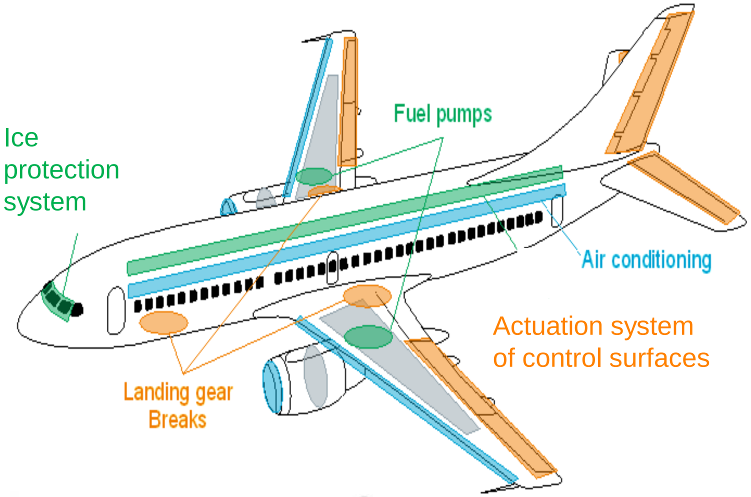
An overview of the modules “Systems” of the ASC major

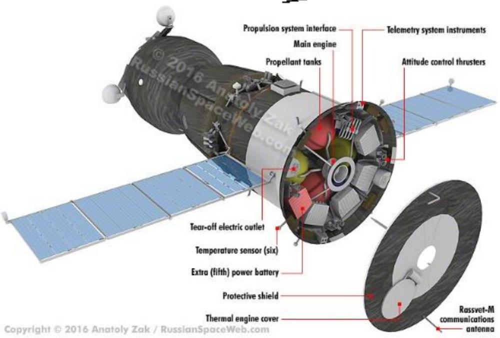
Energy sources

- Heat engine
- Fuel cell
- Battery
- Super capacitors
- Solar energy
- Wind energy

Power transmission and distribution

Power consumers





AIRCRAFT POWER ARCHITECTURE
Part 1: Electrical systems

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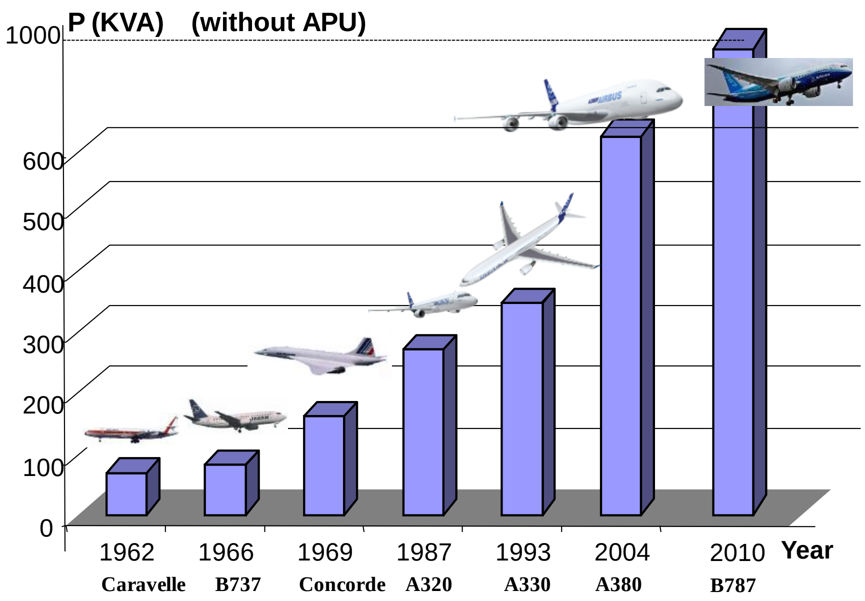
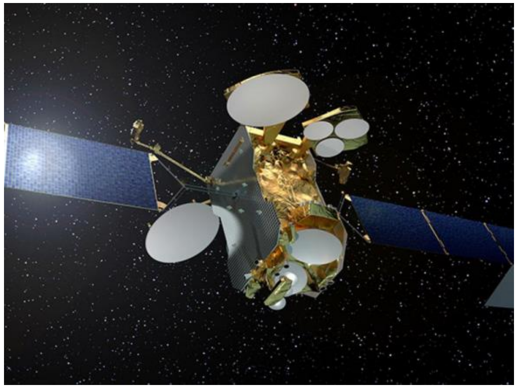
SUPAERO

Electrification of aerospace systems

Sharp increase in the number and power of electrical systems on board airplanes or satellites.



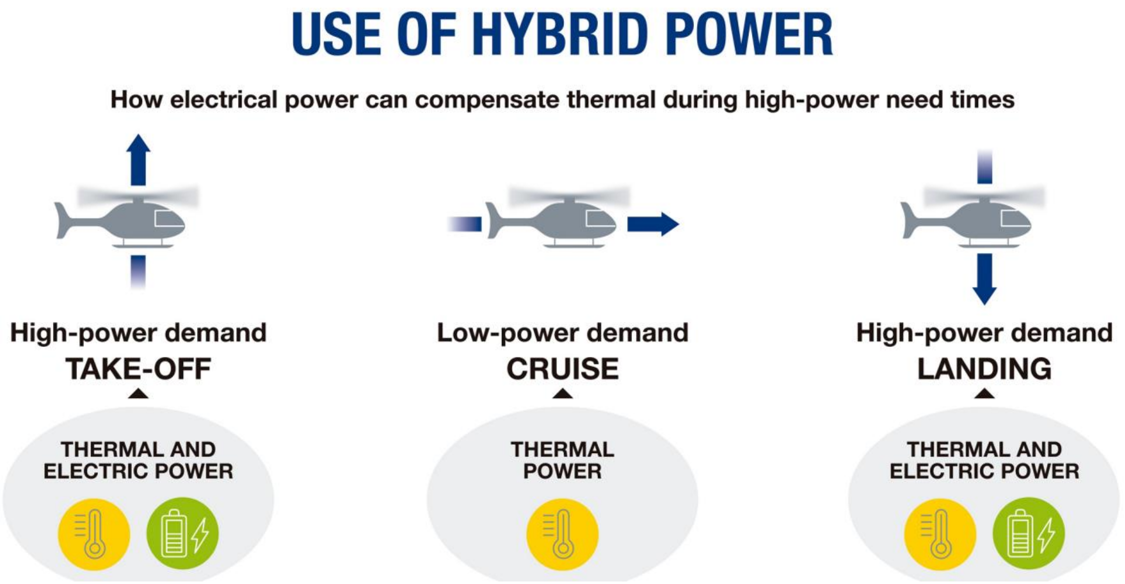


- Eutelsat 172B, the first European electrically powered satellite
- in 2022, 25% of satellites will be fully electric

Why electrify aerospace systems?

Gain in energy efficiency

eg. optimize the turbines for the power required during cruising (non-maximum power) and provide additional power for the phases which require more (take-off, landing) by electric hybridization.



Reduce emissions: less consumption, use of less polluting energy sources

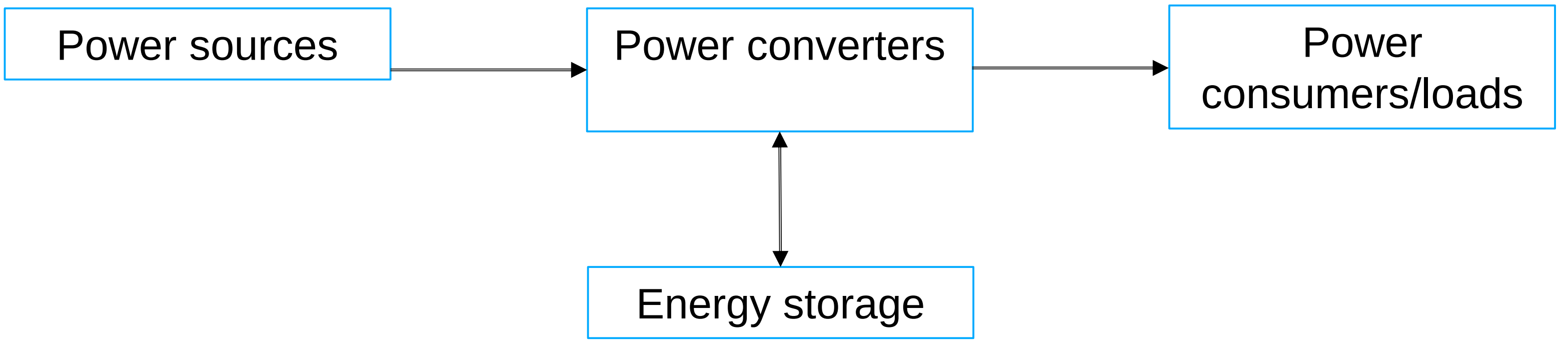
Increase system reliability

Limit noise

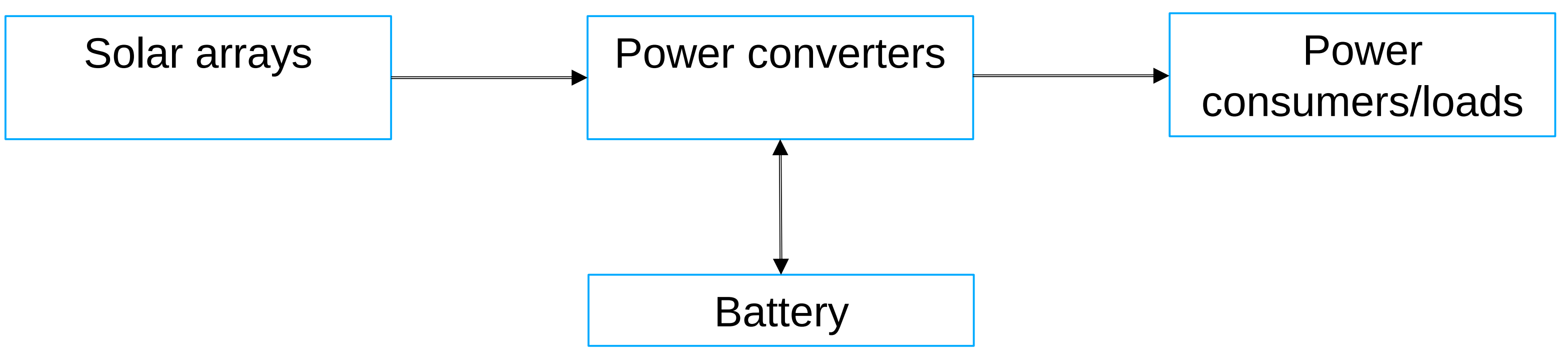
Diagram and basic elements

of an electrical network

Basic principle diagram of an electric architecture



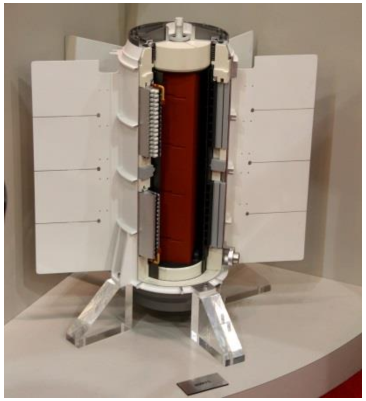
Example for a satellite platform

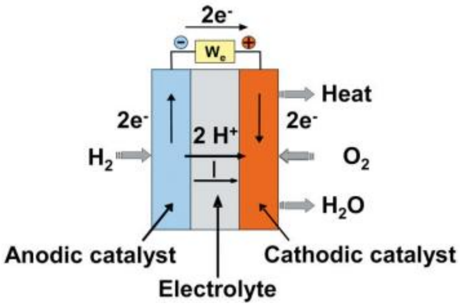


Power sources in a satellite

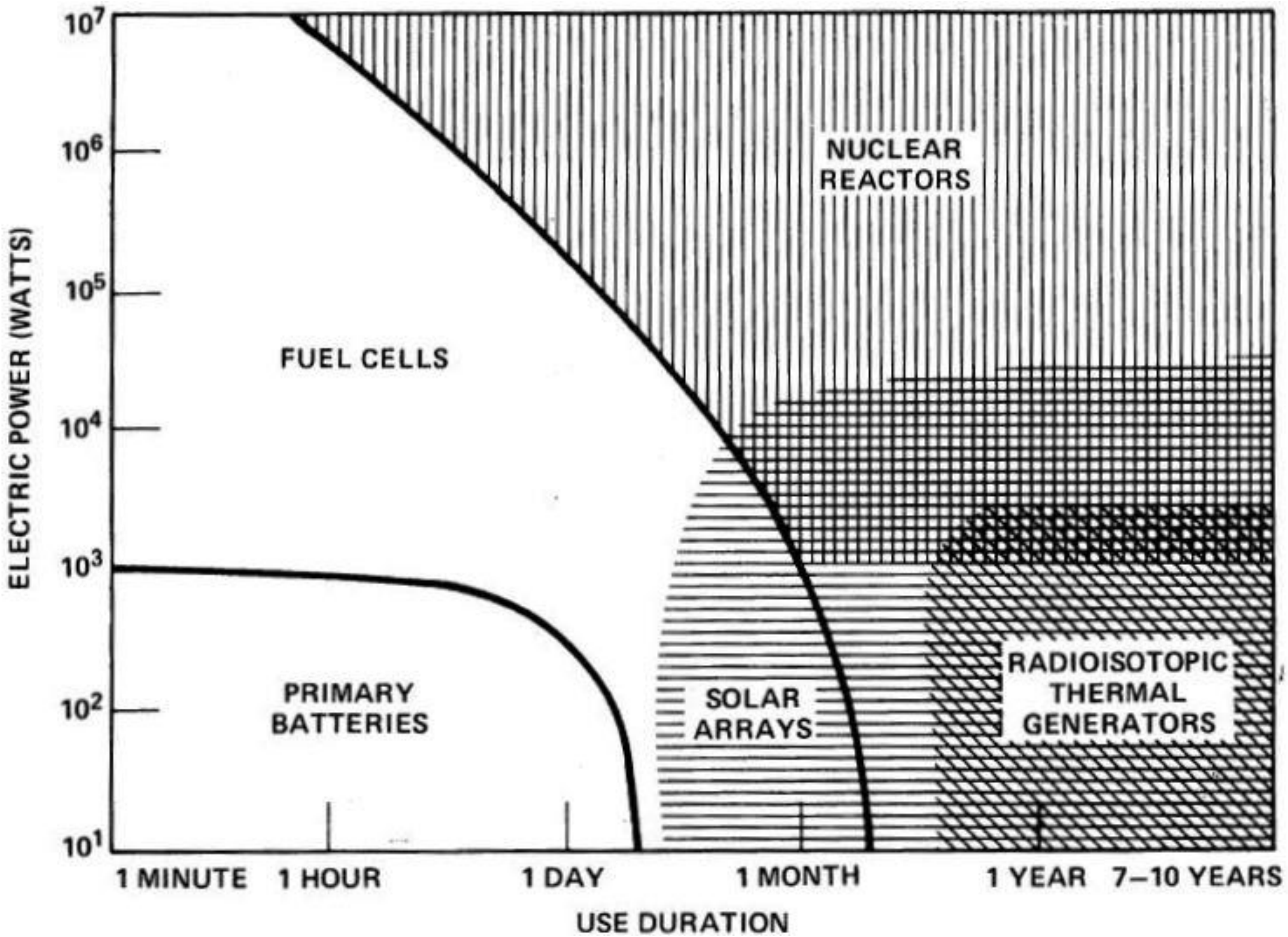
- **Main primary sources**:
  - **Solar panels** that exploit the photovoltaic effect (average efficiency of 25%, intensity of solar radiation in the space of 1366 Watts / m2)
  - **Radioisotope thermoelectric generators or RTGs** (radioisotope thermoelectric generators) based on radioactive decay which produces heat converted into electricity using thermoelectric semiconductors or thermocouples. Useful when solar energy is insufficient or even unavailable (case of distant explorations of space)
  - **Fuel cells** which exploit the electrochemical effect (average efficiency of 40 to 60%, energy available night and day). Example of the hydrogen fuel cell: combustion of hydrogen and oxygen which produces electricity, water and heat. The water produced by combustion can be reused as drinking water. Conversely, by electrolysis, the dihydrogen and dioxygen used can be produced by electrolysis of water.
  - **Primary batteries** (typically useful at the start of the mission)

- **Secondary sources (sources dependent on primary sources)**
  - **Rechargeable secondary batteries**



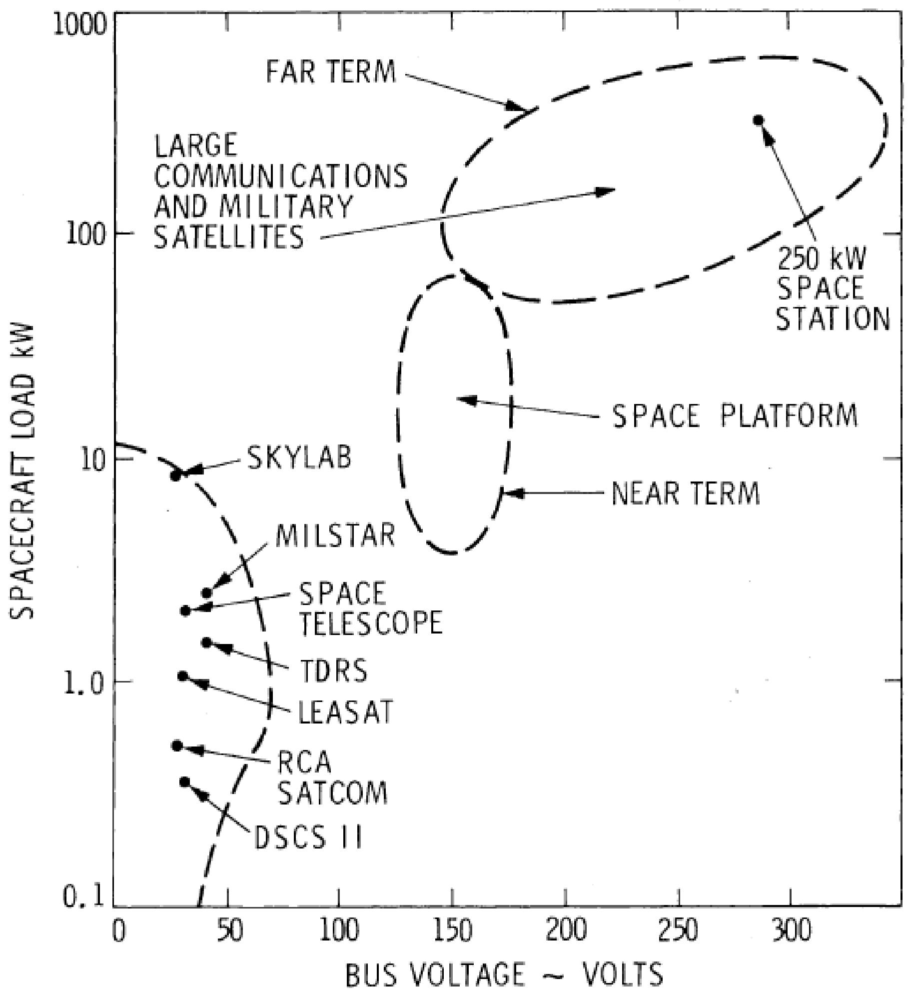


Power Generation Technology vs. Lifetime of Space Systems



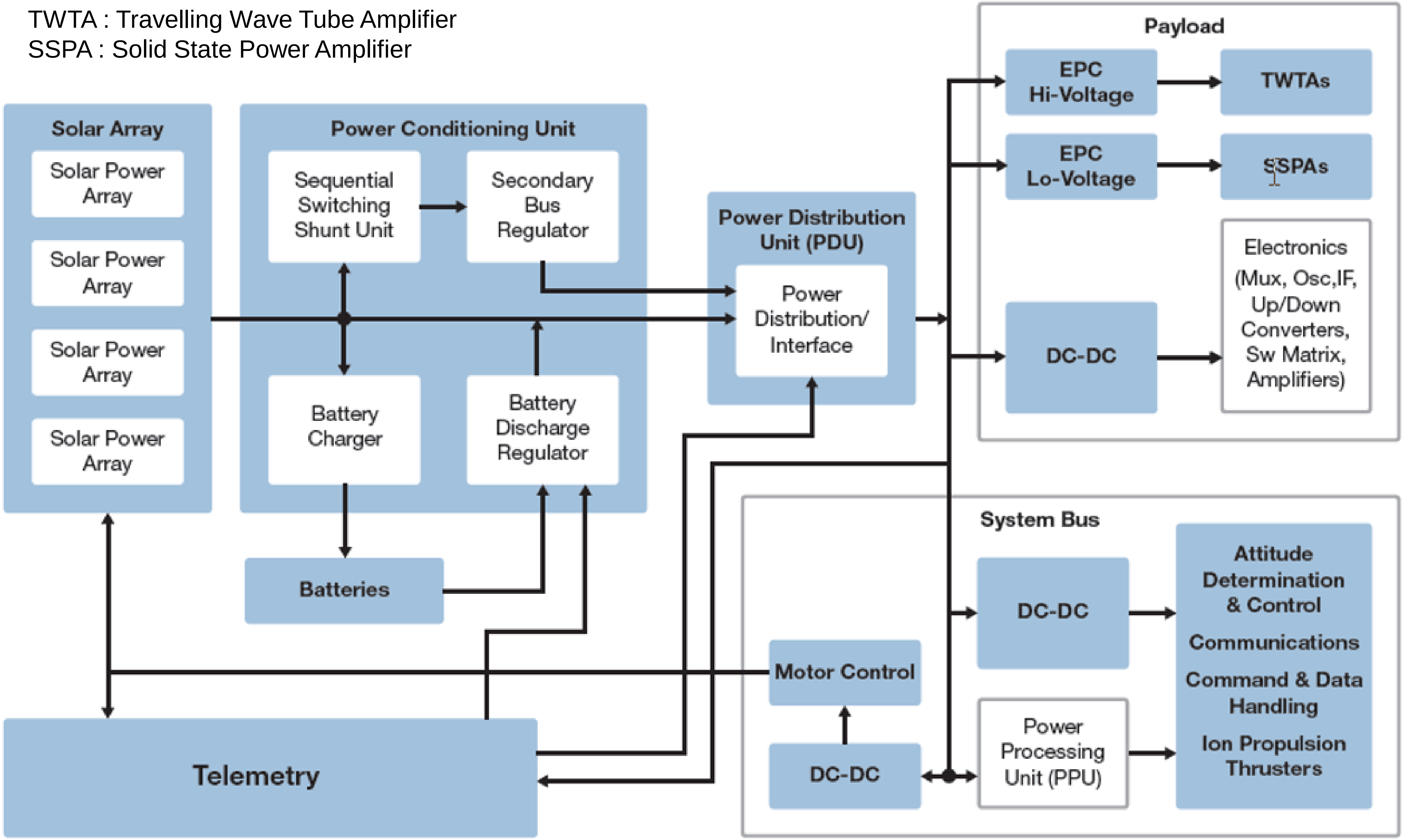
Evolution of power in space systems

SPACE VEHICLE DESIGN



Power sources and consumers in a satellite

EPC : Electronic Power Conditioner
TWTA : Travelling Wave Tube Amplifier
SSPA : Solid State Power Amplifier



Power sources in an airplane

Main or primary generators:

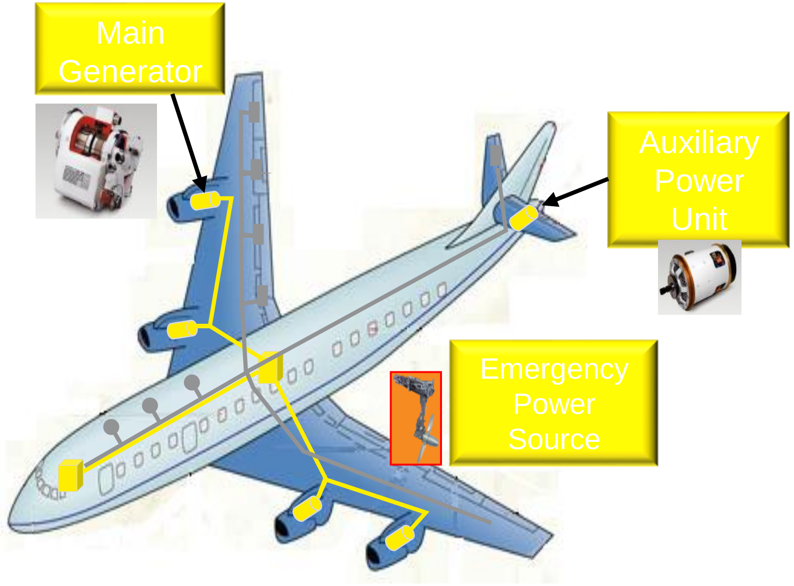
main power units to produce energy (pneumatic, hydraulic or electric) from the jet engines of the aircraft.

Auxiliary Power unit APU:

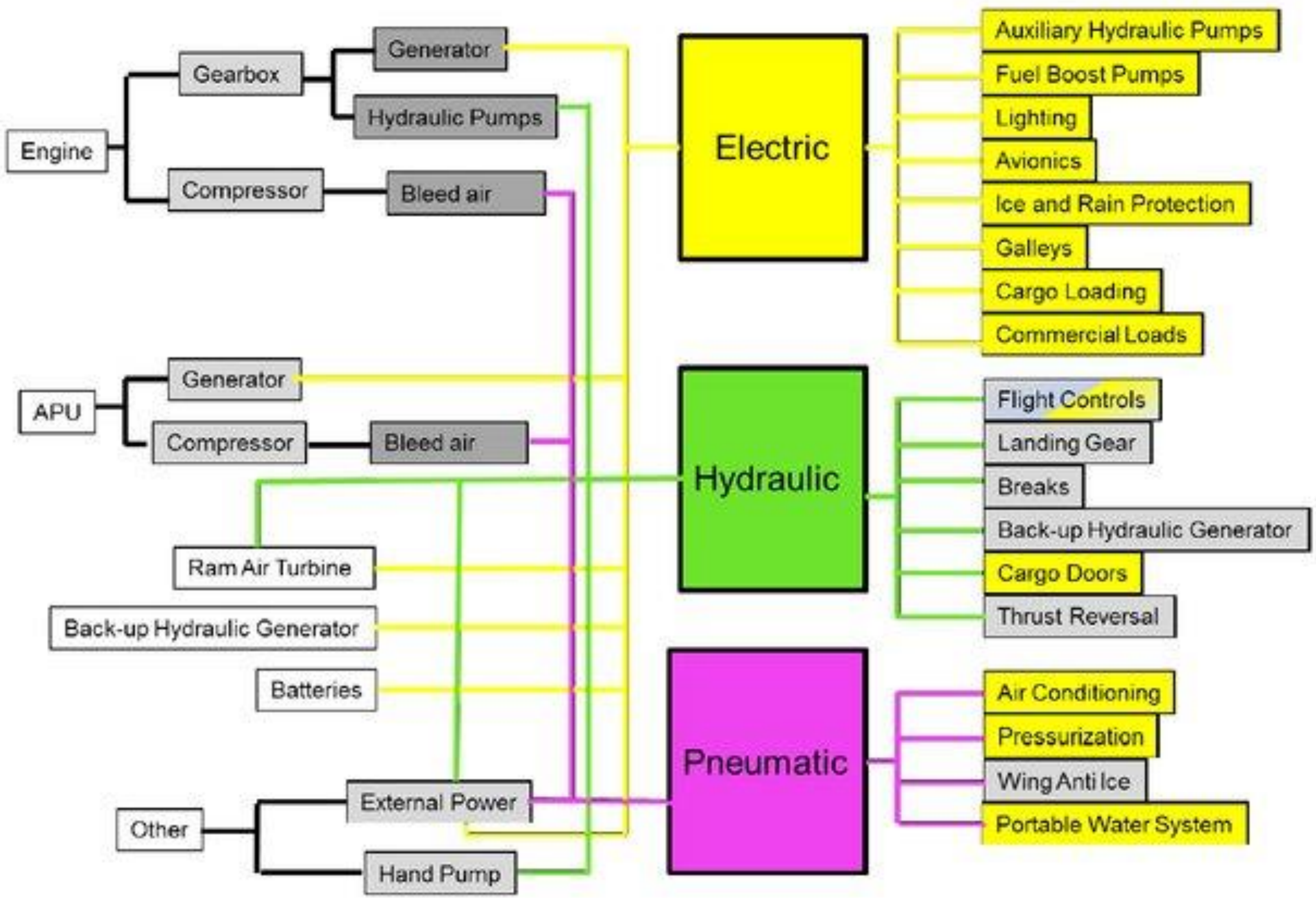
auxiliary power unit driven by an auxiliary turbine to start the primary generators and to produce the energy to be supplied to the various systems of the aircraft on the ground when the engines are off to save fuel. The APU is usually placed at the back of the aircraft.

