Aircraft Power Systems

Electrical

Department of Aerospace Engineering

‘Watt’ is Power?

- Power is the rate of work (energy converted): joules per second
- Measured in watts (SI unit) , symbol ‘W’
  - or horse power (1 hp = 746 watts)
- Product of two quantities, (sometimes phasors)
  - Electrical: power = voltage x current
  - Mechanical: power = force x velocity
    (power = torque x angular velocity)
  - Fluidic: power = pressure x volumetric flow

Scales of power

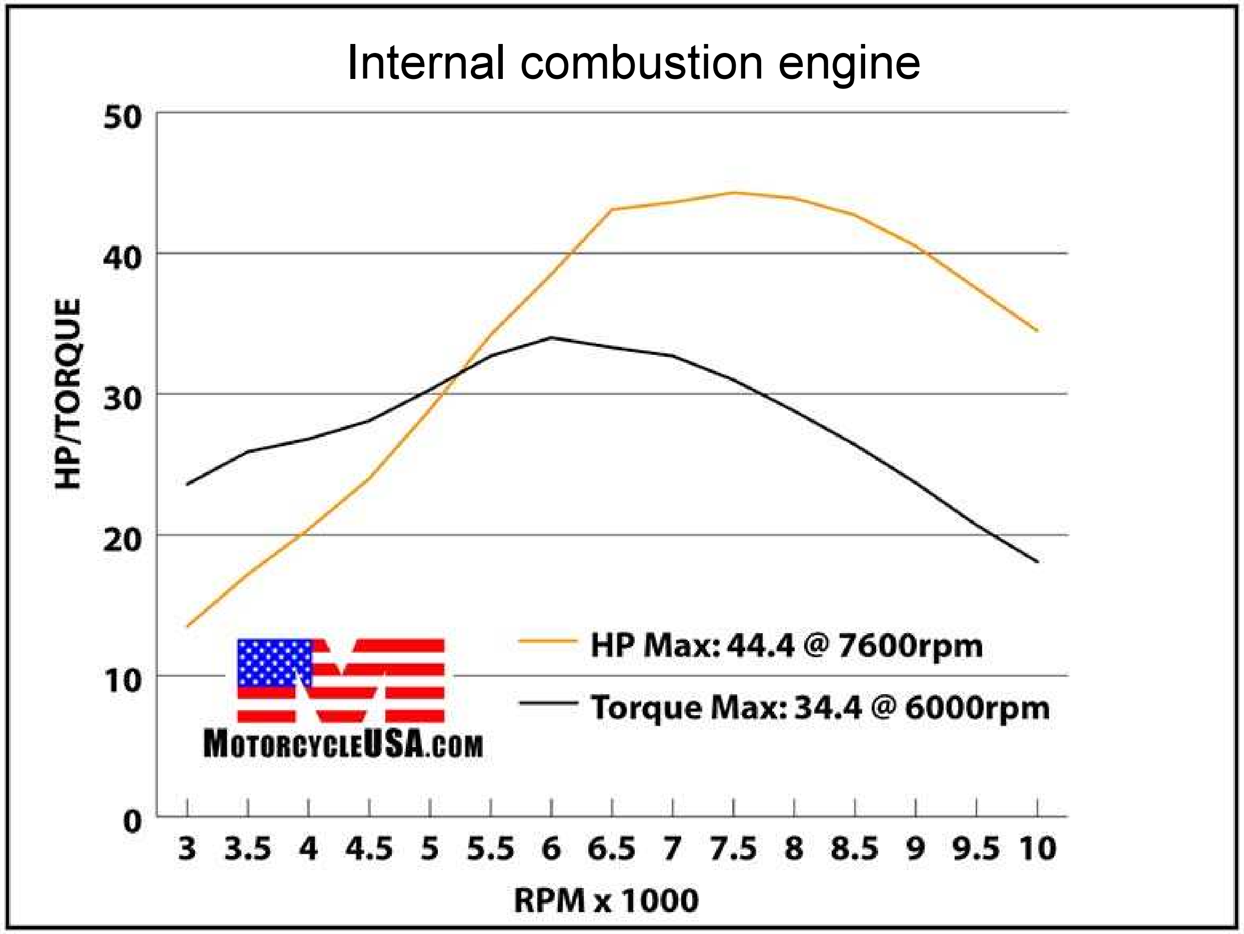
- Pocket Calculator ~ 100 µW (1 x 10^{-4} W)

- Light bulb ~ 15 W

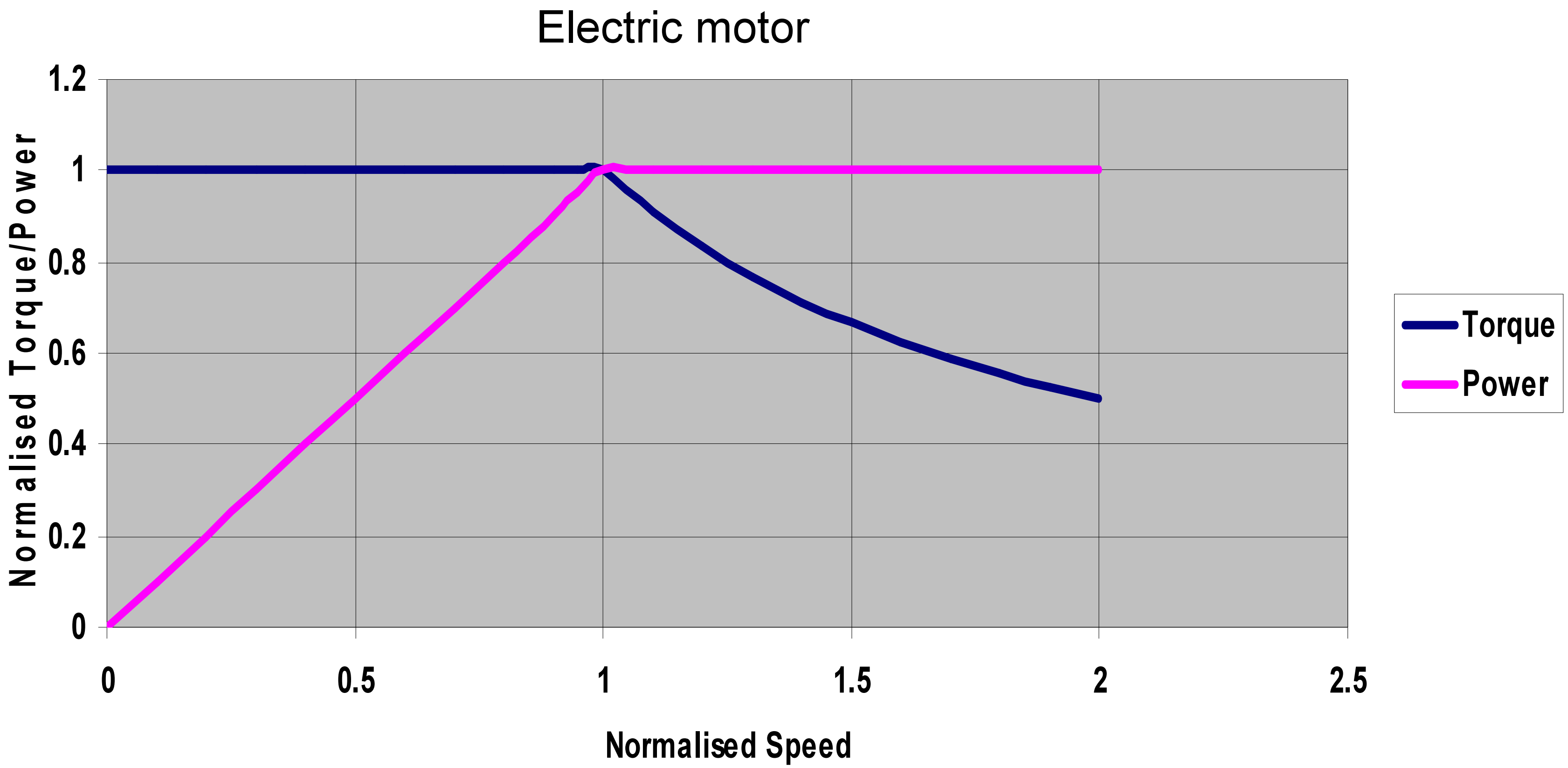
- Backhoe loader hydraulics ~ 70 kW (7 x 10^{4} W)

- 777 engine ~ 75 MW (7.5 x 10^{7} W)

Power/torque curves



Power/torque curves



Aircraft power systems

Electrical Power	**Hydraulic Power**	**Mechanical Power**	**Pneumatic Power**
Avionics	*Flight Control*	Engine-driven	*Air conditioning*
Commercial	*Landing gear*	*Fuel Pump*	*Pressurisation*
Ventilation	*Braking*	*Oil Pump*	*Icing Protection*
Lights	*Doors*		*Engine start*

Aircraft power systems

Electrical Power	Hydraulic Power	Mechanical Power	Pneumatic Power
Avionics *Commercial* *Ventilation* *Lights*	*Flight Control* *Landing gear* *Braking* *Doors*	Engine-driven *Fuel Pump* *Oil Pump*	*Air conditioning* *Pressurisation* *Icing Protection* *Engine start*
~230 kW (115 V)	~240 kW (20.6 Mpa) *(206 bars)* *(3000 psi)*	~100kW *(variable speed with engine; 1000's rpm)*	~1200 kW *peak (3 bars)* *(45 psi)*

Electrical Power

Development

Power trends

Basic background theory

What is the electrical power system?

What is the electrical power system?

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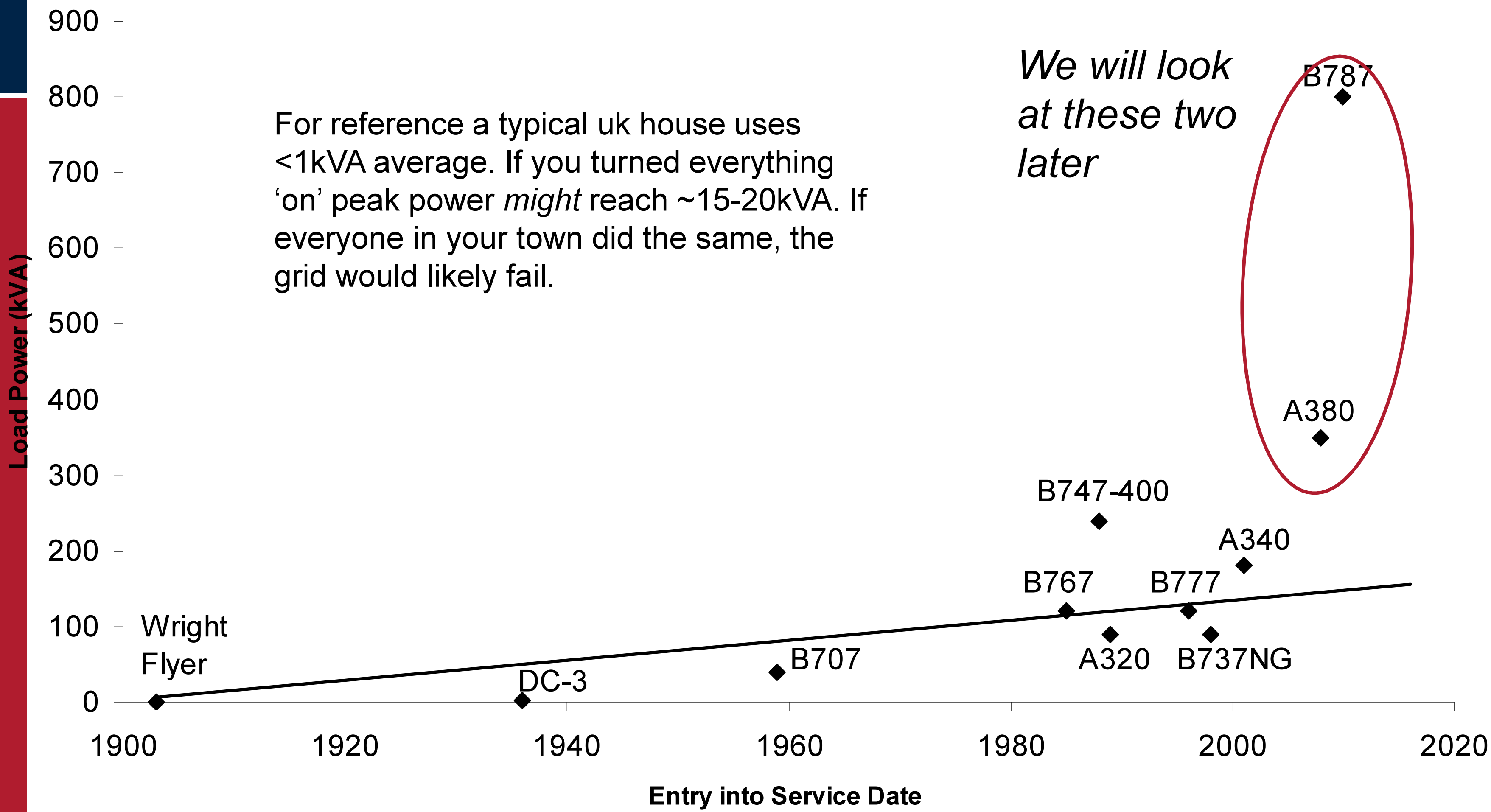
Early aircraft used electrical power for ignition, this demand could be satisfied by a small battery or generator.

