European Organization for Nuclear Research
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Power converters

Definitions and classifications
Converter topologies

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CERN

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Divonne

Menu

- Power converter definition and classification
- Power converter topologies: *commutation*
  Sources, switches,…semiconductors
- Special case for magnet powering
  (Voltage source - Current source)
- Pulsed power converters
- Control and precision

In 1 hour ????

Power converters : Definitions

The source of the beam blow-up when we could not prove it was the RF **(Control room operator)**

A powerful (small) black box able to convert MAD files into currents **(Accelerator Physics group member)**

An equipment with three states, ON, OFF and FAULT **(Another operator)**

Is it the same thing as a power supply? **(Person from another physics lab)**

A big box with wires and pipes everywhere and blinking lamps. Occasionally it goes BANGG! **(Former PO secretary view)**

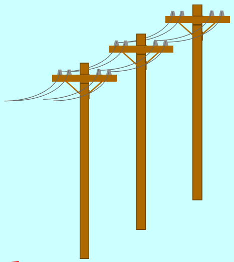
Power converters : Definitions *(cont'd)*

That which feeds the magnets (a visitor)

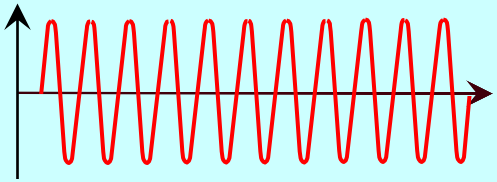
A stupid installation taking a non-sinusoidal current at poor power factor (Power distribution engineer)

A standard piece of equipment available from industry off-the-shelf
(a higher management person, not in in this room !)

Energy source ⟹ Applications


50 or 60 Hz ; AC



Power converter

The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

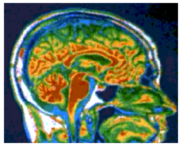
Control

Traction and auxiliary

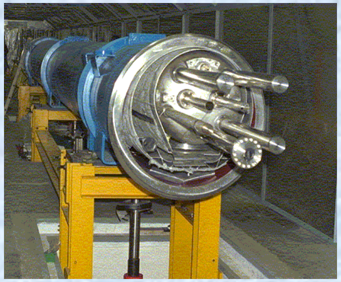


Domestic Appliance

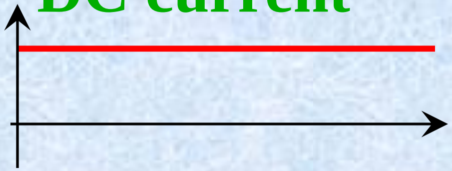
Medical applications

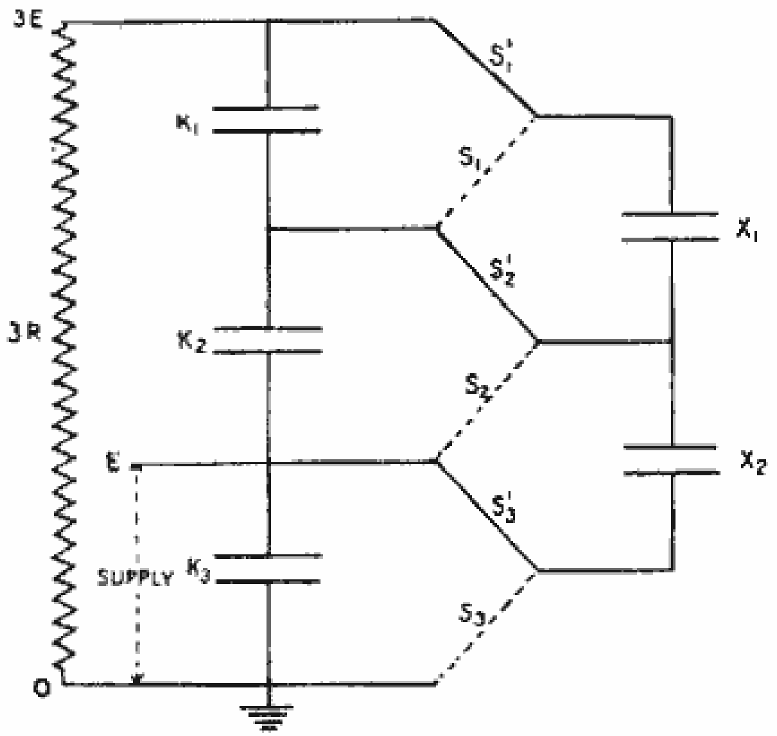


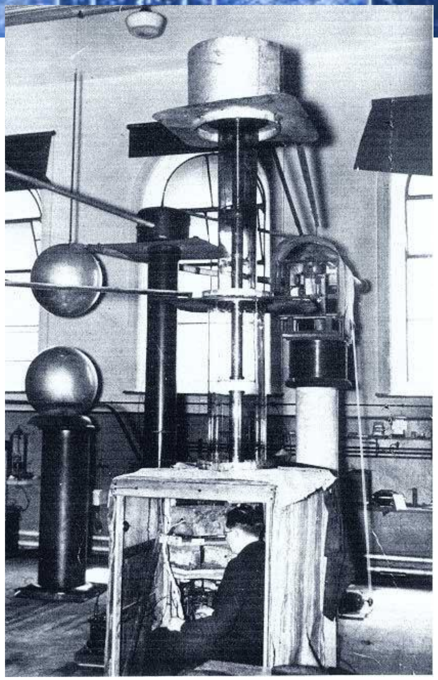
Industrial applications, Welding, Induction Heating, ….

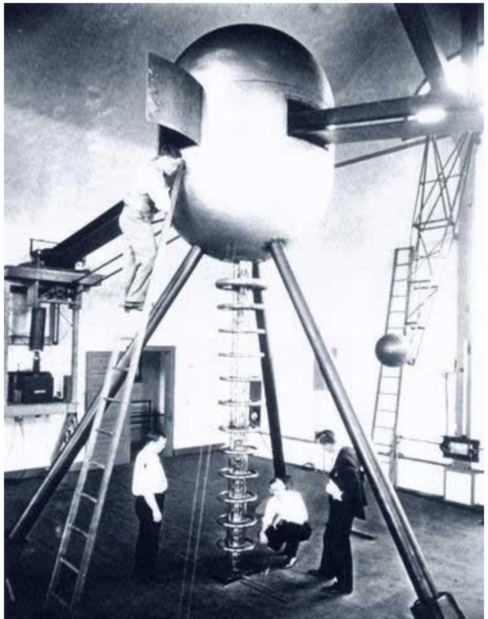


DC current









Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.

Voltage multiplier : switches…

“On a new principle for the production of higher voltages.”

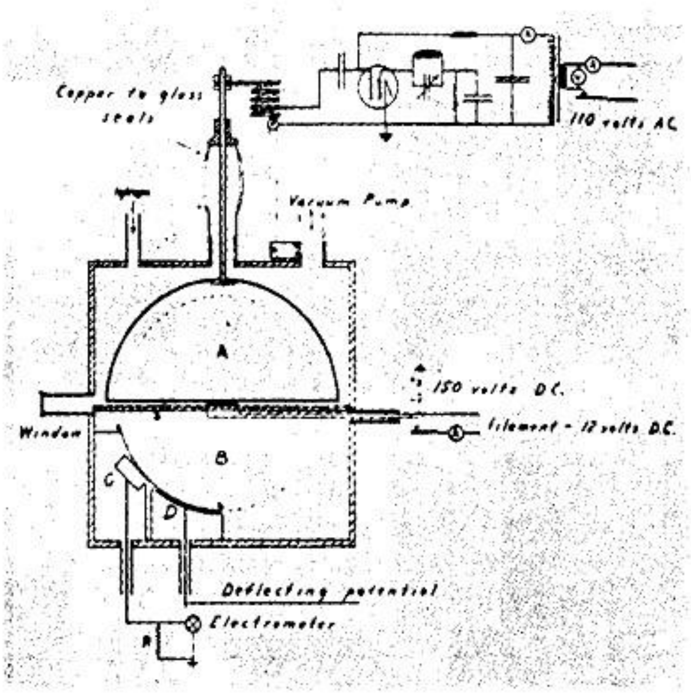
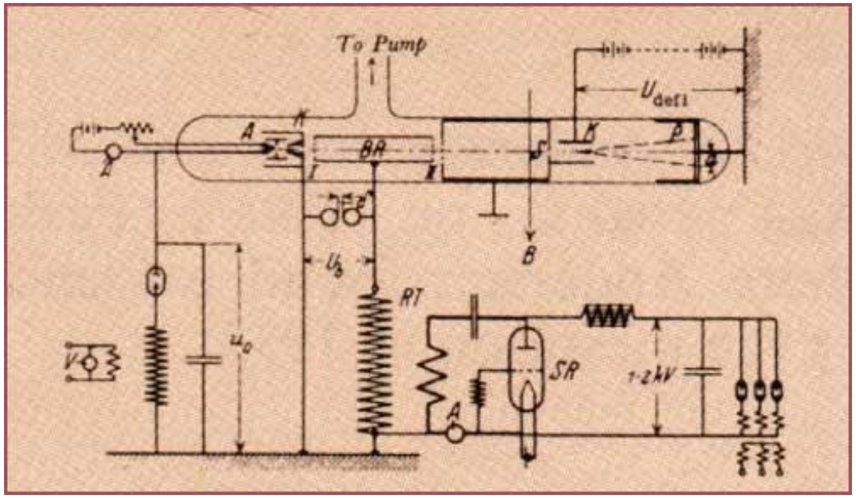


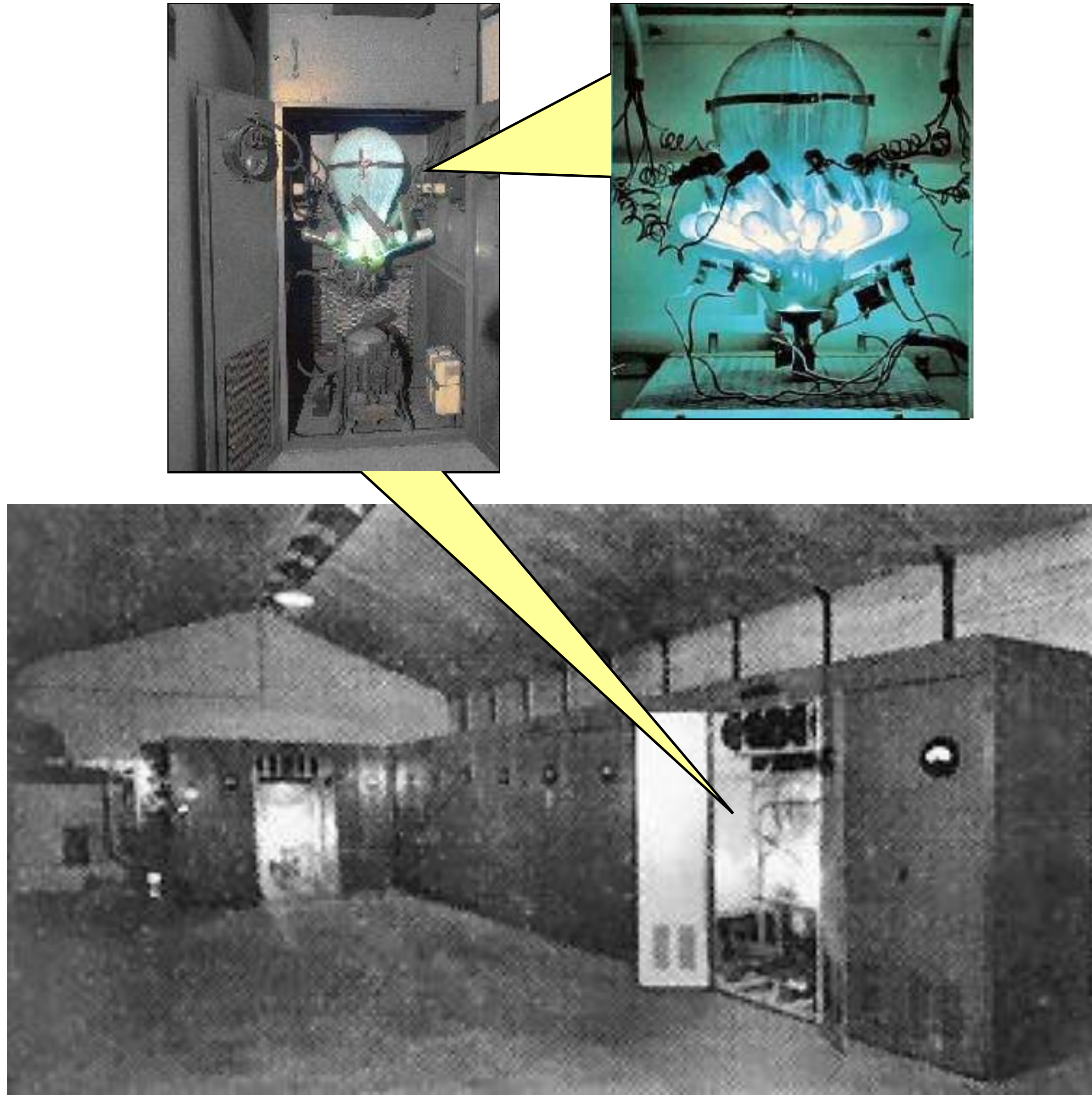
Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.



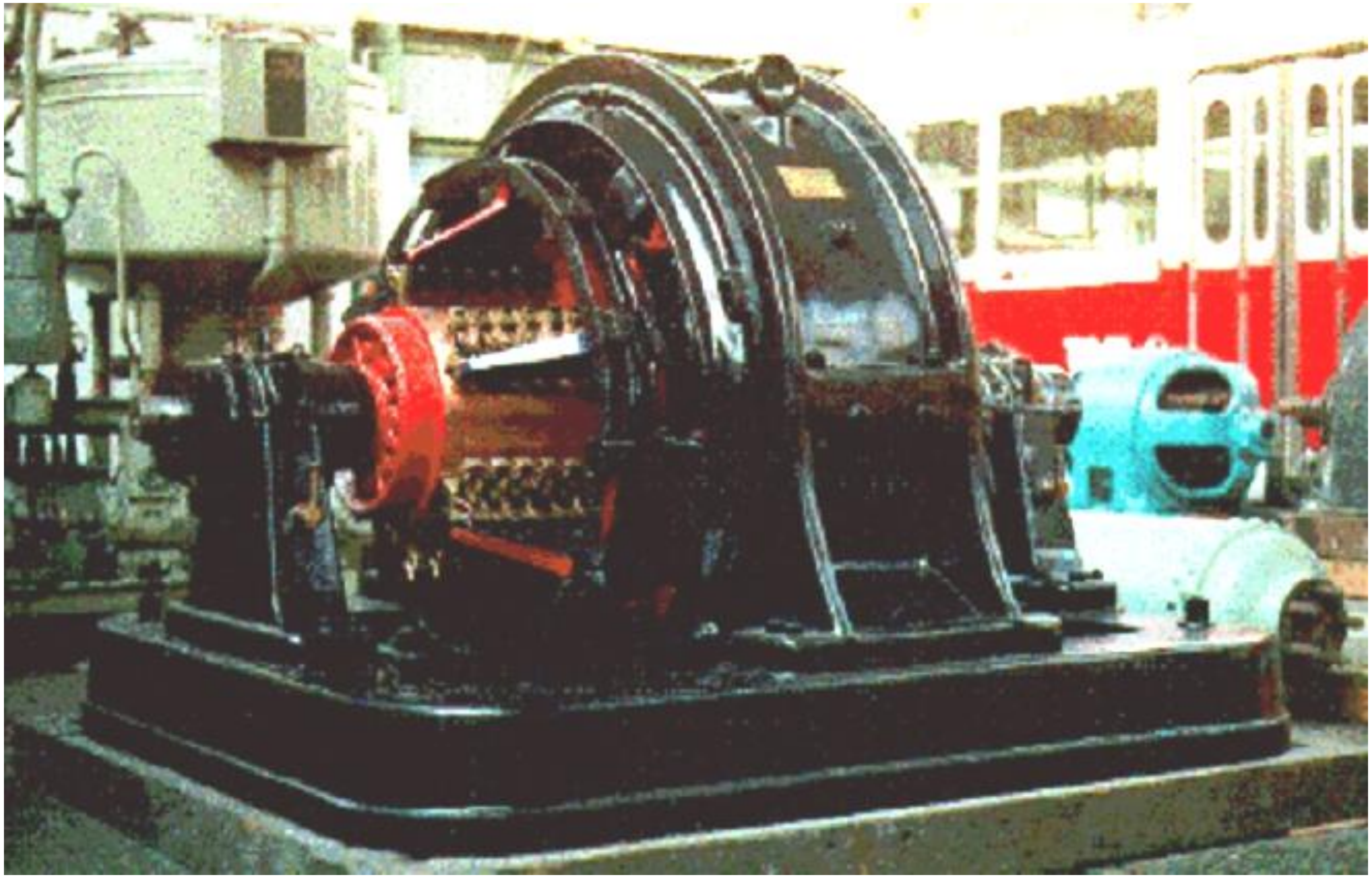
The difficulties of maintaining high voltages led several physicists to propose accelerating particles by using a lower voltage more than once. Lawrence learned of one such scheme in the spring of 1929, while browsing through an issue of *Archiv für Elektrotechnik*, a German journal for electrical engineers. Lawrence read German only with great difficulty, but he was rewarded for his diligence: he found an article by a Norwegian engineer, Rolf Wideröe, the title of which he could translate as “On a new principle for the production of higher voltages.” The diagrams explained the principle and Lawrence skipped the text.

Once upon a time…. not so far

This is a 6-phase device, 150A rating with grid control.
It measures 600mm high by 530mm diameter.



In the beginning… for high power



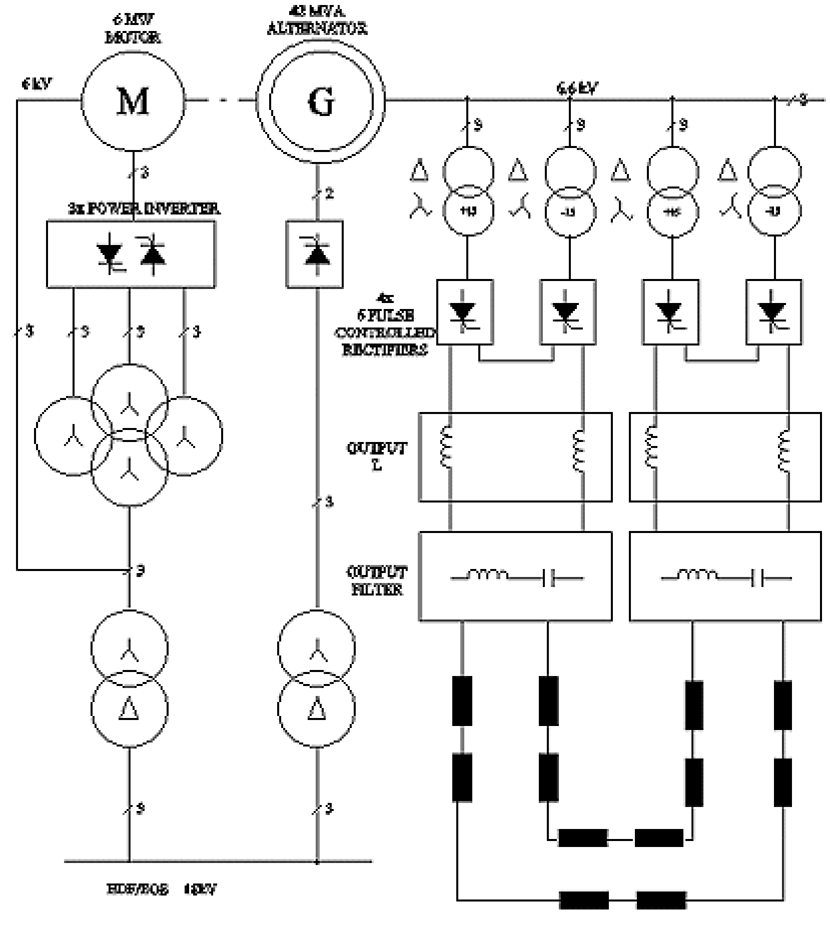
une commutatrice des tramways de Saint-Etienne, datant de 1907 et ayant fonctionné jusqu'en avril 1991

and still now in "old" accelerators…

Brookhaven National Laboratory - AGS

By courtesy: I. Marneris

CERN - PS



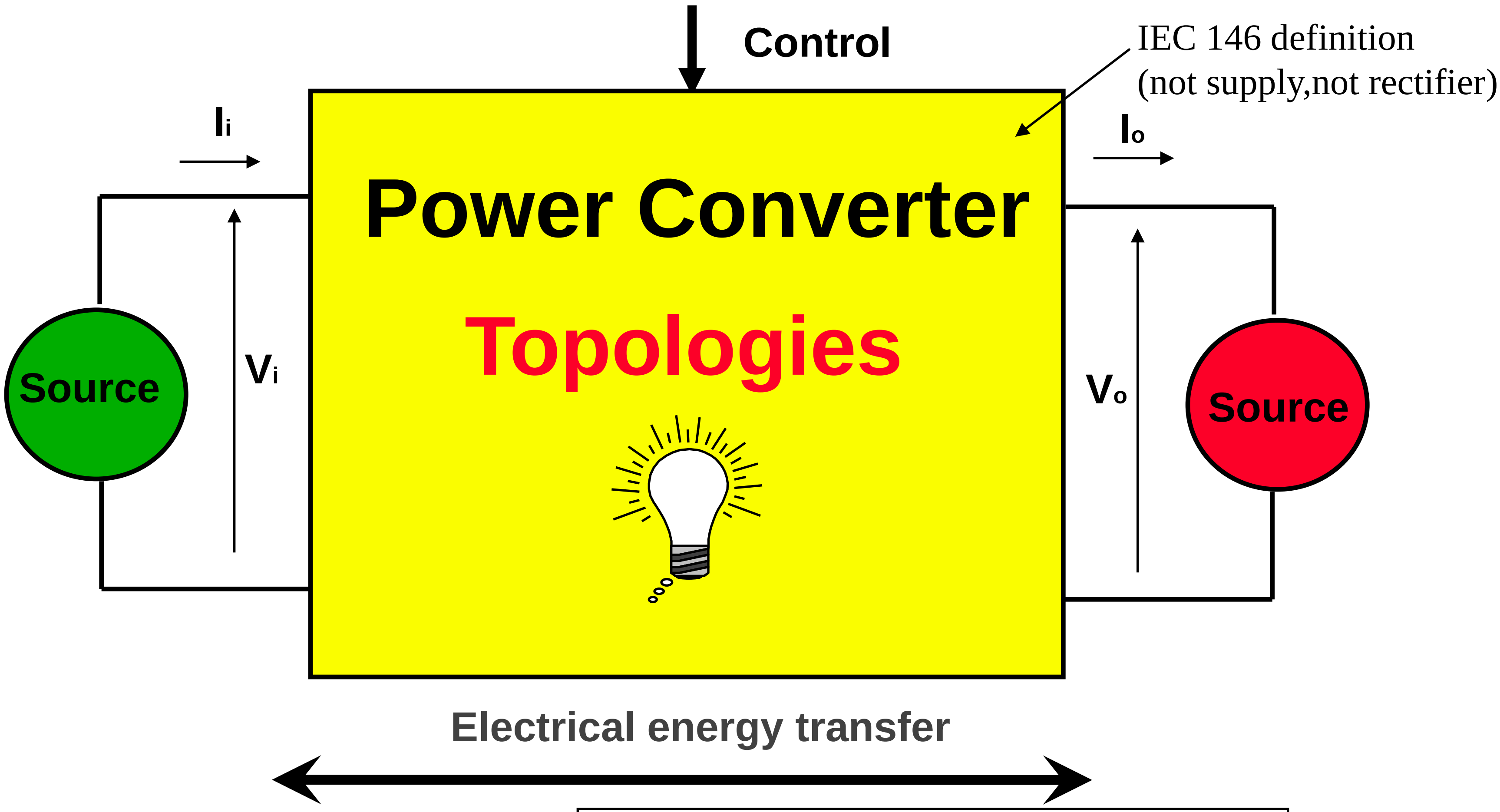
Power converters specifications

"Do you have one or two power converters for the test of magnet prototypes? 200 A will be enough ?
Precision is not important for time being.
Don't worry it's not urgent. Next month is OK "
(Email received 05.12.08)

In general, accelerator designers are not power converter experts and vice versa.

