the usual 60 Hz used in utility power generation, notably in allowing smaller and lighter power supplies to be used. In MEAs, such as the A380 and B787, instead of 400 Hz, the output frequency of the generator is allowed to vary from about 380 to 760 Hz; thus, the engine speed is freely allowed to vary over a speed range of about 2:1. The wide variation of the frequency could have an effect on frequency-sensitive aircraft

Table 12.2 Recent civil and military aircraft power system developments

Generation type	Civil application		Military application
IDG/CF	B777	2×120 kVA	Eurofighter Typhoon
[115 V AC/400 Hz]	A340	4×90 kVA	
	B737NG	2×90 kVA	
	MD-12	4×120 kVA	
	B747-X	4×120 kVA	
	B717	2×40 kVA	
	B767-400	2×120 kVA	
VSCF (cycloconverter)			F-18C/D $2 \times 40/45$ kVA
[115 V AC/400 Hz]			F-18E/F $2 \times 60/65$ kVA
VSCF (DC link)	B777	2×20 kVA	
[115 V AC/400 Hz]	MD-90	2×75 kVA	
VF	Global Express	4×40 kVA	Boeing JSF 2×50 kVA
[115 V AC/380–760 Hz typical]	Horizon	$2 \times 20/25$ kVA	[X-32A/B/C]
	A380	4×150 kVA	
VF	B787	4×250 kVA	F-22 Raptor 2×70 kVA
230 V AC			Lockheed Martin F-35
270 V DC			Under review

loads, the most obvious being the effect on the AC electric motors that are used in many aircraft systems. The VF voltage is converted to 270 V DC and then converted to VF AC to control the ECS compressor motors and fans, electrically driven hydraulic pumps, nitrogen generating systems (NGSs) and so on. The same converter could also be used for starting the engines electrically. VF is being widely adopted in the business jet community as the power requirements take them above the 28 V DC/12 kW limit of twin 28 V DC systems. Aircraft such as the Global Express has had VF designed in from the beginning.

A summary of the electrical power being generated in different airplanes is given in Table 12.2 [6, 7]. As can be seen, over the years the actual power generation in airplanes has increased gradually resulting in the incorporation of sophisticated safety, control and entertainment systems. However, the diversity of electrical power generation methods has introduced new aircraft systems' issues that need to be addressed. The power converters and the increased electrical loads generate extra heat inside the airplane, thus increasing the ECS requirements. In addition, the power switching devices create electromagnetic interference (EMI) to the other electronic systems that need to be addressed at the architecture level and by selection of systems' immune to EMI. Similarly, the adoption of VF can complicate motor loads, power conversion and protection requirements. As conventional circuit breakers cannot be used at high DC voltages, the US military has initiated the development of a family of 270 V DC protection devices.

Wound-field synchronous generators have been used in most civil and military airplanes as generators. Switched reluctance and PMGs have also been considered in a very few military applications. The advantages of wound-field synchronous machines are as follows:

- Known technology in aerospace applications
- Voltage can be controlled easily by controlling the field
- Fairly well-understood power electronics and control requirements
- Robust

The disadvantages of wound-field synchronous machines are as follows:

- Lower torque-to-inertia ratio compared with that of other types of machines, hence lower power density

- Lower efficiency compared with that of other AC machines
- Separate field and armature voltage control are required during motoring operation
- Need brushes if rotating field windings are used or slip rings if the armature is rotating

The PM machine allows operation without commutators or slip rings and the machine is much less susceptible to issues arising from leakage reactance and poor power factor. The PM machine is often found in a variety of configurations:

- conventional inner rotor configuration
- outer rotor configuration, where the rotor is located on the outer diameter of the stator
- axial gap configuration, where the air gap is not a cylinder
- a radial gap machine, but disk shaped with the rotor displaced axially from the stator

While the interior PM rotor design is predominately employed, the other configurations might have merit in applications that utilize their unique geometrical properties. In addition to the various types of rotor geometry, numerous magnetic materials are also available. PM machines also come in a wide variety of pole count and stator slot combinations. The most desirable features of the PM machine are its efficiency, size, weight and potential for quiet operation. However, these benefits are offset by cost and reliability/durability concerns. Reliability of the machine could be compromised by both the potential corrosion of the magnets and the fact that high temperatures and currents in the rotor can cause demagnetization and, therefore, loss of functionality.