As aircraft developed more electrical features were added, such as lighting, instrumentation and communication equipment. The electrical power system became similar to what we would find on a car: a 12V (or 24V) system with a lead-acid battery and recharged by an engine driven generator.

Modern civil aircraft use electrical power for a wide variety of tasks and have a correspondingly higher demand. They feature multiple generators and system voltages, and are architected to provide redundancy in case of individual component failure. A typical system includes a 3 phase 115 VAC system for high power loads and a back-up system based around a 28 VDC supply.

Electrical Power Trends



For reference a typical uk house uses <1kVA average. If you turned everything 'on' peak power *might* reach ~15-20kVA. If everyone in your town did the same, the grid would likely fail.

A Few Uses of Electrical Power

Power for avionic systems e.g. Instrumentation, Radio comms, Radar, Displays, Navigation etc.

Ventilation fans

Door locks

In-flight entertainment, 'Hotel loads'

Actuation of flight control surfaces

Fuel and hydraulic pumps

Internal and external lighting

Galley heaters

Background - Electrical Power

Electric Current (I) is a flow of electrons (-ve charge) along a conductor between two points with differing ***electrical potential (V).*** Current is measured in ***Amps (A)***, electric potential in ***Volts (V).***

A system is said to be ***DC*** if either or both the current and potential are uni-polar. The two quantities are linked by the ***resistance (R)*** and ***Ohm's law***, ***$R = V/I$.***

Power (P), is measured in ***Watts (W)*** and given by; ***$P = VI = I^2R = V^2/R$.***

(750W = 1 hp)

Reminder - Electrical Power

In an ***AC*** system the polarity of both the current and potential are bi-polar and time varying, normally sinusoidally. ***RMS*** quantities are used to simplify calculations. ***V*** and ***I*** are related by the ***impedance (Z),*** where ***Z*** is a complex number of the form ***R + jX***. ***X*** is known as the ***reactance*** and is a function of frequency. $P = V_{rms} I_{rms} \cos\phi$ where $\phi = \arg Z$. $\cos\phi$ is called the ***power factor***.

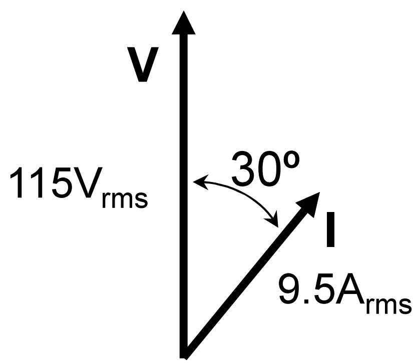
Often, rather than referring to the power of an AC system in **Watts**, we measure the size of an AC system by the **'VA'**. This is the product of the voltage and the current and is independent of power factor.

Electrical Power

In fact three measures of AC power are used: Real power, **P**, measured in Watts. Apparent power, **S**, measured in VA. Reactive power, **Q**, measured in VAR (volt-amps-reactive).

Example:

A ventilation fan is powered by a 115Vac power supply. The electric motor that drives the fan draws 9.5 Amps and has an inductive impedance that causes the current to lag the voltage by 30º.



$V = 115V_{rms}$

$I = 9.5A_{rms}$

Power factor = cos(30) = 0.866

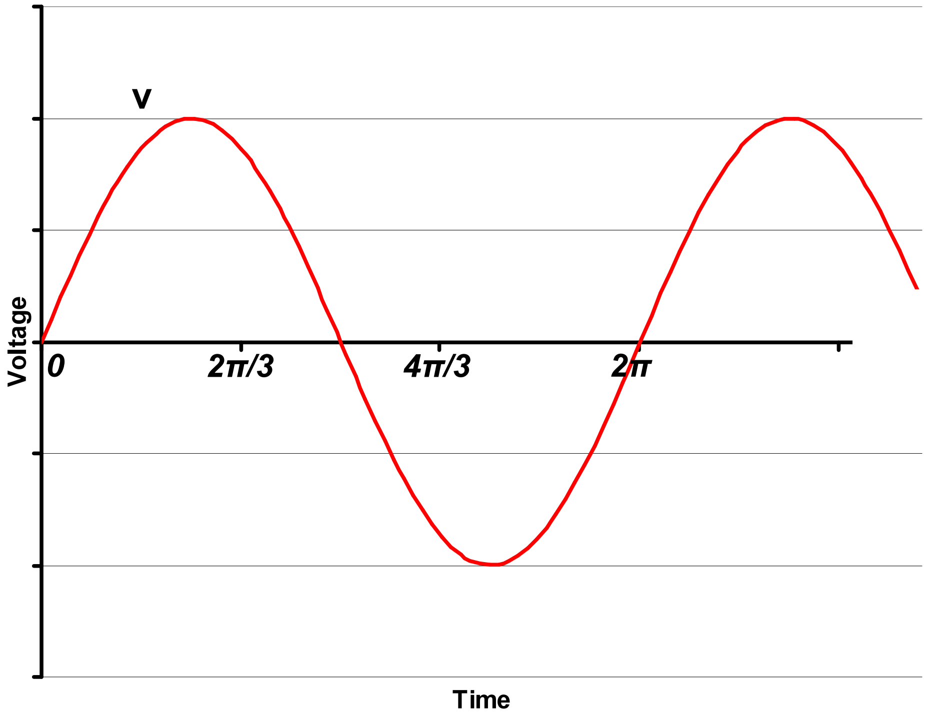
Apparent power, S = 115*9.5 = 1093kVA

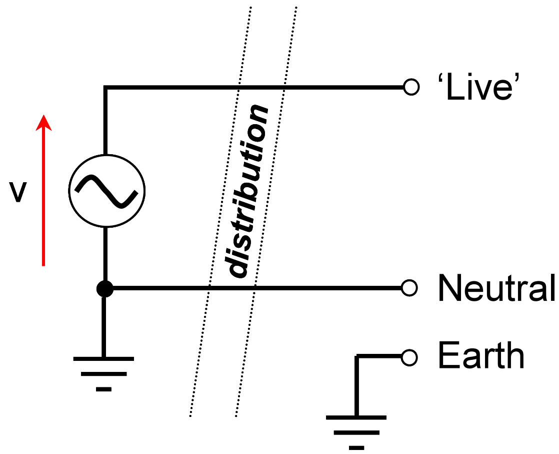
Power, P = 115*9.5*0.866 = 0.946kW

Reactive power, Q = 115*9.5*0.5 = 0.546kVAR

AC Single Phase

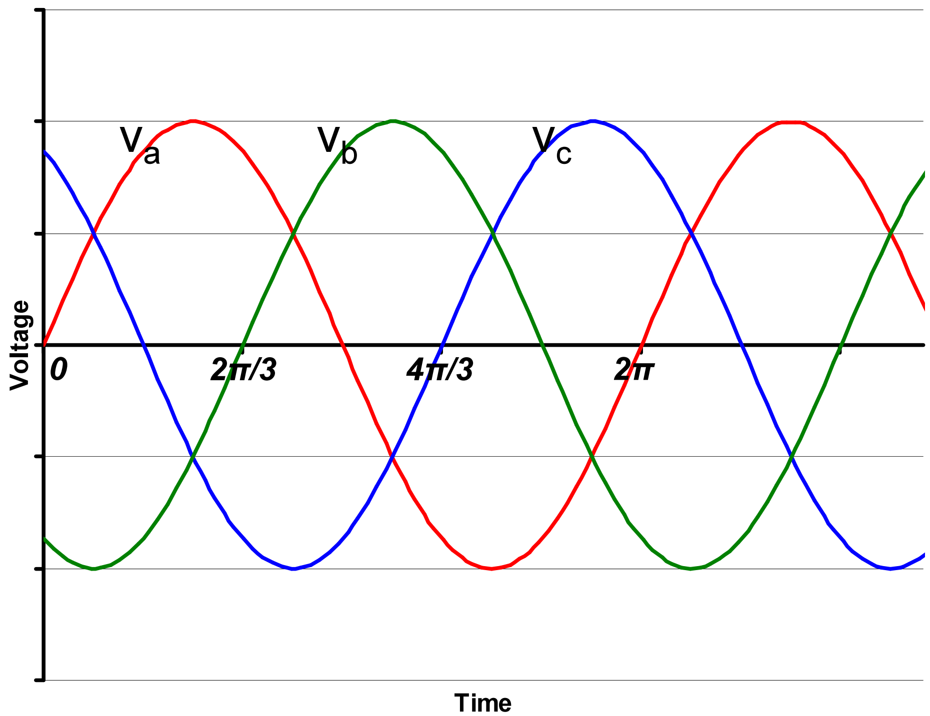
Most people are familiar with domestic single phase AC systems, where we have a live, neutral and earth terminal. However this is normally just a part of a larger generation and distribution system.

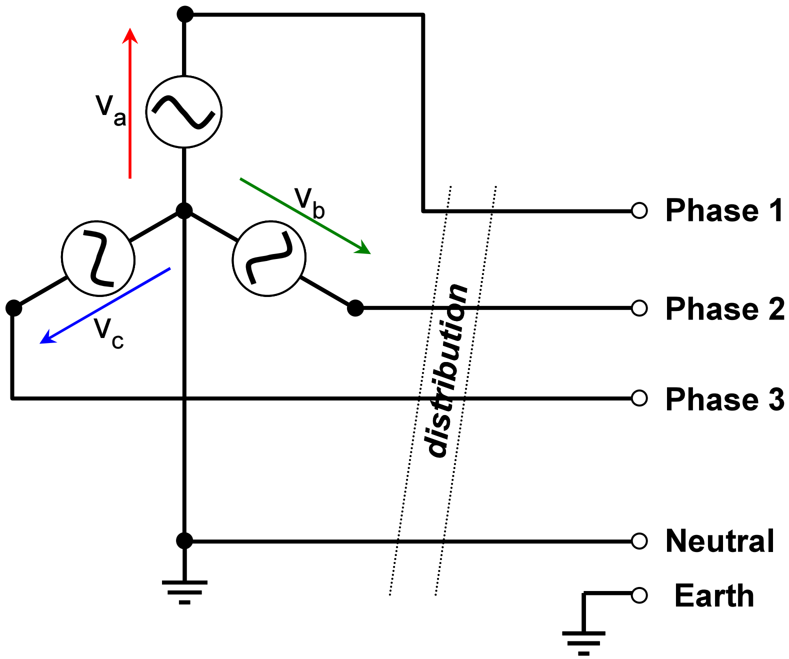




Three Phase AC Systems

Three phase AC systems feature phase voltages displaced by 120°. Most higher power systems are 3-phase AC. This type of electrical system is commonly used on larger aircraft.





Why Do We Use 3 Phase Systems?

- Summation
  - At any point in time the sum of three sine waves with 120° separation is zero. In a balanced three phase system there is no neutral current.
  - Also power ripple is zero.
- Unique Phasor (rotating vector)
  - More than one phase is required to describe a unique rotating vector, e.g. the rotating magnetic field of a machine.
- Minimum Connections
  - A three phase system requires a minimum of 3 connections, the same as a 2 phase system. Systems with more phases require more connections.

Rectification and Inversion

It is often necessary to convert from AC to DC or from DC to AC.

- AC-DC conversion is known as **‘Rectification’**
  - Can be carried out by mechanically, or electrically (with passive or active components)
- DC-AC conversion is know as ‘**Inversion’**
  - More complicated than rectification
  - Complex to achieve with mechanical components
  - Associated with modern power electronic techniques

What is the Electrical Power System?