Emergency power source:

unit of power to produce energy when other generators are out of service



Main power consumers in an airplane
"more electric" airplane configuration



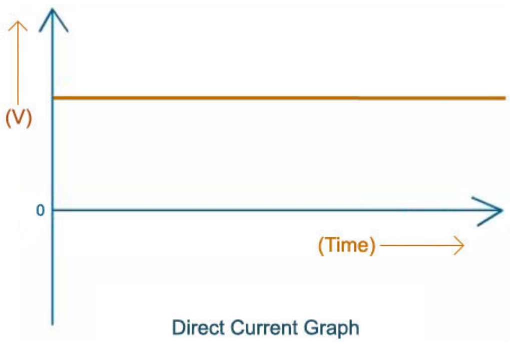
Quantities for analyzing

an electrical network

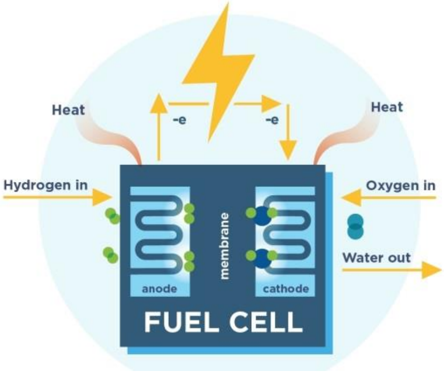
DC voltage

- **DC voltage** (VDC : Direct current)
  Characterized by its amplitude

$$v(t) = V_{DC}$$



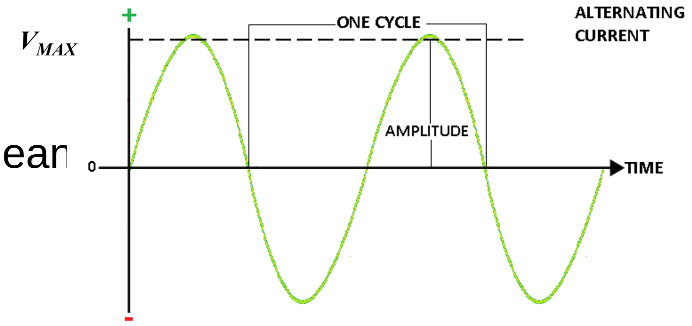
- **DC voltage sources**



Single phase AC electrical voltage

- **Single phase AC electrical voltage**
  (VAC : Alternating current)

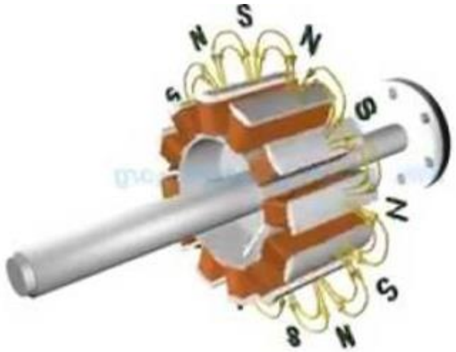
  Characterized by its amplitude V_{MAX} or its RMS (Root Mean Square) value and its frequency f



$$v(t) = V_{MAX} \sin(2\pi f t+\phi)$$

$$\boxed{V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \frac{V_{MAX}}{\sqrt{2}}}$$

- **AC electrical sources**



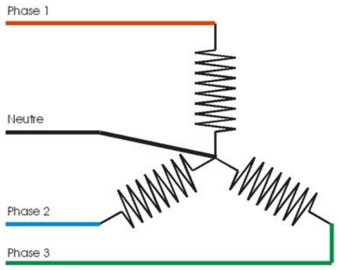
Three-phase AC electrical voltage

A **three-phase system** is made up of 3 conductors (connected in star or delta) carrying alternating currents of the same frequency and of the same amplitude, but phase-shifted by one third and two thirds of a period.

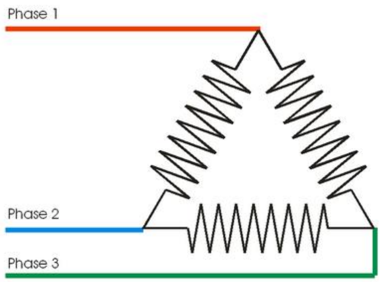
$$v_1 = V\sqrt{2}\sin(\omega t)$$

$$v_2 = V\sqrt{2}\sin(\omega t - \frac{2\pi}{3})$$

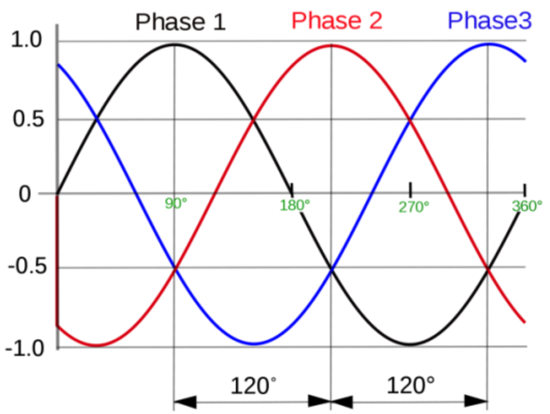
$$v_3 = V\sqrt{2}\sin(\omega t - \frac{4\pi}{3})$$



Star (Y) configuration



delta (Δ) configuration

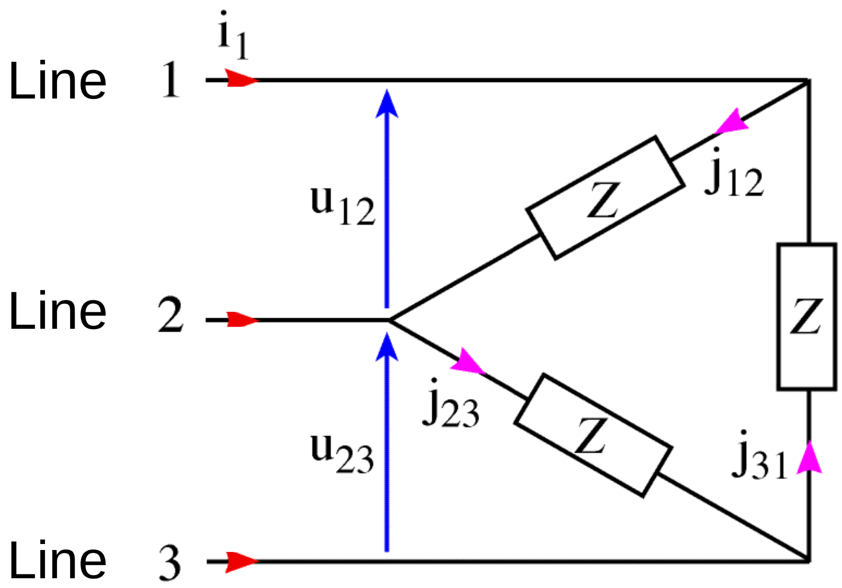


Interests of three-phase AC electric networks

- Three-phase systems can produce a rotating magnetic field used in AC electric machines which have a better power-to-mass ratio than DC machines

- In comparison with single-phase AC systems, three-phase AC systems can produce higher powers for the same current (and therefore the same cable diameter ⇨ saving in mass)

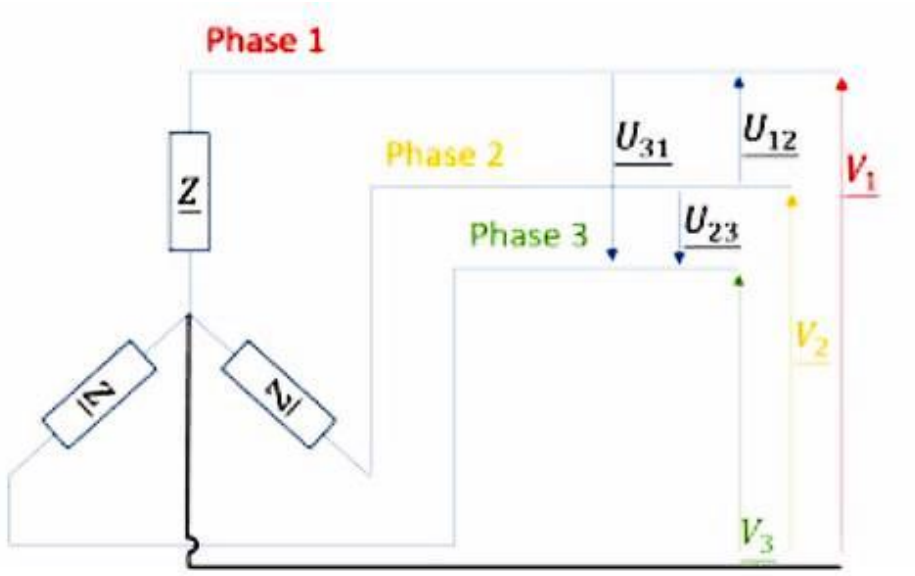
Triangle configuration

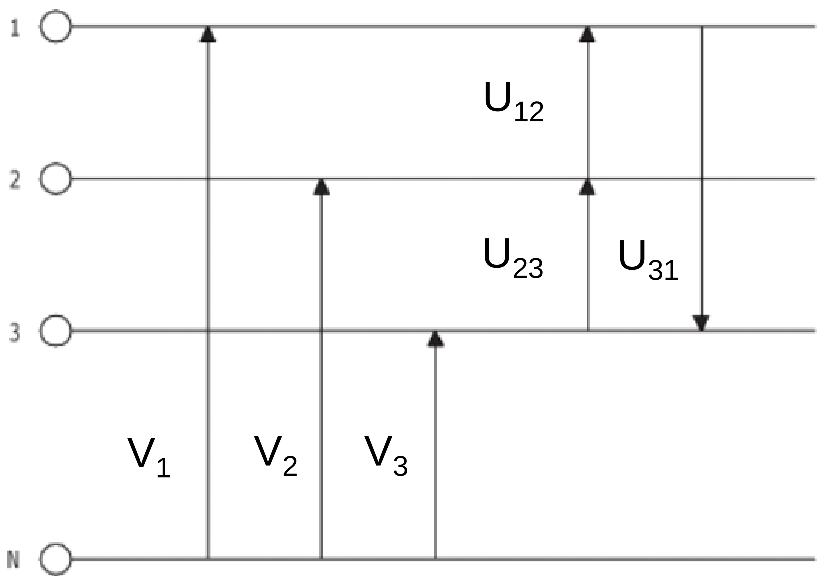


j : phase current

i : line current

Three-phase electrical systems in star configuration: Phase and phase-to-phase voltages

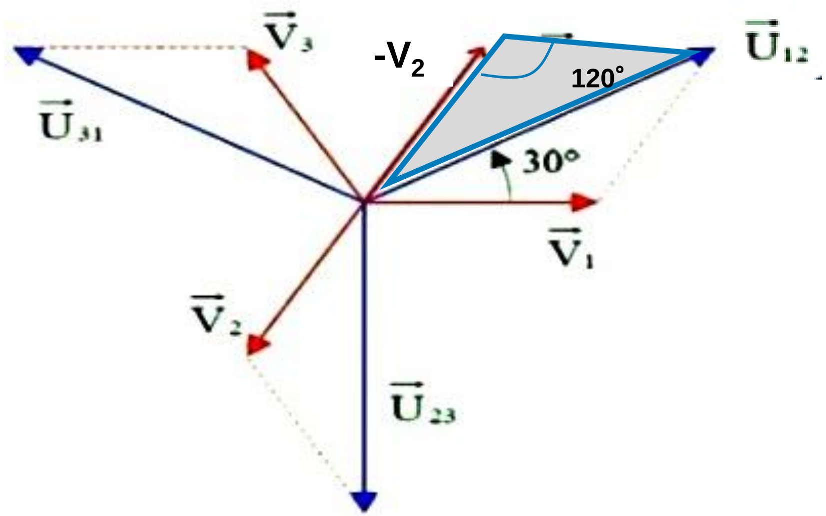


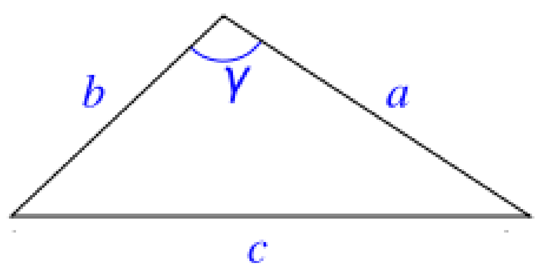


V : phase-to-neutral or phase voltage between neutral and line

U : phase-to-phase or line-to-line voltages between 2 lines

Three-phase electrical systems: Fresnel triangle





Al kashi Formula

$$c = \sqrt{a^2 + b^2 - 2abcos(\gamma)}$$

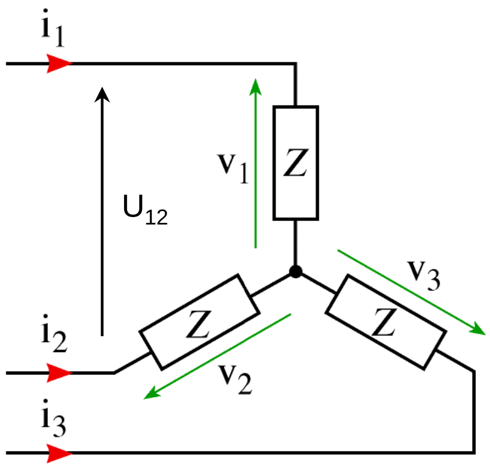
⇨

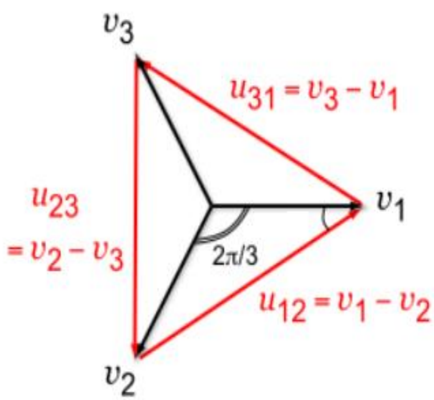
$$U = \sqrt{V^2 + V^2 - 2V^2cos(120°)}$$

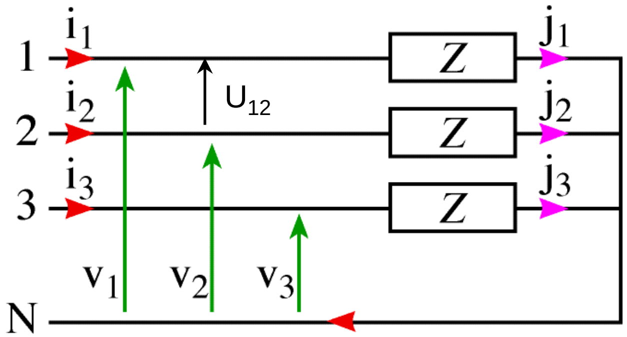
⇨

$$U = \sqrt{3}V$$

Three-phase electrical systems: star configuration (Y)





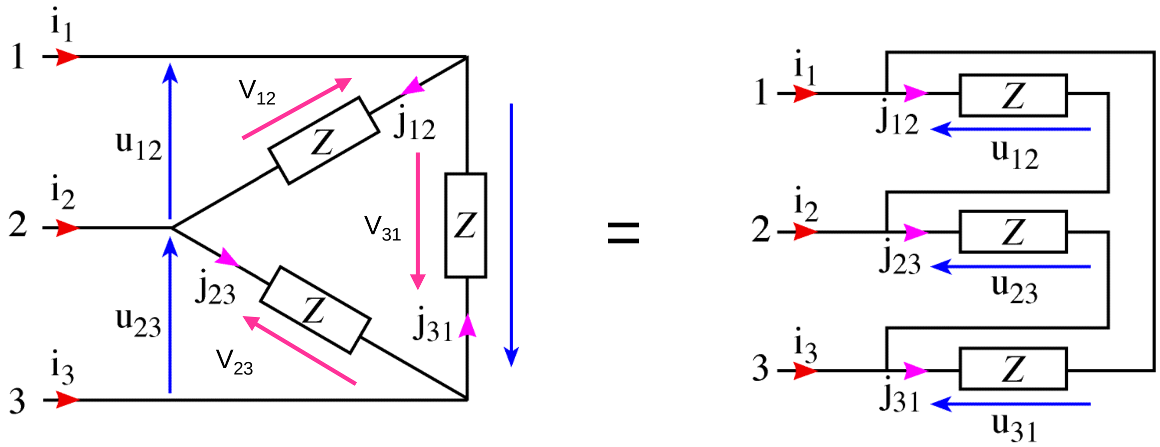


Relation between **line current** *i* and **phase current** *j* : *i=j*

Relation between **phase voltage** *V* and **phase-to-phase voltage** *U* : $V = \dfrac{U}{\sqrt{3}}$

Note: if the system is balanced (same impedance Z for each phase), the neutral line is not necessary

Three-phase electrical systems: triangle configuration (Δ)



Relation between **line current** *i* and **phase current** *j* : $j = \frac{i}{\sqrt{3}}$

Relation between **phase voltage** *V* and **phase-to-phase voltage** *U* : *V*=*U*

Electric power in DC systems

Electric power definition

Instantaneous electrical power P (unit per watt, symbol W) is the scalar product of the electrical voltage across a component and the intensity of the electrical current flowing through it.

$$P = \vec{u}.\vec{i}$$

For DC systems

$$P = U.I$$

Electric power in AC linear systems
Mathematical expressions

- **Apparent power**

 We calculate the apparent power or complex power thanks to the expression

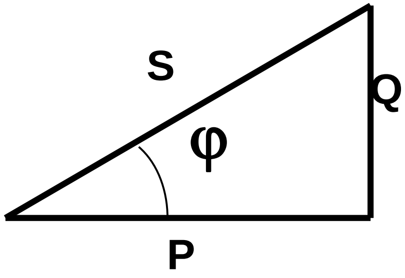
$\underline{S} = \underline{U}.\underline{I}^*$

Where $\underline{U}$ represents the complex voltage across the dipole and $\underline{I}^*$ the complex conjugate value of the current in the dipole.

$i = I\sqrt{2}\sin(\omega t + \theta_i)$ $\qquad \underline{I} = [I\ ;\ \theta_i]$

$u = U\sqrt{2}\sin(\omega t + \theta_u)$ $\qquad \underline{U} = [U\ ;\ \theta_u]$

$\varphi = (\theta_u - \theta_i)$ *voltage / current phase shift*



$\underline{S} = \underline{U}.\underline{I}^* = [U\, I\ ;\ \theta_u - \theta_i] = [S\ ;\ \varphi]$

$\underline{S} = \underbrace{U\, I \cos\varphi}_{P} + j\,\underbrace{U\, I \sin\varphi}_{Q}$

cos φ is called power factor:
cos φ = P/S

S is the modulus of the complex power (= product of the rms value of the voltage across a dipole by the rms value of the current flowing through this dipole) ⇨ $S = \sqrt{P^2 + Q^2}$

We can also write S in the form **$\underline{S} = P + jQ$**

- **Active power**

real part of the apparent power

- **Reactive power**

imaginary part of the apparent power

Electric power in AC linear systems
Physical meaning

- **Active power** is the power actually available to perform work. It is measured in watts (**W**).

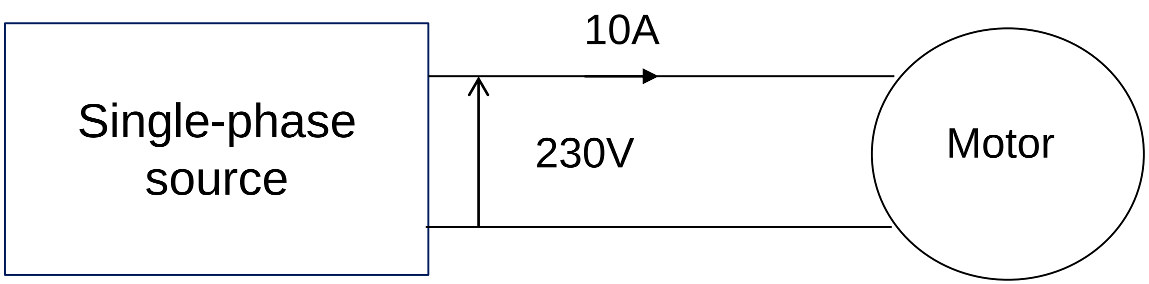
- **Reactive power** represents the power generated by the reactive elements of the circuit (capacitors or coils). Reactive power does not consume energy, but does no work. It is measured in reactive volt-amperes (**VAR**). Reactive power has a real physical meaning linked to the sizing and stability of electrical networks.

- **Apparent power** is the total power supplied to the load. It is measured in volt-amperes (**VA**)

AC Electric power: influence of the power factor

Example of a motor supplied with 230V consuming 10A RMS with a power factor of 0.5.

Compare the apparent power supplied by the source to the active power supplied by the motor.



Apparent power of the source: Ssource = UI = 2300VA

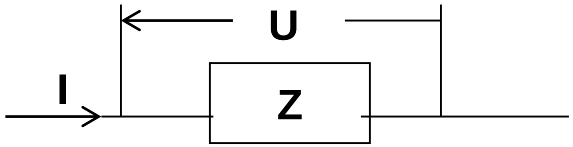
Active power to motor: Pmotor = UI cos φ = 1150W

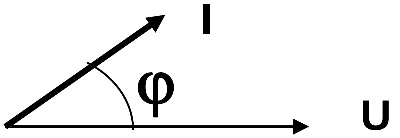
Conclusion: bad power factor (too much reactive power)

⇨ oversizing of the source

Electrical powers of a linear load

If the load Z is linear and has for impedance $Z = R+jX$:





$\underline{S} = U.I^* = ZI^*I = RI^2 + jXI^2$

Then $\boxed{P = RI^2 \text{ et } Q=XI^2}$

Power of basic elements in single phase

Resistance : $\cos \varphi = 1$, $Z = R$

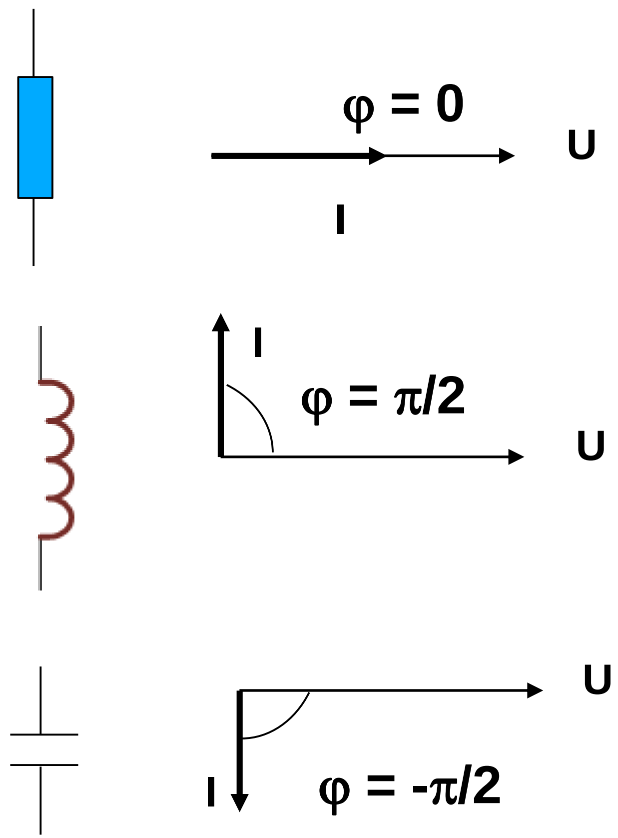
$P = R.I^2_{RMS}$
$Q = 0$
$S = P$

Inductance : $\sin \varphi = 1$, $Z = jL\omega$

$P = 0$
$Q = L\omega.I^2_{RMS}$
$S = Q$

Capacitor: $\sin \varphi = -1$, $Z = 1/(jC\omega)$

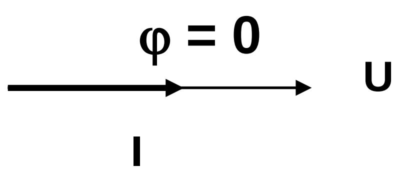
$P = 0$
$Q = -I^2_{RMS}/(C\omega)$
$S = |Q|$

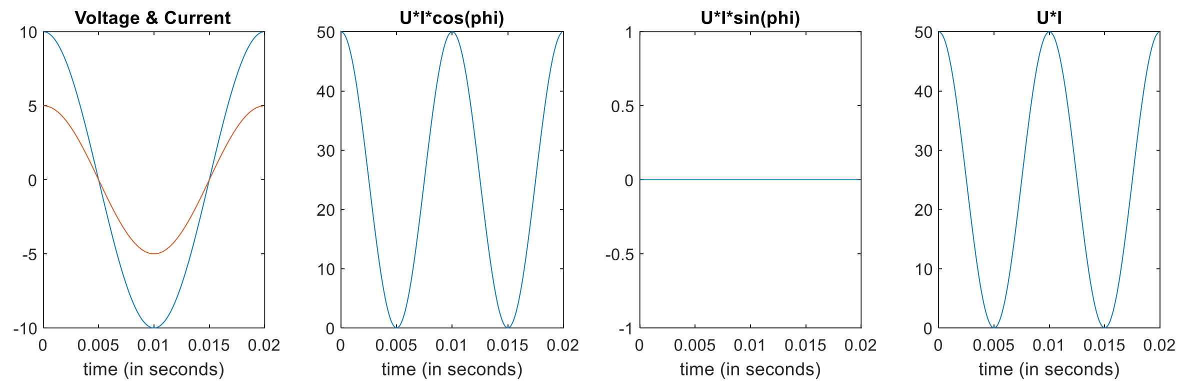


Resistive load ⇨ Q=0
Inductive load ⇨ Q>0
Capacitive load ⇨ Q<0

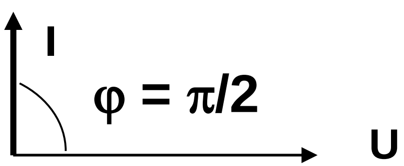
AC Electric power: linear loads

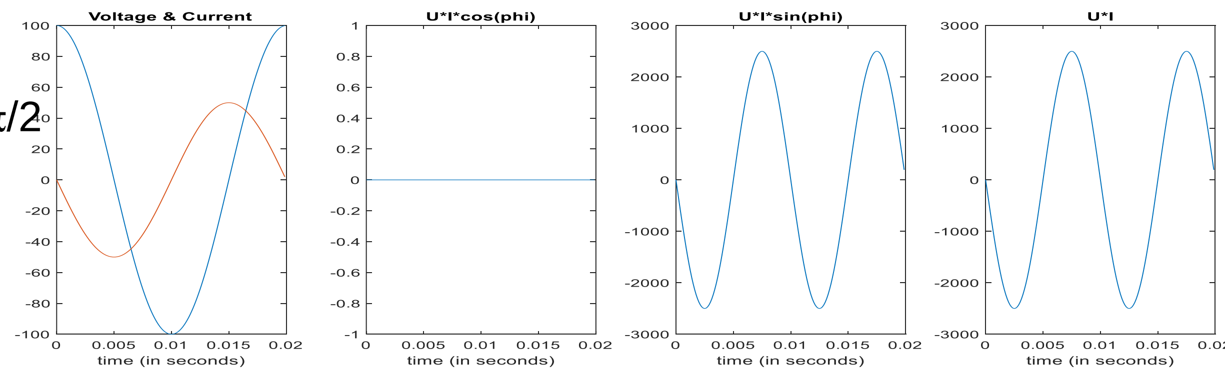
Case 1 : resistive load,
voltage and current in phase



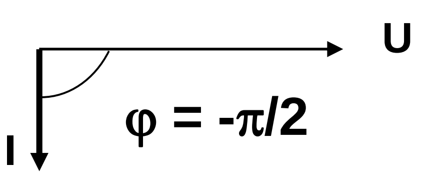


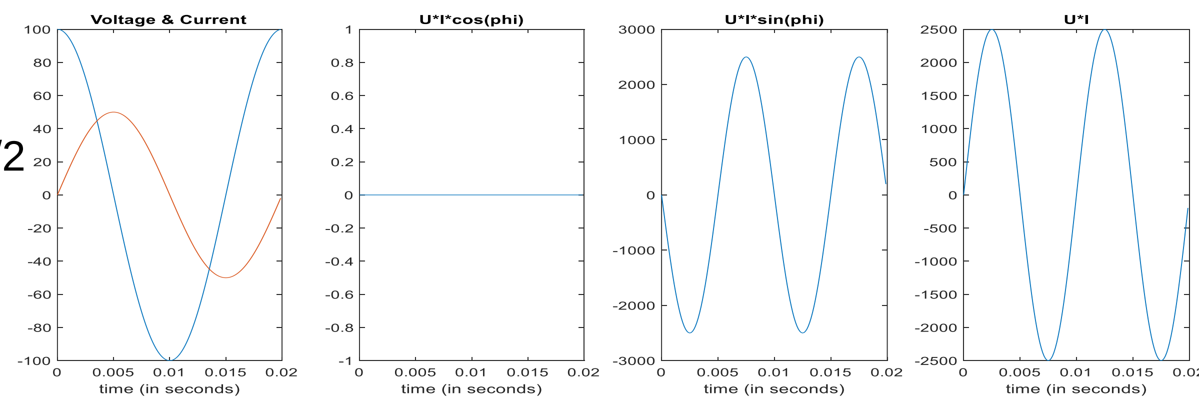
Case 2 : inductive load,
voltage and current dephased by $\pi/2$





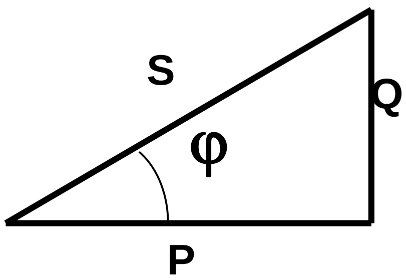
Case 3 : capacitive load,
voltage and current dephased by $-\pi/2$



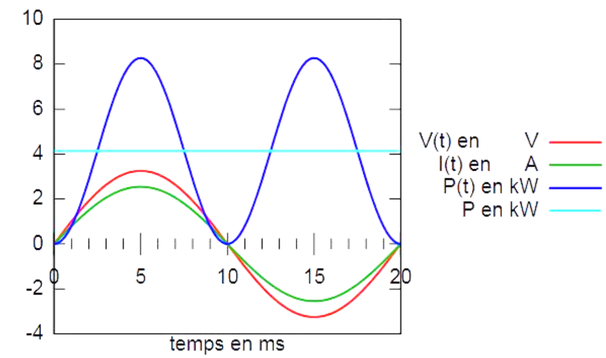


Electric power in AC systems
Synthesis

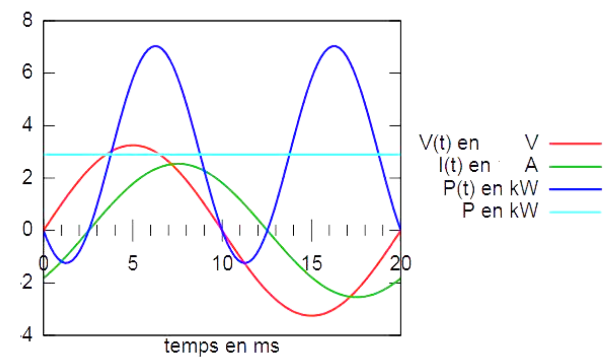
For linear systems *



- Active power $P = UI \cos \varphi$ (W ou Watt)
- Reactive power $Q = UI \sin \varphi$ (VAR ou Volt Ampère réact
- Apparent power $S = UI = \sqrt{P^2 + Q^2}$ (VA ou Volt Ampère)



Cos Phi = 0,7



Cos Phi = 0,2

cos φ is called the power factor: **cos φ = P/S**

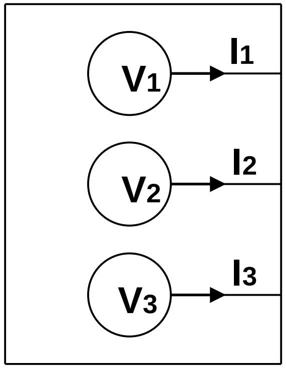
* linear systems ⇨ sinusoidal current and voltages.

