European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Power converters

Definitions and classifications
Converter topologies

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CERN

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Варна - Varna - Bulgaria

Menu

- Power converter definition

- Power converter topologies: *commutation*

  Sources, switches,...semiconductors

- Special case for magnet powering

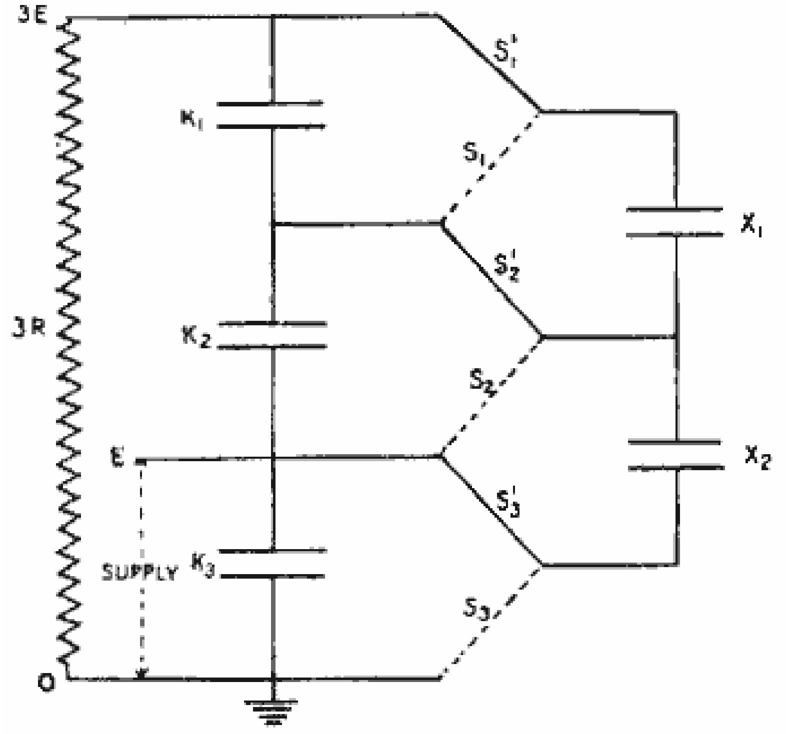
  (Voltage source - Current source)

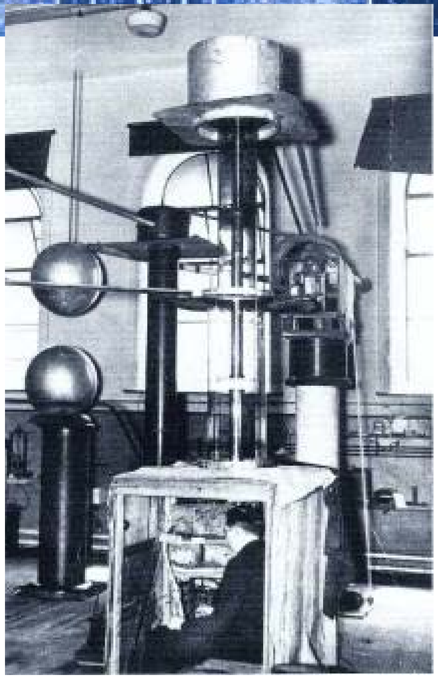
- Pulsed power converters

- Control and precision

- Conclusion

In 1 hour ????





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.”

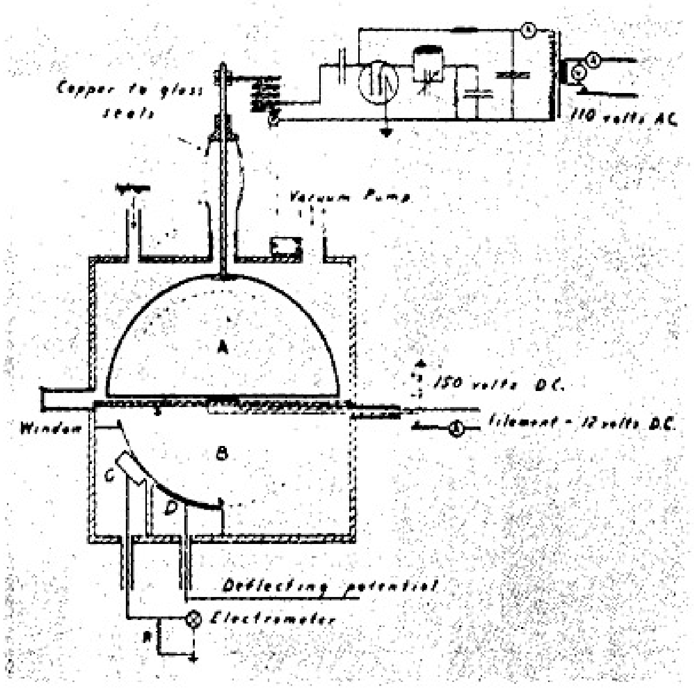
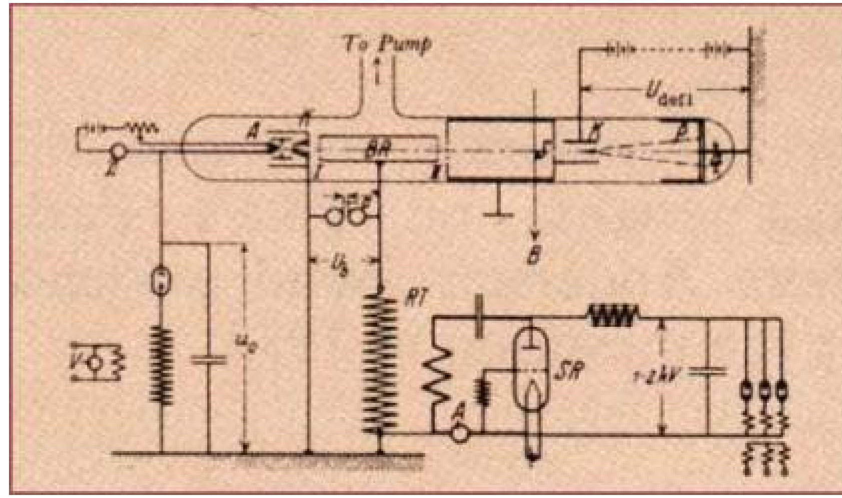


Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.



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.

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 CERN Power Converter Group 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)

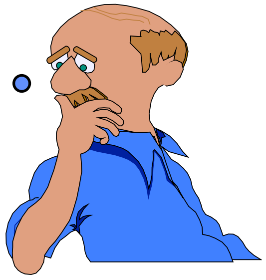
A standard piece of equipment available from industry off-the-shelf
(a higher management person, not in in this room !)

Ровер Цонвертер
(written in Cyrillic)

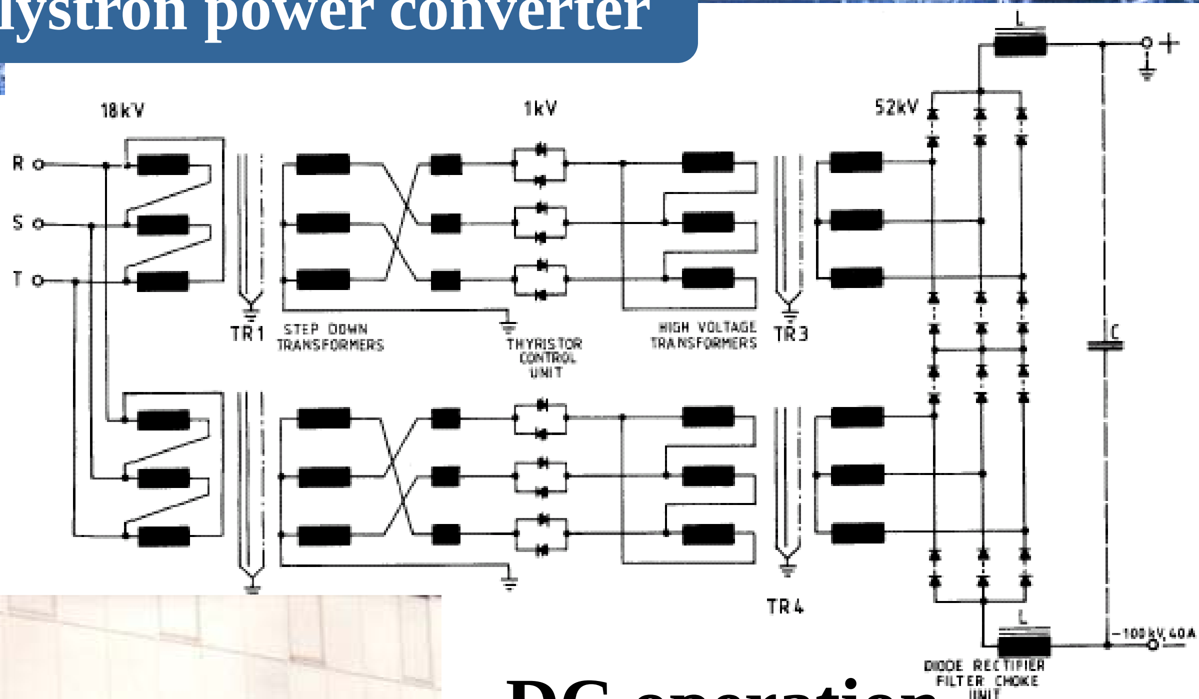
Power converters specifications

"Do you have one or two power converters for the test of magnet prototypes? 40 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)

40A power converter:
Size? Weight ? Cost?



[40A, 100 kV] klystron power converter



DC Power: 4 MW

DC operation

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

Peak power : 2 MW
Average power: 4 kW

LHC orbit corrector : [±60A,±8V]

Magnet : L=7 H ; R = 30 mΩ (60m of 35 mm²)
T = L/R = 300 s

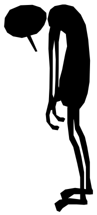
U_{static} = R.I = 1.8V

6 V for the dI/dt with L= 7 H (V = RI + L dI/dt)

=> dI/dtmax < 1A/s

Small signal : $f^{CL}_{B} \cong 1$ Hz : ΔI = 0.13 A ≅ 0.25 % Imax
($L\omega\Delta I = 7 \times 2\pi \times f^{CL}_{B} \times 0.13 \cong 6$ V)

"The power converters involved in feedback of the local orbit may need to deal with correction rates between 10 and 500 Hz";
$f^{CL}_{B} \cong$ 50Hz (ΔI = 2% : Umax = 2500 V ?????...)



(U_{max}= 8V => ΔI ≅ 50 ppm Imax at 50 Hz)

Power converters specifications

"Do you have one or two power converters for the test of magnet prototypes? 40 A will be enough ?
Precision is not important for time being.
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(Email received 05.12.08)

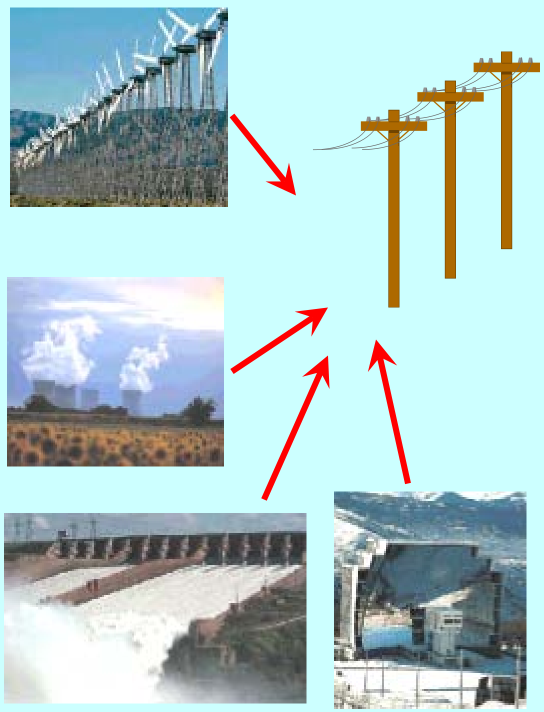
Need of more specification data

Output Voltage
DC or Pulsed (pulse length and duty cycle)

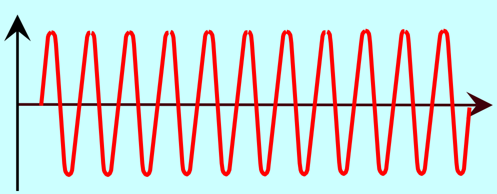
Output voltage and current reversibility
Precision (short and long term)
Ripple

Environment conditions: grid, volume, water ,....

Energy source ⟹ Applications



50 or 60 Hz ; AC



Power converter

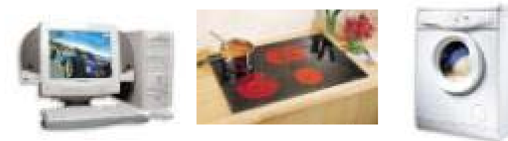
The task of a power converter is

to process and control the flow of electric energy

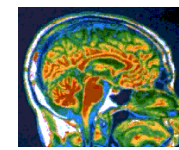
by supplying voltages and currents in a form that is optimally suited for user loads.

Control

Traction and auxiliary



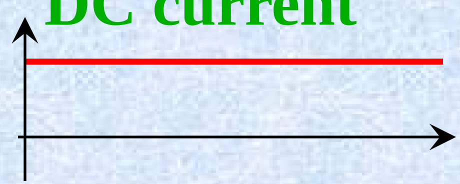
Domestic Appliance

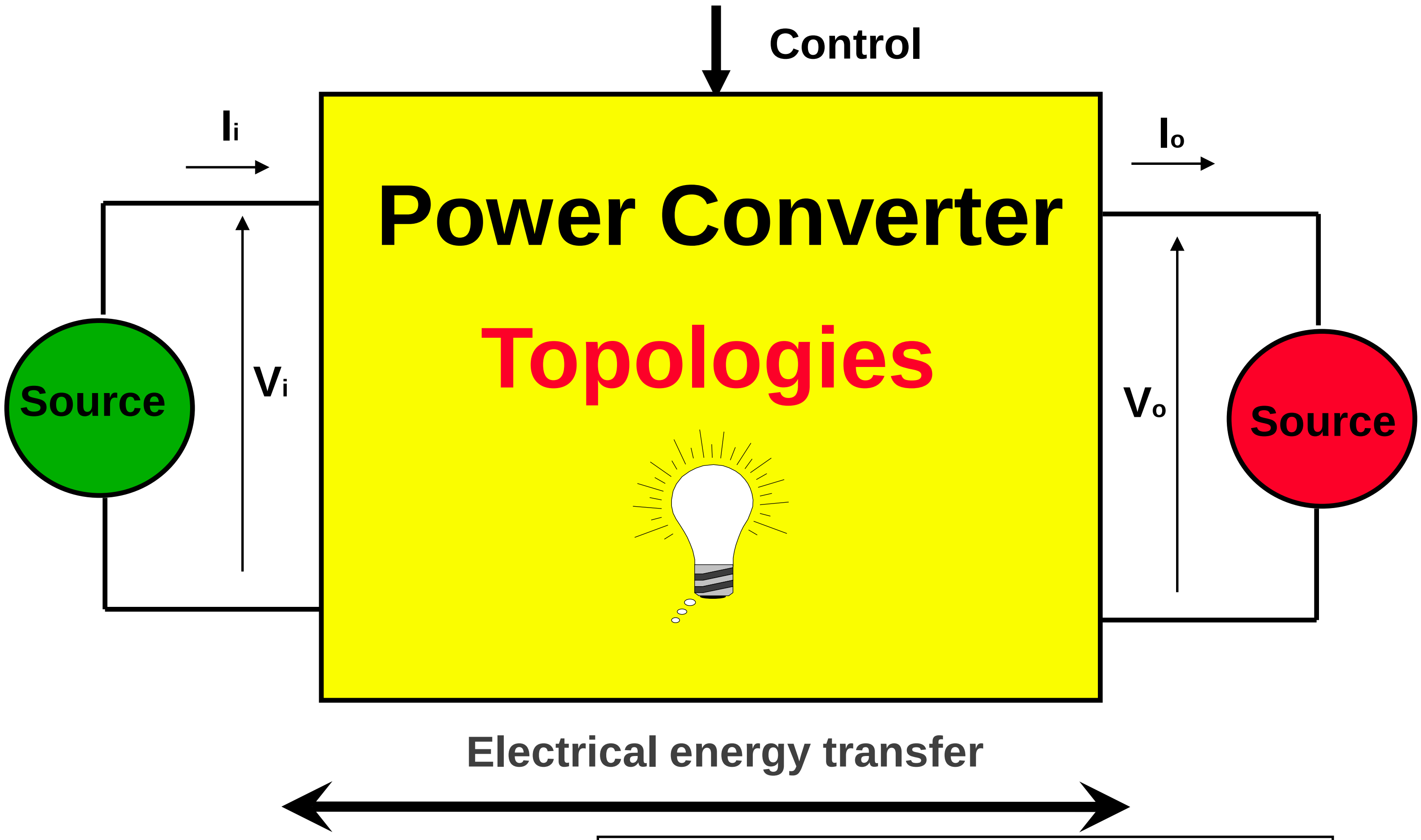


Medical applications

Industrial applications, Welding, Induction Heating, ….

DC current





Power Converter Design

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

Source definition

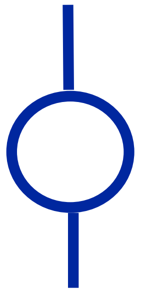
Source definition: any element able to impose a voltage or a current, independently of, respectively, the current flowing through, or the voltage imposed at its terminals.

A source could be a generator or a receptor.