A key requirement for many aircraft generation systems is a degree of fault tolerance, that is, an ability to continue operating at or near-rated power in the event of a single point fault in the generator or its associated converter. One way of achieving fault tolerance is to isolate the phase windings physically, magnetically and electrically. These can be three-phase or higher phase machines, where each phase of the machine is fed separately by a single-phase bridge inverter/converter. Consequently, a fault in one phase will not readily propagate to the adjacent phases. In addition, each phase winding is designed to have one per-unit self-reactance in order to limit the short-circuit current at fault conditions to its rated value. Furthermore, by employing a multiphase (usually >4) design, the machine can continue to provide a useful power output even with a fault in one of the phases. However, this must be balanced against the increased probability of a failure through having more phases. These design features, when combined with the high power density of PM machines, make a fault-tolerant PM machine an attractive option in a safety critical application. Several studies have reported on the possibility of using five-phase fault-tolerant PM machines for embedded aircraft generator applications [20].

The switched reluctance machine (SRM) has been investigated as an alternative to the wound-field synchronous machine as a starter/generator for aircraft engines and other applications [21]. The advantages are in reliability and fault tolerance. The magnetic and electric independence of the machine phases and absence of PMs improve reliability. The mechanical integrity of the rotor permits high-speed high-power density operation. The ability to operate in high-temperature environments and high-speed operation allows the possibility of direct drive and, hence, the elimination of a gearbox and hydraulic system accessories. The simplicity of the SRM translates into a very low cost and reliable machine. However, these machines are generally extremely noisy during operation and have higher torque pulsations, lower efficiency, larger size and weight (than PM machine); and the design has not been advanced to the same extent as the induction or PM machine.

The squirrel-cage induction machine being used as an induction generator in aircraft has not been popular because to obtain the power generation function, it needs to be at supersynchronous speed. Furthermore, a means of providing an excitation has to be incorporated. With the advancement of power converters and control topologies, both these functions can be achieved without much complexity. The induction machines have more fault-tolerant capability than PM machines. These machines have been used in many electric and hybrid vehicles for propulsion and as starter generators.

12.5 Power Electronics and Power Conversion

The power conversion depends on the type of generator being used and the nature of the required output voltage, that is, DC or fixed frequency AC or VF AC. It might also be required to convert power from one form to another within an aircraft's electrical system. Typical examples of power conversion are as follows:

- Conversion from DC to AC power; inverters are used to convert 28 V DC to 115 V AC single-phase or three-phase power.
- Conversion from 115 V AC to 28 V DC power. This function is achieved by using TRUs).
- Conversion from one AC voltage level to another.
- Battery charging. It is necessary to maintain the state of charge of the aircraft battery by converting 115 V AC to a 28 V DC battery charge voltage.
- Conversion to three-phase 115 V AC at 400 Hz from 270 V DC if the main bus voltage is 270 V DC. This conversion is required to power legacy equipment originally designed to operate using these voltages.

A typical power conversion system with various loads is shown in Figure 12.10.

Recent developments in power electronics have advanced active rectifier technologies to the point that they could replace the TRU [22, 23]. Furthermore, the active rectifier could facilitate the replacement of the synchronous machine by an induction machine, because the active rectifier can regulate the voltage at the AC bus of the aircraft. This has significant benefits for the engine by having lower weight and smaller volume of the machine. This enables engine nacelle lines to be redrawn with a reduced frontal area and,

