CERN

Powering Infrastructures

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Special thanks to Frédérick Bordry and Jean-Paul Burnet (both former power converter group leaders at CERN) for the inspiration from previous CAS courses

CAS course on "Normal- and Superconducting Magnets", 19 November - 02 December 2023, St. Pölten, Austria

2023-12-01

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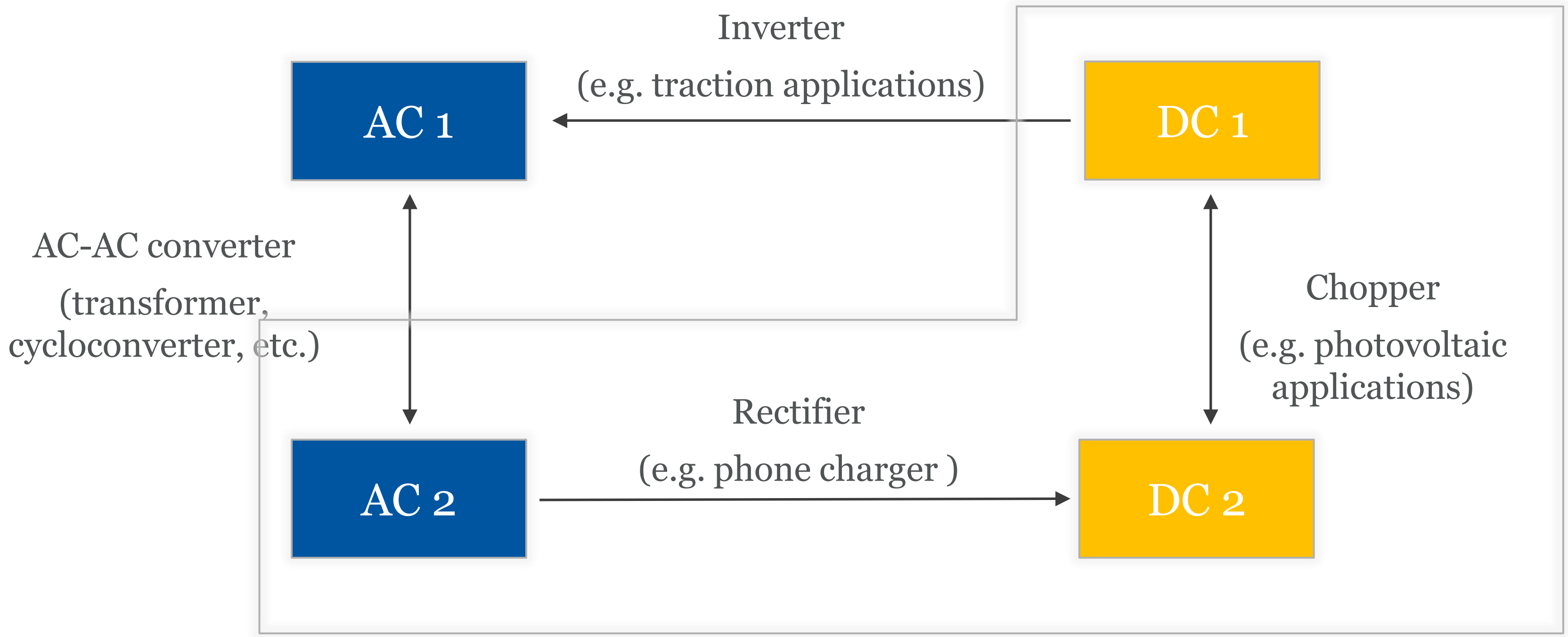
Power Converter Definition

Definition of Power Converters

Power converter is an electrical circuit that transforms the electric energy from one form into the desired form optimized for a specific load.

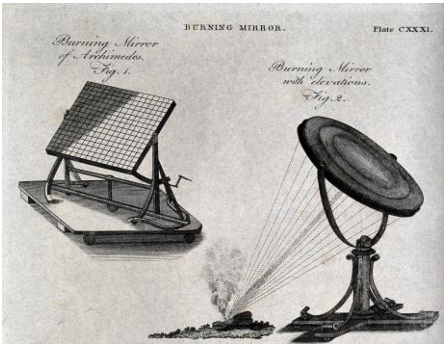


DC: Direct Current

AC: Alternating Current

Choppers and Rectifiers are used for magnets in accelerators and in the scope of today's lecture

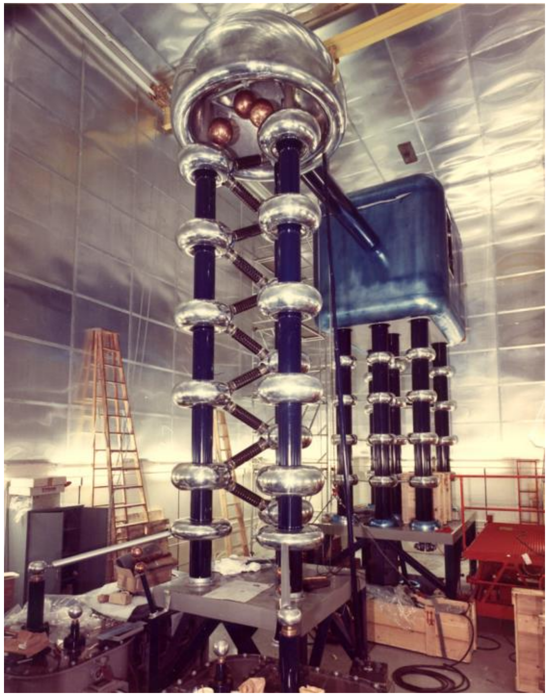
Contribution of Power Converters

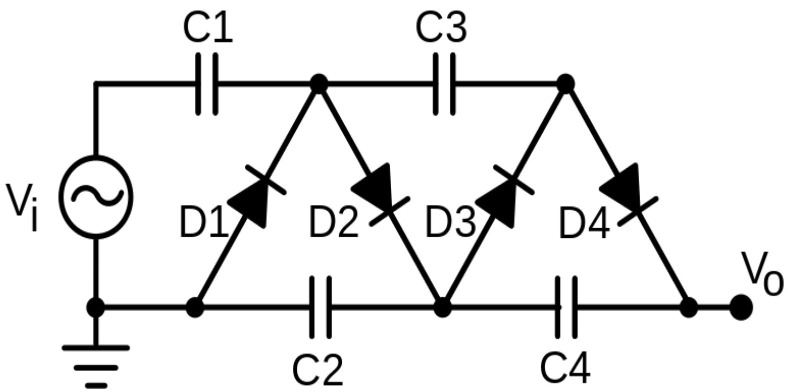


And many more applications...

High Energy Physics and Power Converters

The Nobel Prize Power Converter





Voltage multiplier by diodes

Cockcroft & Walton who in 1932 used a voltage multiplier to power their particle accelerator, performing the first artificial nuclear disintegration in history.

In 1951, they won the Nobel Prize in Physics for "their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles".

What is a Power Converter? Depends who you are asking…

For people outside CERN
Is there a difference between a power converter and a power supply ?