Two types of sources:

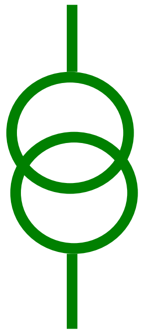
Voltage source

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)

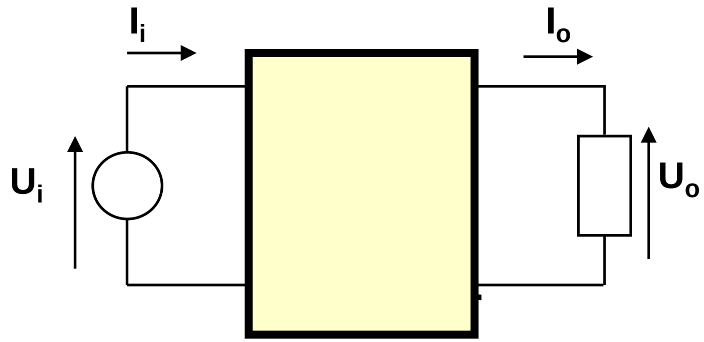


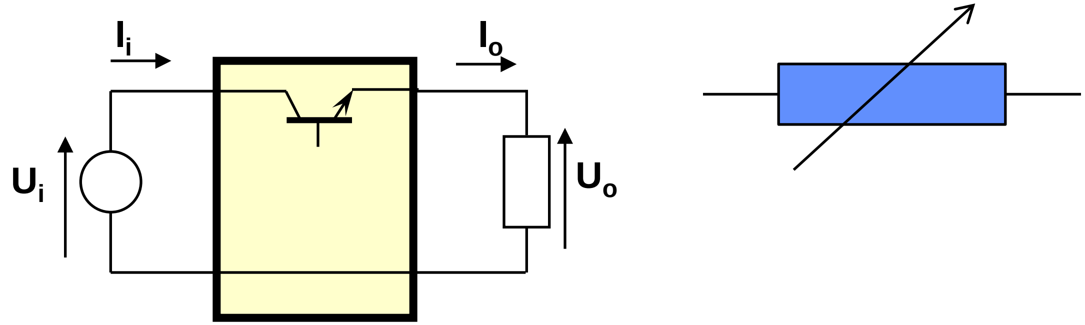
Current source

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)



Introductive example



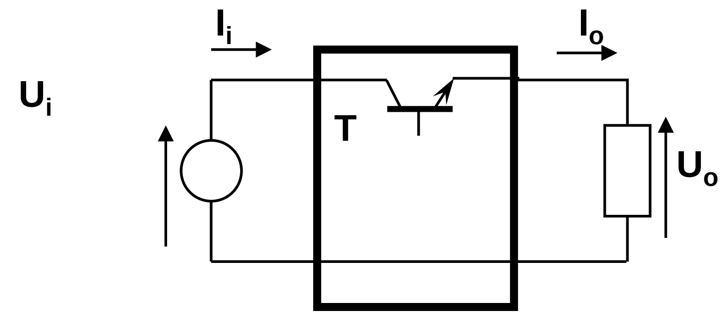


Linear solution

Transfer of energy between
- DC source Ui , Ii
- DC source: 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

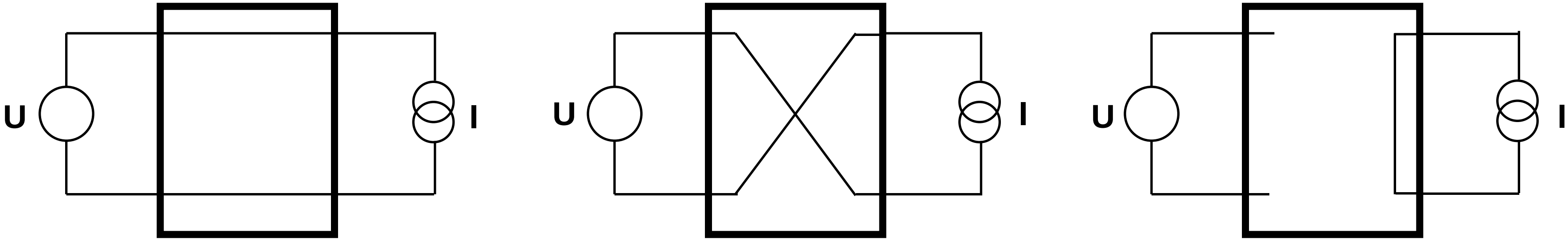
Commutation

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

} $P_T = 0$

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

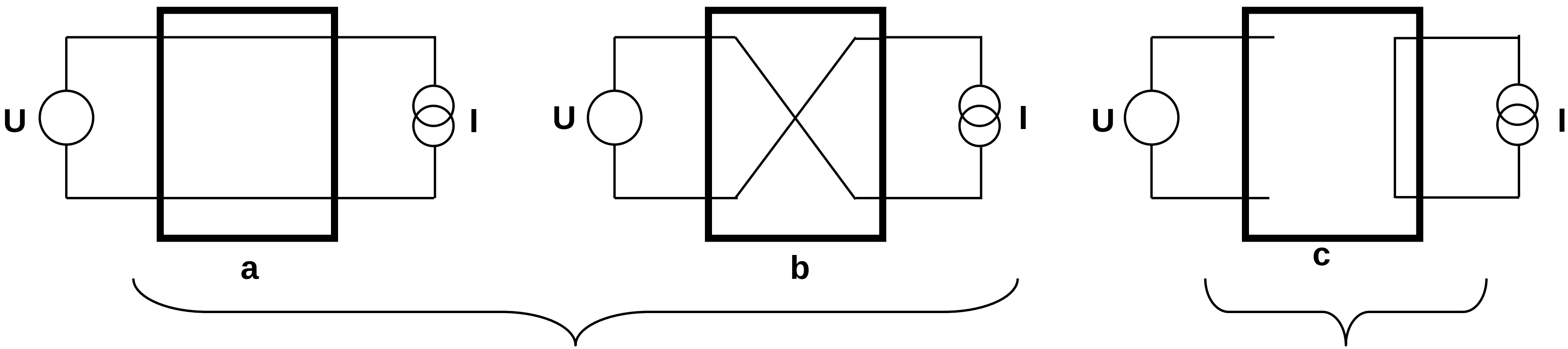
Commutation



Direct Link Inverse Link Open Link

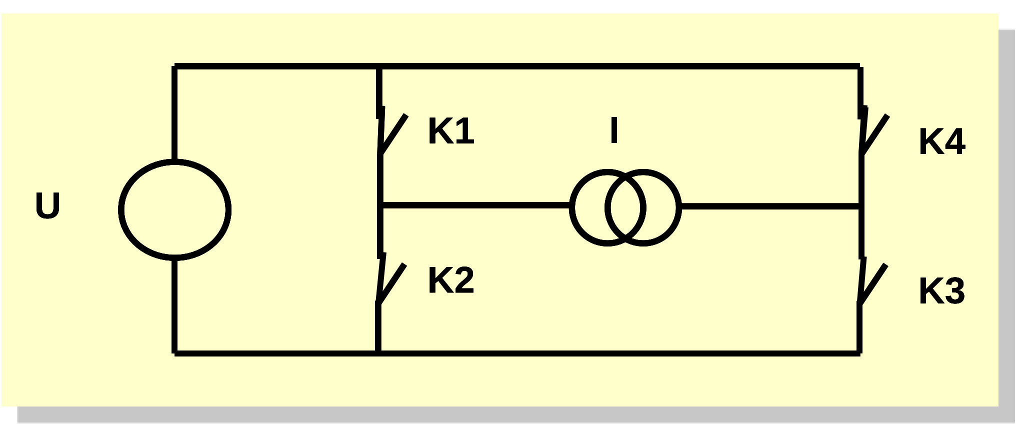
Active components used as switches to create a succession of link and no link between sources to assure an energy transfer between these sources with high efficiency.

Direct link configuration : Direct voltage-current converters



Connexion
(energy flow between sources)

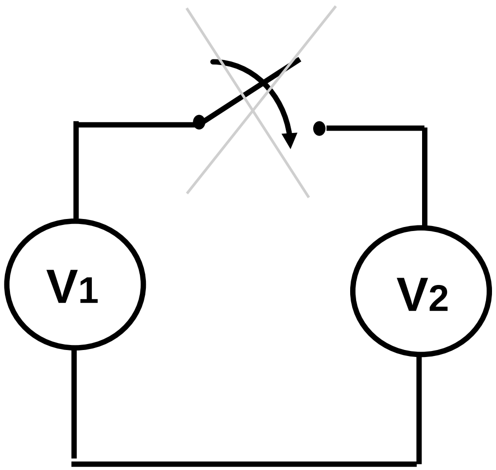
Disconnexion
(current source short-circuited, voltage source open circuited)



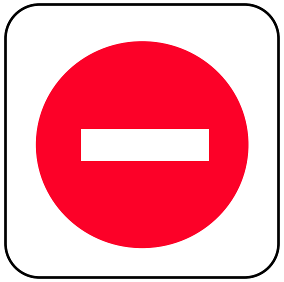
- **K1 and K3 closed => a**
- **K2 and K4 closed => b**
- **K1 and K4 (or K2 and K3) closed => c**

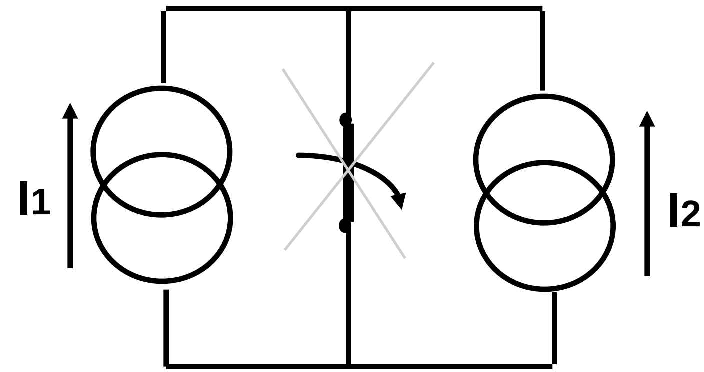
Commutation rules

- *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

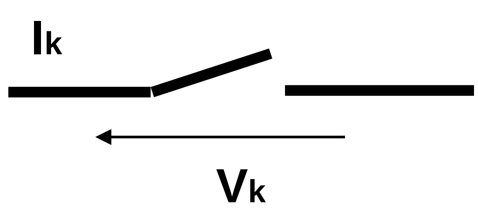
Interconnection between two impeding networks can be modified only if :

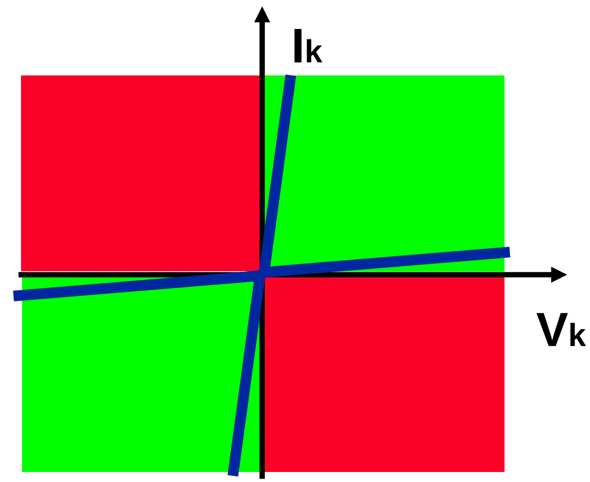
- **the two networks are sources of different natures (voltage and current)**
- **the commutation is achieved by TWO switches. The states of the two switches must be different.**

the interconnection of sources by switches

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

switch characteristics



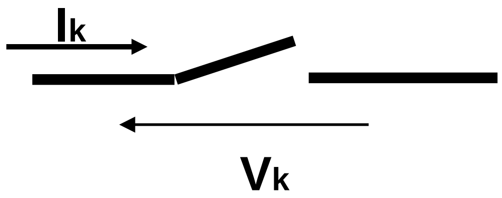


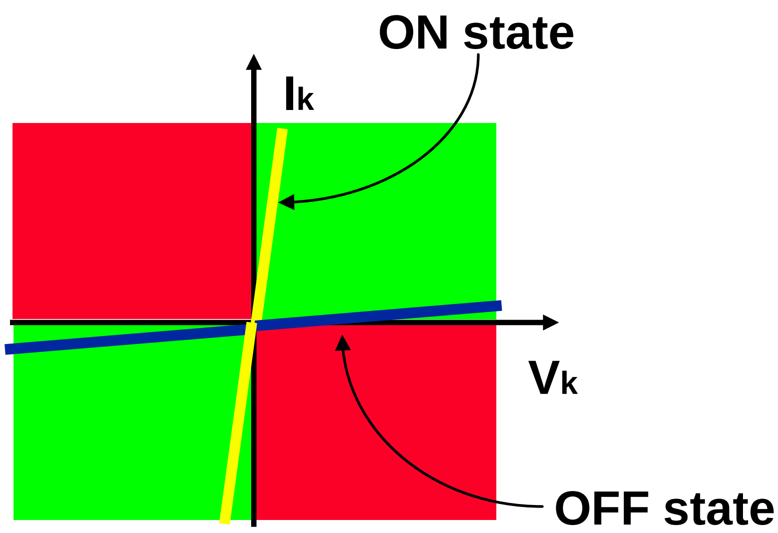
Switch characteristics

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

The losses in the switch has to be minimized

Zon very low
Zoff very high



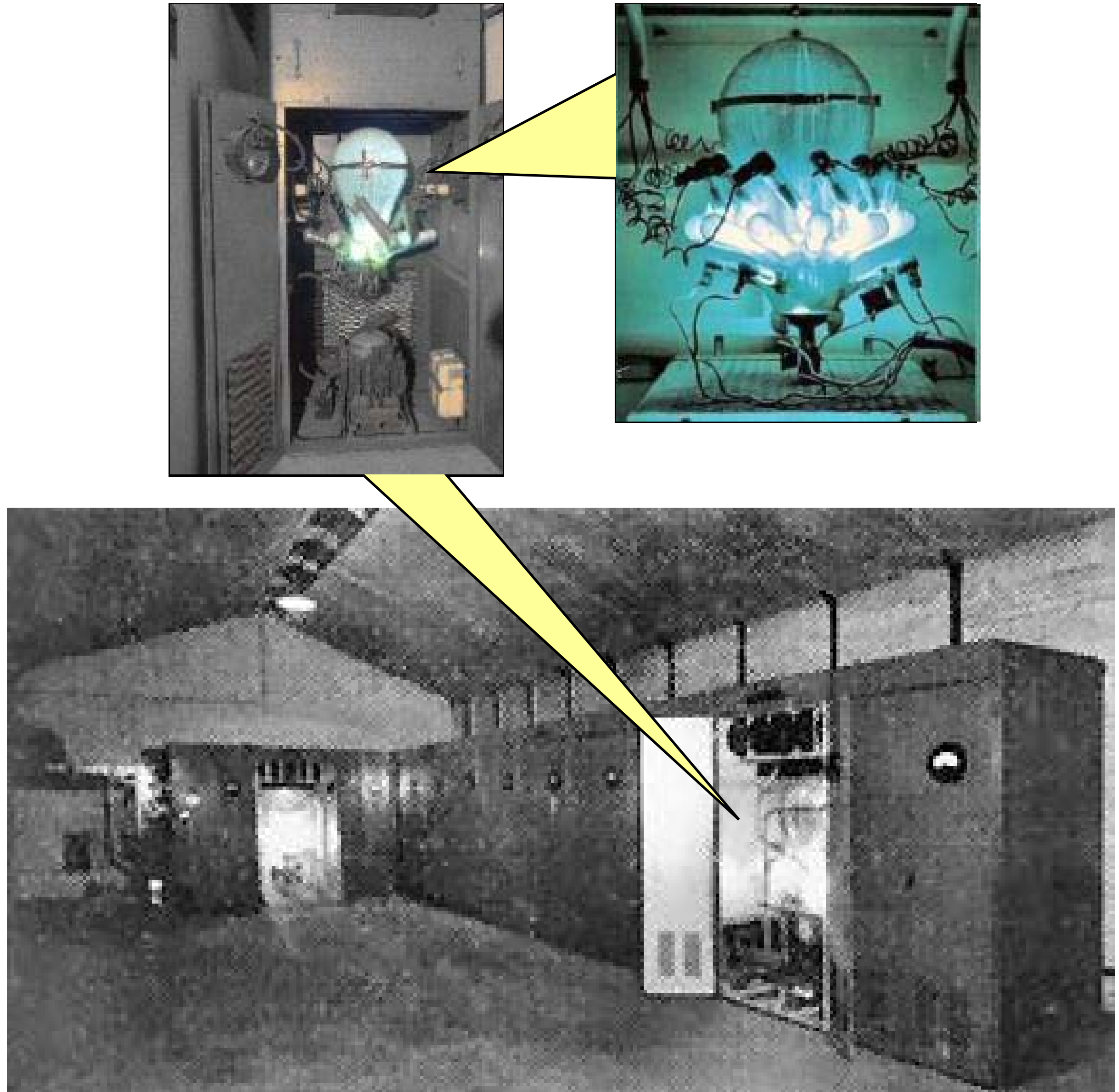


Switch : at least two orthogonal segments

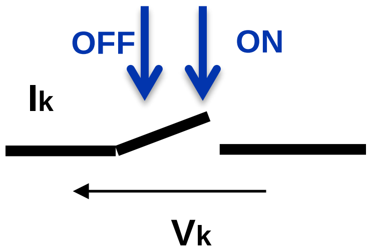
(short and open circuit are not switches)

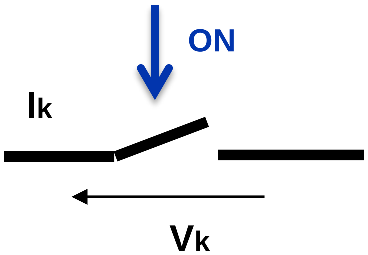
Once upon a time…. not so far

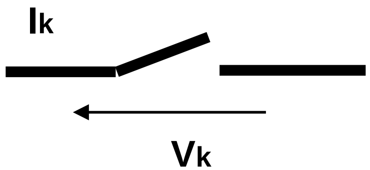
This is a 6-phase device, 150A rating with grid control.
It measures 600mm high by 530mm diameter.