Interface is the list of ***power converter specifications.***

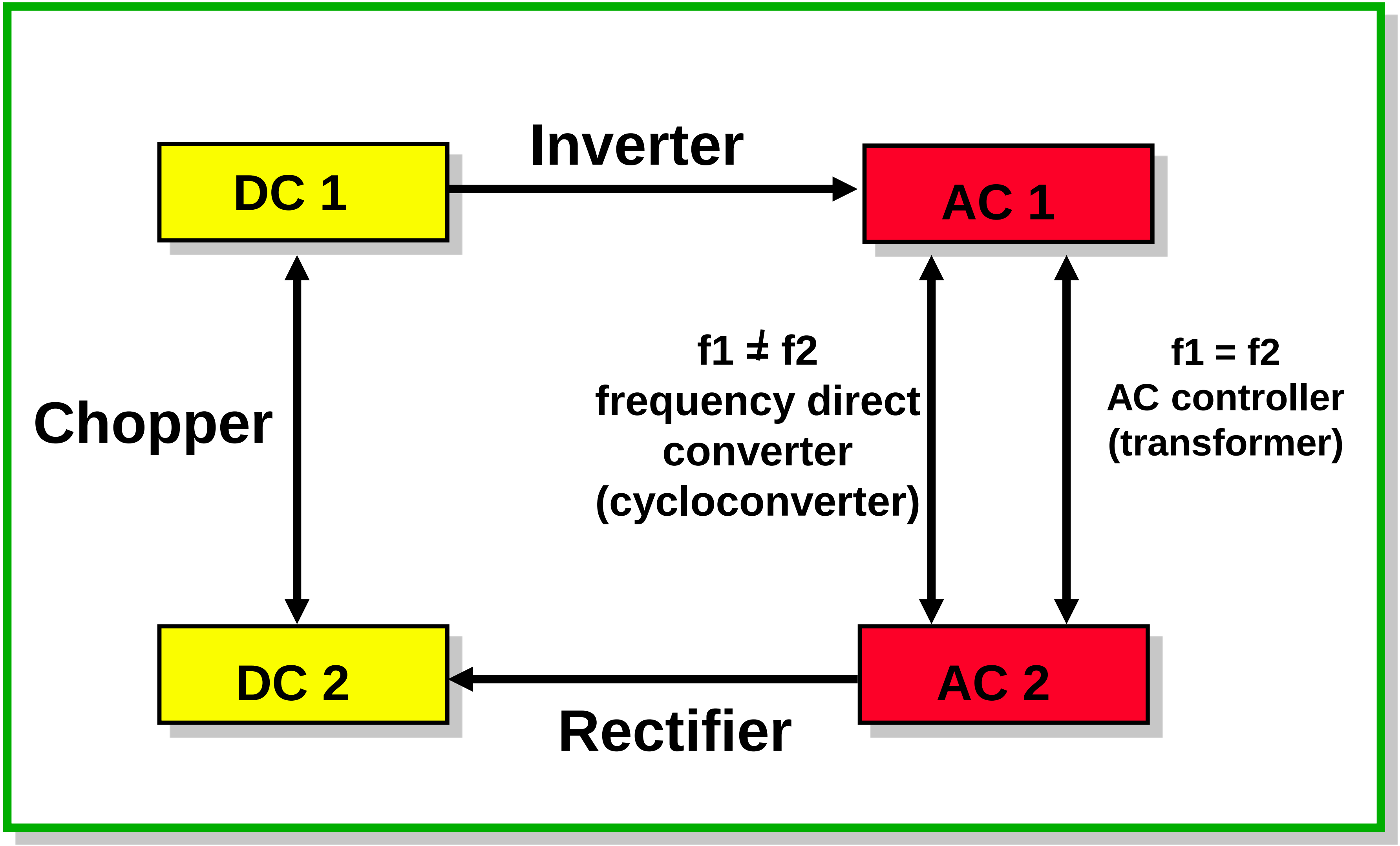
The apparent belief on one side that anything is possible and the impression on the other side that the specification have been chosen at random, sometimes leads to rather cynical feelings
such as:
-if in doubt, ask an extra order of magnitude, there is never a problem or whatever it is, or
- however it is calculated, 1 in 10^3 will be good enough in the end and they'll never note the ripple and the zero crossing !!!



Power Converter Design

- performance
- efficiency
- reliability (MTBF), reparability (MTTR),
- effect on environment (RFI, noise,...)
- low cost

Converter classification



Source definition

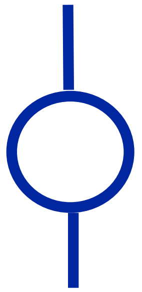
Source definition: any element able to impose a voltage or a current, independently of, respectively, the current flowing through, or the voltage imposed at its terminals.

A source could be a generator or a receptor.

Two types of sources:

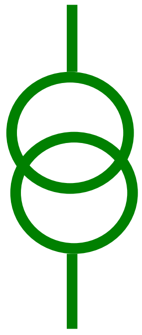
Voltage source

which imposes a voltage independently of the current flowing through it. This implies that the series impedance of the source is zero (or negligible in comparison with the load impedance)

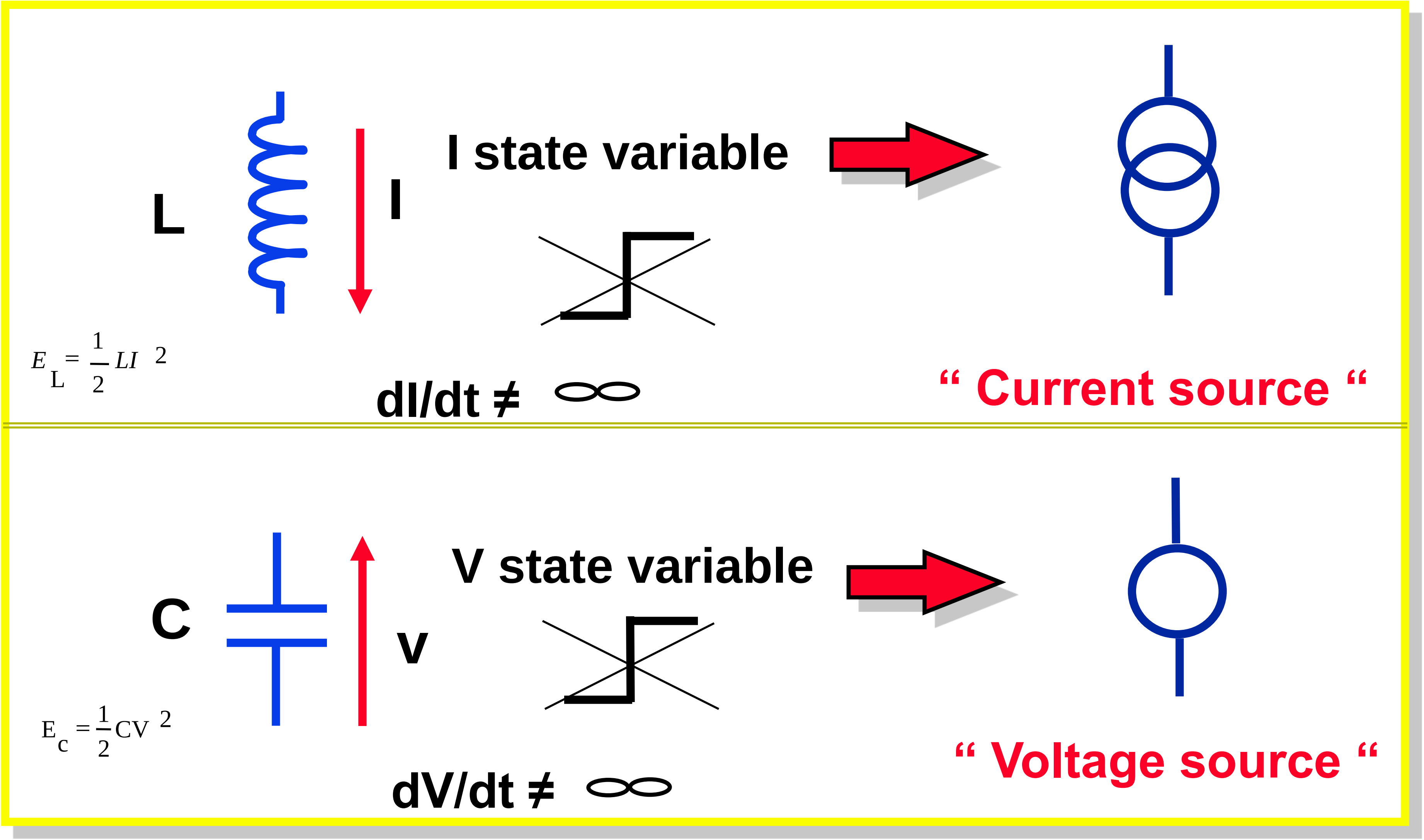


Current source

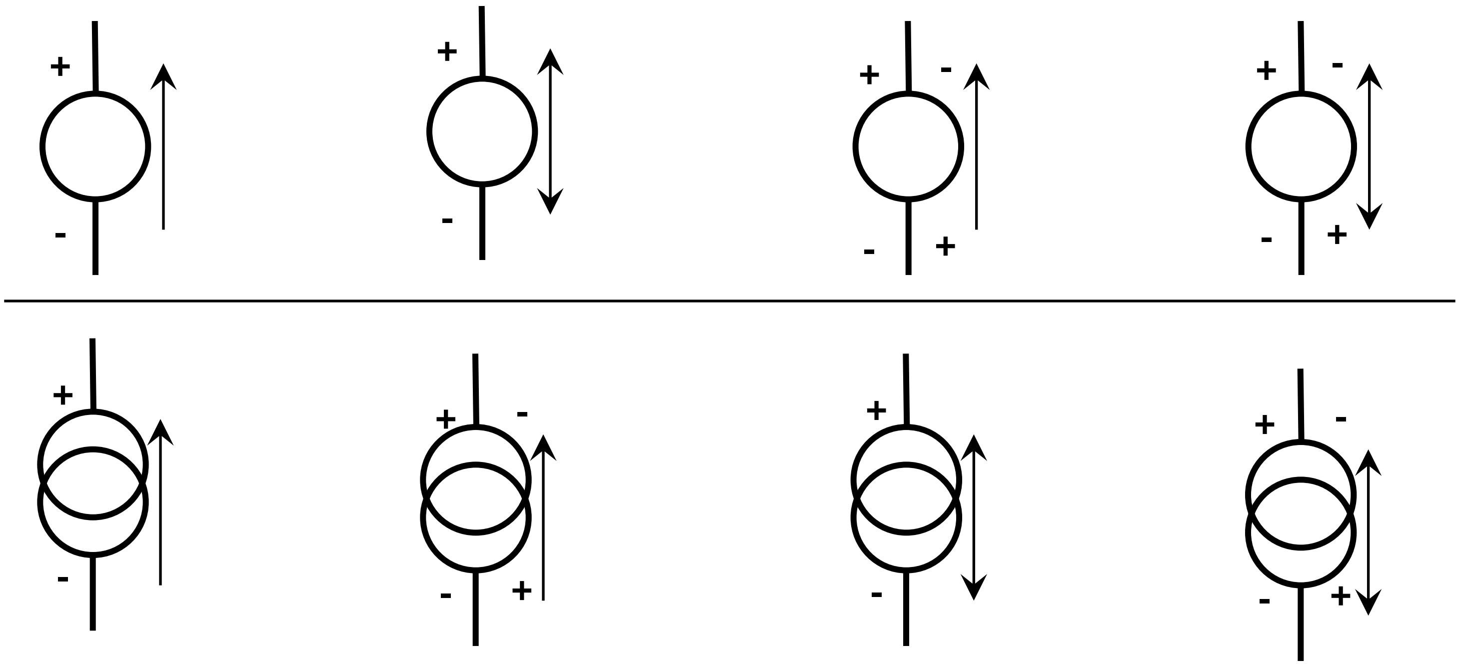
which imposes a current independently of the voltage at its terminals.
This implies that the series impedance of the source is infinite (or very large in comparison with the load impedance)



Source examples



Eight types of sources *(reversibility)*



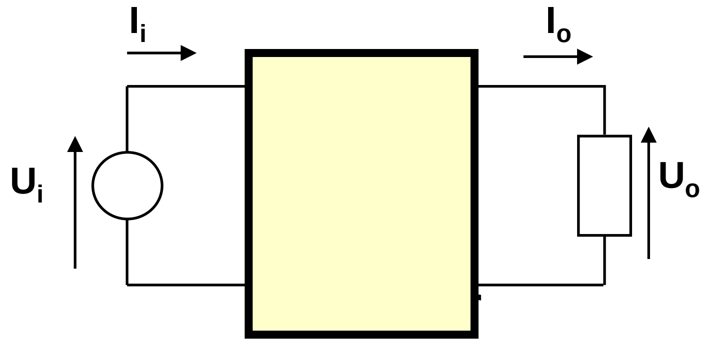
Unidirectional source

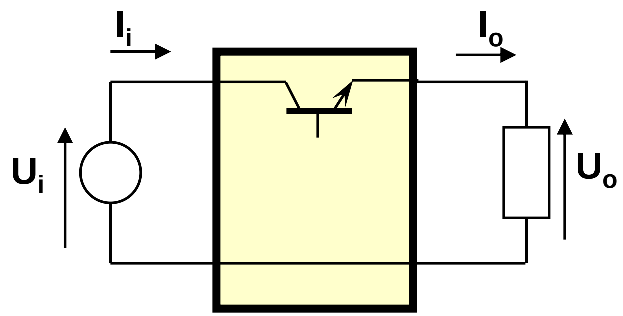
voltage : if the voltage, across its terminal, can't change sign
current : if the current, flowing through it, can't reverse

Bidirectional (reversible) source :

voltage : if the voltage, across its terminal, can change sign
current : if the current, flowing through it, can reverse

Introductive example





Linear solution

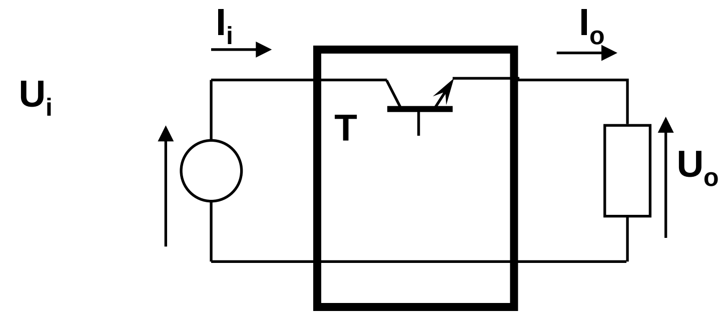
Transfer of energy between

- DC voltage source Ui

- DC source (nature is not defined) : Uo, Io

Linear solution

$U_i = 24V$; $U_o = 10$ V and $I_o = 600A$



Po = Uo . Io = 10 . 600 = 6’000 W

P_T (power dissipated by the switch) = U_T. I_T = (Ui – Uo) . Io = (24 – 10) . 600 = 8’400 W

Converter efficiency = Po / (P_T + Po) = 42 % !!!!!

Furthermore, it’ll be difficult to find a component (semiconductor) able to dissipate 8’400 W .

Then impossible for medium and high power conversion

Commutation

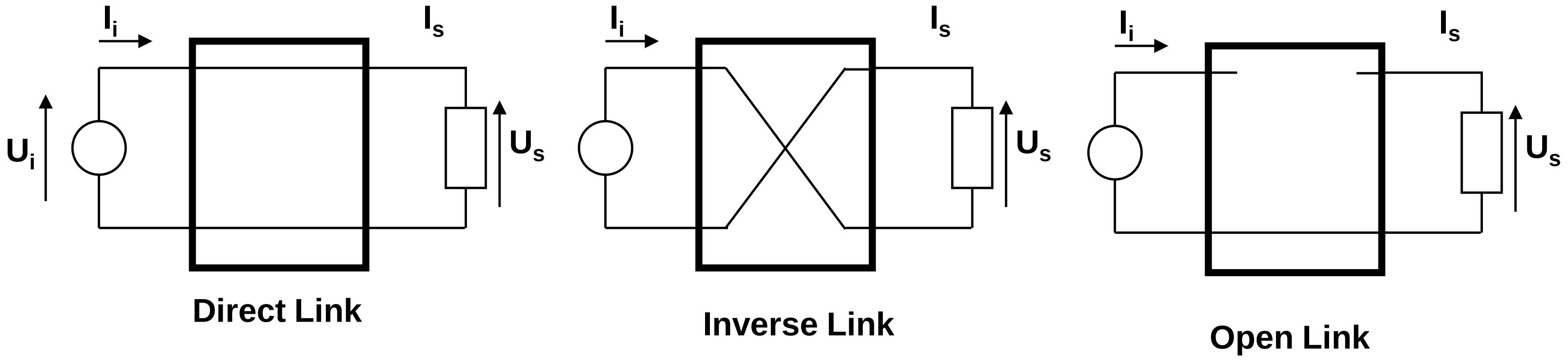
- $U_T = 0$ if $I_T \neq 0$
- $I_T = 0$ if $U_T \neq 0$

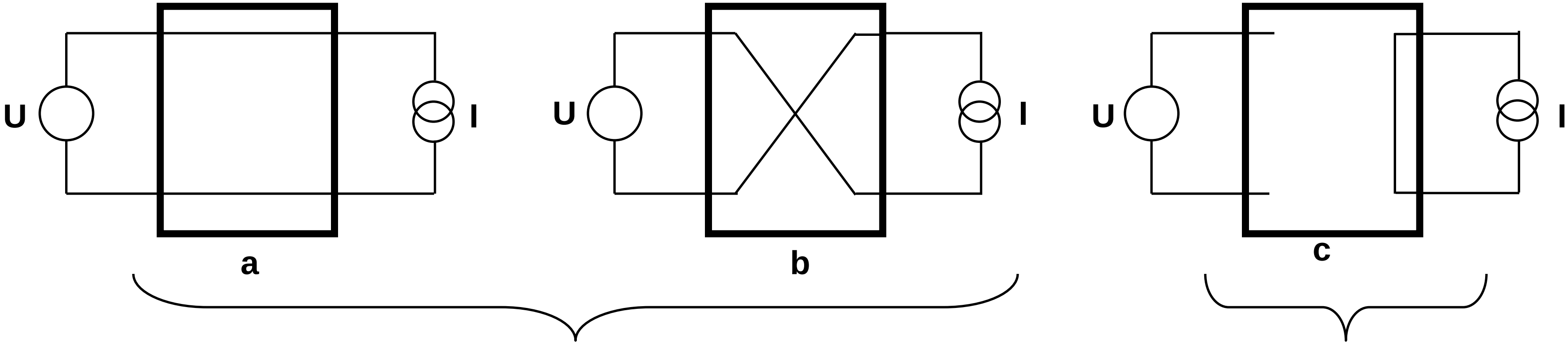
} $P_T = 0$

~~**Linear mode**~~ ⇒ **switch mode (saturated-blocked)**

Commutation

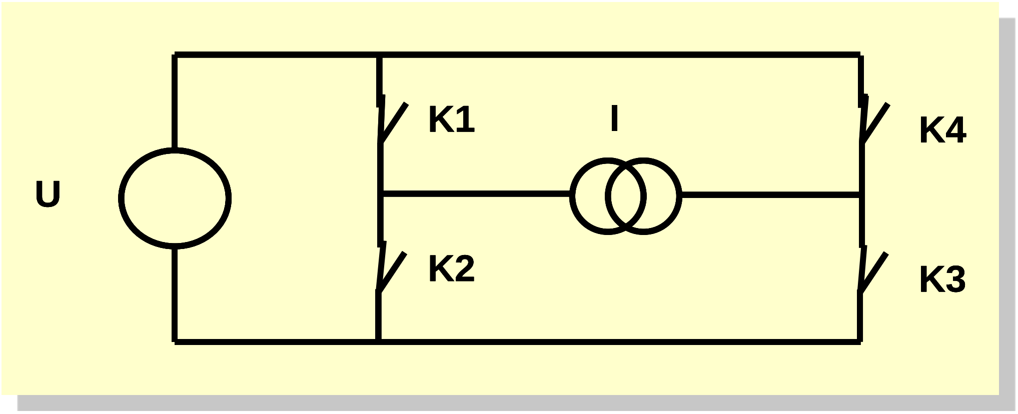
Active components used as switches to create a succession of link and no link between sources to assure an energy transfer between these sources with high efficiency.





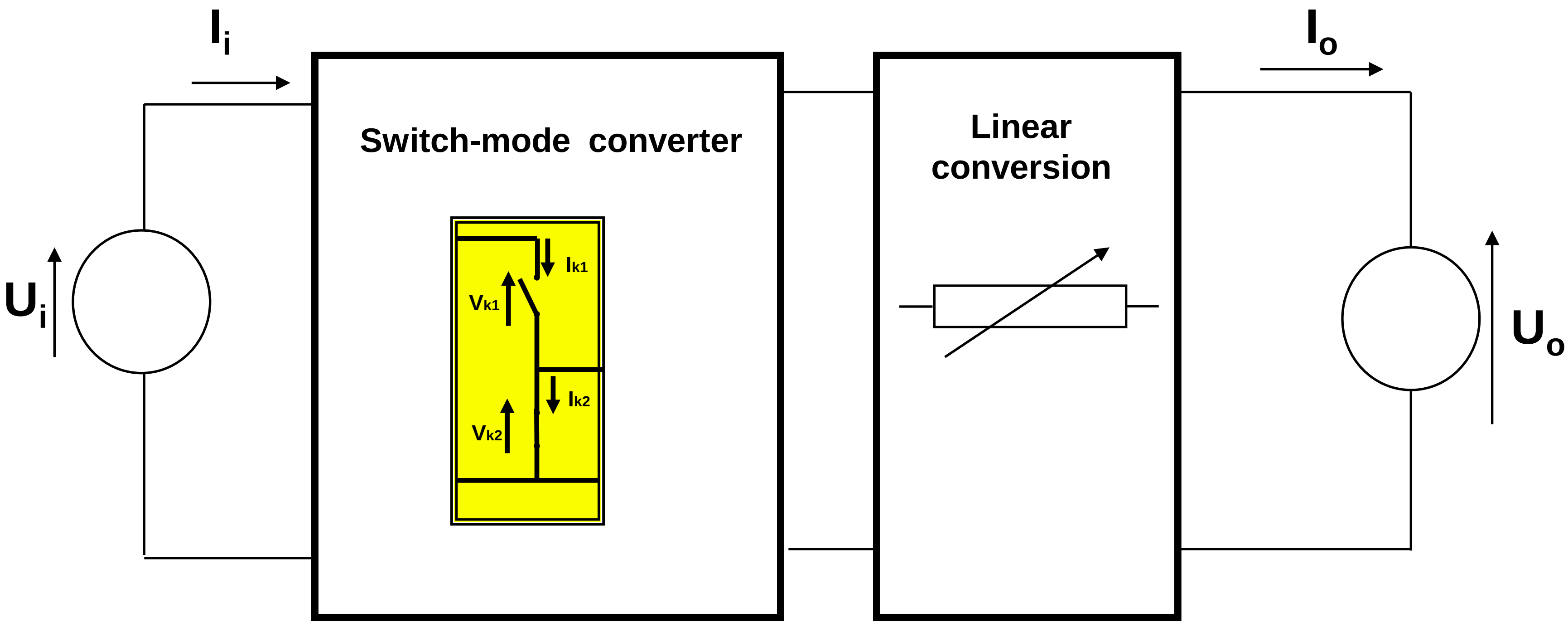
Connexion
(energy flow between sources)

Disconnexion
(current source short-circuited, voltage source open circuited)



- K1 and K3 closed => a
- K2 and K4 closed => b
- K1 and K4 (or K2 and K3) closed => c

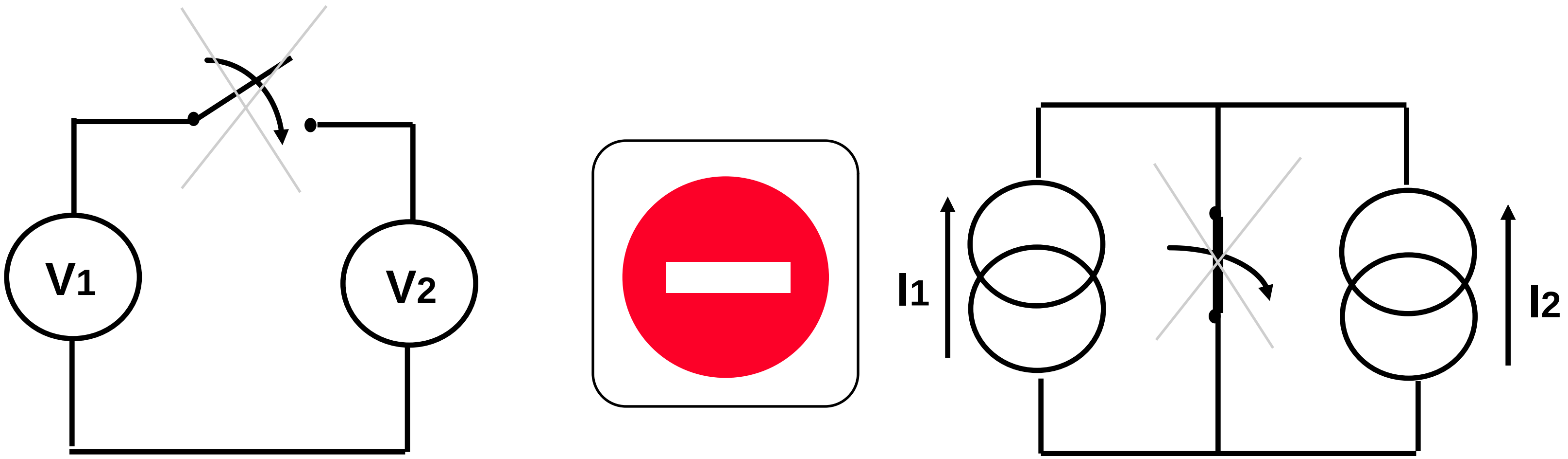
Special case for linear application



- Active filter
- 4-quadrant converters

Commutation rules

- *electronic switches modify the interconnection of impeding circuits*
- *any commutation leading instantaneous variations of a state variable is prohibited*



Turn On impossible **Turn Off impossible**

Interconnection between two impeding networks can be modified only if :