An aircraft electrical power system can be split into three sections;

Sources	Distribution	Users
Generators Battery storage Ground power	Power Buses (cables) Protection (fuses) Circuit Breakers, Connectors Forms: AC, DC, LV, HV etc	Pumps, fans Actuators Avionics Galley loads Entertainment etc

Aircraft Electrical Power Sources

Generators

Batteries

APU

RAT

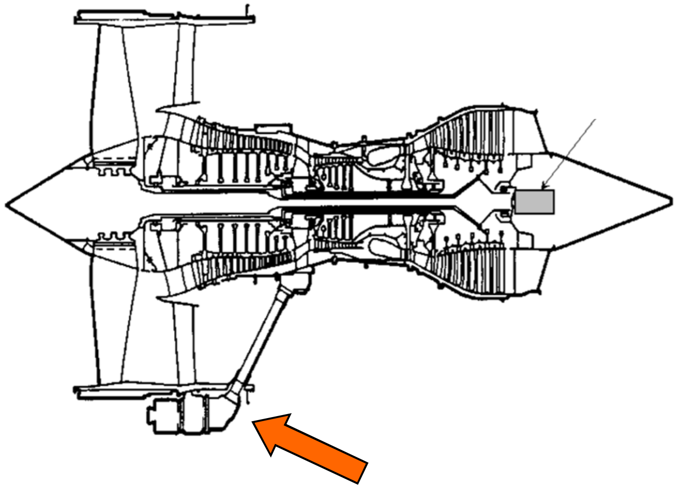
Ground power

Generators

The primary sources of electrical power on aircraft are generators driven from the aircraft engine.

Light aircraft

- simple systems, a few KVA into a low voltage system.



Large aircraft

- Driven by auxiliary gearboxes on engine. Several generators, each 100KVA+, complex multi voltage system.

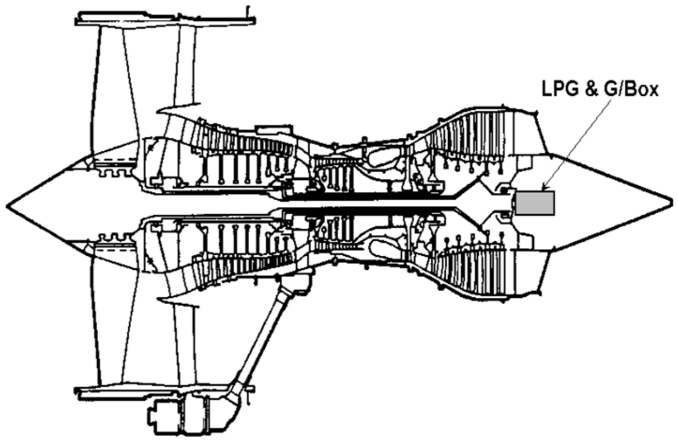
Generators

Generators all produce AC output – electromagnetic induction requires a changing magnetic field which in turn induces a time varying voltage.

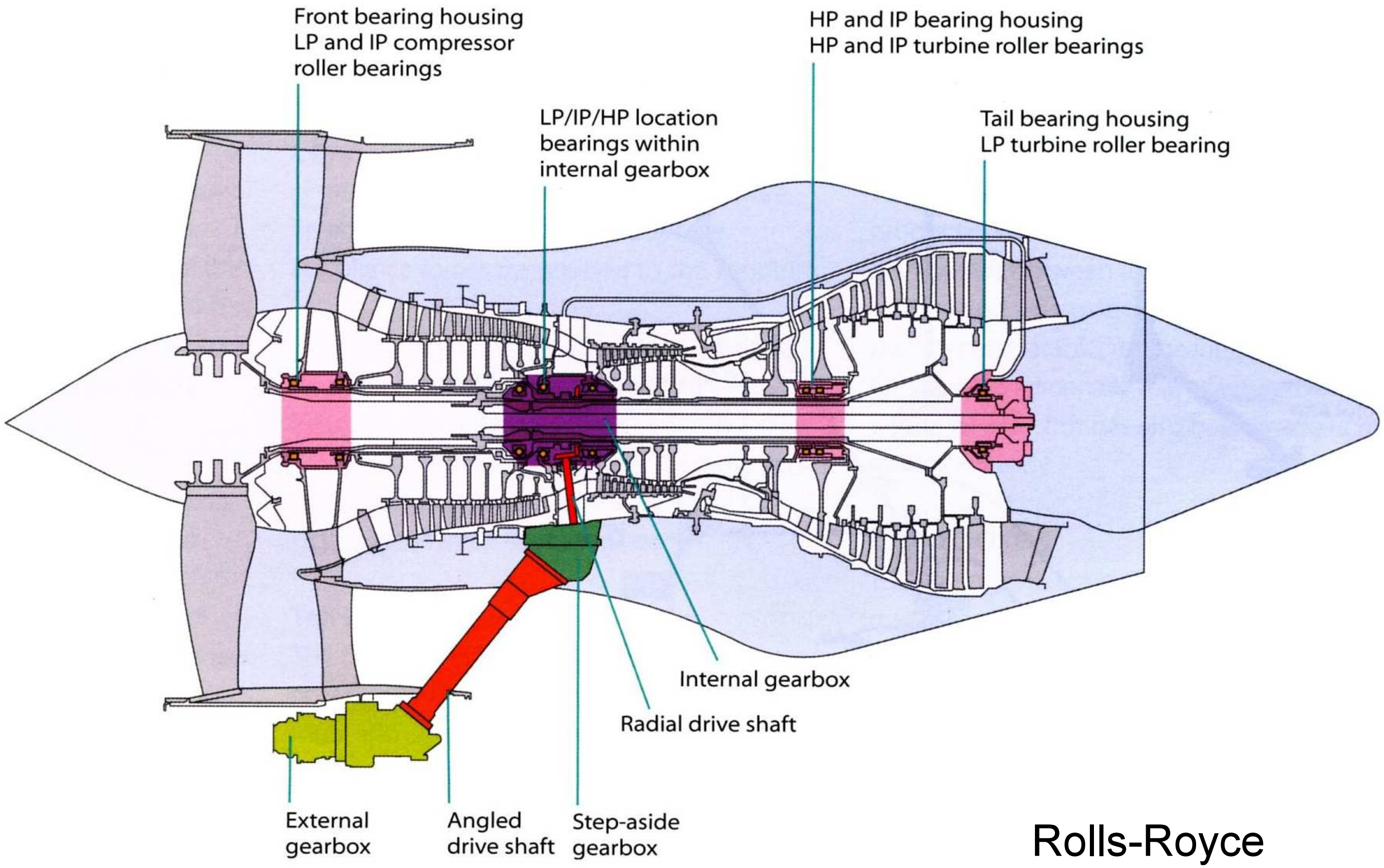
On lower powered systems (a few kW) the AC output might be rectified with a commutator or diode rectifier within the generator itself (as is the case with a car alternator) .

With high power systems it is normal to output AC and convert later as required.

The components and processes used for stepping up or down voltage, rectification or inversion are sometimes known as 'power conditioning'