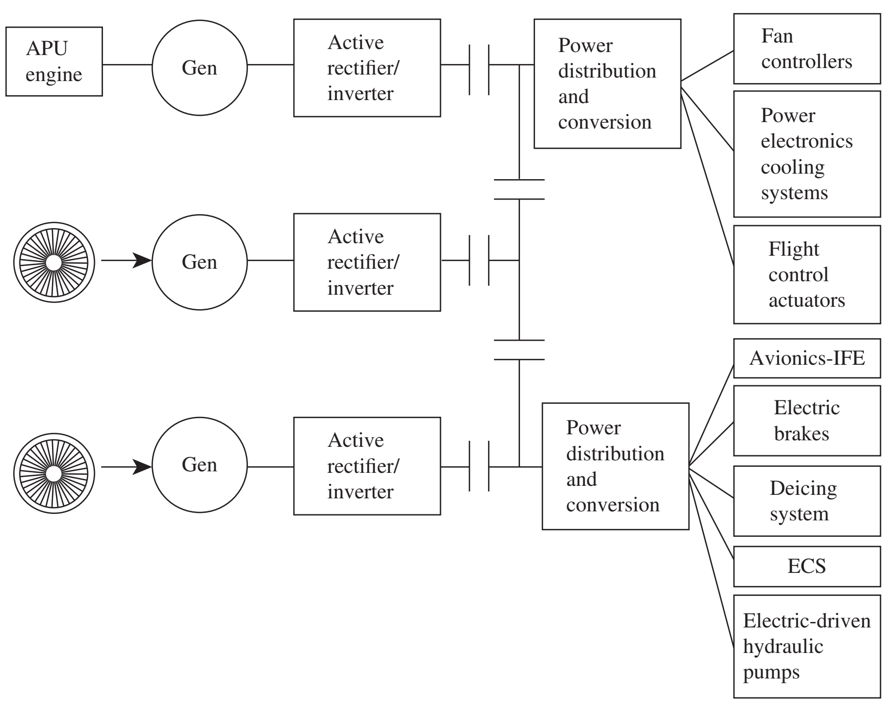

Figure 12.10 Typical power conversion system with various loads

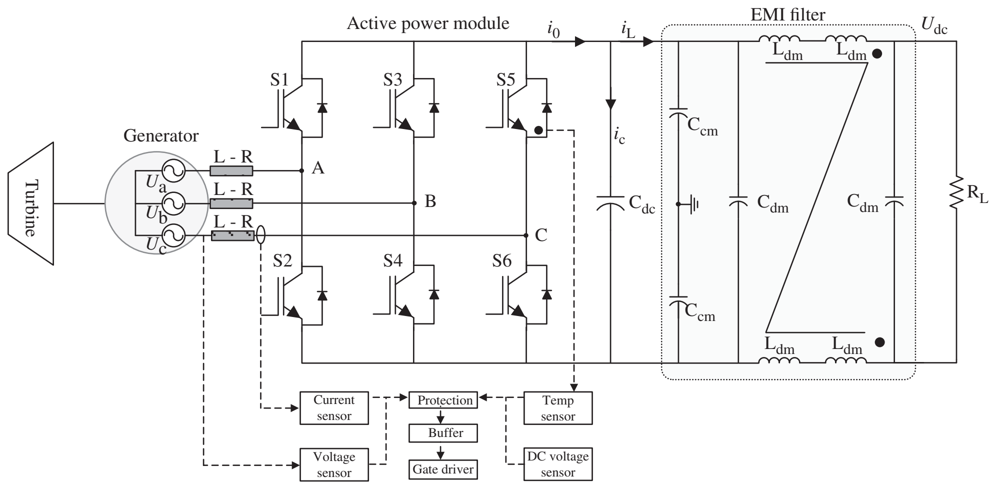

Figure 12.11 PWM active rectifier

therefore, a lower drag. In Figure 12.10, the power conversion from the VF AC output of the generator to controlled DC (±270 V DC) is achieved using an active PWM rectifier; a typical configuration is shown in Figure 12.11. In the rectifier mode, this converter acts as a three-phase boost converter to convert AC to DC. The advantages are that the current or voltage can be modulated with lower harmonics; the power factor can be controlled and can be made lagging or leading; and it can work as a voltage source or current source rectifier. The same power converter could be used as an inverter to convert the DC voltage to VF and variable voltage in order to run the same electric machine as a motor to start the engine. Hence, this topology is used in most starter/generator applications for starting the engine by converting the DC voltage (or battery voltage) to AC to run the electric machine as a motor to start the engine. Once the engine starts and overcomes the peak reactive torque, the electric machine works as a generator to produce the AC voltage at its output. This AC voltage is converted to DC by the active rectifier for powering the accessory motors and other electrical loads of the aircraft, as shown in Figure 12.12.