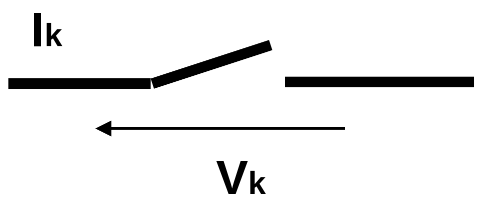
- **the two networks are sources of different natures (voltage and current)**
- **the commutation is achieved by TWO switches. The states of the two switches must be different.**

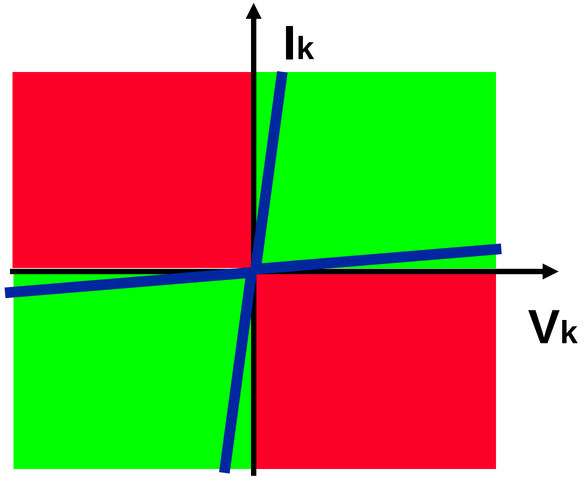
Power Converter topology design: the problem

the interconnection of sources by switches

Fundamental rules and source natures → **Power converter topologies**

switch characteristics





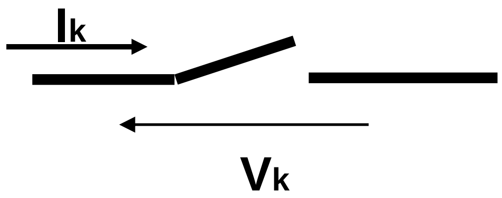
Switch characteristics

Switch : ***semiconductor device functioning in commutation***

The losses in the switch has to be minimized

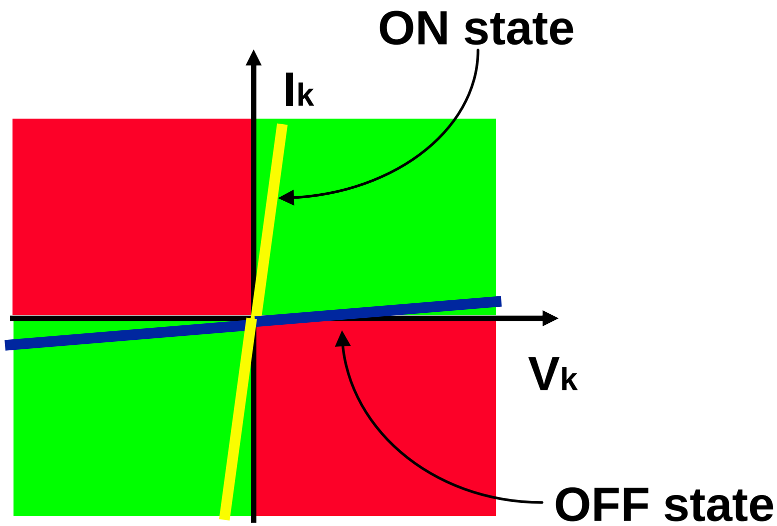
Zon very low

Zoff very high



Switch : at least two orthogonal segments

(short and open circuit are not switches)



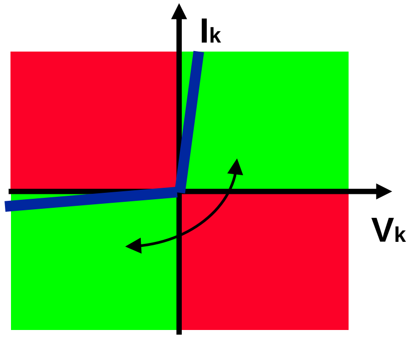
Switches : *Dynamic characteristics*

ON state ⟷ **?** ⟷ **OFF state**

- **spontaneous commutation**

  change of quadrant

  (auto turn-on ; auto turn-off)



no switching losses

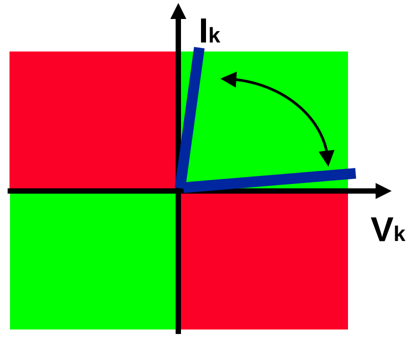
- **controlled commutation**

  no change of quadrant

  (controlled turn-on ; controlled turn-off)

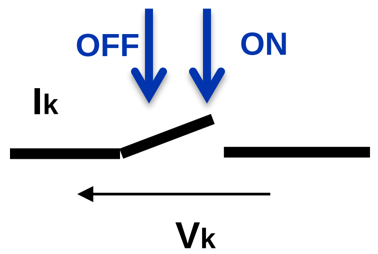
  ↓

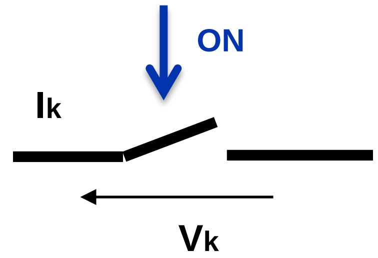
  gate

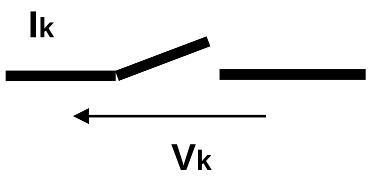


Switching losses

Power Semicondutors







Power Semiconductors

Turn-off Devices

Transistors

- MOSF
- Darlin
- **IGBTs**

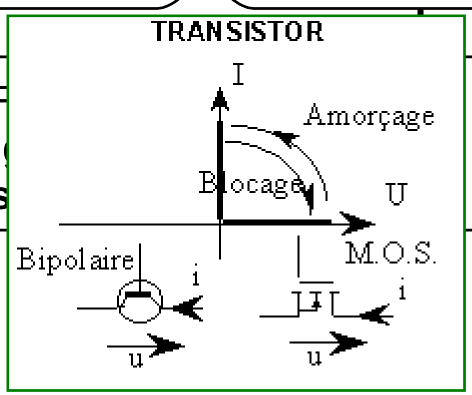
Thyristors

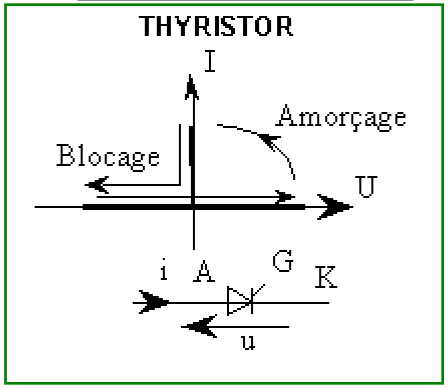
Thyristors

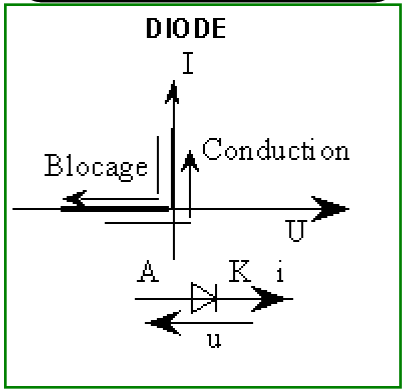
- Line commutated
- Fast
- Bi-directional
- Pulse

Diodes

- Fast
- Line commutated
- Avalanche







Evolution of Power semiconductors

From mercury arc rectifier, grid-controlled vacuum-tube rectifier, inignitron ,….

Power Electronics

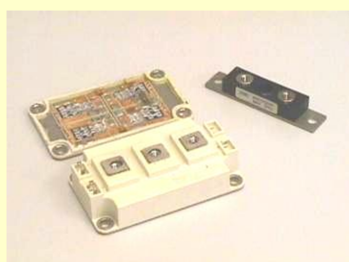
From 1960

Power Diode and Thyristor

or SCR (Silicon-Controlled Rectifier)

Link to frequency of the electrical network
50 Hz (60 Hz)

From 1985

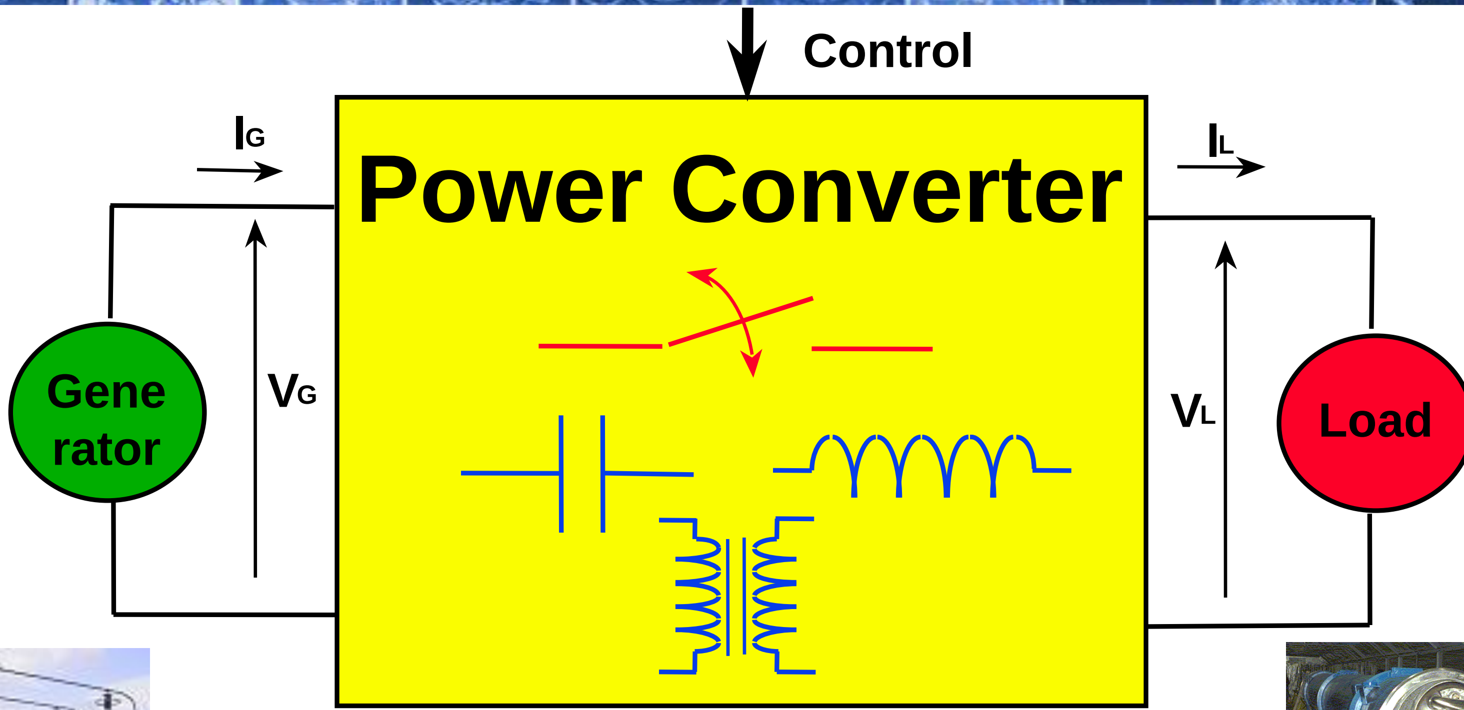


High frequency power semiconductors :

MosFet, IGBTs , GTOs, MCTs,….

High frequency => high performances (ripple, bandwidth, perturbation rejection,...)
small magnetic (volume, weight)

Power Converter for magnets

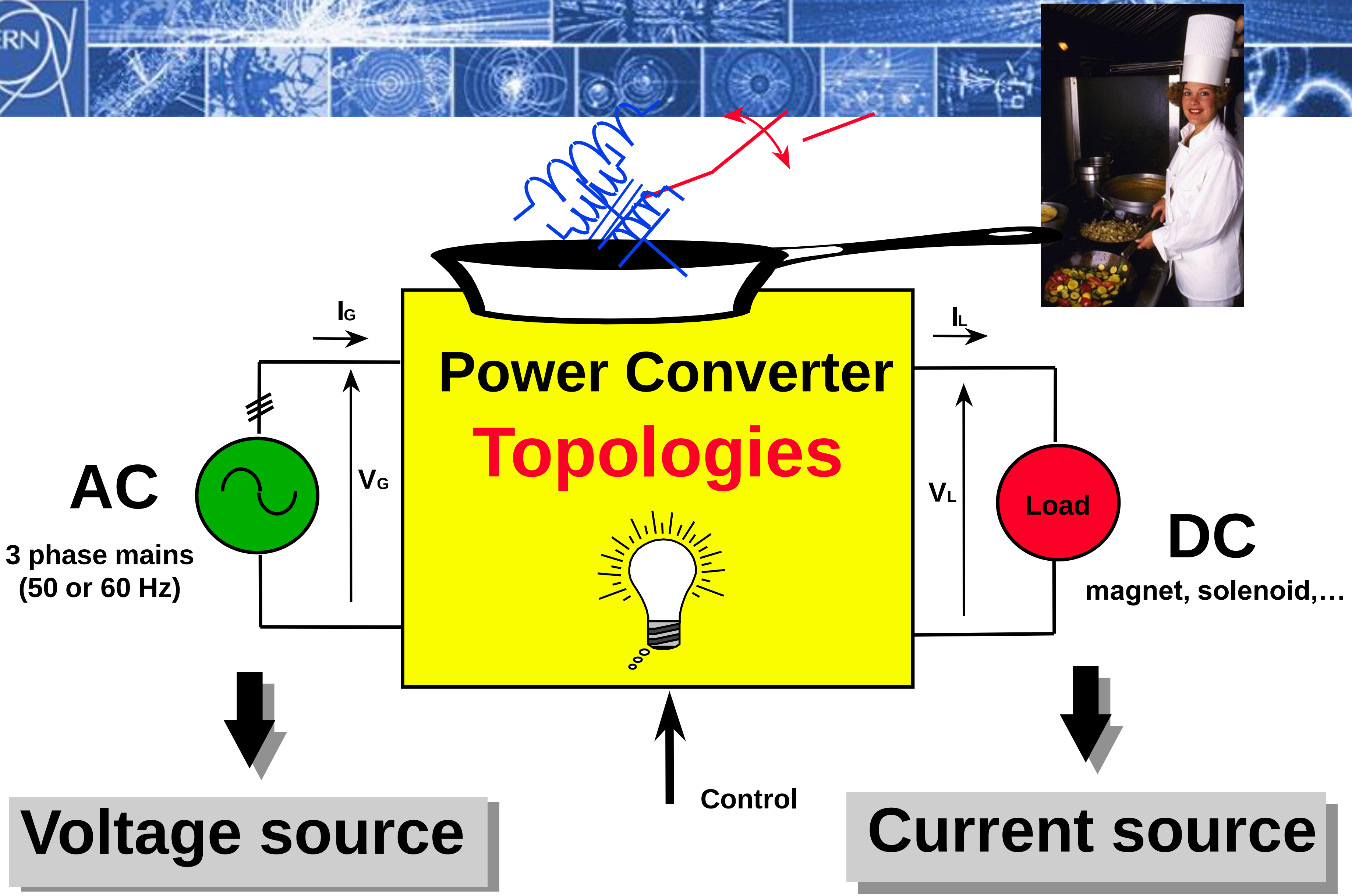


Electrical energy transfer

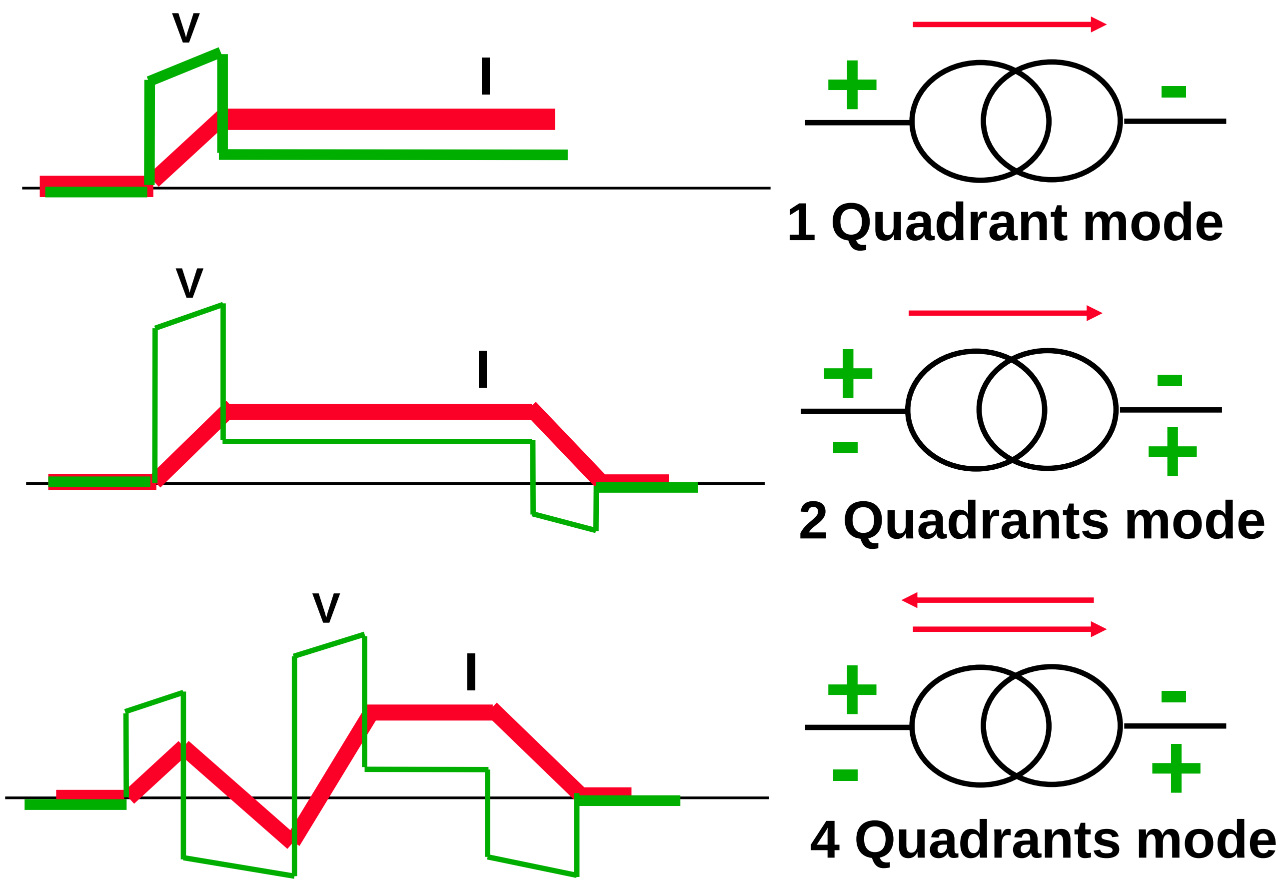
- low mains harmonic distortion
- power factor (closest to 1)

- low ripple (current)
- reproducibility (short and long term)
- rejection of mains disturbance
- dynamic response

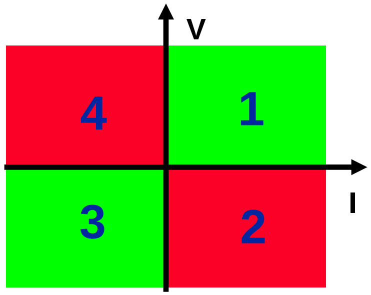
Achieving high performance : COMPROMISE


Power Converter
Topologies
AC
3 phase mains
(50 or 60 Hz)
I_G
V_G
I_L
V_L
Load
DC
magnet, solenoid,…
Control
Voltage source
Current source