Power Semicondutors







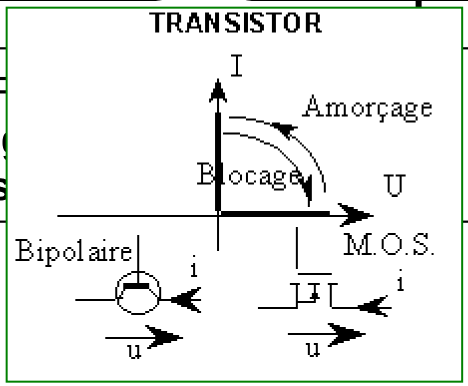
Power Semiconductors

Turn-off Devices

Transistors

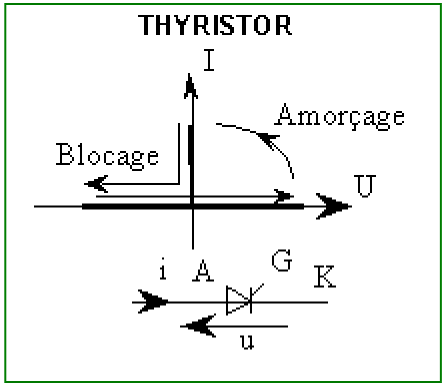
- MOSF
- Darlin
- **IGBTs**

Thyristors



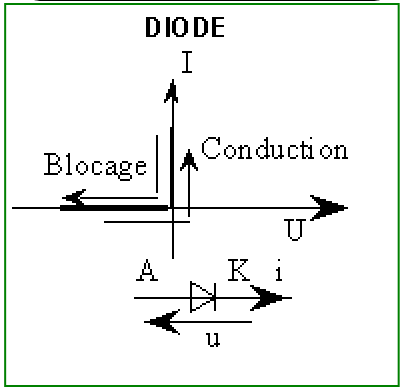
Thyristors

- 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

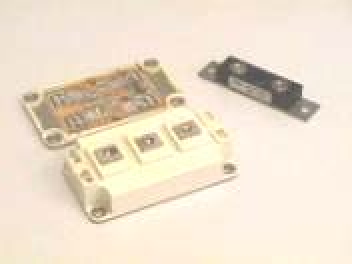
From 1960

Power Diode and Thyristor

or SCR (Silicon-Controlled Rectifier)

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

From 1985



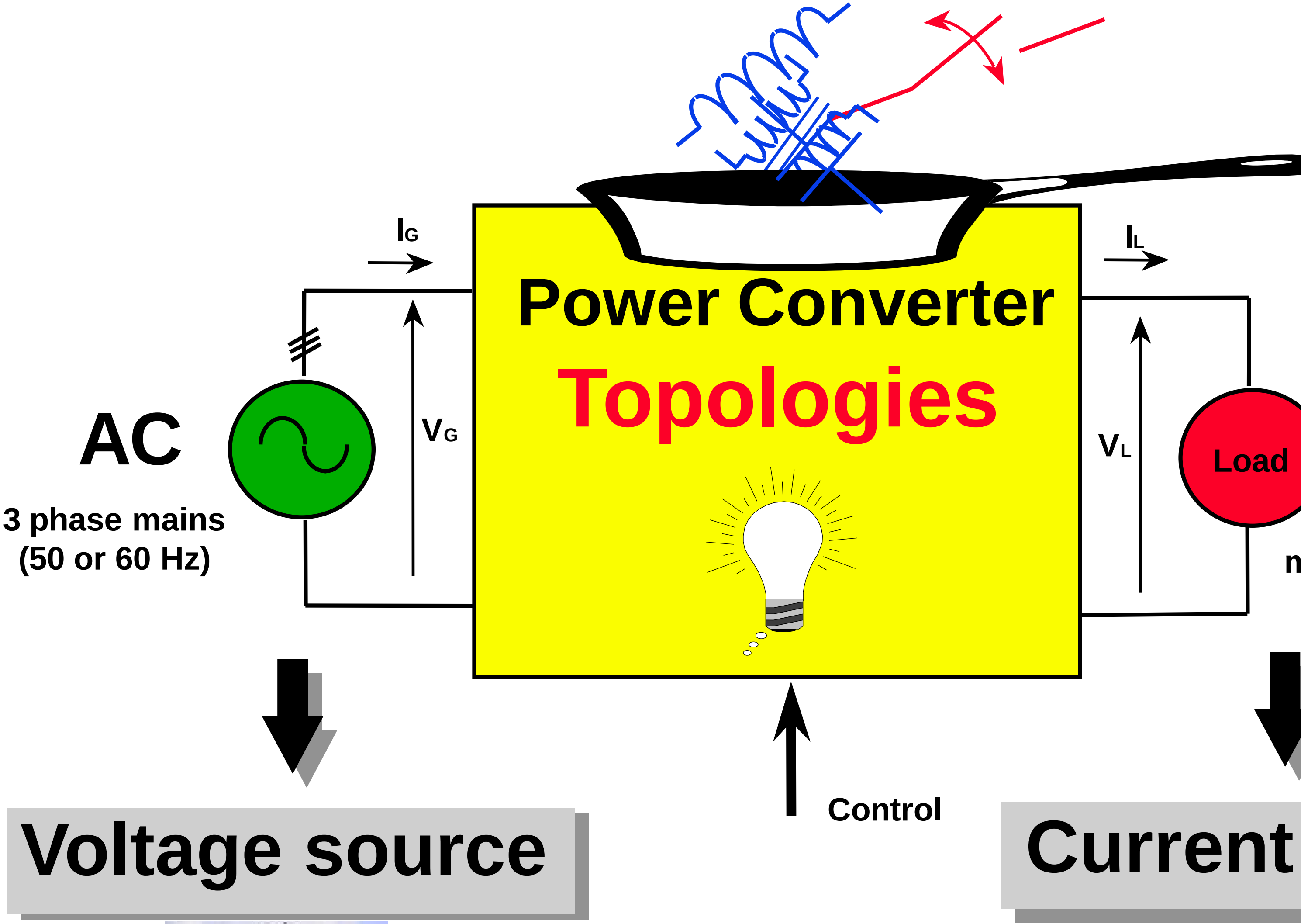
High frequency power semiconductors :

MosFet, IGBTs , GTOs, IGCTs,….

High frequency => high performances (ripple, bandwidth, perturbation rejection,...)

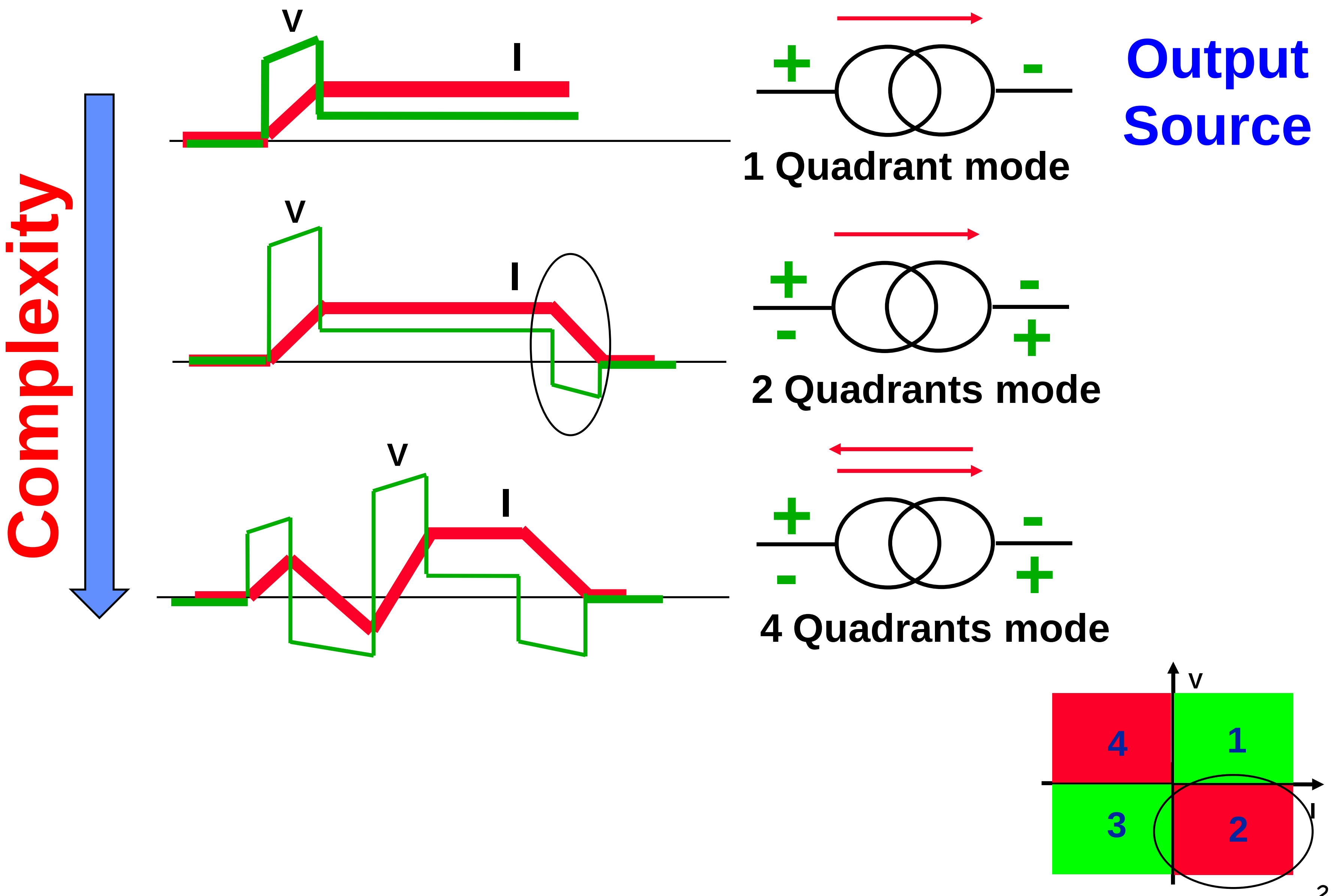
small magnetic (volume, weight)

Power Converter for magnets



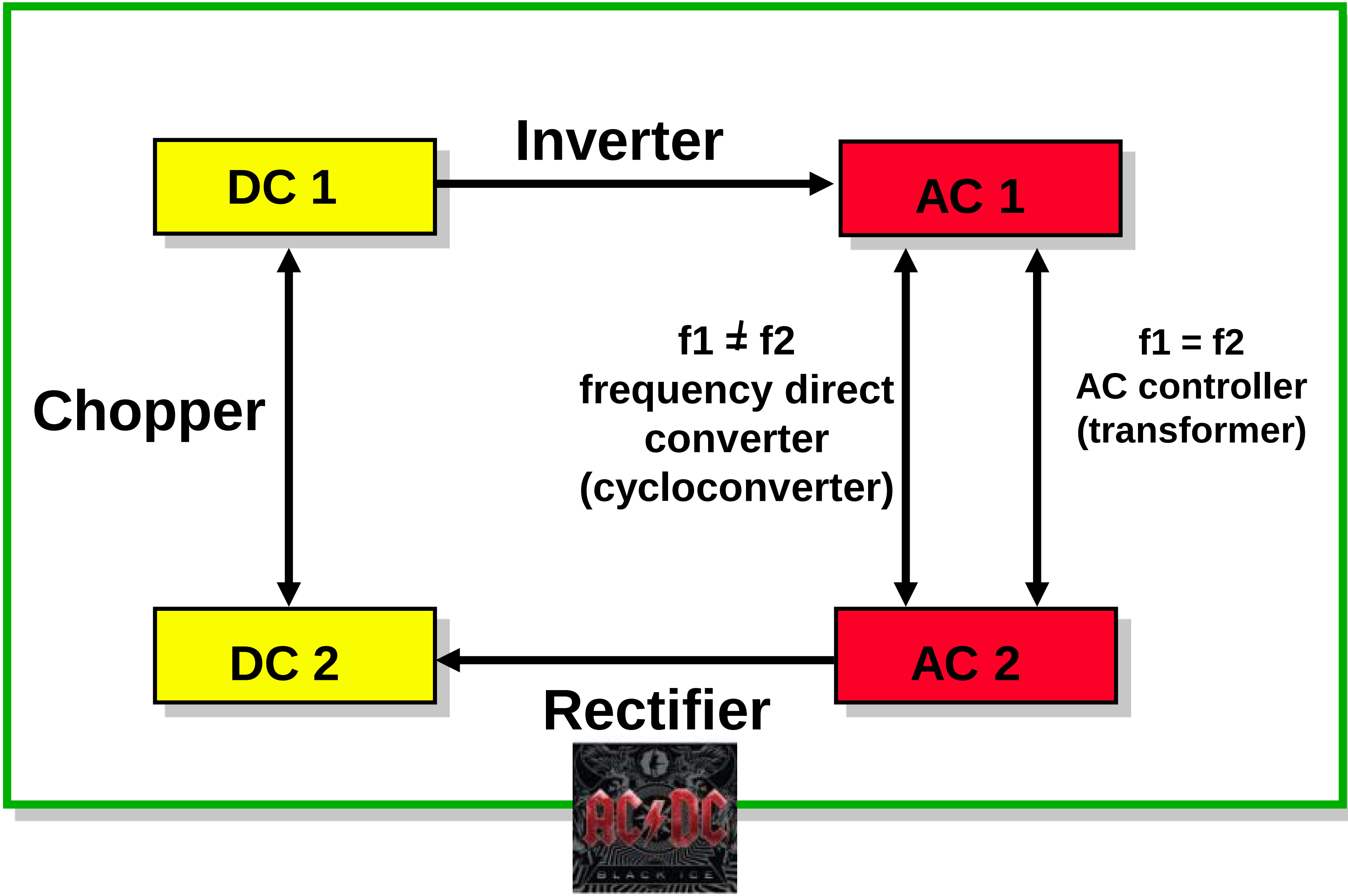
Achieving high performance : **COMPROMISE**