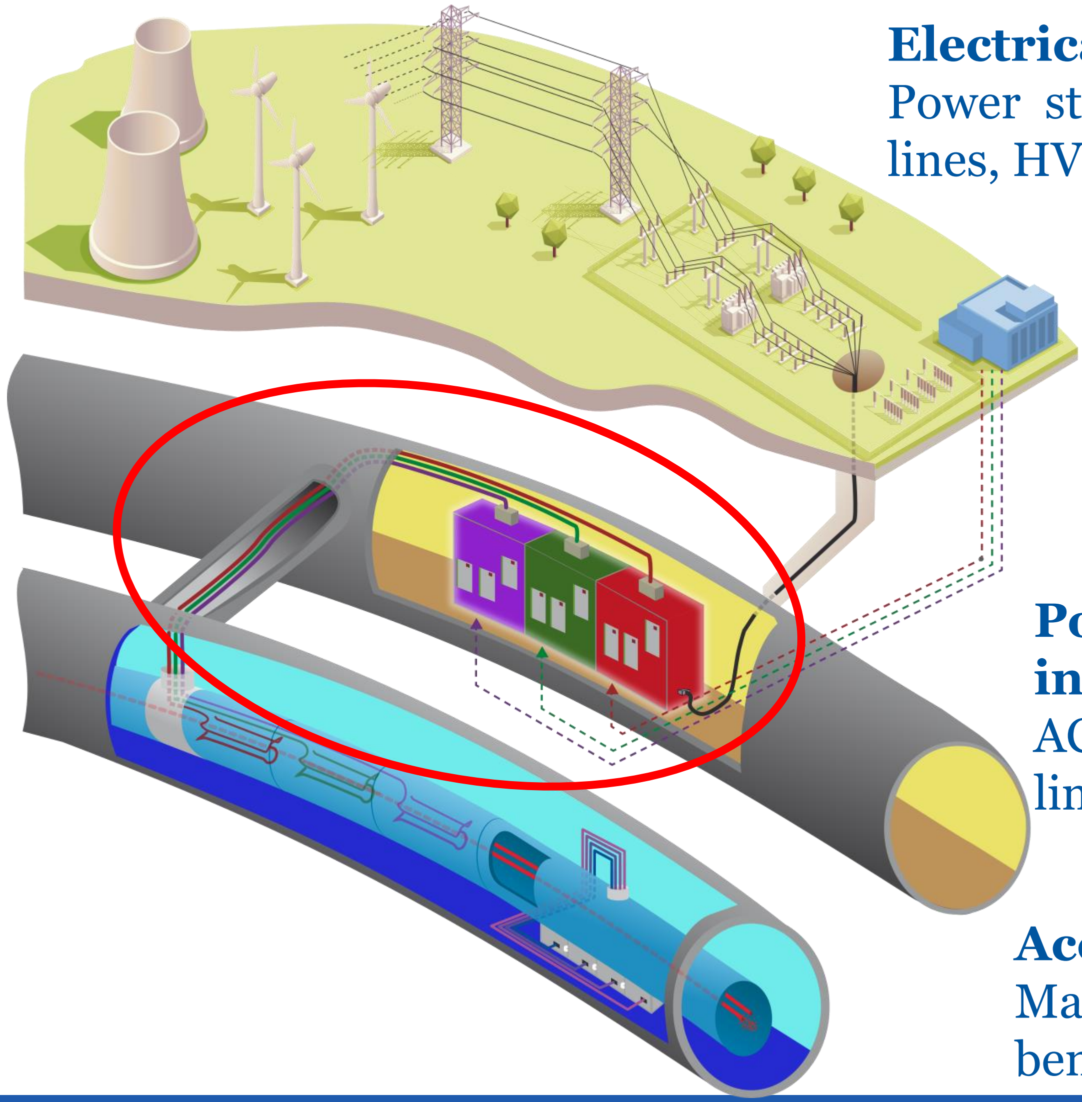
For an accelerator operator
An abstract device that is mainly responsible of the 50 Hz ripple in the beam.

For a magnet expert
Electrical cabinets that take space in the test facility and should deliver whatever current, voltage and energy.

For a magnetic measurements expert
A source of noise and harmonics!

For a magnet power converter designer
A component closely dependant on the magnet design and operation cycles that is developed in parallel to the magnet that takes few years from specification to operation

Power Converters for Accelerator Magnets



Electrical Infrastructure
Power stations, High-Voltage transmission lines, HV/LV transformers, etc.

Accelerator Control Center
Parameters/references for Power Converters, beam operation cycles, information reading, etc.

Power Converters and linked infrastructures
AC/DC conversion connected to DC links to power magnets

Accelerator magnets
Magnetic field generation, beam bending, focusing and correction

2

Main Power Converter Topologies for Accelerator Magnets

Evolution of Power Switches as the Heart of Converters

Mercury arc rectifiers, vacuum valves, etc.

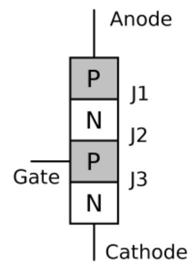
Beginning of the 1900s

Solid State Electronics (semiconductors)

1960s

Power Diode and Thyristor

Silicon-Controlled Rectifier (SCR)

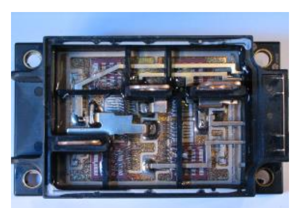


Linked to frequency of the electrical network 50 Hz (60 Hz)

Fast Switching Solid State Electronics

1980s

IGCT, GTO, MOSFET, IGBT, etc.



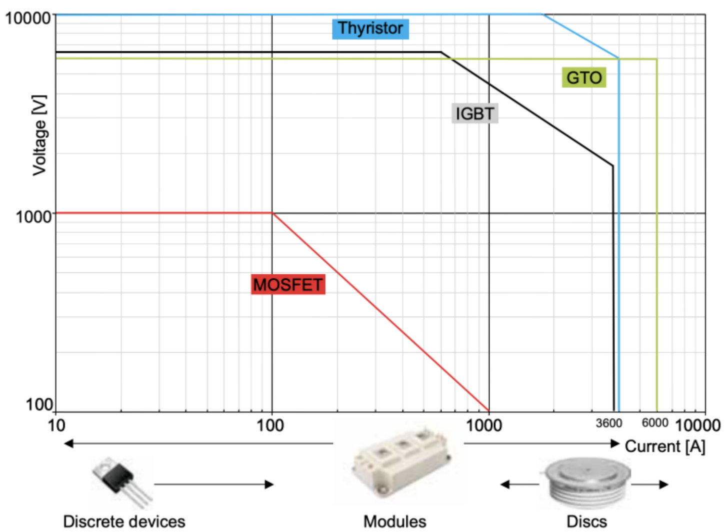
Controller Turn-ON and Turn-OFF with High Frequency → High performance (ripple, bandwidth, perturbation rejection, etc.) and much smaller magnetic components (volume and weight)