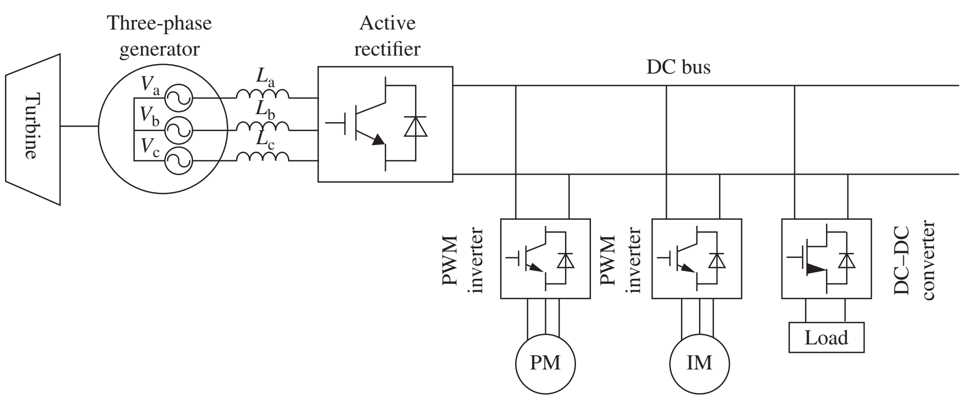

Figure 12.12 Typical DC distribution system with AC and DC loads

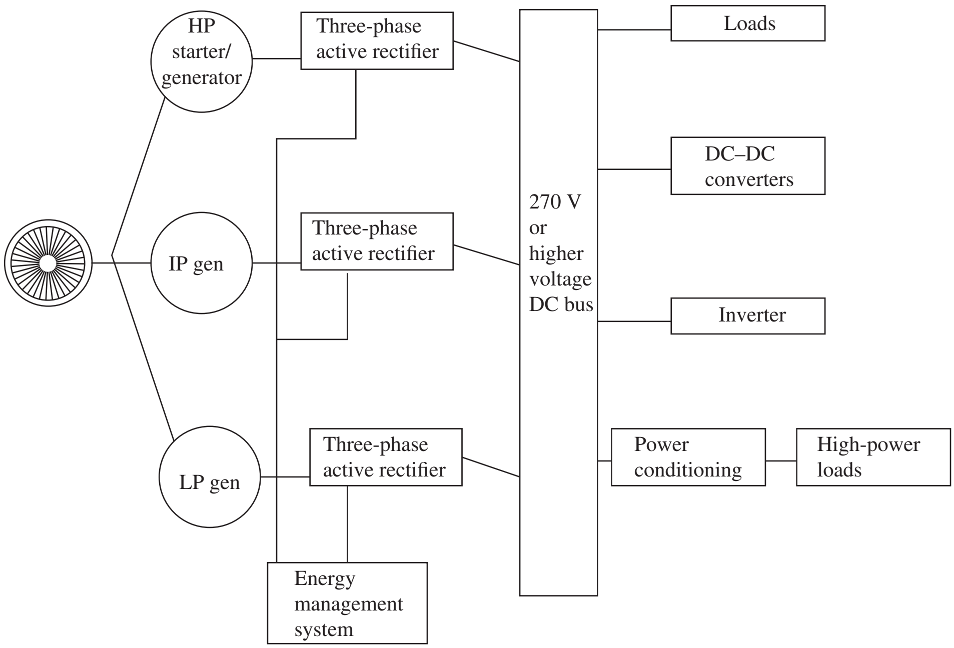

Figure 12.13 Power generation and distribution from a three-shaft engine

The future trend will be off-take of power from each shaft of the engine and load sharing between the buses. A three-shaft engine such as the Rolls-Royce Trent 1000 could be driving three generators with each output connected to a PWM rectifier, which are all paralleled on the DC side, as shown in Figure 12.13. This enables power to be combined from multiple generators operating at different frequency and voltage levels [17].

Although power electronics and electric machine technologies are well advanced, further work is needed in the following areas, particularly for MEAs [18].

- Mitigation of EMI/EMC and improving power quality
- Need for high-temperature materials and components, power devices and passive components
- Power device packaging required to withstand large temperature variations and high thermal cycle capability
- Alternative power conversion topologies with inherently reduced passive components
- Passive components with reduced weight and volume and with high-temperature capability with increased operating frequency
- High power density and high energy density components
- Availability of the components that meet aerospace requirements
- Fault-tolerant power conversion topologies
- Components/systems with long life with stringent vibration and thermal shock requirements

The main objectives are to obtain:

- Higher current density
- Higher power density: weight and volume must be significantly reduced
- High density interconnect

- High thermal conductivity
- Higher reliability and also redundancy
- Ability to withstand harsh environment

In addition to the above items, closer integration of the power electronics and electric machine might also be required. For the MEA, weight, volume including thermal management systems, reliability and redundancy take on a new importance. In addition to the weight and volume constraints, there are key differences in the operating environments for MEA applications. These include the following:

- High-temperature operation: Some applications require generators embedded within the engines making the power electronic systems operate at high temperatures in the range of 200–250 °C. This requires the use of high-temperature capability silicon carbide and gallium nitride power devices and also high-temperature passive devices with efficient packaging technologies
- High-altitude operation: High altitudes give lower ambient pressures that could result in corona discharge. Also, high-altitude flights are more vulnerable to cosmic rays that could cause damage or maloperation of power devices.