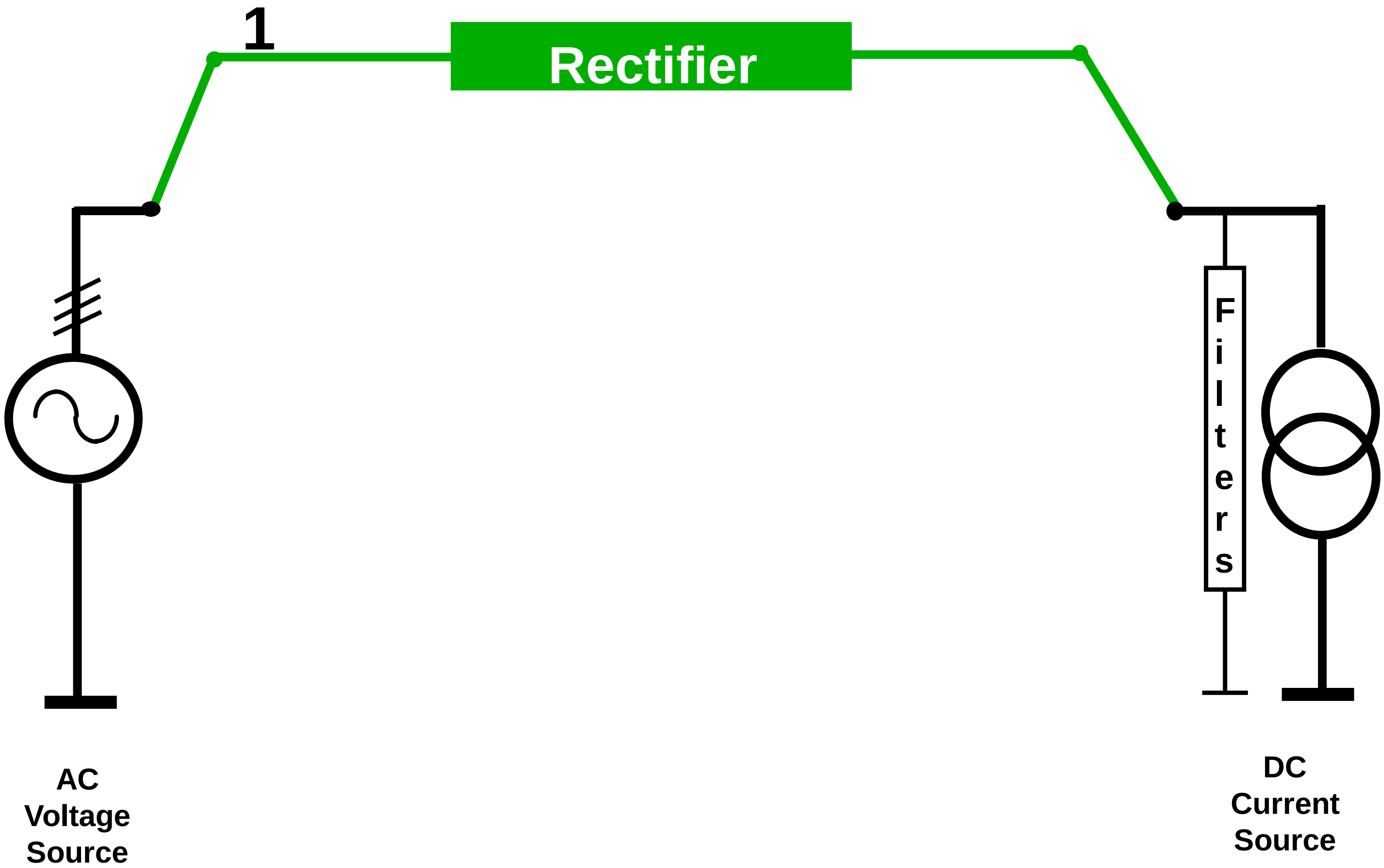
Operating Modes



Output Source

Converter classification

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Rectifier
F
i
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t
e
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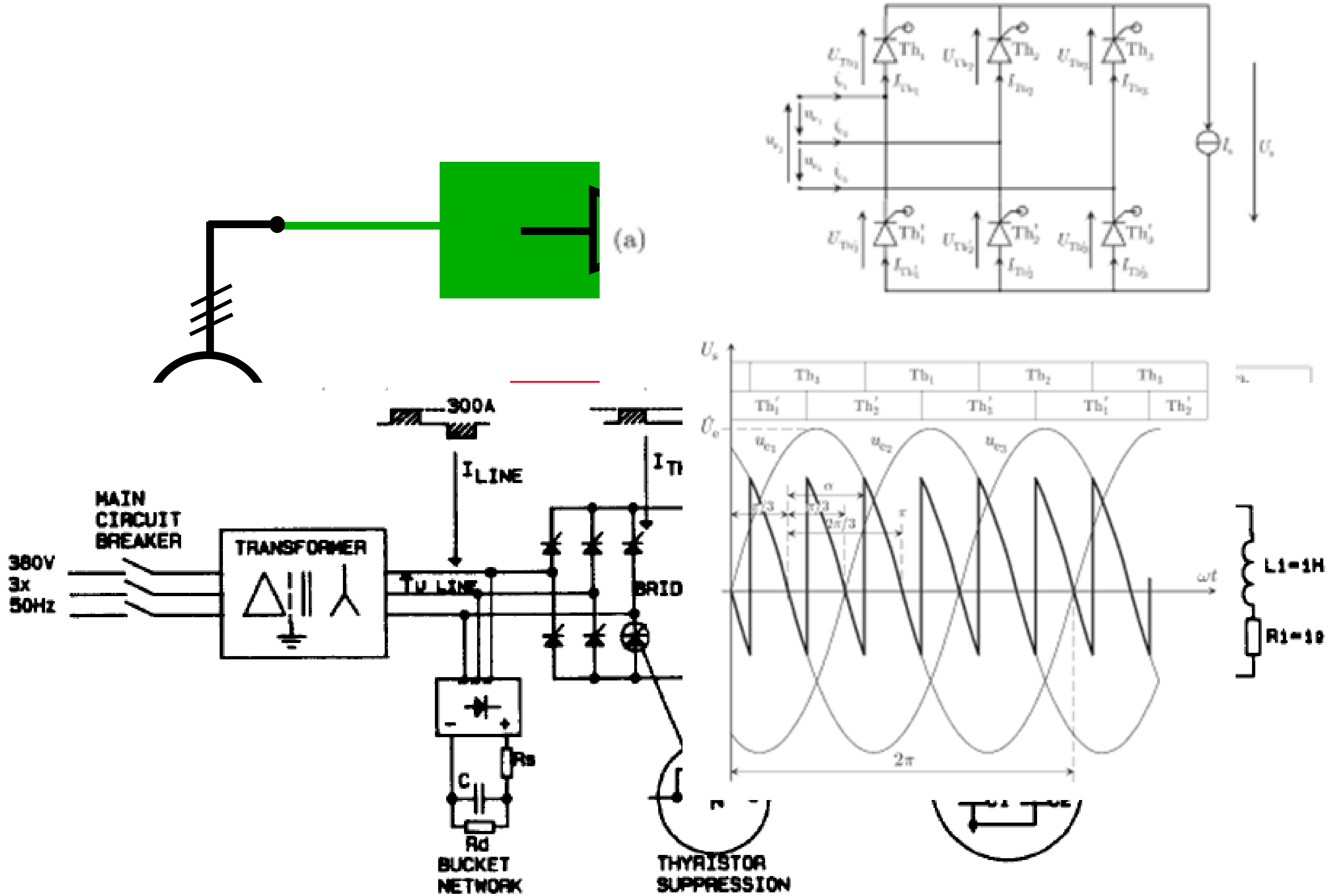
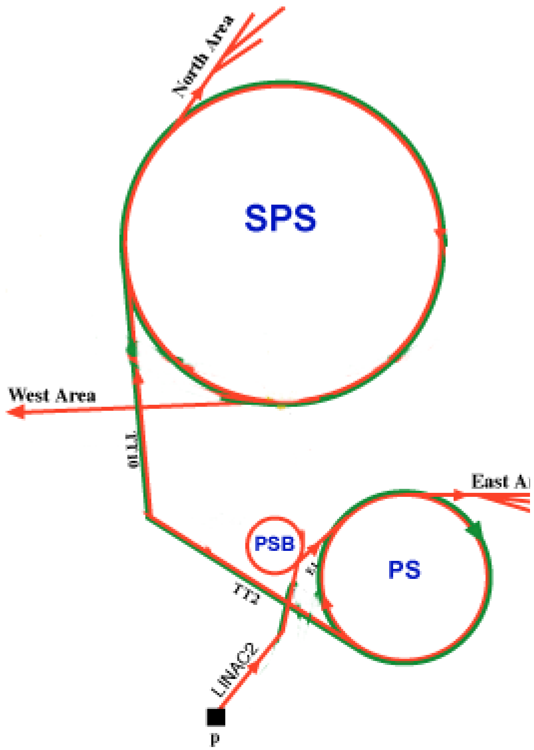
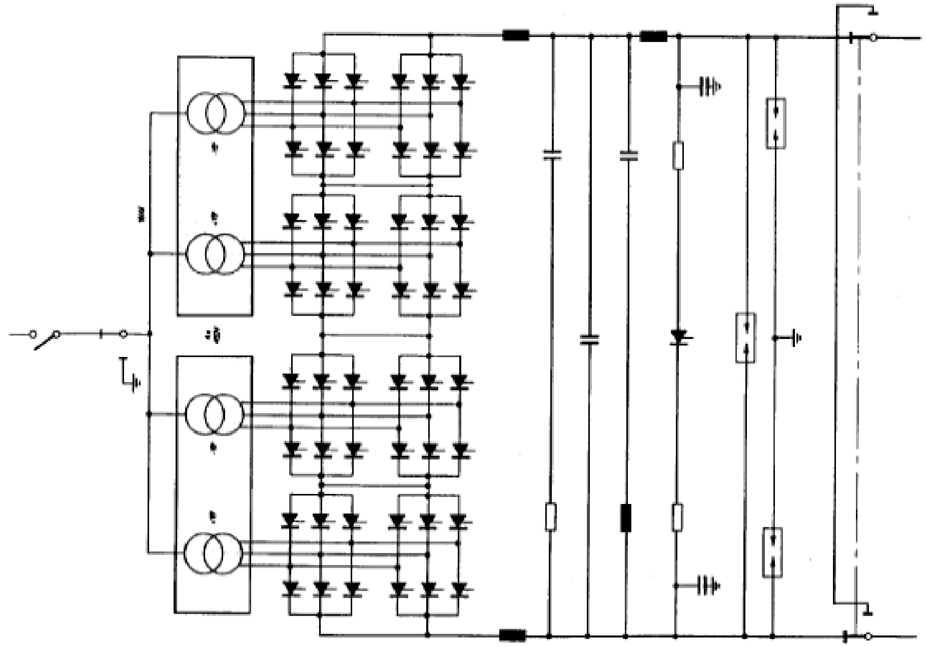
s
AC
Voltage
Source
DC
Current
Source

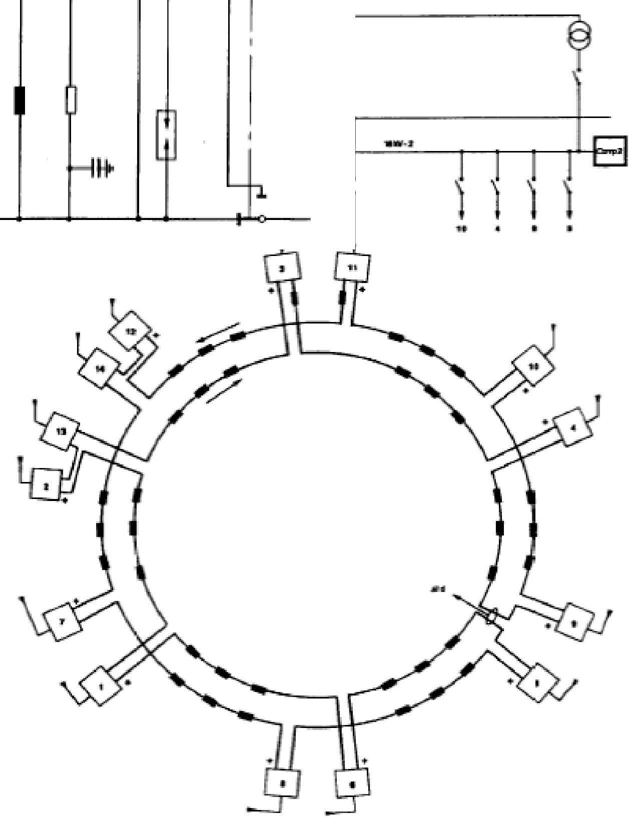
Direct Converters : Rectifiers



SPS Main power converters

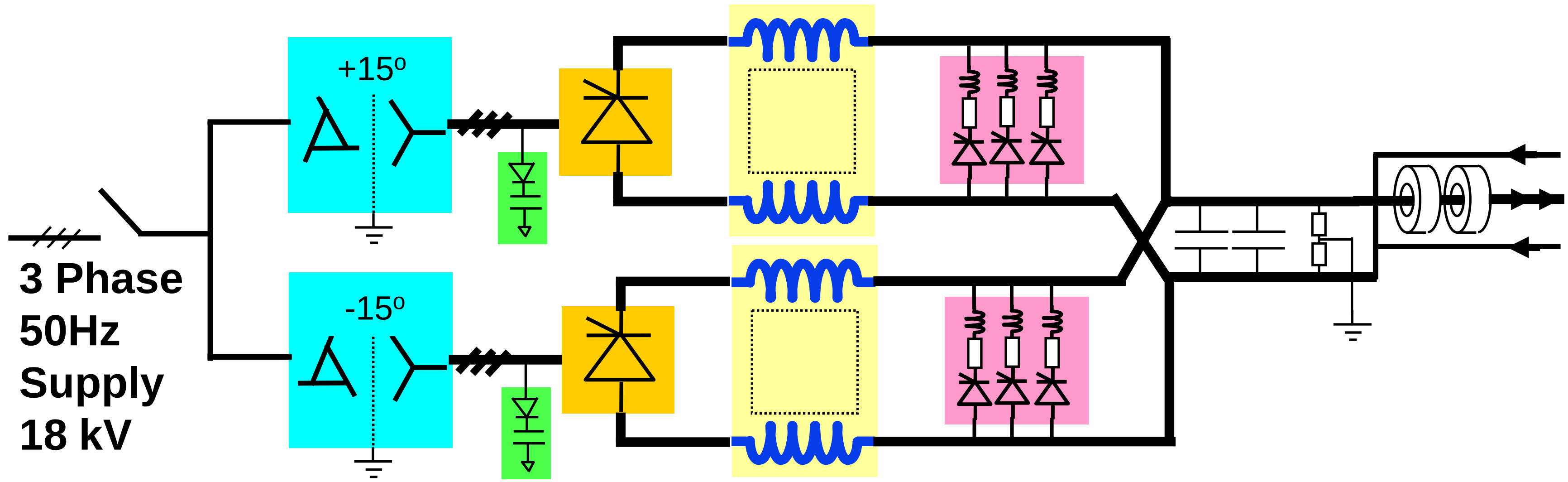




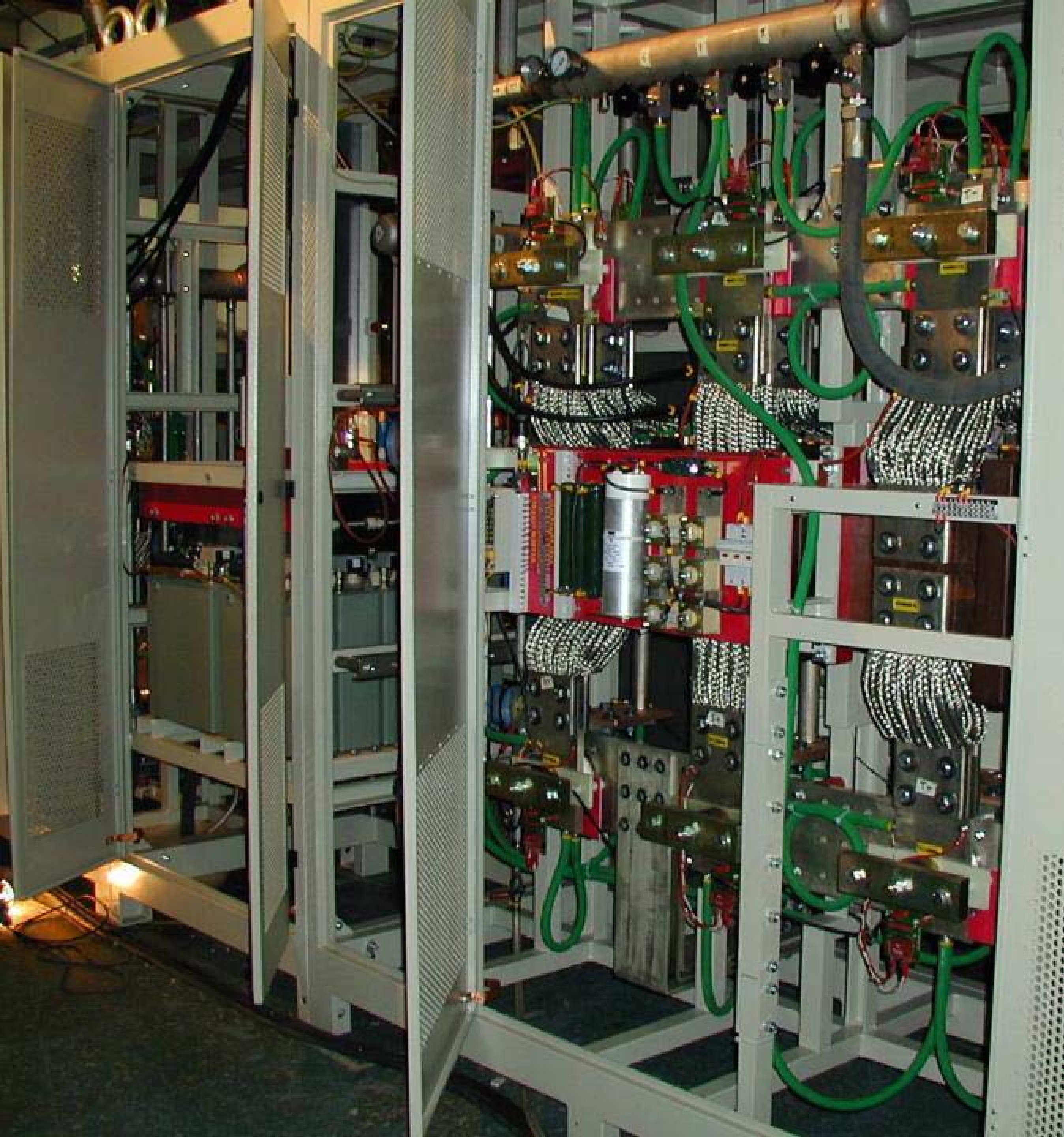


Main power converters
12 x [6kA, ± 2 kV]

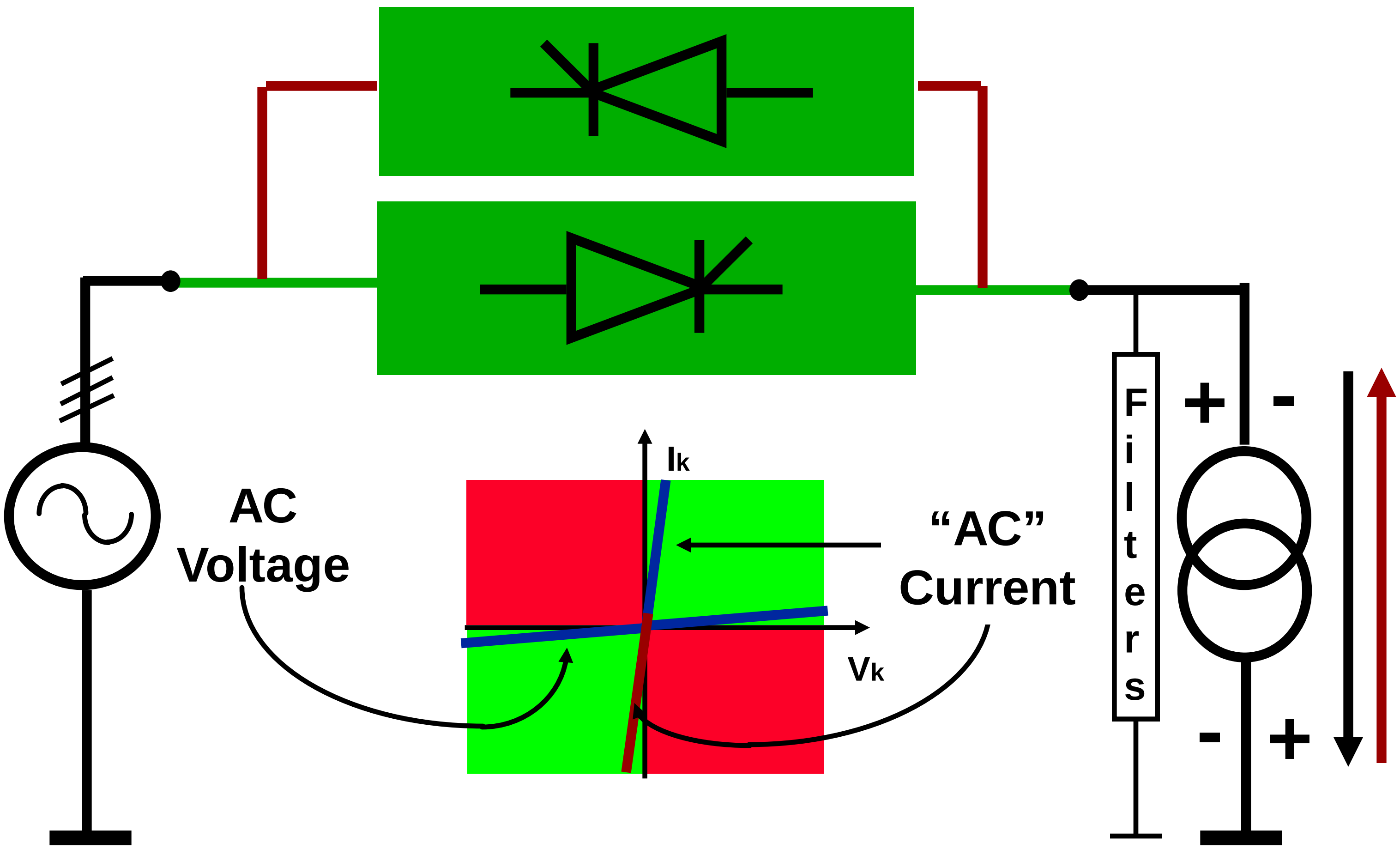
Two Quadrant Phase Controlled Rectifiers for high current SC magnets