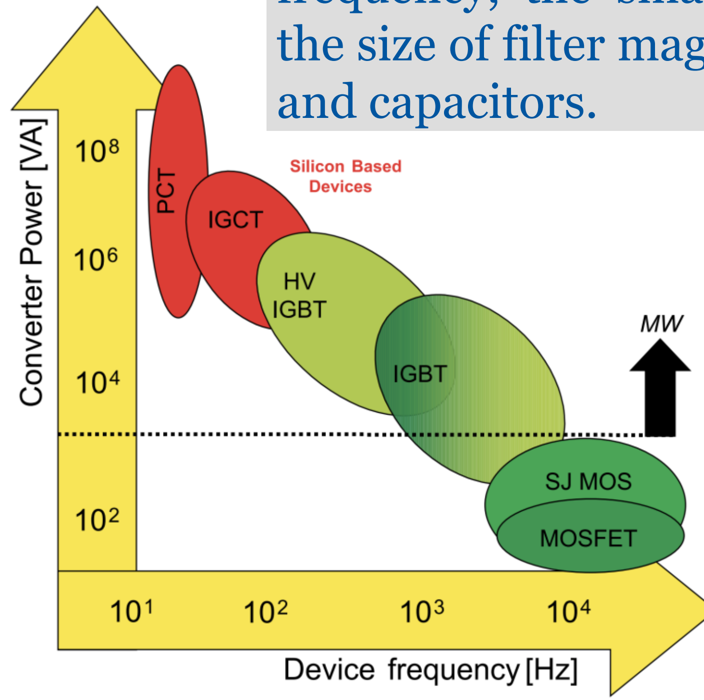
Switching Devices

Nowadays, the main switching power semiconductors used are:

- Thyristor and Diodes
- IGBT
- MOSFET

The higher the switching frequency, the smaller is the size of filter magnetics and capacitors.



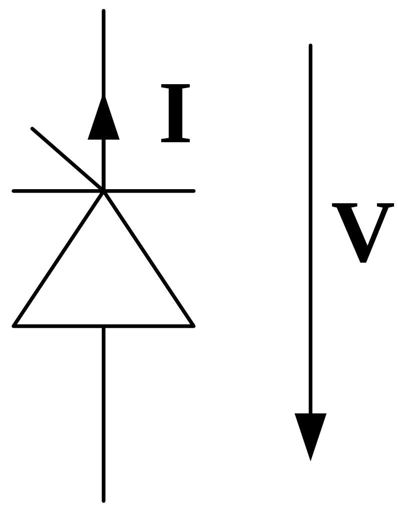


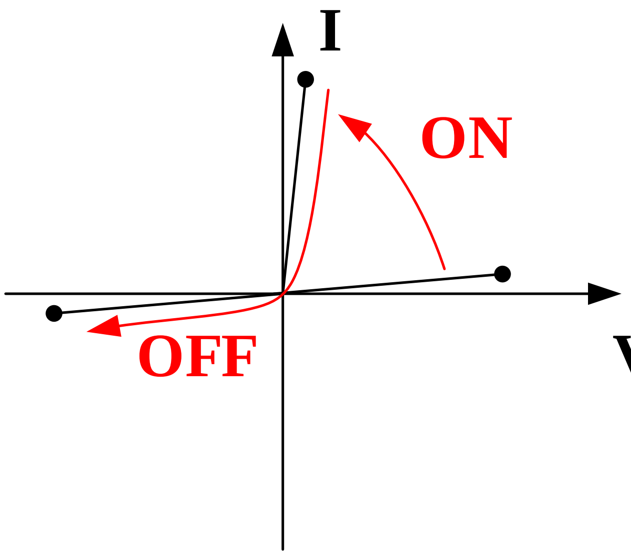
A. Wintrich, U. Nicolai, W. Tursky, and T. Reiman, Application Manual Power Semiconductors, 2nd ed. Nuremberg, Germany: SEMIKRON International GmbH, 2015.

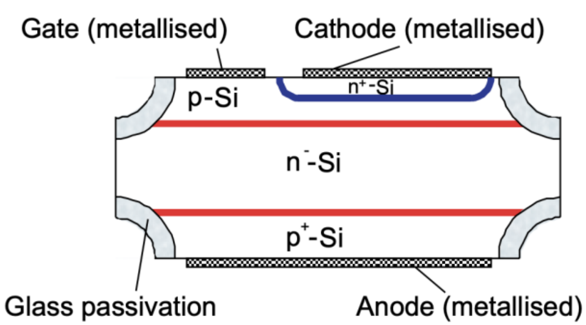
Parallel and series connections in power converters means that virtually any amount of electric power can be converted.

Topologies based on Thyristors

Power Thyristor





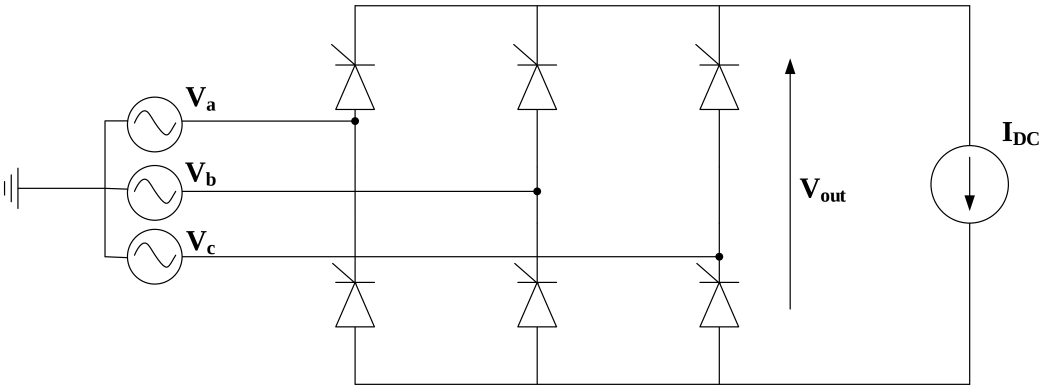


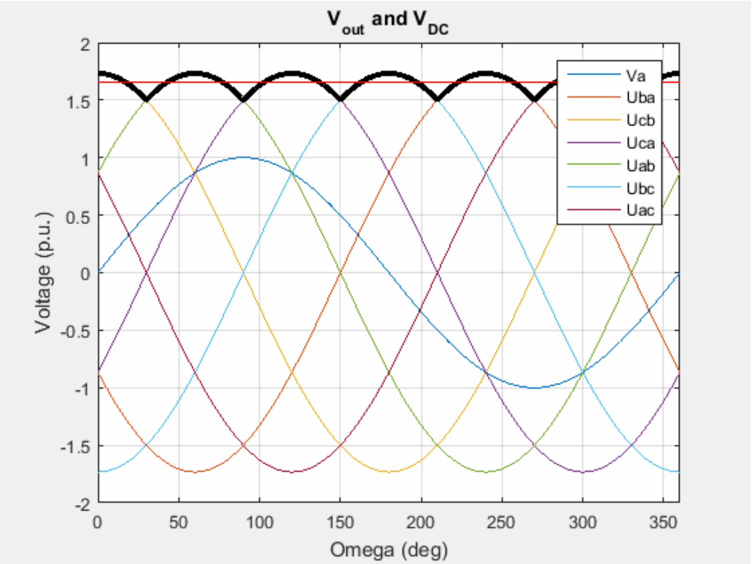
Controlled Triggering from OFF → ON

Circuit Triggering from ON→ OFF when I < holding current

Thyristor Rectifiers (AC/DC) Basic Concepts

6 Pulse Thyristor Bridge





Va = V sin(ωt)