Operating Modes

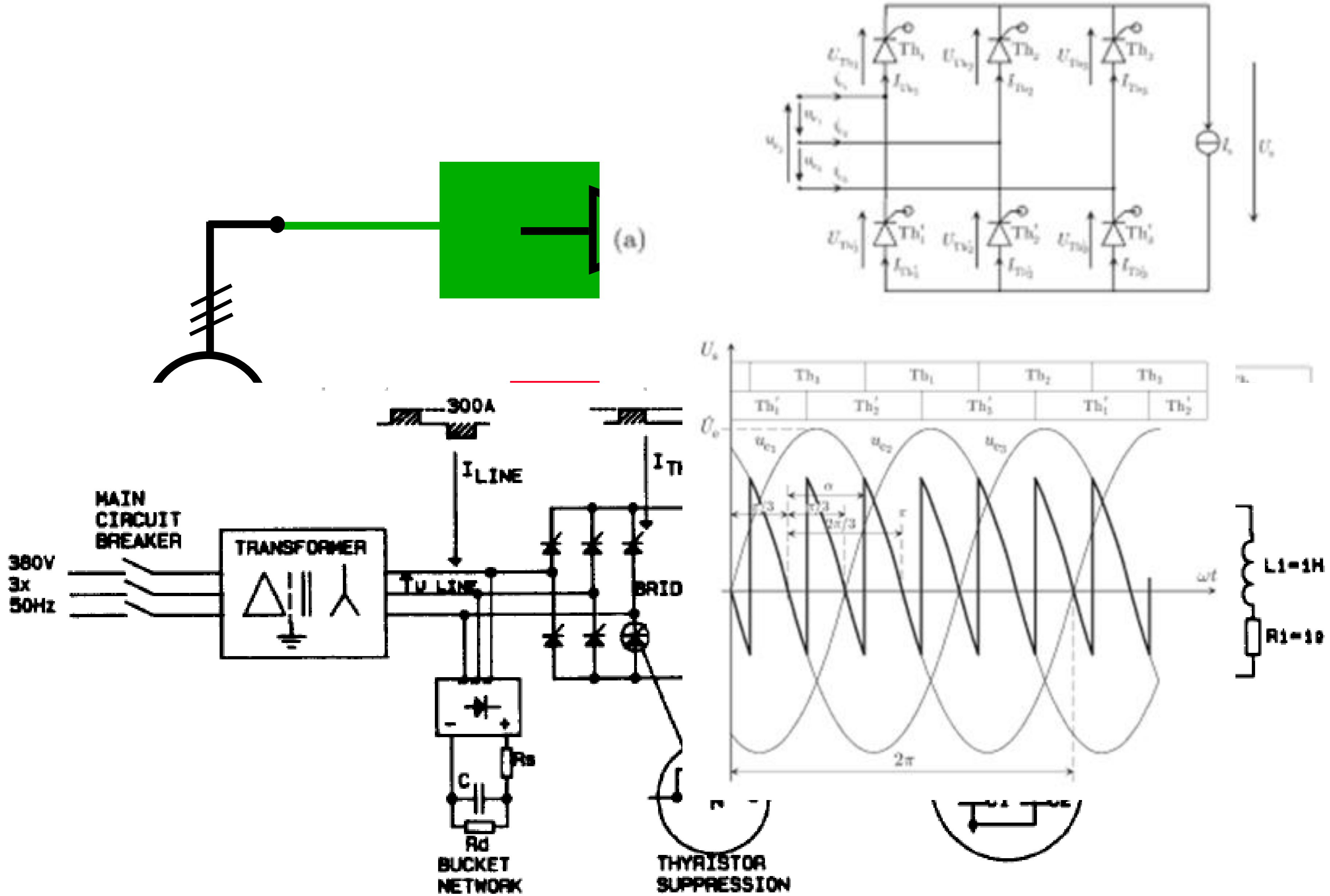


Output Source

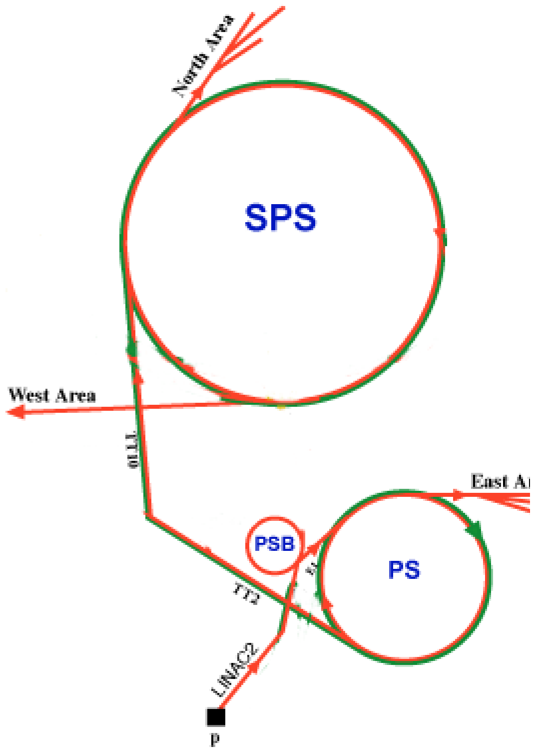


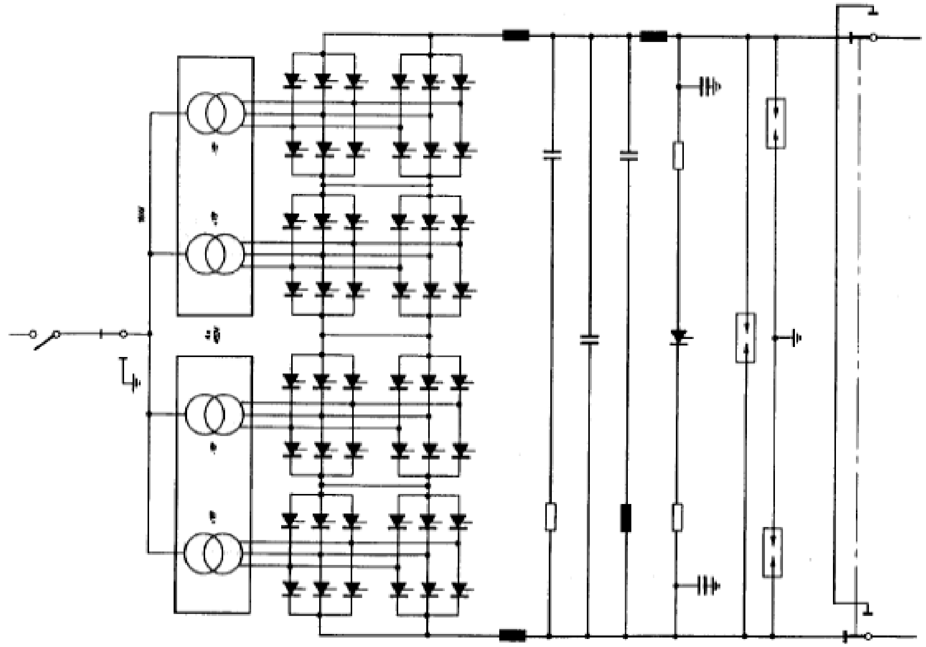
General power converter topologies

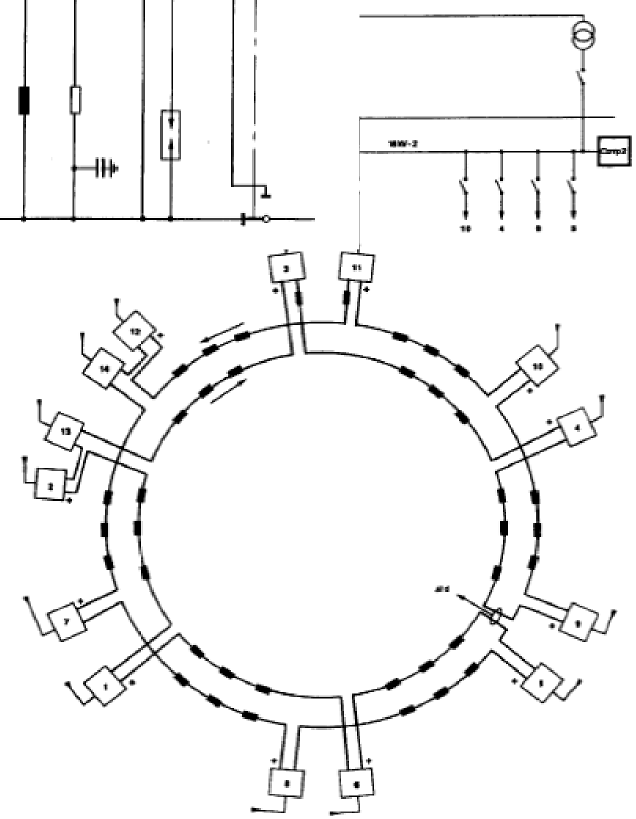
Direct Converters : Rectifiers



SPS Main power converters

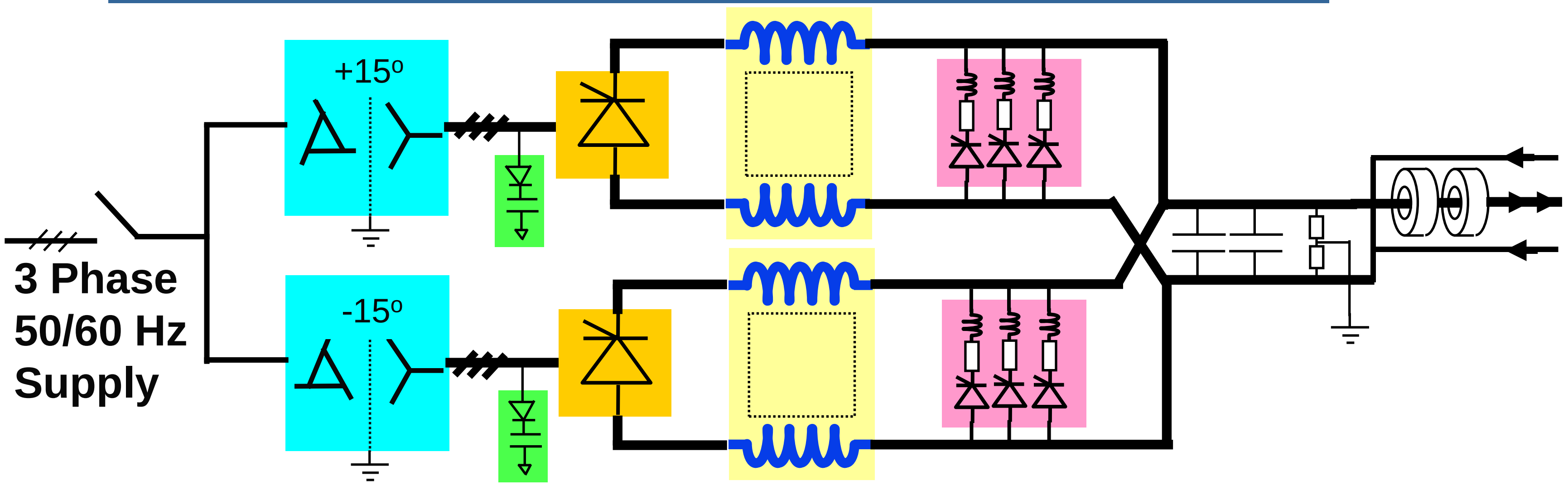


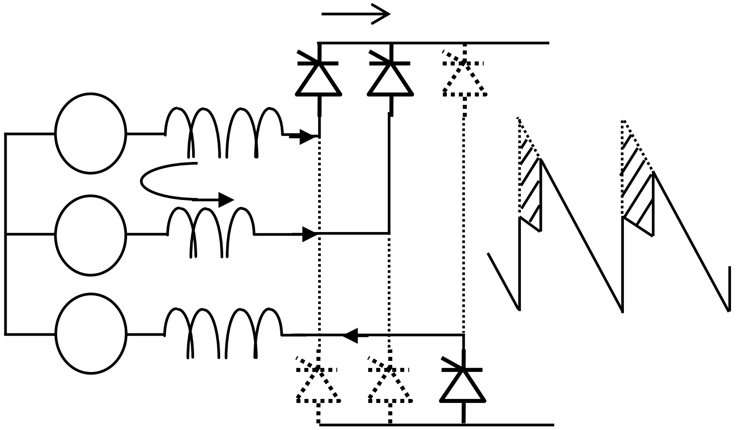


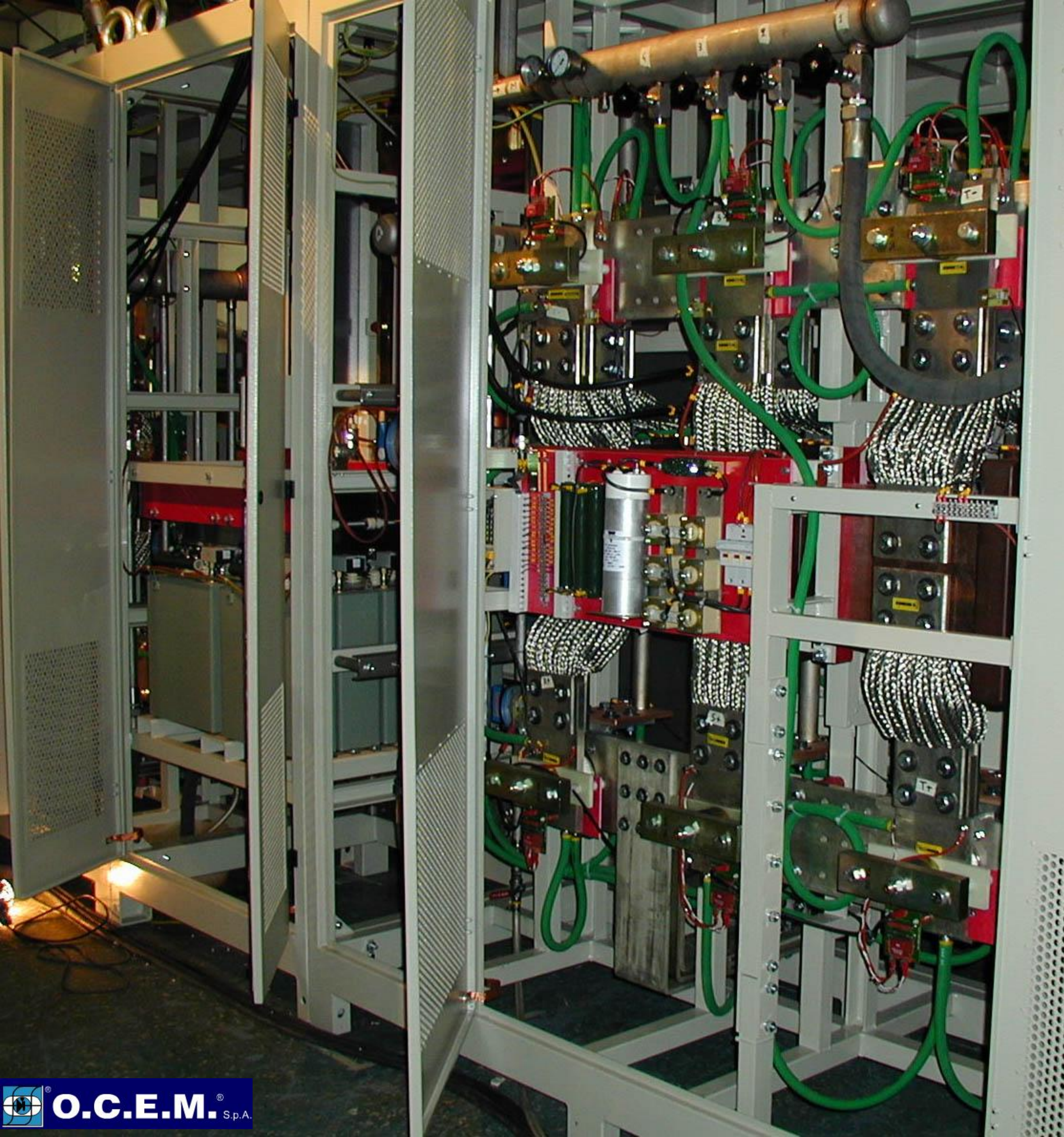


Main power converters
12 x [6kA, 2 kV]

Two Quadrant Phase Controlled Rectifiers for high current SC magnets

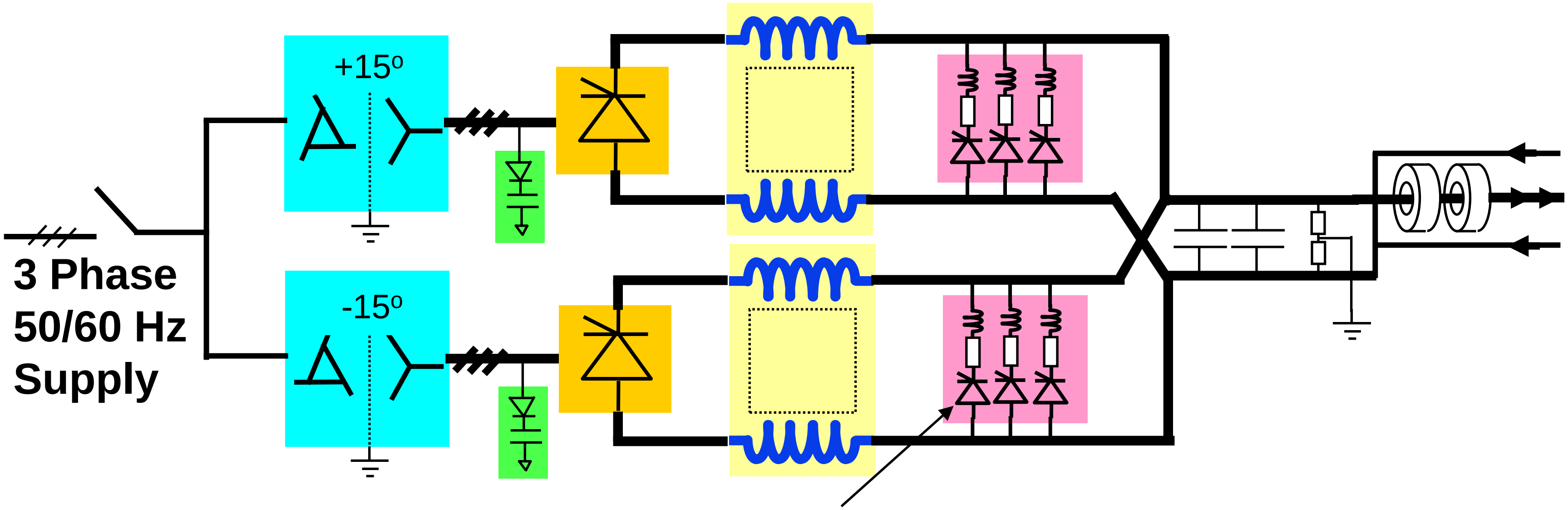






O.C.E.M. S.p.A.

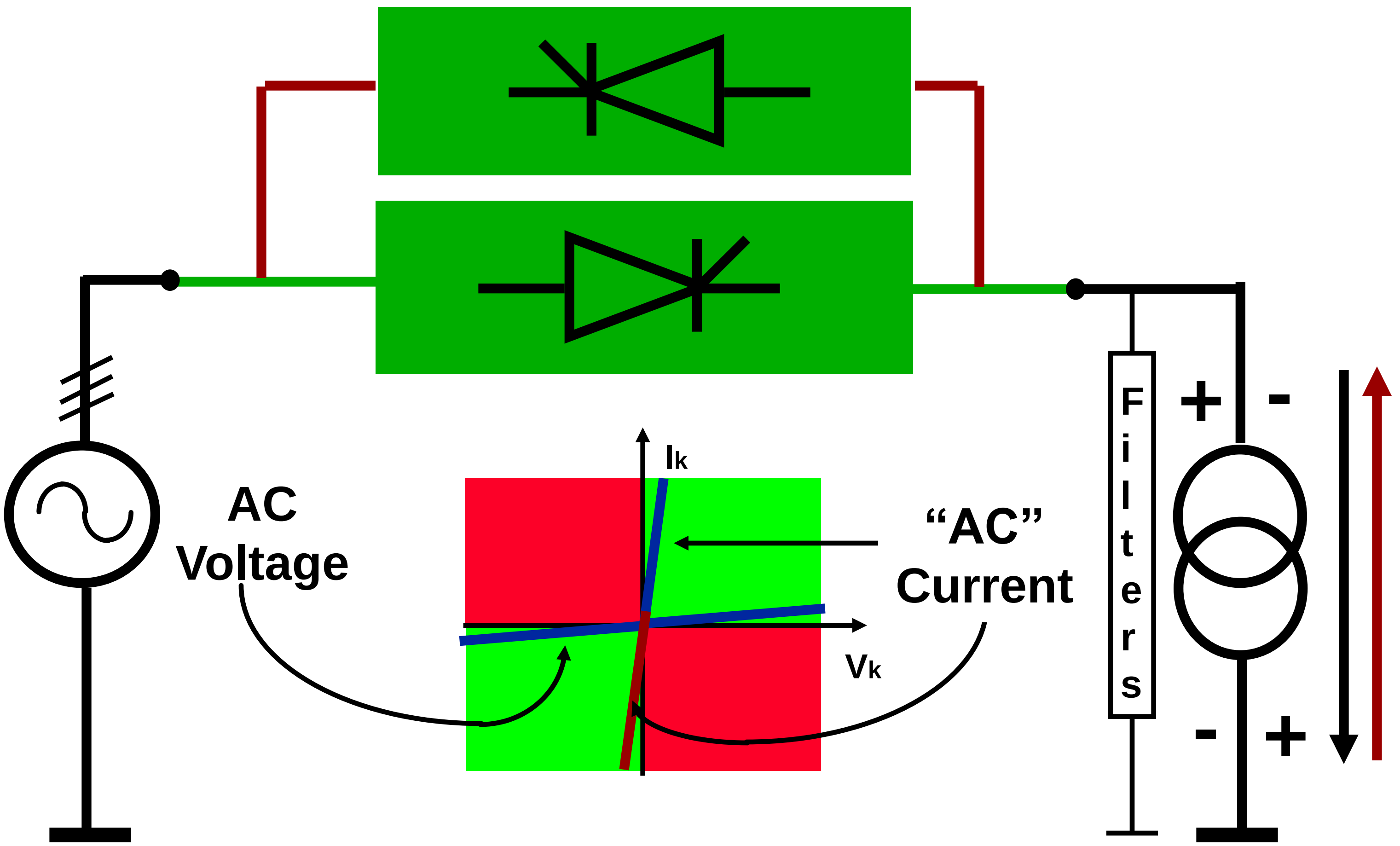
Phase Controlled Rectifiers for high current SC magnets



Free-wheeling path

- **Vital component to assure discharge of magnet.**
- **In the case of thyristors (two quadrant operation), must have reliable firing with avalanche back-up. (Good idea to have same on main bridge thyristors)**
- **Need correct sharing devices, static and dynamic.**
- **Must survive mains failure and no cooling water.**

Direct Converters : Rectifiers



Direct Converters : Phase Controlled Rectifiers

☺ very high power capability

☺ moderate prices and competitive market

☺ simple structure, well understood (but care needed with high currents)

☹ three phase transformer operates at low frequency (50 or 60 Hz)

☹ variable power factor from 0 to 0.8

☹ harmonic content on input current

☹ response time is large (ms)

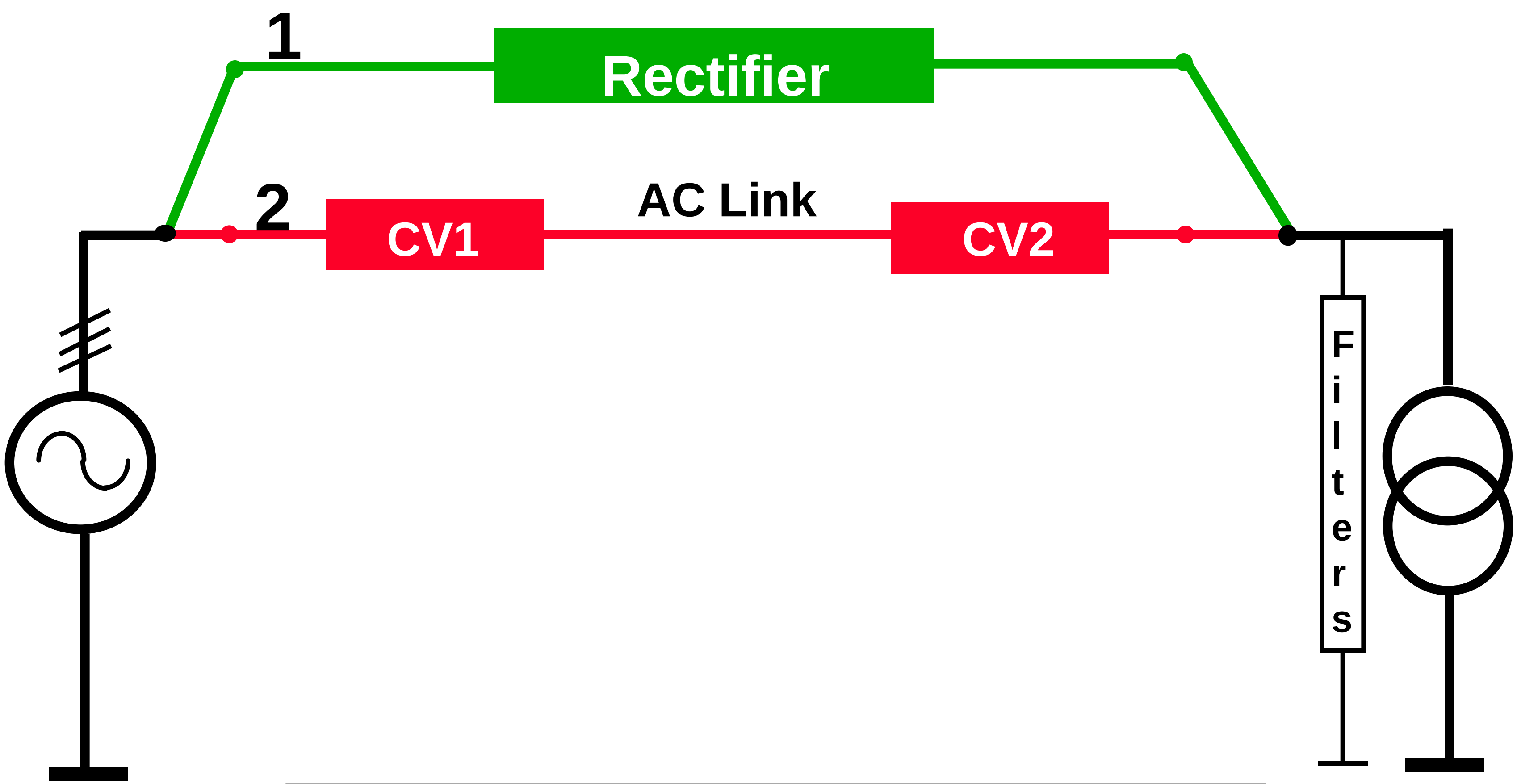
☹ current ripple is large (passive or active filters)

⇒ **passive (active) filters operating at low frequency**

Increase of pulse number (3,6,12,24,48) but

complexity (cost, control,...)