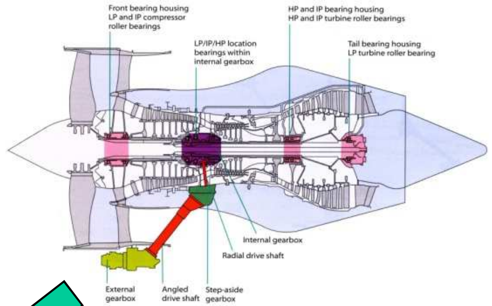


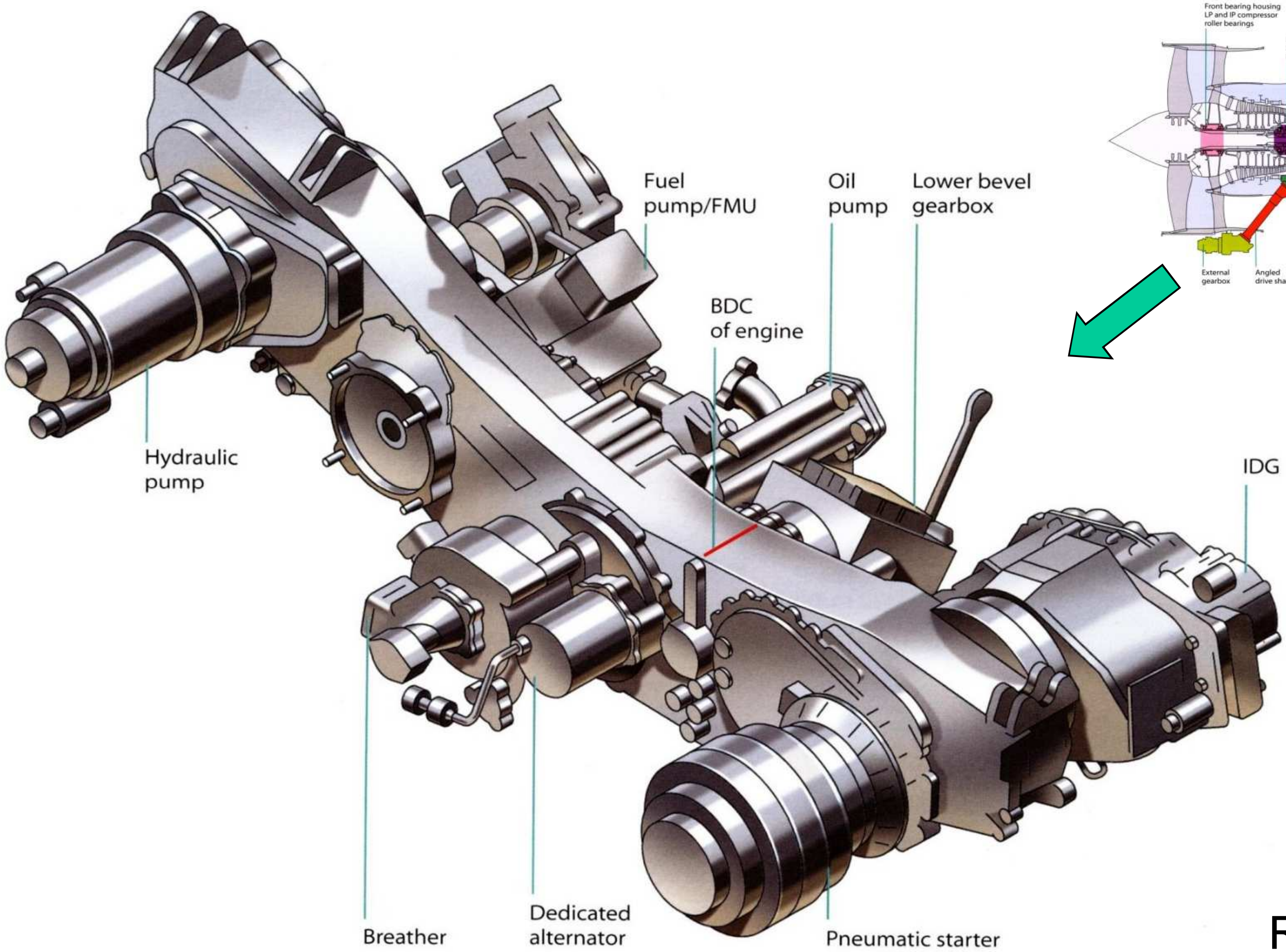
Large Aircraft Generators



Rolls-Royce

Accessory Gearbox



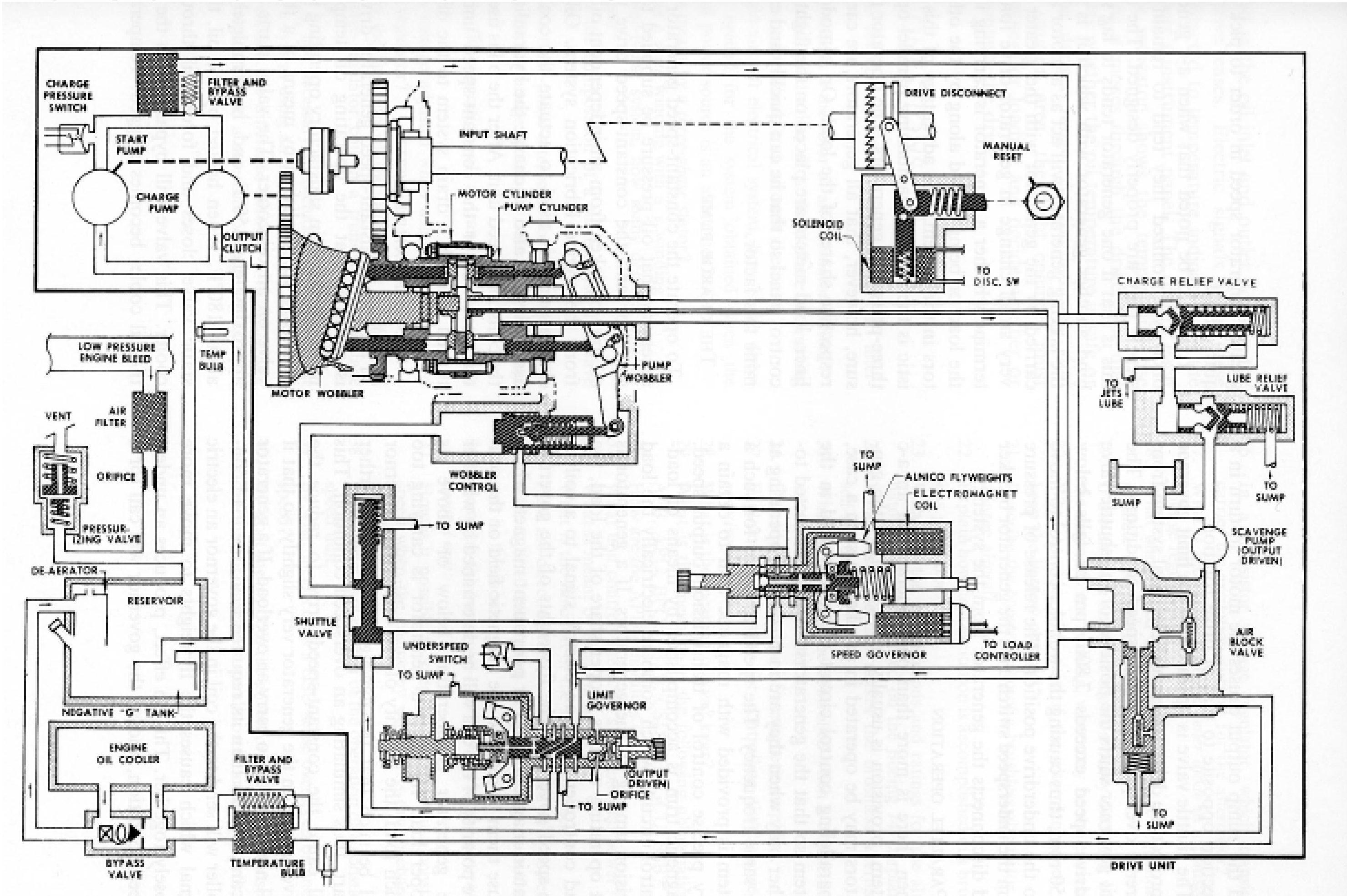


Rolls-Royce

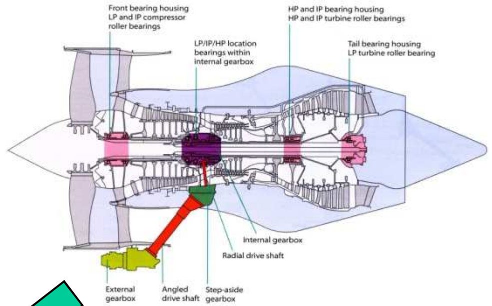
Fixed or Variable Frequency ?

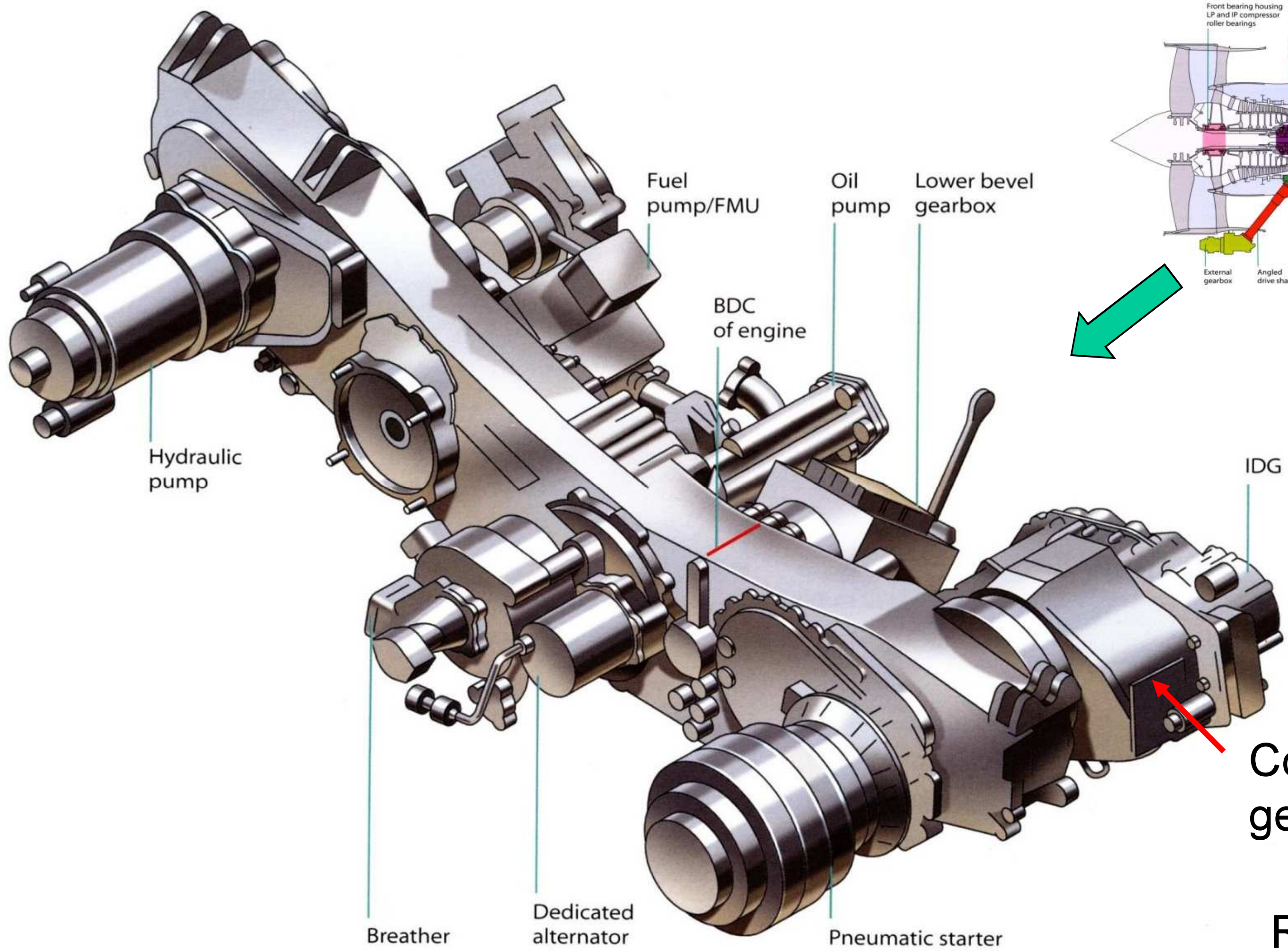
- Aircraft engines operate at variable speeds.
  - *A generator attached to them will have variable output frequency.*
- Not a problem where output is rectified immediately.
- With an AC distribution system…….
  - Allow frequency to vary – ‘frequency wild’.
    - *May cause problems with some loads.*
  - Drive generator from constant speed gearbox
    - *This solution has been used extensively over the last ~50 years.*

The Sundstrand CVG



Accessory Gearbox





Constant velocity
gearbox

Rolls-Royce

Storage

In the majority of aerospace applications the only suitable technology for the storage of electrical energy is batteries. A battery is made up from a number of cells in series. Each cell stores energy in a chemical form. Batteries are inherently DC components.

Aerospace Lead-acid Battery

There are two principle classes of chemical batteries;

- **Primary cells** where the chemical reaction is not reversible and once the cell is fully discharged it is discarded.
- **Secondary cells** where reversing the current reverses the electro-chemical reaction. They can be recharged.

There are several differing types of battery within each class. The chemistry particular to each type determines the charging/discharging characteristics, temperature operating range, capacity etc.

Aerospace Secondary Cells

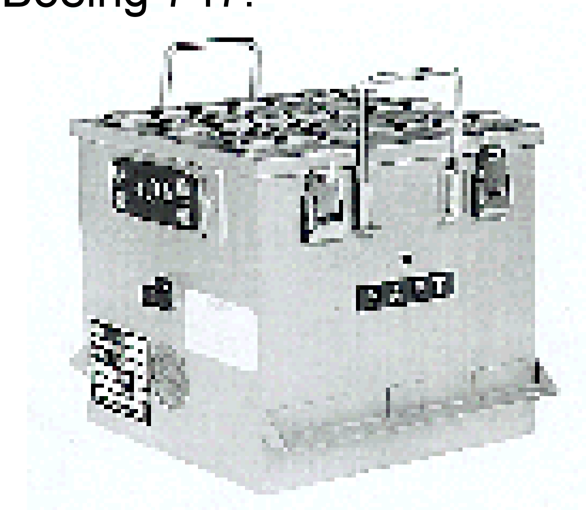
Two types of rechargeable cell are commonly used for aircraft applications;

- **Lead-Acid** cells are the most mature rechargeable cell technology. They have good charge/discharge characteristics but have the drawback that they vent corrosive elements during normal operation (gassing). They have been developed for aircraft applications by using techniques to minimise venting and the risk of leakage by holding the liquid electrolyte within a saturated matting or as a thick gel. They operate of a very wide range of temperatures, are simple to recharge. They can easily be recycled at the end of their life.

- **NI-Cad** cells are commonly used as an alternative to Lead-Acid because their chemistry enables them to be fully sealed and the reduces the risk of leakage. For a given size Ni-Cad batteries will have a greater capacity than Lead-Acid but they operate poorly at low temperatures, have a more complex recharging requirement and are hard to recycle.

Example Battery

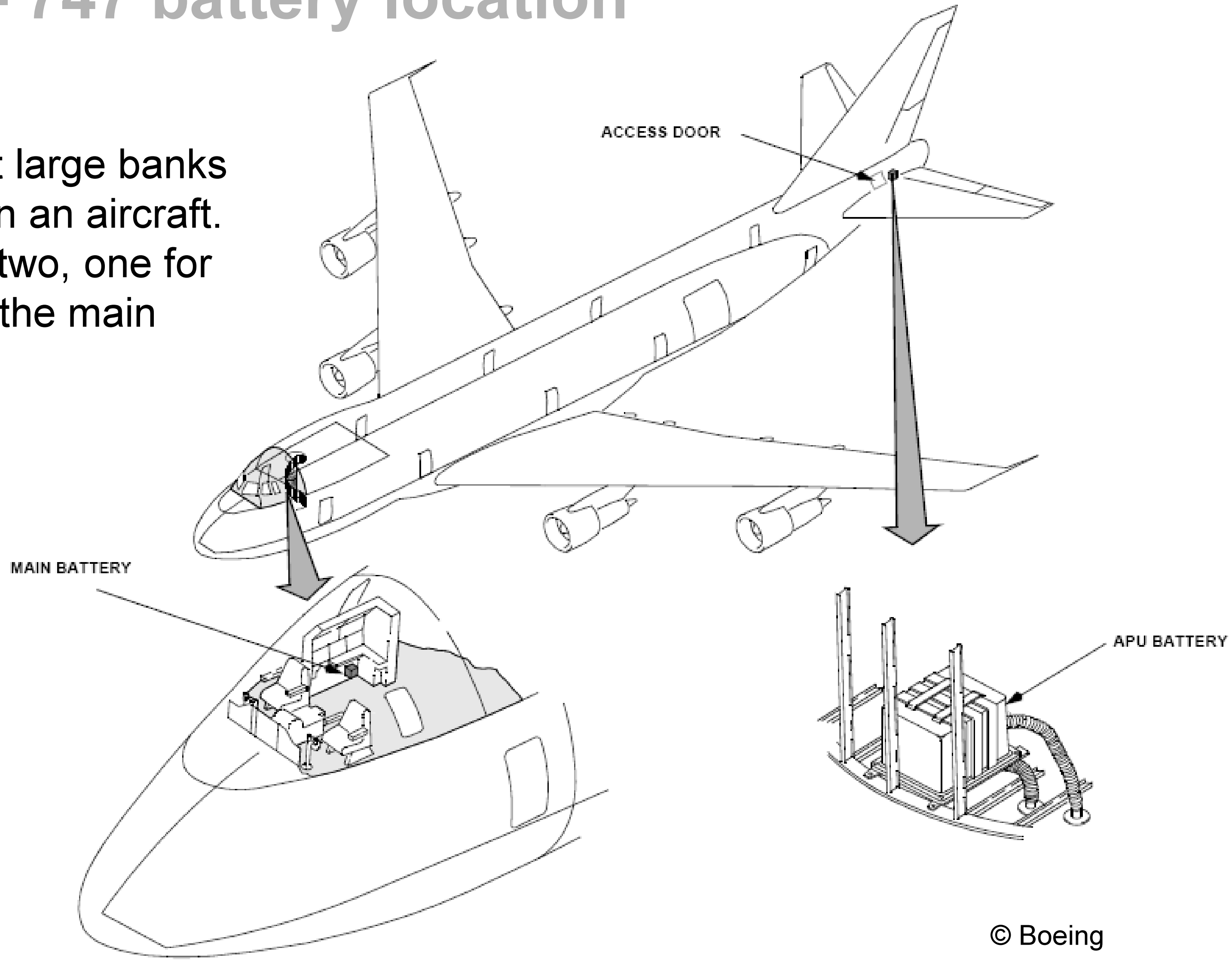
There are hundred of different batteries fitted to aircraft, with differing voltages (12~50V), capacities and packaging. This particular type is a Ni-cad manufactured by Saft and has an application on board the Boeing 747.