12.6 Power Distribution

The power distribution in an aircraft could be AC or DC, as shown in Figures 12.14 and 12.15 [22–26]. Each has its own advantages and limitations. There is an increasing interest in DC power distribution inside an aircraft. High-voltage DC (HVDC) power distribution of about 270 V DC provides a mass and volume advantage over its AC distribution owing to the reduction in the number of feeders from three to

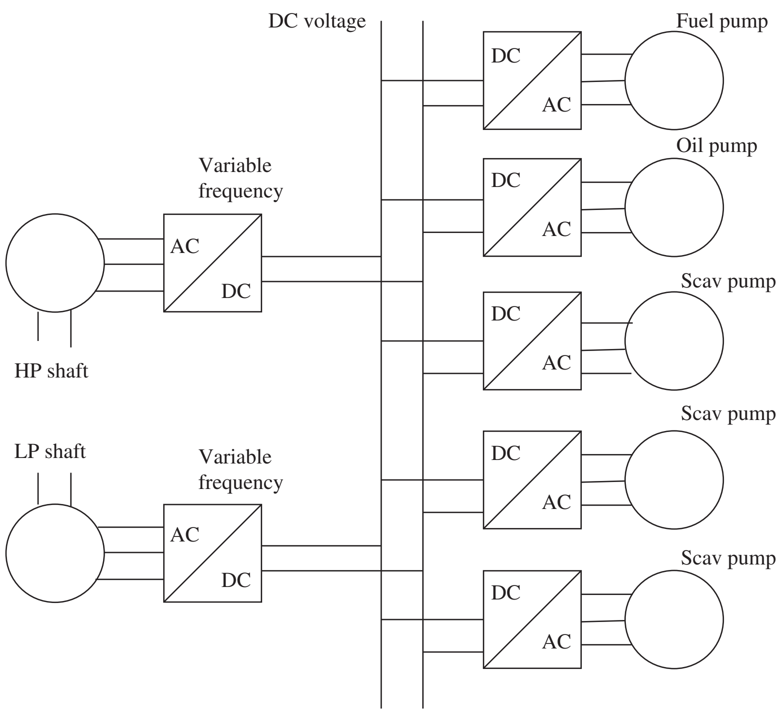

Figure 12.14 DC power distribution architecture

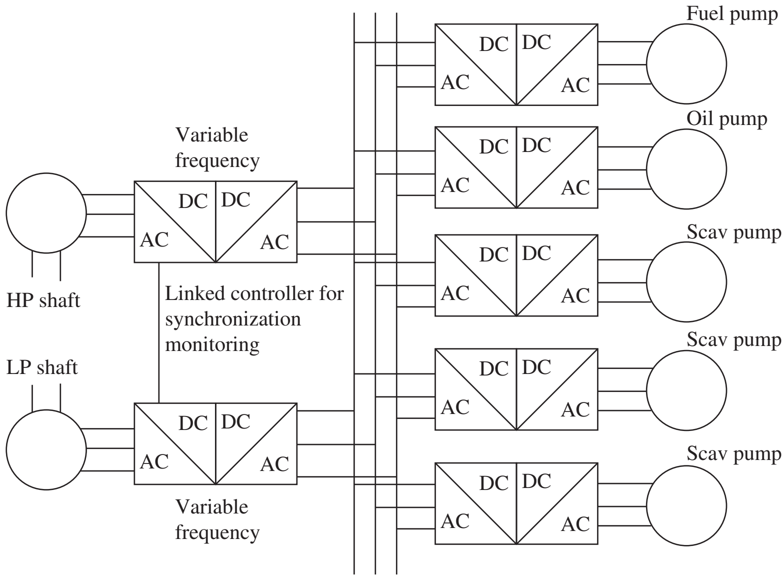

Figure 12.15 AC power distribution architecture

one. As the amount of power to be managed is of the order of MW, the cable size is a concern because of the increased amount of current. In order to avoid this problem, higher voltages have been considered for power distribution inside the aircraft. In the Boeing 787, this is achieved by using ±270 V DC (or 540 V total) rails centered on a zero volt return, but this needs another feeder cable. These HVDC systems enable more efficient use of generated power and aids in paralleling and load sharing between the generators. The 270 V DC is presently produced from TRUs or Autotransformer Rectifier Units (ATRUs) at the output of the generators driven by the engine. But these units are heavy to be deployed in MEA because the power to be handled is much higher than in a conventional aircraft. This is particularly applicable to VF generators where it is not possible to synchronize their outputs directly. A typical DC distribution system is shown in Figure 12.14. The DC distribution enables the use of high-efficiency DC–DC converters and inverters to provide power to the aircraft avionics and accessory motors. However, some issues still have to be addressed for full acceptance of DC distribution in aircrafts. In DC systems, the fault interruption needs specially designed DC contactors or circuit breakers that are bulky because a DC system offers no naturally occurring zero current at which fault can be interrupted.

For many years, AC distribution systems have been the standard for the primary power of aircraft at 115 V (phase voltage), three-phase, 400 Hz. All airports have this voltage for ground power equipment to connect to the aircraft. The use of AC distribution enables the use of a wide range of contactors, relays, and circuit breakers to switch the AC. As AC has a natural zero crossing point, the fault could easily be cleared compared with that of a DC distribution.

The limitations of AC distribution are as follows:

- The AC output from two generators cannot be easily paralleled because they have to be synchronized in magnitude, phase and frequency. Even if both generators are designed to the same specifications and run at the same speed, there could always be a phase difference in voltages of the generator output.
- The motors used for actuators, electric pumps and electric ECS are generally all AC motors. In order to control the speed and torque of these motors, the input frequency and voltage have to be varied over

a wide range. Hence, the distributed AC has to be first converted to DC using the power electronics and then converted to VF and variable-voltage AC using inverters.
- Depending on the frequency of the AC system, the reactive power also has to be managed in the distribution system.