Electric power: case of three-phase systems

The active power supplied by each generator is: $P = VI \cos \varphi$

The total active power is therefore: $P = 3\, VI \cos \varphi$

Likewise, the total reactive power is: $Q = 3\, VI \sin \varphi$

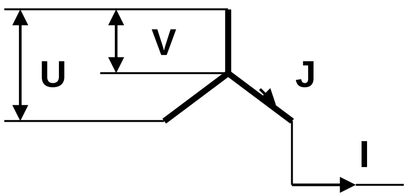


<u>Application to 2 configurations of three-phase systems</u>

Star configuration

$J = I$ and $V = U/\sqrt{3}$ => $P = 3\, VI \cos \varphi = \sqrt{3}\, UI \cos \varphi$

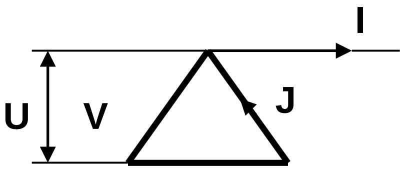
=> $Q = 3\, VI \sin \varphi = \sqrt{3}\, UI \sin \varphi$



Triangleconfiguration

$I = J\sqrt{3}$ and $V = U$ => $P = 3\, VJ \cos \varphi = \sqrt{3}\, UI \cos \varphi$

=> $Q = 3\, VJ \sin \varphi = \sqrt{3}\, UI \sin \varphi$



Remember: whatever the star or delta configuration

$P = \sqrt{3}\, UI \cos \varphi = 3\, VI \cos \varphi$

$Q = \sqrt{3}\, UI \sin \varphi = 3\, VI \sin \varphi$

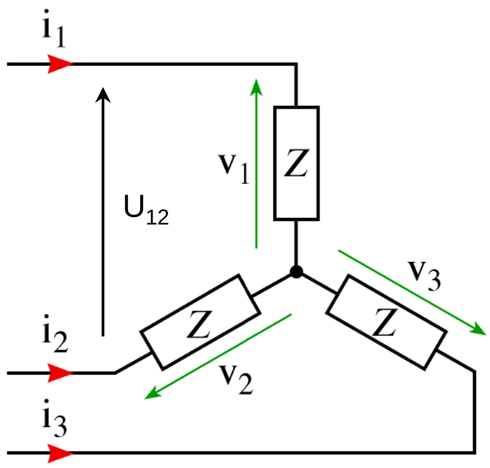
$S = \sqrt{3}\, UI = 3\, VI$

Power of the three-phase basic elements

<u>Star configuration</u>

$P = 3RI^2$

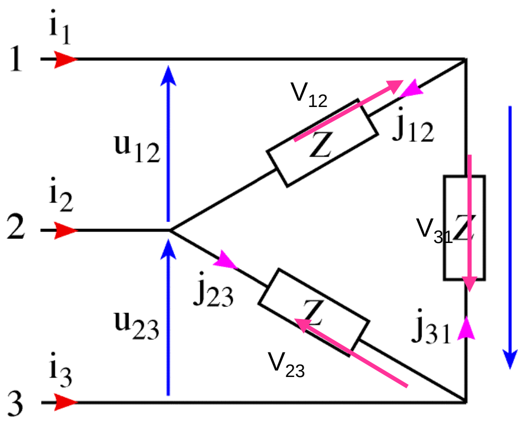
$Q = 3XI^2$



<u>Triangle configuration</u>

$P = 3RJ^2$

$Q = 3XJ^2$



Electric energy

Electric energy definition

Electrical energy refers to the energy transferred or stored through electricity. It is proportional to the active electric power and to the time.

$$E = P.t$$

An electrical consumer will be characterized by its power.
A battery (energy source) will be characterized by its energy.
Unit of energy: Joule

Example

If a phone that has a 3200mAh battery for a voltage of 3.85V consumes 500mW in active mode, it can work:

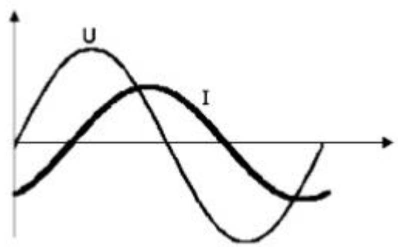
$$time = \frac{E}{P} = \frac{3.2x3.85}{0.5} = 24.6\ h$$

Electrical loads and quality of an electrical signal

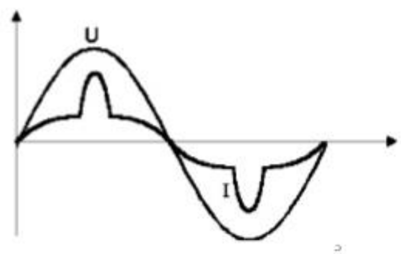
A load is said to be linear if the current in the load is sinusoidal when it is supplied by a sinusoidal voltage. This type of load does not generate harmonics.

A load is said to be non-linear if the current in the load is not sinusoidal when it is supplied by a sinusoidal voltage. This type of load generates harmonic currents. Nonlinear loads distort electrical signals.

Linear load



Non linear load



Example of non-linear loads: Low consumption lamps, computers, inverters,…

The pollution of electrical networks by harmonic currents is an inevitable consequence of the proliferation of non-linear loads.

Electrical loads and power factor

In an electrical architecture where there are only linear loads, the Power Factor is the Cosine of the phase angle between Voltage and Current.

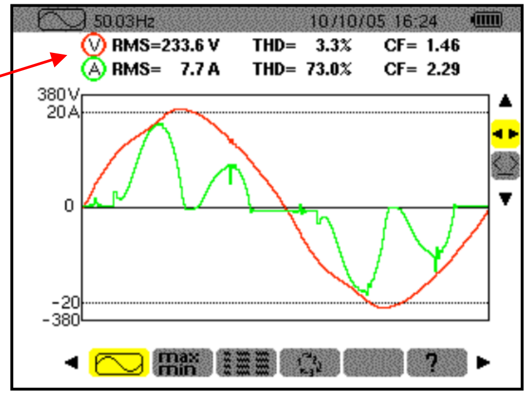
$$\text{Power factor FP} = \cos\varphi = P/S$$

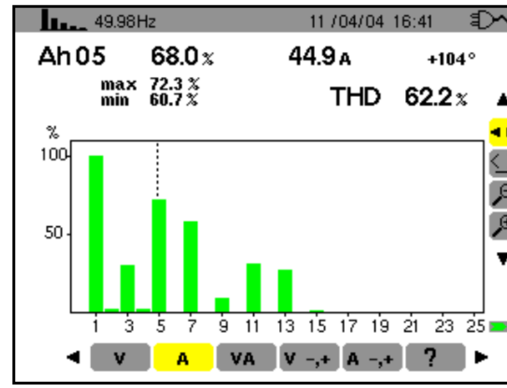
In an architecture with non-linear loads, the cos φ is no longer applicable.

$$\text{Power factor FP} = P/S < \cos\varphi$$

The quality of an electrical signal is characterized by its purity and is quantified by the rate of total harmonic distortion (THD).

Note :
the measuring devices give the RMS values





The total harmonic distortion rate (THD) is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

The lower the THD, the better the signal.
The treatment of harmonics makes it possible to reduce the apparent and reactive powers.
To reduce the THD, we can set up filters with capacitors or active filters with static converters.

Stability of an electrical signal

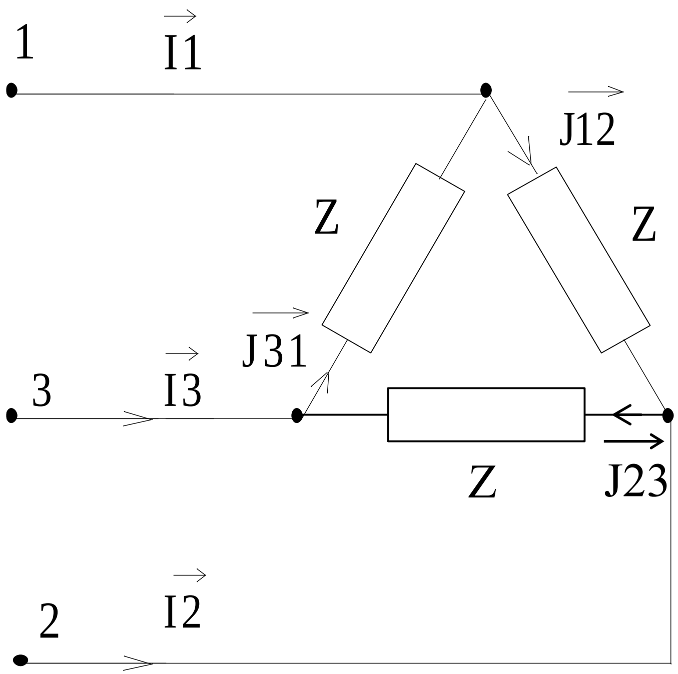
The stability of an electrical signal is characterized by the stability of the frequency and the amplitudes of the voltages or currents.

To increase the stability of the signal:

- the power sources and the loads must be well balanced,

- the filters must be well sized: they increase the quality of the signal but reduce its stability!

Example 1



Three single-phase loads, purely resistive, are connected in delta configuration on the 220 / 380V 50Hz sector.

Under 380V they consume 2.2kW each.

What is the value of the line current I?

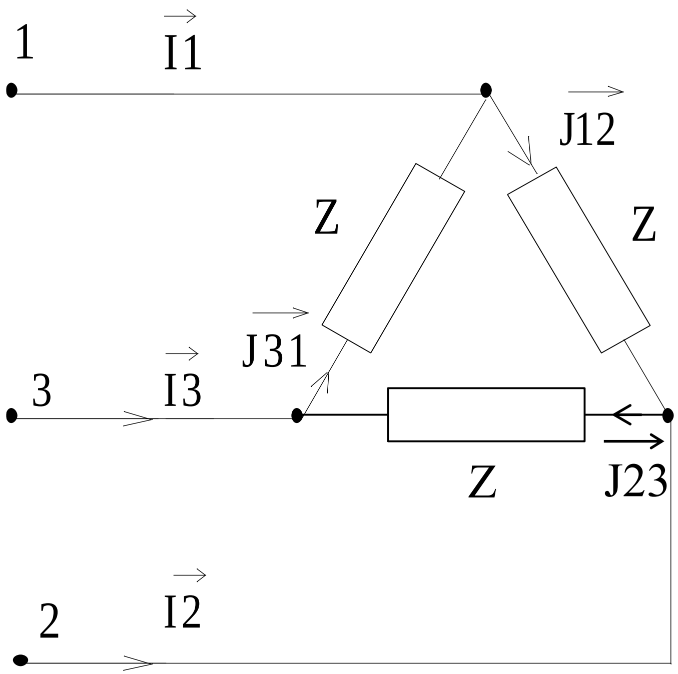
A) I = 7A

B) I = 10 A

C) I = 14,4 A

D) I = 20 A

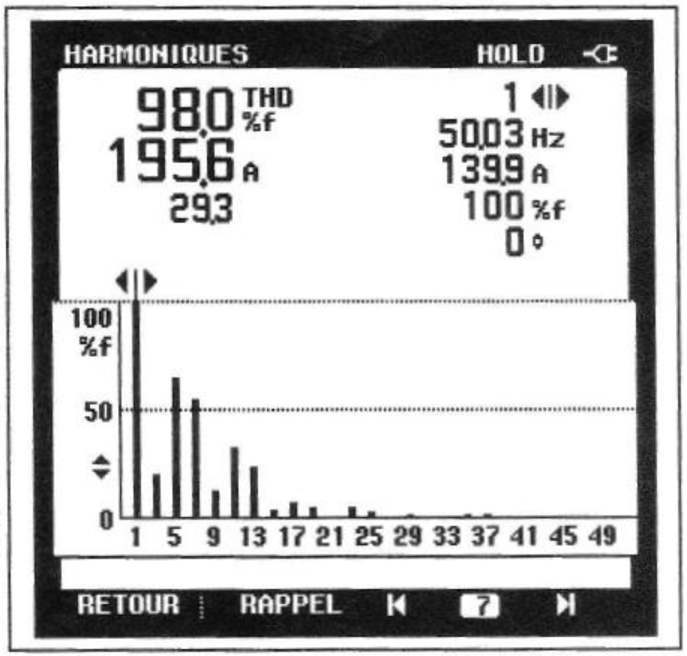
Example 1 - Answer



Delta configuration
2.2kW per load=> P= 3*2.2=6.6kW

P = √3UI => I = 10A

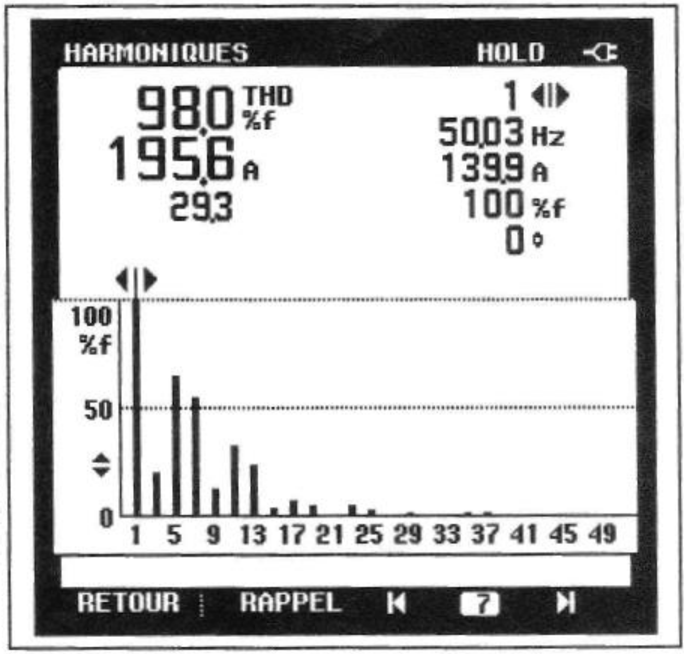
Example 2



What is the maximum value of the fundamental of the measured current?

A) 50 A
B) 139,9 A
C) 195,6 A
D) 197,8 A

Example 2 - Answer



I_{RMS} = 139.9 A

=> Imax = $\sqrt{2} * I_{RMS}$ = 197.84 A

Electric power conversion

Choice of electrical voltages in aircraft

Use of the 28VDC network for on-board electricity at the start of aviation. Choice of direct current to allow storage in batteries. Always used for low power loads

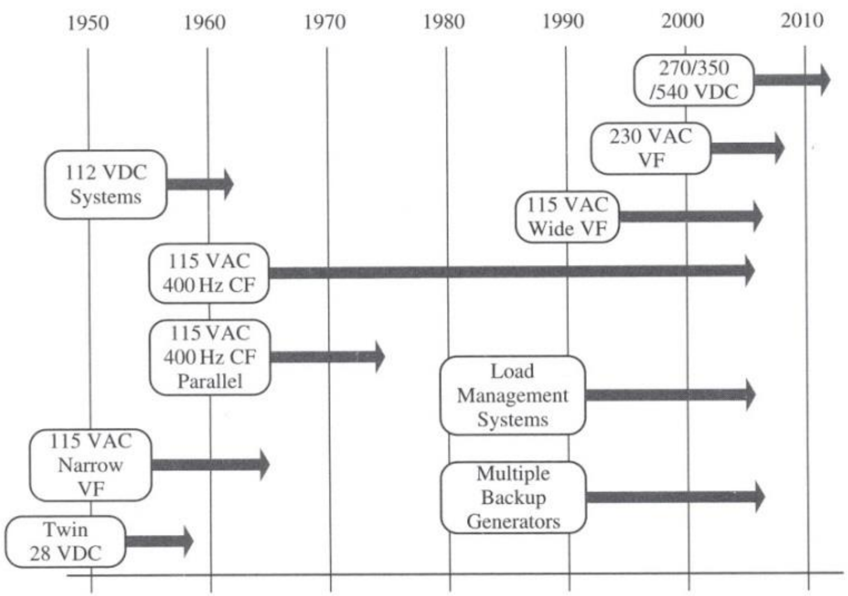
Interest of higher voltages for a given power:
Lower current and lower weight (smaller diameter conductors)
reduction of losses in conductors

Advantages of AC voltages compared to DC voltages: higher voltage levels can be used because there is no risk of electric breakdown

Benefits of AC 400Hz voltages compared to AC 50Hz voltages: at equal power, the mass of the alternative machines is very approximately inversely proportional to the frequency of use 80% gain on the mass of an alternator if it is powered in 400Hz

Benefits of AC voltages at variable frequency: variable frequency (370-770Hz) from the A380 allows driving variable speed machines without mechanical speed regulator.

But the trend is changing: 540VDC or 800VDC (interesting for supplying variable frequency loads via an inverter)



Notation
VDC: voltage direct current
VAC: voltage alternative current
VF : variable frequency
CF: constant frequency

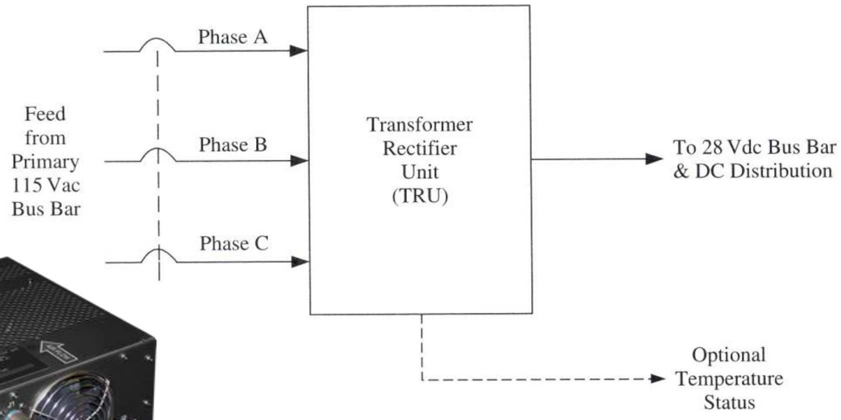
source: Aircraft systems, AIAA education series

Typical conversions in an airplane

- Conversion 115VAC ⇨ 28VDC
- Conversion DC ⇨ AC : 28VDC ⇨ 115VAC single phase or three-phase and 270VDC ⇨ 115VAC single phase or three-phase
- Conversion AC ⇨ AC with another voltage level : eg : 115VAC ⇨ 26VAC
- Conversion DC ⇨ DC (270VDC ⇨ 28VDC)

<u>Systems:</u>

- Inverters
- TRU: Transformer Rectifier Unit
- Auto-transformer

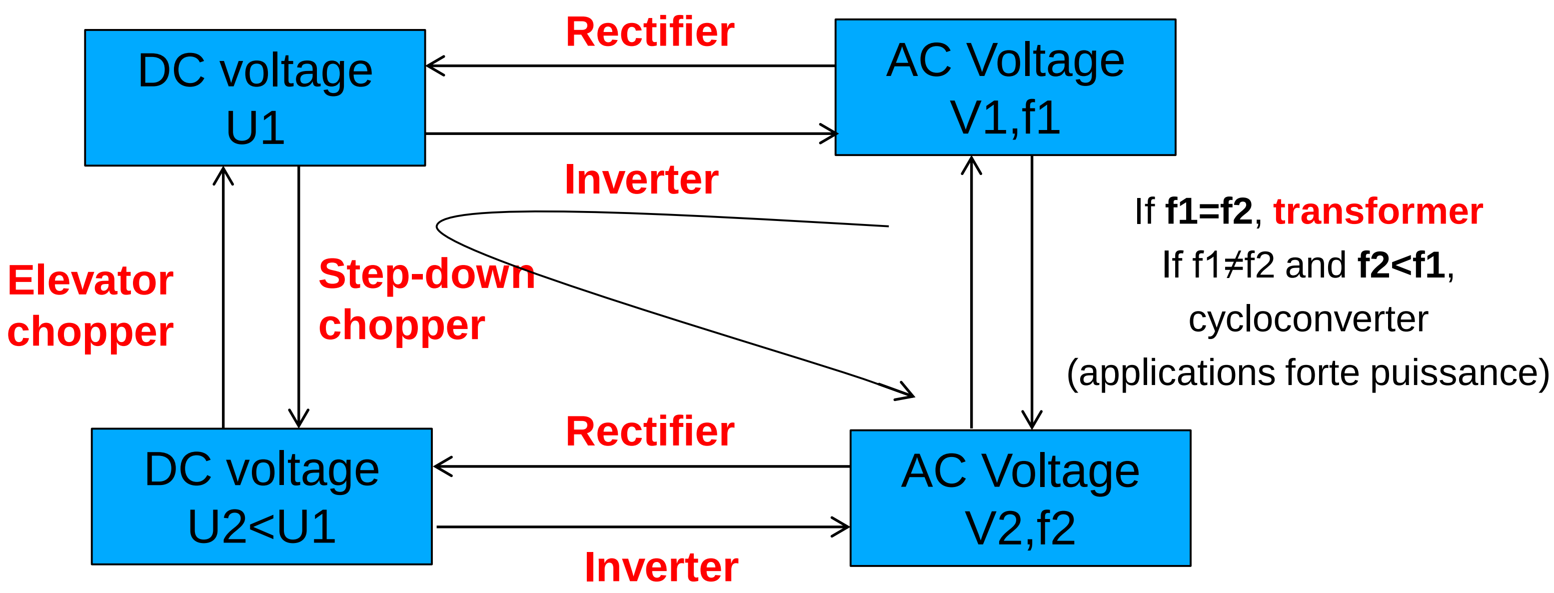


source: Aircraft systems, AIAA education series

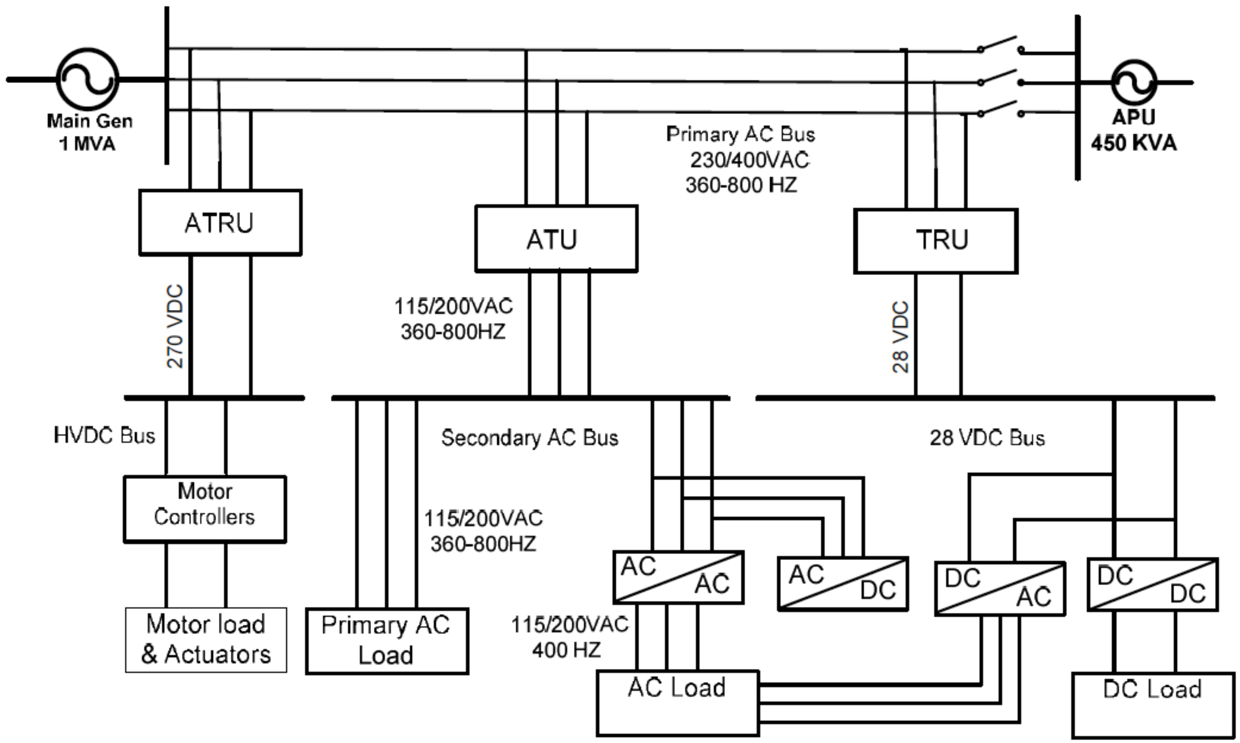
Electrical power conversion: typical conversions

Electric power conversion is the conversion from one form of voltage to another:

- By changing the nature (AC ↔ DC)
- By changing the amplitude of the voltage
- or its frequency or a combination of these 2 quantities



Typical conversions in an airplane



B787/A380 aircraft power distribution system

Notation
APU: Auxiliary Power Unit
ATU: Auto Transformer Unit
TRU: Transformer Rectifier Unit
ATRU: Auto Transformer Rectifier Unit

source: Aircraft systems, AIAA education series

Conversion AC<->AC: Transformer

Function: change the amplitude of AC voltages

Equations for an ideal transformer

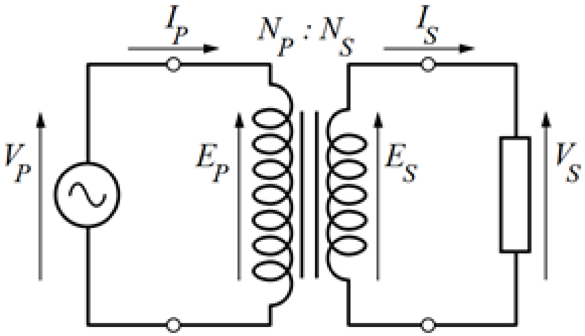
Primary: $V_p = N_P d\Phi / dt$

Secondary: $V_s = N_s\, d\Phi / dt$

Φ: magnetic flux

N_P: number of turns in the primary winding

N_s: number of turns in the secondary winding



Principle of a single-phase transformer

$d\Phi / dt$ = cste and power conservation : $V_p I_P = V_s I_s$

$$\Rightarrow \frac{Vs}{Vp} = \frac{Ns}{Np} = \text{transformation ratio}$$

$$\Rightarrow \frac{Ip}{Is} = \frac{Ns}{Np} = \text{transformation ratio}$$

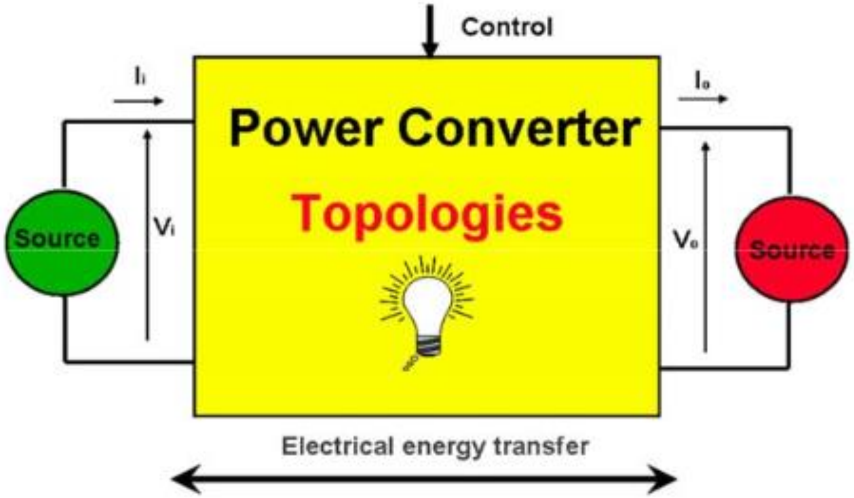
three-phase transformer

Conversions AC <-> DC ou DC <->DC : static converters

Static converters are electrical circuits mainly composed of:

- semiconductors operating in non-linear switching mode (switches)
- elements considered as linear such as capacitors and inductors

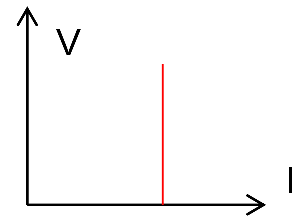
The opening and closing sequences of the switches allow electrical energy to be transferred between two sources with different electrical characteristics (amplitude, frequency).