Vb = V sin(ωt-2π/3)

Vc = V sin(ωt-4π/3)

α: Triggering Angle of Bridge

(angle between Va and Triggering)

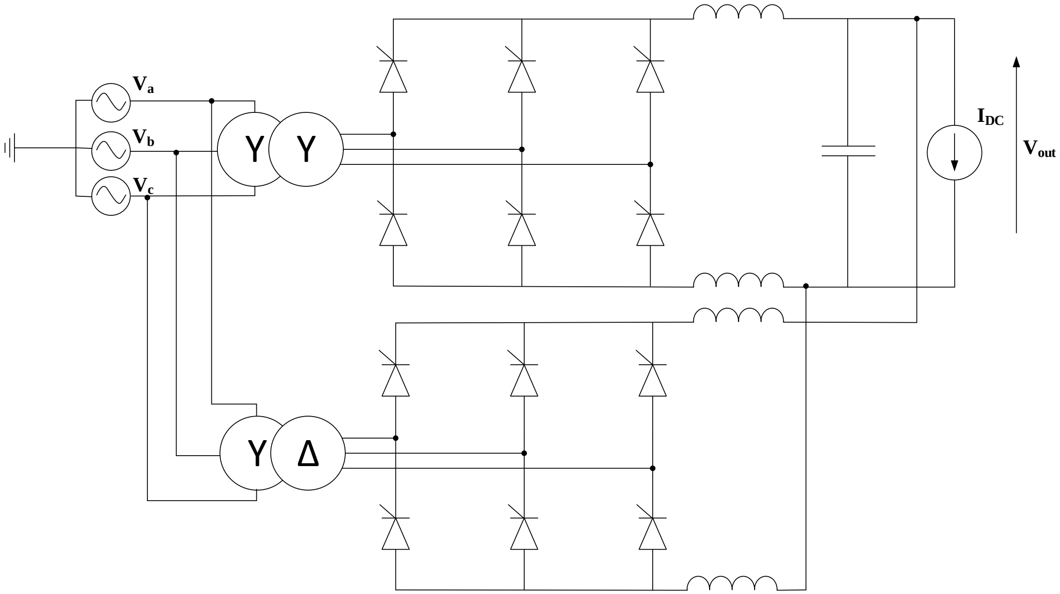
α = [0 , 180°]

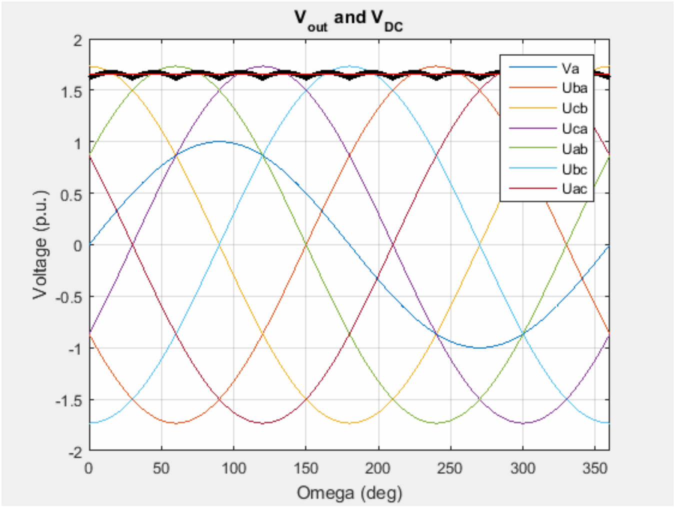
$V_{DC} = \langle V_{out} \rangle = \frac{3\sqrt{3}}{\pi} V \cos(\alpha)$

Main Harmonic = 300 Hz for 50 Hz network and 360 Hz for 60 Hz network

Thyristor Rectifiers (AC/DC) Basic Concepts

12 Pulse Thyristor Bridge





2^{nd} Bridge is 30° phase lagged

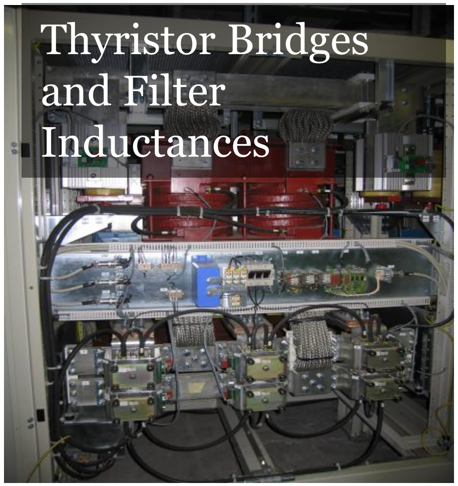
$\alpha = [0 , 180°]$

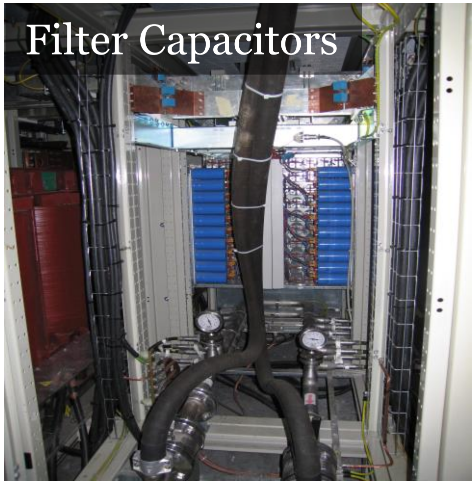
$V_{DC} = \langle V_{out} \rangle = \frac{3\sqrt{3}}{\pi} V \cos(\alpha)$

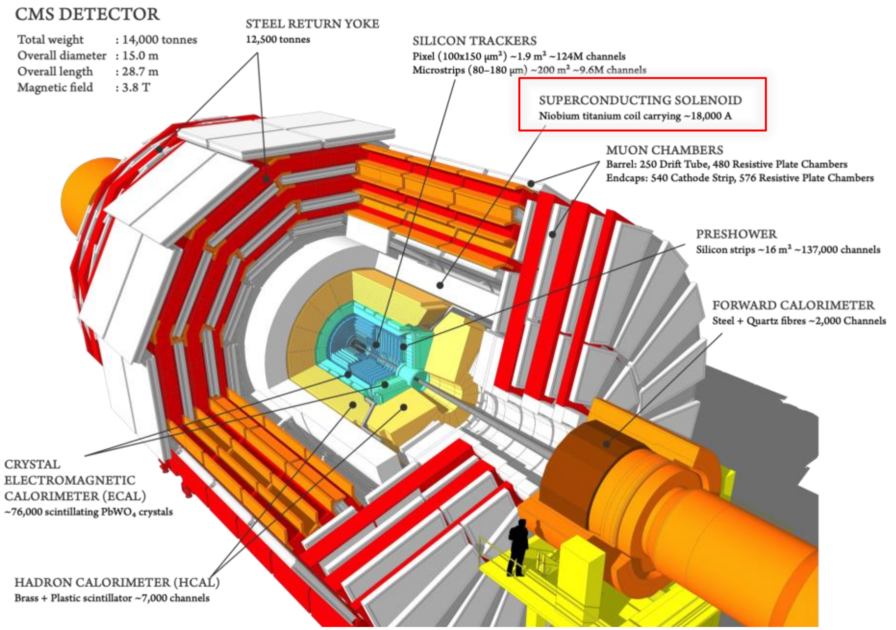
Main Harmonic = 600 Hz for 50 Hz network and 720 Hz for 60 Hz network