[13kA, ± 200 V]



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

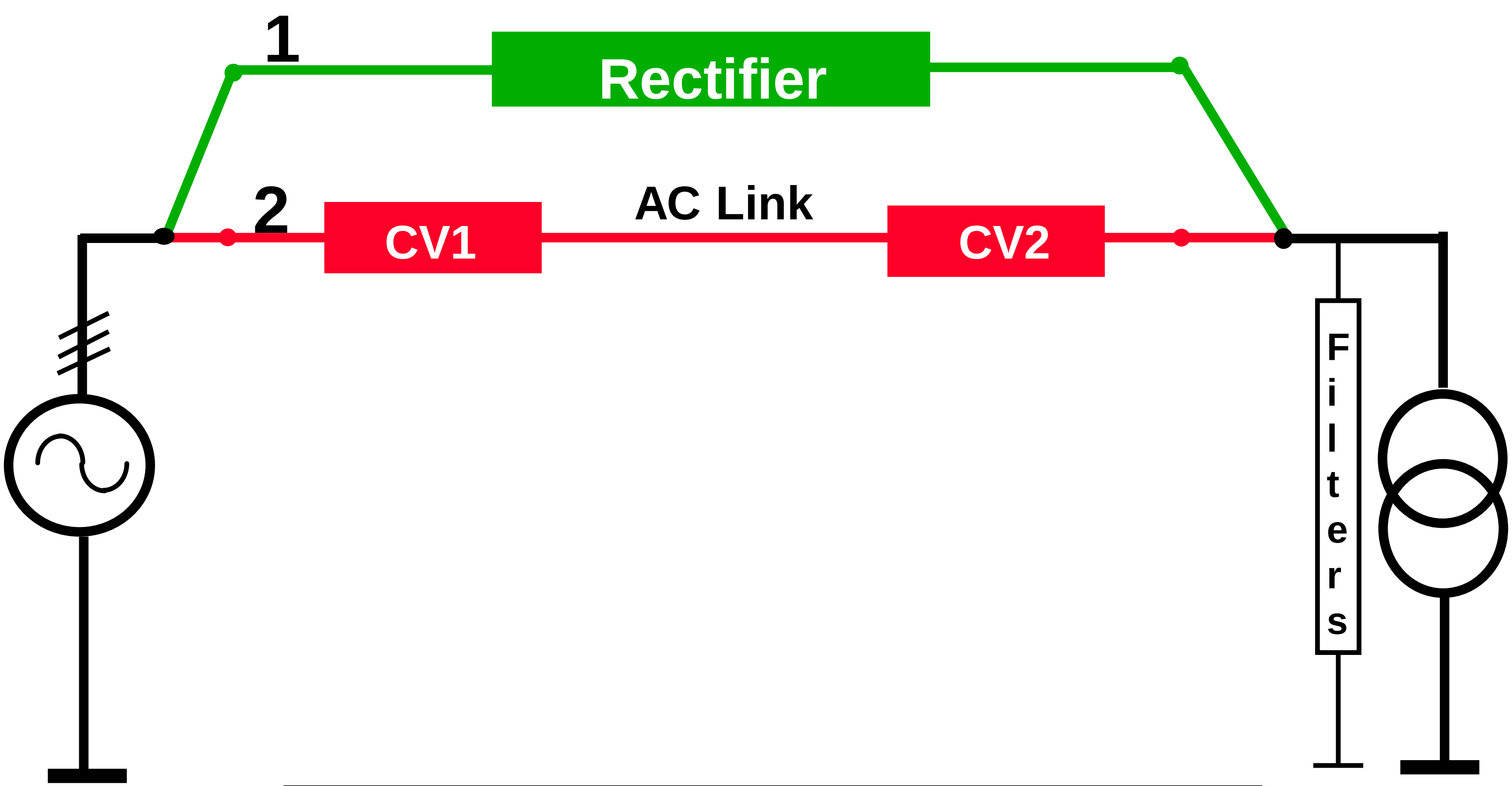
☹ response time is large (ms)

☹ 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,...)

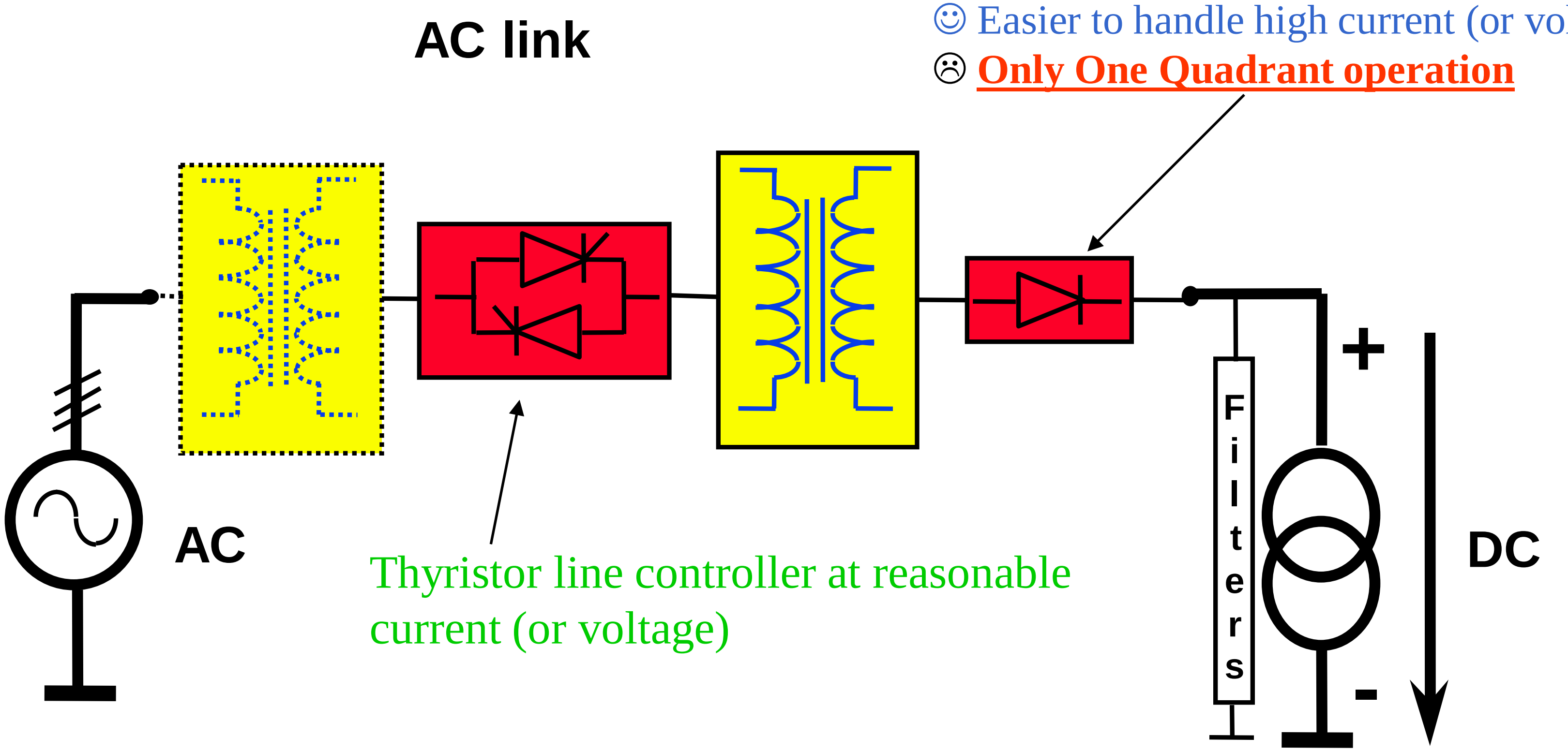
General power converter topologies



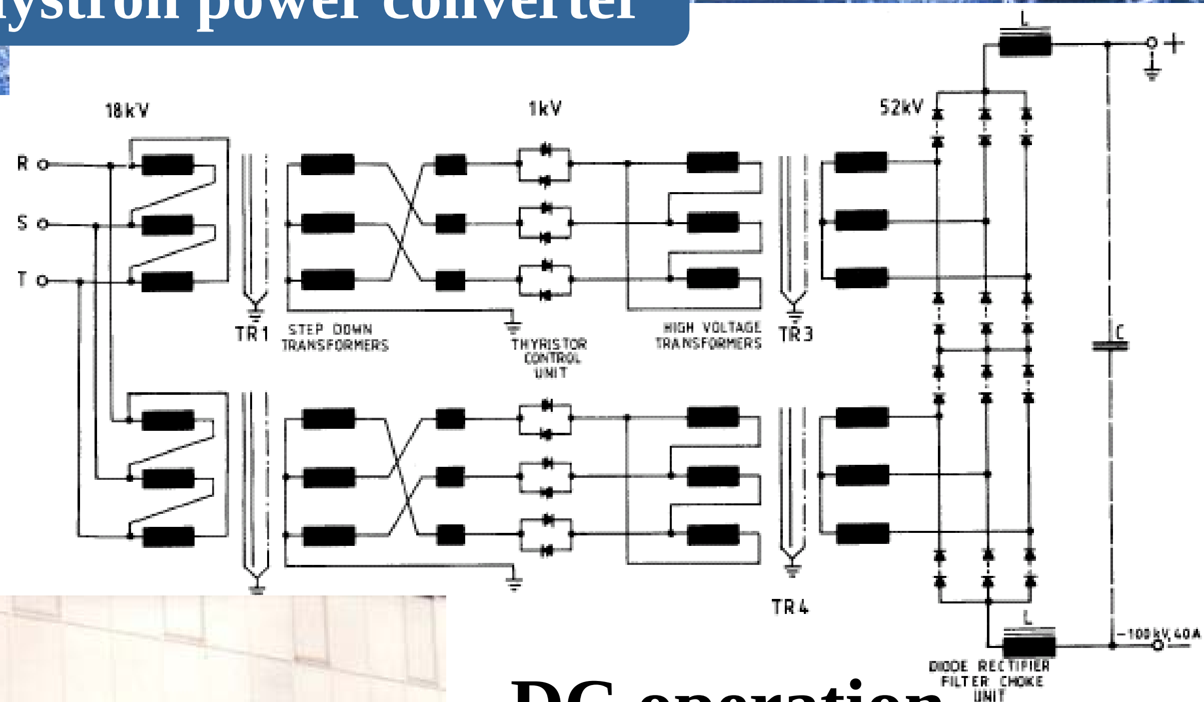
Application :- very high currents with low voltages
- (very high voltages with low currents)

Direct Converters : AC link (AC line controller)

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

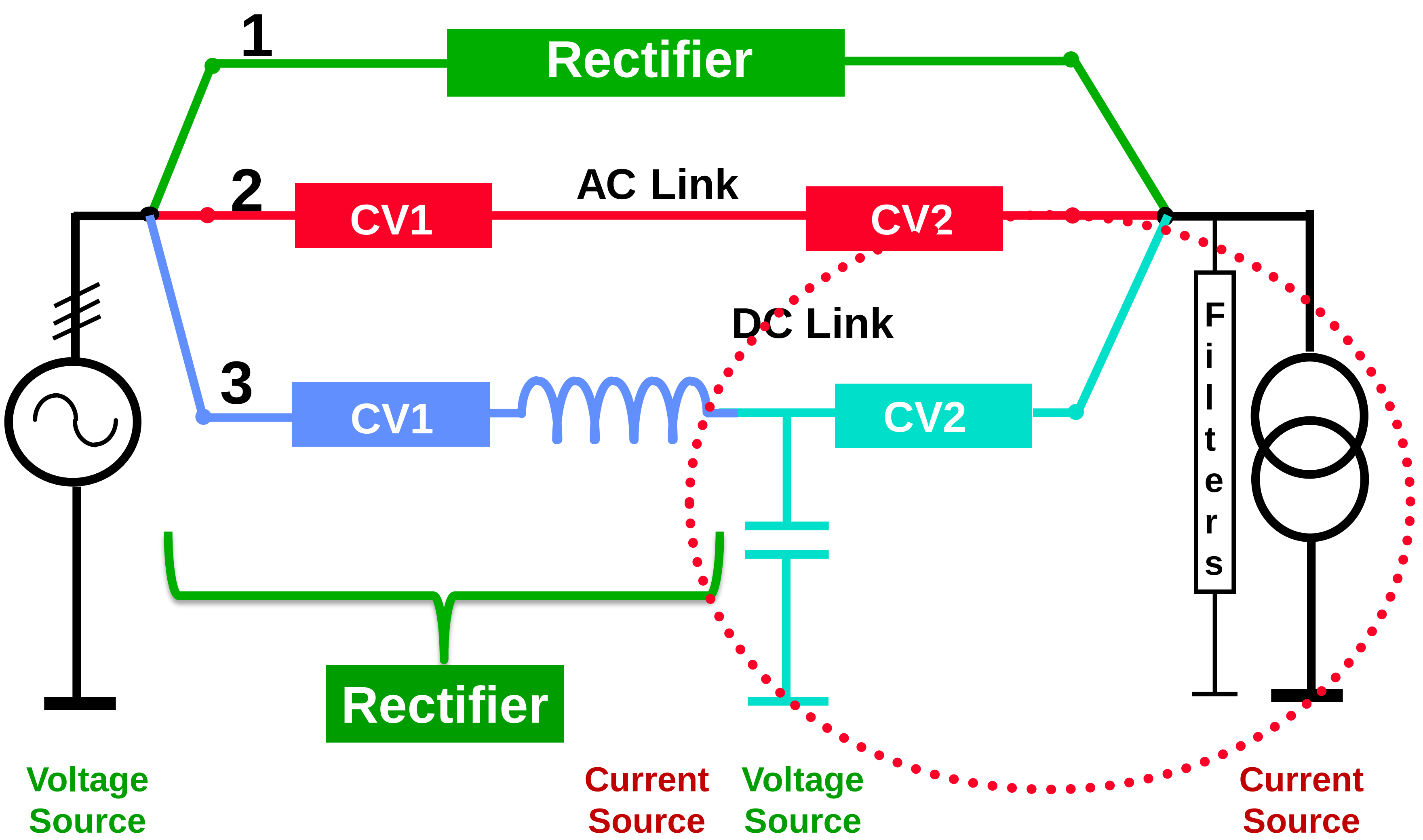


[100 kV, 40A] klystron power converter

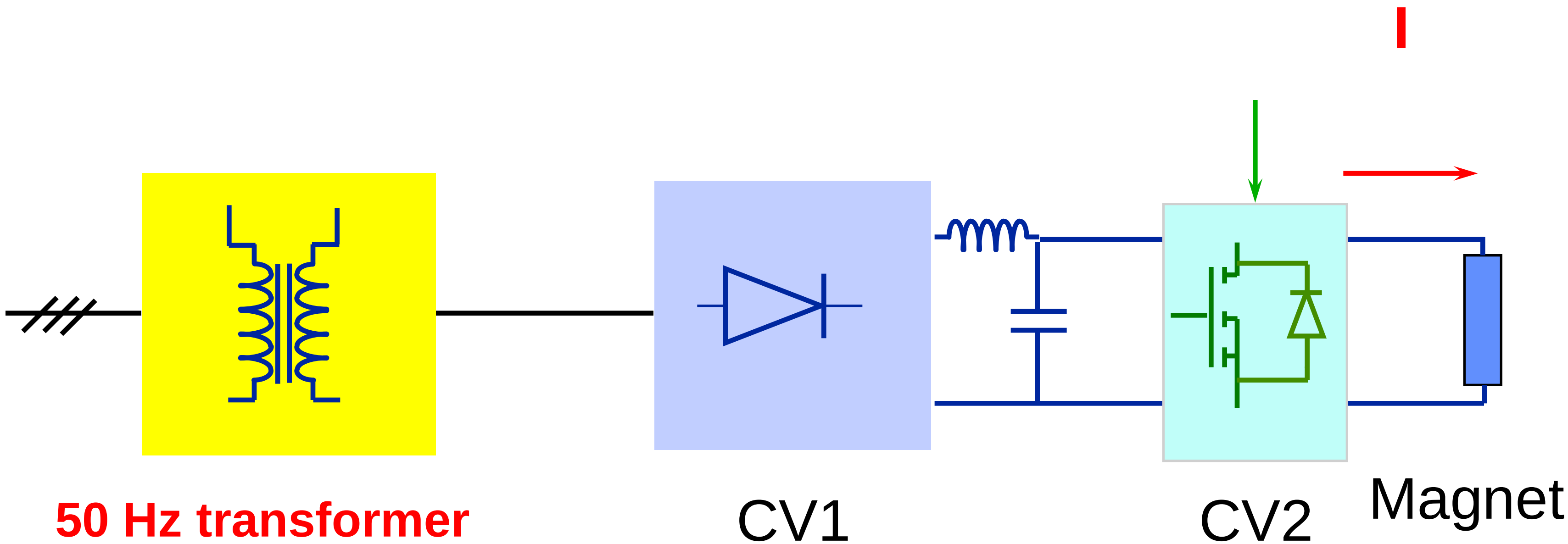


DC operation

General power converter topologies



Galvanic isolation at AC input source (50Hz transformer)



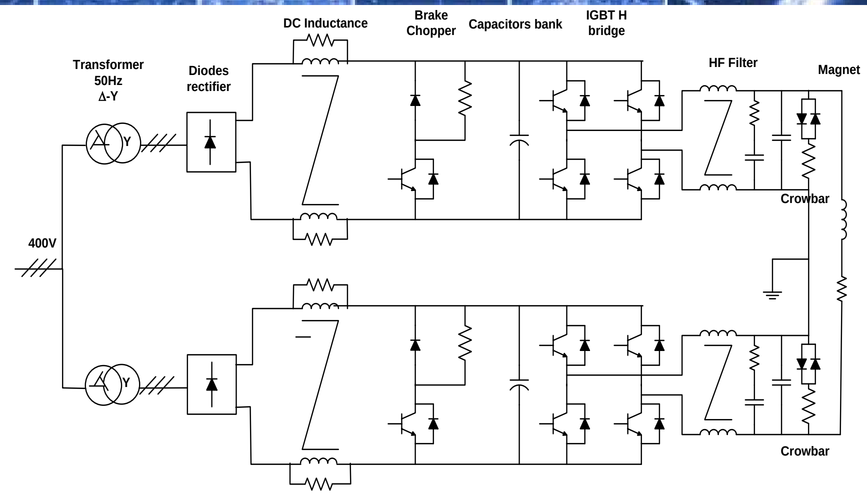
50 Hz transformer
Optimal voltage output
Galvanic isolation