Nature of the sources

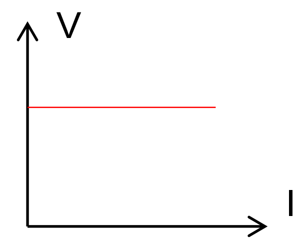
2 kinds of sources :

- **Current source** : imposes a current whatever the voltage at the terminals of the load => impedance in series very large in comparison with that of the load
- example : inductance

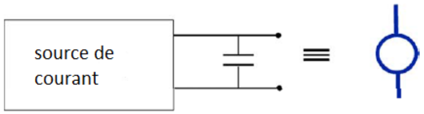


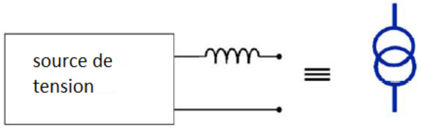
- **Voltage source** : imposes a voltage whatever the current consumed by the load => impedance in series very small in comparison with that of the load

  example : capacitor



To modify the nature of a source :





Reversibility of sources

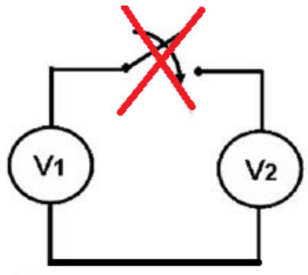
A source is reversible in voltage if the voltage at its terminals can change sign.

A source is reversible if the current flowing through it can be reversed.

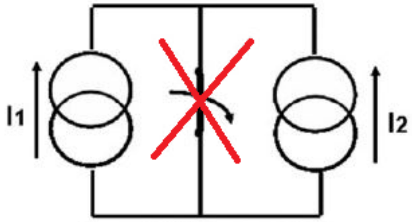
Eg battery: source which is non-reversible in voltage and reversible in current (charging and discharging)

Rules for connecting sources

A voltage source can not be short-circuited but can be opened.



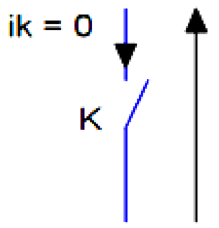
A current source can be short-circuited but can not be opened.



Consequences:

Never connect two sources of the same nature.
Only a current source and a voltage source can be connected to each other.

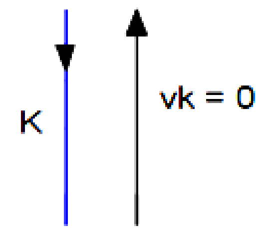
Switches in power converters



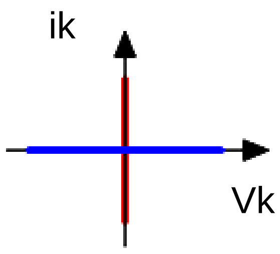
Vk imposed by the external circuit

Open

ik imposed by the external circuit



Closed



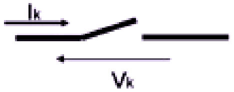
In the closed state, the switch is said to be on or ON.

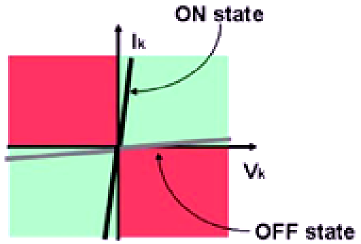
In the open state, the switch is said to be open or OFF.

The static characteristic, which is an intrinsic property of a switch, is made up of four segments coincident with the v and i axes.

Static and dynamic characteristics of switches

Static characteristics: it corresponds to the operating points of the switch on the diagram Ik = f(Vk). It is represented by segments located in quadrants of the diagram Ik = f(Vk). One of these branches is very close to the Ik axis (ON-state) and the other is very close to the Vk axis (OFF-state). Each of these branches can be located in one or two quadrants. In the case of an ideal switch, the static characteristics are the half-axis to which they are close.



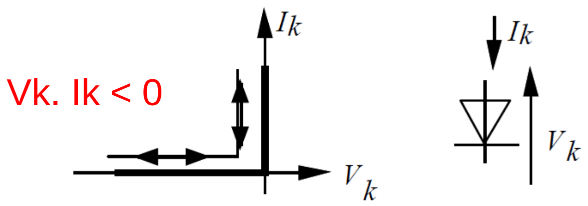


Dynamic characteristics: it corresponds to the trajectory described by the point of operation of the switch during its commutation, going from one half-axis to the perpendicular half-axis. A switch being either ON or OFF, there are two commutation dynamic characteristics corresponding to the turn-ON and to the turn-OFF .
If the static characteristics are in a quadrant such that Vk. Ik < 0, the commutation is spontaneous. Otherwise, the commutation must be controlled, that is to imposed by an external circuit.

Examples of switches with 2-segment

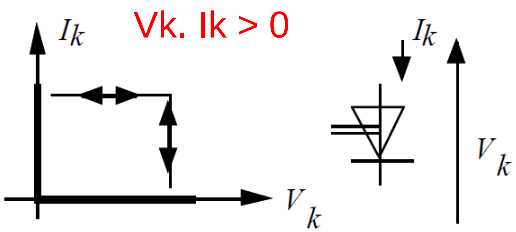
Diode

Current Ik and Voltage Vk are of opposite sign => Spontaneous commutation



Transistor

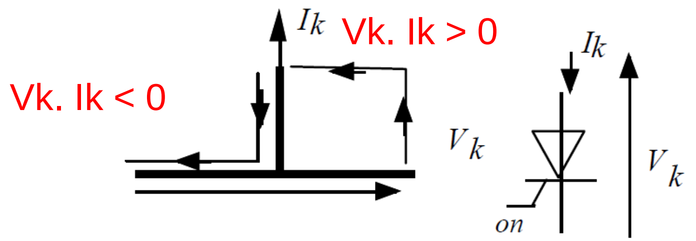
Current Ik and Voltage Vk are of same sign => Controlled commutation



Examples of switches with 3-segment

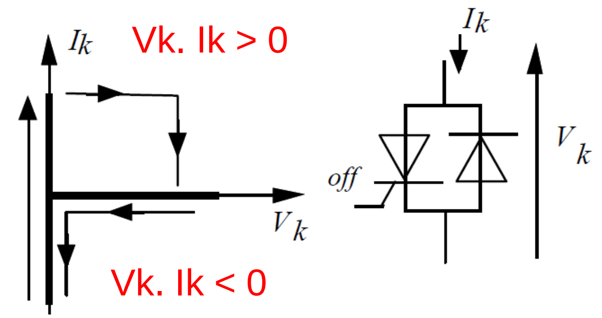
Thyristor

one controlled commutation (turn ON) and one spontaneous commutation (turn OFF)



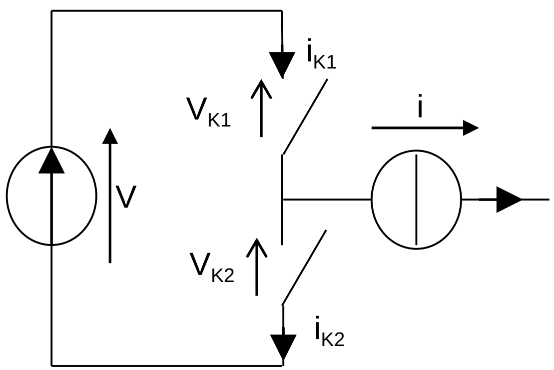
Dual Thyristor

one controlled commutation (turn OFF) and one spontaneous commutation (turn ON)



Switching cell

A switching cell is a cell consisting of two switches with complementary sequencing.



Switching cell with sign convention

$$V = V_{K1} + V_{K2}$$

$$i = i_{K1} - i_{K2}$$

<u>State 1</u>

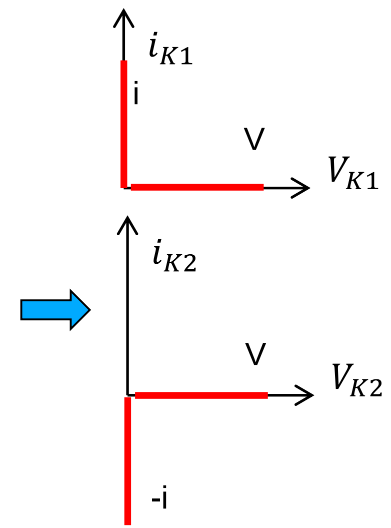
$K1\ on \Rightarrow V_{K1}$ = 0 and i_{K1}=i

$K2\ off \Rightarrow V_{K2}$ = V and i_{K2}=0

<u>State 2</u>

$K1\ off \Rightarrow V_{K1}$ = V and i_{K1}=0

$K2\ on \Rightarrow V_{K2}$ = 0 and i_{K2}=-i



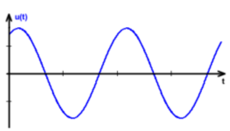
In a switching cell, the voltage at the terminals of a blocked switch is equal to the voltage of the voltage source.
In absolute value, the current in a switch that conducts is equal to the current of the current source.
The nature of the switches depends on the sign of the voltage source and the current source.

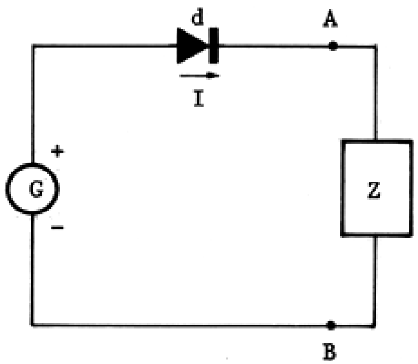
A rectifier converts the alternating voltages into DC voltages

Basic switch for uncontrolled rectifiers: diode

Basic principle for rectifying an alternating source on a resistive load:
Positive alternation of the input signal ⇨ diode on, Vdiode = 0, Vout = Vinput
Negative alternation of the input signal ⇨ non-conductive diode, Vdiode = -Vinput, Vout = 0

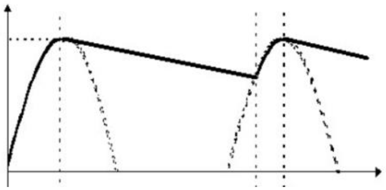
sinusoïdal input signal





Output signal rectified on one alternance

+ filter RC to get a DC voltage

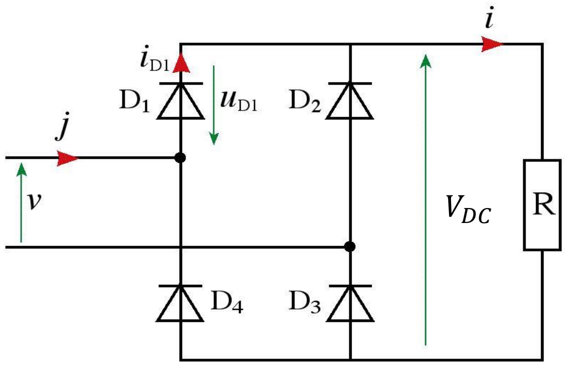


Specifications of a not controlled rectifier :
- Spontaneous switching, no control circuit required
- Amplitude of the output voltage not adjustable (depends only on the input voltage)

Conversion AC->DC : single-phase rectifier

Example of single-phase diode bridge with 2 alternations

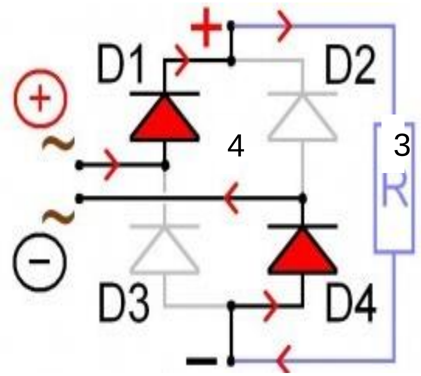
⇨ 2 commutation cells, 4 diodes



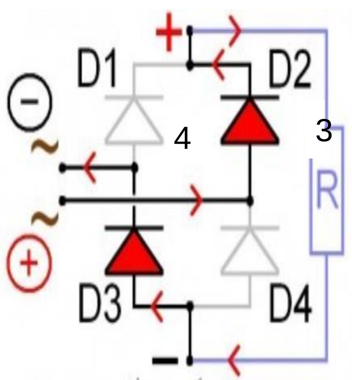
Rules for opening and closing the switches: it is not possible to short-circuit the voltage sources

⇨ 2 sequences

Sequence 1



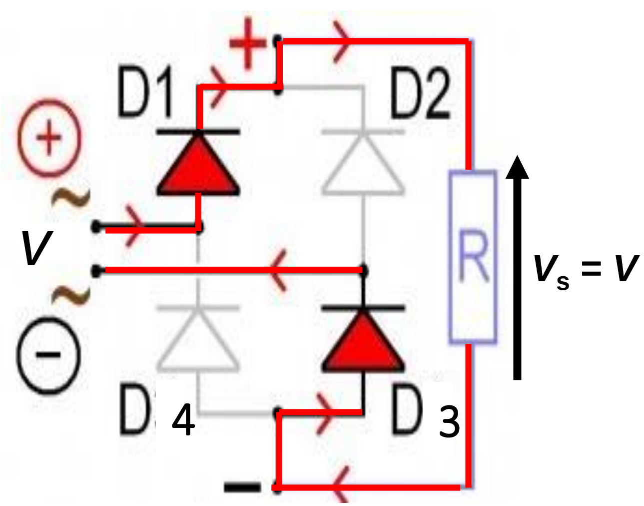
Sequence 2

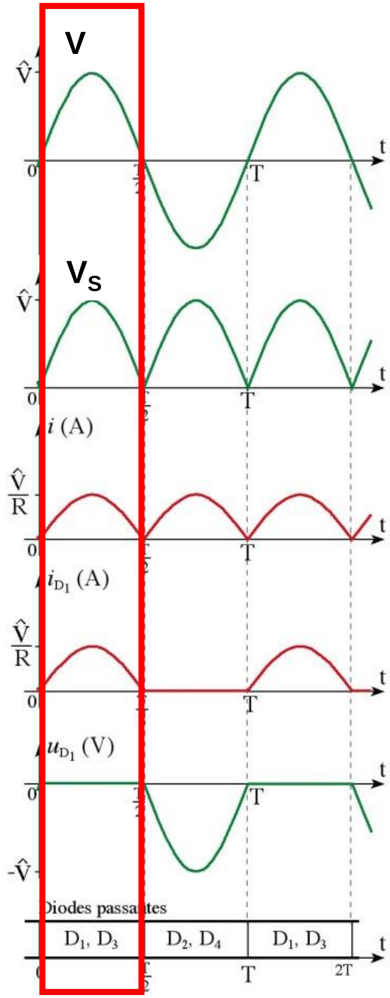


Single-phase diode bridge with 2 alternations
Waveforms on a resistive load

Sequence 1

D1 et D3 ON
$V_{D1} = V_{D3} = 0$
$V_{D2} = V_{D4} = -v$



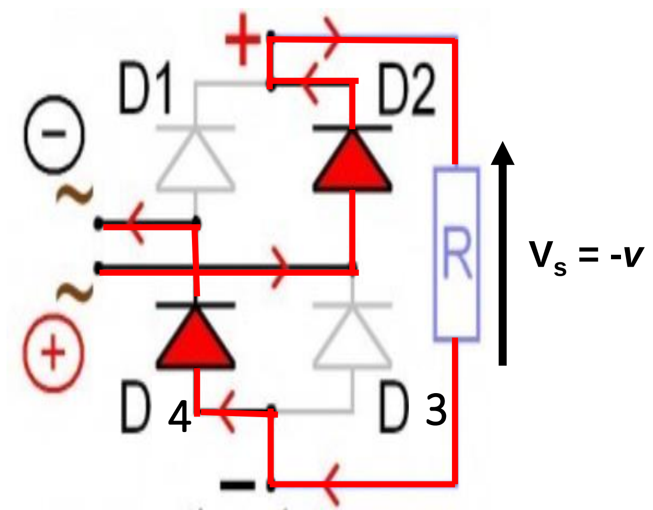


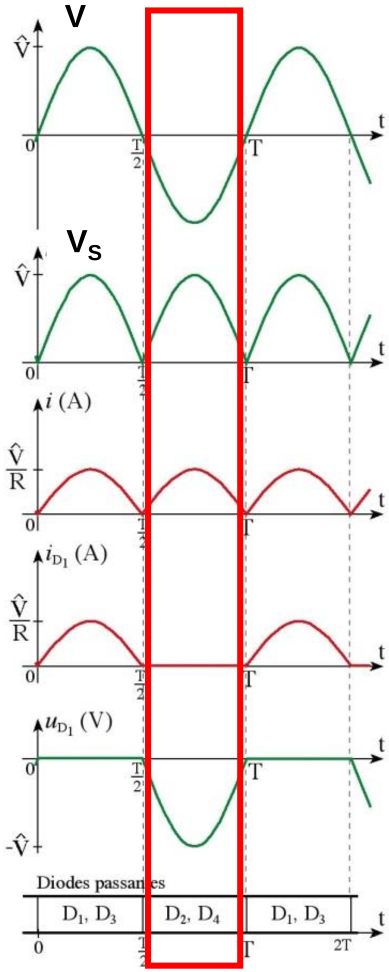
Conversion AC->DC : single-phase rectifier

Single-phase diode bridge with 2 alternations
Waveforms on a resistive load

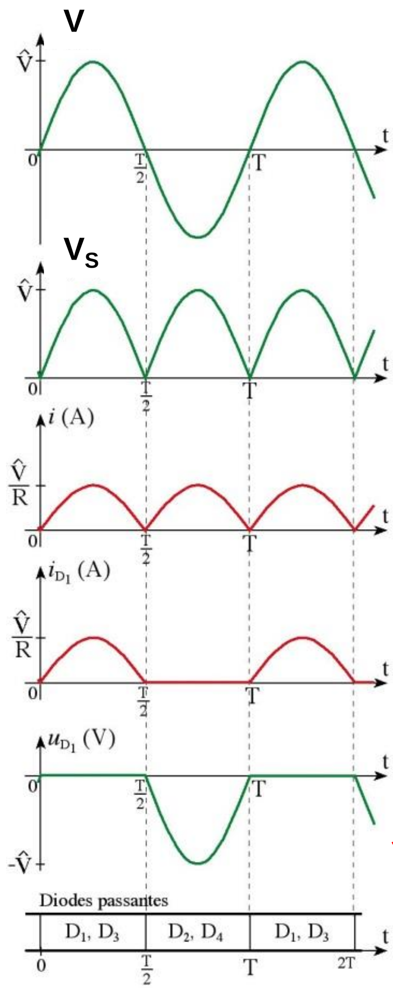
Séquence 2

D2 et D4 passantes
$V_{D2} = V_{D4} = 0$
$V_{D1} = V_{D3} = -v$





Single-phase diode bridge with 2 alternations
Waveforms on a resistive load

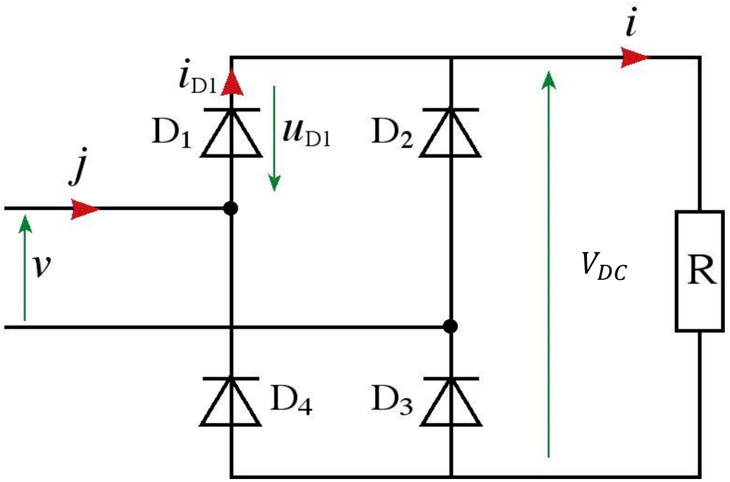


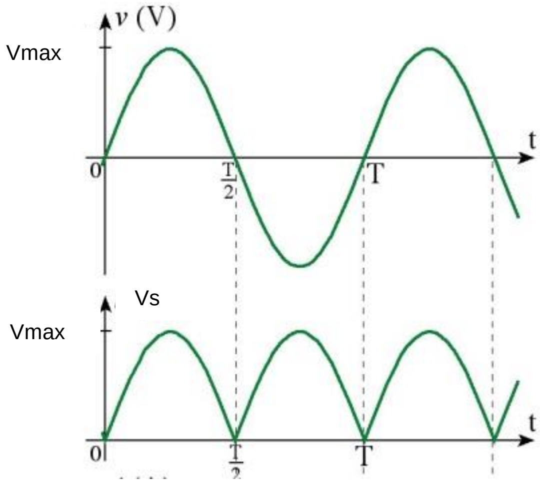
☹ **The rectifier input current contains harmonics**

Sizing rule: diodes sized with respect to the maximum current flowing through them and the reverse voltage at their terminals

Conversion AC->DC : single-phase rectifier

Relation between output rectified voltage/input voltage



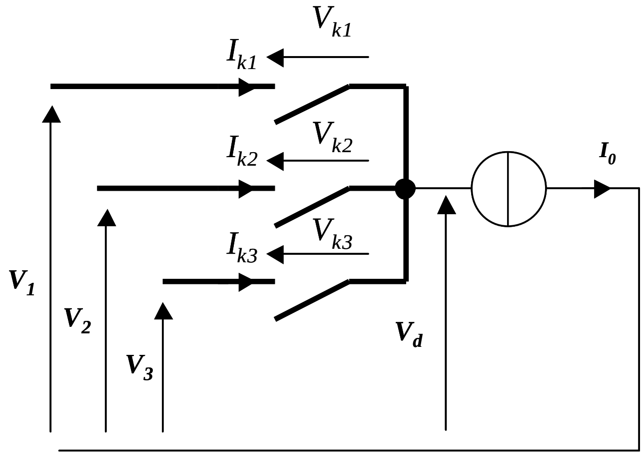


$$V_{DC}{=}{<}\,Vs\,{>}=\frac{1}{\pi}\int_0^{\pi} V_{max}\,\sin\theta d\theta=\frac{2V_{max}}{\pi}$$

Conversion AC->DC : three-phase rectifier

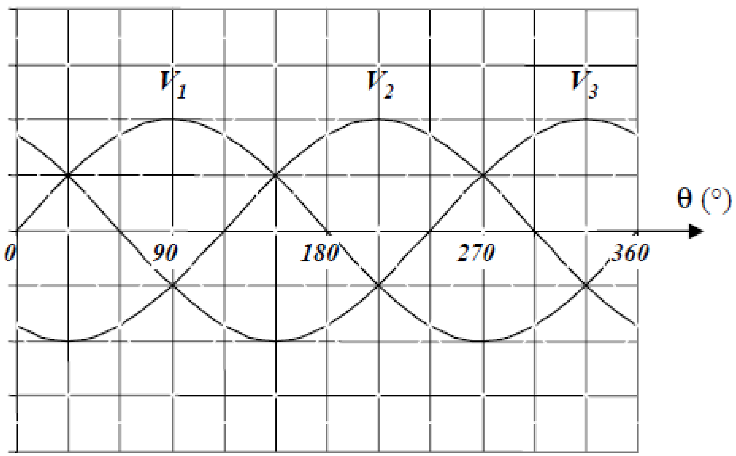
Three-phase cell of commutation ⇨ 3 diodes

Basic principle for rectifying a three-phase alternating source



Plot the voltage V_d and the currents i_1, i_2 and i_3.
Compute the average value of the rectified voltage U_d.