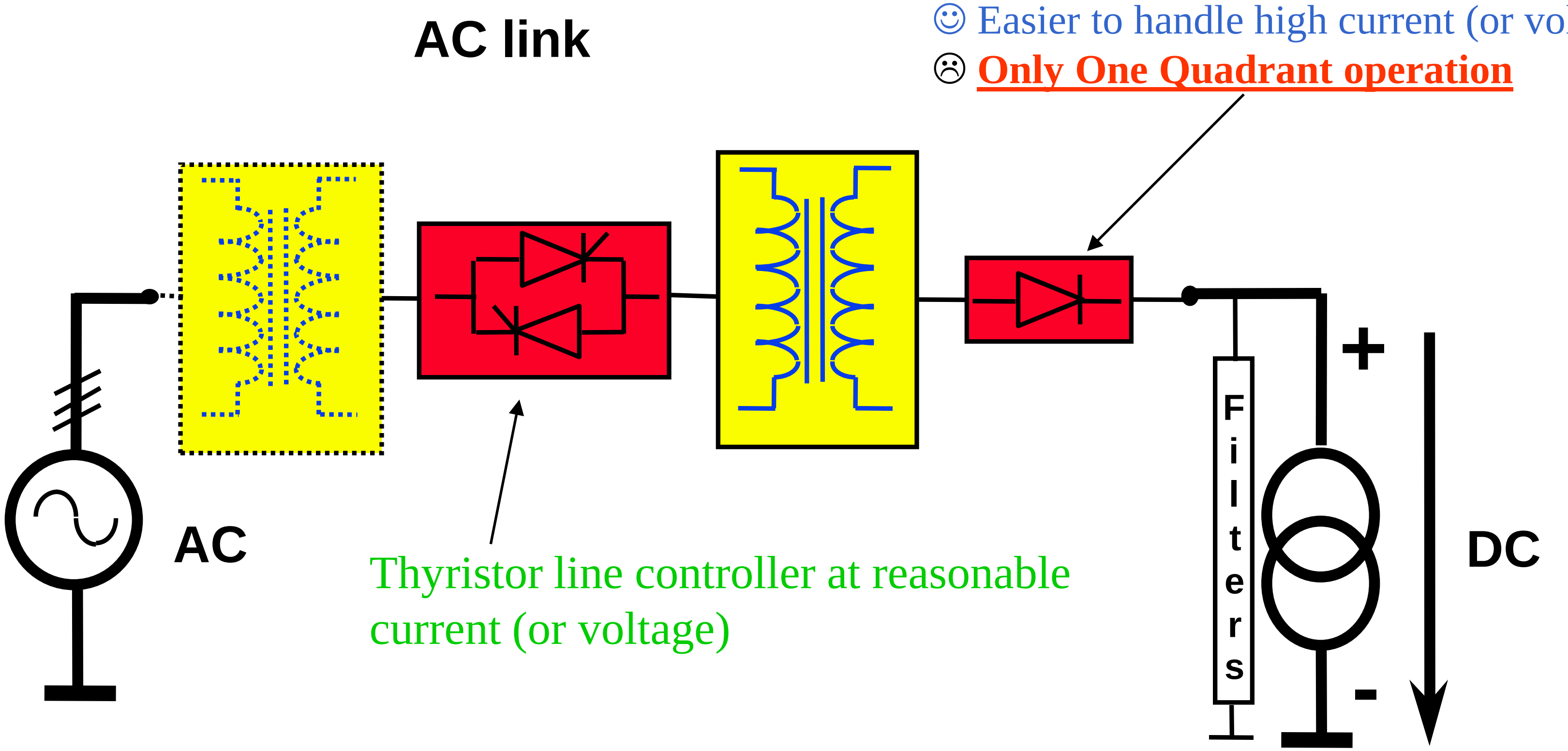
General power converter topologies



Application : - very high currents with low voltages
- (very high voltages with low currents)

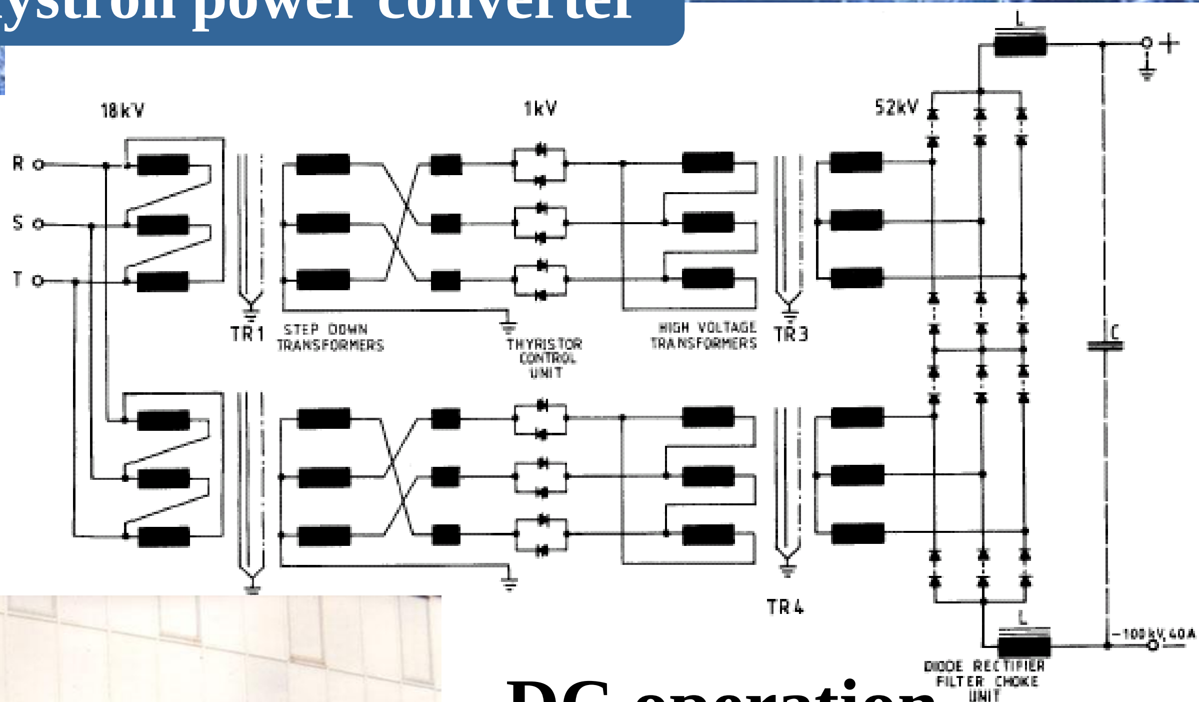
Direct Converters : AC link (AC line controller)

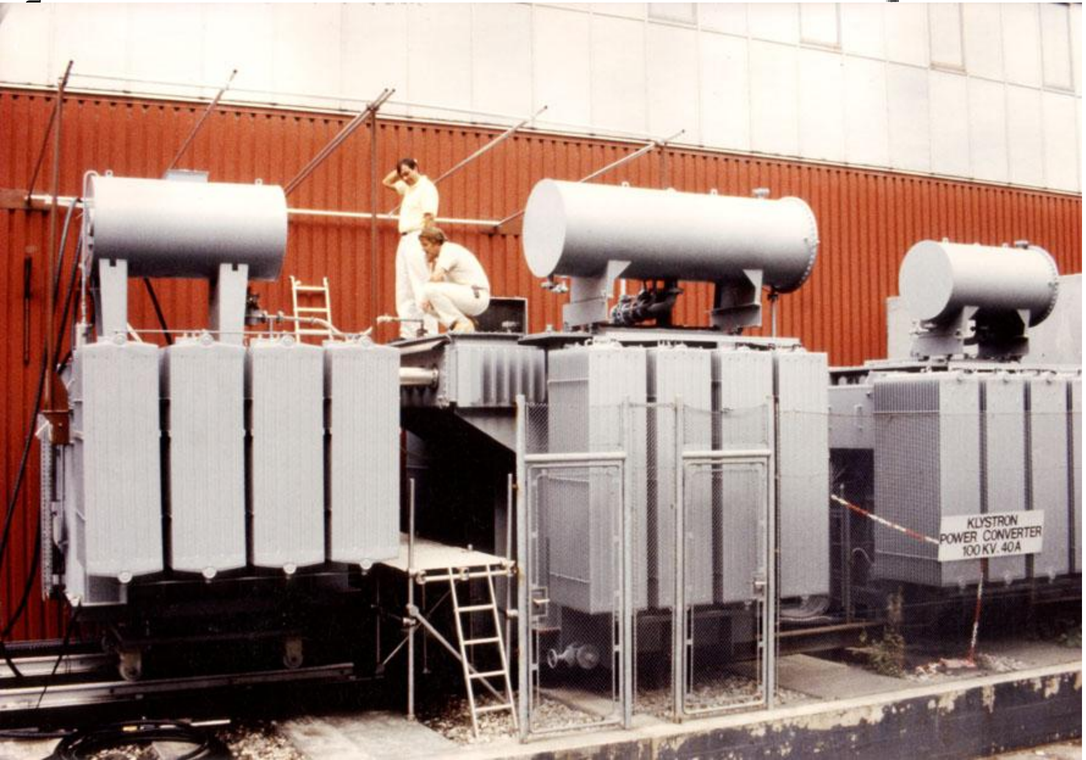
☺ Simple diode rectifier on output stage
☺ Easier to handle high current (or voltage)
☹ **Only One Quadrant operation**



Thyristor line controller at reasonable current (or voltage)

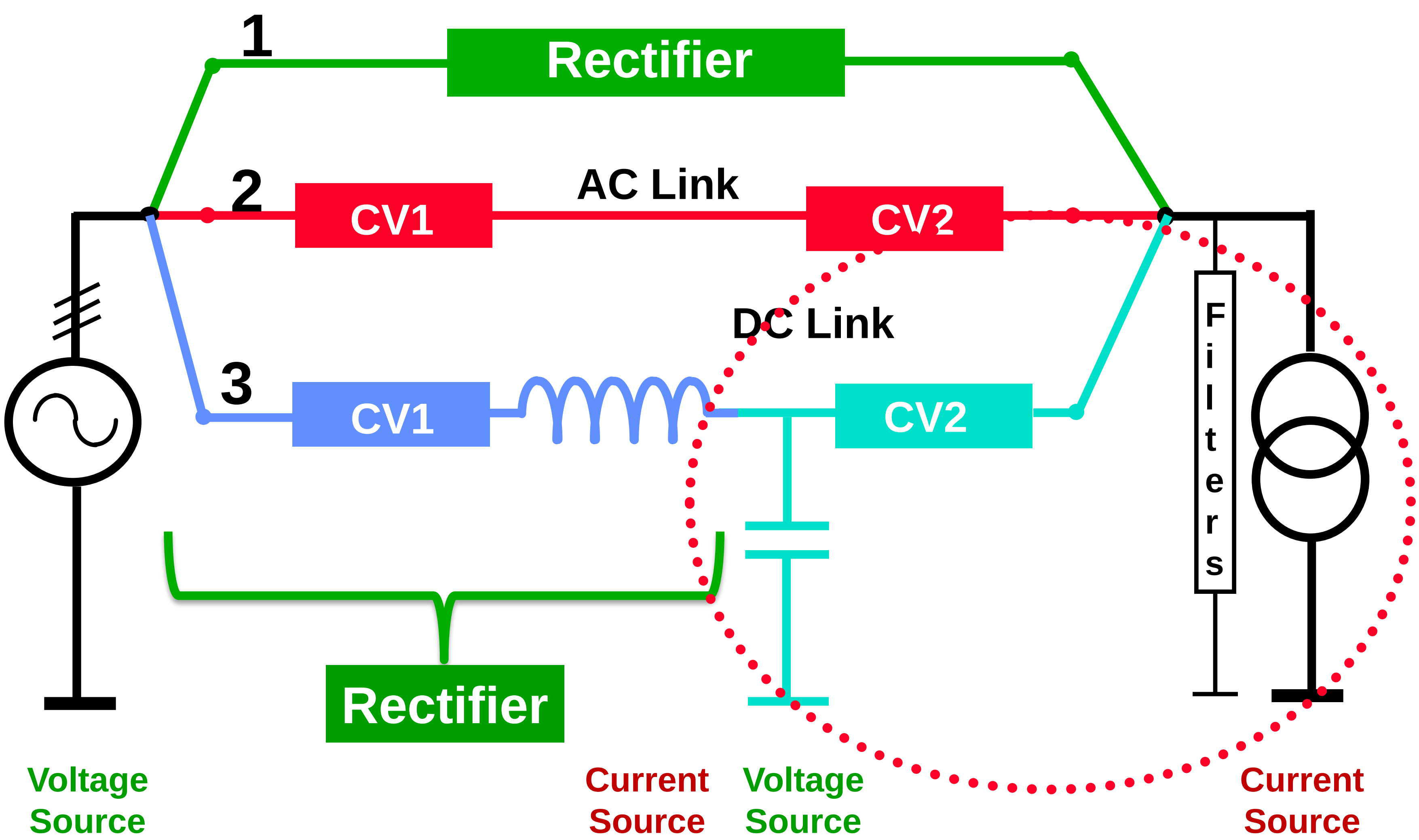
[100 kV, 40A] klystron power converter



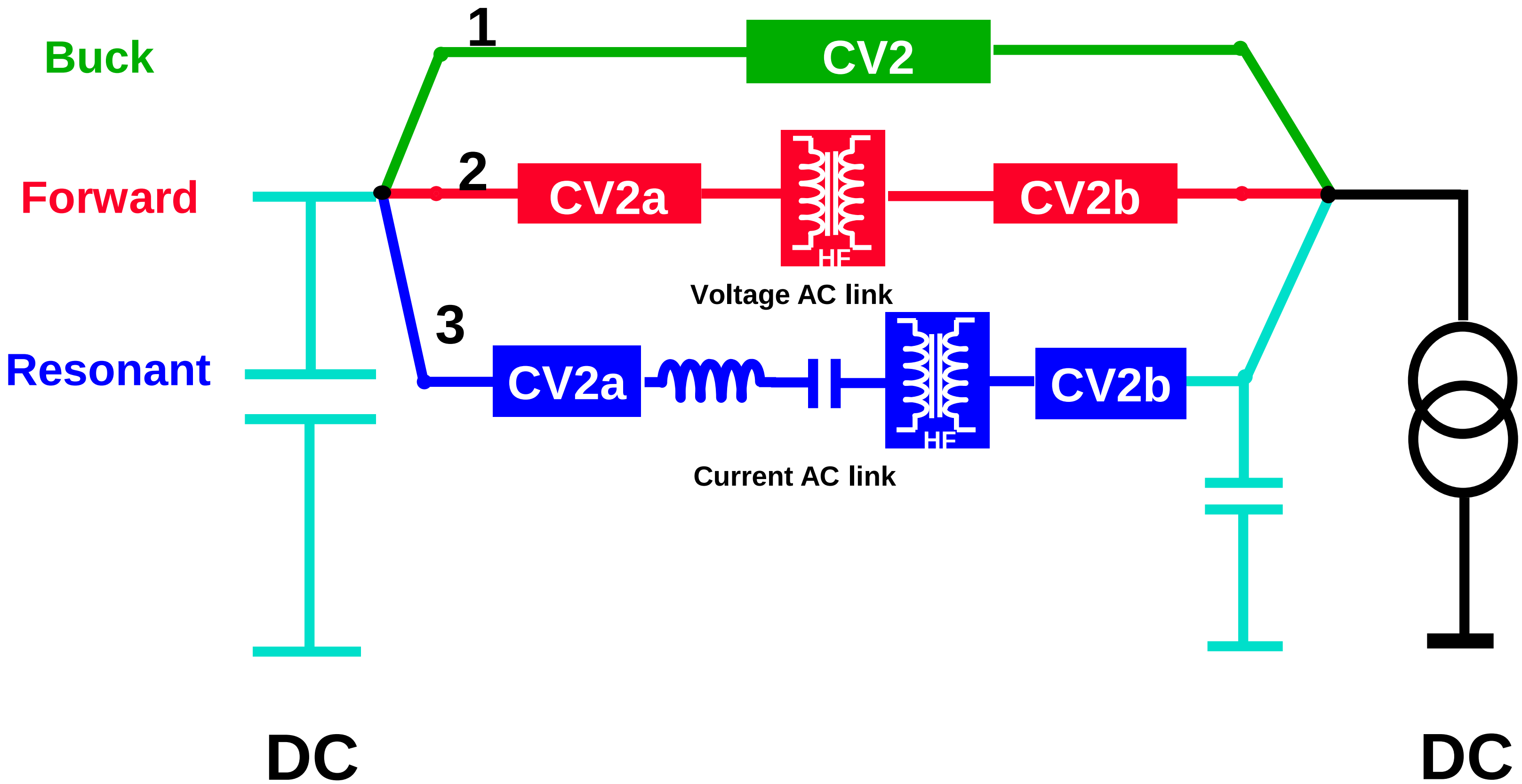


DC operation

General power converter topologies

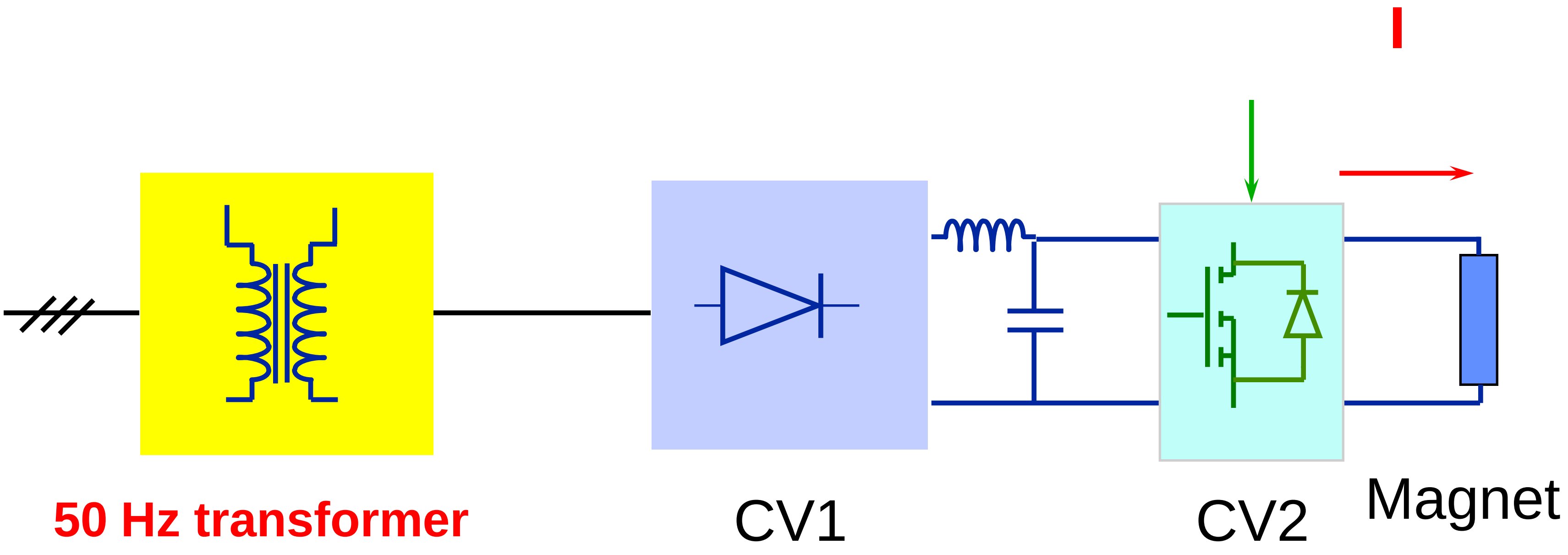


Power converter topologies : DC - DC



DC-AC-DC converter

Galvanic isolation at AC input source (50Hz transformer)



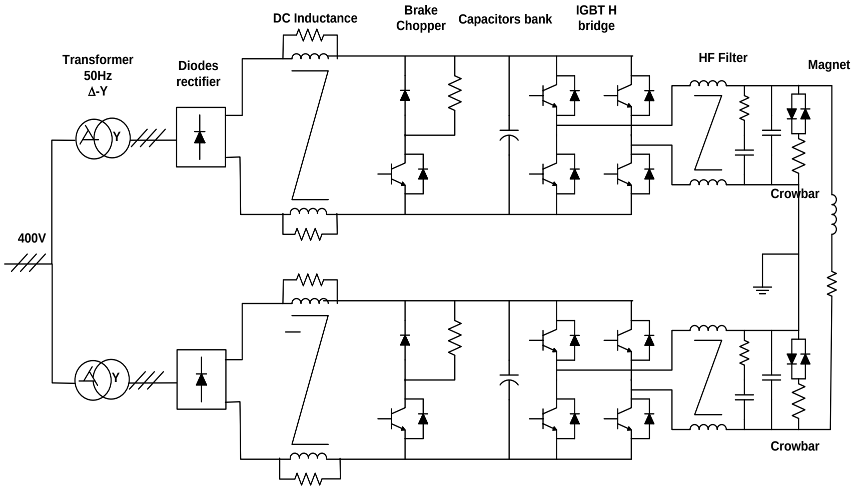
50 Hz transformer
Optimal voltage output
Galvanic isolation

Diode bridge
6 or 12 pulses

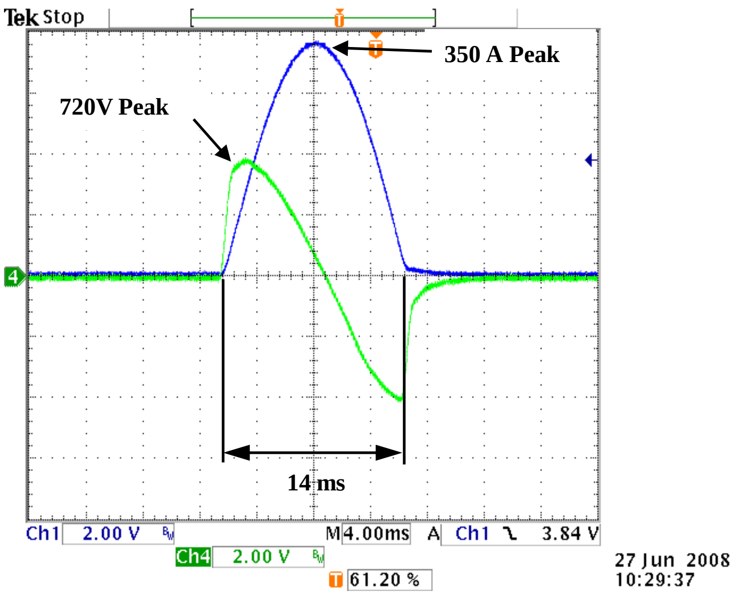
PWM Converter
Hard commutation

New PS Auxiliary Power Converters

Peak Power: 405 kW
Voltage: ± 900V
Max Current: ± 450A



Multi-Turn Extraction: Current/Voltage waveforms



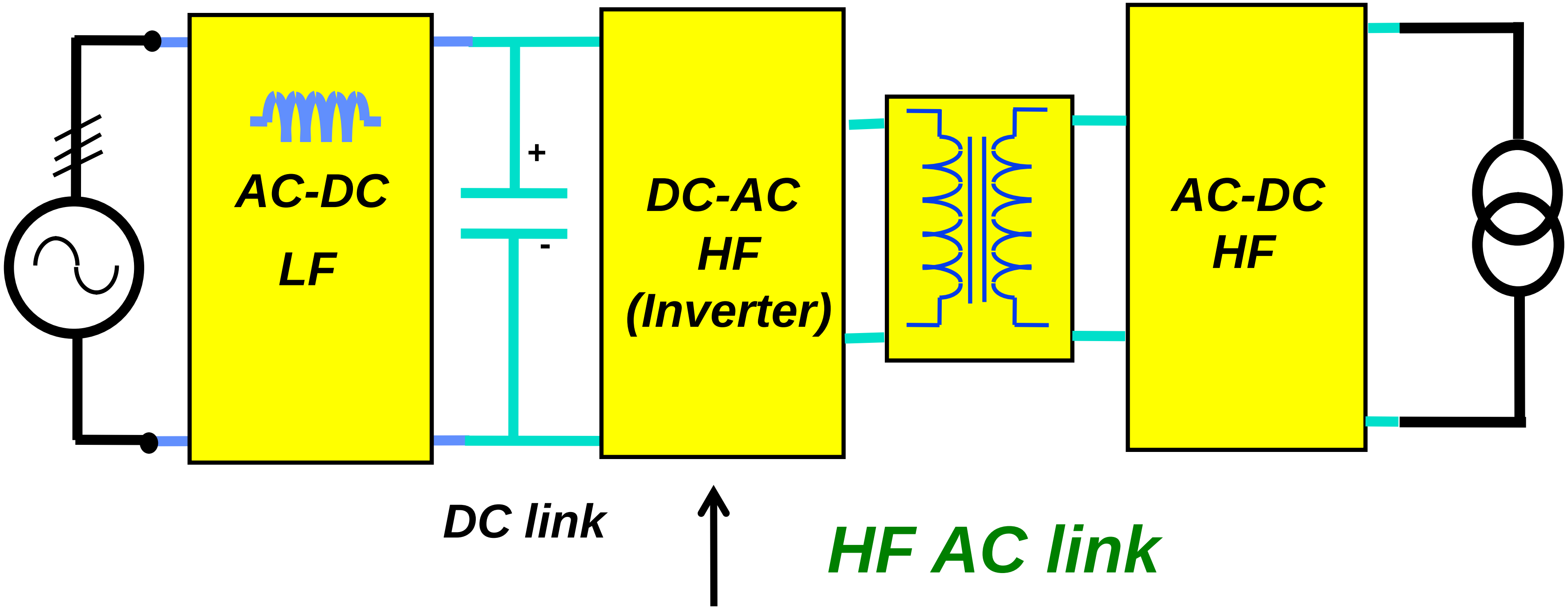
Current Loop Bandwidth ≈ 1kHz

Indirect AC-DC-AC-DC converter

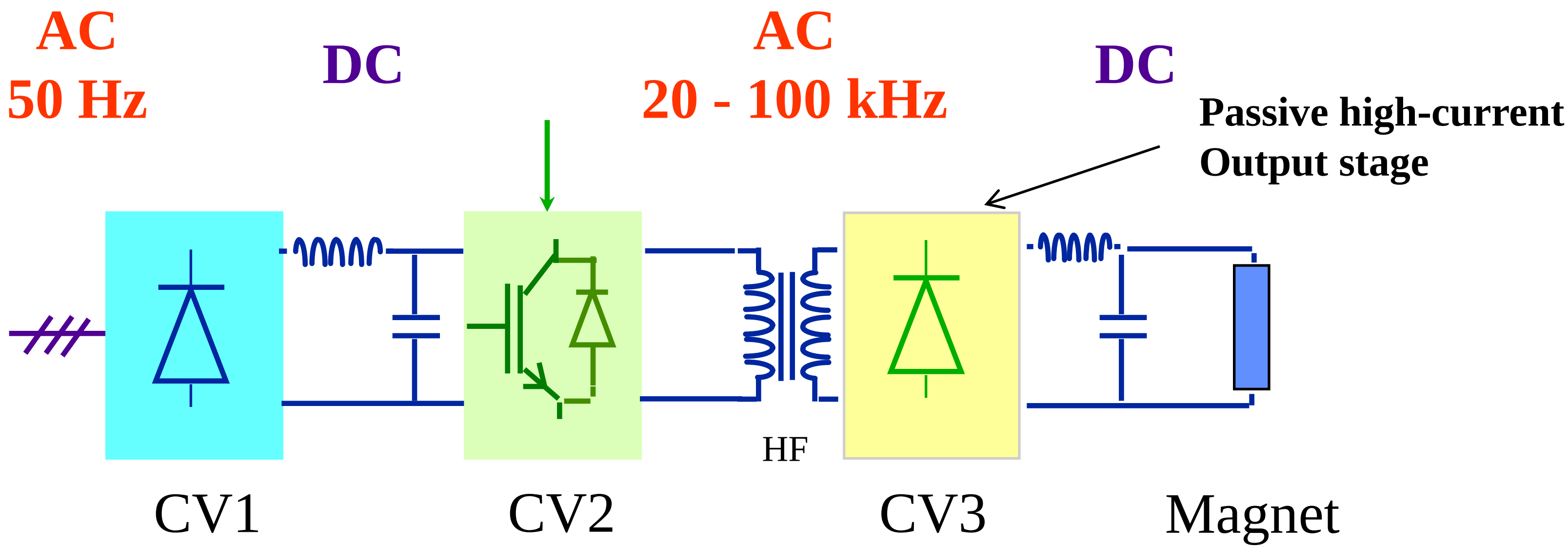
Three cascade power conversion stages:

1) Simple DC source (Diode (thyristor) rectifiers)
2) HF DC-AC converter (Inverter)
3) HF AC-DC converter (Rectifier) (often diode rectifier)