Example of Thyristor Rectifier for Magnets

CMS Solenoid Power Converter (20kA/±26V)







14 H Circuit

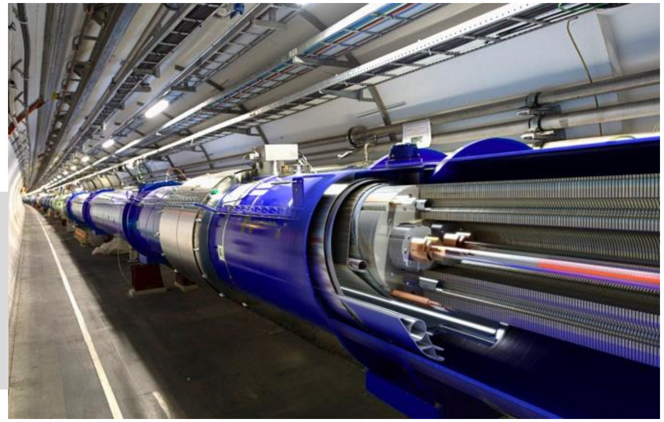
2.2 GJ stored magnetic energy

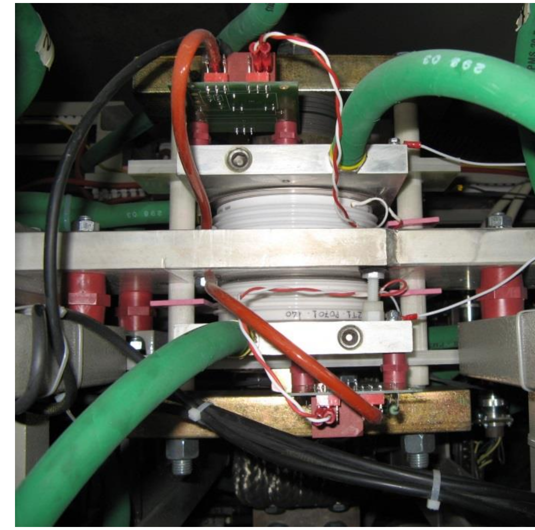
1 Lighting bolt ~5 GJ

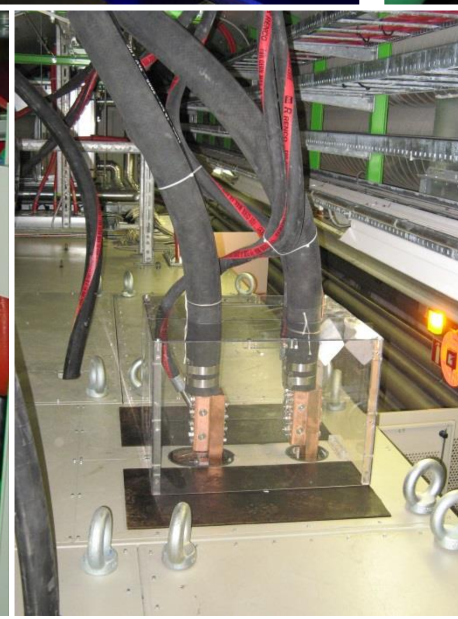
Example of Thyristor Rectifier for Magnets

LHC Dipole Circuit Power Converter (13 kA/190 V)

Powering 154 magnets in series
15 H circuit
2.2 GJ stored magnetic energy





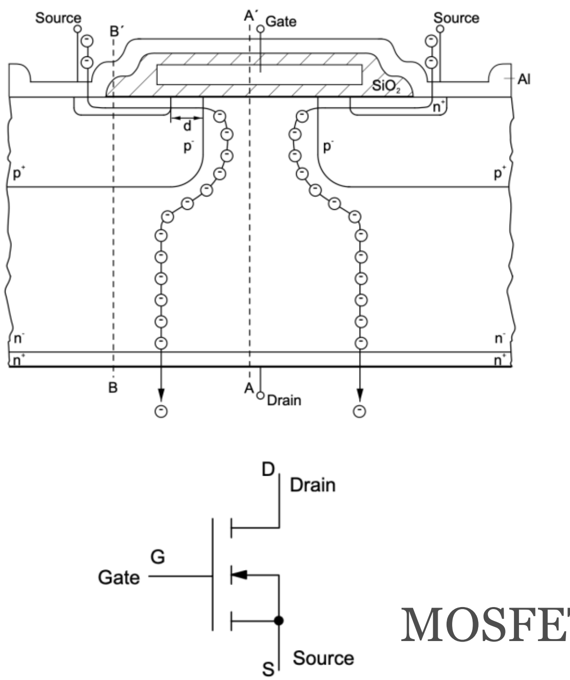


Topologies based on IGBT/Power MOSFET

IGBT and MOSFET have an almost identical structure.

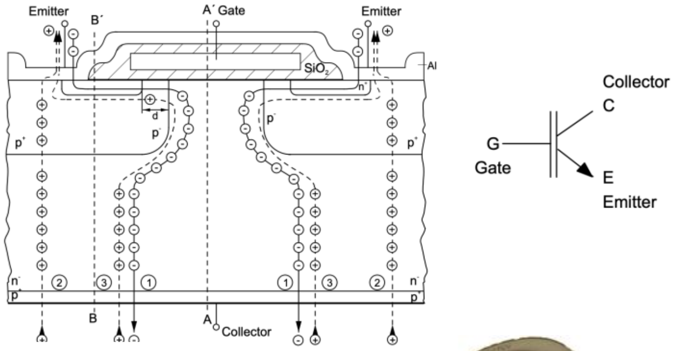
The differences in properties result from the different structures used in the third electrode (MOSFET: drain / IGBT: collector).

