TAS Astro
Power conditioning

Laurent GAJEWSKI

13th December 2022

DEFENCE AND SPACE

AIRBUS

Agenda

9:à0 – 10:00:	**From mission to electrical power subsystem**
10:00 – 10:15:	**Coffee break**
10:15 – 11:15:	**Power conditioning**
11:15 – 11:30	**Coffee break**
11:30 – 12:30:	**Power conditioning** **Distribution – Protection (optional)** **Quizz (optional)** **Summary**

About the presenter

- **Laurent GAJEWSKI**

System engineer for phase E2, since 2018

ADS expert pool for Power and Electrical aspects (10 years experience)

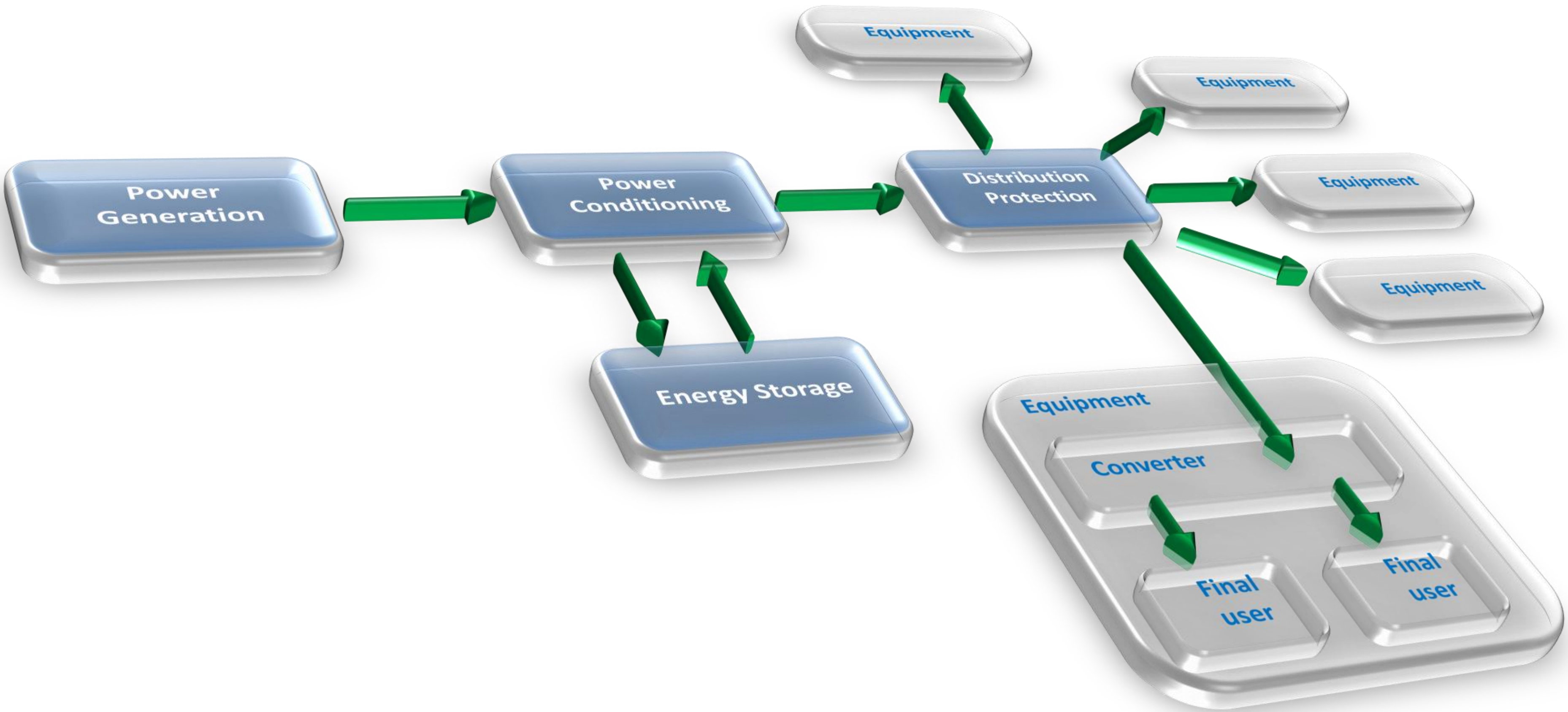
- **Experience:**
  - Airbus Defence & Space (2008 – 2022)

- **Education:**
  - ENSEEIHT engineering graduation / CHALMERS university (Gothenburg)
  - Power engineering
  - System control

Acronyms

Solar Array	**SA**
Power SubSystem	PSS
Solar Array	SA
Electrical Power Subsystem	EPS
Power Management And Distribution	PMAD
Solid State Power Controller	SSPC
Depth Of Discharge	DOD
State Of Charge	SOC
Battery Discharge Regulator	BDR
Battery Charge Regulator	BCR
Sequential Switching Shunt Regulator	S3R
End Of Charge	EOC
End of Discharge	EOD
End Of Eclipse	EOE
Beginning Of Eclipse	BOE
Beginning Of Life	BOL
End Of Life	EOL
Converter	CV

Scope



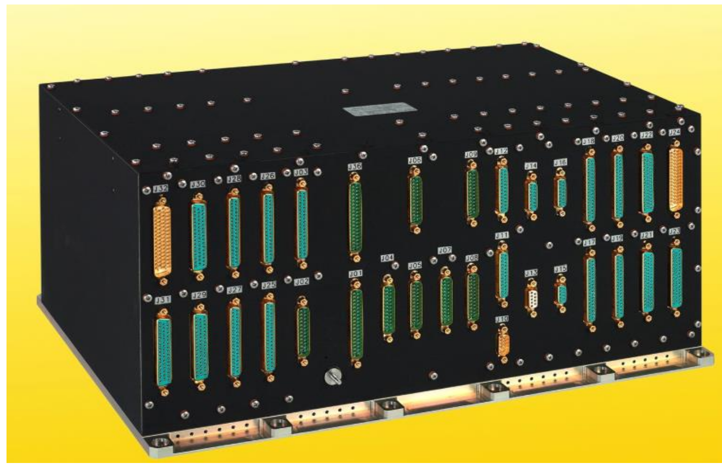
Power Generation
Power Conditioning
Energy Storage
Distribution Protection
Equipment
Equipment
Equipment
Equipment
Equipment
Converter
Final user
Final user

Scope

POWER CONDITIONING

- ✓ All that is necessary for adapting the primary and / or secondary sources to the needs of the user equipment...
- ✓ ...and ensuring the continuity of the power supply.
  - PCDU (Power Conditioning Unit)
  - PSR (Power Supply Regulator)

Telecom PSR (ADS)



PCDU (ADS)

Scope

REGULATION

- ✓ All that is necessary for maintaining a voltage or a current or a power at constant level.
- ✓ The voltage regulation may be a part of the power conditioning.
- ✓ It is generally required by the electronic circuits of user equipment.

  - S3R (Sequential Switching Series/Shunt Regulator)
  - MPPT (Maximum Power Point Tracker)
  - BDR / BCR (Battery Discharge / Charge Regulator)

Scope

DISTRIBUTION

- ✓ All that contributes to carrying the conditioned electric power to the users.
- ✓ Generally includes the switch on / switch off capability.
- ✓ Generally excludes the harness.

  - PDU (Power Distribution Unit)
  - DRU (Distribution and Regulation Unit)

Scope

PROTECTION

- ✓ All that contributes to preventing the propagation of faults between users via the common point represented by the power system.

- ✓ The compatibility of users in terms of perturbations generated / suffered is a matter of EMC in conducted mode.
  - SSPC (Solid State Power Controller)

Scope

IMPORTANCE OF SOURCES

- ✓ **The solar array and the battery together represent about 80 to 90% of the mass and the cost of a power system.**
- ✓ **The performance of a power system for a given mission therefore depends largely on the best possible use of sources.**
- ✓ **The interactions of the EPS with the rest of the satellite are such (mechanical, thermal, launch) that the global optimisation must be made at the level of the complete system:**
  - Mass : Launch costs, propellants, inertia (SA) ...
  - Dissipation : Radiative surfaces
  - Solar array (SA) surface : AOCS perturbations

Scope

IMPORTANCE OF SOURCES

- ✓ **For the solar array, the objective is to maximise the specific power of the source (W/kg & W/m²).**

- ✓ **For the battery, the objective is to maximise the specific energy of the source (Wh/kg & Wh/l).**

FROM MISSION TO ELECTRICAL POWER SUBSYSTEM

From mission to electrical power subsystem

The mission has an influence onto the EPS through

- ✓ **The orbit (low orbit (LEO), sun synchronous (SSO), geostationary (GEO), elliptic, interplanetary...)**

  Illumination (Sun distance, eclipse regime), Radiations (Van Allen belts, solar flare...)

- ✓ **The mission duration (from few minutes to several years)**

  Total radiation dose, total energy to deliver, reliability

- ✓ **The nature of the payload**

  Average and peak consumption, Transients, Attitude constraints...