Type	*NI-Cad*
Application	*Boeing 747*
Length	*268.4 mm*
Width	*304.8 mm*
Height	*264 mm*
Weight	*36 Kg*
Nominal voltage	*24 V*
Nominal capacity	*36 Ah @ 1h rate*
Recommended constant charging voltage	*28.5 V*
	Information © Saft

Storage – 747 battery location

There are not large banks of batteries on an aircraft. The 747 has two, one for the APU and the main battery.



APU – Auxiliary Power Unit

- APU - a small gas turbine engine.
- Provides back-up for hydraulic, pneumatic and electrical power systems.

- Enables the aircraft to 'self-start'
- Fitted with electrical generator similar to the main engines.

RAT – Ram Air Turbine

The Ram Air Turbine is an air driven generator that is dropped into the air stream of a moving aircraft when all else has failed.

It will provide hydraulic as well as electrical power in the case of a failure of both the engine driven generators and the APU's.

GPU - Ground Power Unit

Although strictly not part of the aircraft, the GPU has to be interfaced to the aircraft electrical system. The GPU provides power for certain functions on the ground and plugs into the aircraft 'on stand'. It is often a diesel powered portable generator at smaller airports.

Aircraft Electrical Distribution

Standards

Architecture

Components and layout

Battery voltage

Distribution - Standards

Two common standards of power supply exist for aircraft. Most current aircraft feature an electrical system conforming to these standards.

- **AC System – 115V 3 phase 400Hz**
  - A constant frequency, constant voltage supply, capable of supplying high power loads.
- **DC System – 28V**
  - Battery backed-up system for critical applications. On smaller aircraft this may be the only supply.

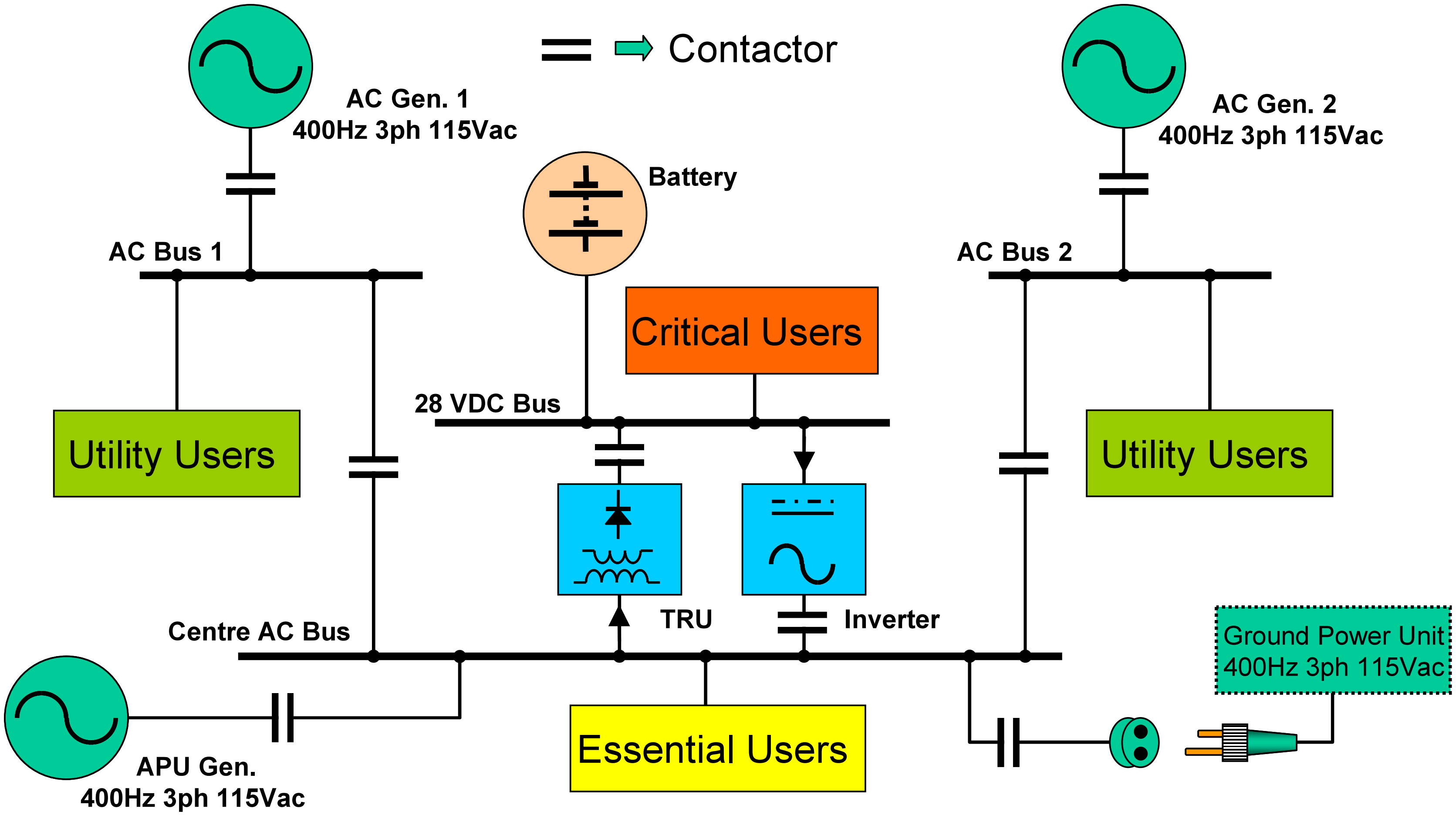
Distribution – why 115 VAC and 28 VDC?

The distribution system on-board an aircraft can be as simple as a single **'power bus'** and protection equipment (breakers) or may consist of a variety of buses at differing voltages and the equipment to transfer power between each.

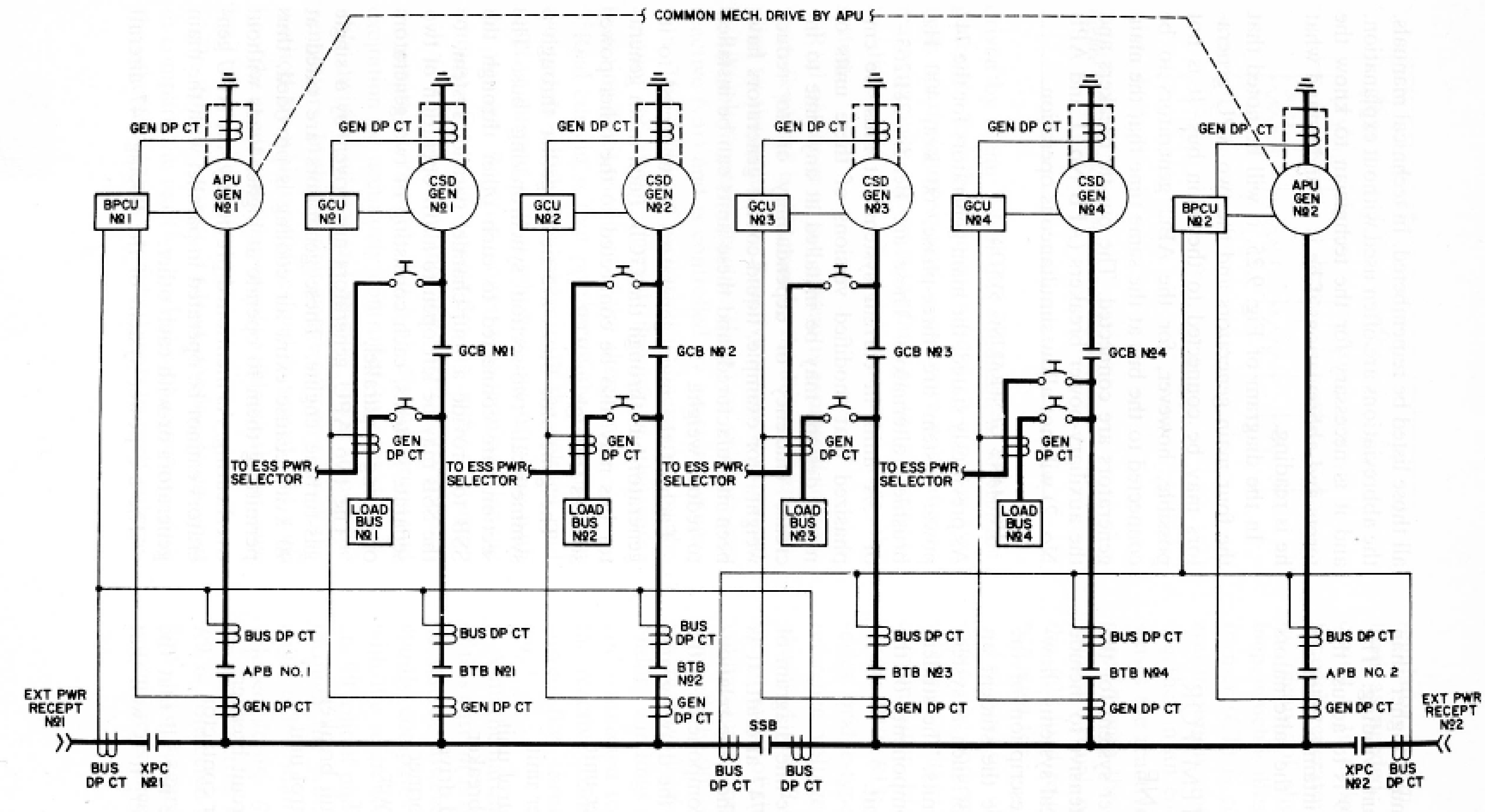
We need to consider ;

- Power is most efficiently transmitted at high voltages.
- On-board aircraft power is generated in an AC form.
- Power stored is in a DC form (important for emergency supply).
- AC power can easily be converted from one voltage level to another.
- Components can be sensitive to frequency (AC system).
- End user requirements differ;
  - Voltage levels, AC/DC.
  - Some systems are safety critical.

Simplified Bus Architecture



Architecture Example - 747 AC System



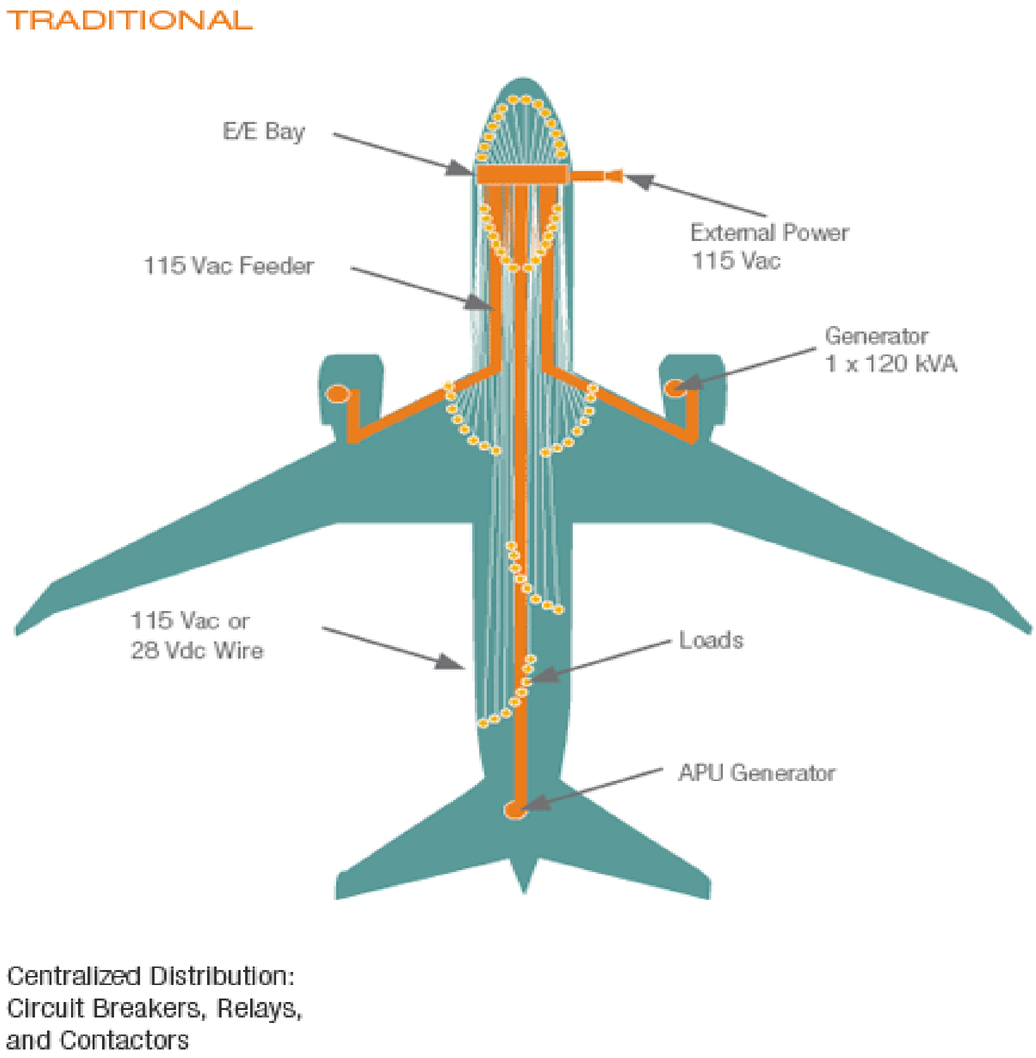
AC SYSTEM SINGLE-LINE DIAGRAM

CT – Current Transducer

System Components Boeing 747

- AC System;
  - 4 engine driven generators, cf, 3ph, 400Hz, 115VAC, 90kVA each.
  - 2 APU generators, cf, 3ph, 400Hz, 115VAC, 90kVA each.
  - 2 ground power sockets, cf, 400Hz, 115VAC, 70kVA.
- DC System;
  - 4 x 75Amp TRU's fed from AC buses.
  - 1 x 20Amp TRU fed from ground supply bus.
  - 2 x 24 V Ni-Cad batteries
    - 1 Main battery
    - 1 APU battery

Physical system layout



Battery Nominal Voltage

The DC bus on an aircraft is 28V, but the battery is 24V ?