HF transformer to provide the galvanic isolation



LHC Switch-Mode Power Converters



Voltage loop:
bandwidth few kHz

Fast power semiconductors (IGBT)
Semiconductor losses : soft commutation
HF transformer and output filter : ferrite

- **light weight, reduced volume (HF transformers and filters)**
- **good power factor (0.95)**
- **high bandwidth and good response time**
- **Soft commutation gives low losses and low electrical noise**
- **small residual current ripple at output**
- **More complex structure, less well understood, limited number of manufacturers**

LHC:1-quadrant converter: modular approach

1-quadrant converters:
- [13kA,18V] : 5*[3.25kA,18V]
- [8kA,8V] : 5*[2kA,8V]
- [6kA,8V] : 4*[2kA,8V]
- [4kA,8V] : 3*[2kA,8V]

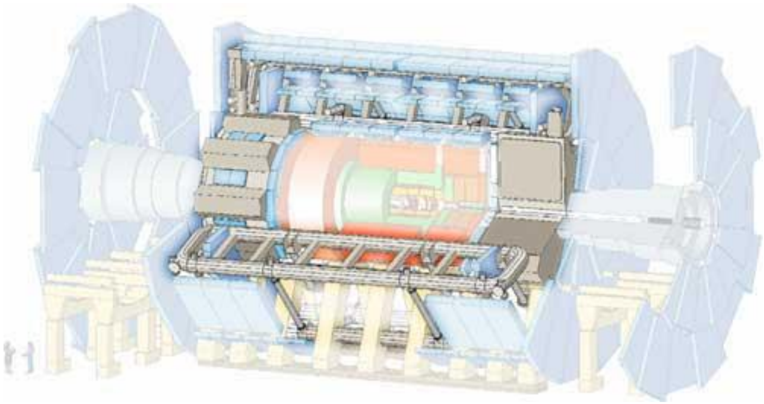
MTBF and MTTR optimization

[2kA, 8V]

20.5kA power converter for the ATLAS toroid

The load

- Superconducting magnet: L= 7.5 H
- Nominal current: 20.5 kA
- Stored energy: 1.6 GJ
- Time constant: 37'500 s



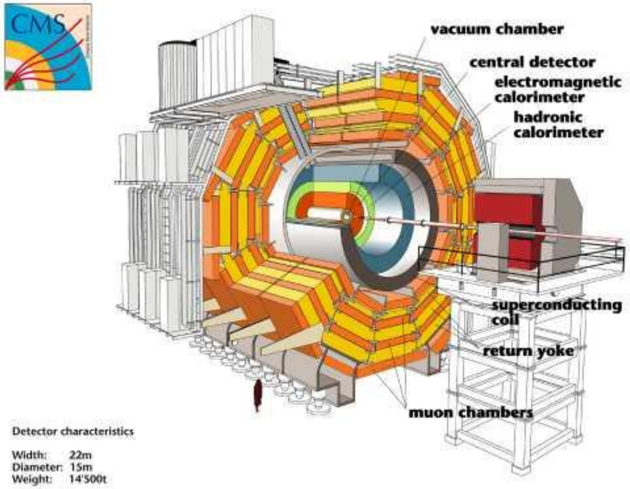
The power converter : *[20.5 kA, 18V] ; (7+1) x [3.25kA,18V]*

20kA power converter for the CMS solenoid

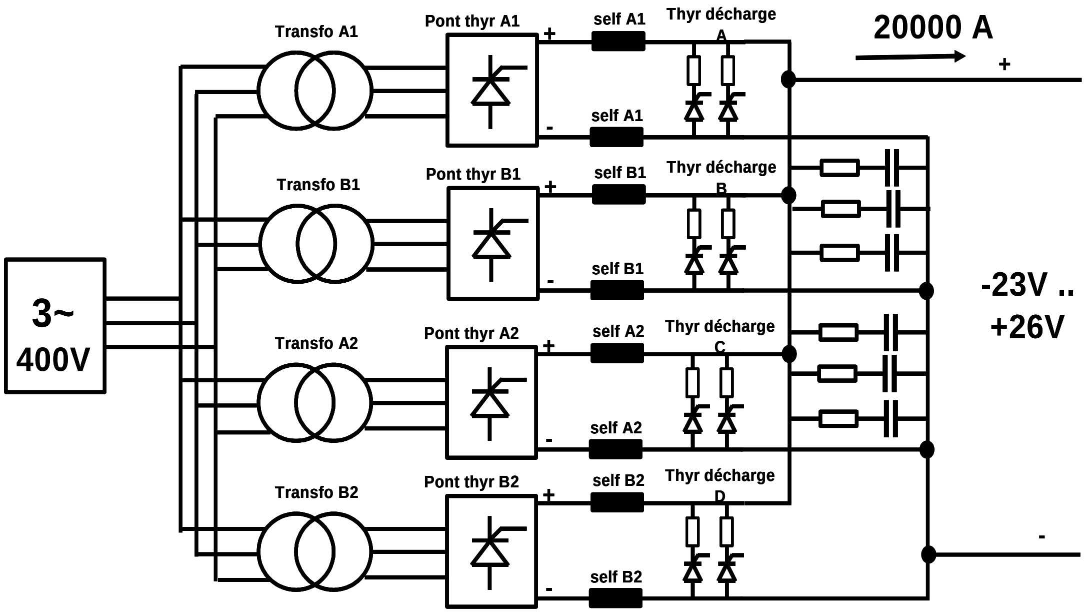
The load

- Superconducting magnet: L= 14H
- Nominal current: 20 kA
- Stored energy: 2.8 GJ
- Time constant: 39 hours
- Time for current ramping up: 3h15m

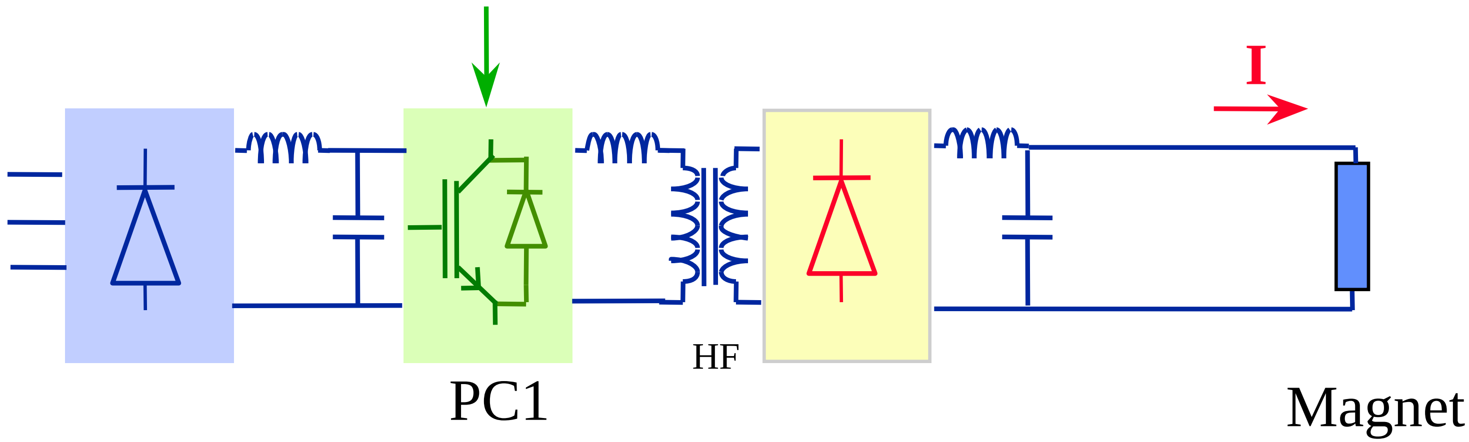
- Energy extraction system (resistor bank, not shown)



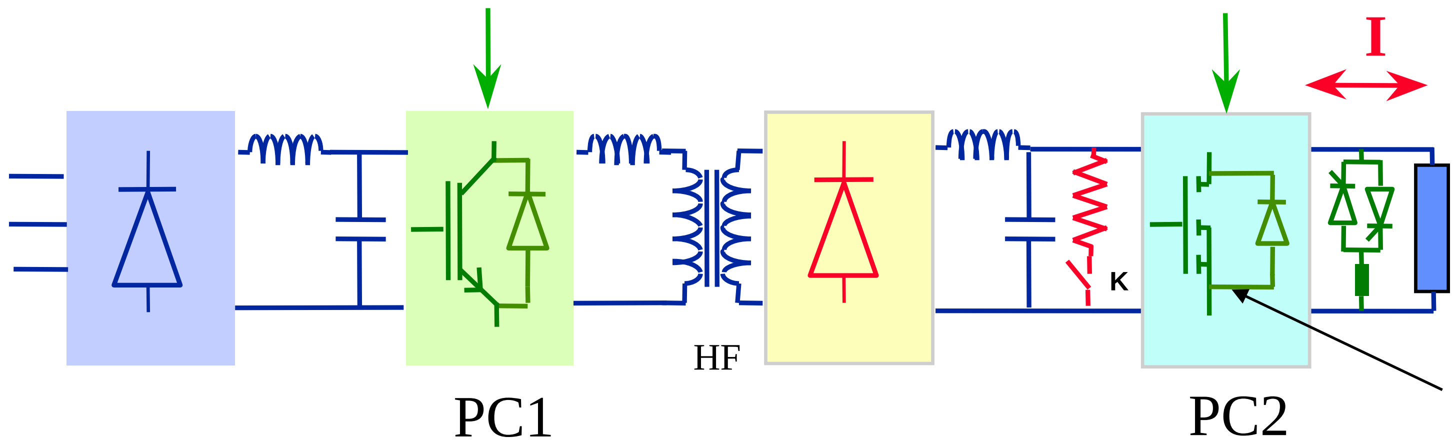
The power converter

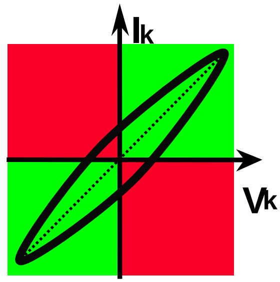


LHC:4-quadrant converter topology



1-quadrant converter





Difficult to find suitable switch

4-quadrant converter

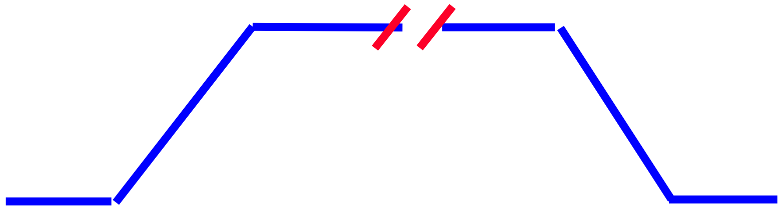
LHC:4-quadrant converters

[600A, ±10V]
2 converters per rack

[600A, ±40V]
1 converter per rack

[120A, 8±V]
Up to 4 converters per rack

DC and slow pulsed converters



Rise and fall time < few ms

Control of the ramps

High and medium power

Phase Controlled Rectifiers

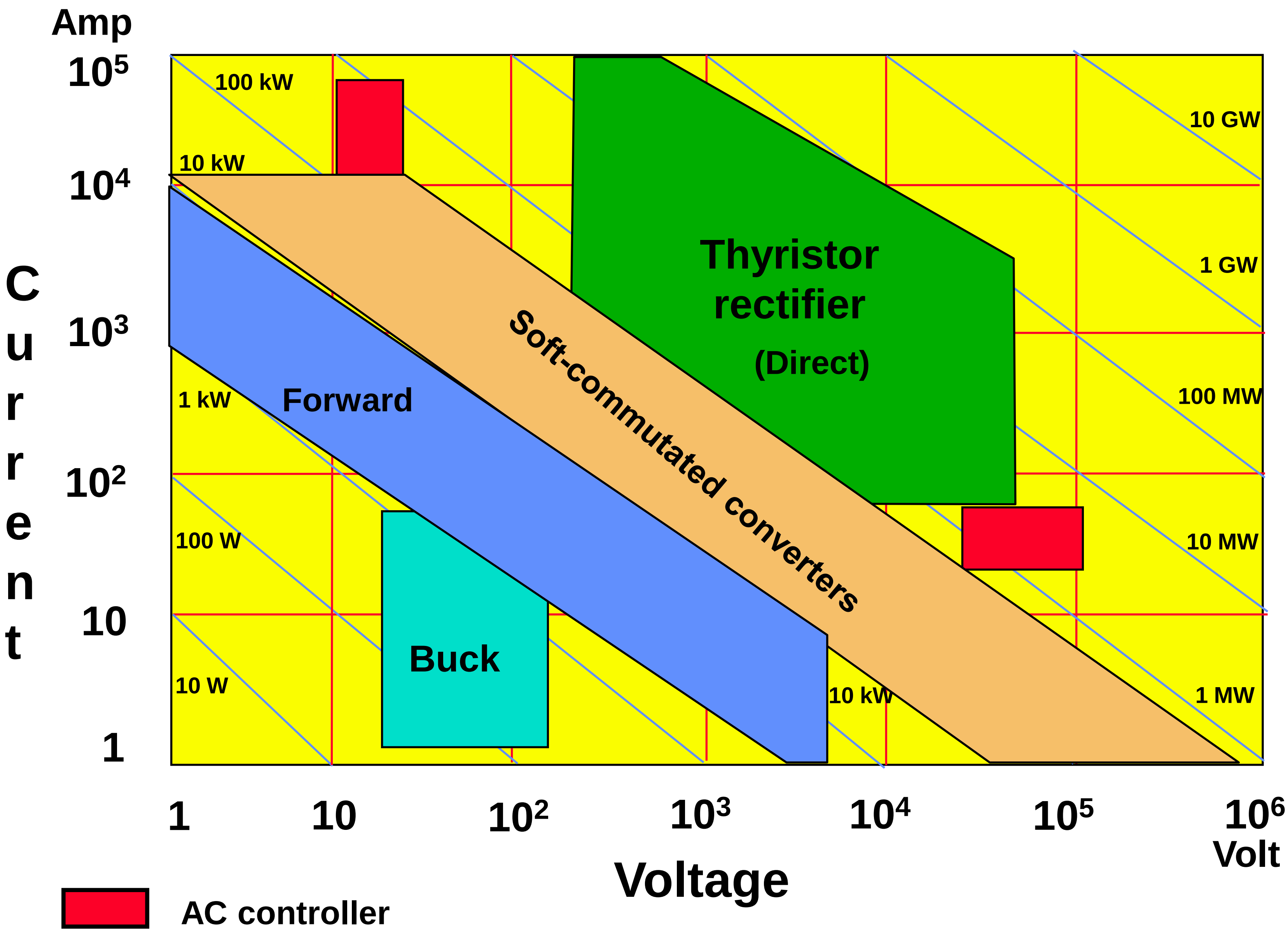
- Diodes and thyristors rectifiers
- 50Hz transformers and magnetic component (filters)
- 1-quadrant and 2-quadrants (but unipolar in current) : energy back to the mains
- 4-quadrant: back-to-back converters

Low and Medium power

Switch-mode power converters

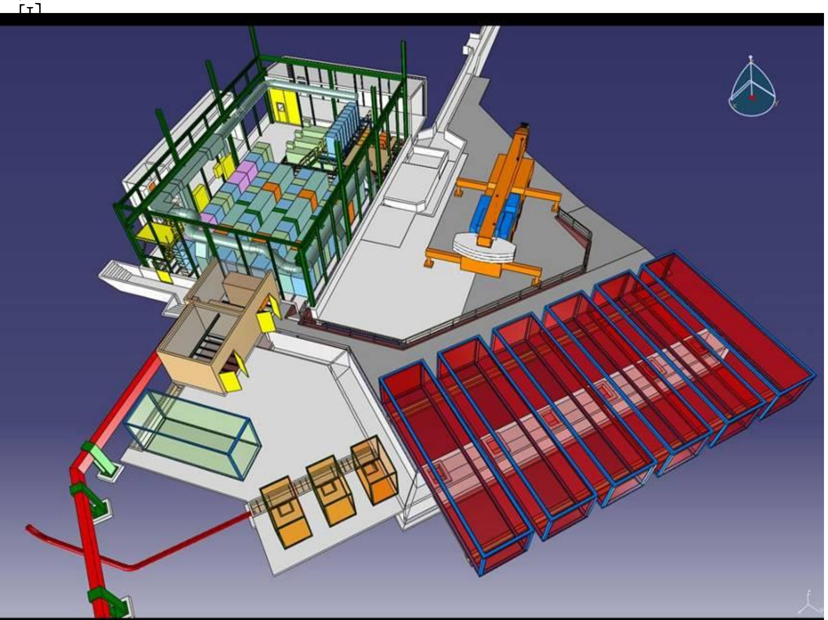
- Mosfets , IGBTs, IGCTs,… turn-off semiconductors
- HF transformers and passive filters
- excellent for 1-quadrant converter
- 4-quadrant converters but with energy dissipation (very complex structure if energy back to mains)

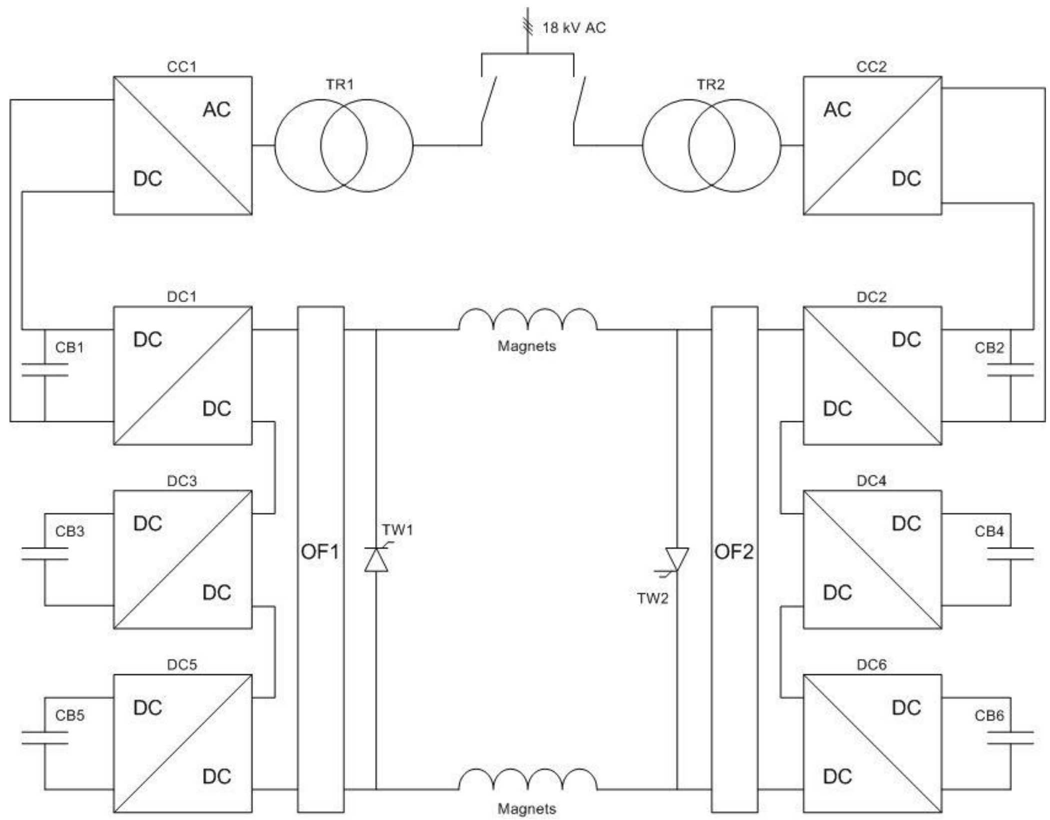
Power converter : Operational domains for accelerators



New Power converter for PS (60 MW)

New PS power system (POPS)
Fully static power converter
Exchange of energy between
capacitor banks and the magnets

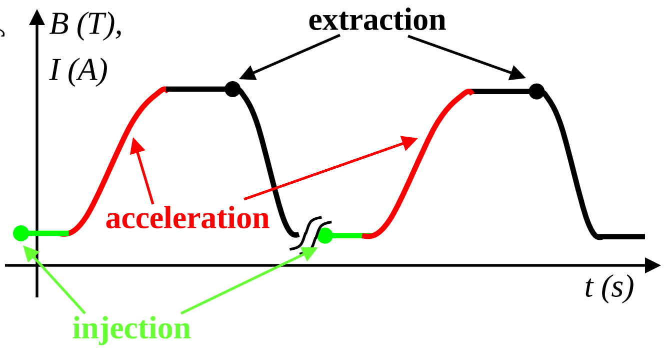




Pulsed converters

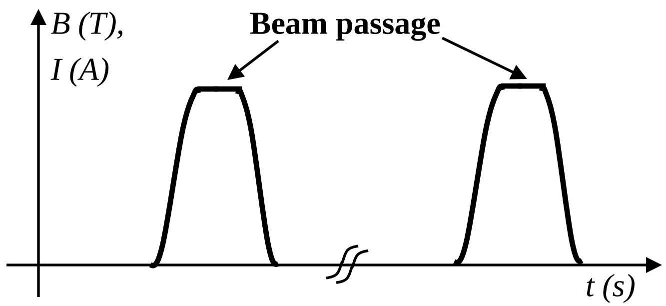
Synchrotrons

• Beam is injected, accelerated and extracted in several turns;



Linac's and transfer lines

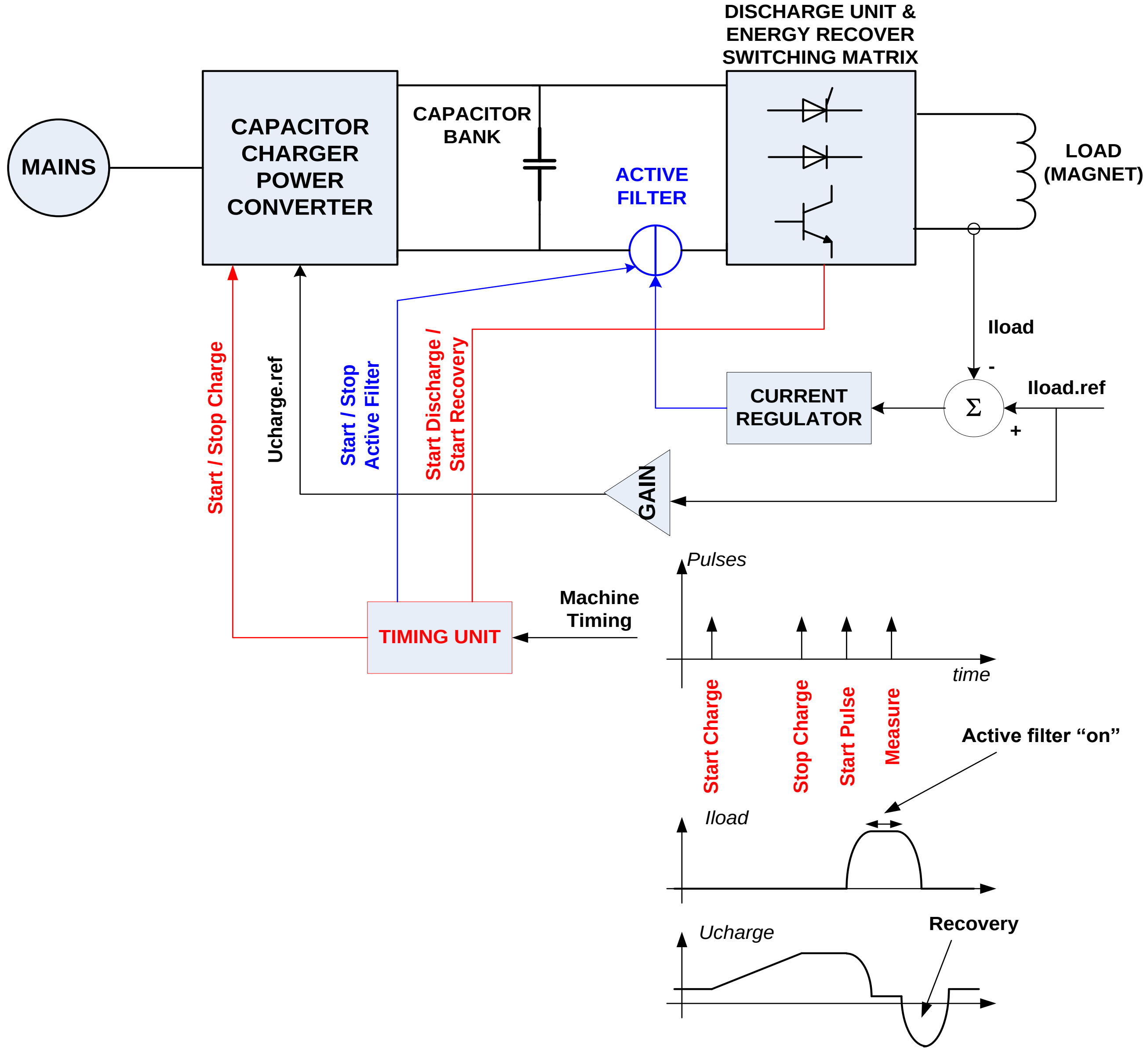
• Beam is passing through in one shot, with a given time period;