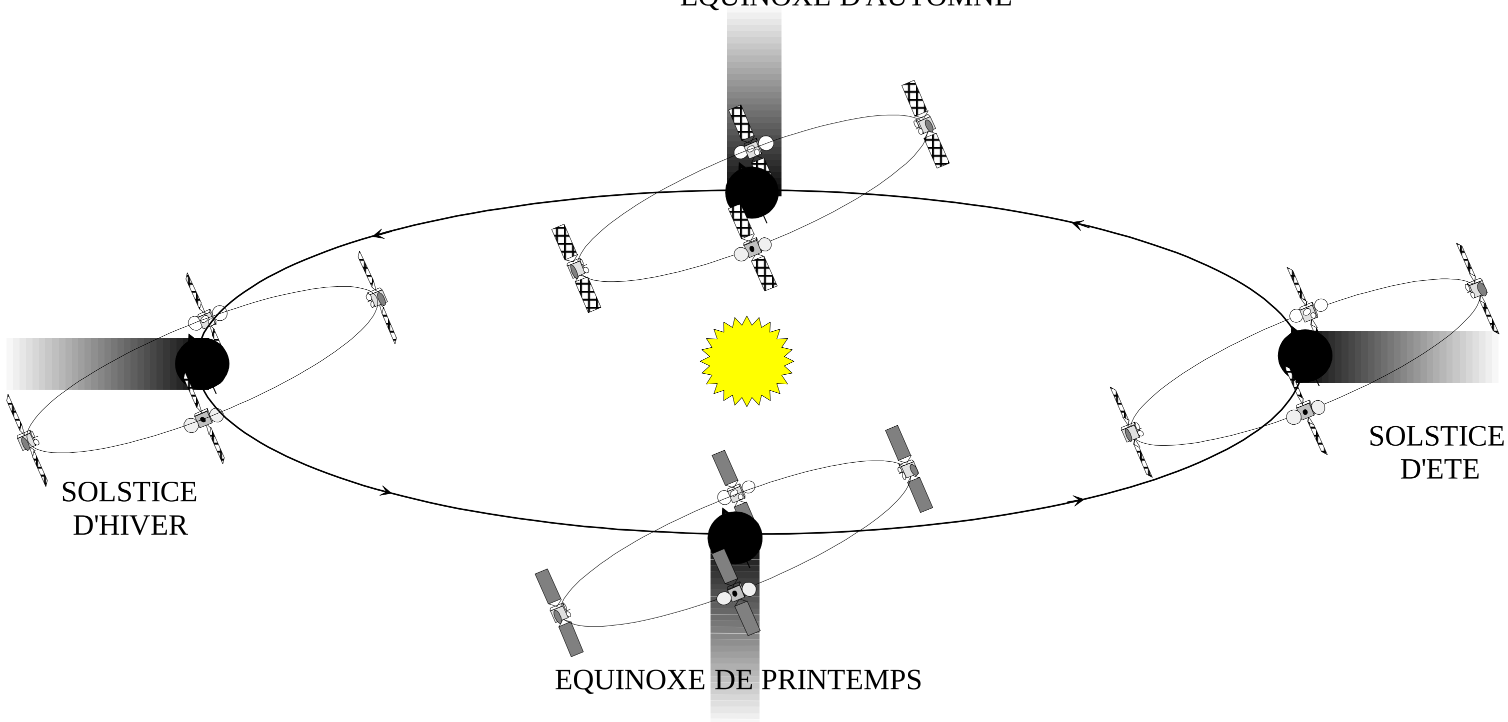
- ✓ **The available budget**

  Reliability, safety, autonomy

From mission to electrical power subsystem

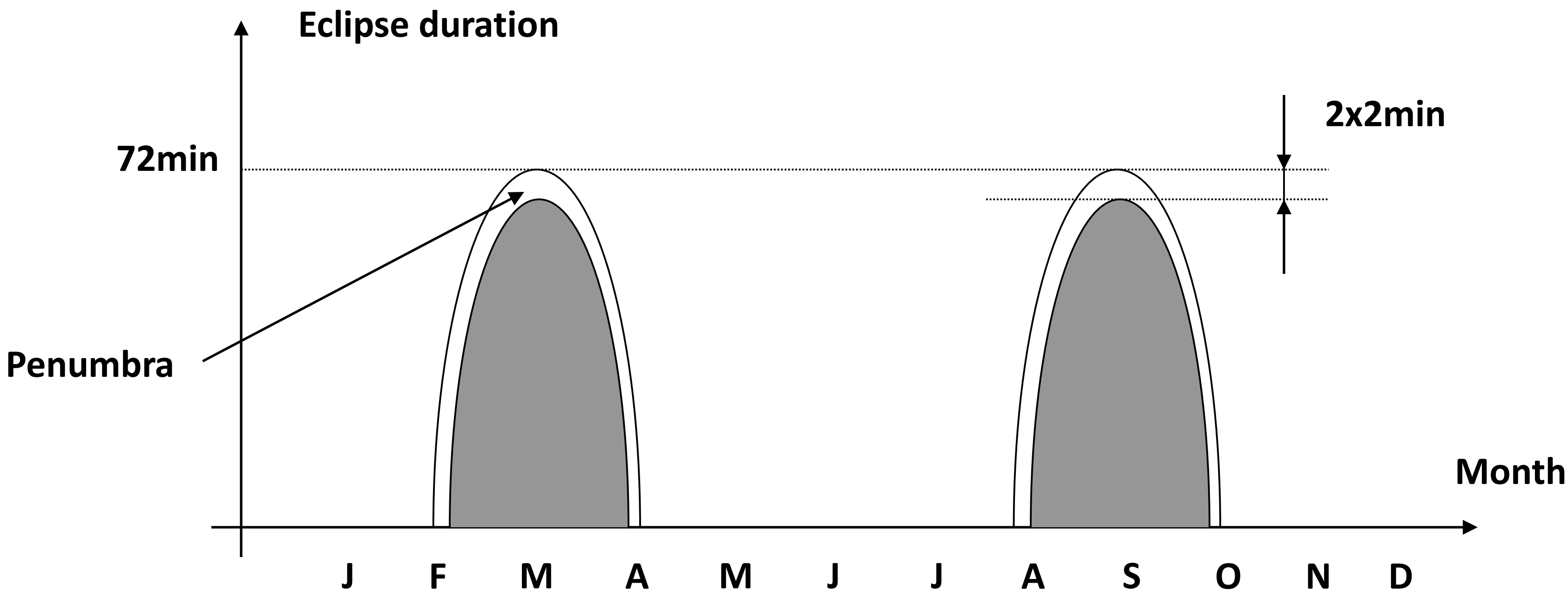
Orbit Influence - Geostationary orbit (GEO) - Telecommunication

Seasons and eclipses



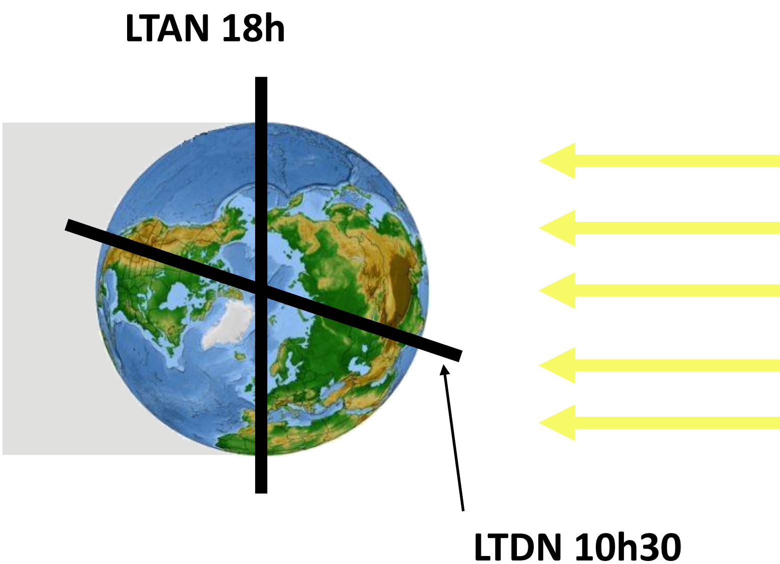
From mission to electrical power subsystem

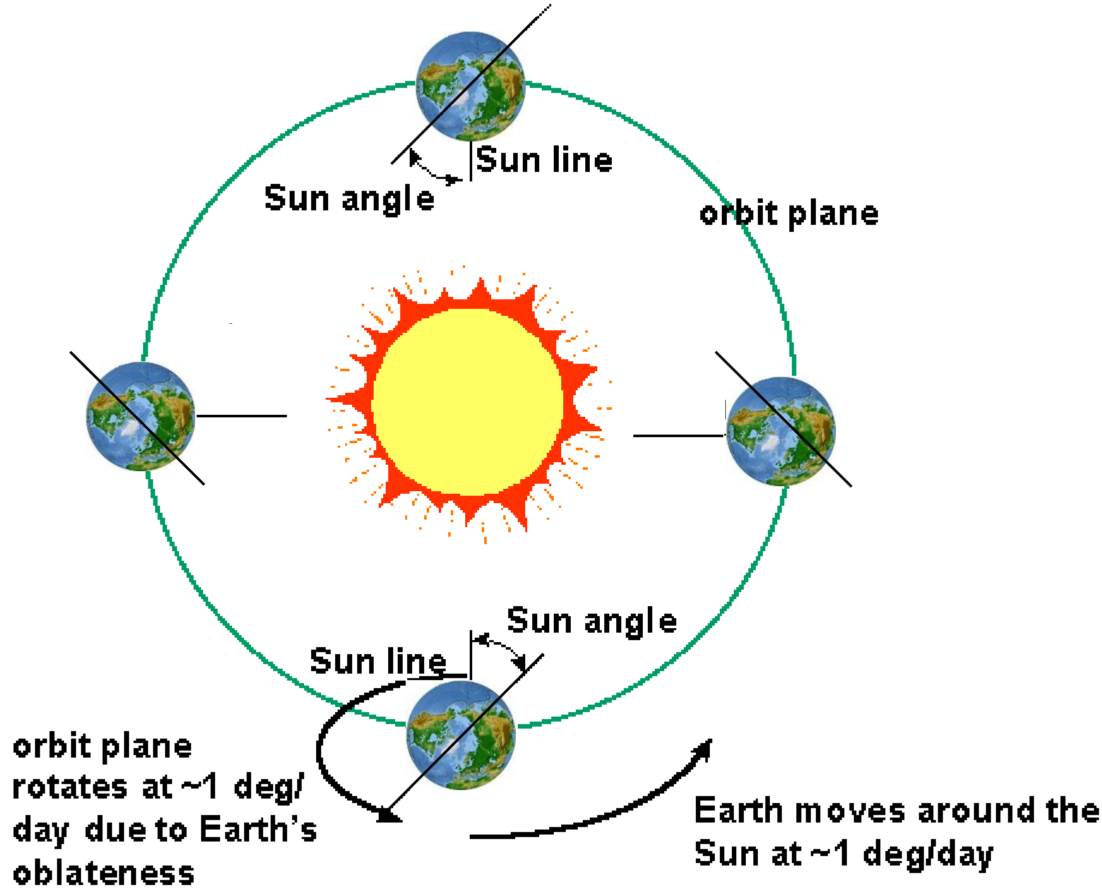
Orbit Influence - Geostationary orbit (GEO) - Telecommunication



From mission to electrical power subsystem

Orbit Influence – LEO Sun synchronous orbit – RADAR & Observation





From mission to electrical power subsystem

Orbit Influence – eclipses number

✓ **GEO** orbit (0° of inclination) encounters each year two eclipses seasons of 45 days centred at equinox

- **90 eclipses per year x 15 years = 1350 cycles**

✓ **LEO** orbits experiment a number of eclipses that depends on altitude and LTAN but that is most often close to 5000 per year

- **SSO 10h-22h, 5300 eclipses per year x 10 years = 53000 cycles**

From mission to electrical power subsystem

Orbit Influence – eclipses duty cycle

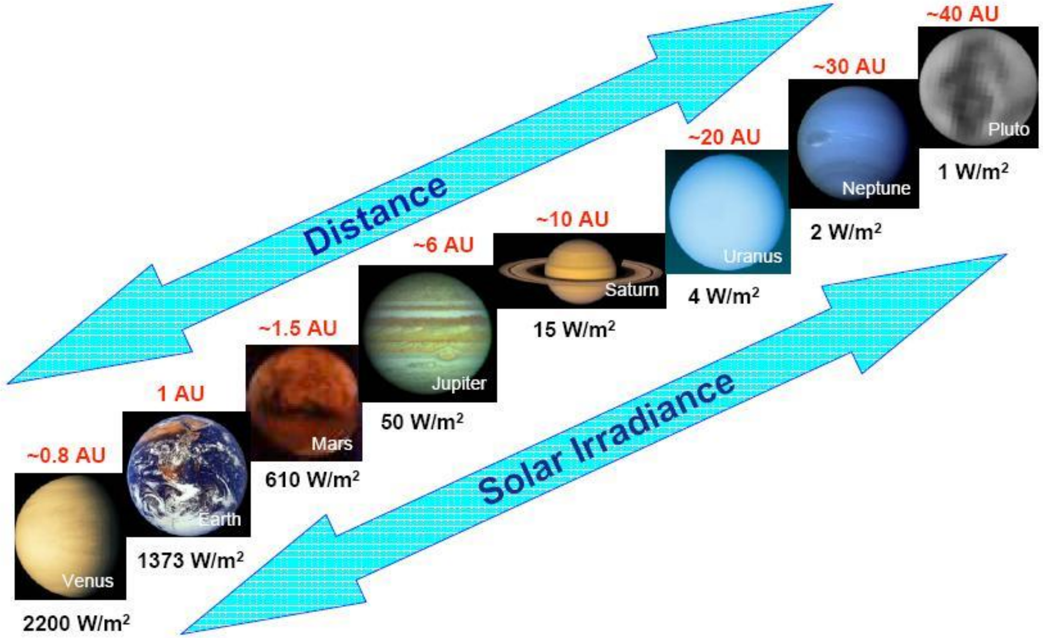
- ✓ On **GEO**, a battery that delivers power to the satellite during 1.2 hours has 22.8 hours available to charge. Including efficiency aspects and margins, **charging power corresponds to approximatively 10% of the S/C consumption.**

- ✓ On **LEO**, a battery that delivers power to the satellite during 35 minutes has 65 minutes available to charge. Including efficiency aspects and margins, **charging power is of the same order of magnitude as the total spacecraft consumption.**

From mission to electrical power subsystem

Orbit Influence – solar flux illumination

- ✓ The solar flux is around **1372 W/m² in Earth environment (@ 1 AU)** outside atmosphere and is varying in inverse proportion to the square sun distance
- ✓ **Solar array up to Jupiter, beyond RTG**
- ✓ Around Earth, season effect between **1320W/m² and 1420W/m²**



From mission to electrical power subsystem

Power consumption

✓ Average power consumption

- Microsatellites: some tenth of watts
- Earth Observation: around kW
- Large telecommunication satellite : 10 to 15 kW
- ISSA : 100 kW and more

✓ Power consumption profile

- Very stable : direct broadcast
- Highly variable : Earth observation (predictable) or telecom constellation (unpredictable)
- Pulsed : radar : 1kW average with 10kW peaks during few seconds

From mission to electrical power subsystem

Power consumption – typical telecommunication satellite (GEO)

	Mode Normal
Payload heating	70 W
Payload	11000 W
Plasmic propulsion	1500 W
Bus heating	200 W
Power management	120 W
AOCS	115 W
OBC	60 W
TTC	115 W
Total	13110 W