The battery voltage is a nominal figure: the voltage appearing at the terminals of a battery depends on the state of charge of the battery and the operating conditions (recharging, heavy load etc).

- A fully charged battery is likely to have an open circuit (nothing connected) voltage above the nominal figure e.g. 13V for 12V nominal.
- As the battery is discharged the open circuit voltage will fall 10-20%.
- Under heavy load the voltage at the terminals may drop below the nominal figure.
- When recharging it is necessary to raise the voltage at the terminals above the nominal figure e.g. 28.5V for a 24V battery.

The specification of the aircraft DC bus allows for variations in the voltage.

The More Electric Aircraft

Aircraft power systems

4 forms, 3 distribution systems: Power rationalisation should be possible

Electrical Power

Avionics
Commercial
Ventilation
Lights

~230 kW (115 V)

Hydraulic Power

Flight Control
Landing gear
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~240 kW (20.6 Mpa) *(206 bars)* *(3000 psi)*

Mechanical Power

Engine-driven
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Pneumatic Power

Air conditioning
Pressurisation
Icing Protection
Engine start

~1200 kW *peak (3 bars)* *(45 psi)*

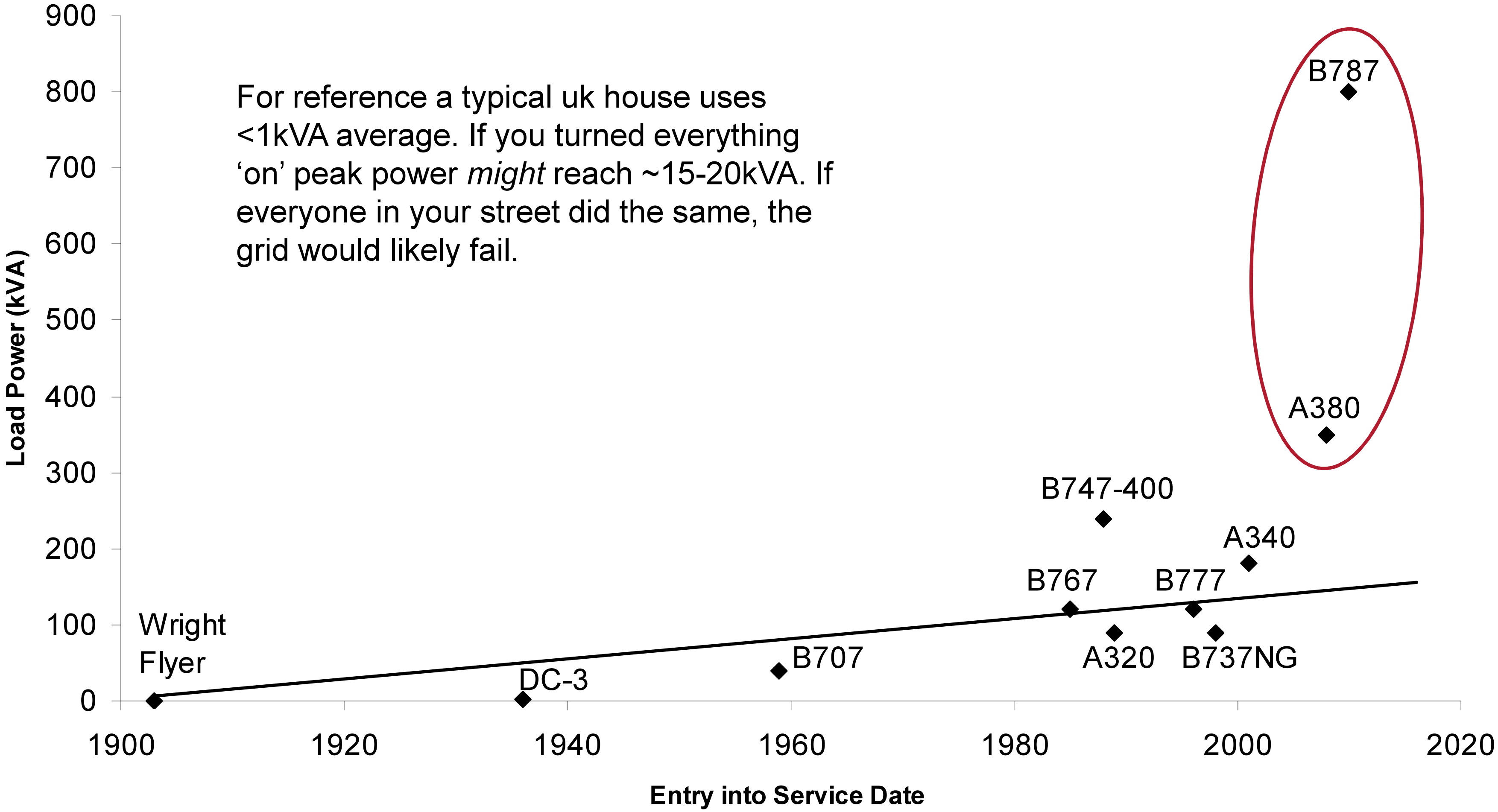
The MEA - 'More Electric' Aircraft

The term 'More electric' aircraft is used to describe trends in current and future aircraft design that are leading to an increased use of electrical power on-board civil airliners.

The primary driver for using more electrical technologies is reducing the cost of operating aircraft. Reduced cost can be achieved in many ways, reliability, maintainability, are as important as weight saving, fuel efficiency etc.

One of the effects of migrating to electrical systems has been the large increase in electrical power demand of MEA's. Elimination of the engine air bleed system has caused the massive jump in power in the 787 – this extra power is required to run the environmental control system.

Electrical Power Trends

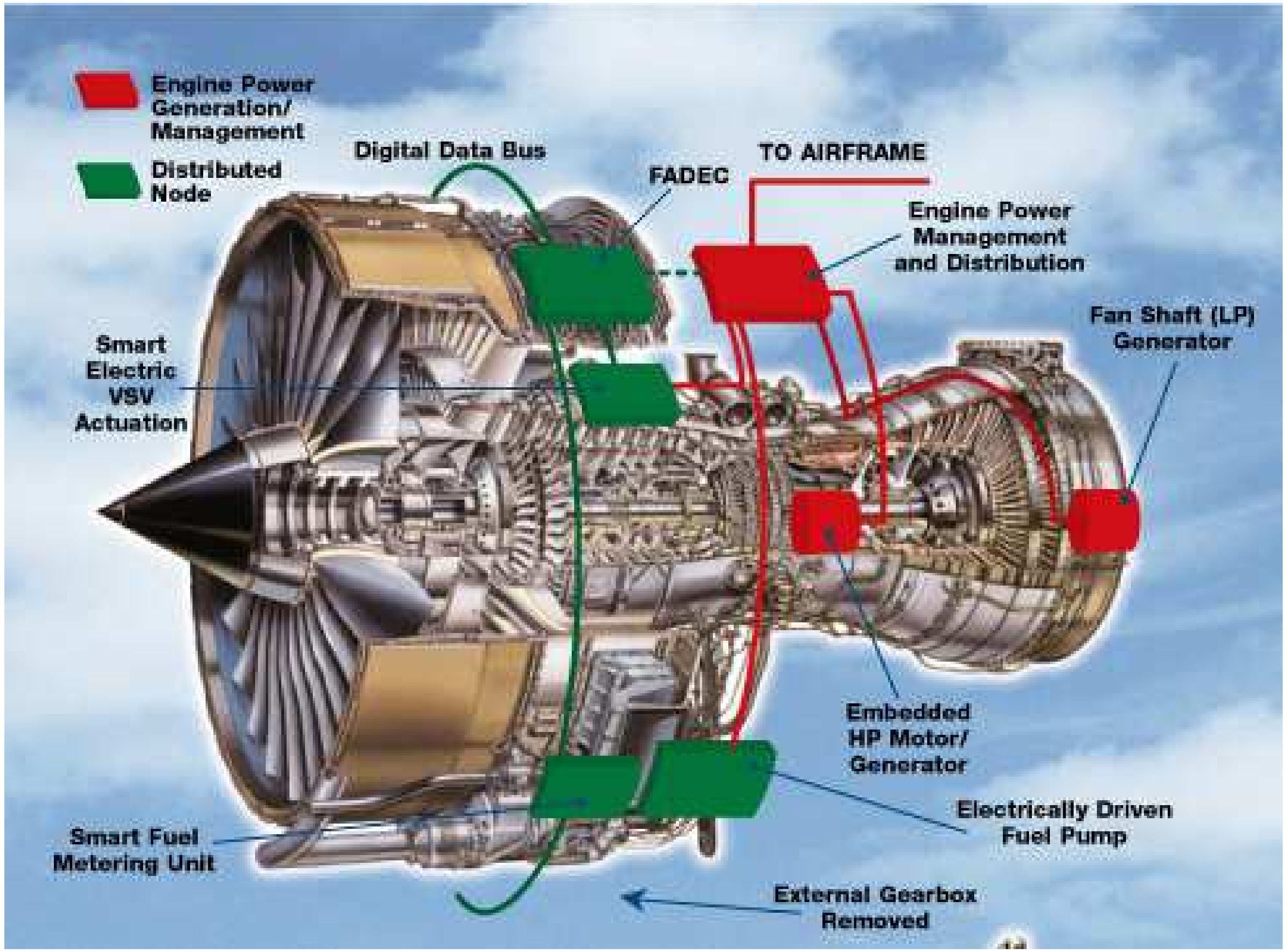


MEA

The more electric concept can be applied to practically all of the aircraft power systems;

Electric Function	*Replaces*
Actuation of flight surfaces	Hydraulic system
Landing gear extension/retraction	Hydraulic system
Actuation of thrust reversers	Hydraulic/Pneumatic system
Actuation of brakes	Hydraulic system
Ice protection	Pneumatic system
Main engine start	Pneumatic system
Air conditioning	Pneumatic system
Fuel & oil pumps	Mechanical system
Ground manoeuvring	Tug?

The More Electric Engine



Source: Rolls-Royce

A380 - Stepping Stone to the MEA

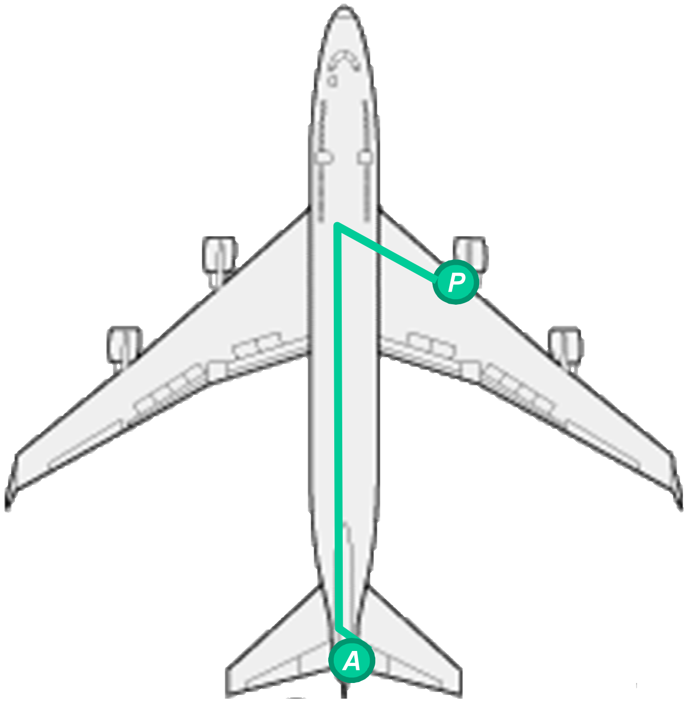
The Airbus A380 aircraft features many ME technologies.