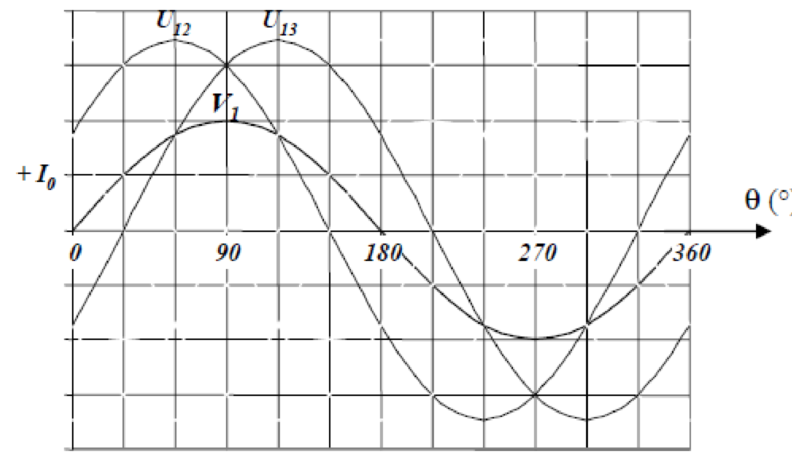
Tracé de V_d



K3	K1	K2	K3

Séquences de fermeture des interrupteurs

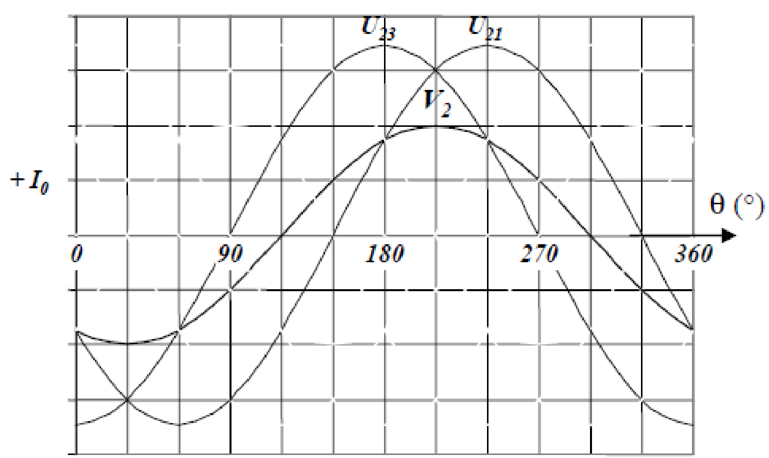
Tracé de I_{k1} et V_{k1}



K3	K1	K2	K3

Séquences de fermeture des interrupteurs

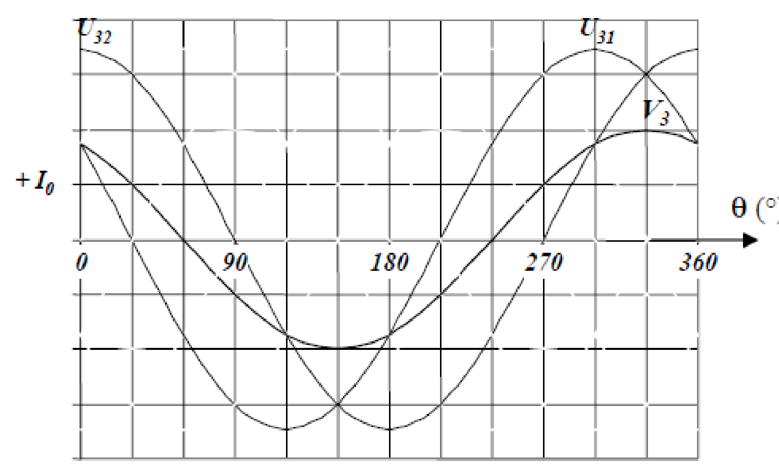
Tracé de I_{k2} et V_{k2}



K3	K1	K2	K3

Séquences de fermeture des interrupteurs

Tracé de I_{k3} et V_{k3}

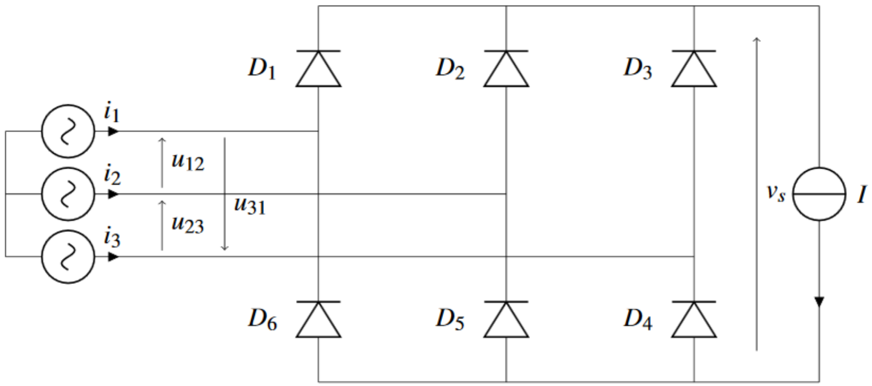


K3	K1	K2	K3

Séquences de fermeture des interrupteurs

Conversion AC->DC : three-phase rectifier

Rectifier three-phase full-wave: Graetz bridge
⇨ 3 switching cells, 6 diodes

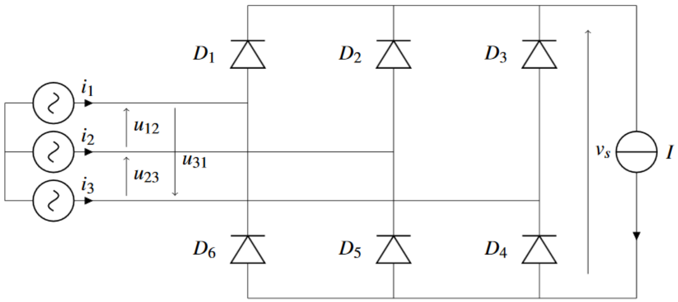


Relationship between the input and output voltages : $\langle V_{DC} \rangle = \frac{3\sqrt{3}}{\pi} V_{Emax}$

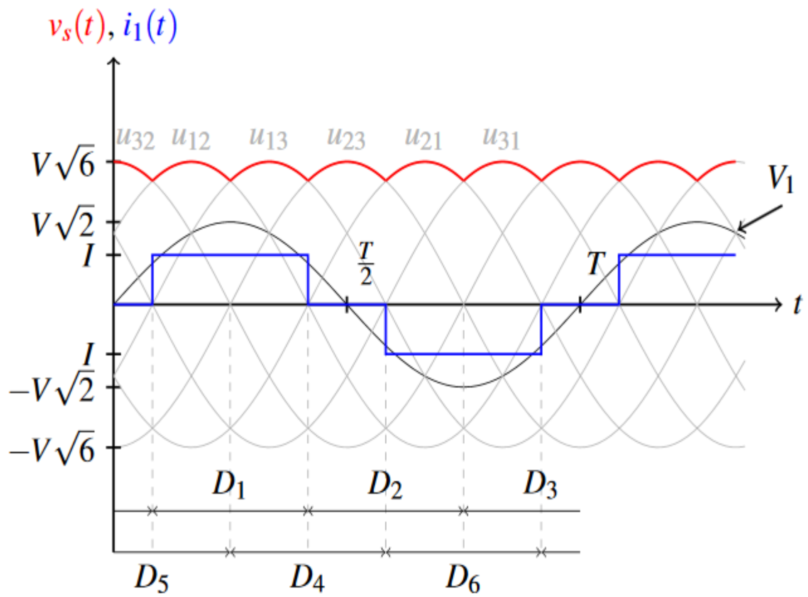
Voltage ripple: $\Delta V \approx 0.23 V_{Emax}$

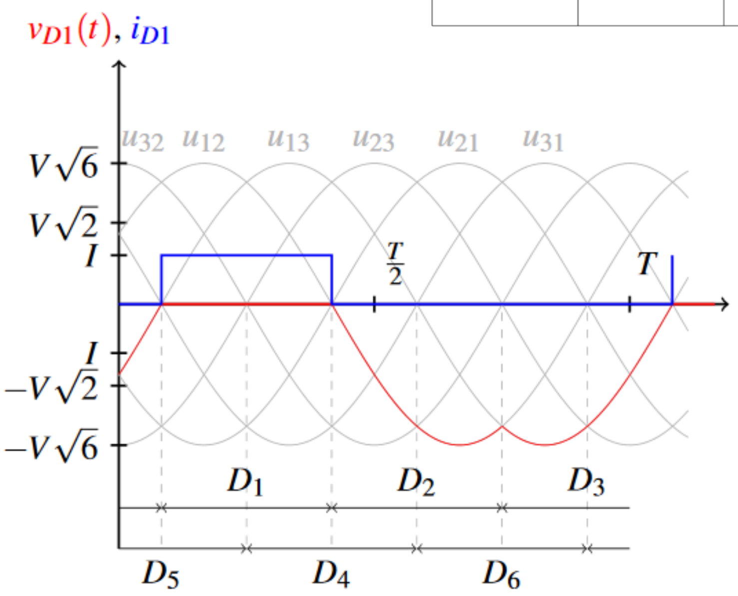
Conversion AC->DC : three-phase rectifier

Rectifier three-phase full-wave: Graetz bridge



Waveforms





To remember :

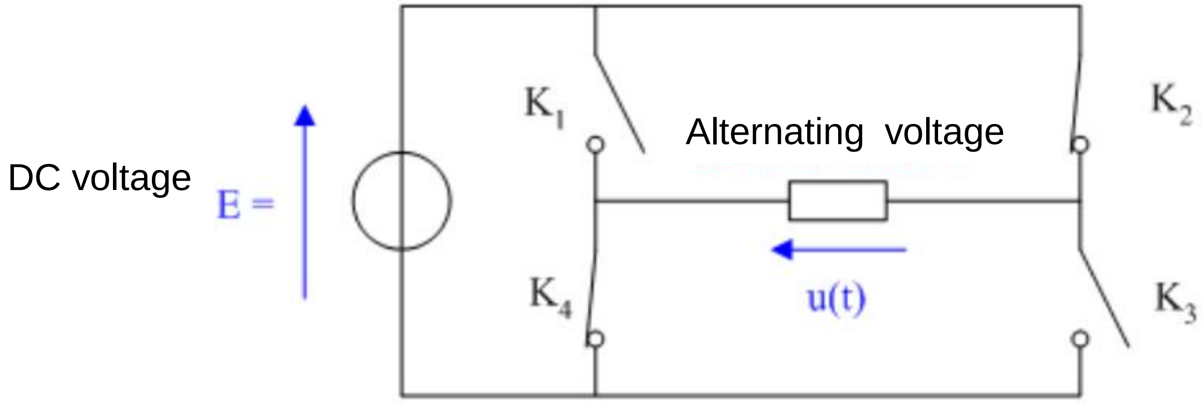
- Rectifier input current with many harmonics
- Diodes dimensioned with respect to the maximum current flowing through them and the reverse voltage at their terminals

Conversion DC->AC : inverter

An inverter is an electrical energy converter that changes the DC voltages into alternating voltages. The inverters use semiconductors arranged in an "H-shaped" bridge.

Example of single phase inverter:

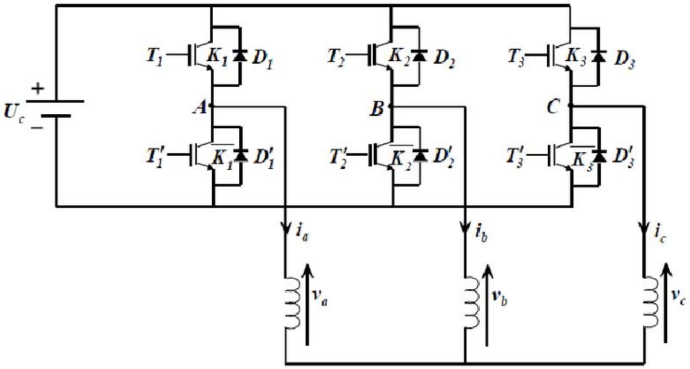
2 switching cells or arms ⇨ 4 switches



Conversion DC->AC : inverter

Basic switch for rectifiers: transistor or thyristor
⇨ controlled switching
⇨ Need for control circuits for switches

Example of a three-phase transistor inverter



For a three-phase inverter, the commands of the three switching cells, which are shifted by one third of a period, make it possible to reconstitute a three-phase system of voltages and currents.

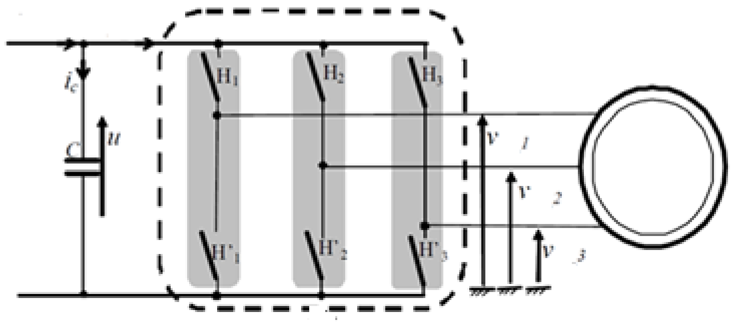
The shape of the output voltage (square or sinusoidal), its amplitude and its frequency depend on the switches of the switches.

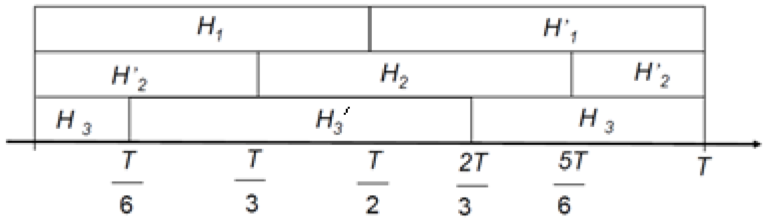
Conversion DC->AC : full wave inverter

In a full-wave inverter, the switches are controlled as follows:

- For each arm:
  "Top" Interrupter: Open during T / 2, closed during T / 2
  “Bottom” Interrupter: closed during T / 2, open during T / 2 (complementary to the other switch)

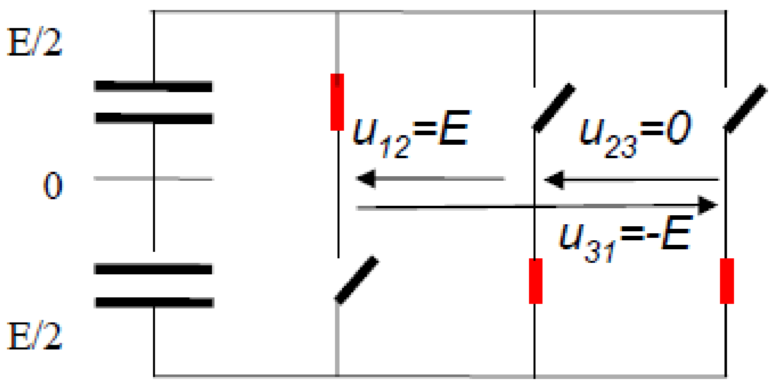
- Each arm is shifted by T / 3



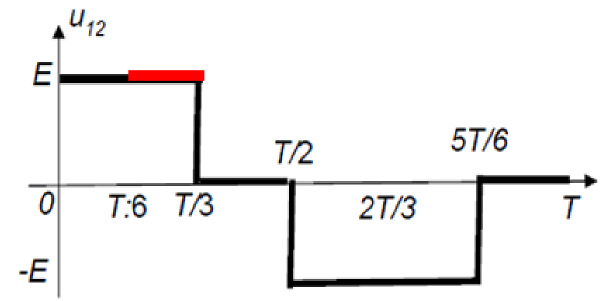


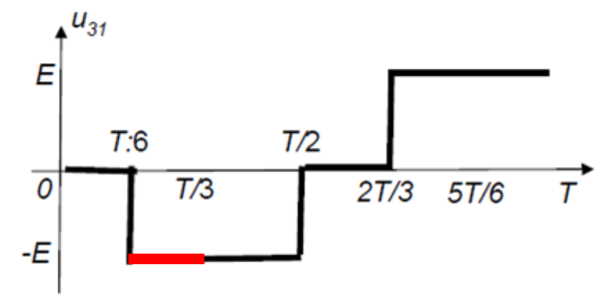
Conversion DC->AC : full wave inverter

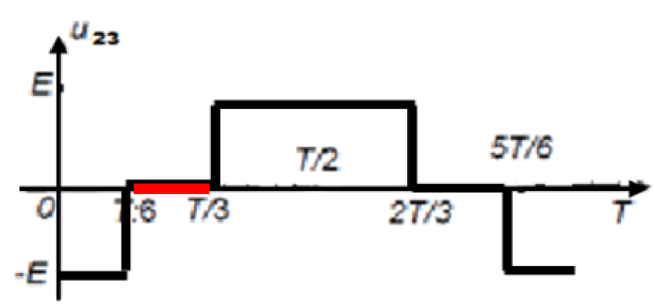
Example of a sequence



De T/6 à T/3







$$\frac{E}{2} = V_{K1} + U_{12} + V_{K'2} - \frac{E}{2} \rightarrow U_{12} = E$$

$$\frac{E}{2} = V_{K1} - U_{31} + V_{K'3} - \frac{E}{2} \rightarrow U_{31} = -E$$

$$U_{23} = V_{K'2} - V_{K'3} \rightarrow U_{23} = 0$$

Conversion DC->AC : full wave inverter

If the load is well-balanced: $v_1+v_2+v_3 = 0$

Knowing that:

$$u_{12} = v_1 - v_2$$

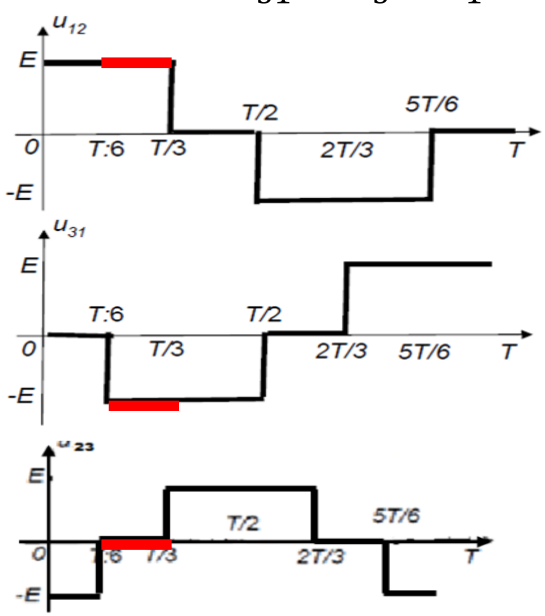
$$u_{23} = v_2 - v_3$$

$$u_{31} = v_3 - v_1$$

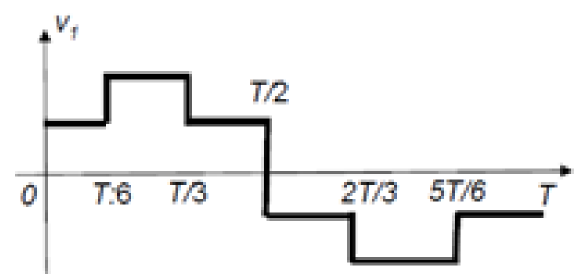
$$v_1 = \frac{1}{3}(u_{12} - u_{31})$$

$$v_2 = \frac{1}{3}(u_{23} - u_{12})$$

$$v_3 = \frac{1}{3}(u_{31} - u_{23})$$



The waveform of the voltages v1, v2 and v3 can be retrieved:



v_2 and v_3 : same waveform but shifted by T/3 and 2T/3

Conclusion on full wave inverters: The frequency of the output wave depends on the opening sequence of the switches but the amplitude is not easily adjustable with this type of inverter.

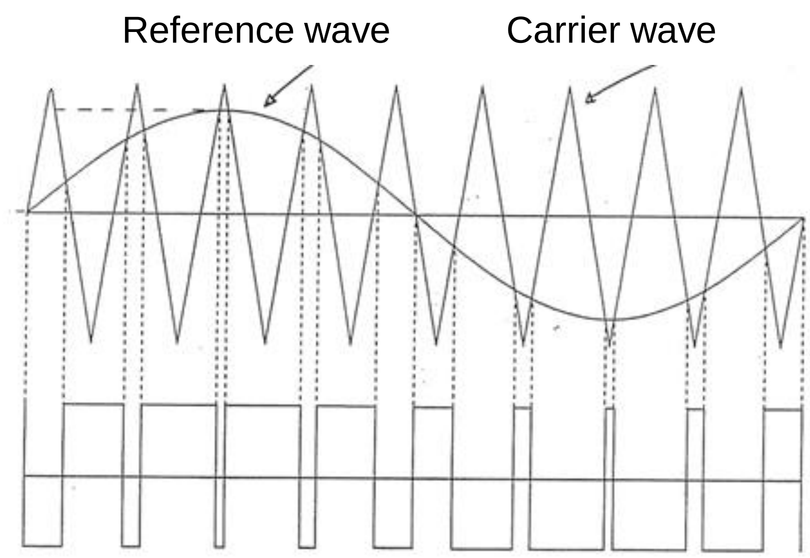
Conversion DC->AC : PWM (Pulse Width Modulation) inverter circuits

The structure of the inverter is the same as for other inverters, only the control of the switches is changed. PWM is the most commonly used technology.

The switching times of complementary switches (H1 and H'1 for example) are determined by the intersection:

- A reference wave of frequency f and amplitude V_m, representing the desired output voltage u from the inverter. This reference voltage is generally sinusoidal.

- A triangular carrier wave of frequency f_p well above f

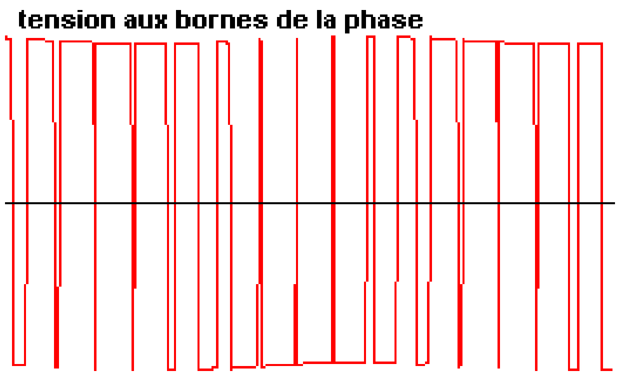


Advantages of PWM inverters:

- The RMS value and frequency of the output signal can be easily tuned
- Harmonics are of high levels and are easy to filter

Conversion DC->AC :
PWM (Pulse Width Modulation) inverter circuits

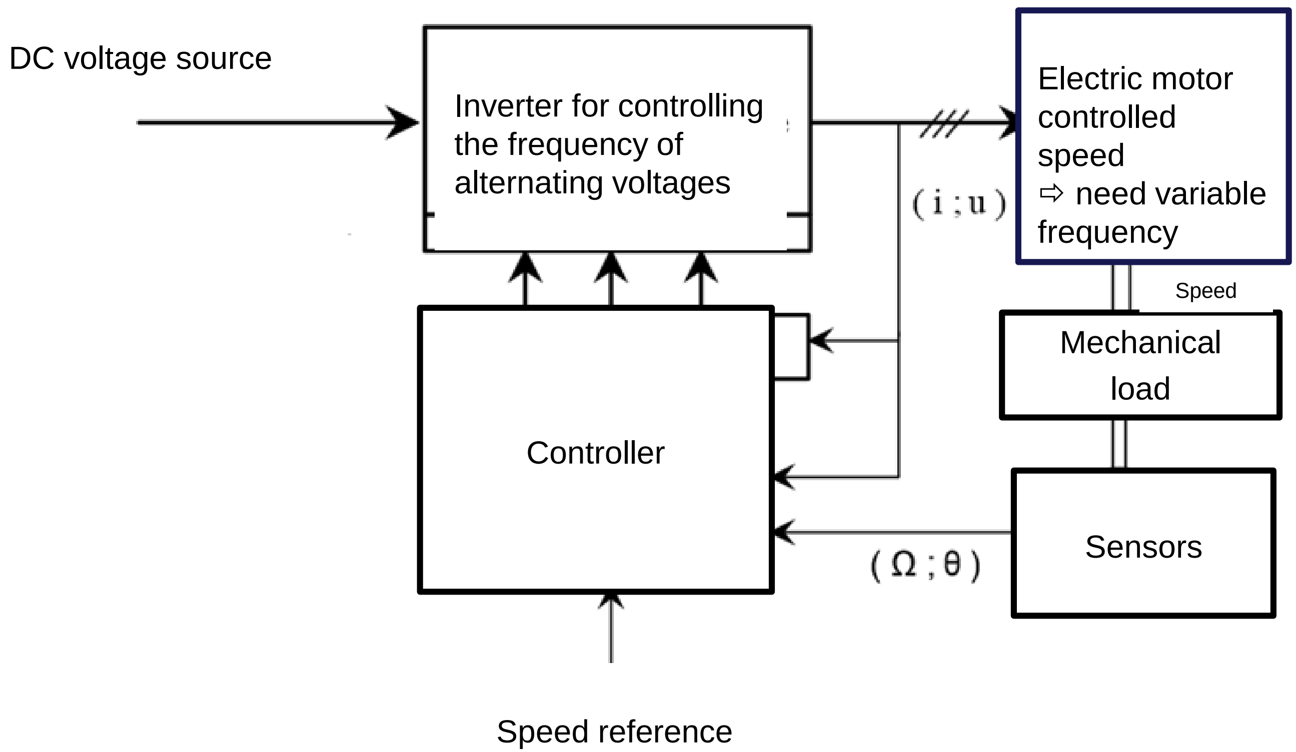
Finally, at the output of the inverter, one obtains:



Advantages of MLI or PWM inverters:
- RMS value and frequency of output signal easy to adjust
- Harmonics at high frequencies and easy to filter.

Conversion DC->AC : inverter
Typical application: speed control of a motor

Important note: the speed of a synchronous machine (SM) depends on the frequency of the stator current
⇨ control the speed of a MS = control the frequency of the supply voltages



$\Omega = 60\, f / p$

with
f frequency (hertz)
p number of poles pairs
Ω Speed (rpm)

Electric power generation and storage

in aircraft

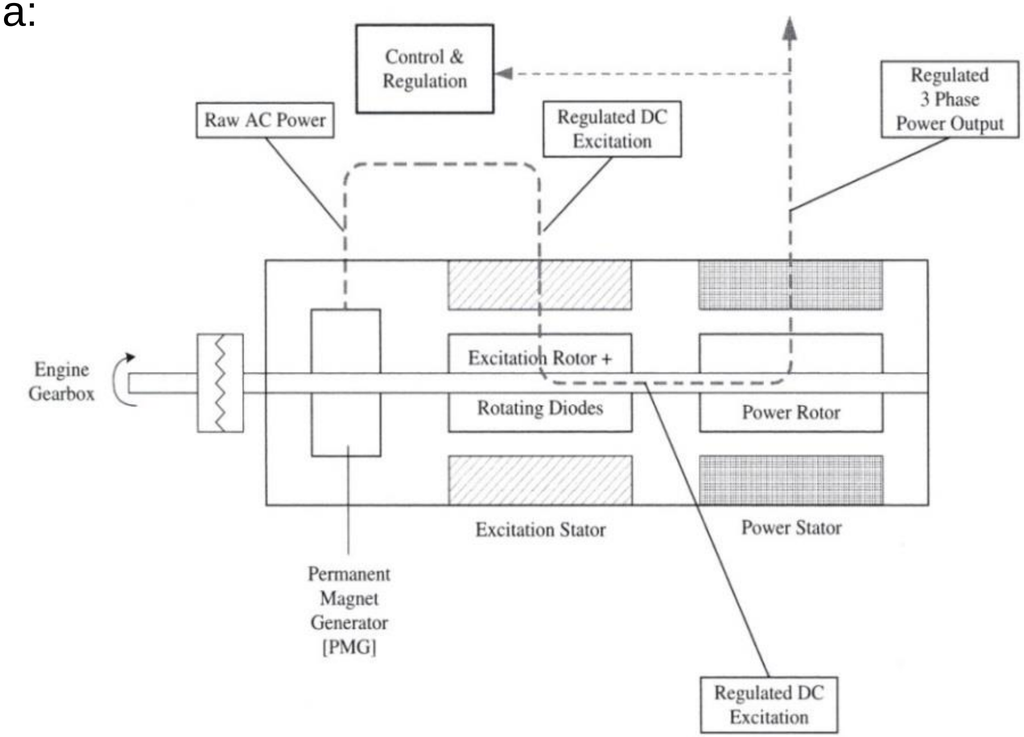
AC power generators: principle

The generation of electrical power is mainly carried out by generators mechanically coupled to the axes of the turbomachines. When the engines are on (on the ground or in flight), it is these generators that primarily supply the aircraft with electrical energy.

The synchronous machine with wound excitation is the machine chosen to fulfill the function of the main generator on an airplane.
In a synchronous machine, the speed of rotation and the frequency of the currents in the stator windings are related by the formula:

$$\Omega = 60\, f / p$$

f frequency in hertz,
p number of pole pairs
Ω speed in rpm.

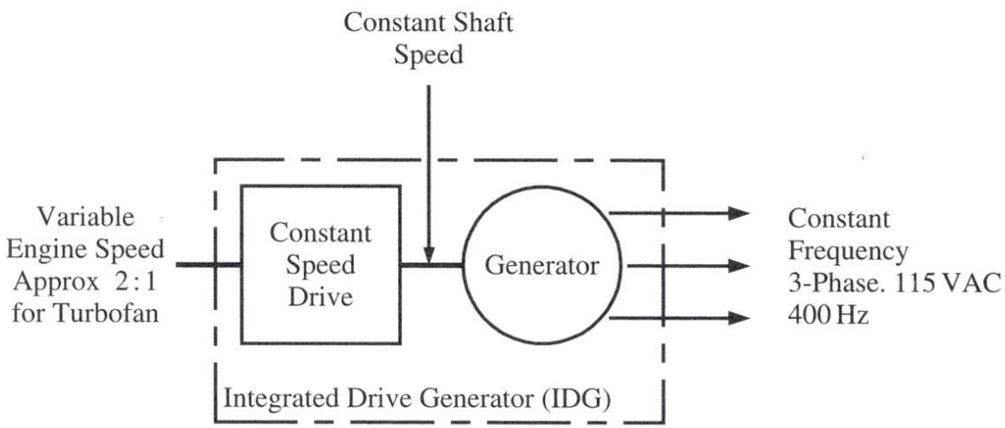


Fixed frequency AC power generation: IDG

The Integrated Driven Generator (IDG) provides a three-phase voltage of 115/200 VAC at a fixed frequency of 400 Hz.

Principle of Integrated Drive Generator (IDG):
A Constant Speed drive (CSD) maintains the generator shaft speed at a constant rpm which results in a an output voltage with constant frequency (400Hz±10HZ).