Diode bridge
6 or 12 pulses

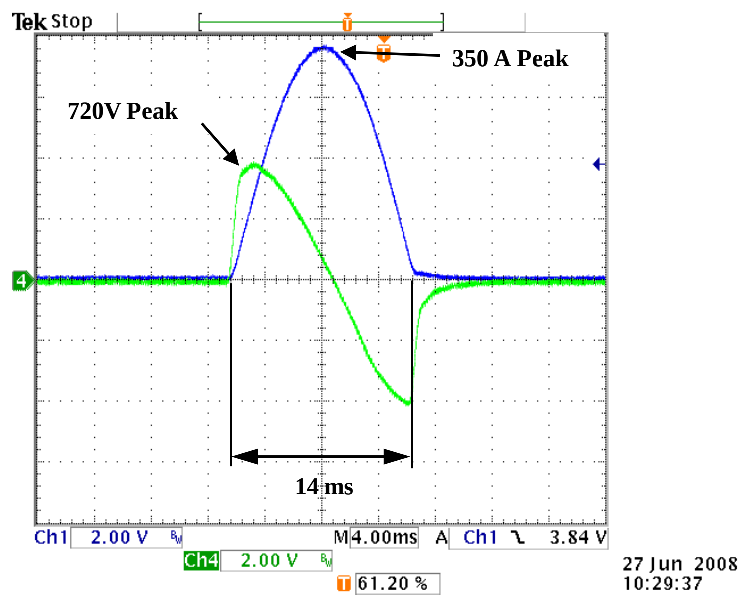
PWM Converter
Hard commutation

New PS Auxiliary Power Converters

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



Multi-Turn Extraction: Current/Voltage waveforms



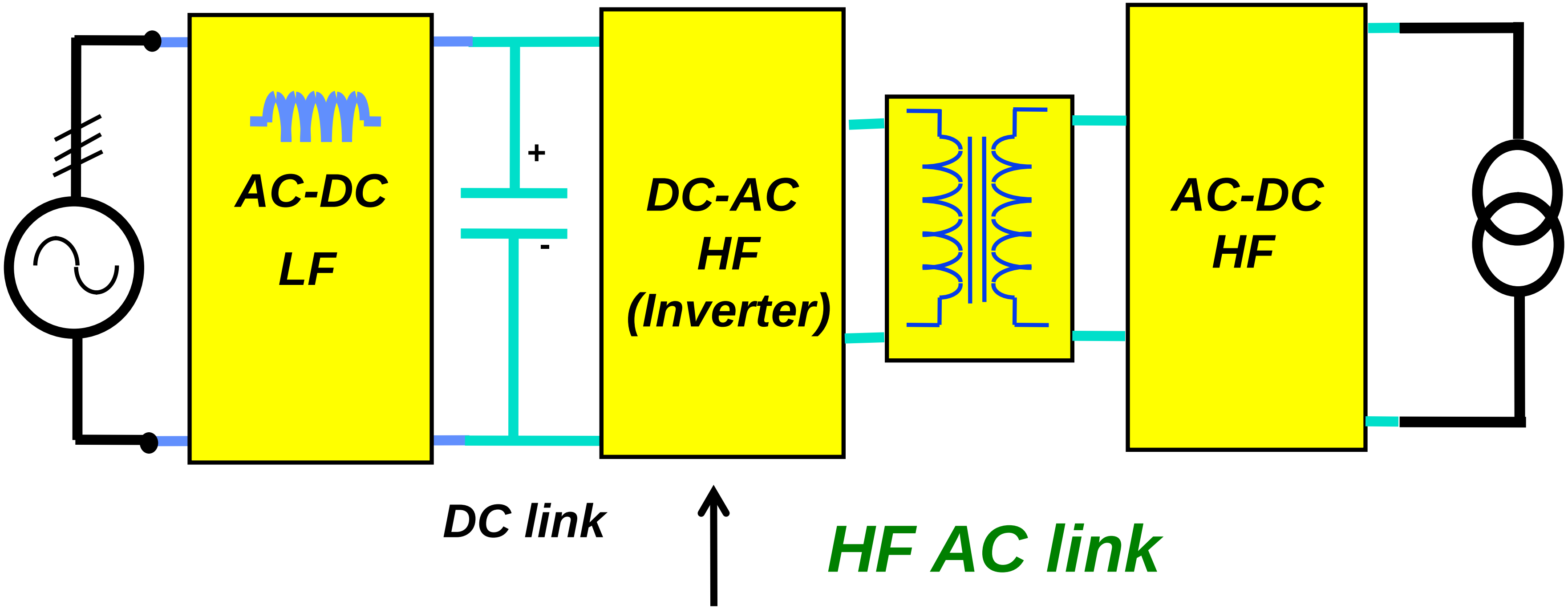
Current Loop Bandwidth ≈ 1kHz

Indirect AC-DC-AC-DC converter

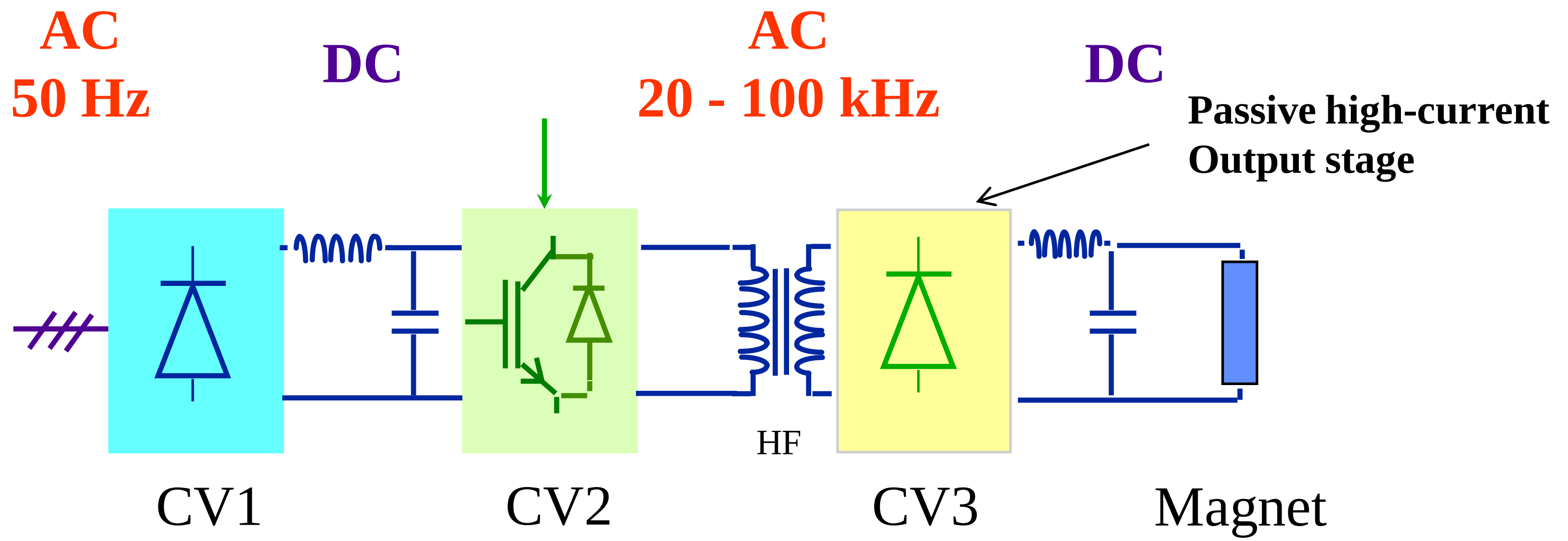
Three cascade power conversion stages:

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

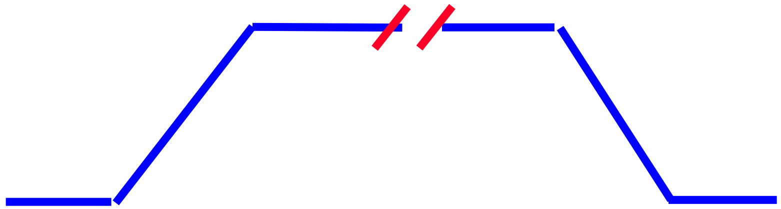
1-quadrant converters:

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

[2kA, 8V]

MTBF and MTTR optimization

DC and slow pulsed converters



Rise and fall time < few ms

Control of the ramps

High and medium power

Phase Controlled Rectifiers

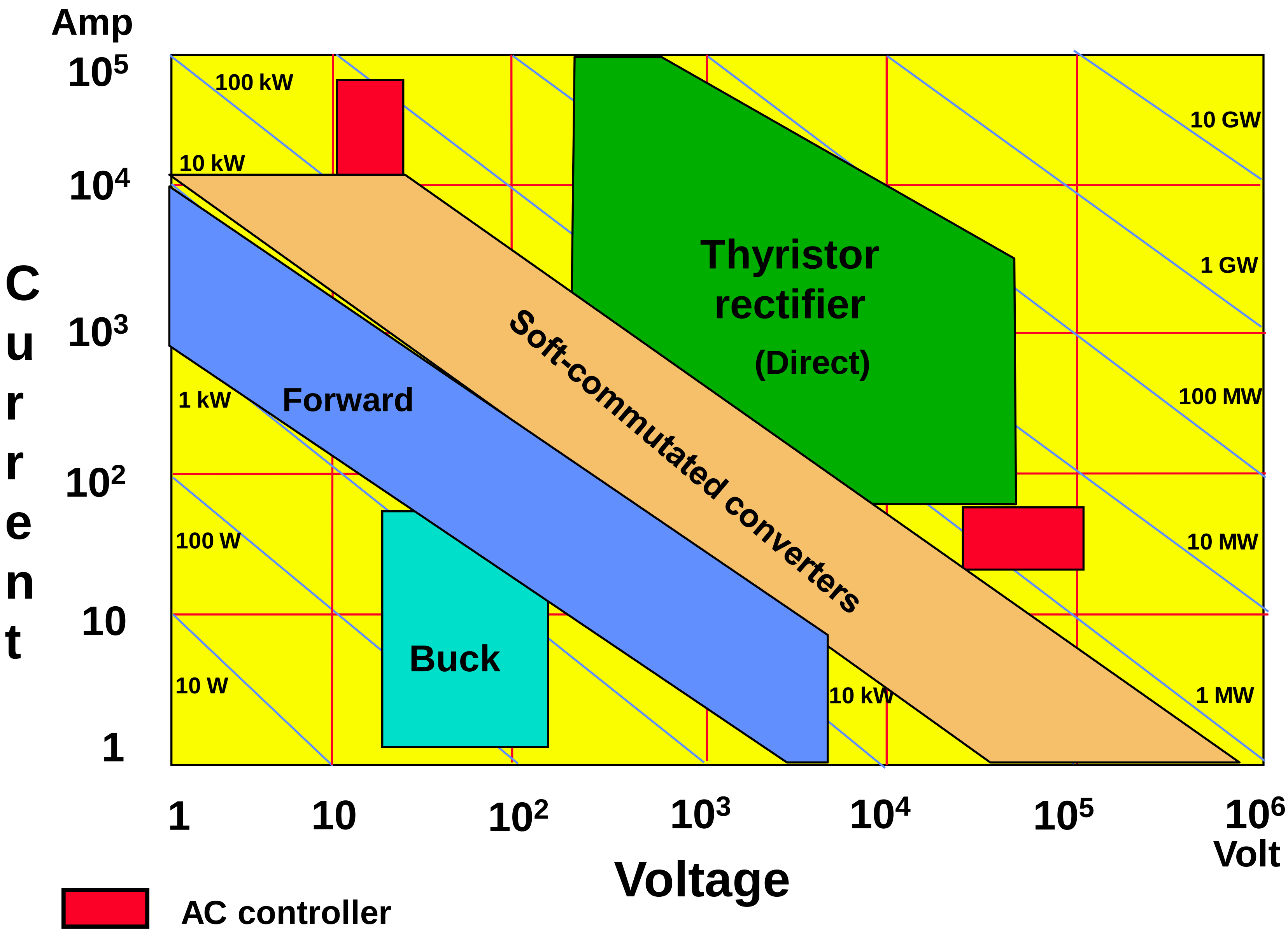
- Diodes and thyristors rectifiers
- 50Hz transformers and magnetic component (filters)
- 1-quadrant and 2-quadrants (but unipolar in current) : energy back to the mains
- 4-quadrant: back-to-back converters

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 has to be re-injected to mains)

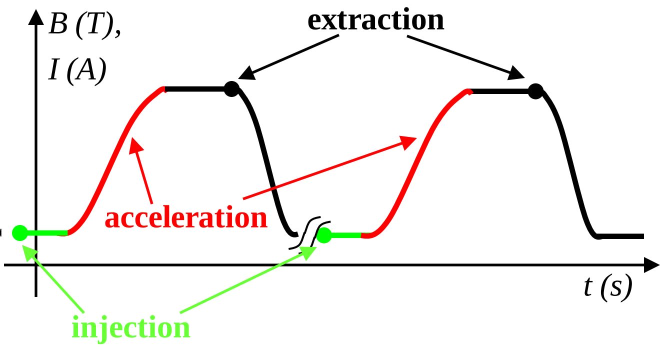
Power converter : Operational domains for accelerators



Pulsed converters

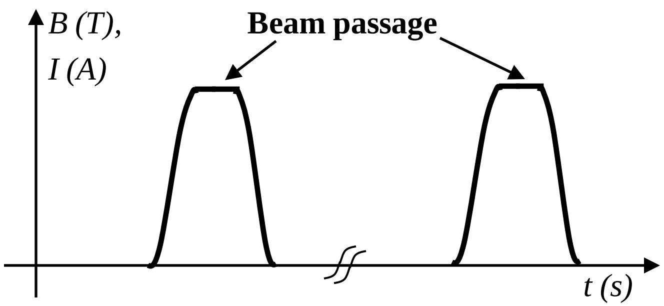
Synchrotrons: injections and extractions

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



Linac's and transfer lines

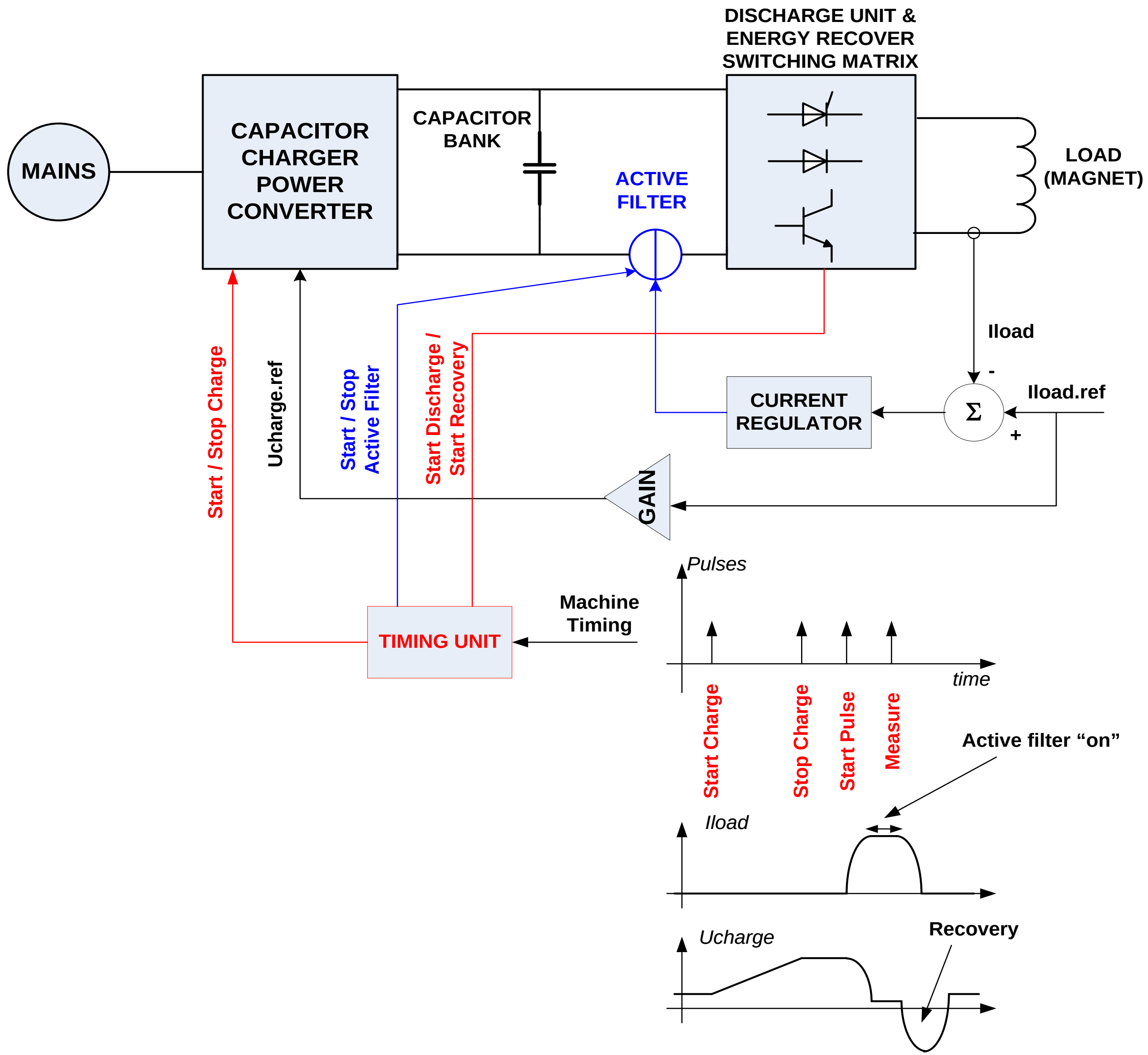
- Beam is passing through in one shot, with a given time period;