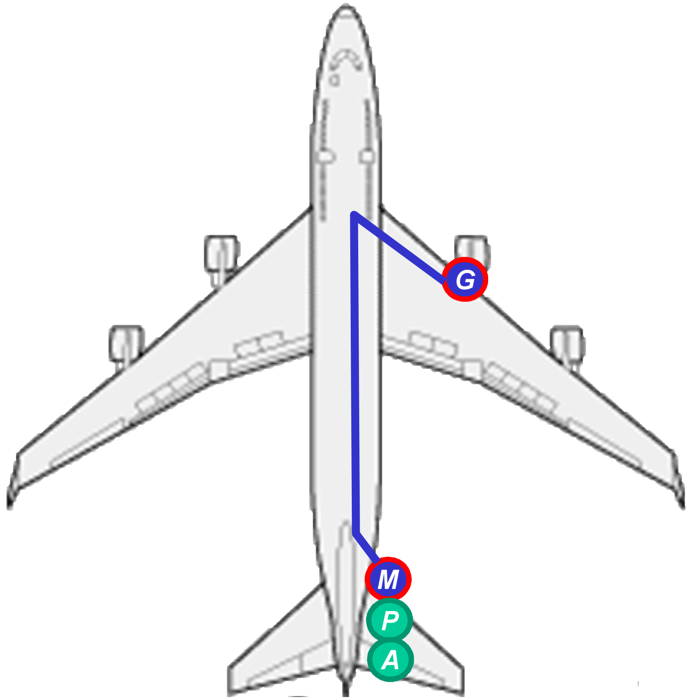
- **Electro-hydraulic flight surface actuation**.
  - On back up flight controls but essential to achieve certification. Will lead on to the development of direct electro-mechanical systems.
- **70% of the 106 electric motors are fitted with local power electronics.**
  - More efficient operation, new types of motor can be used.
- **Contactors and breakers replaced with solid state devices.**
  - Offer faster switching and more reliable operation in a smaller and lighter package.
- **Four 3-phase, 115VAC, 150kVA variable frequency engine driven generators**
  - Eliminating the complex constant velocity gearbox

Just some of the 106 electric motors fitted to A380

Application	Power	No. of
LP recirculation fans (fixed speed)	3100	10
LP recirculation fans (fixed speed)	3100	1
HP recirculation fans (speed controlled)	13000	4
Aft lavatory & Galleys compartment air extract fan (CAX)	2500	1
Fwd lavatory & Galleys compartment air extract fan (CAX)	2500	1
Avionics blowing fan side 1	3010	1
Avionics blowing fan side 2	3010	1
Avionics extract fan	5400	1
Cargo compartments ventilation (Fwd)	3400	1
Cargo compartments ventilation (Aft & Bulk)	2600	1
Central Refrigeration Unit (CRU) compressor	11390	2
CRU fan	3560	4
Pump Unit	5263	2
Inboard ailerons (EHA) (intermittent)	18000	2
Mid ailerons (EHA) (intermittent)	18000	2
Outboard ailerons (EHA) (intermittent)	18000	1
Outboard ailerons (EHA) (intermittent)	18000	1
Inboard elevators (EHA) (intermittent)	28000	2
Outboard elevators (EHA) (intermittent)	28000	2
Green & yellow Upper Rudder (EBHA) (intermittent)	22000	2
Green & Yellow Lower Rudder (EBHA) (intermittent)	22000	2
Spoilers (EBHA) (intermittent)	11000	6
THSA (Back-Up Electrical Motor) (intermittent)	7500	1

Electro Hydraulic FCS Actuator

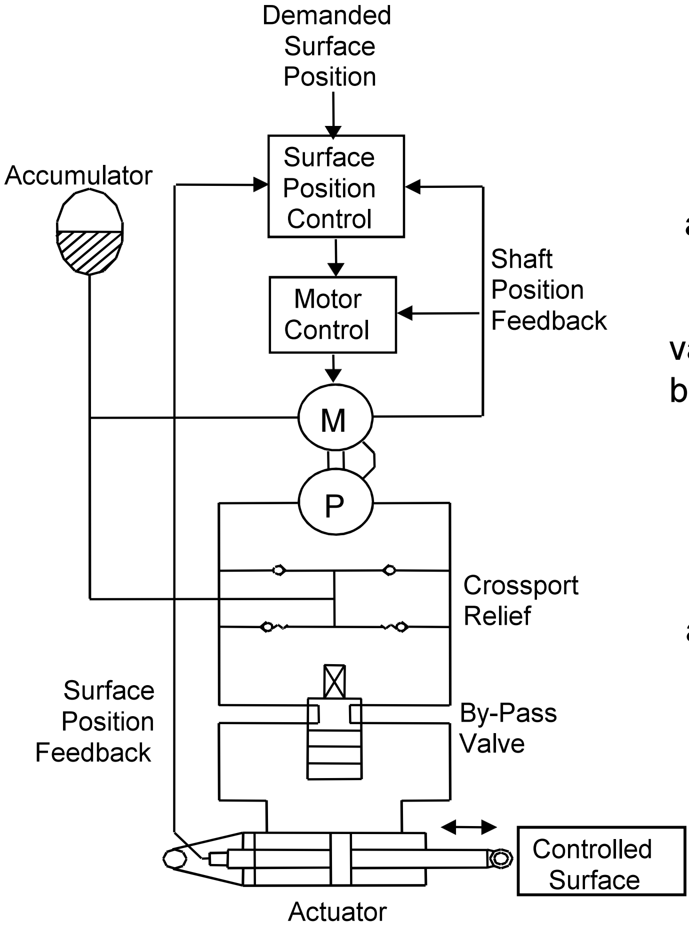


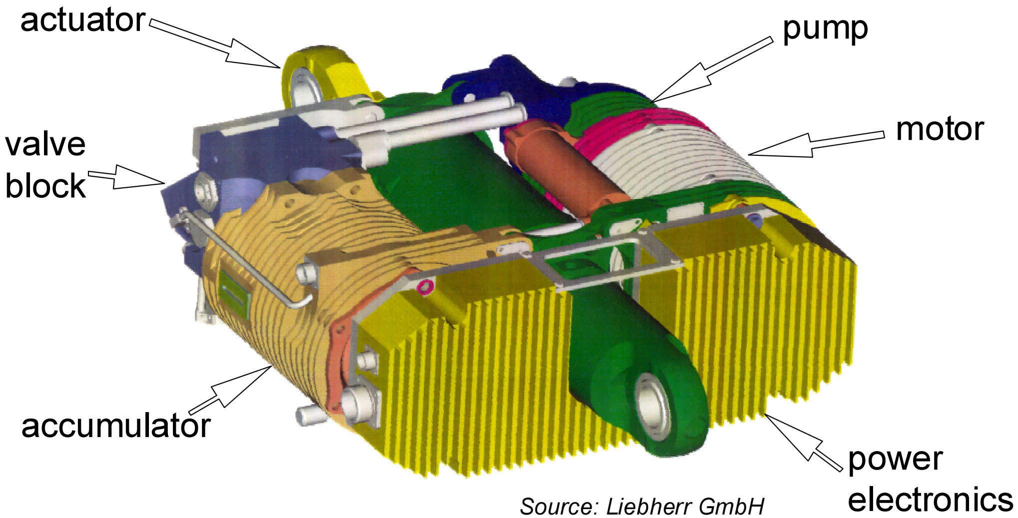


Conventional airliners have a hydraulic distribution system – transferring hydraulic power from engine to flight surface actuator.(this diagram represents just one channel of a redundant multi-channel implementation)

The A380 broke with tradition and distributed power electrically to the flight surface and then used a local electrically powered system to drive the flight surface. However to meet safety requirements, the electro-hydraulic actuator is part of a system with two parallel conventional systems