From mission to electrical power subsystem

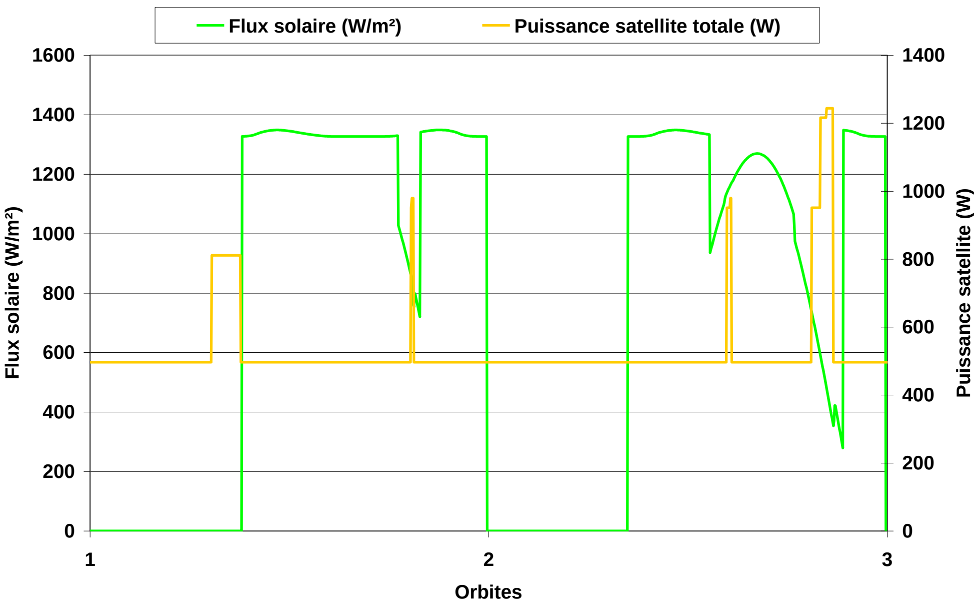
Attitude constraints

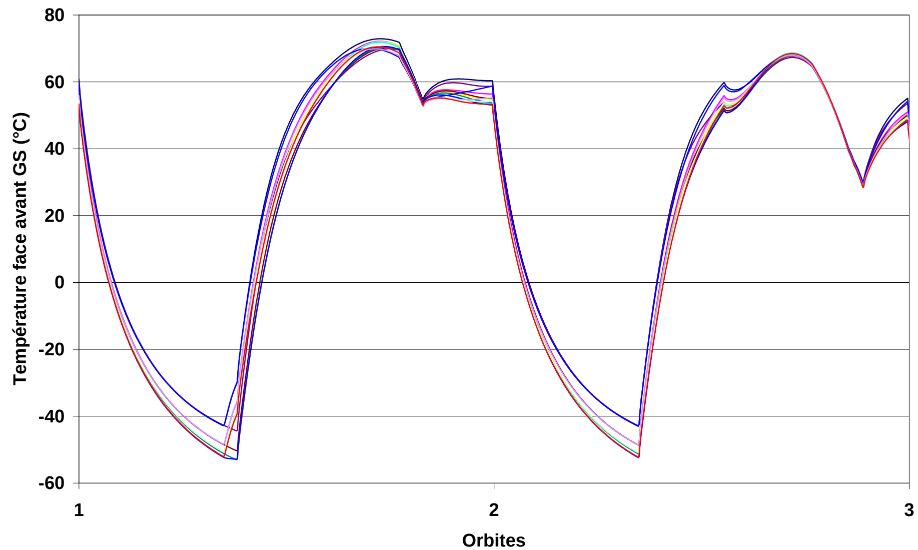
✓ The attitude has an impact over the sizing and, possibly, the choice of the primary and secondary power sources

- **First, the attitude determines the solar flux received by the solar array**
- **Consequently, the attitude plays a role on the solar array temperature and thus on the solar array performances**
- **This has a major impact on the architecture of the electrical power subsystem**

From mission to electrical power subsystem

Attitude constraints (example for agile observation satellite)





From mission to electrical power subsystem

Available budget

- ✓ **Military : Very large budgets (specially in the USA) - Reliability and availability mandatory**
  Example : GPS

- ✓ **Governmental : Large budgets (specially in the USA) - Reliability, availability and/or safety very important**
  Examples : SPOT, scientific S/C, manned missions

- ✓ **Cheaper : NASA Concept, aimed at scientific applications - Failure is accepted**
  Examples : success : Mars Pathfinder/Sojourner

- ✓ **Commercial : Budget imposed by the business plan - Reliability and availability important**
  - Examples : direct broadcast S/C, telecom constellations, export

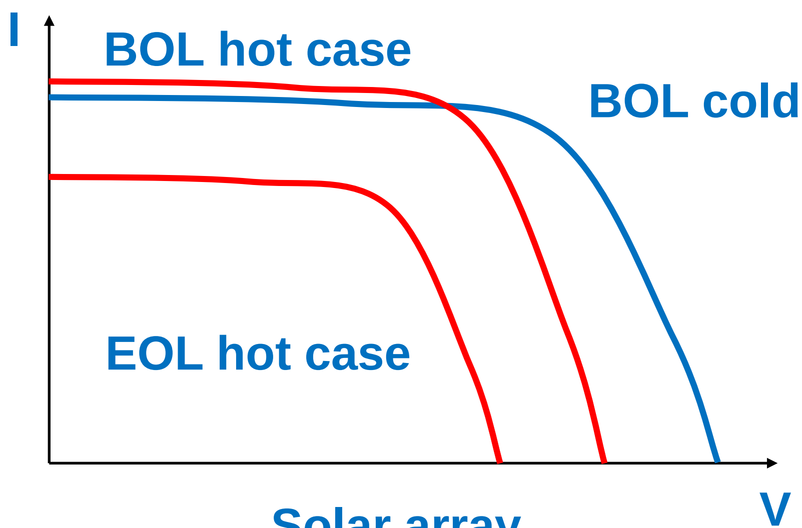
- ✓ **Amateur : "Shoe string" budget - pragmatic approach**
  - Examples : Microsats, Students satellites, Beagle 2 , Cubesat, Nanosat,…...

POWER CONDITIONING

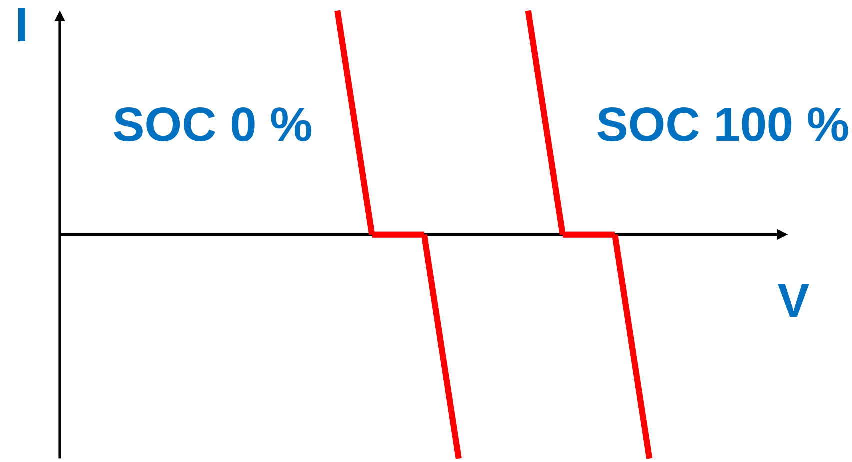
Power Conditioning

- **Everything that is necessary to adapt primary and secondary sources to the needs of user equipments...**

- **...and guarantee the continuity of the electrical energy delivery**



Solar array



Battery

Power Conditioning

WHAT ARE THE USERS?

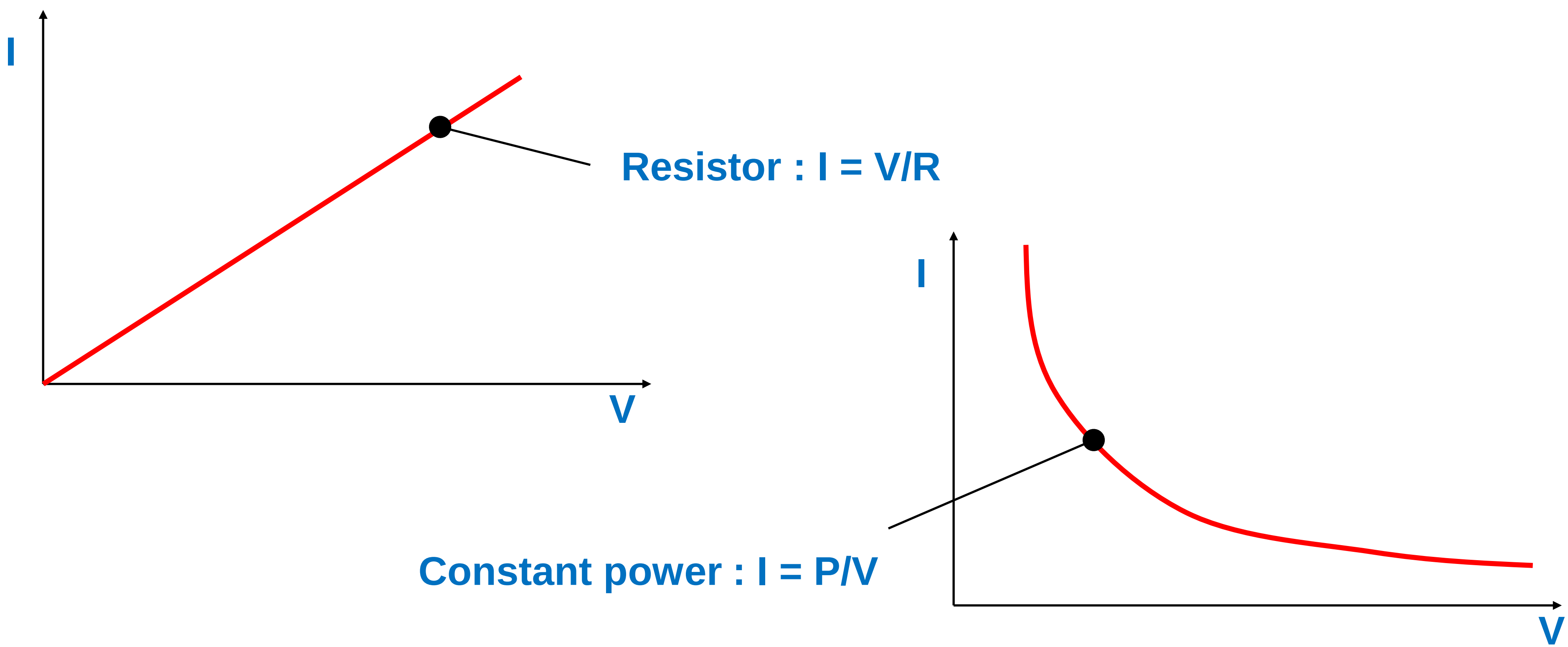
- ✓ **Resistances**
  - Heaters
  - Magneto-couplers
  - Solenoid valves (when they are established)

- ✓ **Constant intensity dissipators**
  - Rare, but of academic interest !

- ✓ **Constant power dissipators**
  - All the equipment containing a converter
    - at CV output, in a given mode, the circuits (cards) consume a constant current under a regulated voltage => constant consumption
    - The efficiency of the converter varies little depending on the input voltage
    - Therefore, the input consumption in a given mode is roughly constant