Drawback: CSD expensive to purchase and maintain



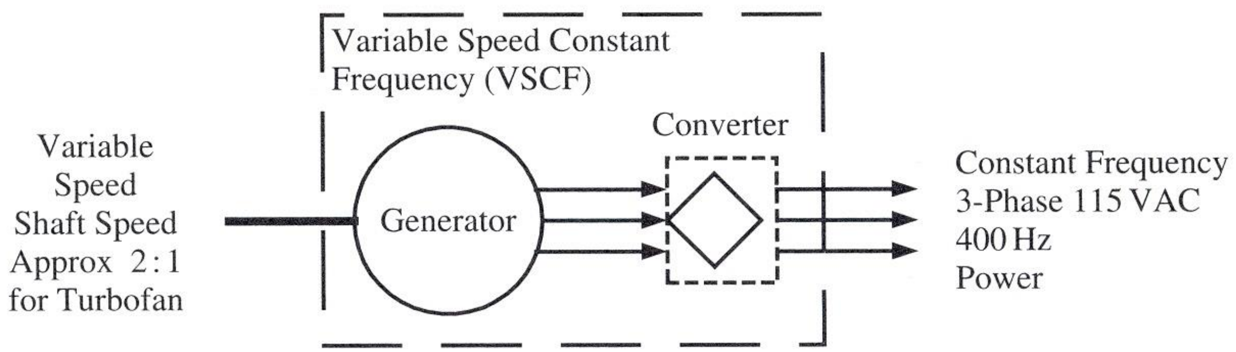
source: Aircraft systems, AIAA education series

Fixed Frequency AC power generation: VSCF

The Integrated Driven Generator (IDG) provides a three-phase voltage of 115/200 VAC at a fixed frequency of 400 Hz.

In a **Variable Speed Constant Frequency** (VSCF) converter, the variable frequency produced by the generator is electronically converted by solid state power switching devices (**typically: rectifier + inverter)** to constant frequency 400Hz.

Drawbacks: power electronics => non-linear consumers impacting network quality



source: Aircraft systems, AIAA education series

Variable Frequency AC Power Generators : VFG

The **Variable Frequency Generator** (VFG) produces a three-phase voltage with variable frequency ranging from 370 to 770 Hz.

It consists of a synchronous wound rotor machine in which the CSD has been removed. The removal of this hydro-mechanical regulator reduces the mass and increases the reliability of the machine. The generation of a variable frequency voltage is made up of electronic converters. This type of generator was introduced since the A380.

According to aircraft, the voltage produced is 115/200 VAC (for the A380 and A400M) or 230/400 VAC (for the A350).

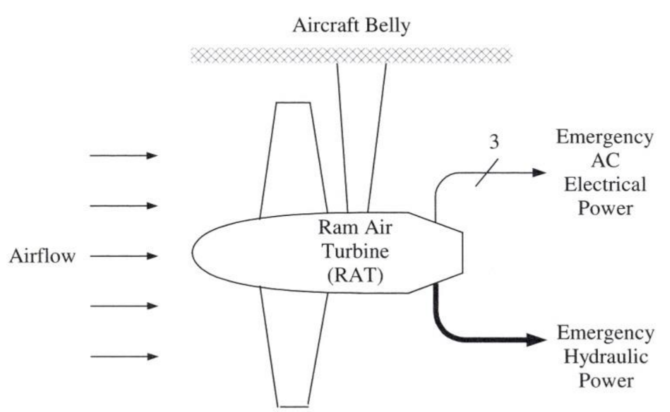
Drawbacks: power electronics => non-linear consumers impacting network quality

source: UTC Aerospace

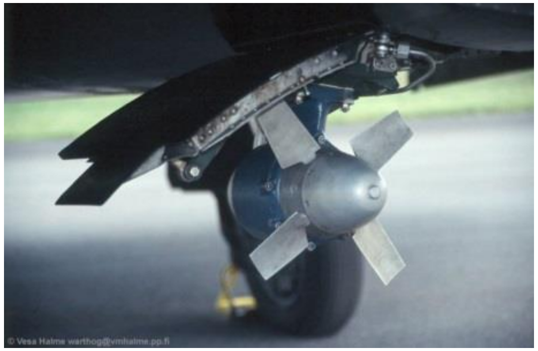
Emergency power generation: Ram Air Turbine

The Ram Air Turbine (RAT) is a small emergency wind turbine connected to an alternator.

It produces energy from the air blown under the plane in the event of loss of primary and secondary energy sources. It can produce 5 to 70 KVA to supply the aircraft's vital systems (flight control actuators, critical flight instruments, etc.).



source: Aircraft systems, AIAA education series



Use of batteries

Batteries are a source of energy that allows:

- to assist the DC generators during the peaks of the transient phases
- to provide energy at start-up when other sources are not active
- to provide energy in the event of failure of other energy sources

Mass energy of a battery

Mass energy is energy divided by mass. For a battery one defines 2 energies masses, one at the level of the cell, the other at the level of the system.

At the cell level

The mass to be considered is the mass of the active electrochemical materials at the anode and at the cathode.

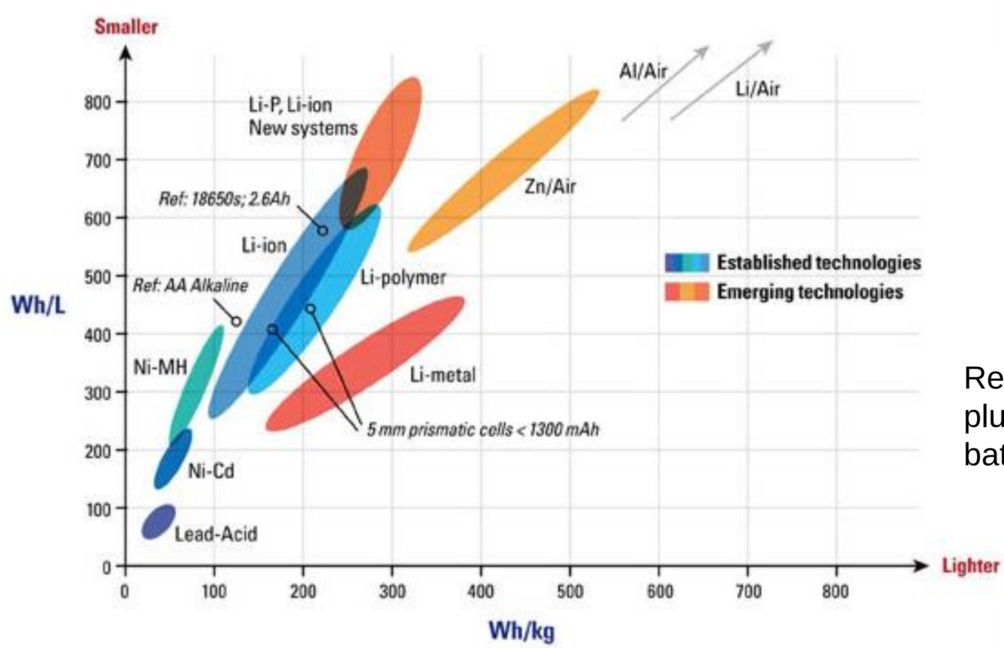
At the level of the "battery" system

The mass to be considered is that of all the electrochemical cells (with a series or parallel assembly depending on the intended voltage and amperage objective) and the numerous components (mechanical, thermal, electrical, etc.) which make up battery. For the same technology, the mass energy of the battery system is therefore lower than the mass energy of a cell.

Technology of batteries

A comparative element of battery technologies is the specific energy per Kg.
It is given for the cell or the system:

	Li-ion	Li-S	Li-Air
Specific Energy (Wh/kg) @ cell	**400-500**	**550- >600**	**710**
Specific Energy (Wh/kg) @ system	**280-350**	**300- >400**	**280**



Remarque : il existe plusieurs « chimies » de batteries au Lithium

Choice of batteries on aircraft

The batteries commonly used are of Nickel-Cadmium type and are temperature controlled to increase their service life.

This technology has the main drawback of requiring regular maintenance. In addition, cadmium is a hazardous substance whose marketing is controlled.

On the Boeing B787, Li-Ion technology with higher specific energy was used

⇒ identification of new problems (eg thermal runaway) and new certification requirements

Hydrogen

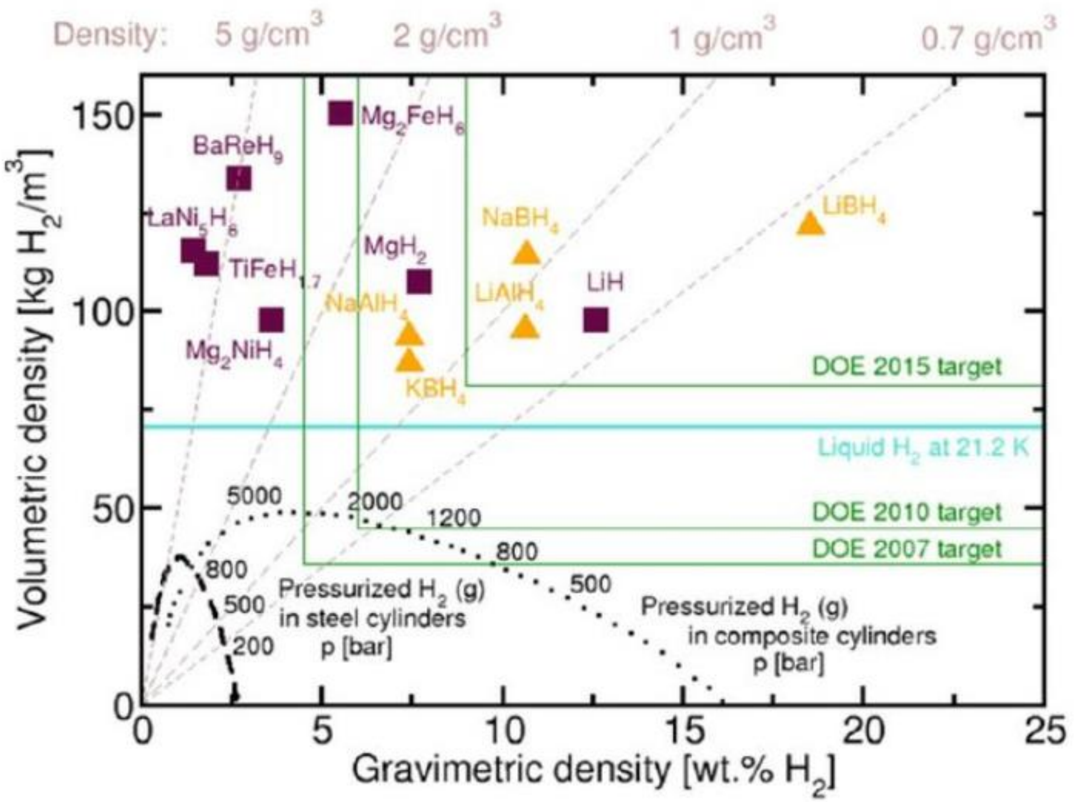
- ☺ hydrogen specific energy = 4x kerosene specific energy
- ☹ Very low volumetric capacity if gas (Pressurized gas to increase volumetric capacity)
- ☹ Heating : 1kW of electricity produced ⇨ 0.5-1 kW of heat emitted
- ☹ storage

Storage type	Hydrogen (gas)	Hydrogen (liquid)
kWh/kg (MJ/kg)	33.29 (119.93)	33.29 (119.93)
kWh/l (MJ/L)	2.75×10^{-3} (9.9×10^{-3})	2.36 (8.50)
Volumetric capacity/ g/L	0.08	70.85

Hydrogen

Hydrogen storage options

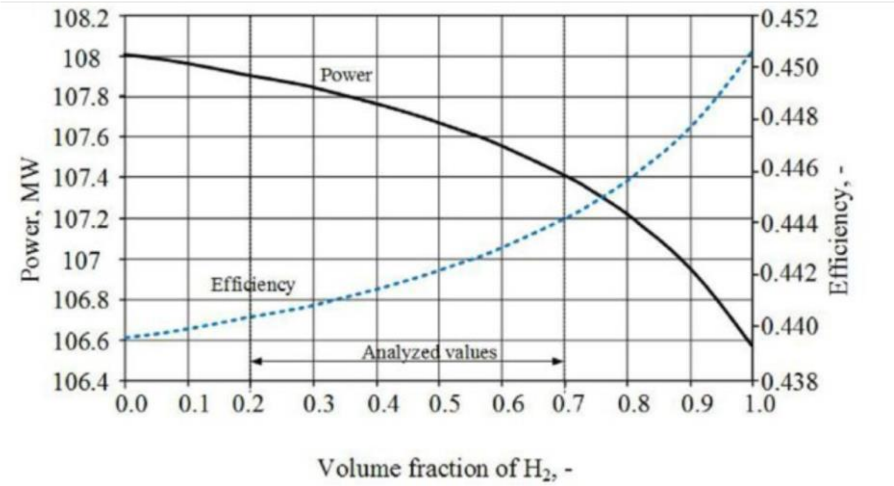
- Compressed gas – lightweight composite cylinde
  - 300 bar – 700 bar pressure
    - Diminishing returns with increasing pressure because of r ideality of hydrogen
  - Fibre-reinforced composite with fiberglass, aramid o carbon fibre and gas-impervious liner
    - Type III cylinder uses metal liner (typically aluminium)
    - Type IV cylinder uses thermoplastic liner
- Cryogenic storage
  - Hydrogen is liquid below −252.87 °C
  - Double-walled vessel with vacuum insulation
  - Low pressure (a few bar)
  - Need to allow for losses of hydrogen to boil-off
    - ~1 to 3 % per day
  - Benefits most from economies of scale
  - 7.5 wt% for 5 kg H_2, ~15 wt% for 50 kg



$$\text{gravimetric density (wt\%)} = \frac{m_{H_2}}{m_{H_2} + m_{tank}}$$

Use of Hydrogen

Hydrogen-Fueled Gas Turbines: Hydrogen burnt directly in turbines



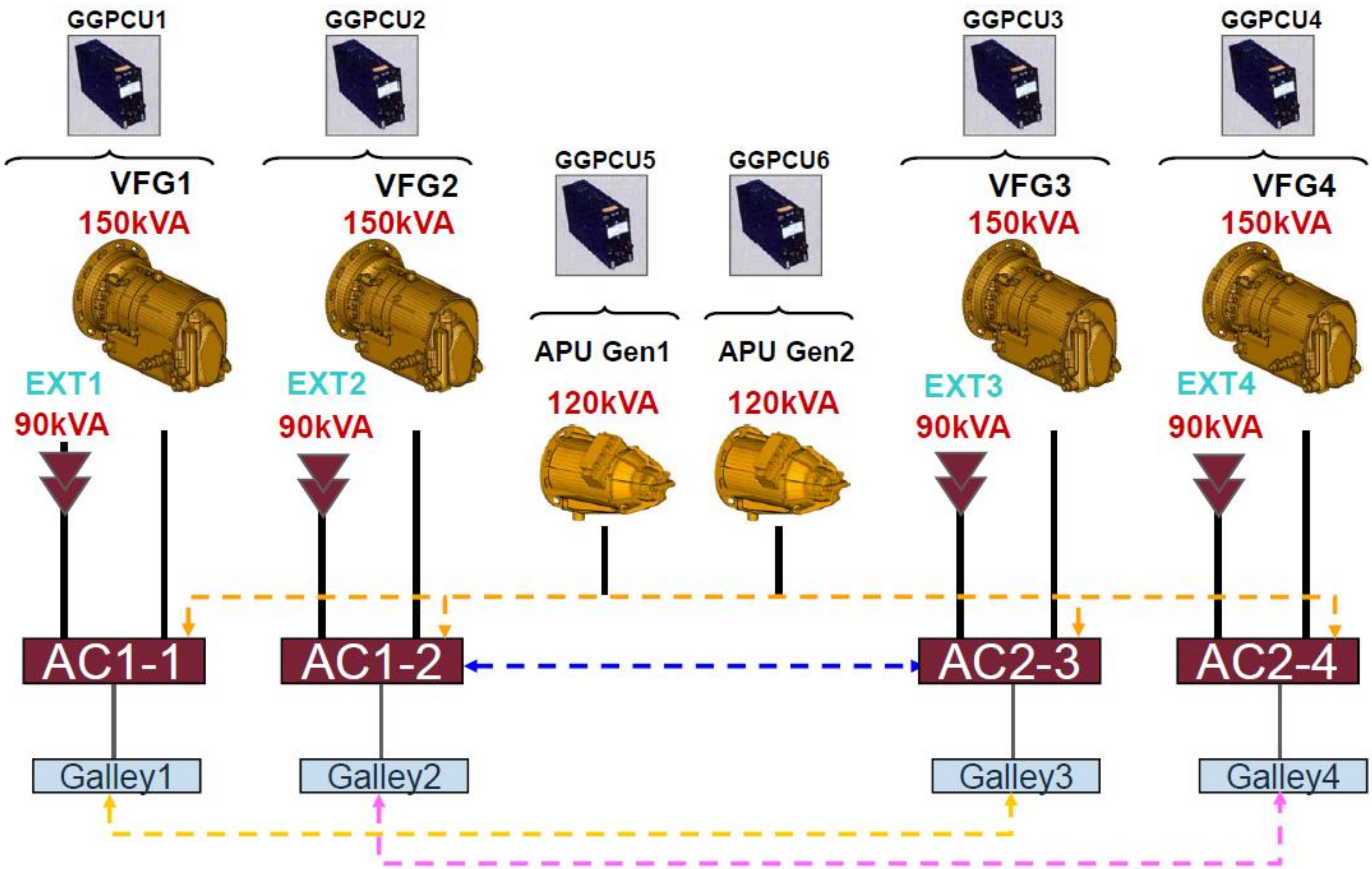
Hydrogen Fuel cell

	PEM-HT / GH_2	PEM-HT / LH_2	PEM-LT / LH_2	PEM-MT / LH_2
Maturity horizon	2020/2025	2020/2025	2020	2030
Stack-level specific power	0,8 kW/kg	0,8 kW/kg	2,5 kW/kg	4 kW/kg

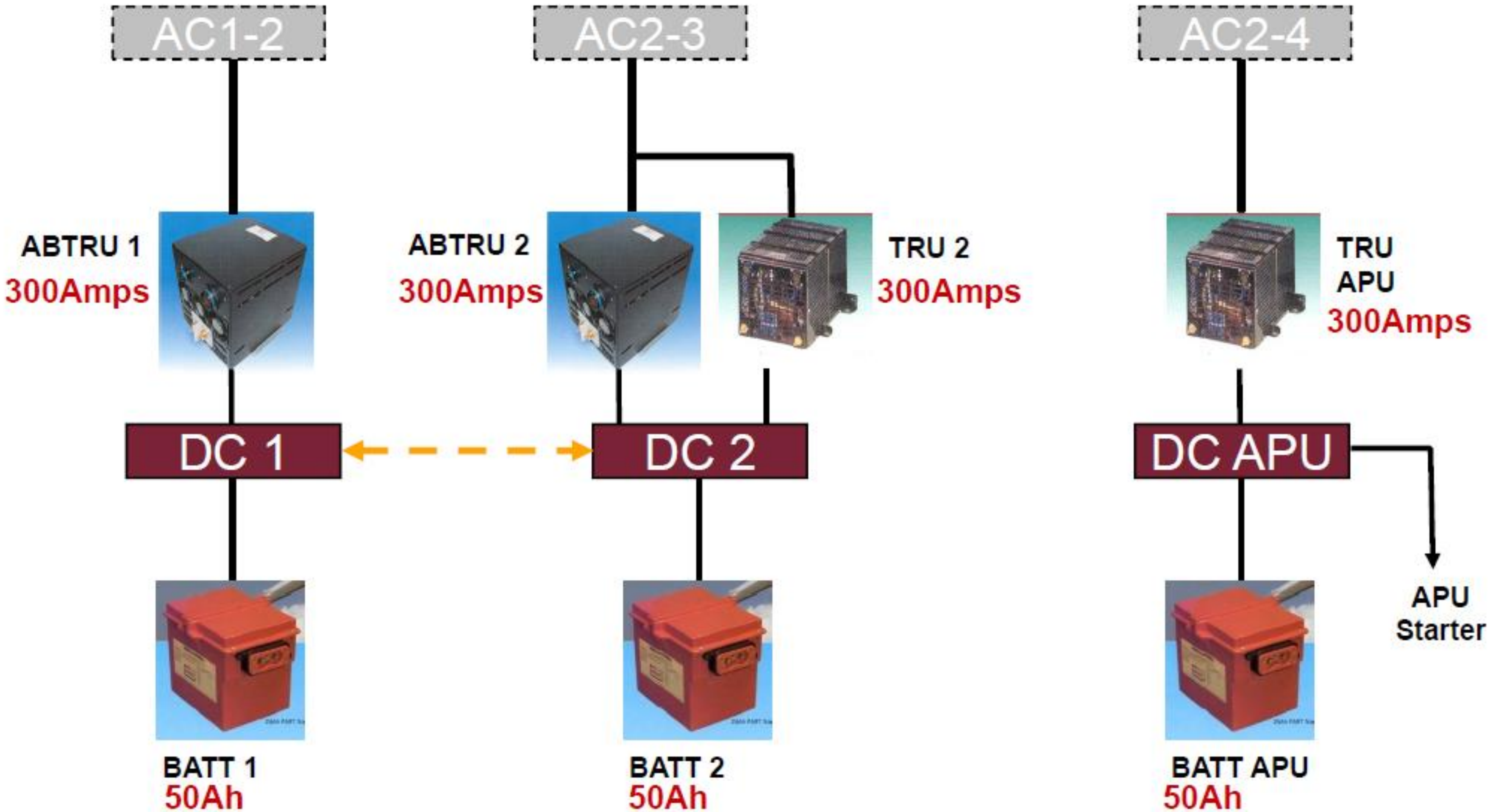
PEM-HT : Proton Exchange Membrane - High Temperature
PEM-LT : Proton Exchange Membrane - Low Temperature

Electrical Architecture

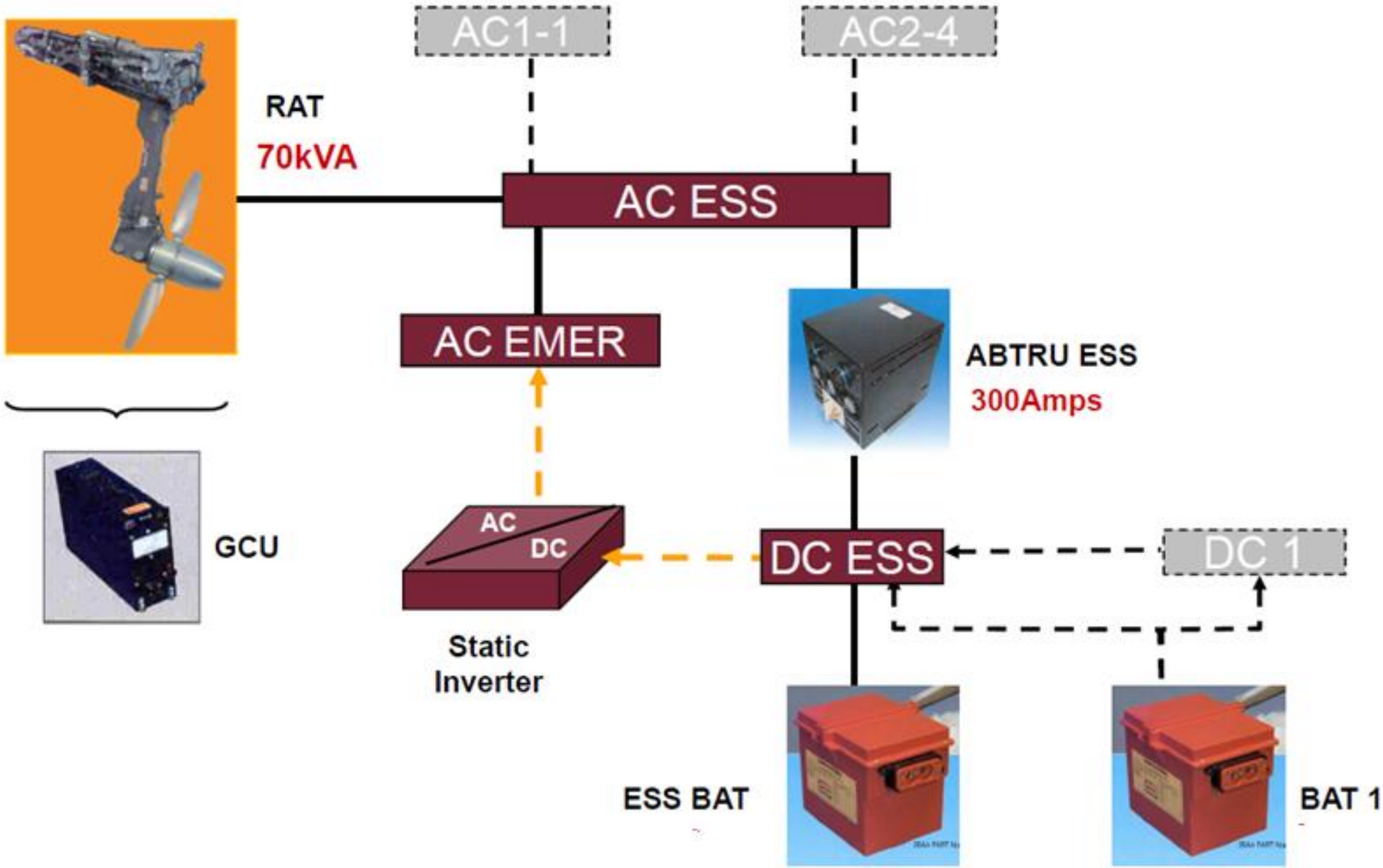
A380 : generation of AC power



A380 : generation of DC power

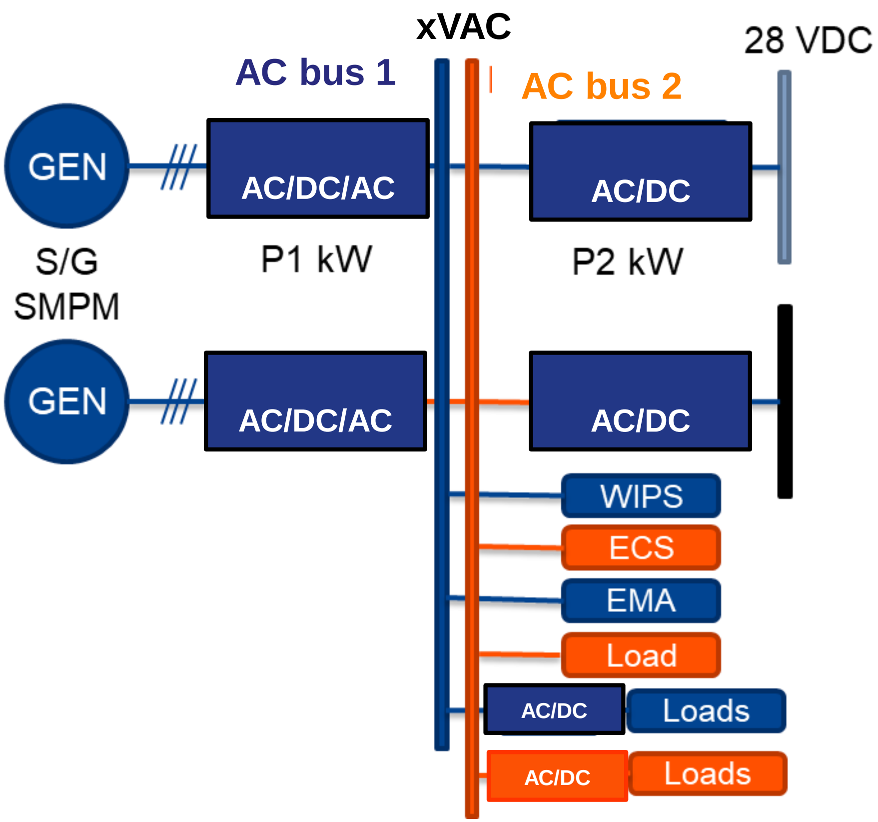


A380 : generation of urgency powers



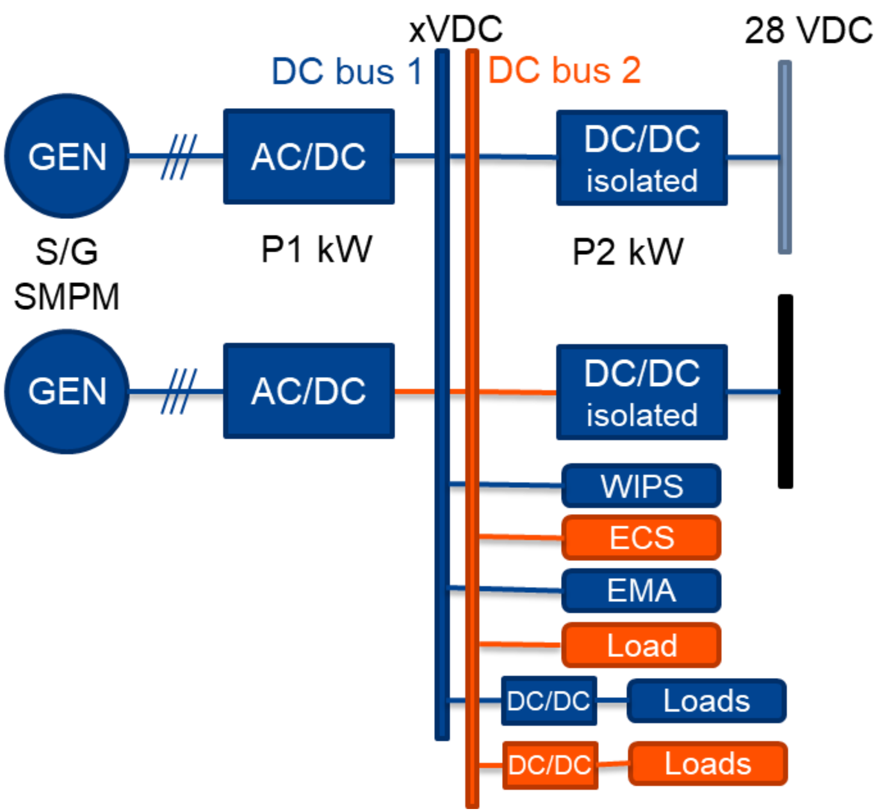
New electrical architecture: AC Network vs. DC network