A380 Electro Hydraulic FCS Actuator

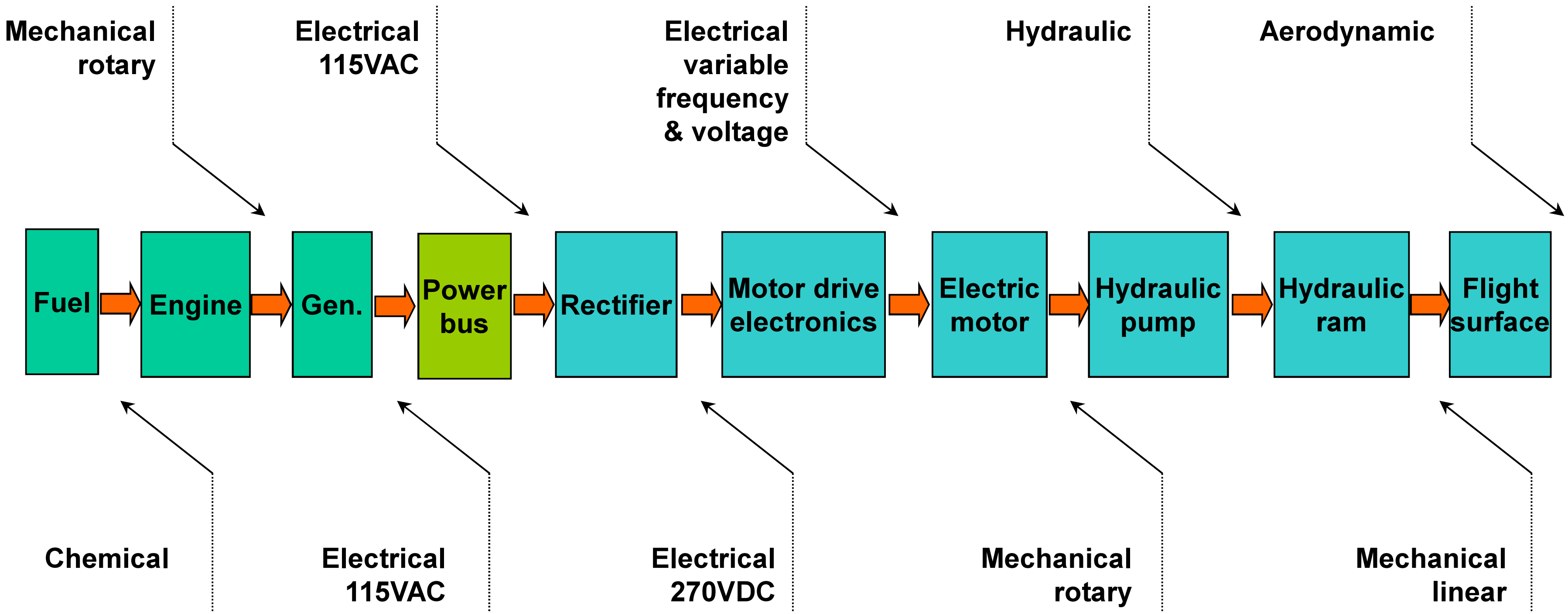




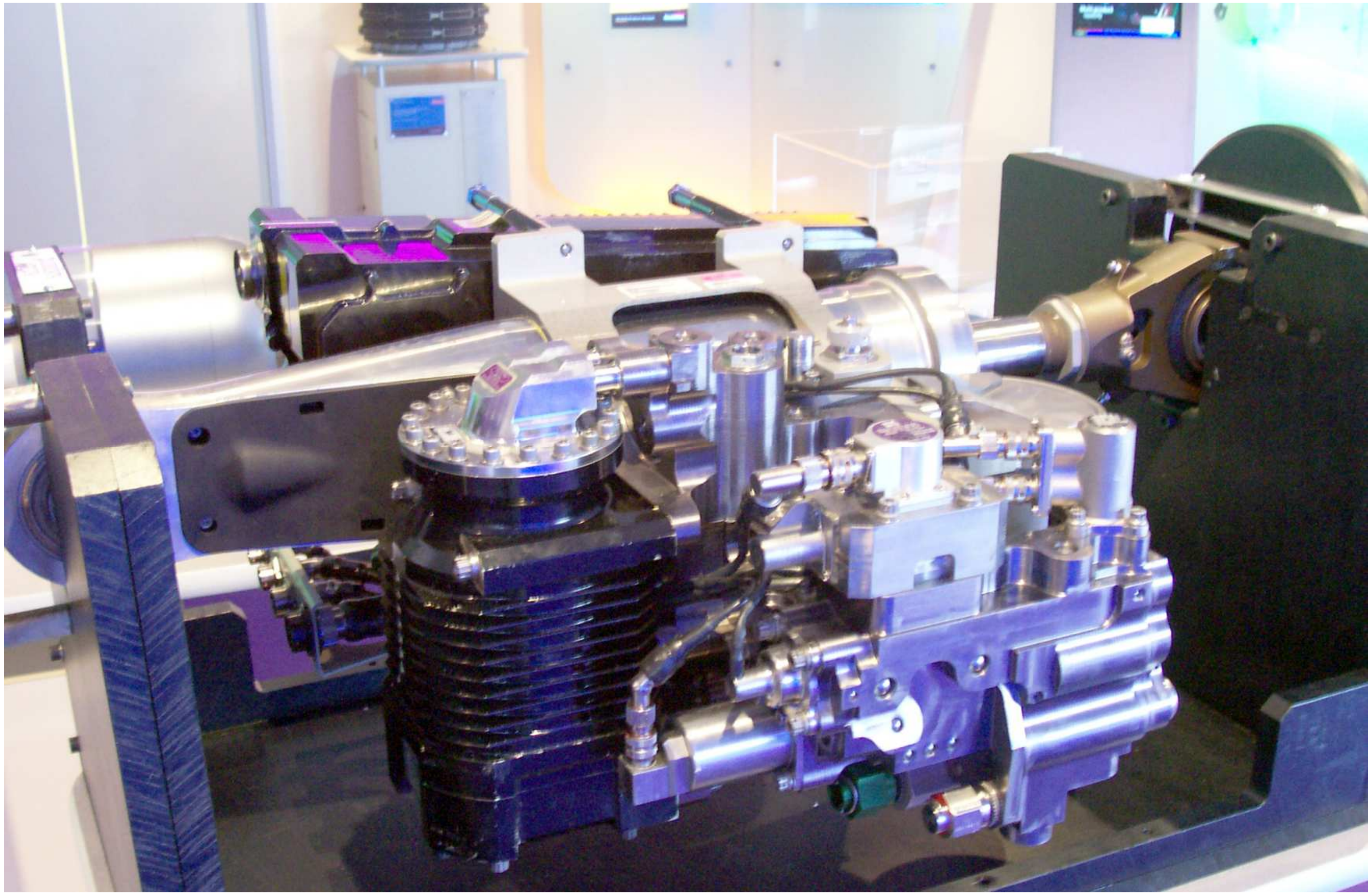
Source: Liebherr GmbH

A380 Electro Hydraulic FCS Actuator

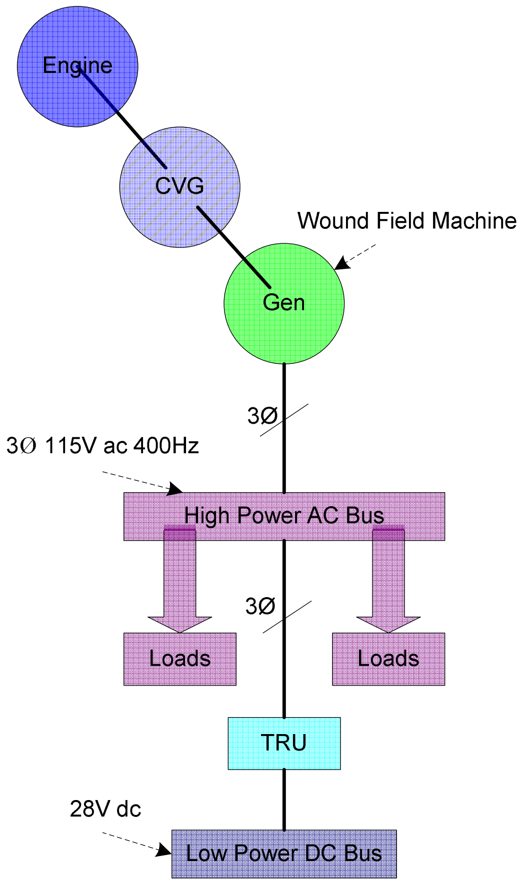
The electro-hydraulic actuator system employs multiple power conversions



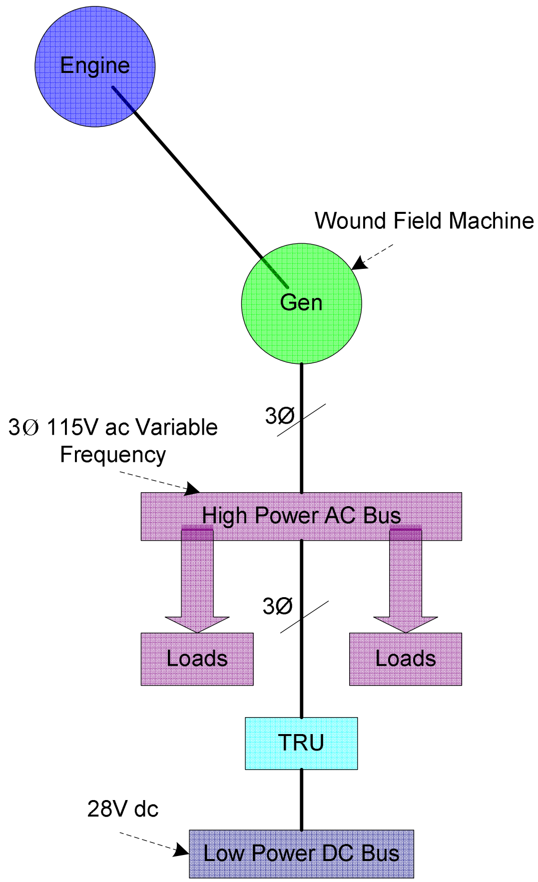
A380 Rudder Actuator



MEA Generator Channel



Pre MEA channel

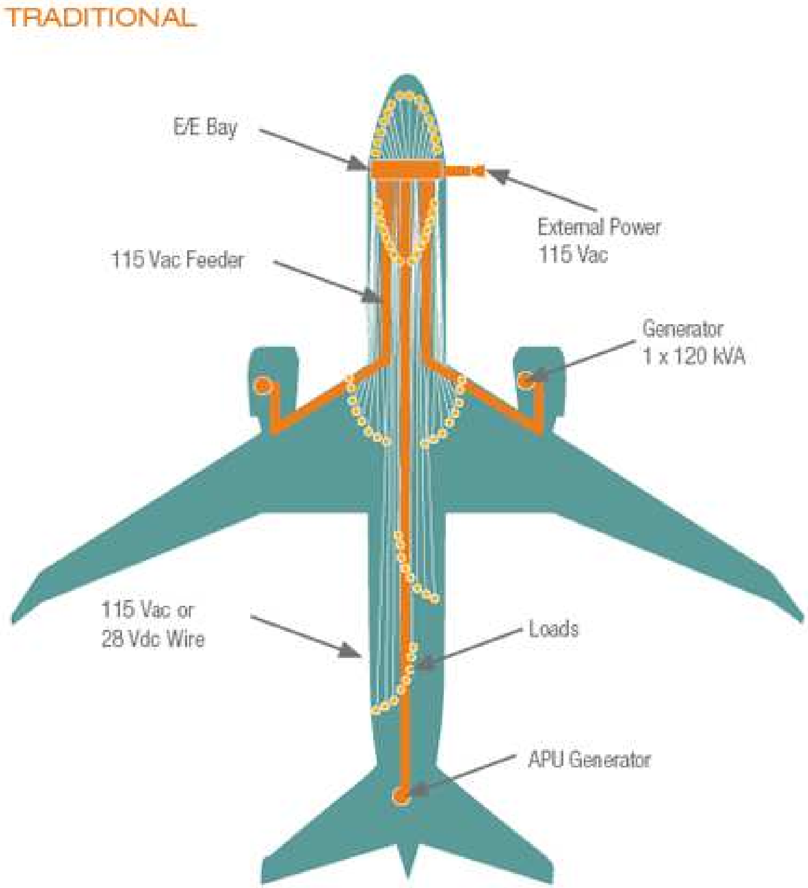


A380 Channel

MEA Generator Channel

- CVG removed
- Frequency wild operation
- GCU still controls voltage
- Split type architecture
- AC bus voltage 115VAC (A380), 230VAC (787)
- Rectified to 270 or 540 VDC locally
- Significant increase in generator size (250KVA 787)

787 physical layout



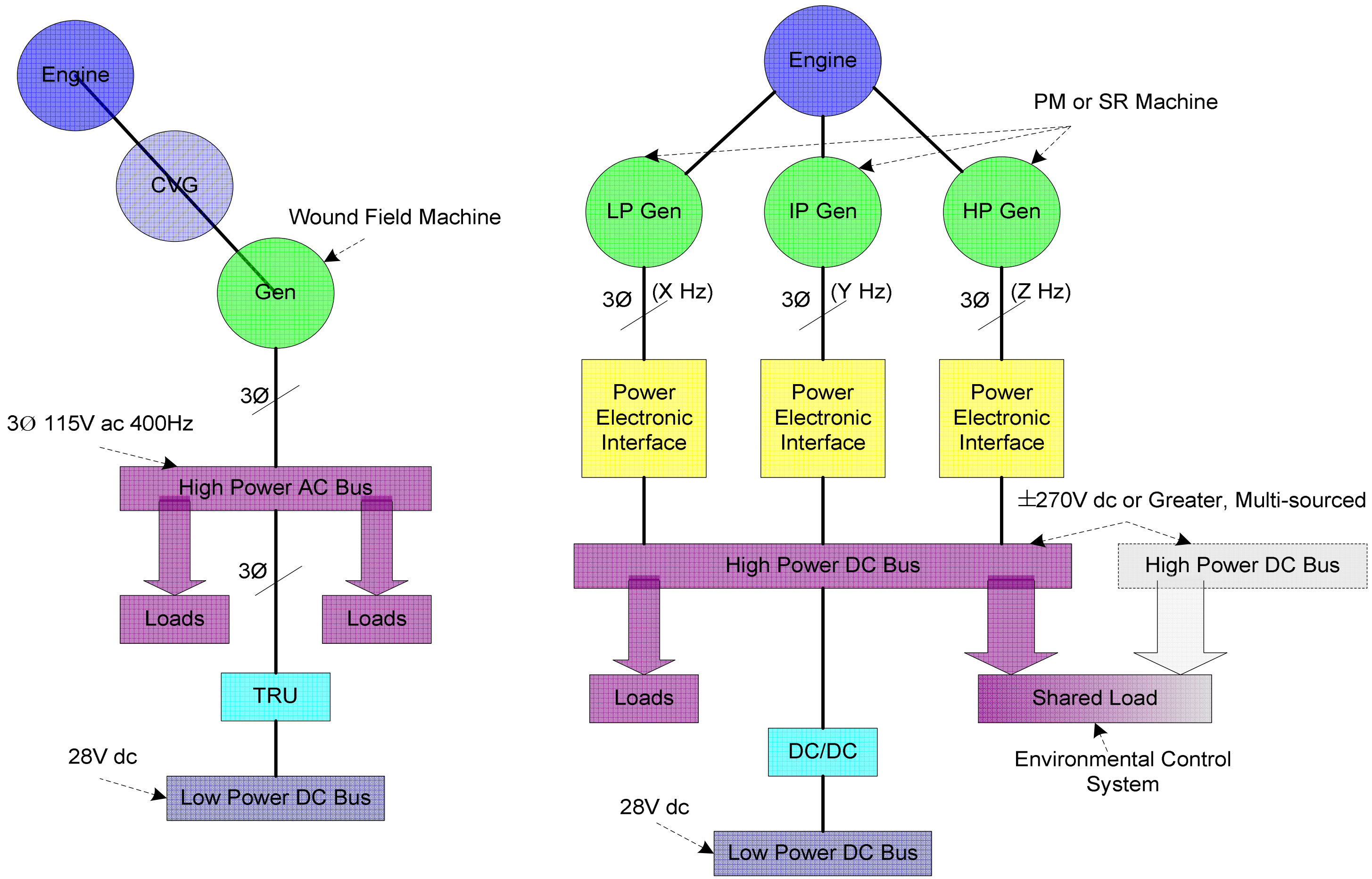
Centralized Distribution:
Circuit Breakers, Relays,
and Contactors

Remote Distribution:
Solid-State Power Controllers
and Contactors

The future: the AEA

- The increased demand for electrical power has pushed generator technology to the limits – to get more power they need to turn faster or become bigger and both are currently limited by materials.
- Also the power take-off from an engine has become a significant fraction of the engine power, resulting in the possibility that engine performance could suffer.
- To meet the need for for more power, new technologies are also set to be incorporated in future aircraft such as fuel cells as an alternative to the APU and high efficiency machines for generators and motors.

Future AEA Generator Channel



Pre MEA channel

Possible Future Channel

Future Generator Channel

- CVG removed
- Frequency wild operation
- Multiple generators per engine
- Generators embedded within engine
- Power electronics interface generator to bus
- Parallel DC type architecture – shared high power loads
- DC buses
- High voltages 540VDC+ ?