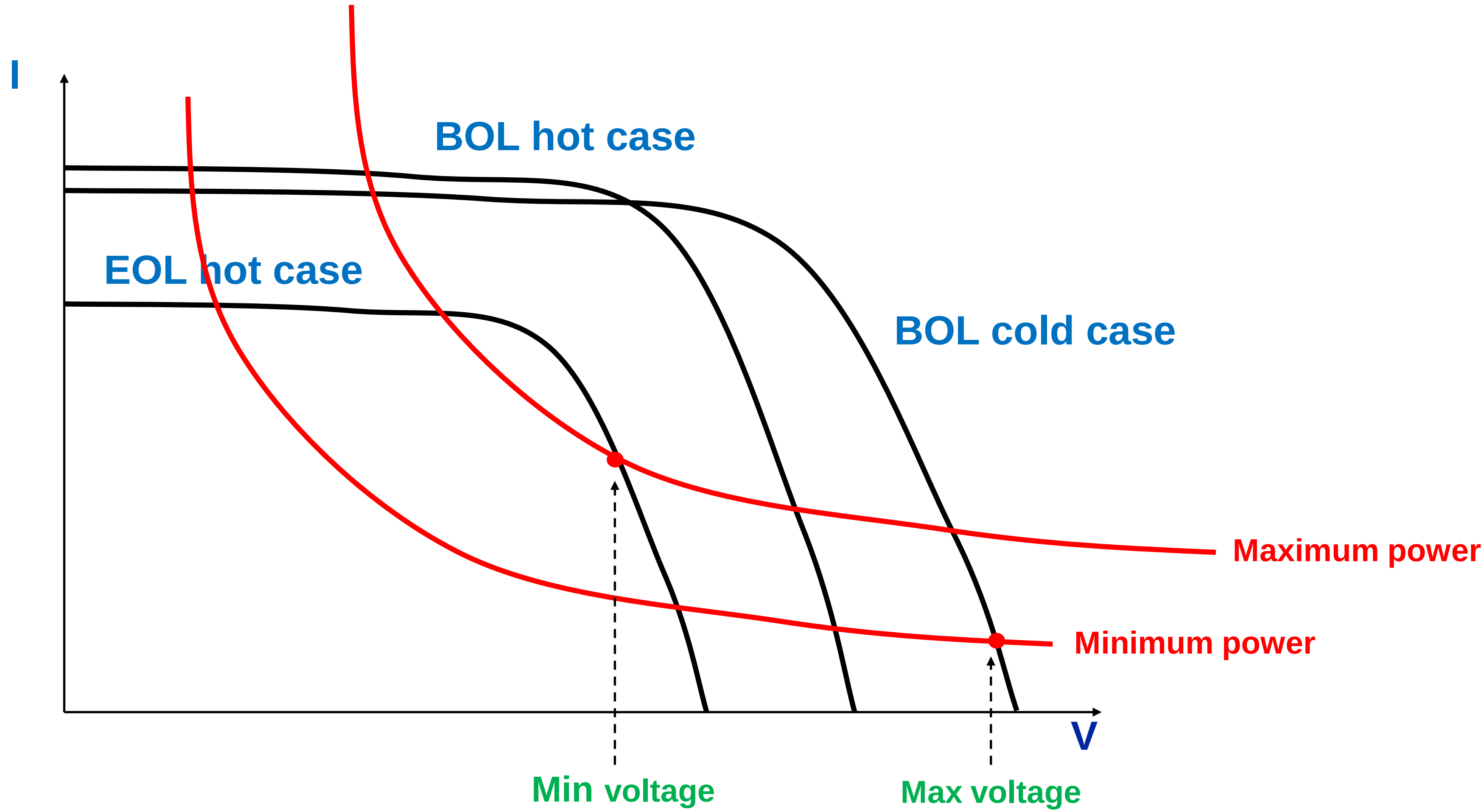
Power Conditioning

CHARACTERISTICS OF THE USERS



Power Conditioning

EXAMPLE OF COHABITATION



Power Conditioning

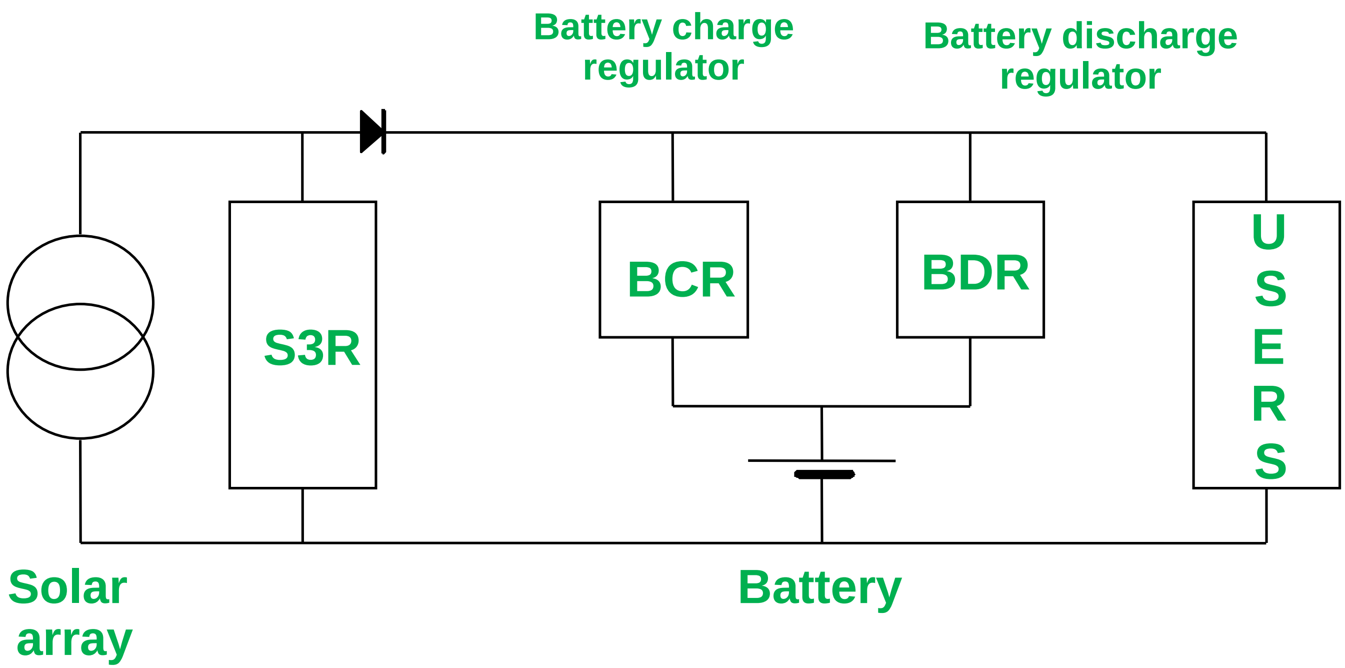
TOPOLOGIE

- ✓ It is **the detailed architecture of the power system**
- ✓ The **mission** and **orbit** (GEO, LEO...) has an importance influence on the choice of topology
- ✓ The « **story** » of the company, its experience and known-how has a prime importance (typically SPOT platform, Telecom platforms…)
- ✓ Adequate tools must be available to perform significant trade off, since differences between solutions are generally in the range of a few percents. These trade off must encompass all system impacts

Regulated Topology

LAYOUT DIAGRAM

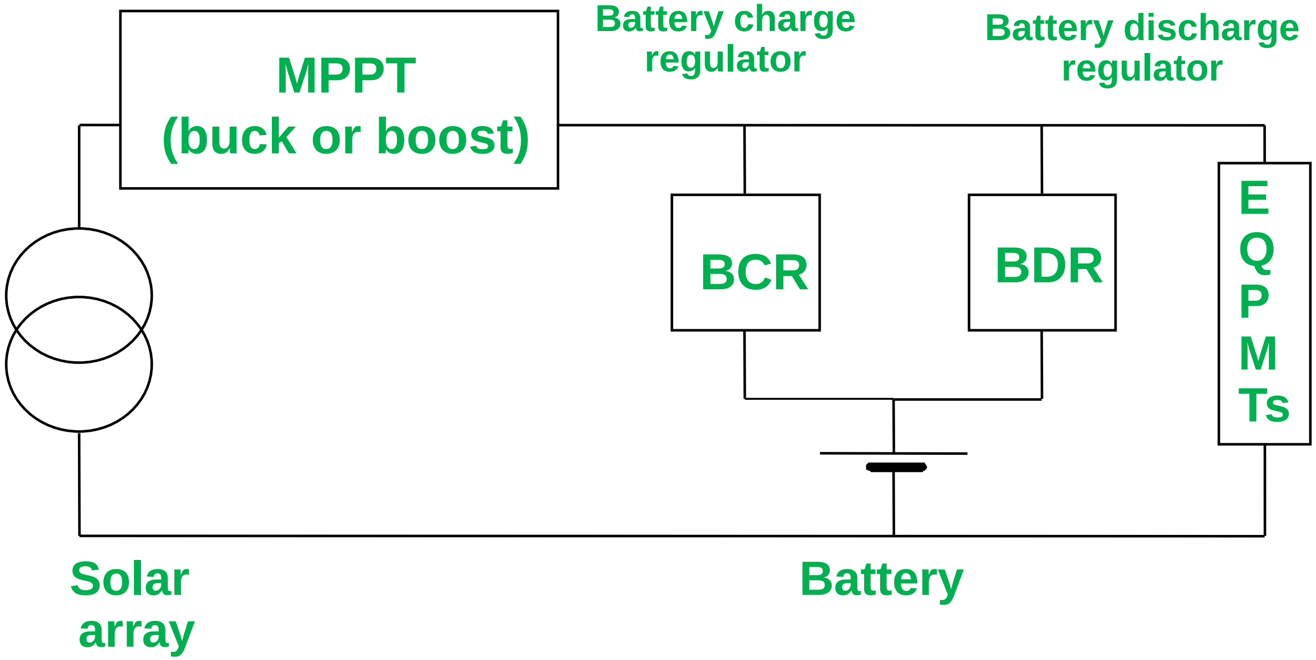
Direct Energy transfer (example using a S3R)



Regulated Topology

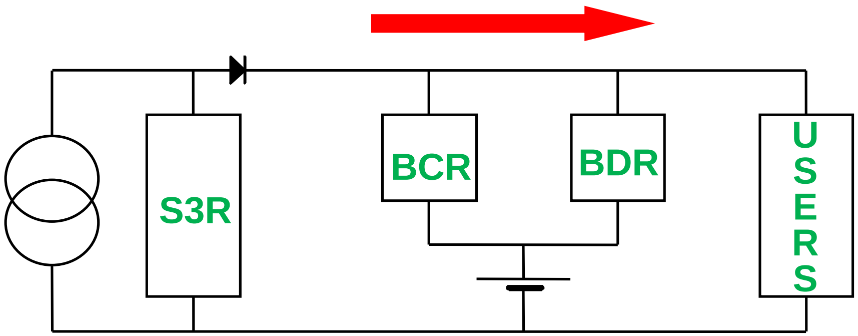
LAYOUT DIAGRAM

Maximum power point tracking (MPPT)