Many topologies using IGBT or Power MOSFET since Turn-ON and Turn-OFF can be controlled



MOSFET

IGBT



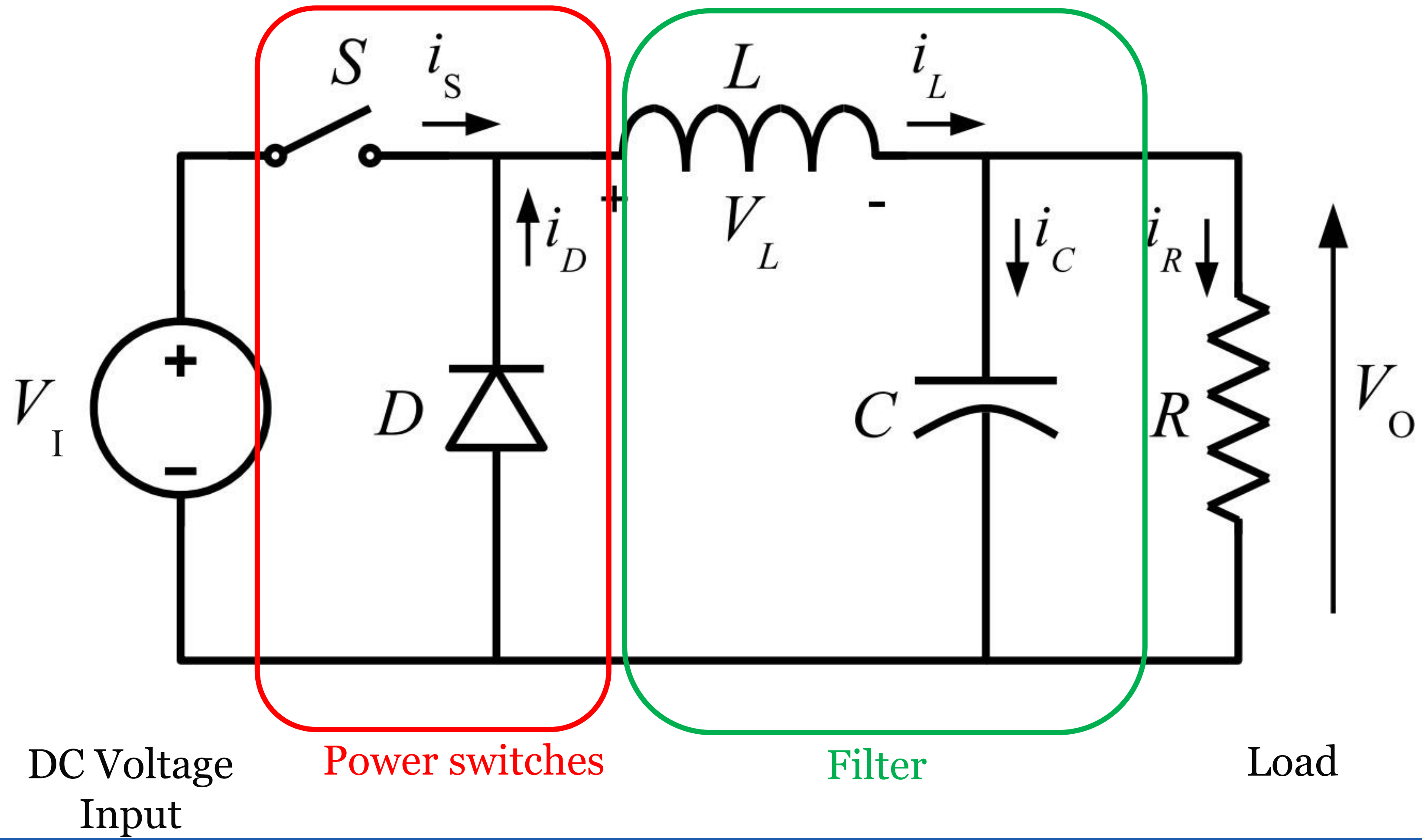
10 A

1 kA

3 kA

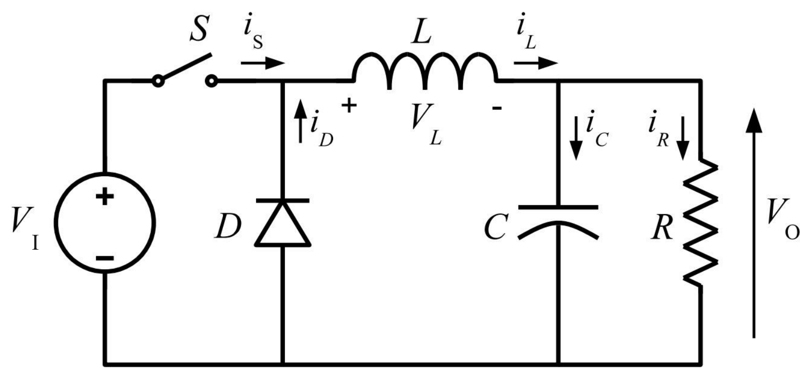
DC/DC Conversion Basic Concepts

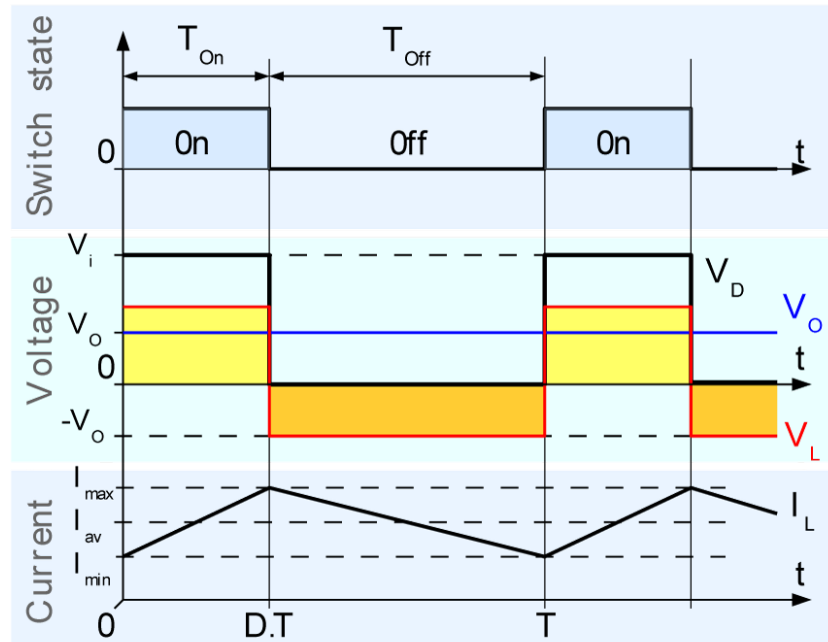
Basic principle is to control a switch to transfer the energy from a source to a load with an example of a BUCK (step-down) converter with a switch that can be an IGBT or a MOSFET



Switching a Semiconductor and Duty Cycles

The switch S is switched ON during a short period which is repeated periodically.