AC Network



Used for longer
More feedback

DC Network



More flexible
Fewer converters

Electrical architecture: principles

Ensure the mission and avoid total loss on simple failure:

- Supply of essential loads by so-called "essential" buses whose power supply is redundant
- System redundancy
- Segregation of circuits

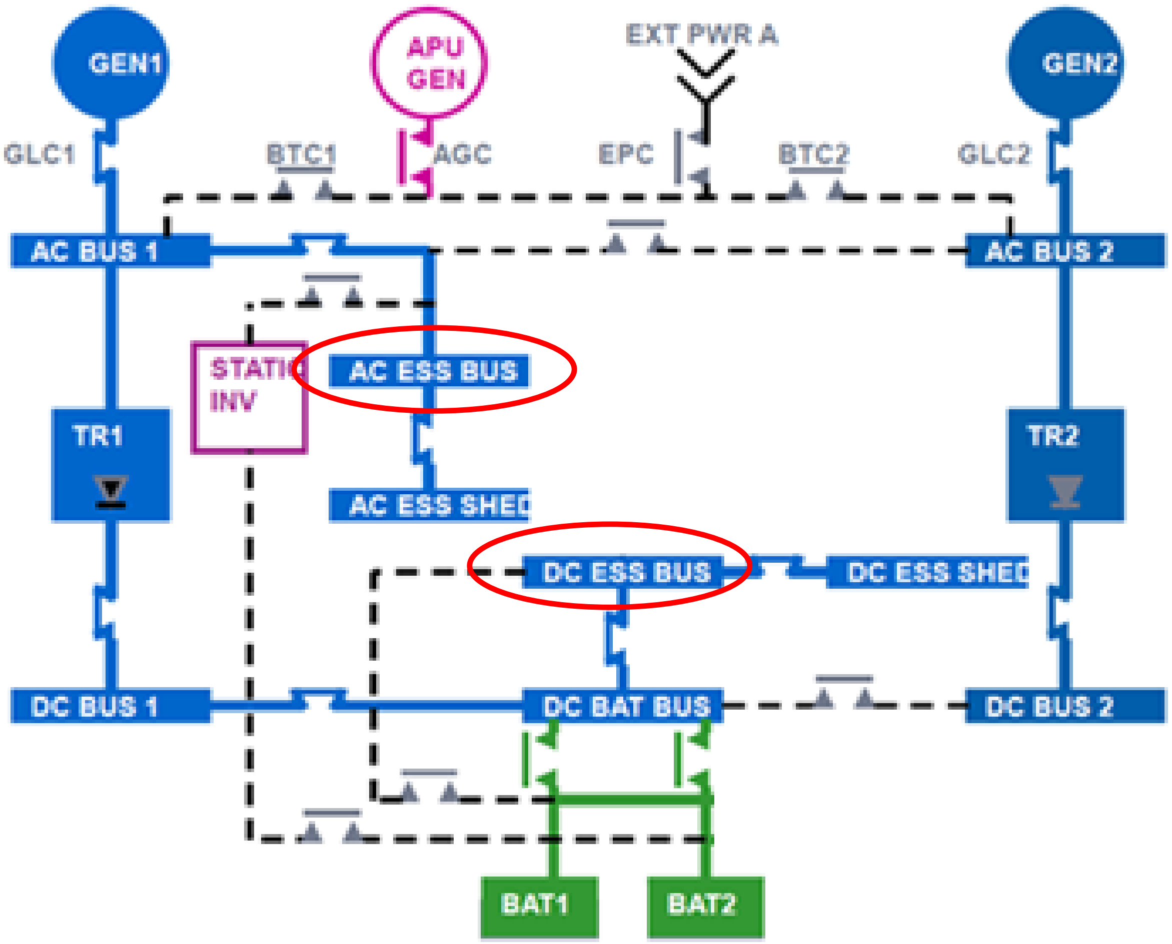
Avoid fires

- Short-circuit protections
- Limitation of cable heating

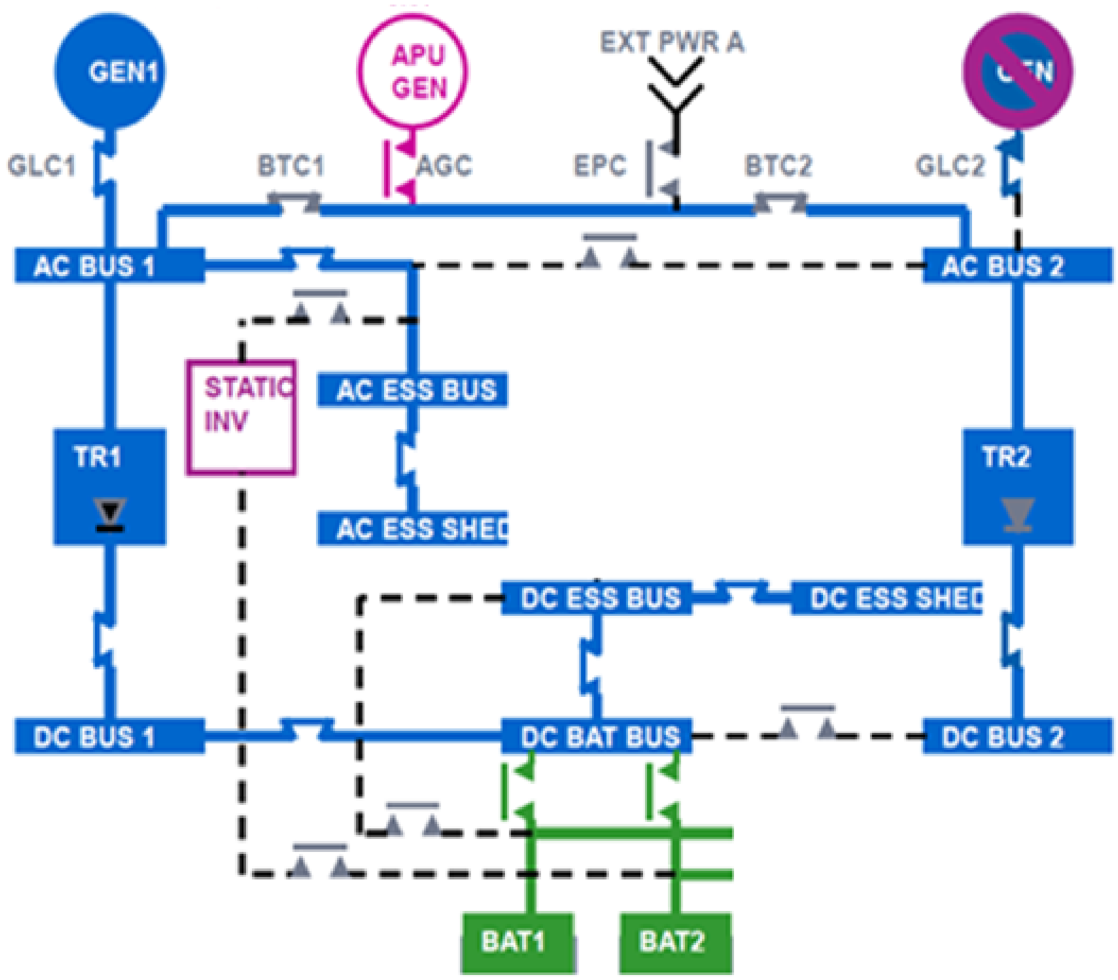
Minimize losses

- Limitation of voltage drops

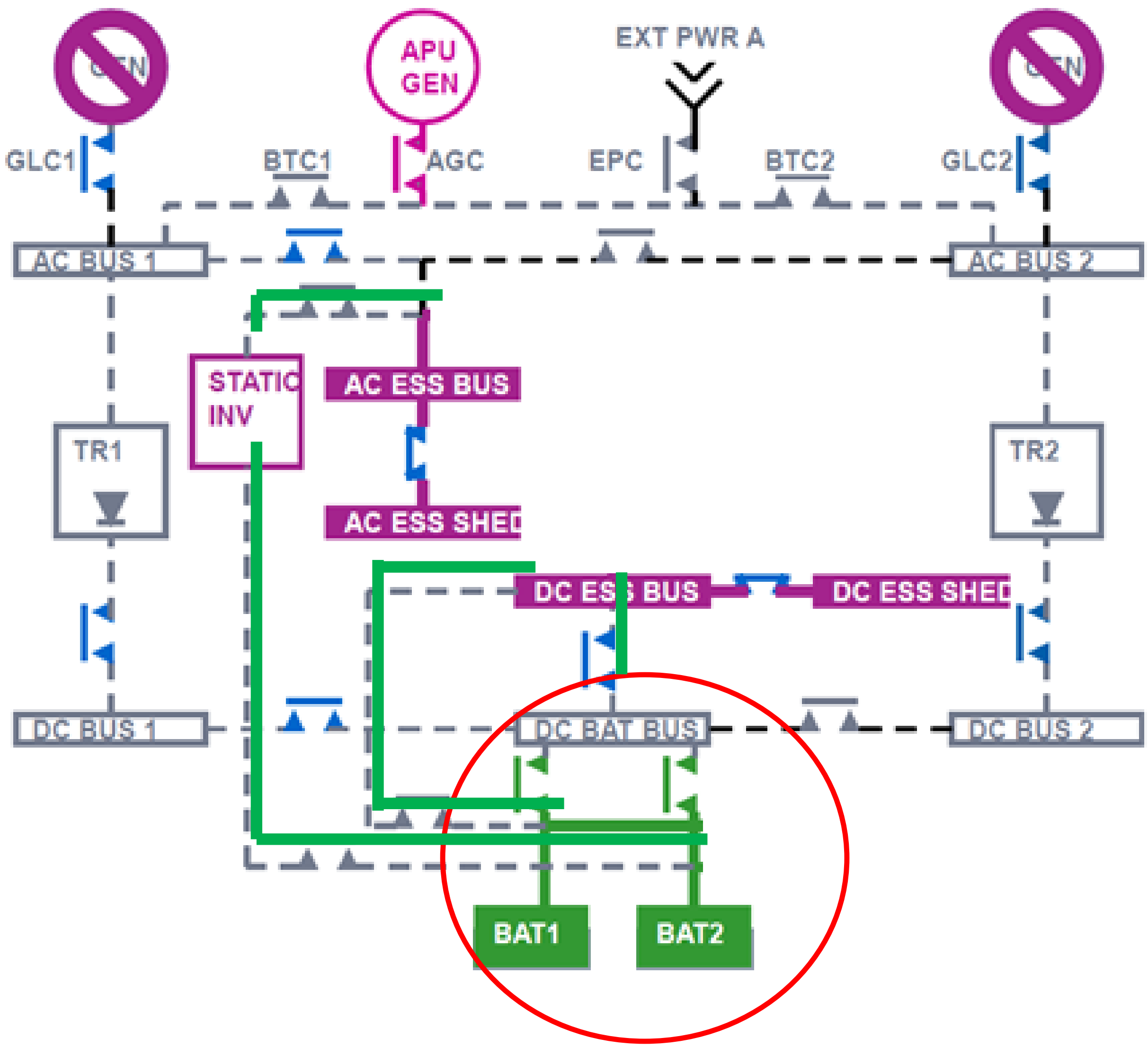
Aircraft electrical architecture: nominal configuration with 2 generators



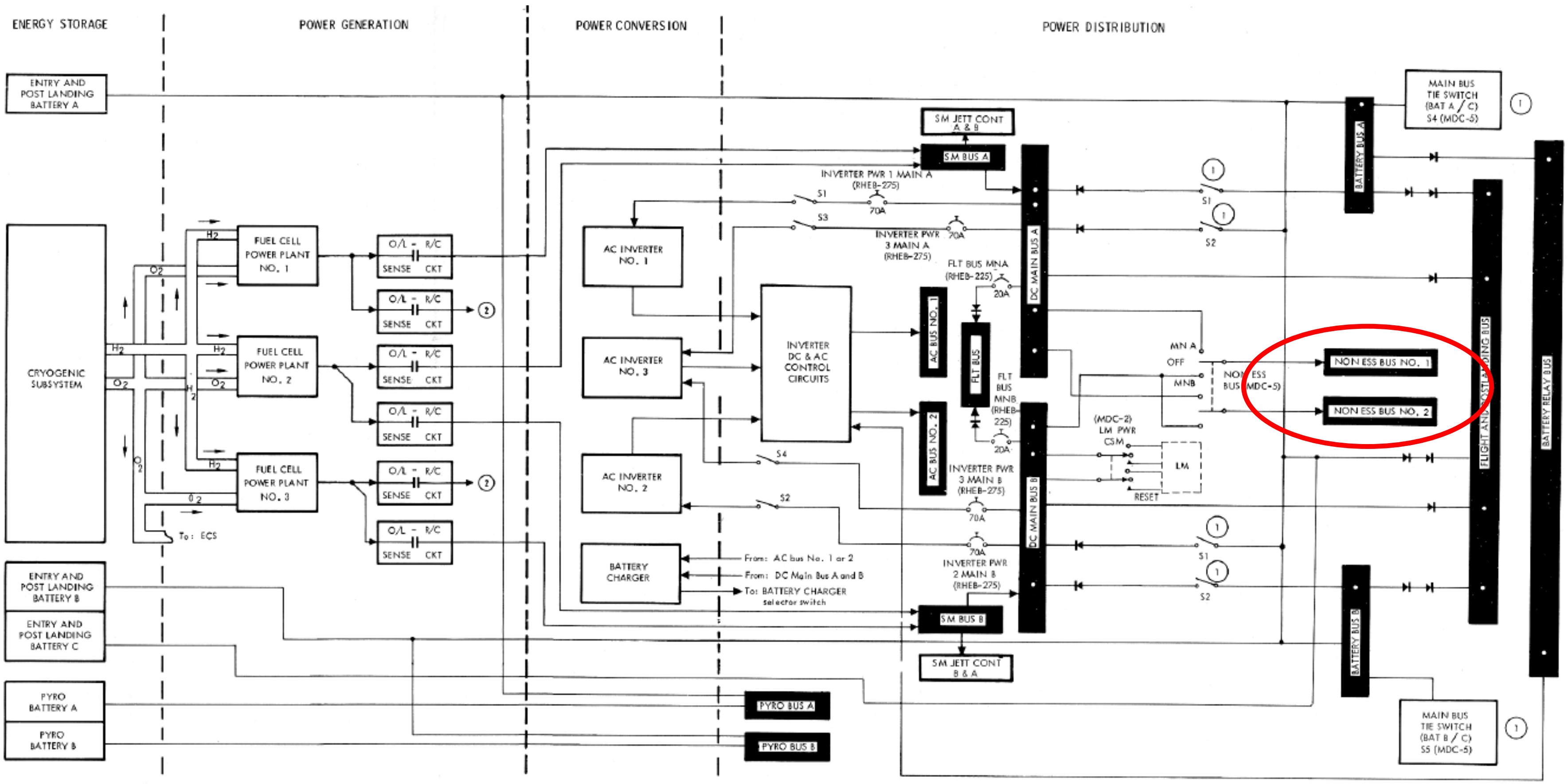
Electrical architecture: failure of 1 generator



Electrical architecture: failure of 2 generators and AC bus



Electrical architecture of the Apollo shuttle



Electrification of aircraft

Electrical power in conventional aircraft

A/C type	DC Generator	VF AC Generator	FF AC generator
Caravelle	27KW – 28V	2 x 18kVA	
Concorde			4 x 60kVA
B747			4 x 90kVA 2 x 90kVA (APU)
A320			2 x 90kVA 1 x 90kVA (APU)
A340-300			4 x 115kVA 1 x 115kVA (APU)
A330-200			4 x 75kVA 1 x 115kVA (APU)
A380		4 x 150kVA	2 x 120kVA (APU)
B787		4 x 250kVA 2 x 225kVA (APU)	
A350		4 x 100kVA	1 x 150kVA (APU)

Notation
DC: direct current
AC: alternative current
VF AC: variable frequency alternative current
FF AC: fixed frequency alternative current

How did it start?

The objectives of ACARE (Advisory Council for Aeronautics Research in Europe) require air transport to respond to environmental constraints to reduce noise, polluting emissions (NOx, CO, HC, smoke), CO2, and therefore consumption.

Objectives 2020

Environmental Goals

- 50% less fuel and CO_2
- 50% less noise
- 80% less NO_x
- Reduction of environmental impact

Air Transport System Efficiency Goals

- Three times more movements
- 99% on schedule performance in all weather conditions

To achieve these objectives, a solution is the electrification of some systems of the aircraft.

Electrification in 2 steps

***Step 1 :* Electrification of non-propulsive loads (years 2000 - 2010)**
(actuation systems, air conditioning systems, ice protection systems, etc)

⇨ A380, A350, B787

<table>
<tr><th></th><th>Airbus A320</th><th>Airbus A380</th><th>Boeing 787</th><th>Nouvelle génération</th></tr>
<tr><td>De-icing</td><td rowspan="2">Pneumatique</td><td rowspan="2">Pneumatique</td><td rowspan="5">Électrique</td><td rowspan="5">Electrique</td></tr>
<tr><td>Air conditioning</td></tr>
<tr><td>Avionics</td><td rowspan="2">Électrique</td><td rowspan="2">Électrique</td></tr>
<tr><td>Inner loads</td></tr>
<tr><td>Breaking</td><td rowspan="3">Hydraulique</td><td rowspan="3">Partiellement électrique</td></tr>
<tr><td>Flight control actuators</td><td rowspan="2">Hydraulique</td><td rowspan="2">Partiellement électrique</td></tr>
<tr><td>Landing gear & Thrust reversers</td></tr>
<tr><td>Total Electrical Power</td><td>< 200 kW</td><td>600 kW</td><td>1 000 kW</td><td>> 1 000 kW</td></tr>
</table>

***Etape 2 :* Electrification of propulsion (years 2020 and more)**

Hydraulic Systems ⇨ Electric Systems

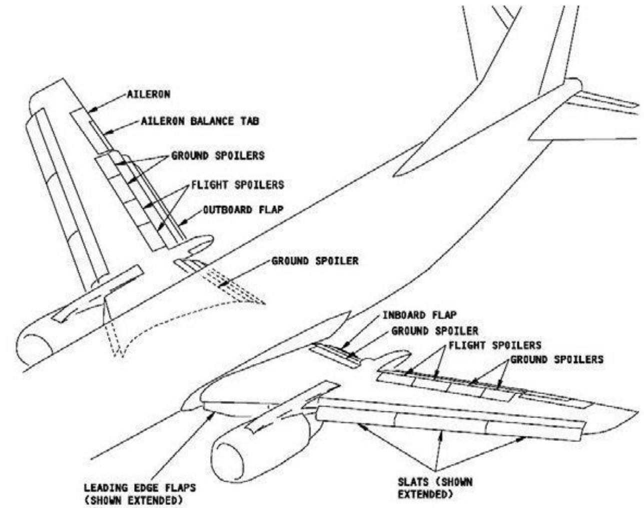
Hydraulic systems:

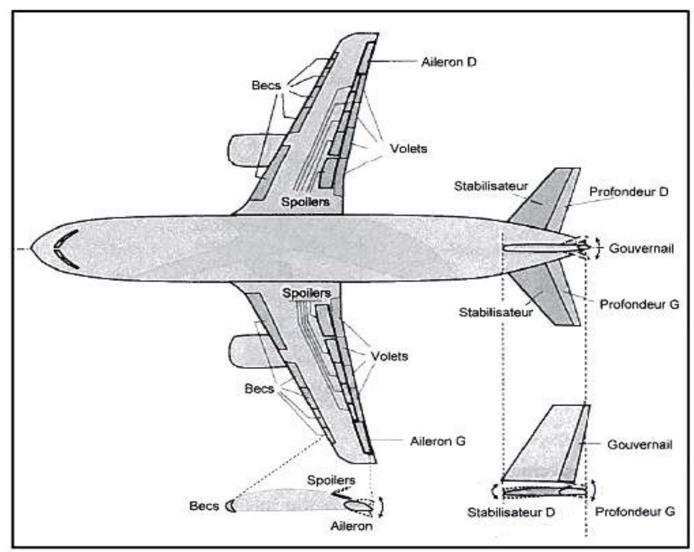
•The ***flight control system*** divided into two subsystems: the primary flight controls and secondary flight controls . The primary flight control system controls the altitude, direction and speed of the aircraft through the moving surfaces: spoilers and ailerons (located on the wings) and the rudder and elevator (installed on the plane vertical / horizontal to the rear of the aircraft). These surfaces control the orientation of the aircraft from 3 angles: roll, pitch and yaw. The secondary flight control system controls the lift of the aircraft through devices such as the slats and flaps.

•The ***landing gear system*** which allows rolling and braking of the aircraft on the ground. An aircraft has two types of landing gear: the Nose Landing Gear for taxiing phase and towing and the Main Landing Gear located in the center of the plane that supports the weight of the aircraft and allows braking.

⇒ Electrifying these functions consists of replacing the hydraulic actuators by more electric actuators:

- EHA actuators for flight control (A380 and A350)
- Electrical brakes (B787)





Pneumatic systems ⇨ Electric systems

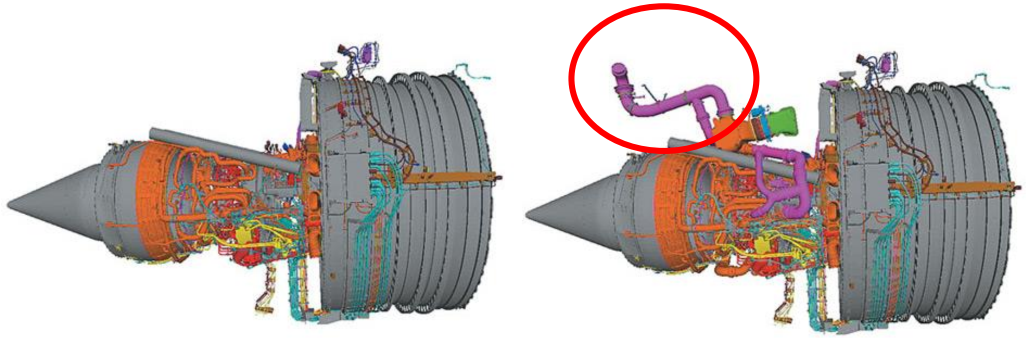
Pneumatic systems are power-consuming. The compressed air taken from the engines of the aircraft (bleed air) is distributed to various consumers through. These consumers are:

- ***ECS (Environmental Control System):*** in charge of controlling an atmosphere in the aircraft under conditions of pressure and temperature sufficient to take a trip in high altitude.
- ***WIPS (Wing Ice Protection System):*** in charge of avoiding (anti-icing system) or eliminating (de-icing system) ice formation on surfaces such as wings or engine input
- The ***engine start*** that uses hot compressed air bleed from APU

⇒ Bleed-less aircraft: aircraft in which the bleed of compressed air is suppressed to increase the efficiency of the turbine

⇒ electric ECS, WIPS and electric start

A comparison of typical engine buildups of a no-bleed engine (left) and the traditional bleed engine (right)



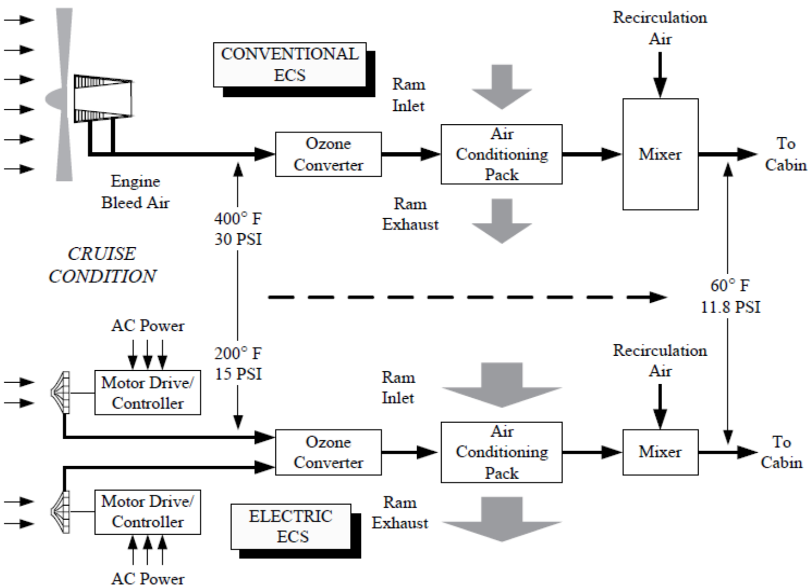
Pneumatic systems ⇨ Electric systems
Environmental Control and Ice Protection Systems

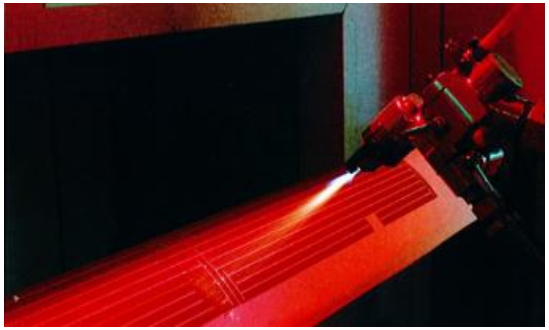
- ***ECS (Environmental Control System):*** controls the temperature and pressure in the aircraft to enable high altitude flights.