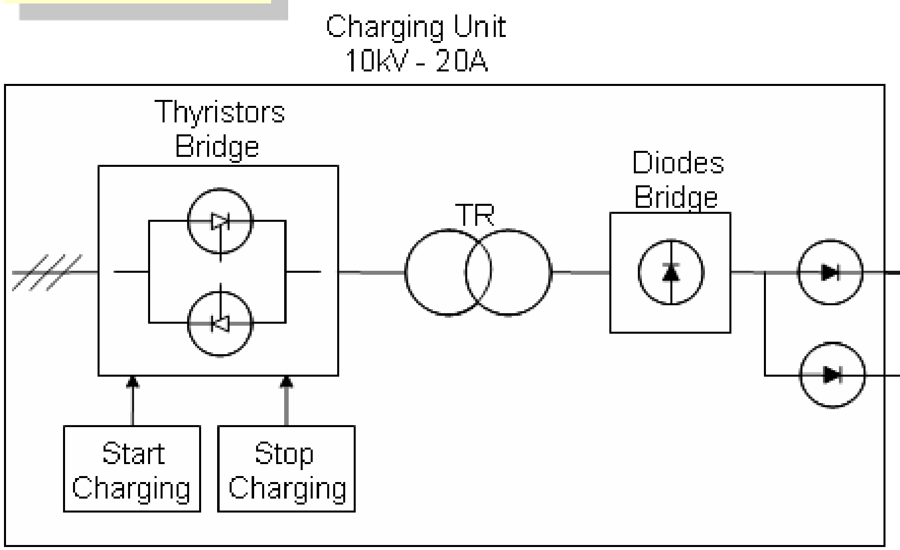
Rise and fall time < few ms

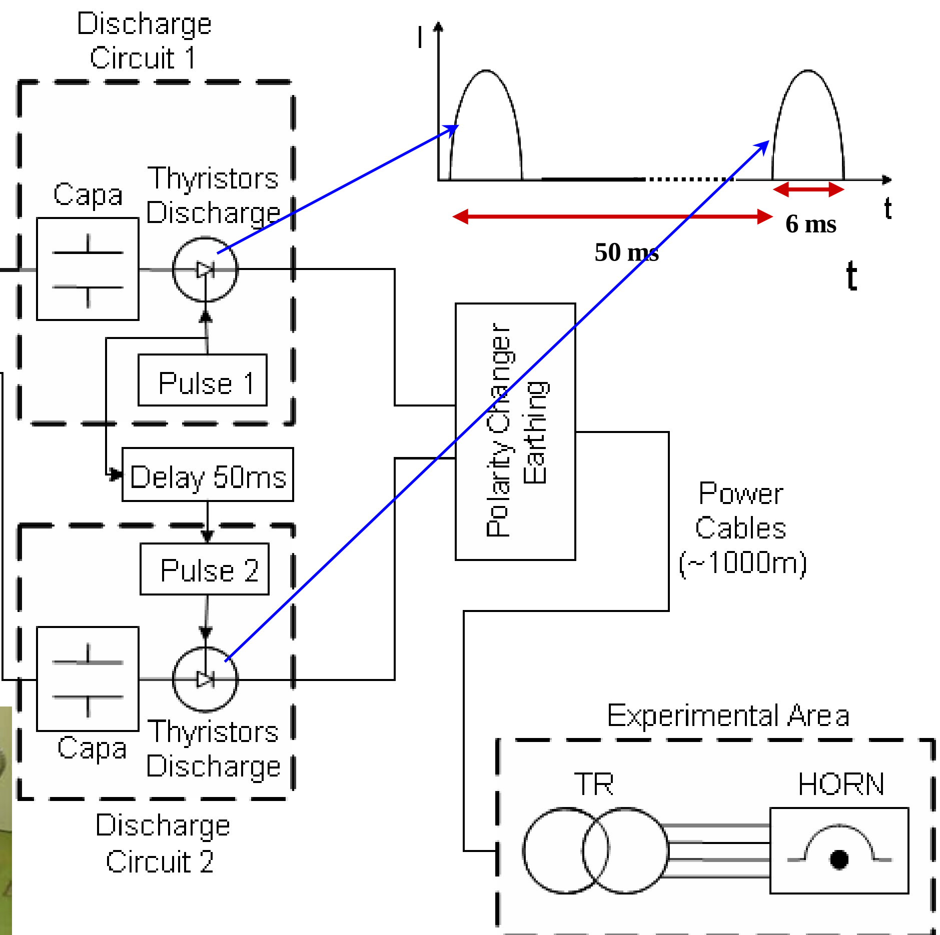
Direct Energy transfer from mains is not possible:
Intermediate storage of energy
Peak power : could be > MW (average power kW)

Block schematic of a fast pulsed converter



CNGS





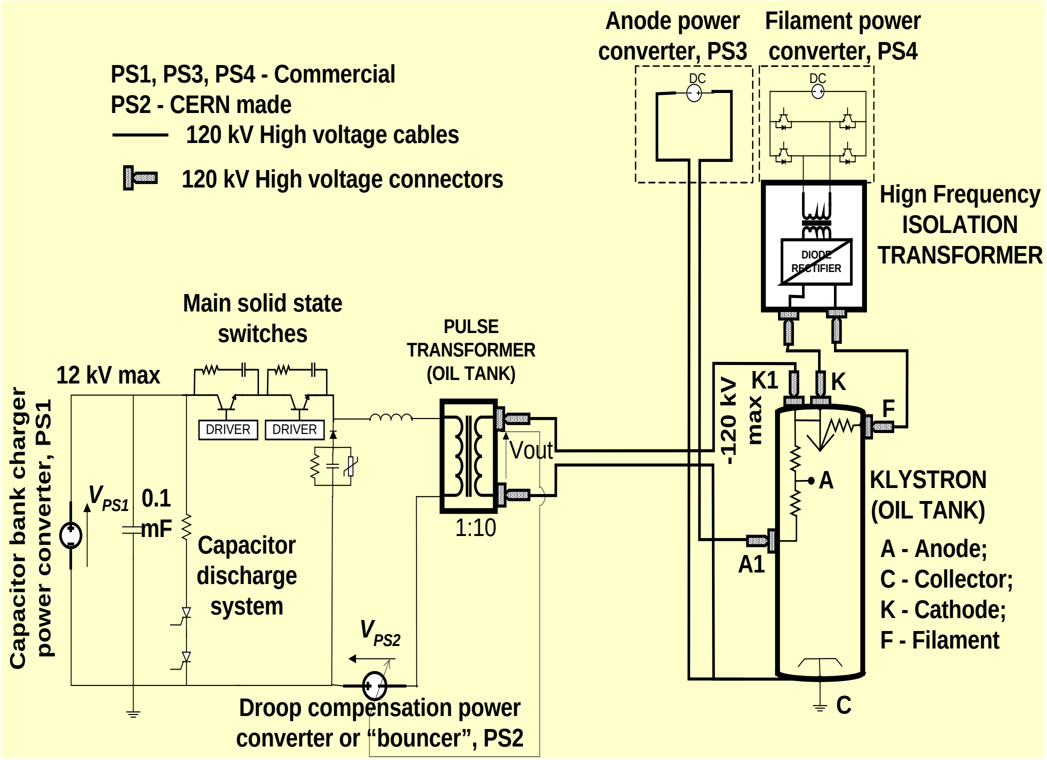
150 kA for the horn

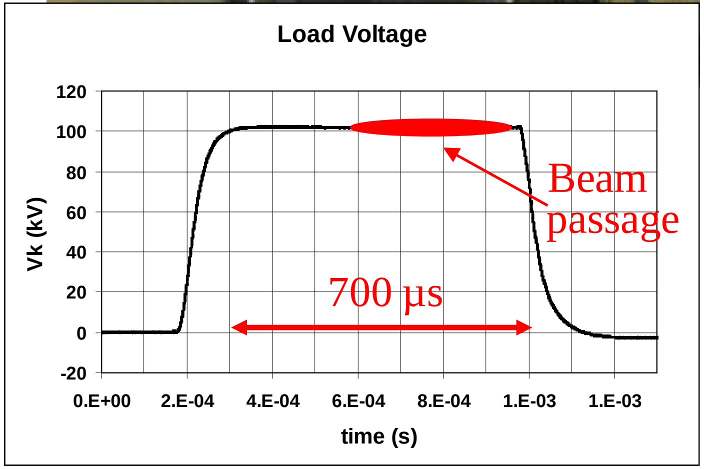
180 kA for the reflector

Pulsed Klystron modulators for LINAC's (Linac 4)

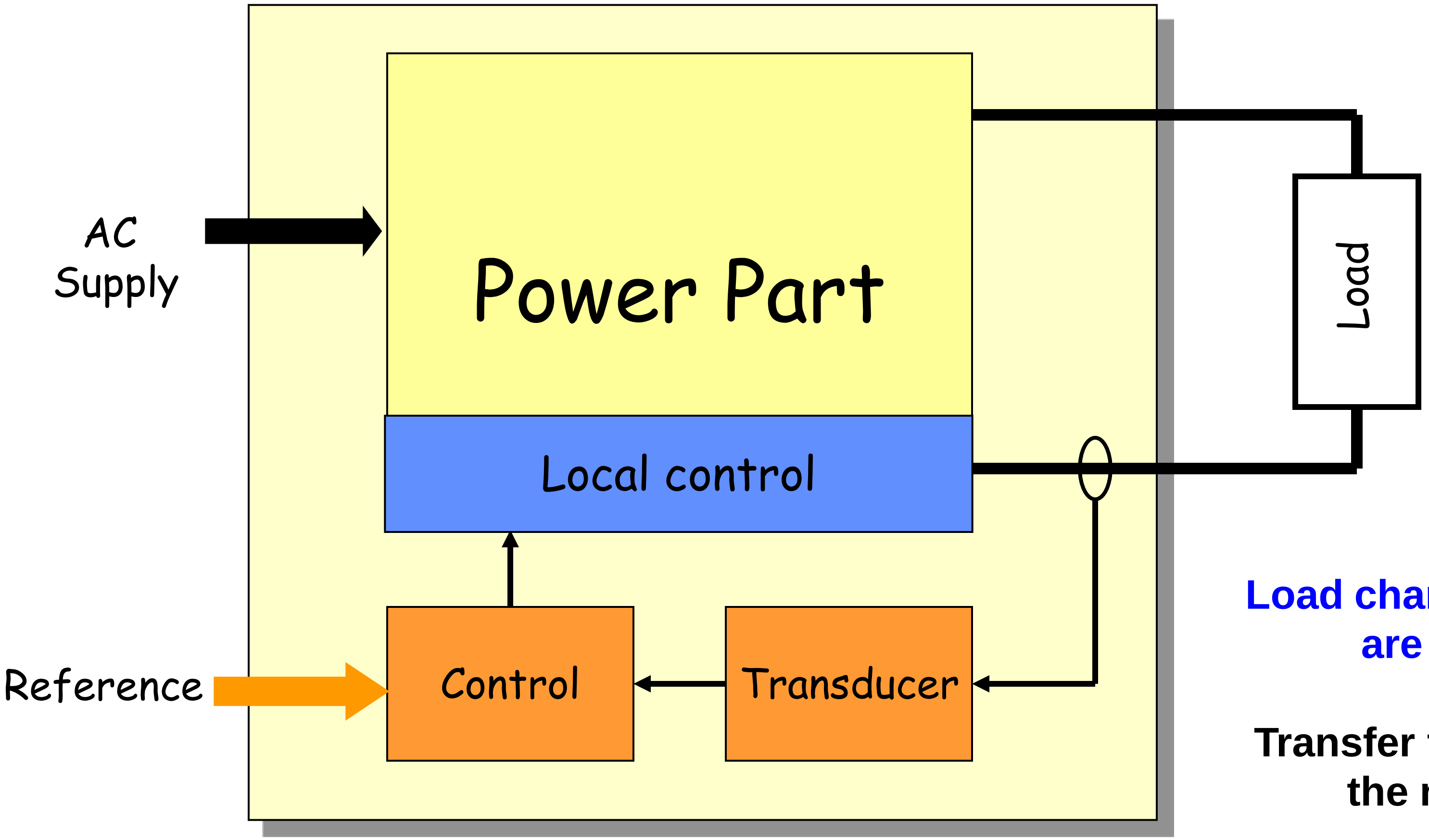
- Characteristics :
  - output voltage : 100 kV
  - output current : 20 A
  - pulse length : 700 μs
  - flat top stability : better than 1%
  - 2 Hz repetition rate

Peak power : 2 MW





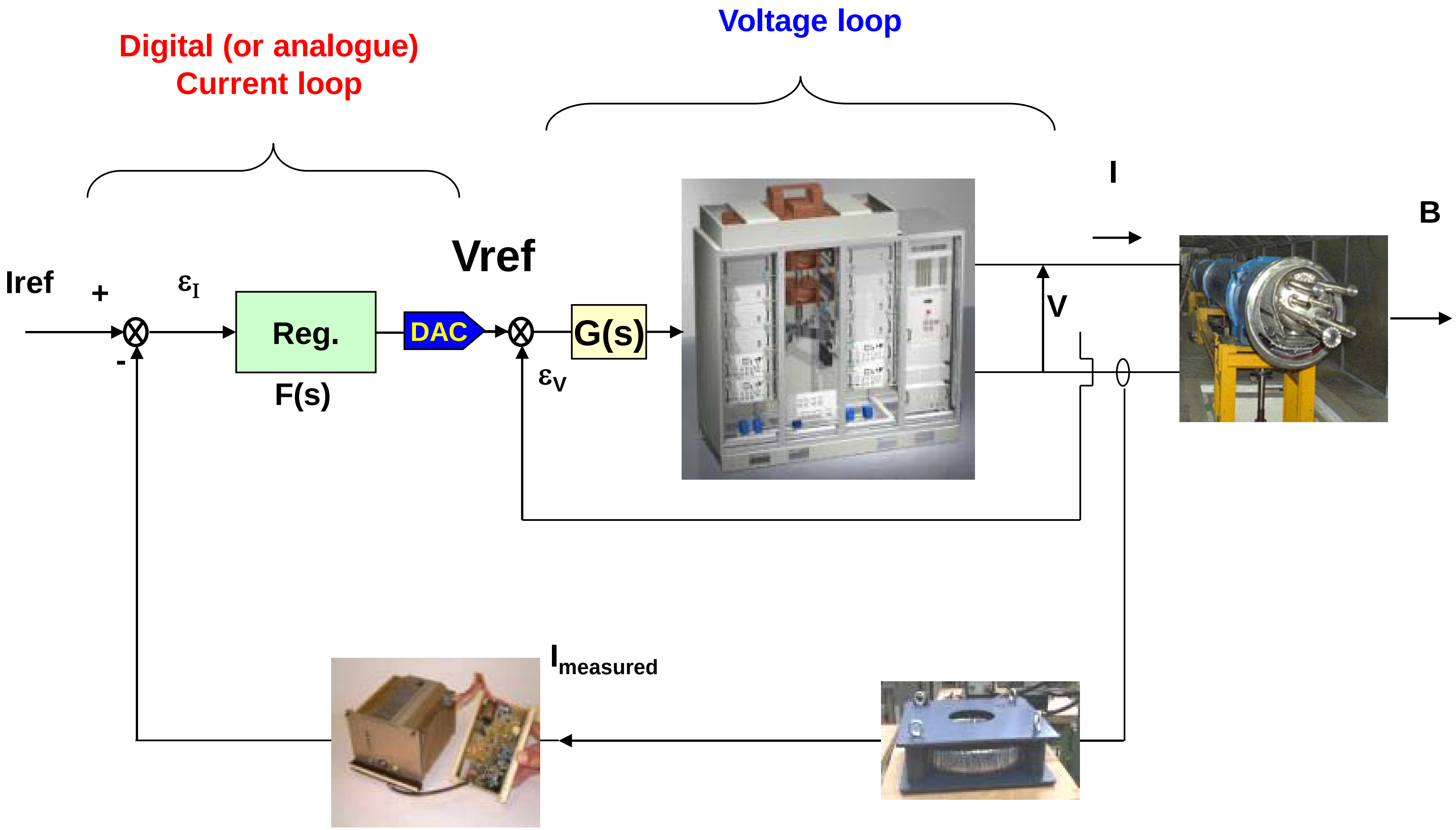
Power Converter % Load



Load characteristics are vital.

Transfer function is the must !

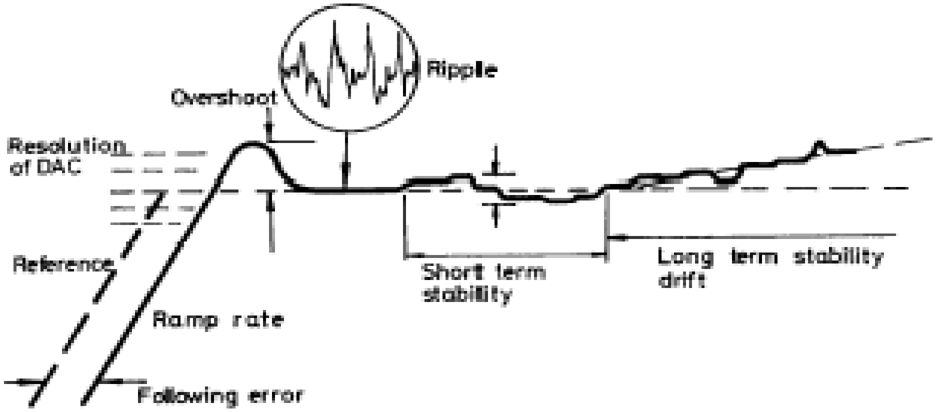
Example :LHC power converter control

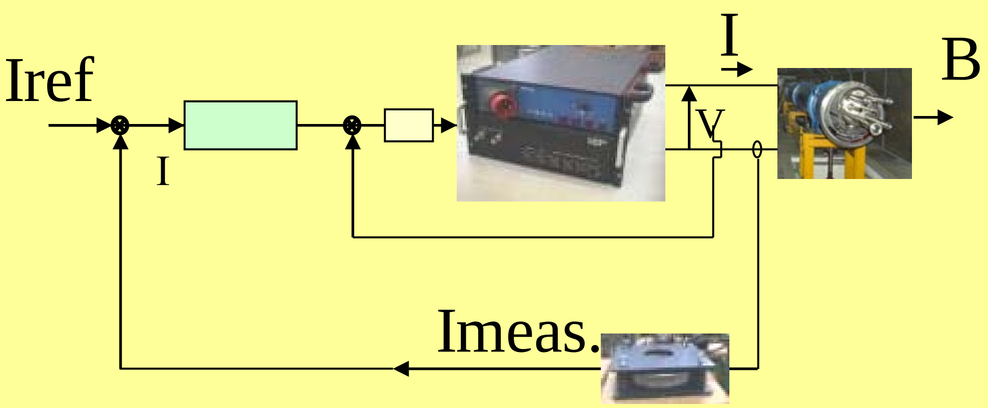


Power converter :Performance requirements

Overshoot

Bandwidth





Accuracy Reproducibility Stability Resolution ?