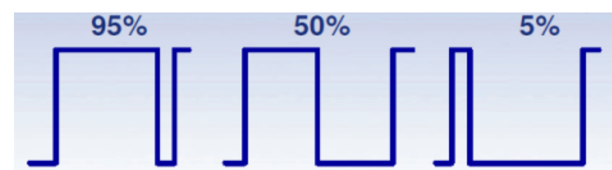




$\langle V_o \rangle = T_{on}/T \times V_i$

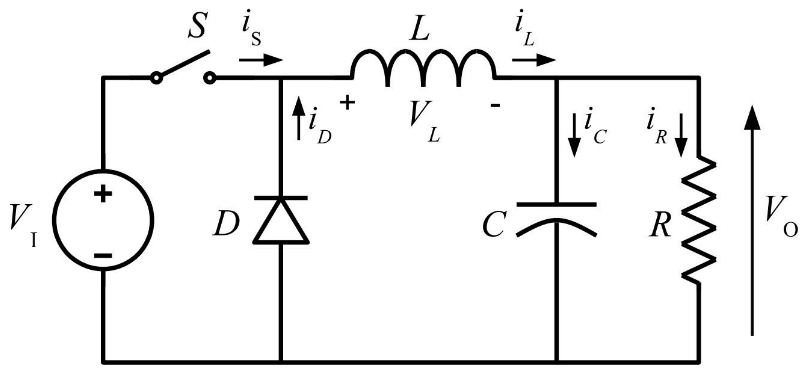
$V_{out} = \alpha \times V_i$

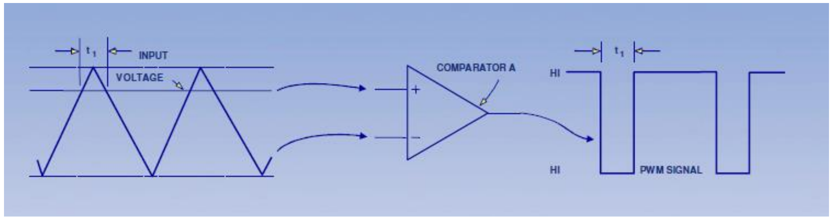
The output voltage can be controlled by playing with the duty cycle α.

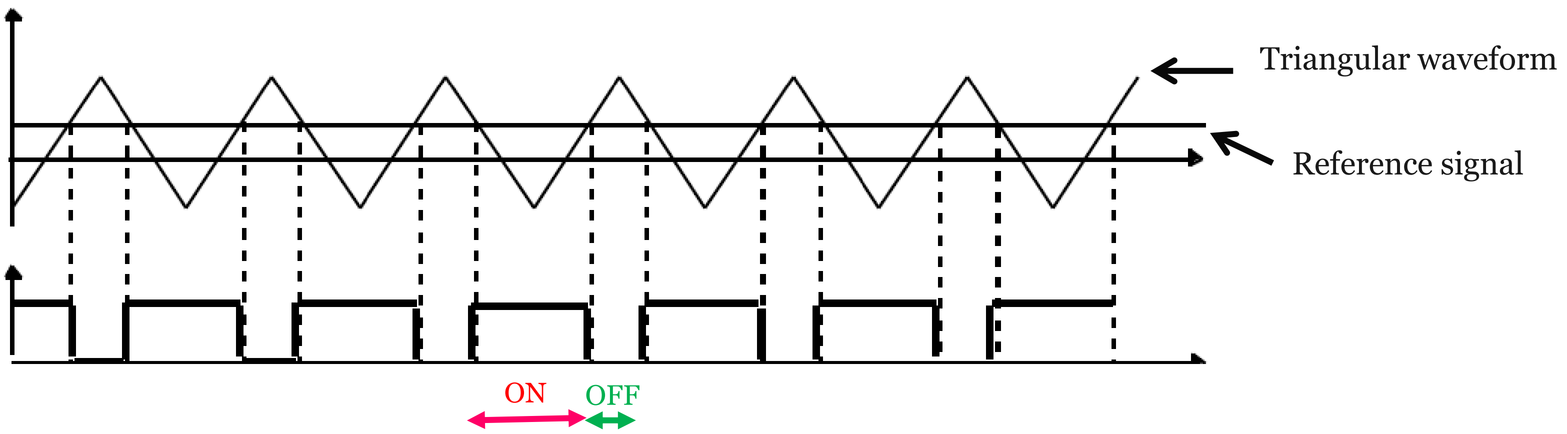


Pulsed Width Modulation

Pulsed Width Modulation (PWM) techniques are used to control the switch. A triangular waveform is compared to a reference signal, which generates the PWM command of the switch.



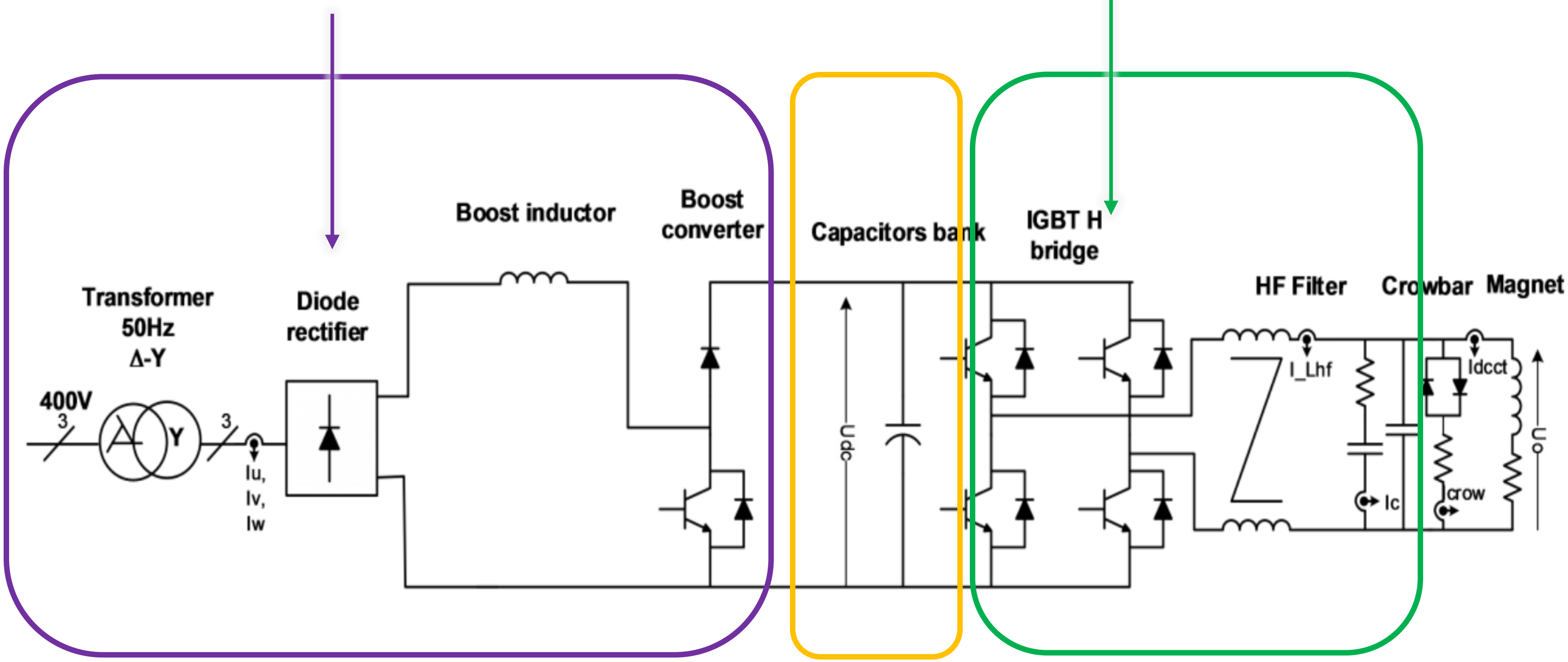




Example of a Switch-mode Power Converter

Diode Rectifier is identical to Thyristor Rectifier with α = 0°

4 current bidirectional switches (H-Bridge) that can provide three voltage level [-Udc, 0 , +Udc]