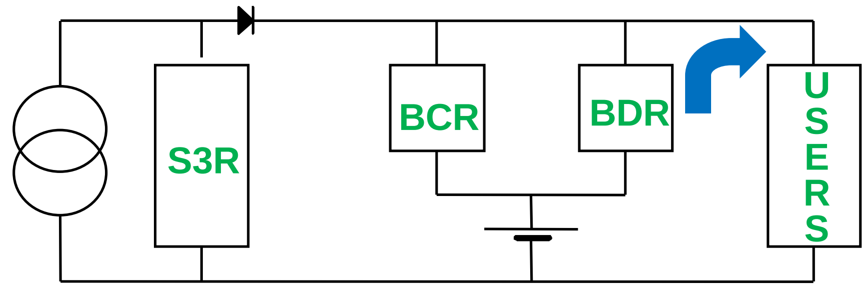


Regulated Topology

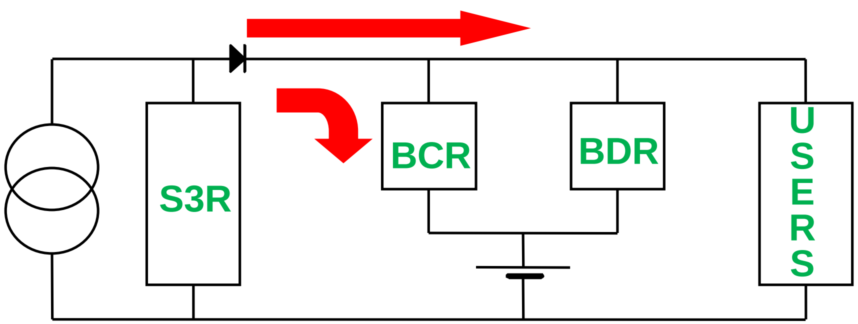
OPERATING MODES



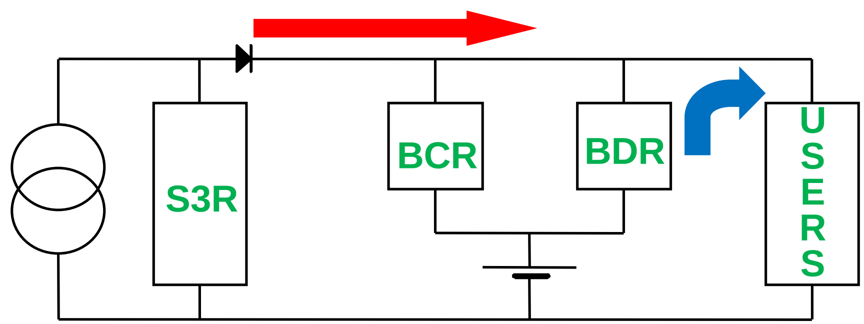
Day, battery charged



Eclipse



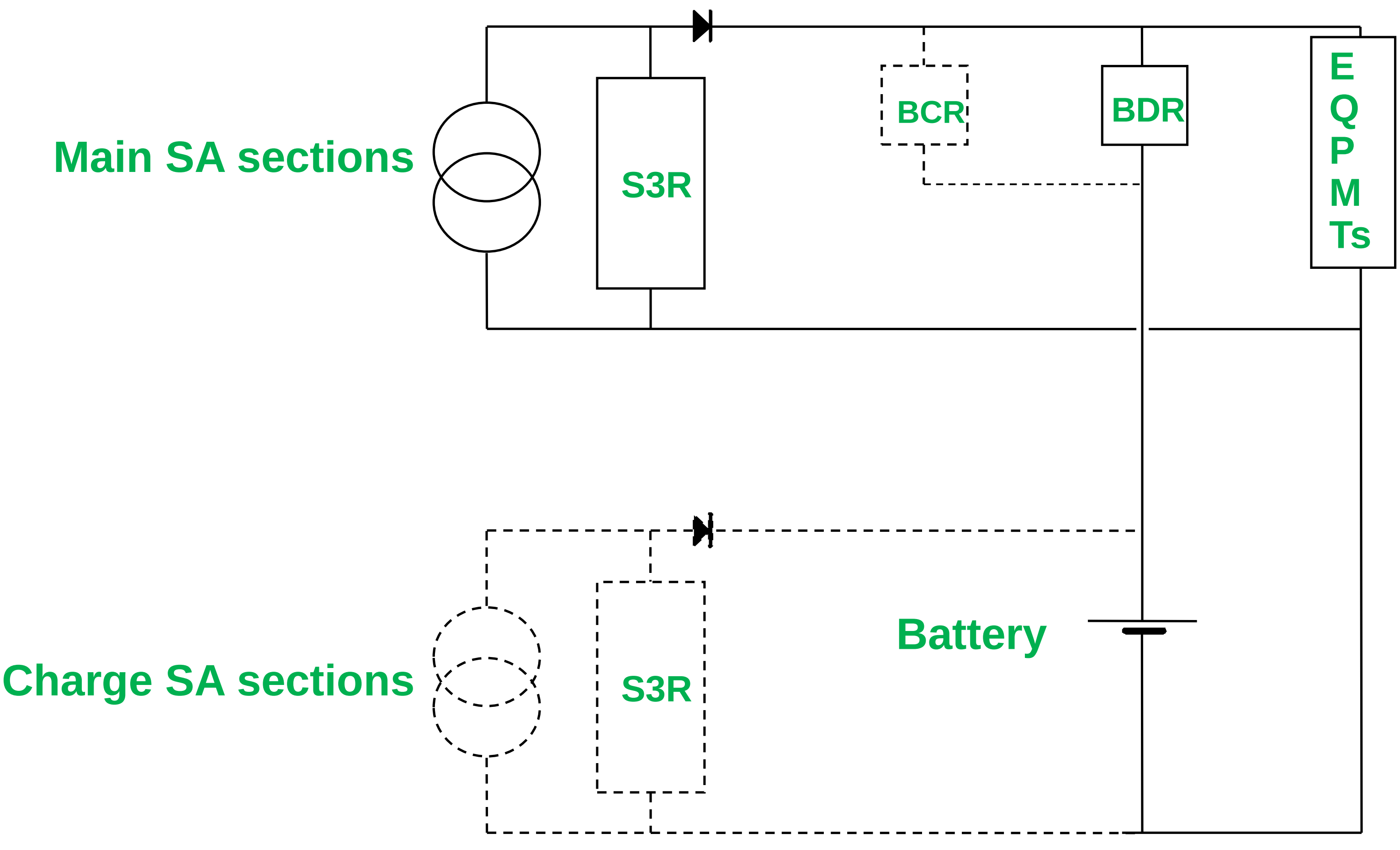
Day, battery in charge



Day, peak of power

Regulated Topology – Main solar array sections / Charge sections

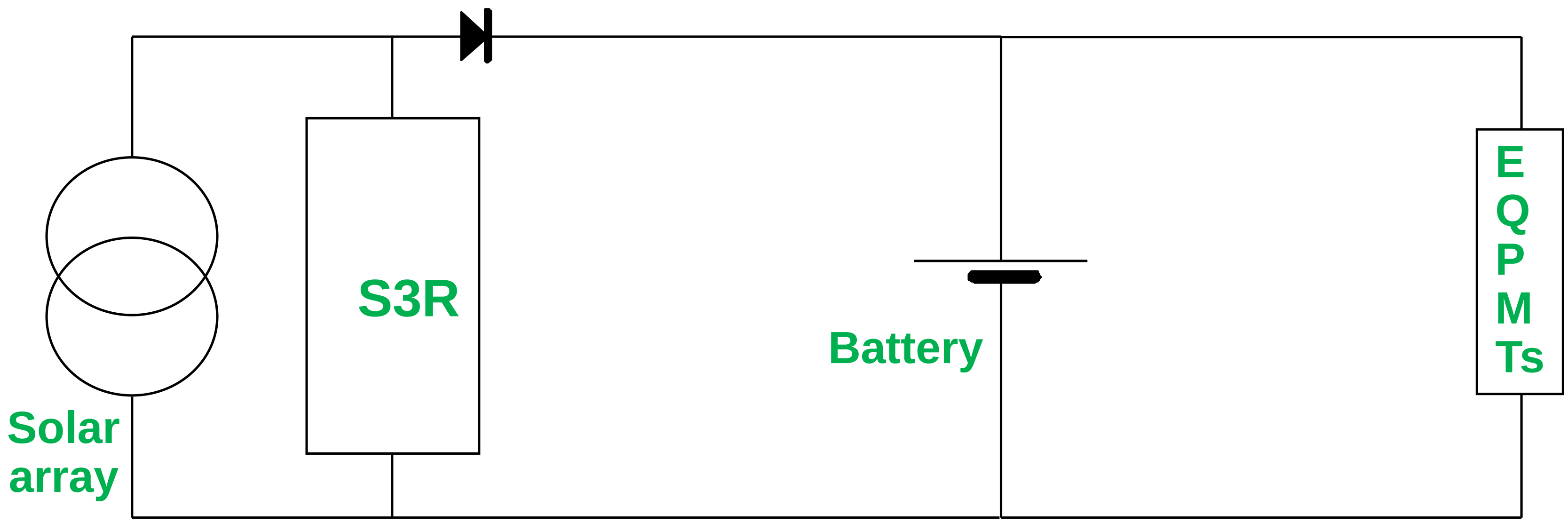
LAYOUT DIAGRAM



Battery Follower Topology

LAYOUT DIAGRAM

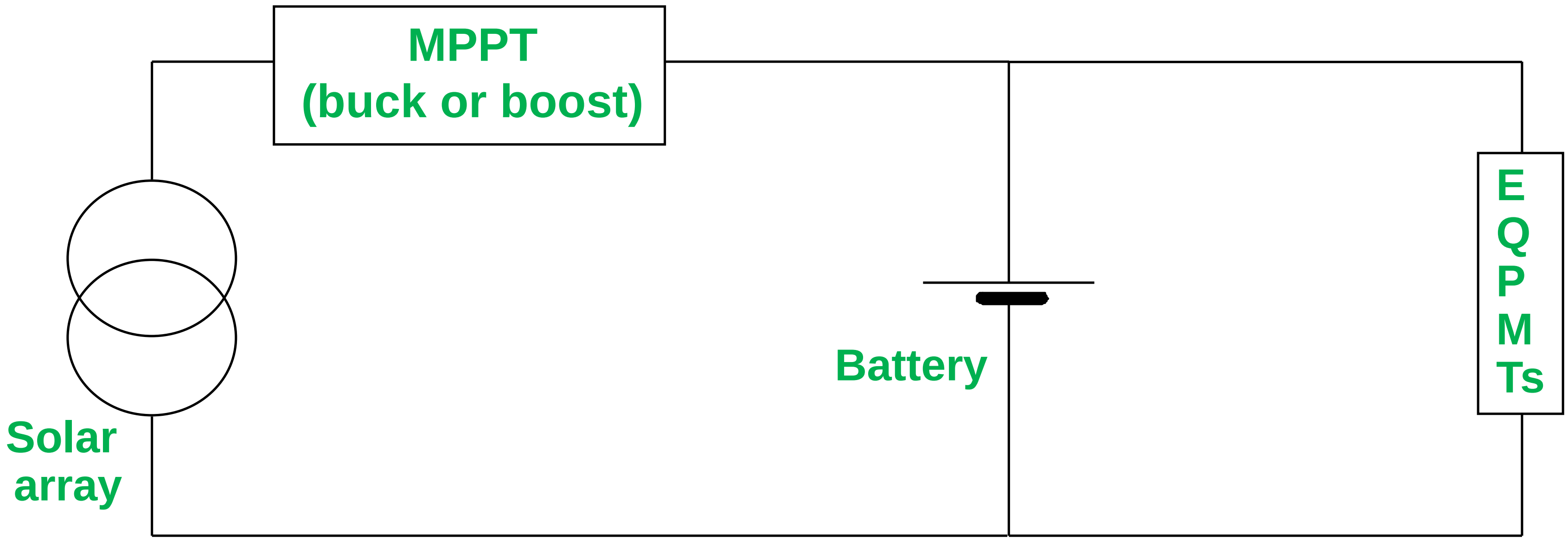
Direct Energy transfer (example using a S3R)



Battery Follower Topology

LAYOUT DIAGRAM

Maximum power point tracking (MPPT)



Topologies Trade-Off

	Battery follower	Regulated
Power conditioning	S3R: simple MPPT: complex	Complex and costly (BDR, MPPT)
Users converters	Low efficiency and mass increase	Optimal efficiency and mass
Peak power capability	Good	Good
Solar array maximal power operation	S3R: Good, if solar array correctly sized MPPT: optimal	S3R: Good, if solar array correctly sized MPPT: optimal
Battery and solar array design flexibility	Weak	Good
Applications	LEO, high solicitations of the battery	All missions, all power

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Topologies Trade-Off

This academicals trade-off is actually limited to 2 families of architectures :

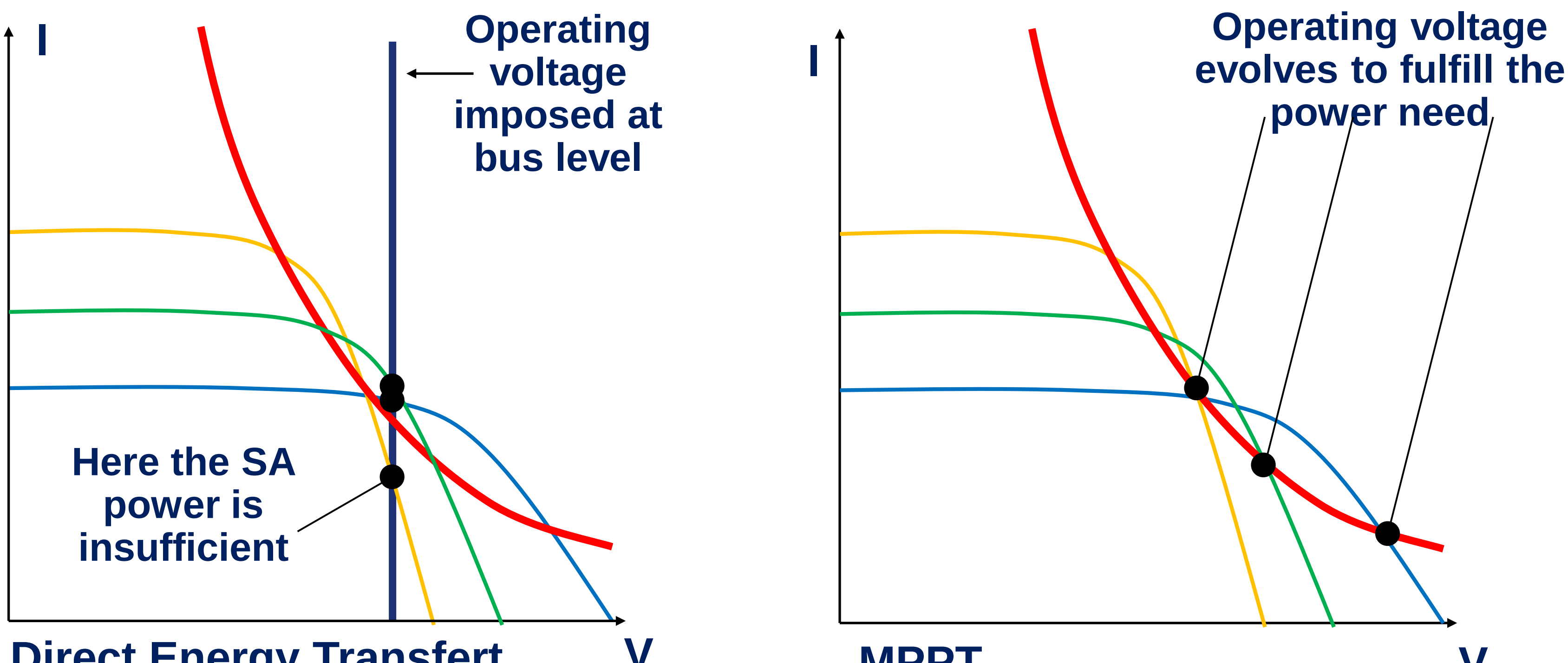
- **Battery follower: use particularly in LEO**
- **Regulated: used particularly in GEO and interplanetary**

Trade-off are focussed on the capability of the power system to extract the maximal power of the solar array

- **MPPT or DET regulators ?**

MPPT or DET ?