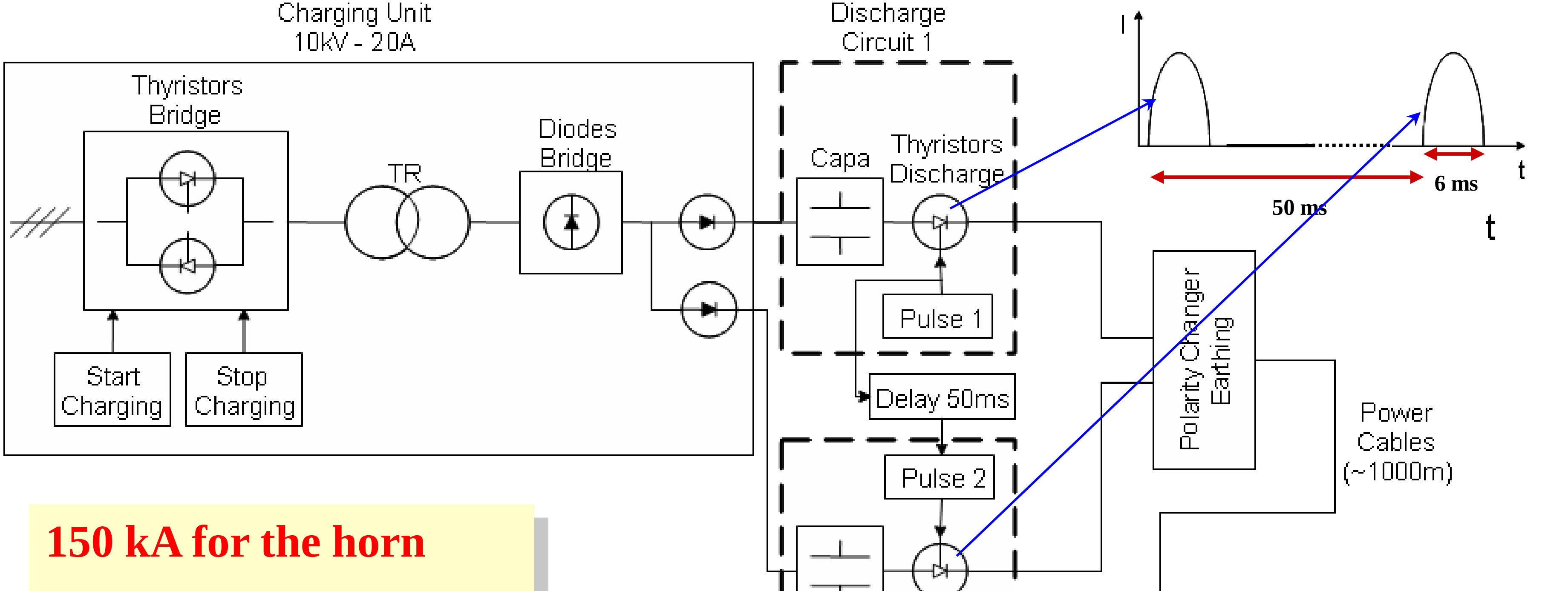
Rise and fall time < few ms

Direct Energy transfer from mains is not possible:
Intermediate storage of energy

Block schematic of a fast pulsed converter



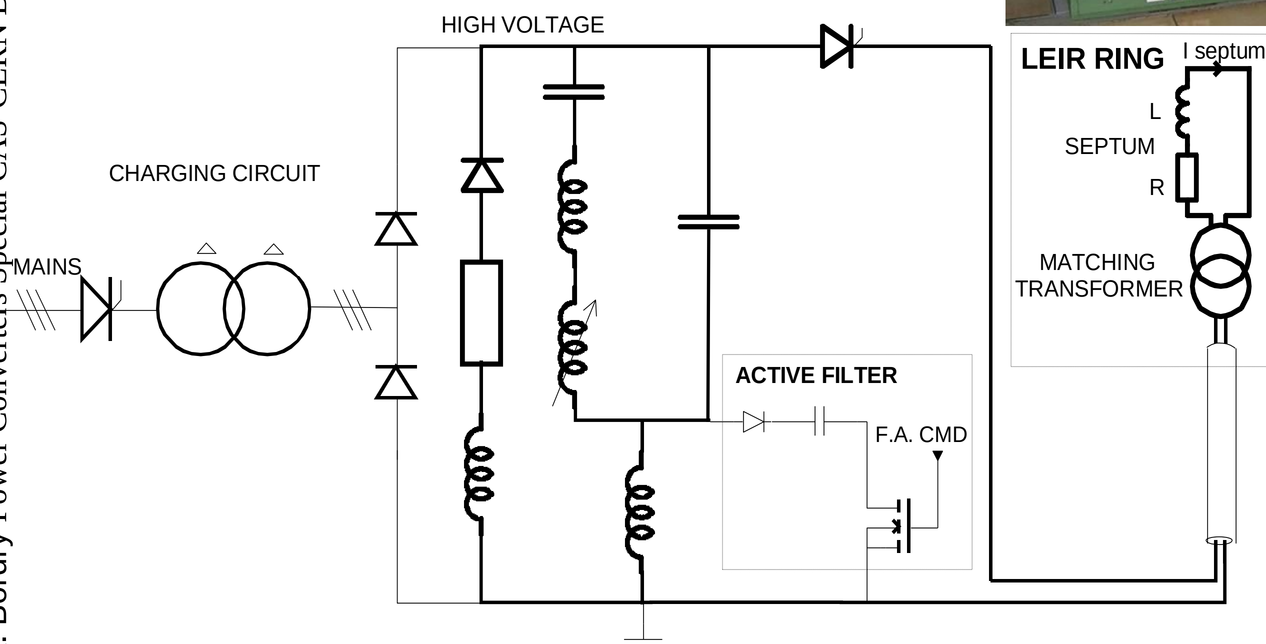
High current, high voltage discharge capacitor power converters

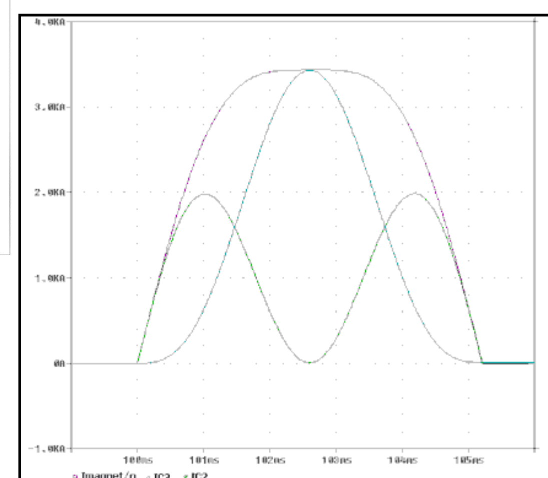


150 kA for the horn

180 kA for the reflector

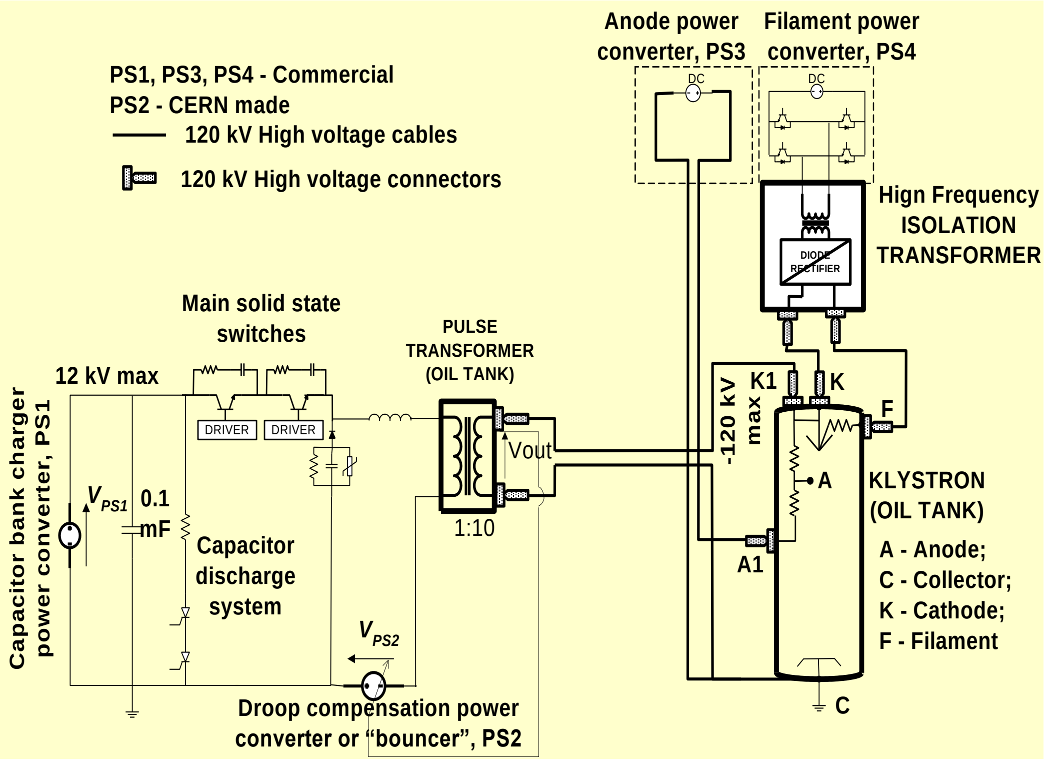
- Characteristics :
  - output current : 33.7 kA
  - flat top stability < 3.10^{-4}
  - charging voltage : 2.1 kV
  - 1 Hz repetition rate

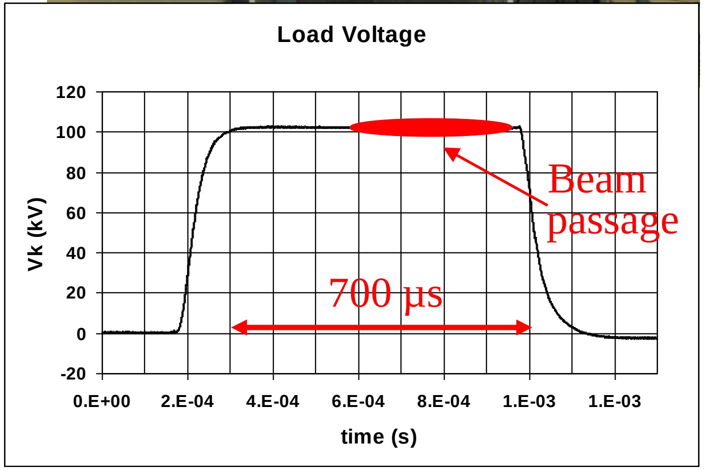




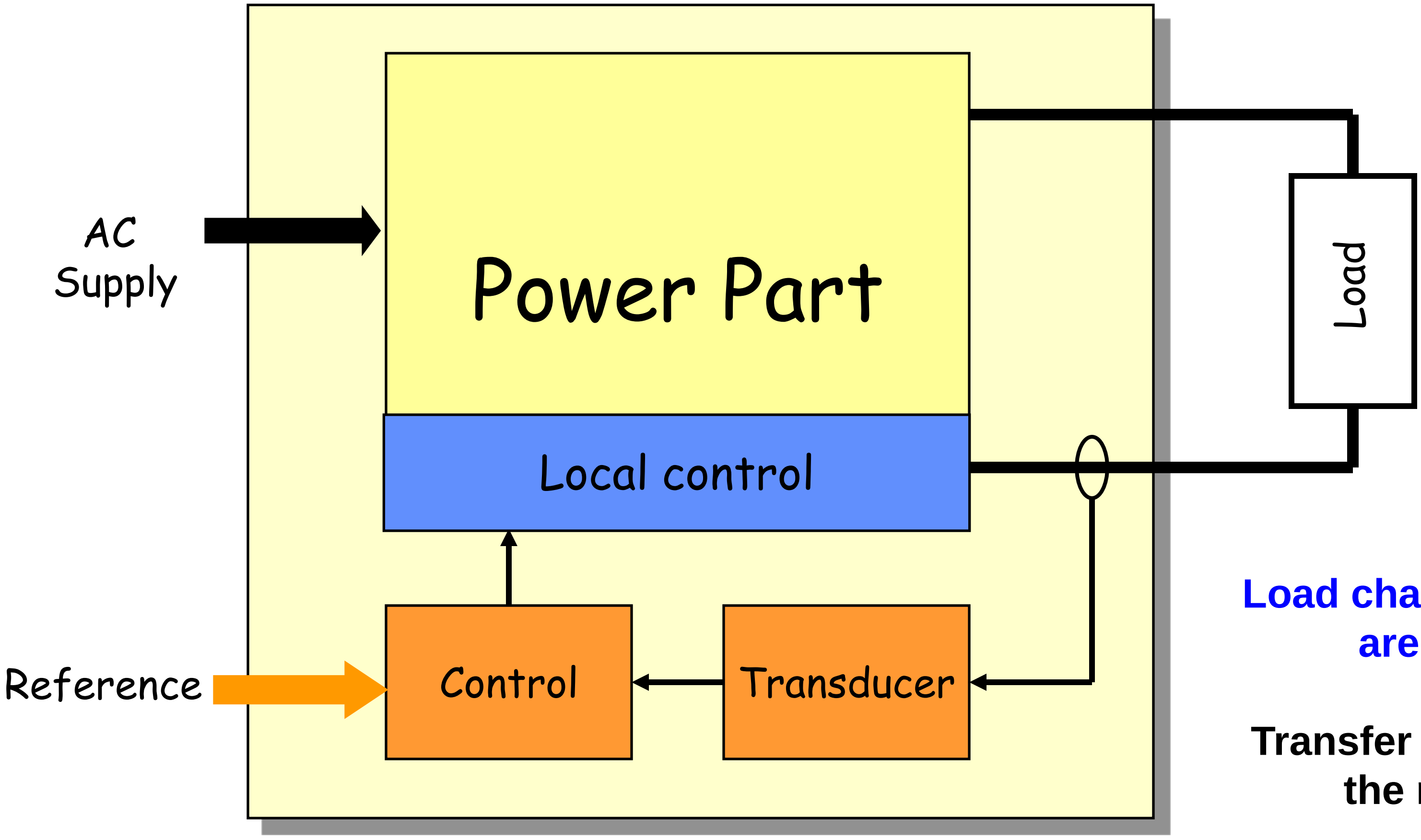
Pulsed Klystron modulators for LINAC's (ex. Linac 4)

- Characteristics :
  - output voltage : 100 kV
  - output current : 20 A
  - pulse length : 700 μs
  - flat top stability : better than 1%
  - 2 Hz repetition rate





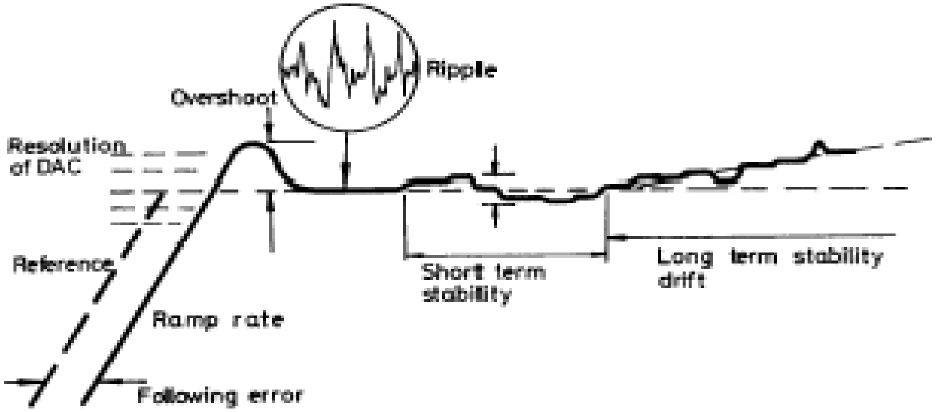
Power Converter % Load

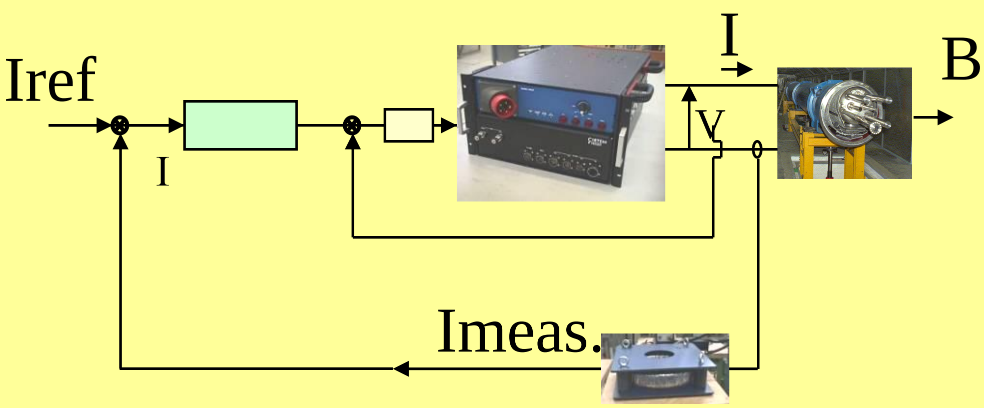


Load characteristics are vital.

Transfer function is the must !

Power converter :Performance requirements





Resolution

Overshoot

Bandwidth

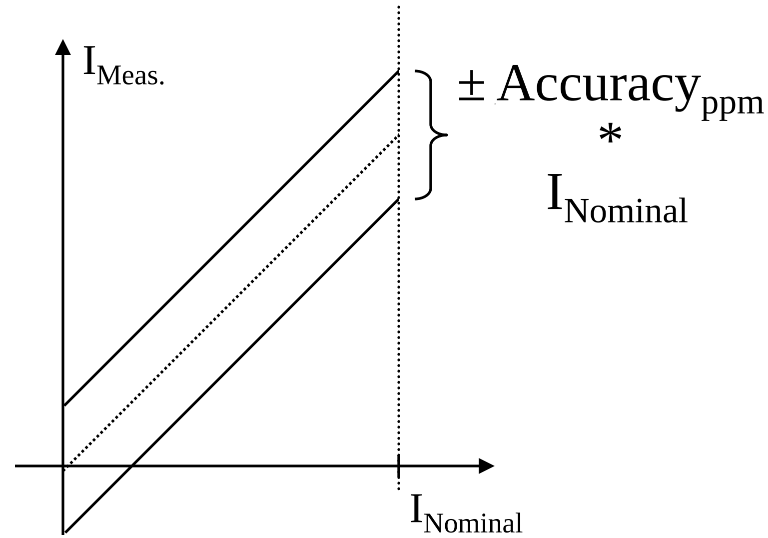
?

Accuracy Reproducibility Stability

Accuracy

Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

***requires definition :**
(e.g. Electrical distribution system perturbation, temperature variation,…)



The accuracy is defined by default for a defined period (Ta) (e.g. one year)

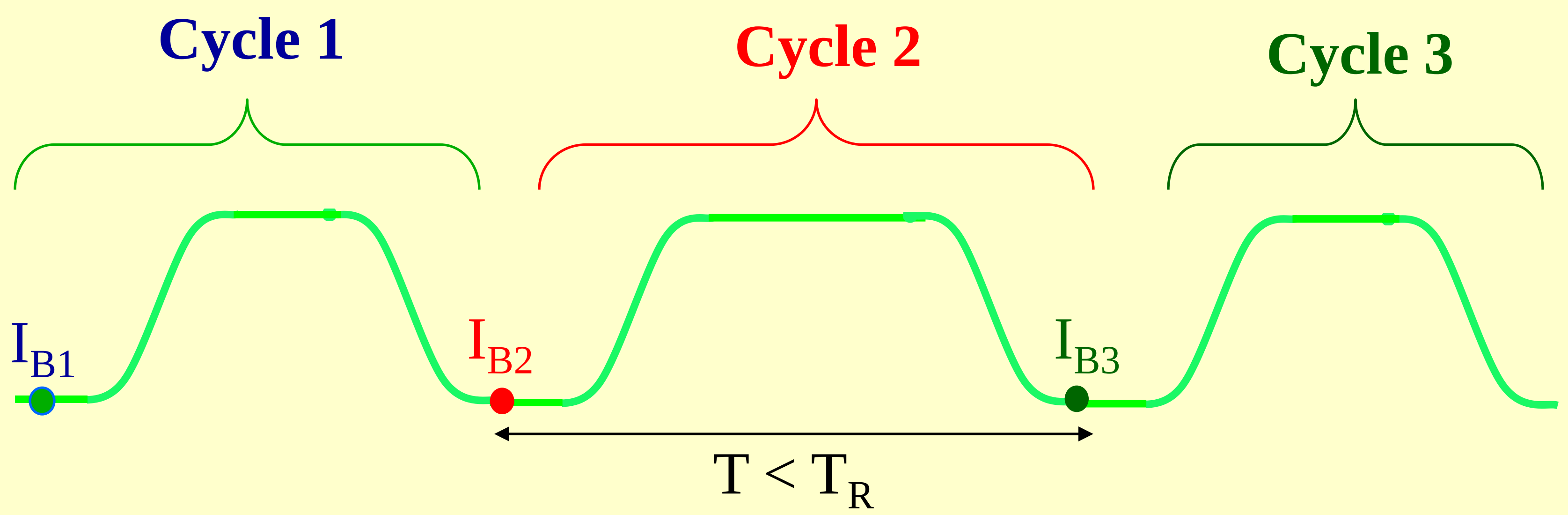
The accuracy is expressed in ppm of $I_{Nominal}$.

If the defined period (Ta) is too large, a calibration process should be executed more often (e.g every month)

Reproducibility

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.

The reproducibility is defined by default for a period of time T_R without any intervention affecting the calibrated parts (e.g. DCCT, ADC)
The reproducibility is expressed in ppm of $I_{Nominal}$.

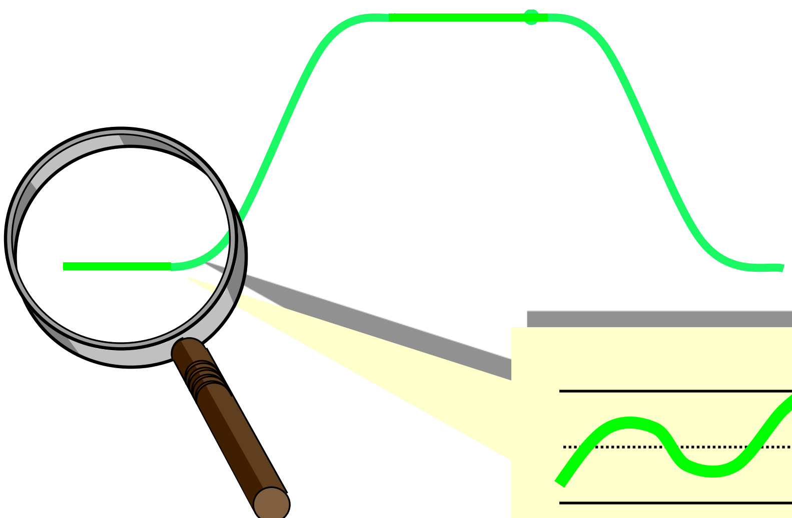


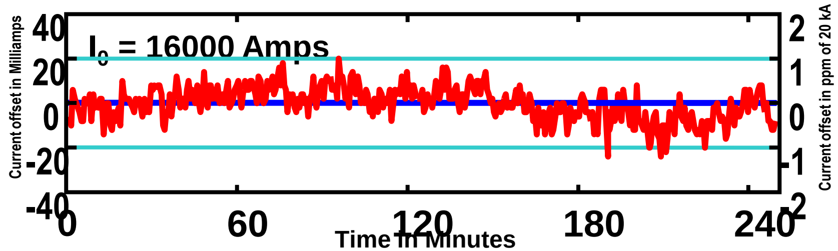
$$I_{B2} = I_{B1} \pm (\text{Reproducibility}_{pmm} \cdot I_{nominal})$$
$$I_{B3} = I_{B2} \pm (\text{Reproducibility}_{pmm} \cdot I_{nominal})$$

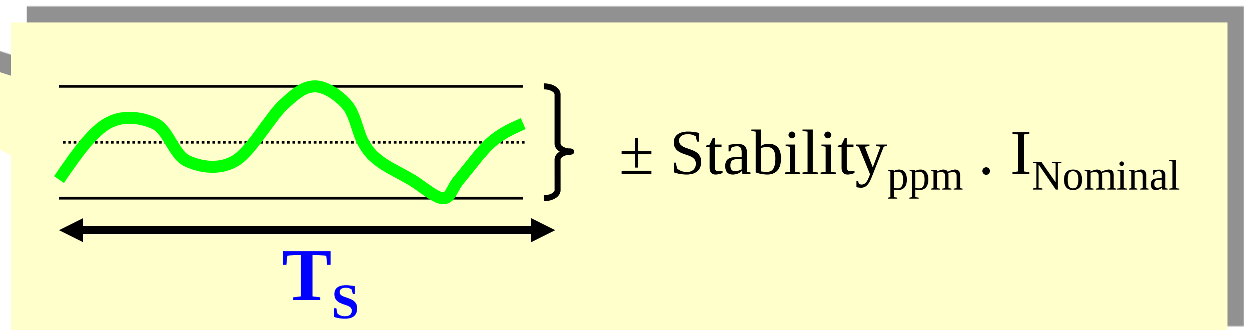
Stability

Maximum deviation over a period with no changes in operating conditions.

The stability is defined by default for a period of time T_S (typically ½ hour)
The stability is expressed in ppm of $I_{Nominal}$.