- The feeders within the 115 V AC systems would be heavy, particularly for large loads. For example, the Wing Ice Protection System and the ECS will require both large currents and heavy feeders if supplied from a 115 V AC system.

12.6.1 High-voltage operation

Whether it is an AC or DC distribution system, the main advantage of a higher voltage system is the smaller cable size because of the reduced current for the same power [22, 27, 28]. Ground-based power systems always operate at a high voltage to minimize the I^2R losses and conductor size. Current aircraft electrical systems operate under well-established conditions, namely 115 V AC, altitudes of up to 60 000 ft and temperature cycles between −55 and 200 °C over a wide range of humidity. Moving to higher voltages (>270 V) could lead to several problems.

- The active and passive components capable of switching at these levels of voltage, with characteristics qualified for aerospace applications, have only recently come to the market and have limited availability.
- Although some aerospace-qualified DC contactors at 270 V DC are available, the technology of contactors operating at higher than 270 V DC and the protection systems are still not advanced for aerospace applications.
- The safety aspects related to the use of more than 540 V still needs to be investigated.
- Increased voltage can lead to undesirable effects from tracking and partial disruptive discharges, particularly at higher voltages because of the lower pressures at higher altitudes.

The breakdown voltage of an air gap in uniform field conditions is a function of the product of pressure and gap distance, as stated by Paschen's law, named after Friedrich Paschen in 1889. This law describes the breakdown voltage of parallel plates in a gas as a function of pressure and gap distance. According to his observation, the voltage necessary to arc across the gap decreased up to a point as the pressure was reduced. It then increased gradually, eventually exceeding its original value (Figure 12.16). He also found that decreasing the gap with normal pressure caused the same behavior in the voltage needed to cause an arc. Paschen observed that the minimum breakdown voltage between two conducting surfaces for a uniform electric field in air can be as low as 327 V. In practical terms, this means 5.8 kV that is required to breakdown a 1 mm gap at atmospheric pressure reduces to 1.1 kV at an altitude of 50 000 feet, where the atmospheric pressure is approximately one-tenth of that at sea level.

High-frequency switching in power conversion introduces new operating regimes for materials developed for more conventional DC and AC systems. The effect of microsecond level transients with high repetition rates on corona and insulating systems is not well understood and is of concern in electrical systems, particularly where PWM control is used. The use of DC reduces the peak voltage for the same current carried in a conductor and, therefore, increases the available voltage margin before corona begins. Furthermore, in DC, a system with a potential difference of X can be operated as a two-bus/wire system with voltage of $\pm X/2$ (as in the Boeing 787); the risk of corona onset can thereby be reduced still further. More investigation of corona is required; however, it can be clearly seen that DC has an advantage over AC with respect to levels of corona onset. The extent to which this advantage is reduced by transient effects emanating from power electronic converters requires further analysis.