OPERATION AT SOLAR ARRAY MAXIMAL POWER



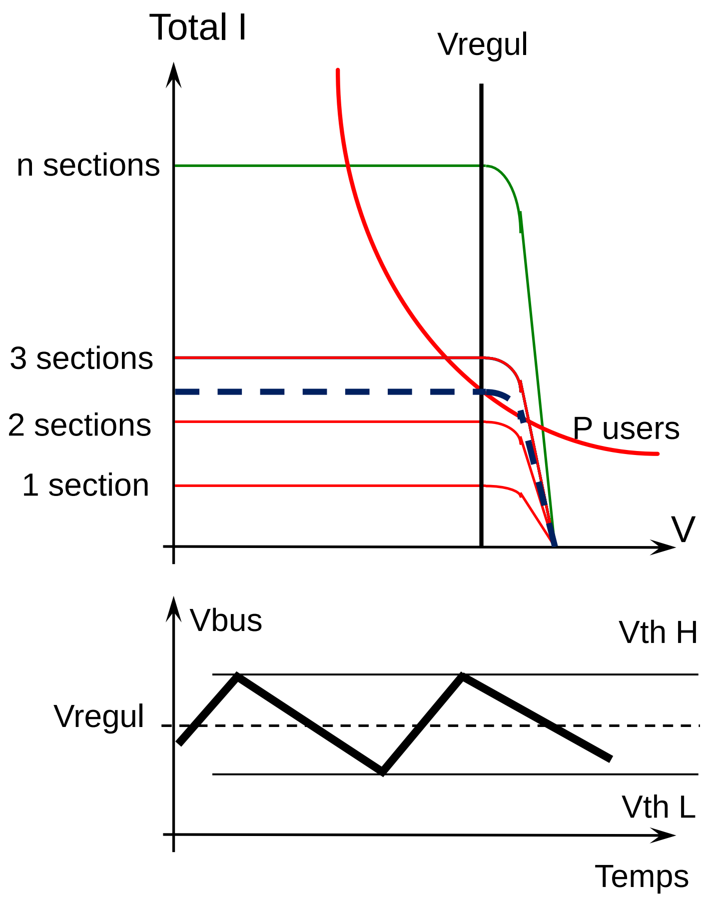
Direct Energy Transfert

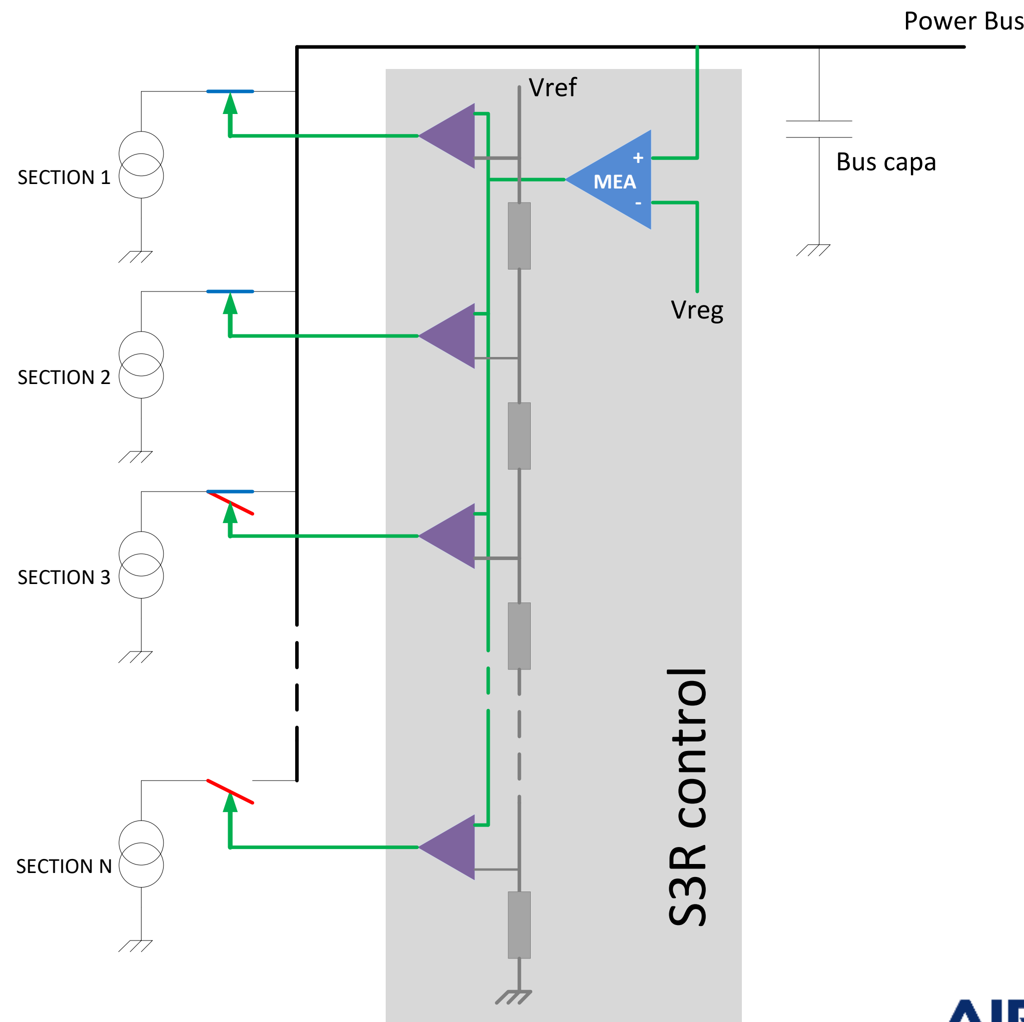
MPPT

DEFENCE AND SPACE

DET (Direct Energy Transfert)

S3R (SEQUENTIAL SHUNT/SERIES SWITCHING REGULATOR)





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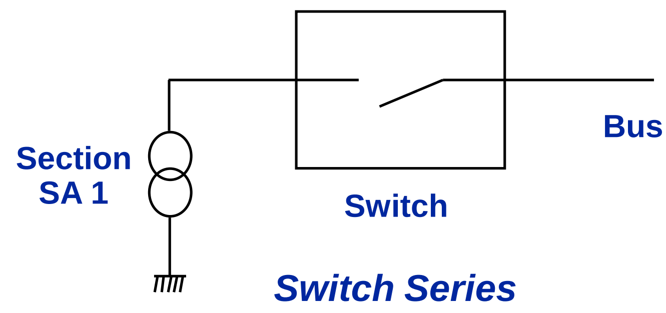
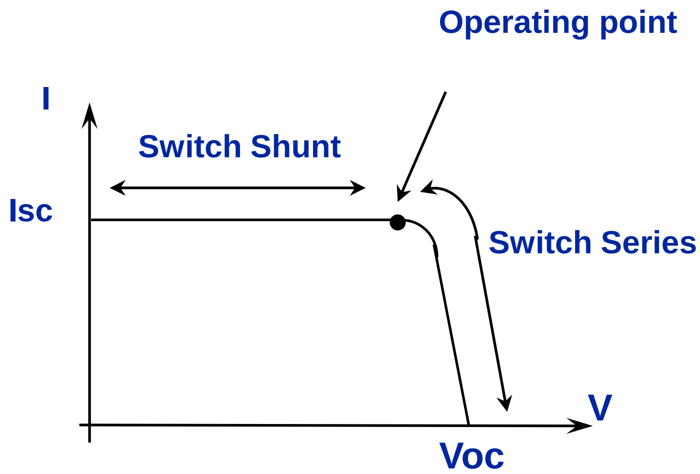
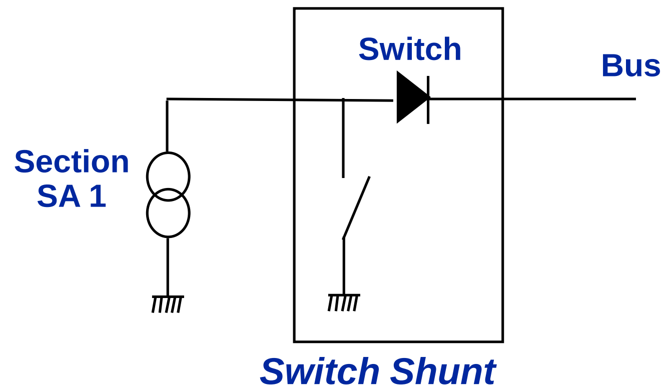
DET (Direct Energy Transfert)

S3R (Shunt or Series?)

- Operating SA voltage and constraints on Mosfet more important on series conf.
- The constraints due to SA capacitance are different
- Best efficiency in series than in shunt (based on state of the art) (losses Mosfet < losses diode)



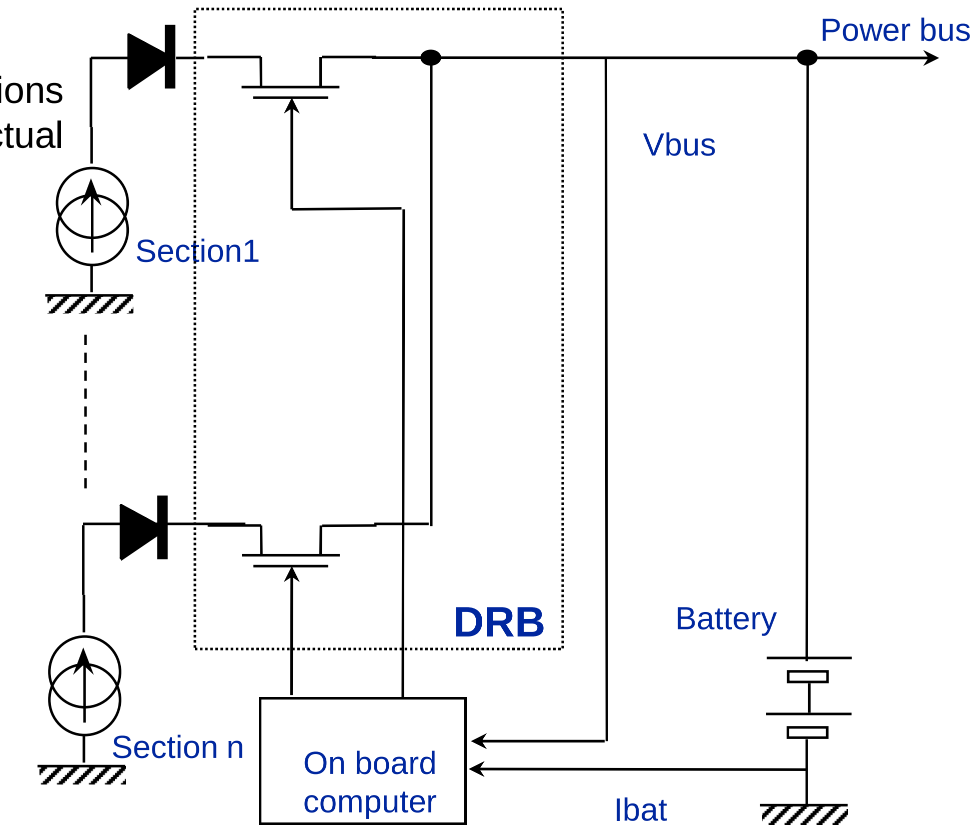




DET (Direct Energy Transfert)

Digital serial regulator (S2R)

- The on board computer adjusts the number of sections on the bus depending on actual Vbat +/- hysteresis
- Frequency of few Hz
- Only suitable for battery follower
- Flexible thanks to on board computer
- Maximal efficiency and low power dissipation



MPPT (Max Power Point Tracker)