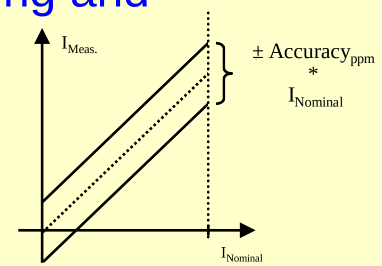
Glossary

Precision

– Accuracy

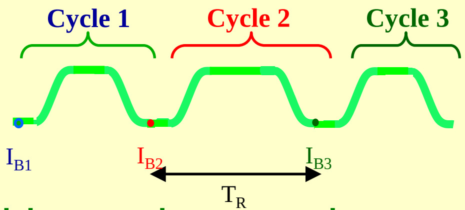
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

* requires definition



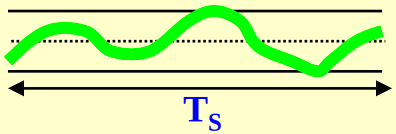
– Reproducibility

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.



– Stability

Maximum deviation over a period with no changes in operating conditions.



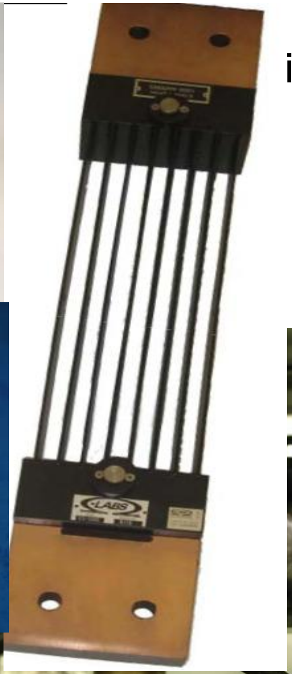
Accuracy, reproducibility and stability are defined for a given period

Precision is qualitative . Accuracy is quantitative.

Current measurement for power converter applications

The most common current measurement technologies used in power converter applications and the electrical principles behind them are summarised below:

- **Resistive shunts, current sense resistors:** Current to voltage conversion (Ohm's law)



- **Hall effect current transducers:** Based on the ical conductor in the presence of an external magneti

- **DCCTs:** A zero flux detector (of the second har to generate a compensation current which is a measured. This current is converted to a voltag

•**Current Transformers (CTs):** Based on ma

Ts can also sed on similar ly useful in can be a proble

ke **Optical CTs** are not so com e use of the Faraday effect (p

Accuracy Class: 10^{-2} to 10^{-3} (1% to 1000 ppm)

For this accuracy class, any of the technologies mentioned previously could be chosen. However DCCTs are relatively expensive and "over qualified" for this class so they are not listed below:

Shunts
- High Currents (tens to hundreds of kA) -> might require forced cooling for 10^{-2} accuracy
- Medium Currents (up to the kA) -> might require forced cooling for 10^{-3} accuracy
- In DC applications performance is limited by power and temperature coefficients
- Low bandwidth. The AC performance is limited by parasitic components and by skin effect
- No isolation from primary current circuit. Common mode might be a problem !

Hall effect transducers
- Available for a wide range of currents (from hundreds of mA to tens of kA) and accuracies
- Medium bandwidth (tens of kHz)
- Provide isolation from the primary current circuit

CTs
- Available for medium to high Currents (up to tens of kA) with accuracies of 0.5%
- High bandwidth (up to the MHz) but no DC response
- Provide isolation from the primary current circuit
- Low maintenance (passive device)

Rogowsky coils
- Available for very high currents (up to hundreds of kA) with 10^{-3} accuracy. No saturation
- Very high bandwidth (up to tens of MHz) but no DC response
- Provide isolation from the primary current circuit

Accuracy Class: 10^{-3} to 10^{-4} (1000 ppm to 100 ppm)

Shunts

- Available for medium Currents (10A..1kA) at DC and 50/60Hz with accuracies to 500ppm
- On the 1 to 100A range, a new generation of laboratory coaxial shunts has pushed the accuracy to 10^{-4} at frequencies up to 100kHz. Not viable for industrial applicatons.
- Small currents (<10A) up to a few kHz can be measured close to 10^{-4} using current sensing resistors (metal foil resistors are the most used)

DCCTs

- Available for the medium to high current ranges (up to tens of kA) to 10^{-4}
- Most suited for DC applications with tight accuracy requirements
- AC response up to a few tens of kHz
- Provide isolation from primary circuit

Accuracy Class: 10^{-4} to 10^{-5} (100 ppm to 10 ppm)

Current sense resistors

- Can be used for small currents (<10A) at DC and AC (few kHz). Metal foil current sensing resistors are suited for this range of accuracy. Particularly Zeranin foil resistors offer very low Temperature and Power Coefficients and have a very low inductance.

DCCTs

- Available for the medium to high current ranges (up to tens of kA) to 10^{-5}
- Need good current sensing resistors to convert the compensation current into a measurable voltage
- Factors like magnetic head design, output stage drift, thermal management, output noise become very important at this level

Accuracy Class: 10^{-5} to 10^{-6} (10 ppm to 1 ppm)

Current sense resistors

- Small currents (<10A) at DC and AC (some kHz). Special designs can achieve accuracies of a few ppm but factors such as humidity, temperature, power dissipation, ageing and EMI mean that it is very difficult to assure this performance outside a controlled environment.

DCCTs

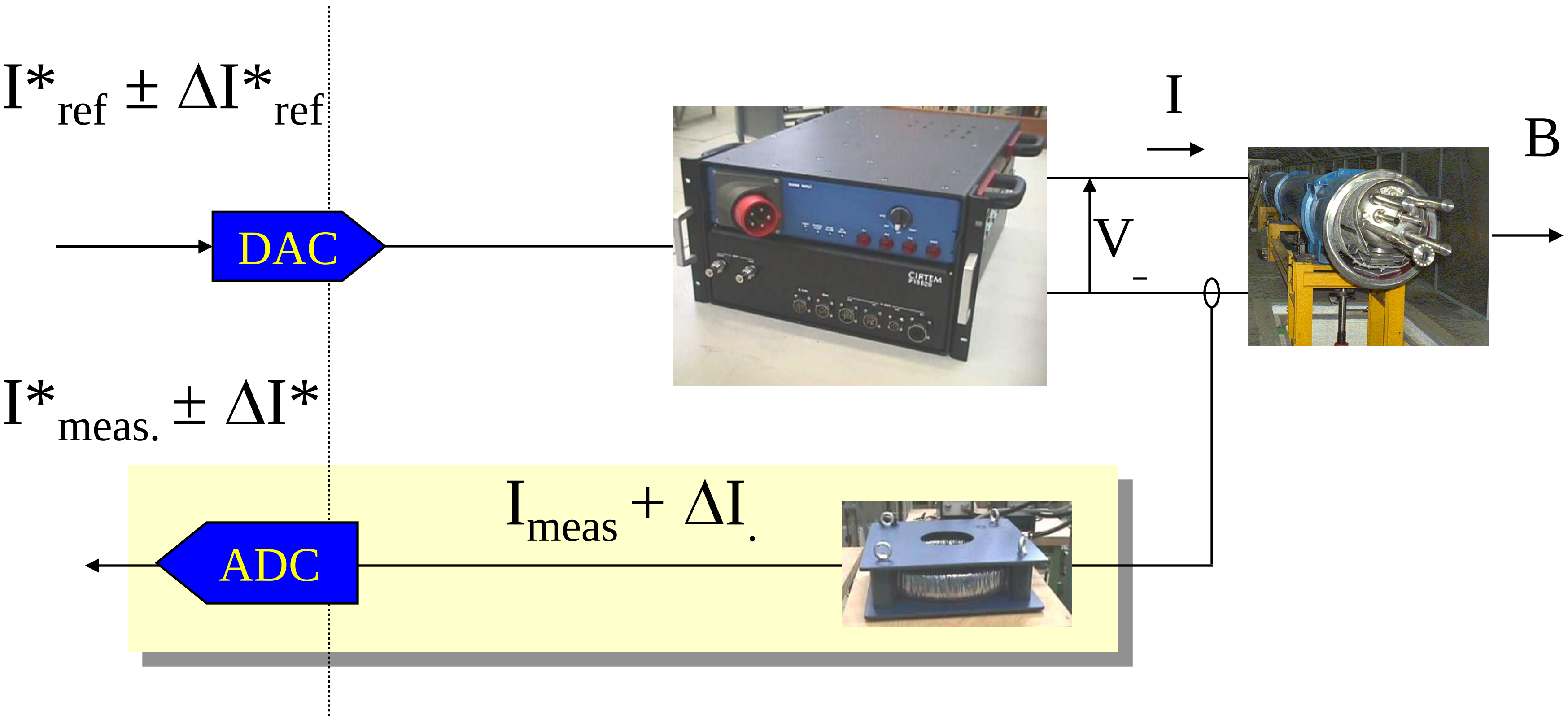
- Available for the medium to high current ranges (up to >kA) to better than 10^{-5}.
- High quality current sensing resistors are essential. ppm level performance is only possible to achieve in a controlled environement.
- Factors like head centering, head error, magnetic remanence become very important

Picture: Temperature controlled EMC Racks housing 6 electronic chassis for the 13kA High Precision DCCTs for the LHC main power converters

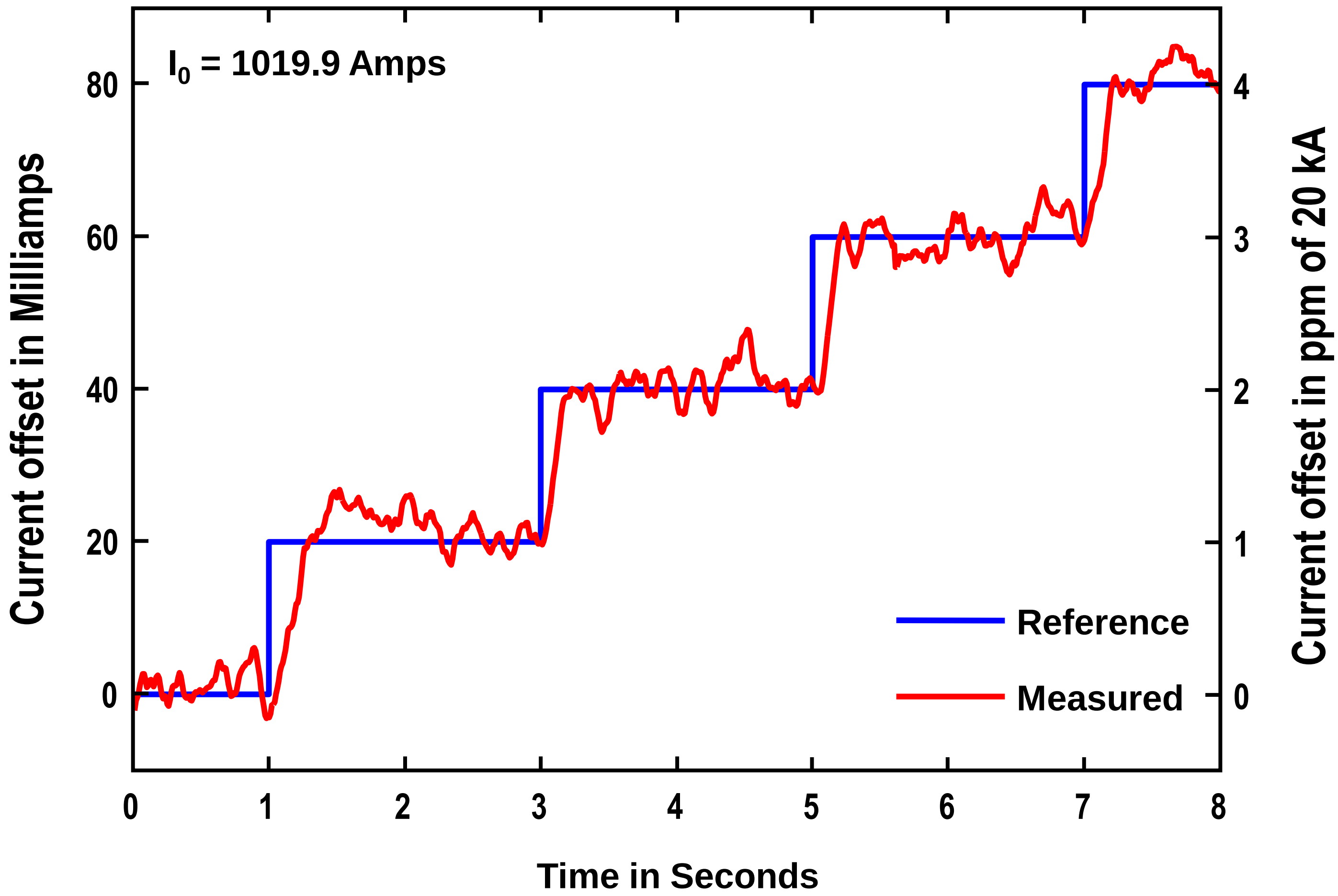
Resolution

Smallest increment that can be induced or discerned.

The resolution is expressed in ppm of $I_{Nominal}$.
Resolution is directly linked to A/D system



Results of Resolution Test with the LHC Prototype Digital Controller

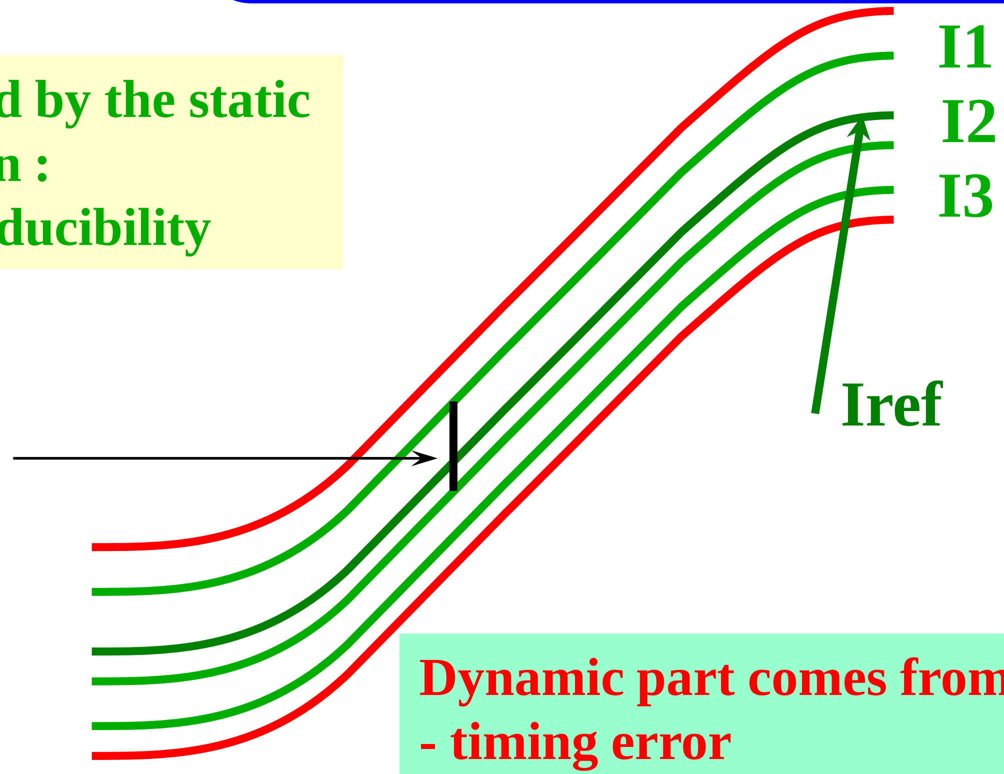


Tracking

Ability of the converterS to follow the reference function (static, dynamics)

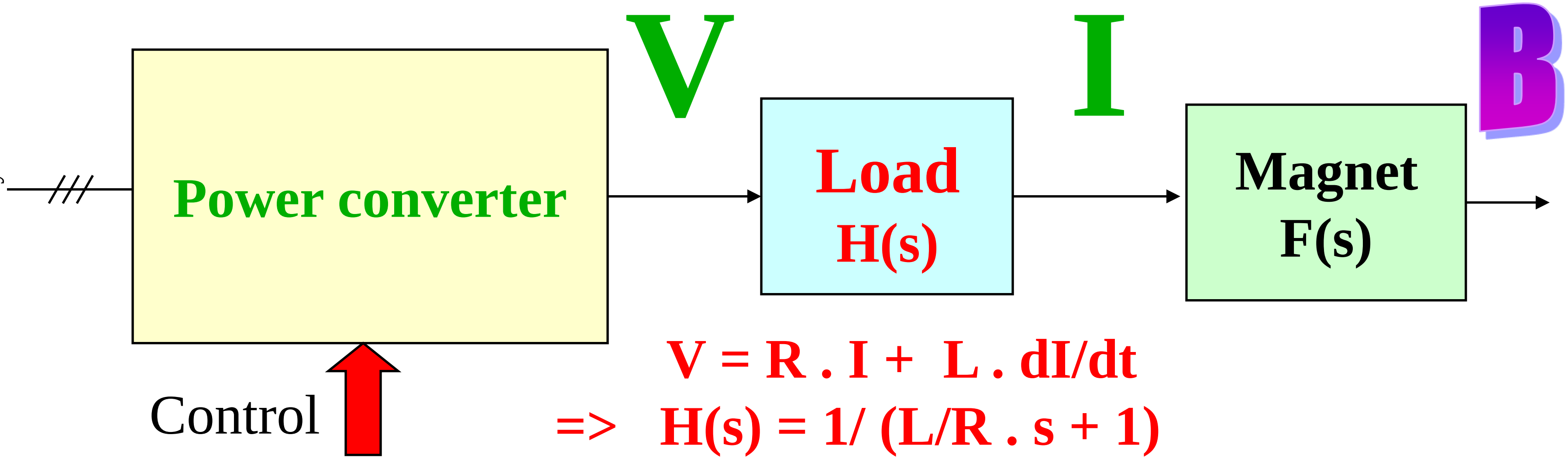
Static part is covered by the static definition :
accuracy, reproducibility

Tracking error
between I1 and I2



Dynamic part comes from :
- timing error
- lagging error in the regulation

RIPPLE



$$V = R \cdot I + L \cdot dI/dt$$

$$\Rightarrow \quad H(s) = 1/\left(L/R \cdot s + 1\right)$$

Voltage ripple is defined by the power converter

Current ripple : load transfer function

(cables, magnet inductance,…)

(good identification is required if the load is a long string of magnets)

Field ripple : magnet transfer function (vacuum chamber,…)

COMPATIBILITY : Emission - Immunity

IEC 61204 -3

Norms for the power converters :

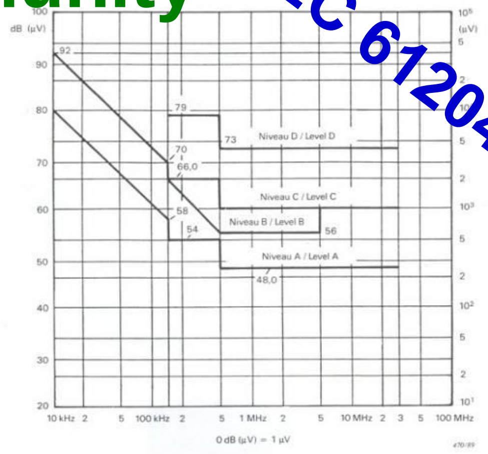


Figure 3 - Valeurs limites pour PEM par conduction

Limit values for conducted EMI

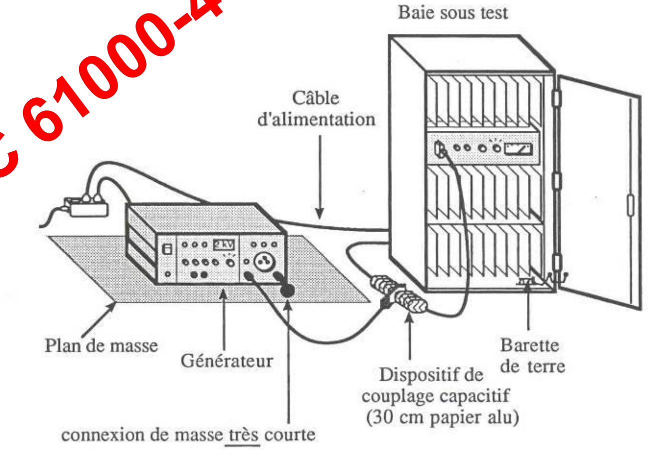
Emission :

IEC 61204-3 (replaced IEC-60478-3)
(CISPR 11 ; EN 55011)

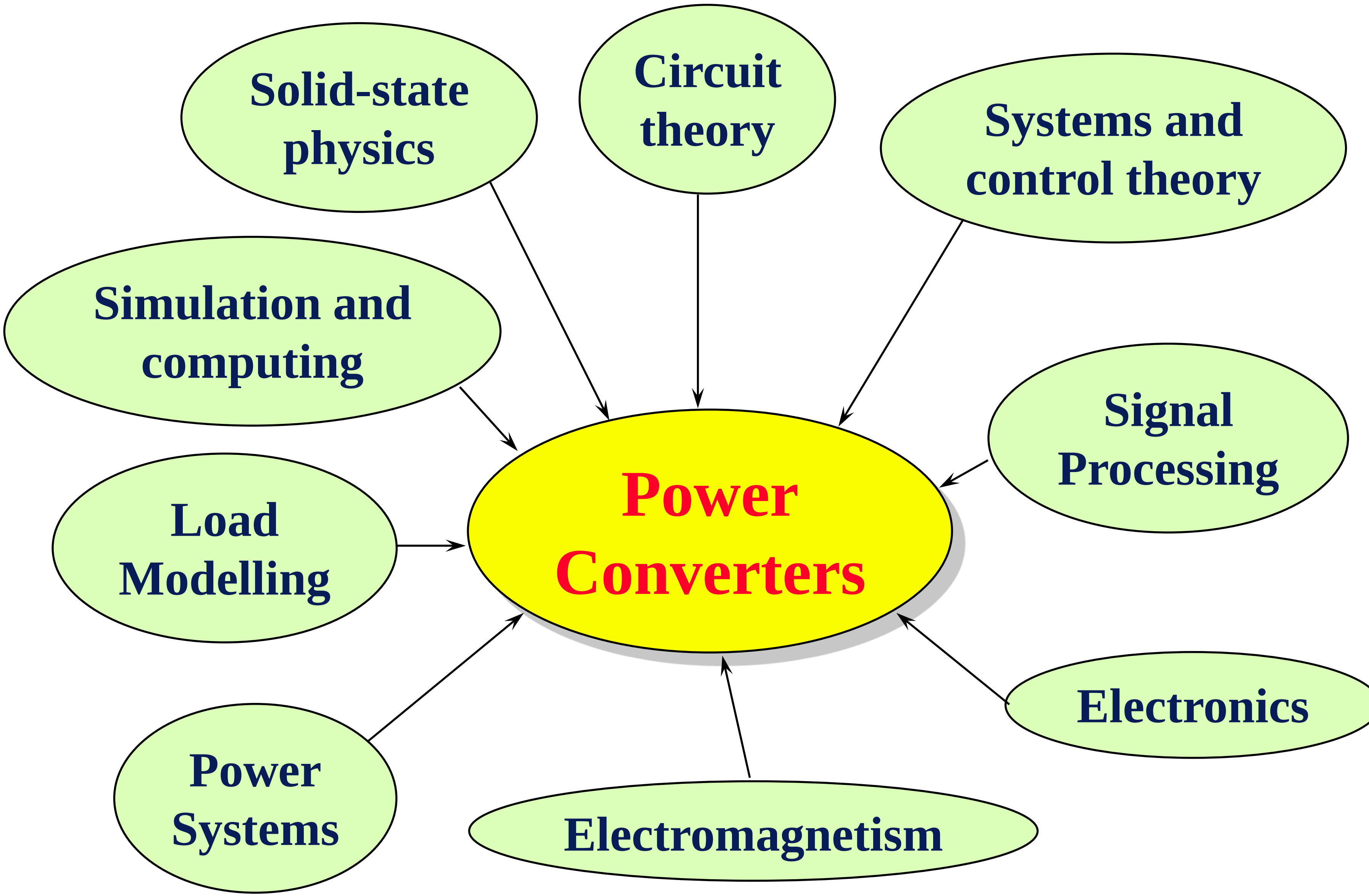
Immunity :

IEC 61000 - 4 :
Burst 61000 - 4 - 4
Surge 61000- 4 - 5

IEC 61000-4-4



Interdisciplinary nature of power converters



Power converters specifications

"Do you have one or two power converters for the test of magnet prototype? 200 A will be enough ? Precision is not important for time being. Don't worry it's not urgent. Next month is OK "
(Email received 05.12.08)

Load characteristics : I and V reversibility (1 , 2 or 4-quadrants ?) ;
Transfer function (at least R, L, C) => will define V and the power

Range : Imax (and Imin)

Rise and fall time (dI/dt max; voltage constraint on the load); is the precision an issue during the ramps (beam or no beam) => Pulsed converters with intermediate storage ?
=> bandwidth (topology and control strategy)

Precision: accuracy, reproducibility, stability

Ripple: $\Delta V(f)$ => passive (or active) filters ; control strategy (SMPC)

Is the volume a constraint ? Is water cooling possible ?

Environment: temperature and humidity; EMI conditions, radiation,…

Hardware design and production take time…..

The end

CAS - CERN Accelerator School :
Power converters for particle accelerators
26 - 30 Mar 1990, Switzerland

CERN Accelerator School and CLRC Daresbury Laboratory :
Specialised CAS Course on
Power Converters for particle accelerators
12 - 18 May 2004 - Warrington, UK