The increased voltage rating does not always compensate the reduction in current rating because of the insulation thickness required for a given voltage. There should be a trade-off between the current reduction and increased insulation thickness. Moving to a higher voltage does not necessarily imply that

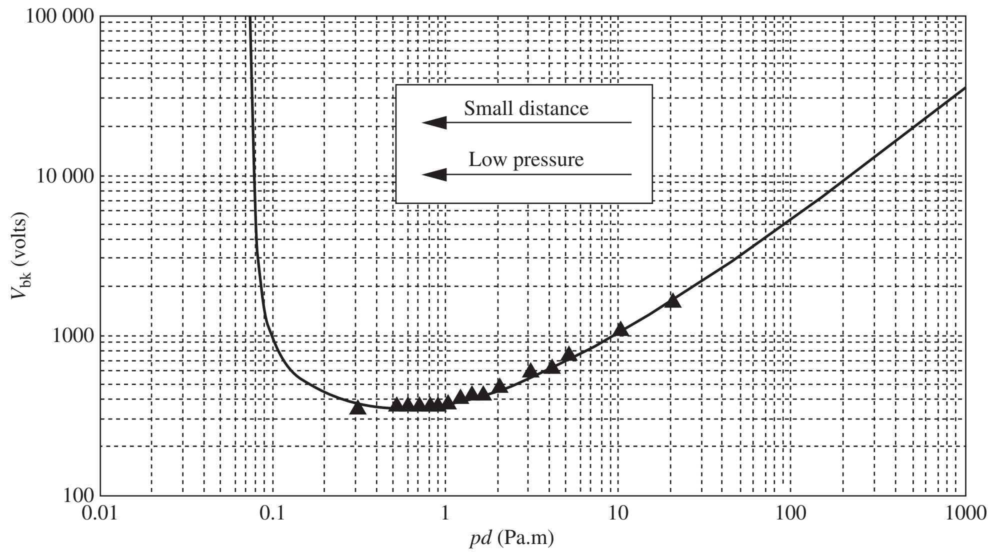

Figure 12.16 Illustration of Paschen's law (*p* is the pressure and *d* is the gap distance)

the system's weight will be reduced. By looking at the MEA as an entire integrated system and not as individual components, a decision related to the individual components and the voltage level has to be made. Hence, for a given aircraft, it is necessary to study the architecture of the entire system and understand the requirements of each individual component.

12.7 Conclusions

MEA technologies are evolving continually and there is much opportunity for improvement as systems continue to be refined and enhanced. As MEA technologies advance, smaller components will be used, continuing the reduction of cost of the components and improvements in operating efficiencies. The long-term goal is an "all-electric" aircraft with MEA being the evolutionary step. The transition to an all-electric aircraft, where the propulsors will be driven by the electric motors, is still many years in the future. Meanwhile, MEA will bridge two eras in aircraft technology as airplanes shed some of the traditional pneumatic and hydraulic systems for lighter, simpler, electric and electronic replacements.

Power electronics plays a significant role in the advancement of MEA technologies in terms of improving system efficiency, architecture, size and so on. In terms of power generation, in all likelihood, the aircraft's primary electrical power will remain as AC obtained from generators driven from the engines for the foreseeable future. Some interest has been shown in fuel cell technology, which could produce DC output for ground power, where its quiet operation would compare favorably with that of the APU. However, this is probably still some way off for both the military and commercial aircraft markets. The use of hybrid fuel cell APUs consisting of a solid oxide fuel cell and gas turbine has also been examined for powering electrical loads in an aircraft, but this technology is still in the feasibility study stage. The distribution of the primary power could be AC or DC and each approach has its merits and limitations. The move to a higher voltage generation and distribution would lead to a decrease in the mass of cables and loads and significant benefits from the use of higher voltages can be derived.

The main objectives are to obtain high power and volume density, high efficiency, reliability and the ability to withstand harsh environments. In addition, closer integration of power electronics and the electric machine might be required for operation in the hostile engine environment. In addition to the above requirements, achieving lower weight and volume is very critical in (MEA) systems.

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