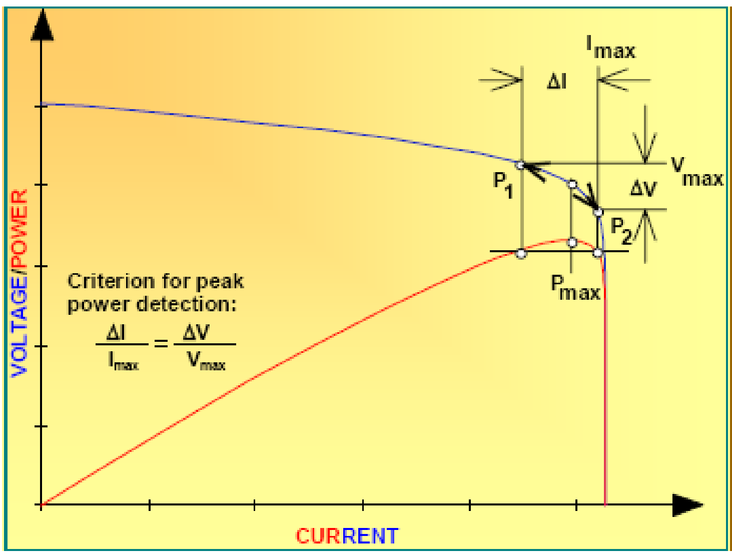
MPPT description

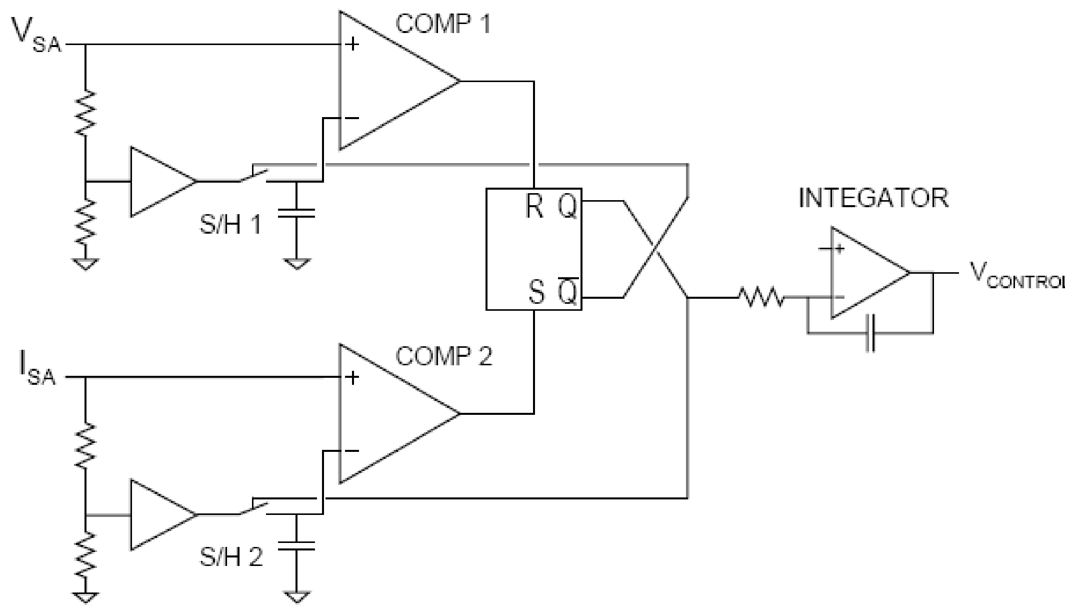
- **DC/DC converter which adapts the solar array voltage to its maximal power point voltage (Vmp) if needed**
- **Can work in buck (SA operating voltage higher than bus voltage) or boost (SA operating voltage lower than bus voltage)**
- **MPPT includes an algorithm for maximal, power tracking at low frequency (typically cents of Hz)**

MPPT (Max Power Point Tracker)

MPPT tracking principle

- **Pmax if dP=0, i.e. if dV.I+V.dI=0 ⇔ si dV/V=-dI/I**
- **Solar array voltage is oscillating around Vmp**





MPPT (Max Power Point Tracker)

MPPT: buck or boost?

- Generally the bus is non regulated 22V – 37V
  - Boost : Vmp shall be always lower than 22V (not optimal efficiency for boost compared with buck)
  - Buck : Vmp shall be always higher 37V (n cells in series, constraints on the maximal voltage)
- Mission around Mercury, SA temperature up to 200°C
  - Boost : At the beginning of the mission (around Earth), the SA temperature is usual and then around Mercury it is higher (SA voltage reduced).
- Mission around Mars, SA temperature lower than around Earth
  - Buck : At the beginning of the mission (around Earth), the SA temperature is usual and then around Mars it is lower (SA voltage increased).

MPPT or DET?

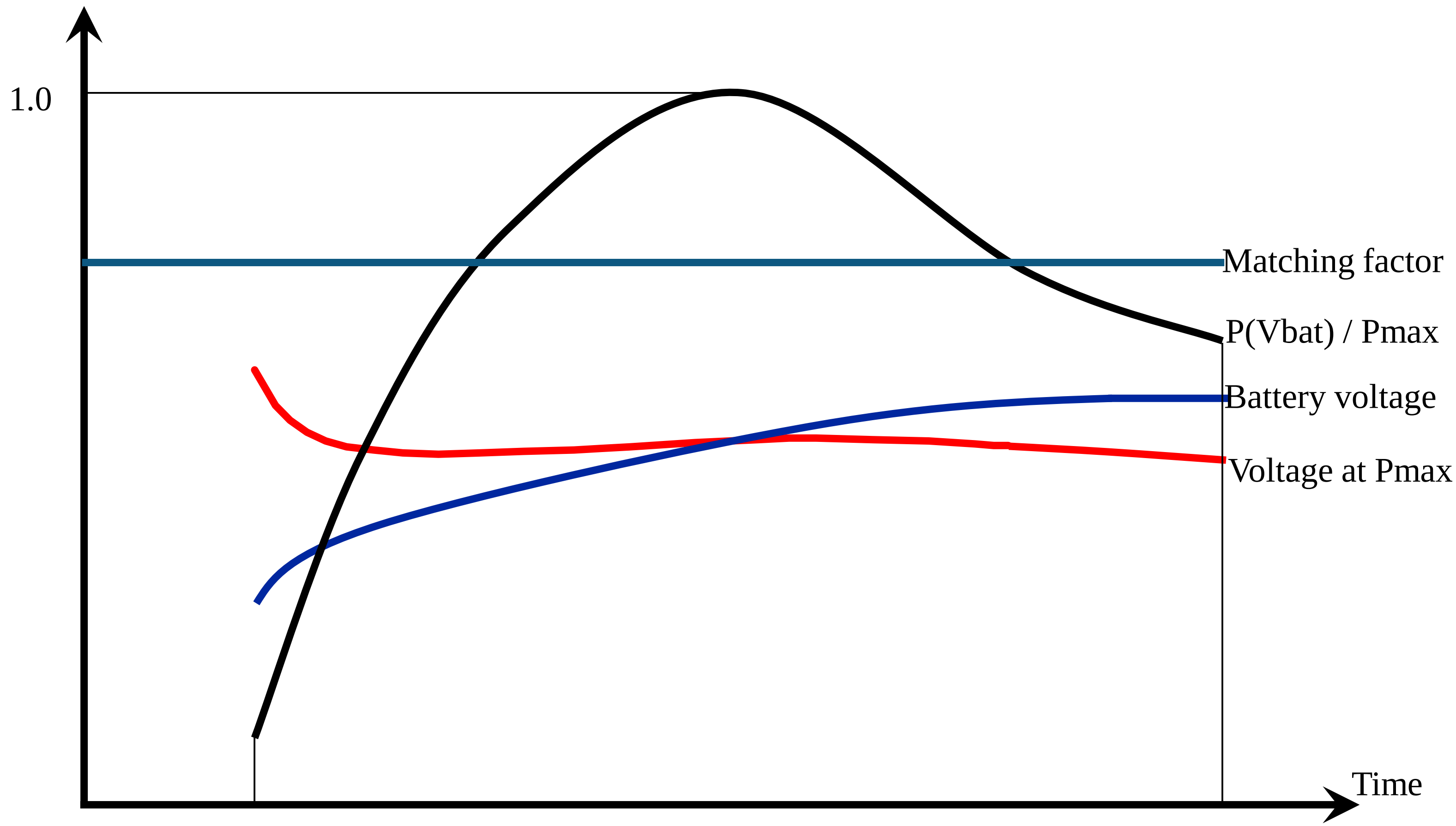
Adaptation coefficient (or matching factor)

- **The solar array temperature is varying over the orbit according to :**
  - the received fluxes (Planet infrared, solar flux, albedo)
  - the fluxes variation due to satellite attitude
- **Consequently, the solar array electrical characteristics and especially the maximal power point are varying**
- **SA adaptation coefficient (matching factor) is the ratio between :**
  - the energy effectively delivered
  - the energy which could have been delivered at Pmax

► **SA matching indicates the real use of the Solar Array**

MPPT or DET?

SA Matching factor - Example in DET on battery follower tapology



In this example, the voltage drop (losses) between SA and battery are neglected. It is assumed that battery voltage is equivalent to SA voltage operating point

MPPT or DET?

SA Matching factor - Conclusions

- **In DET, the SA matching factor depends directly on the SA sizing (number of cells in series). Oversizing the number of cells in series is equivalent to have a not used SA area. Under-sizing the number of cells can lead to a catastrophic lack of power.**

- **In MPPT, the theoretical SA matching factor is 1 (if MPPT mode is always needed)**

MPPT or DET?

MPPT (Maximum Power Point Tracker) versus DET (Direct Energy Transfer) trade-off

Advantages MPPT	Drawbacks MPPT
The maximum power of the solar array is used whatever the situation. This topology is very well adapted for interplanetary missions, but also to mission with variable sun illumination. The system is also very tolerant to unpredicted situation.	The solar array regulator is a DC/DC buck or boost regulator, more complex and costly than classical S3R. The efficiency of MPPT is around 95% (non negligible dissipations !).

Choice of a topology and associated regulator

CRITERIA FOR THE CHOICE OF A TOPOLOGY

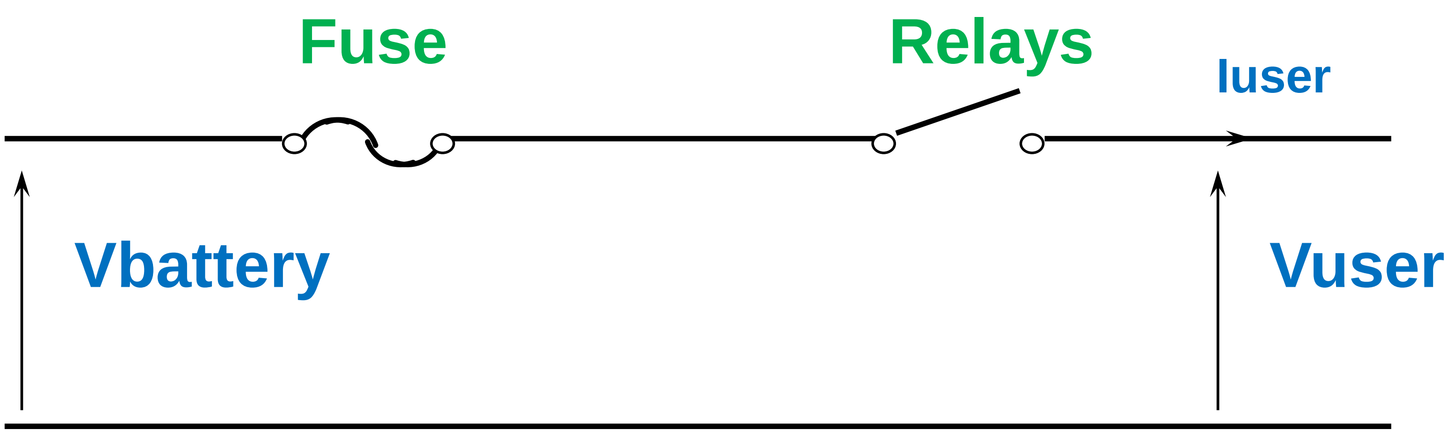
- **When there is free choice about the architecture of a power system, it shall be based on the lowest system cost.**

- **This cost includes:**
  - The non-recurrent costs (studies, prototypes, software..)
  - The recurrent costs of the power systems and the other systems affected (particularly the payload)
  - The launch costs linked to the mass of the power system and to the impacts of the mass on the other systems.

- **A complete comparative analysis should then be made:**
  - Relatively simple tools are sufficient, provided they are same from one topology to another
  - Detailed final sizing shall use precise tools, therefore quite complex

DISTRIBUTION ET PROTECTIONS

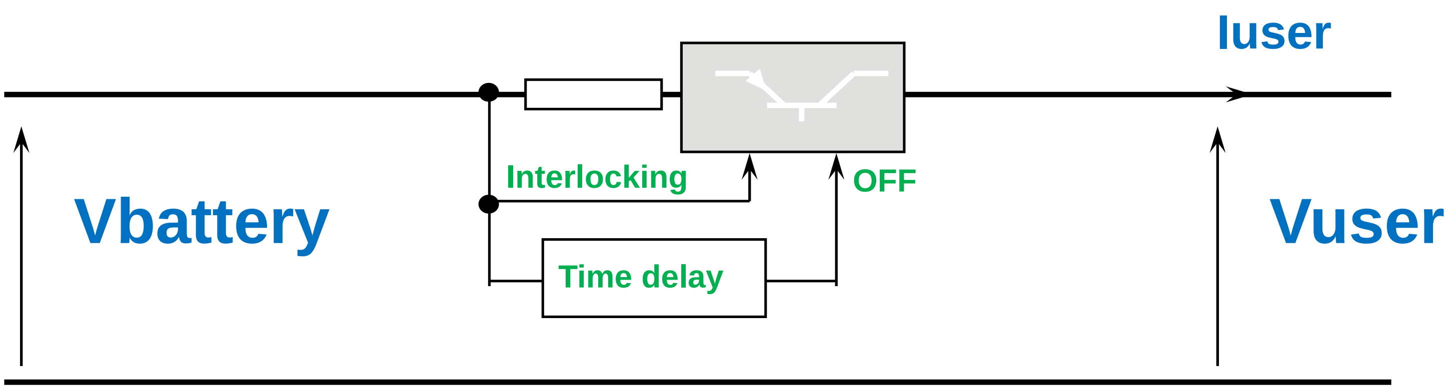
FUSE/RELAY PROTECTION



Sizing:	Imin fuse > 2 x Iuser	(derating)
	fuse rating > Imin fusible	(limited number of ratings)
	Imax fuse = 2 x rating	(manufacturer commitment)
	I min relay > Imax. fuse	(circuit opening under failure)