Boeing 787 : electric ECS ⇨ compressors that pressurize the air supplied to the air conditioning pack rather than drawing air from the engines

- ***WIPS (Wing Ice Protection System):*** prevents ice formation (anti-icing) or removes ice (de-icing) on critical surfaces such as the leading edges of the wings and nacelle entrances

Boeing 787 :
electric WIPS ⇨ electro-thermal mats

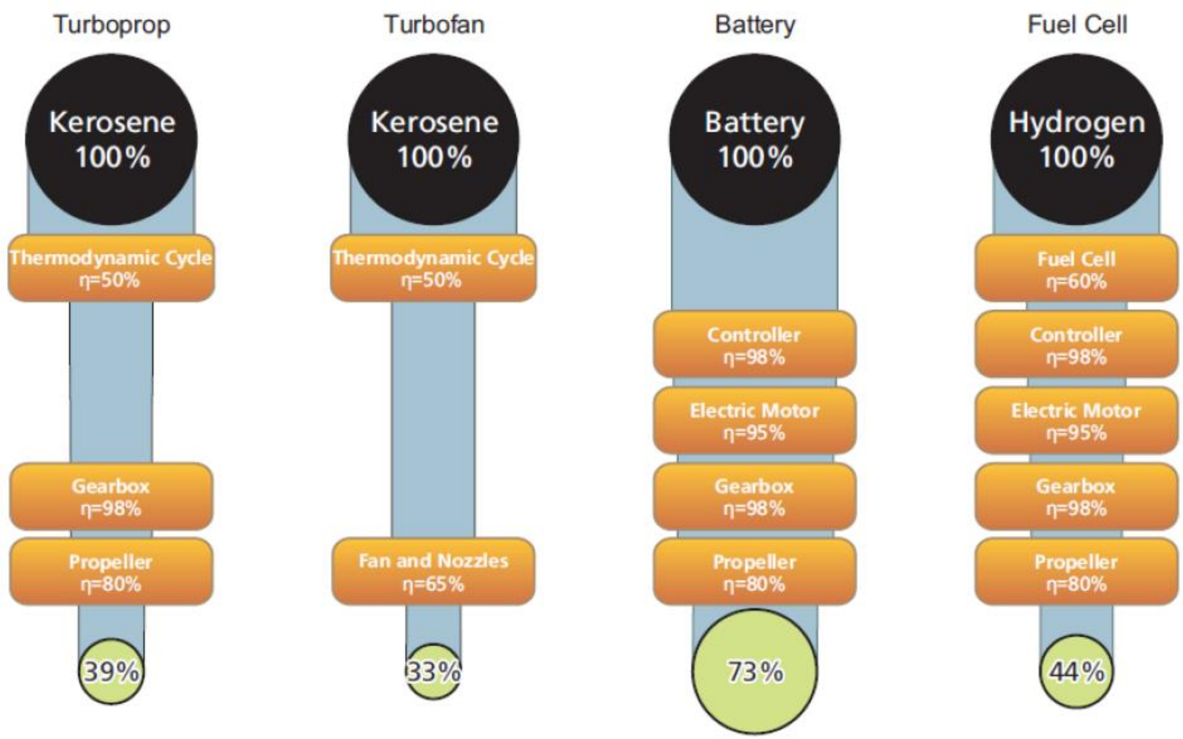




Step 2: Electrification of propulsion

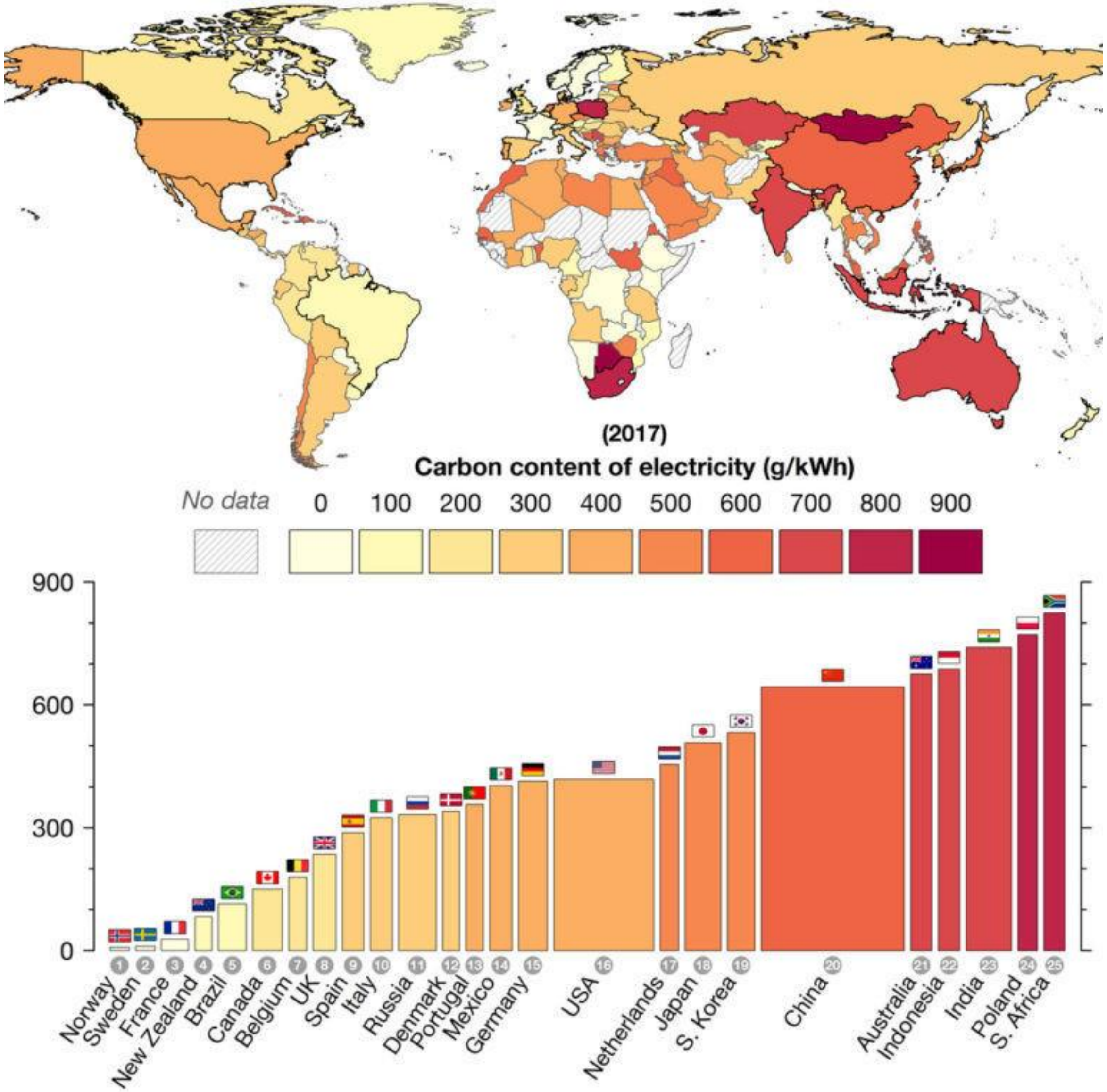
Electric Propulsion

☺ efficiency
☺ Quiet
☺ No emission of polluting gases
☹ Energy storage weight (50 times worse than fuel) ⇨ storage cost
☹ Certification uncertainties and lack of standards



STO-MP-AVT-209, Martin Hepperle

Is electricity a green source?



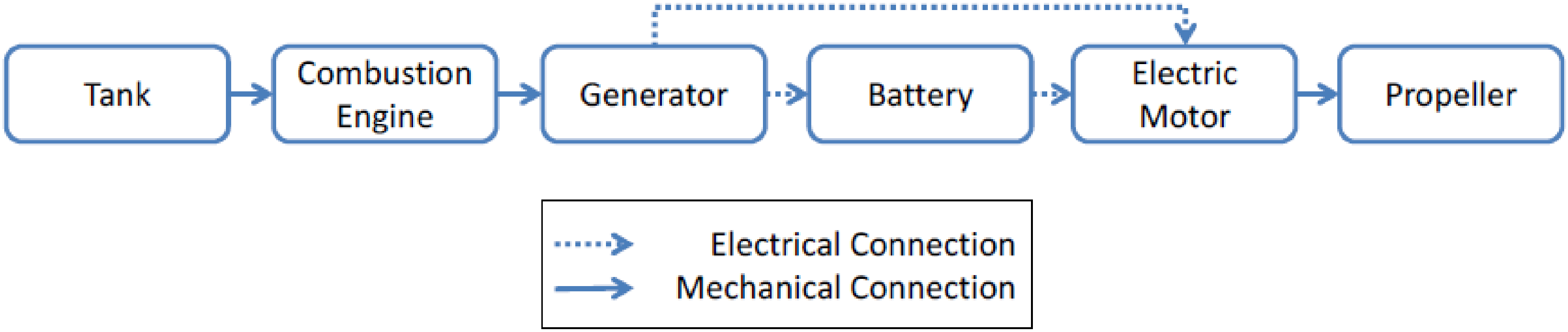
Step 2: Electrification of propulsion

2 options for the electrification of the propulsion

- **Hybrid aircraft**: thermal and electric engines
- **All-electric aircraft**: electric motors only

Hybrid propulsion: series configuration

- ☺ Combustion engine operates at its optimum point (because it is decoupled from the pushing power)
- ☺ Easy implementation of the solution
- ☹ The electric motor must provide all the thrust power

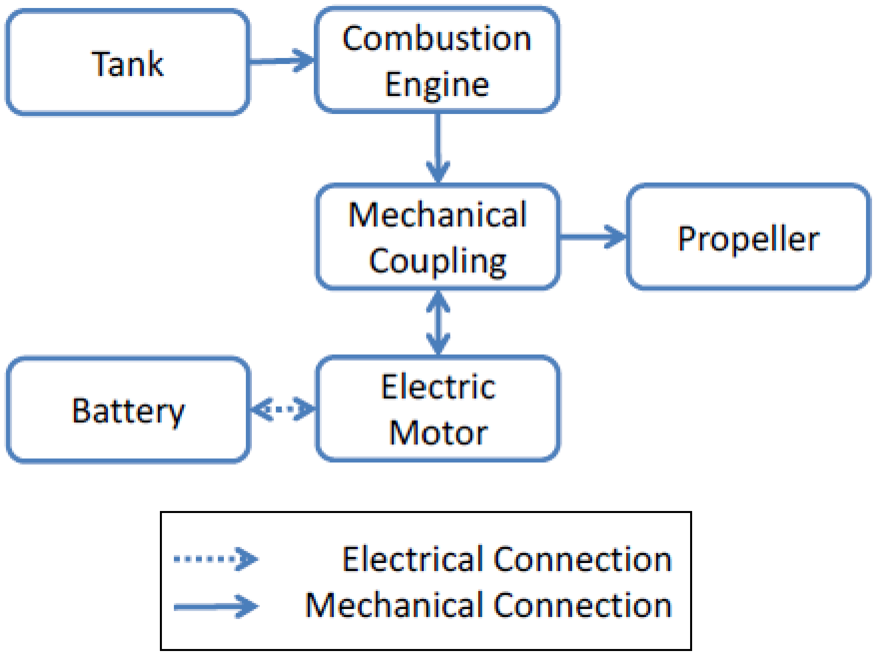


Hybrid propulsion: parallel configuration

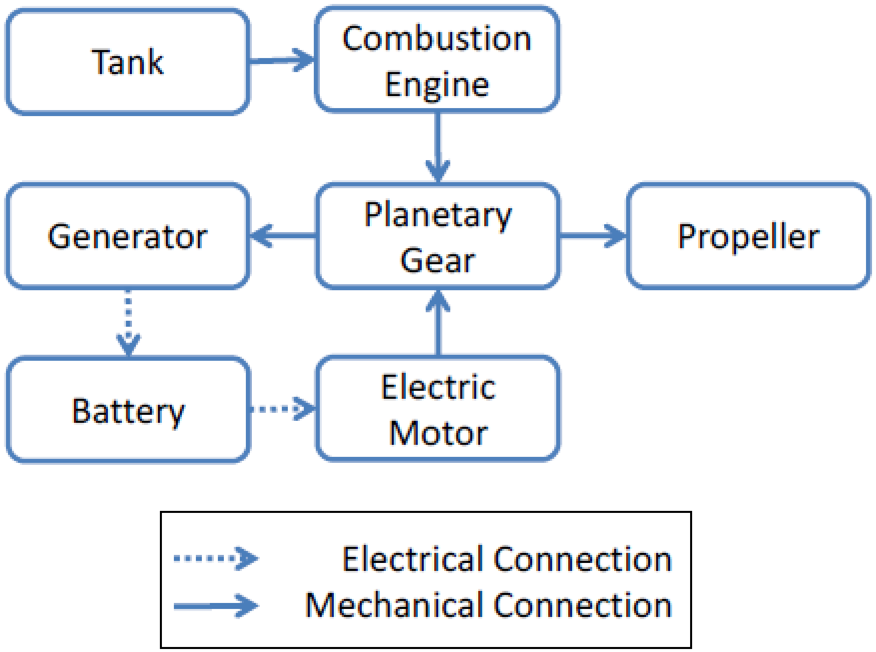
☺ Maximum power is provided by combustion engine and electric motor, both can be smaller in size than in series configuration

☺ Possibility of redundancy

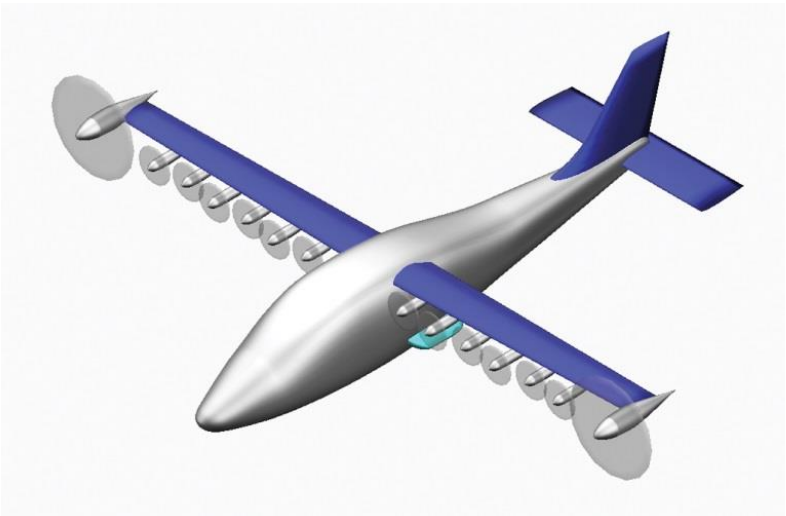
☹ Complex implementation of the solution: need for a mechanical device for (de) coupling the 2 motors + control problem

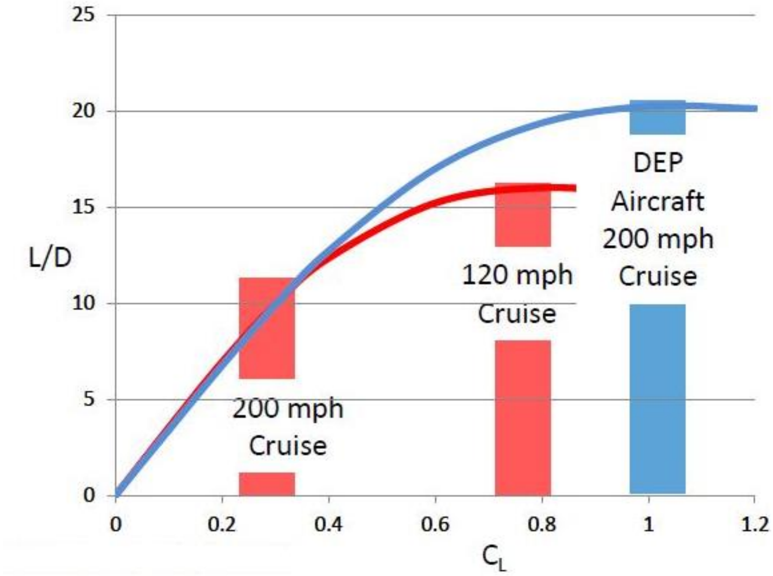


Hybrid propulsion: combined configuration series/parallel



Electrification of propulsion: Distributed Electric Propulsion





Interest of distributed propulsion: Higher L / D ratio (Lift / drag) for distributed propulsion

Blue: DEP : Distributed Electric Propulsion
Red: conventional aircraft

Electrification of propulsion
Example of an all-electric 4PAX aircraft: E-fan2

An example of an all-electric airplane: E-fan2 : Prototype electric powered airplane designed by Airbus Group Innovations.

	Thermal Aircraft	Project goals of electric aircraft
Weight	<600 kg	<600 kg
TCO ***(Total Cost of ownership))***	100 à 120 €/h	Less than 90 €/h (low energy cost, minimizing immobilization with low maintenance)
Autonomy	4 - 5 hours	1h + 15 min for security reasons
Availability	10 hours / day **scheduled maintenance every 50h**	5 hours / day (quick charge in 45 min) **Yearly scheduled maintenance*****

- 650 kg (with 130 kg of Li-Ion 250V batteries)
- Energy : 13 kWh
- two motors of 60 kW each
- charge in about 2 hours
- 45-50 minute flight
- 4 passengers

Electrification of propulsion
Example of an all-electric 9PAX aircraft: Alice

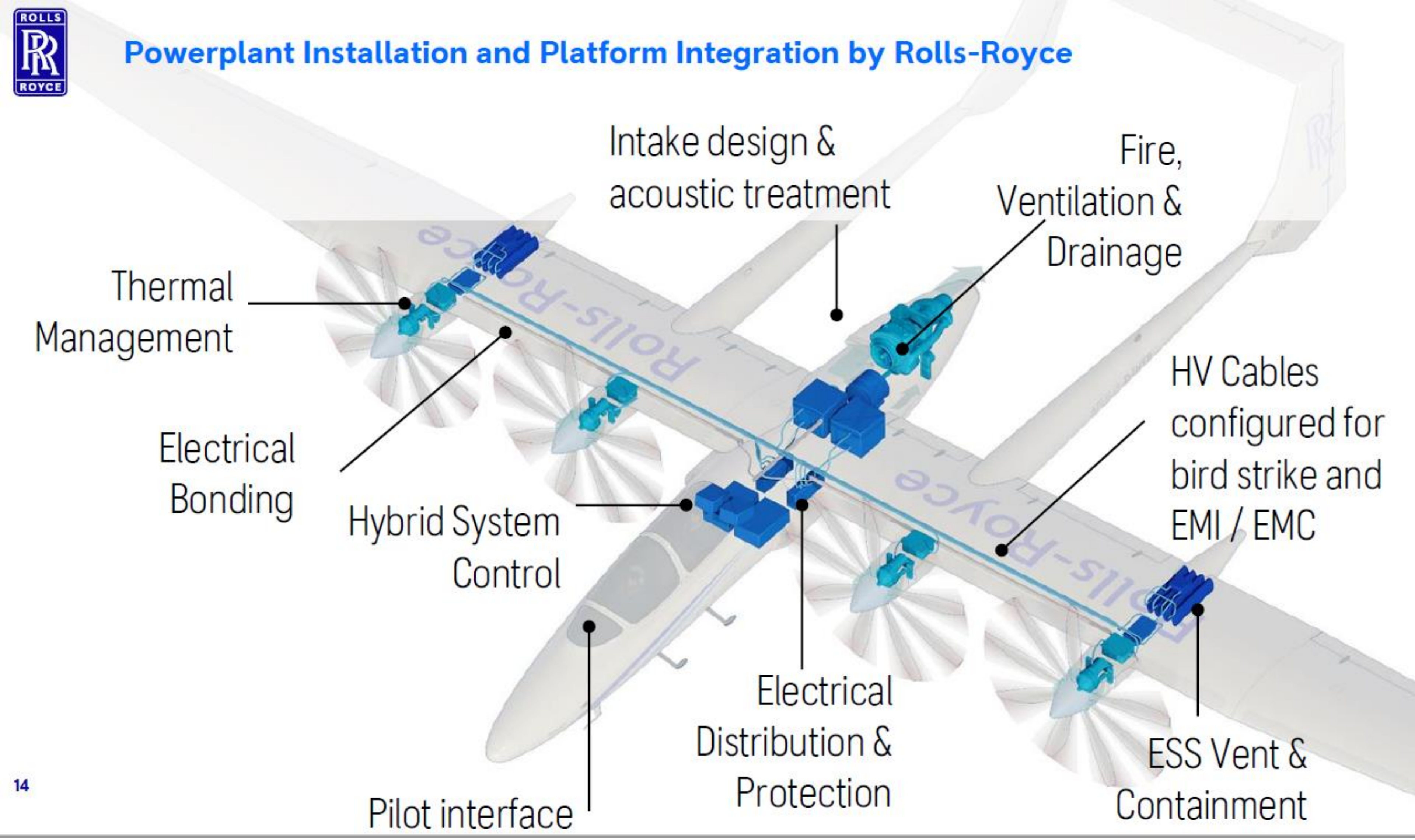
Prototype d'avion à propulsion électrique conçu par Eviation Aircraft (Israel).

PERFORMANCE		CHARACTERISITICS	
Cruise speed	220 KTAS	Occupants	9 Pax (+2 crew)
Takeoff field length	3,000' / 914 m	Useful load	2,500 lbs / 1,134 kg
Cruise altitude	10,000'	MTOW	14,000 lbs / 6,350 kg
Service ceiling	12,500'	Powerplant (total)	900 / 260 kW (peak/cruise)
Range	440 NM (+45min IFR reserve)		

Battery:
920 kWh, 3,600 kg Li-ion

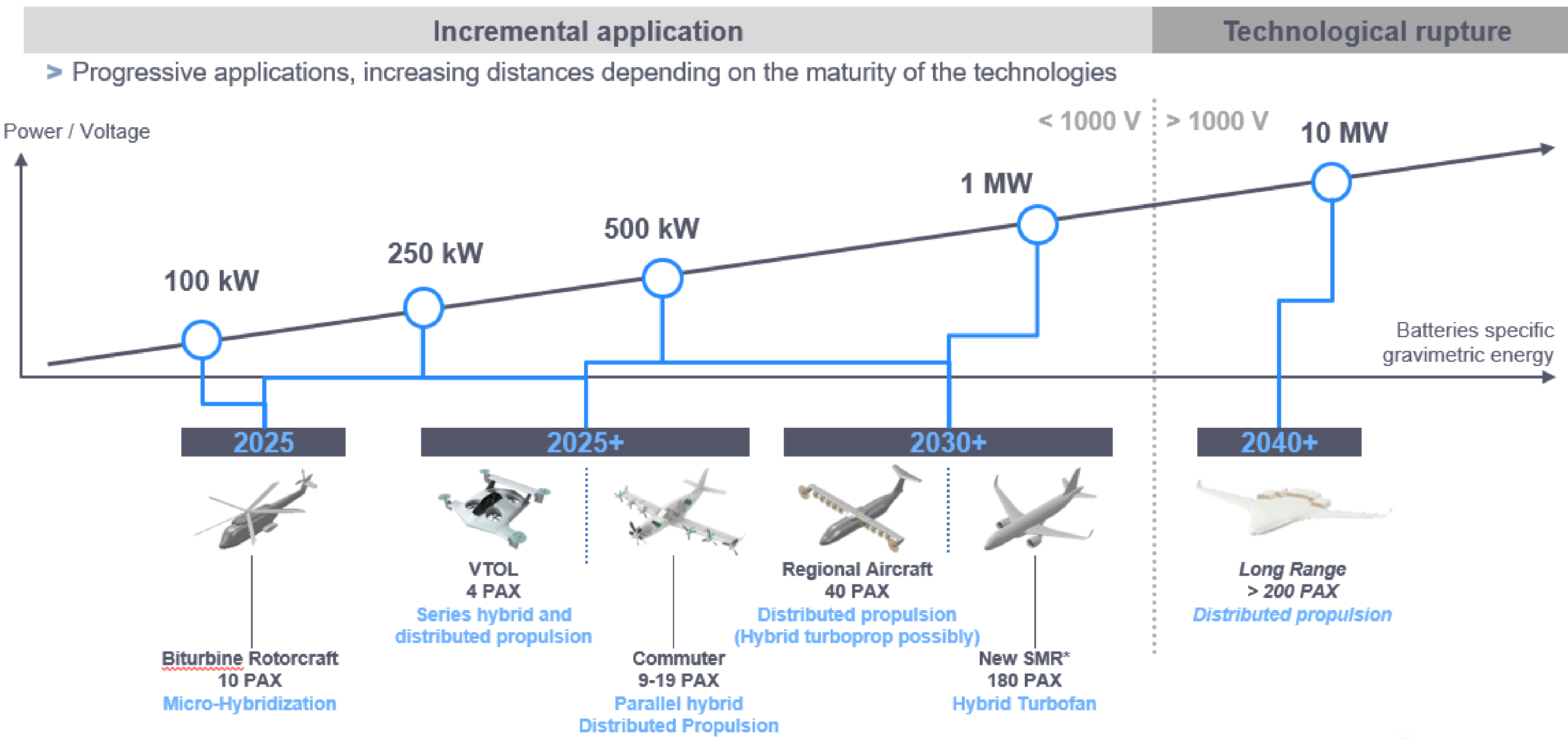
Powerplant:
3 × electric motors total 260–900 kW cruise/peak

Challenges of electrification



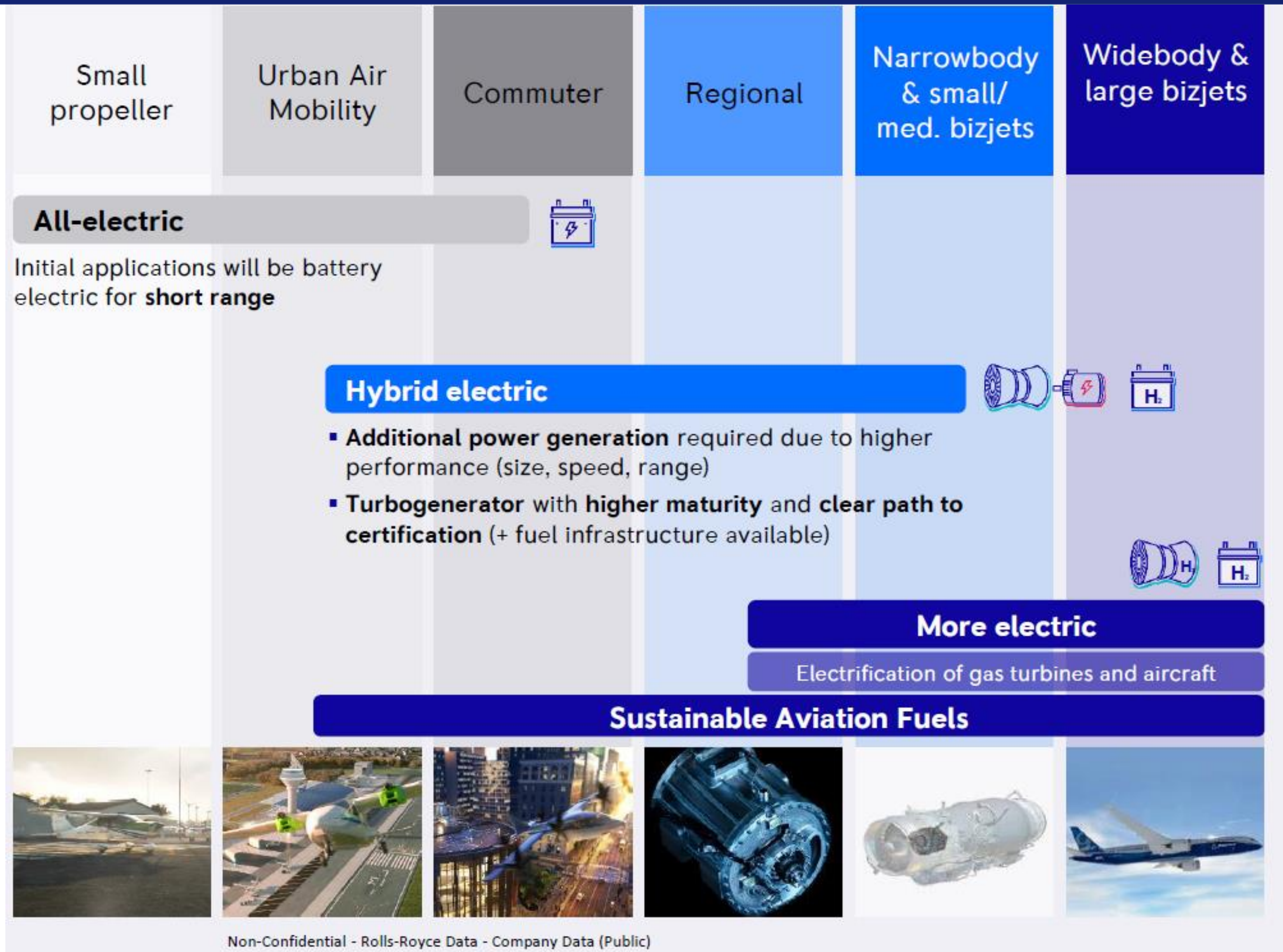
Electrification of propulsion
Safran Roadmap

Safran's vision of the progressive application of hybridization



*SMR: short medium range

Electrification of propulsion
Rolls Royce roadmap



Current studies

Table 1. Development Trajectory of Aircraft Electrification

Timing	Use case	Description	Companies
2020–2025	**Pilot Training**	• 1 pilot and 1 passenger • Cruise speed: ~125 mph	• Pipistrel • Bye Aerospace • Rolls-Royce
	General Aviation /Personal and Business	• 1–6 passengers • Average flight time: 43 minutes	• Pipistrel • Bye Aerospace
2025–2040	**Regional Commuter (<5 passengers)**	• Air taxi under 20 miles • Up to 4 passengers and 1 pilot • Closer to 50-mile range (eVTOL)	• Joby • Bell • Hyundai • Jaunt • Archer • Lillium • Elios • Beta Technologies • Many others (Blain 2020)
	Light Air Cargo	• Maximum payload: 7,500 pounds • Cruise speed: ~200 mph • Custom cargo deliveries (e.g., United Parcel Service, medical products, and military)	• Ampaire • magniX • Beta Technologies
	Regional (<15 passengers)	• Up to 15 passengers for scheduled and/or unscheduled operations/Federal Aviation Administration (FAA) Part 121 Commuter air service	• Ampaire • Eviation (Reid 2019); Siemens/magniX (2022) • magniX
2040–2050	**Commercial Aircraft**	• 186-seat electric aircraft	• Wright/EasyJet (2030)