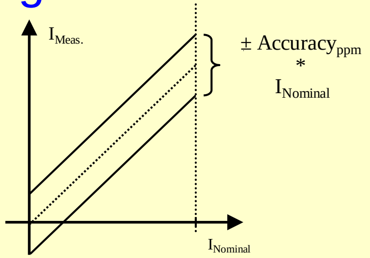
Glossary

Precision

– Accuracy

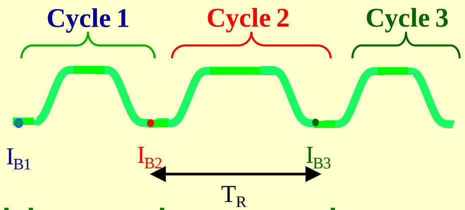
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

* requires definition



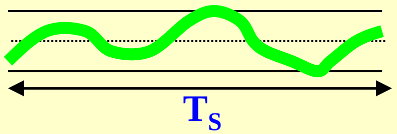
– Reproducibility

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.



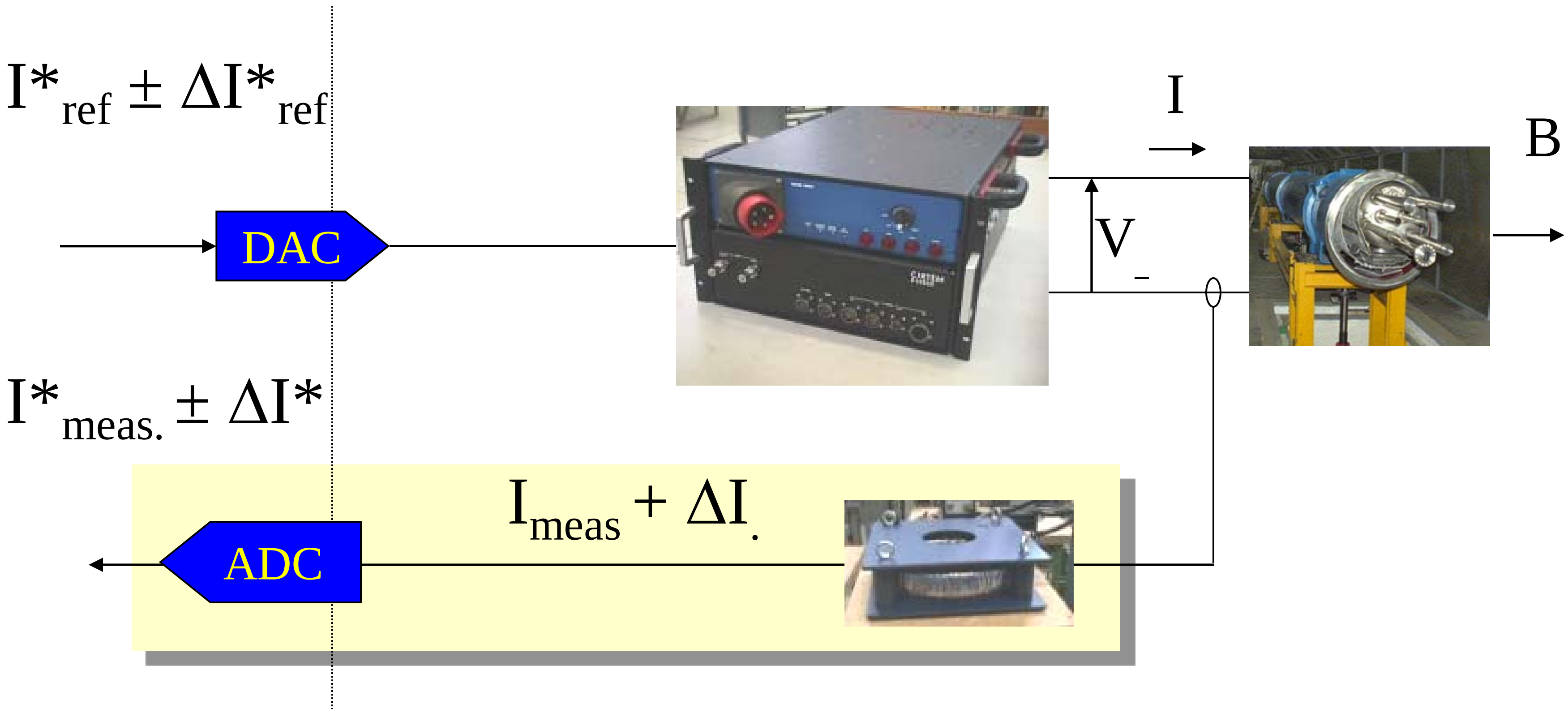
Accuracy, reproducibility and stability are defined for a given period

Precision is qualitative . Accuracy, reproducibility, stability are quantitative.

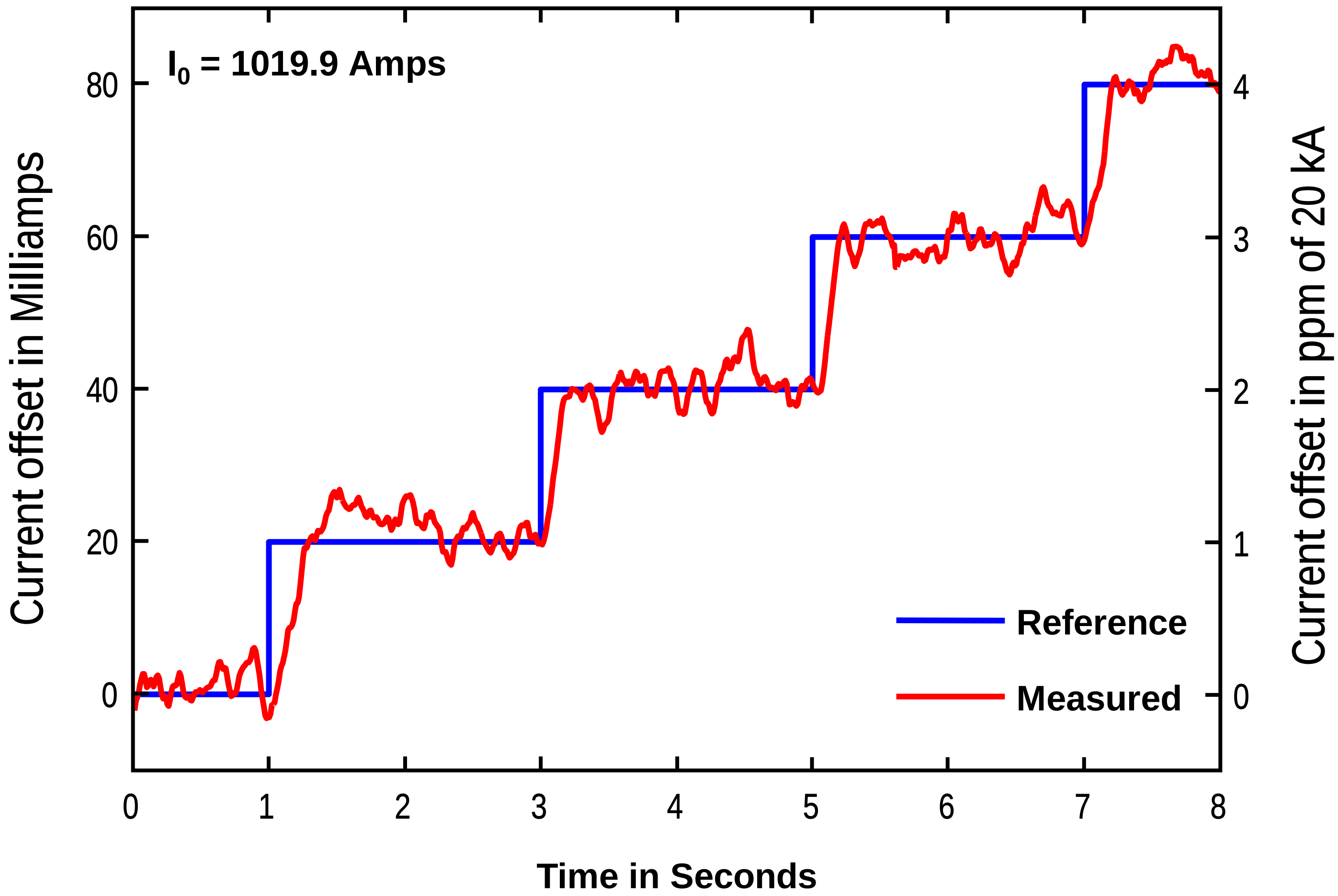
Resolution

Smallest increment that can be induced or discerned.

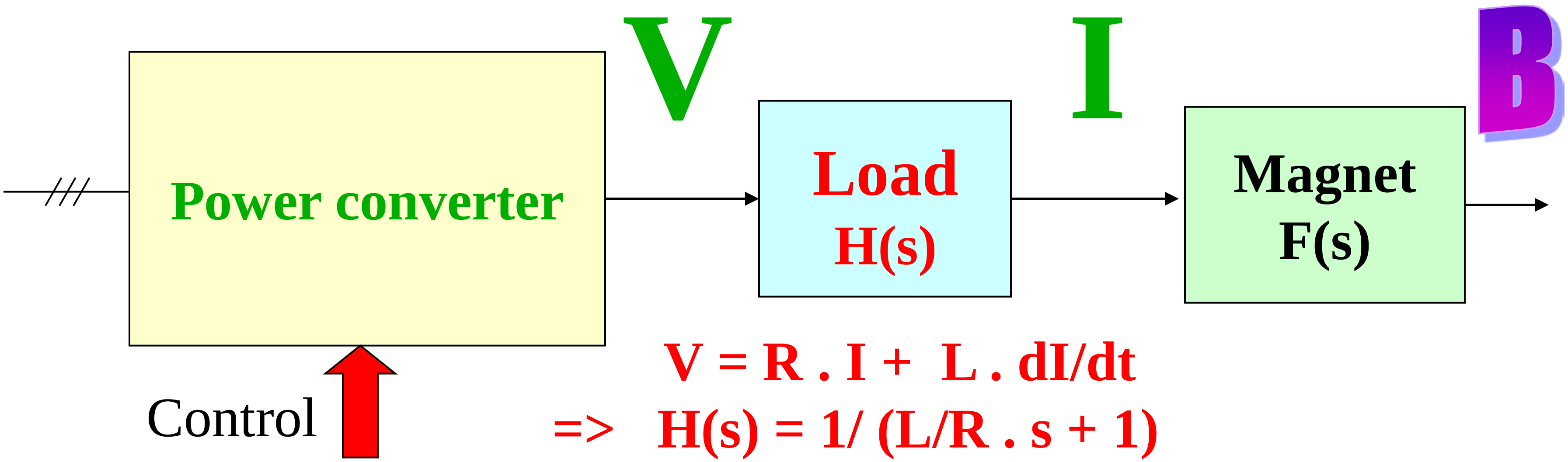
The resolution is expressed in ppm of $I_{Nominal}$.
Resolution is directly linked to A/D system



Results of Resolution Test with the LHC Prototype Digital Controller



RIPPLE



V = R . I + L . dI/dt

=> H(s) = 1/ (L/R . s + 1)

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

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

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

Norms for the power converters :

Emission :

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

IEC 61204 -3

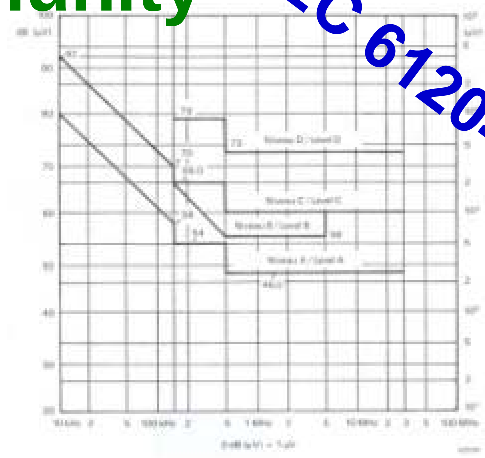
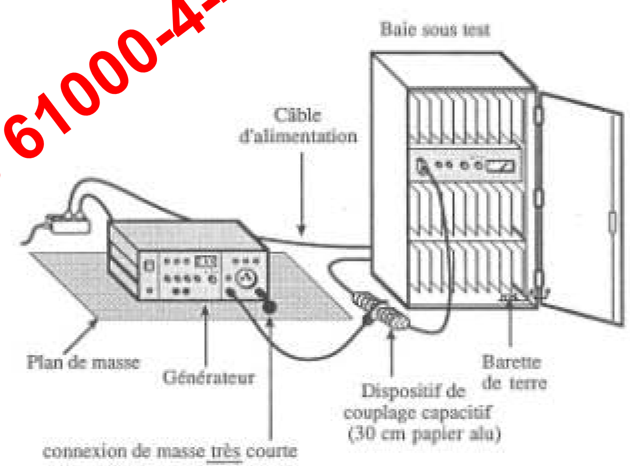


Figure 3 – Valeurs limites pour PEM par conduction
Limit values for conducted EMI

Immunity :

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

IEC 61000-4-4



Power converters specifications

"Do you have one or two power converters for the test of magnet prototypes? 40 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 then 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)

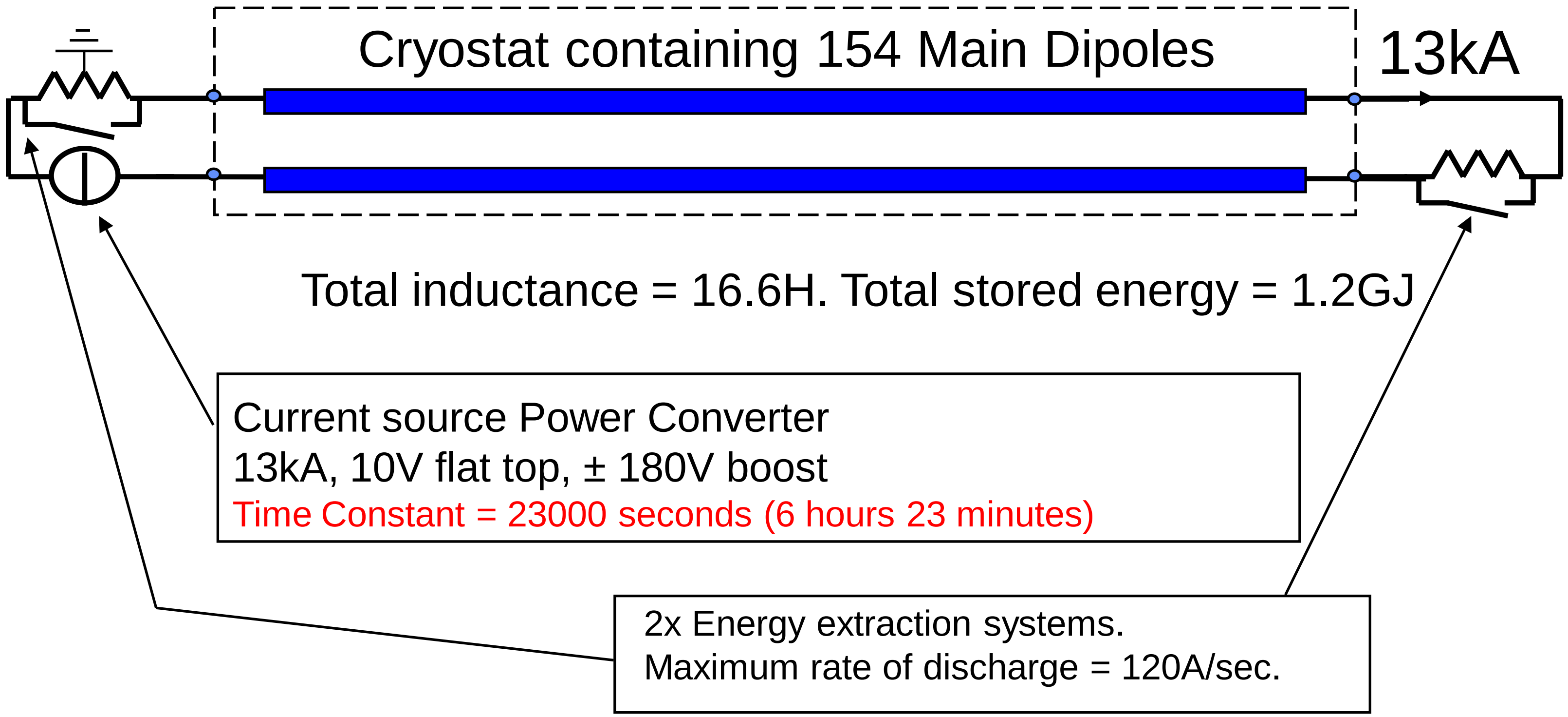
Precision: accuracy, reproducibility, stability - Resolution

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…..

One Sector (1/8) of the LHC Machine

Need to think at circuit level : power converters, water cooled cables, extraction system (resistances and breakers), HTS current leads, cryogenics feed box, magnet string, diode, QPS,...



благодаря

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