Consequence: **fault current >> nominal current**

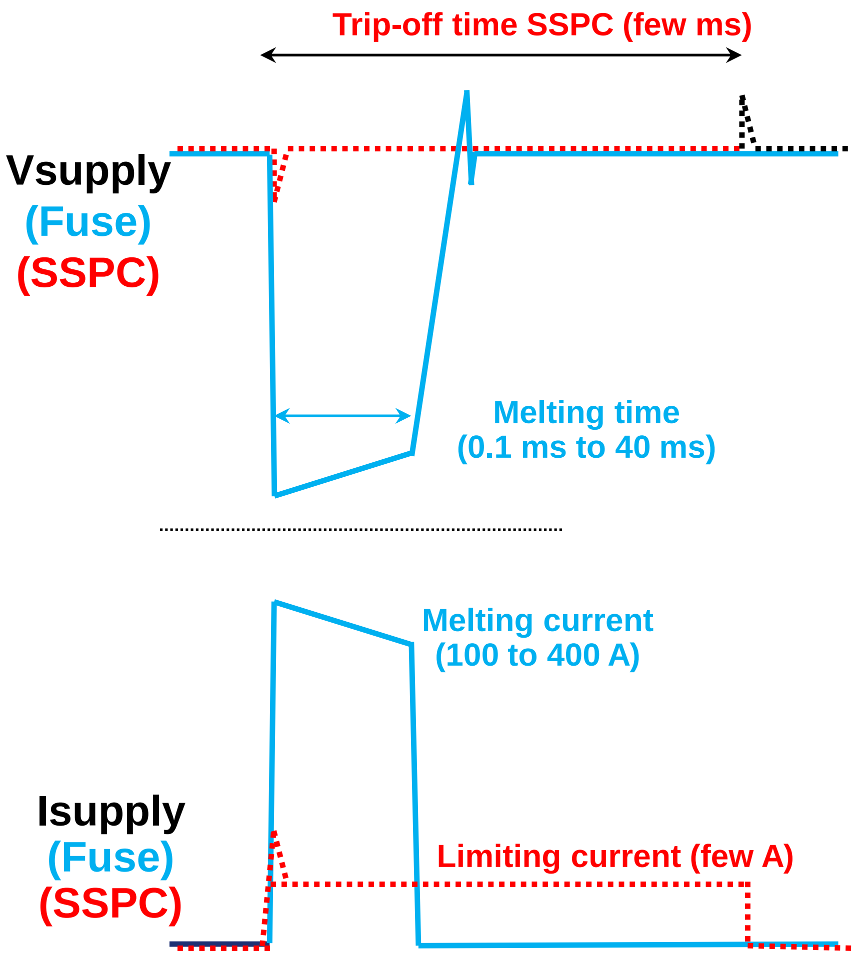
CURRENT LIMITER PROTECTION



Principle: the user current is measured thanks to a series resistor
when Iuser > I nominal, the transistor limits the current, (linear mode)
the device switches OFF after a few ms to avoid transistor overheating

Sizing : Ilimit = 1.2 to 1.5 times Inominal or Ilimit = Inominal + Ifault max
Resistor and transistor sized for minimum voltage drop
Trip off time defined by transistor behaviour in temperature

SHORT CIRCUIT EFFECTS

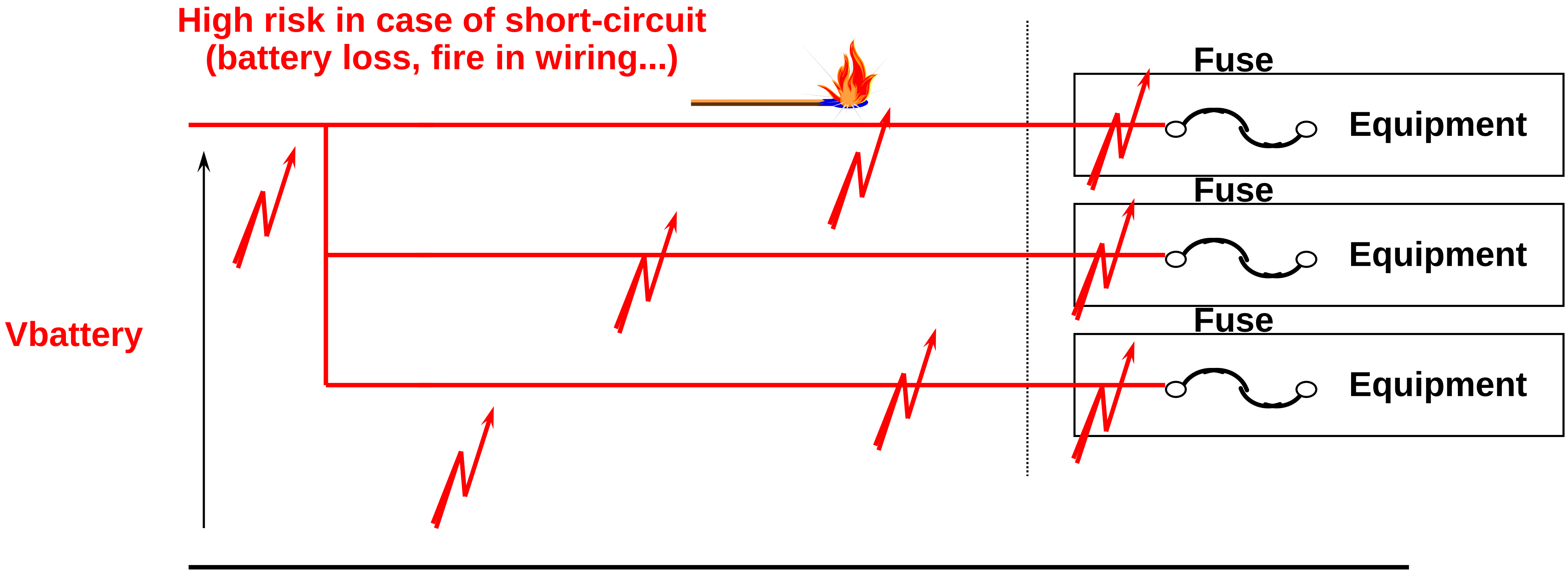


FUSE: Interruption of the supply not known
SSPC: Supply voltage within specifications

FUSE OR LIMITER ?

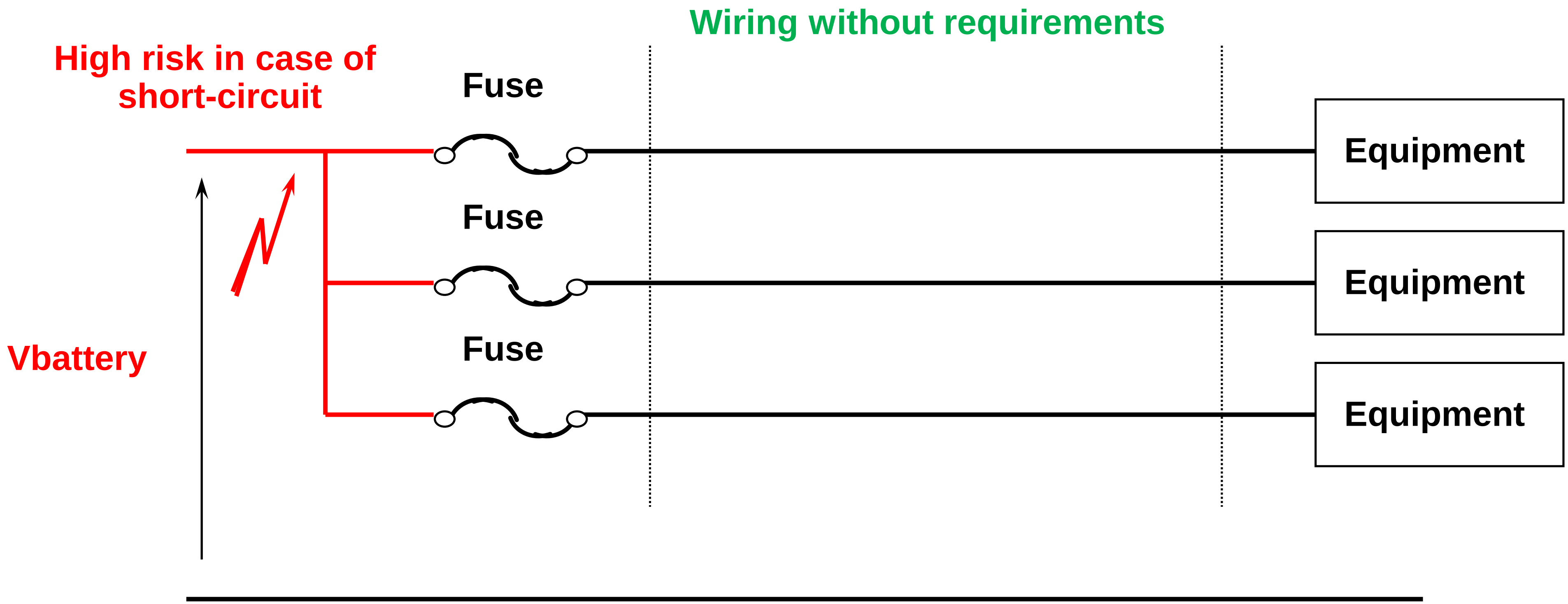
	ADVANTAGES	DISADVANTAGES
FUSE + RELAYS	- Size / mass - Easy to design - Low cost - Bidirectional - Memory - Large experience - Compatible with all the loads - ON/OFF command isolated - Several contacts (status...)	- Dispersion - Large non-melting current (wiring) - Melting period - Ipeak not controlled (--> in-rush, holes of bar) - Cannot be rearmed - Fuse technology badly managed (obsolete) - Wear of relays - Relay stress on self-charge - High voltage relays and fuses
LIMITER	- Precise limitation (optimum wiring) - Ipeak controlled (no hole of bar) - Limited in-rush - ON/OFF switching by low level signal (+5V)	- Difficult to find - Complexity, thermal design - Instabilities of inductive charge - Number of components, mass - Command isolation difficult (opto, transfo) - Line drop

Decentralised Protection



The part of the wiring to be protected (double insulation) is extended to all the wiring. A part of the wiring of the equipment is also to be protected.

Centralised Protection



The part of the wiring to be protected (double insulation) is limited to a small zone near the battery. It can be managed easily.

QUIZZ

SYSTEMES DE PUISSANCE (QUIZZ)

Which topology, bus voltage, power source, energy storage technologies would you propose?

- Large LEO satellite, Nadir pointing, sunsynchronous 10h, institutional market, 1kW average power, lifetime 10 years
- Mars observation mission, ESA, 1kW, lifetime 2 years
- Deep space exploration probe, lifetime 20 years
- Titan exploration probe, 500W, lifetime: 7 years cruise + 10 hours mission
- Launcher, mission duration 2 hours. 100W average power with several peaks at 1kW few seconds

SUMMARY

Summary

From mission to electrical power subsystem

- The mission (orbit, payload, attitude, budget) has an influence on the electrical power subsystem (sources sizing, choice of topology)

- The electrical power subsystem has many interaction at system level (thermal aspects, AOCS)

Summary

Power conditioning : basics and topologies type

- Everything that is necessary to adapt primary and secondary sources to the needs of users and guarantee the continuity of the electrical energy delivery.
- Cohabitation between primary source, secondary source and users
- Two types of topology : regulated topology (regulation of the bus voltage to a fixed value) and battery follower (bus voltage imposed by battery/ regulation of the battery recharge)

Summary

Power conditioning : SA regulators (DET / MPPT)

- On each topology, the regulation is based on DET or MPPT
- DET (Direct Energy Transfer) adapts the provided SA power by connecting / disconnecting SA sections. The SA operating voltage is imposed by the bus voltage (+ voltage drop between bus and SA).
- MPPT (Max Power Point Tracker) is a DC/DC converter which adapts the provided SA power by changing the operating voltage at SA level.

Summary

Power conditioning : SA regulator - DET

- DET is cost efficient compared with MPPT
- DET has lower dissipation than MPPT
- Based on DET, the Power Subsystem (PSS) behaviour is very dependant on the SA sizing (number of cells in series). Oversizing or under-sizing the number of SA cells in series lead to non optimal PSS.
- DET is adapted to mission around Earth, when the thermal behavior of the SA is well known.

Summary

Power conditioning : SA regulator - MPPT

- **The MPPT tracks the MPP, only if needed.**
- **MPPT is costly**
- **MPPT has non negligible dissipation / Not adapted for high power mission**
- **MPPT is adapted for interplanetary missions**