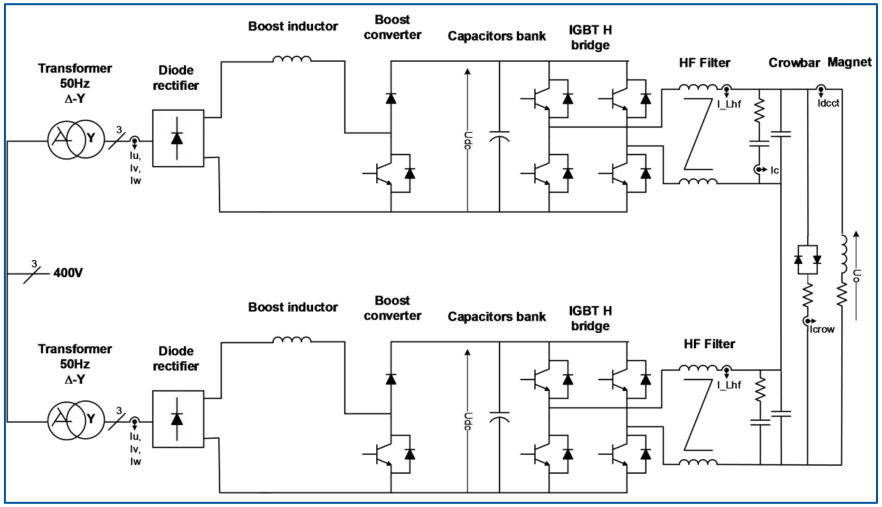


50-60 Hz AC/DC stage

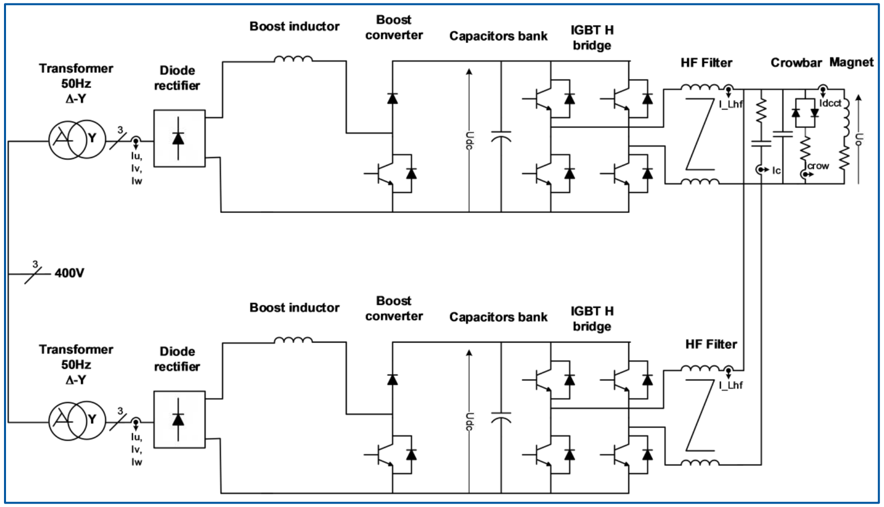
DC Link

High-frequency DC/DC stage

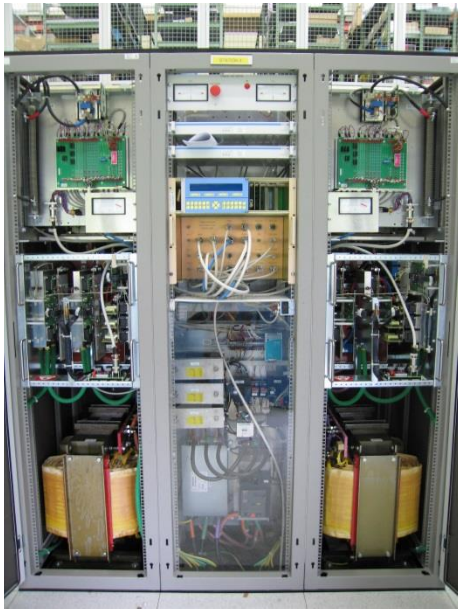
Series/Parallel Connection with IGBT Converters



Series Connection to provide more voltage



Parallel Connection to provide more current



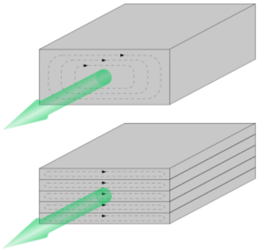

1
3
2
4

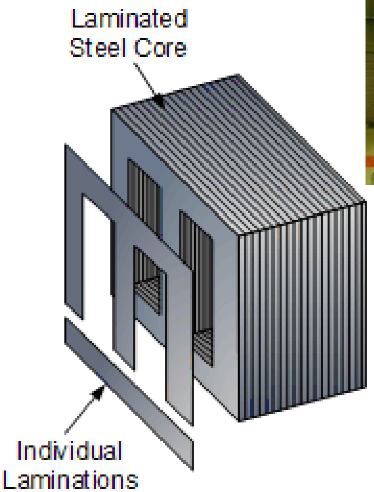
Transformer Technologies

Two technologies are used for power transformers:

Laminated magnetic core:

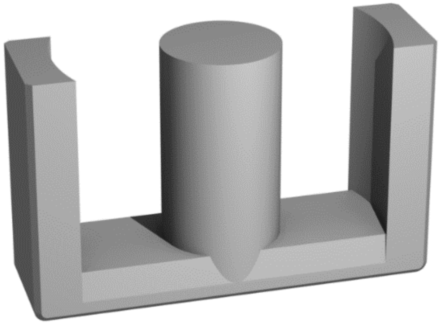
- 50Hz technology
- High field (1.8T)
- Limitation due to eddy current
- Low power density
- High power range

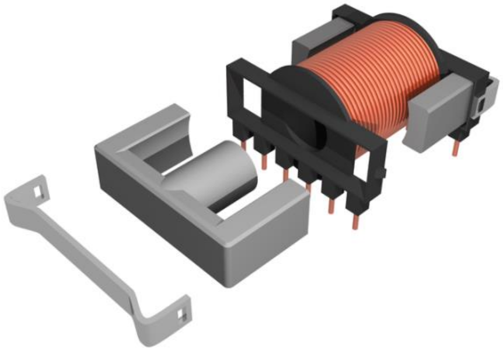




Ferrite core (like kicker):

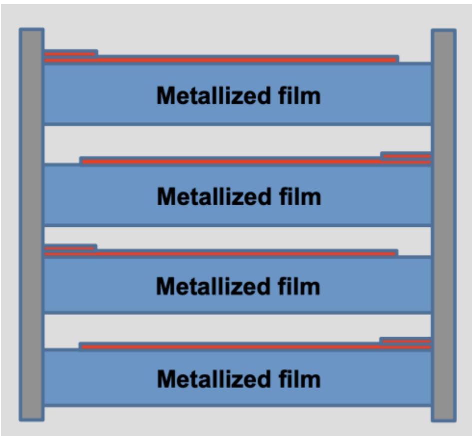
- kHz technology
- Low field (0.3T)
- Nonconductive magnetic material, very low eddy current
- High power density
- Low power range (<100kW)



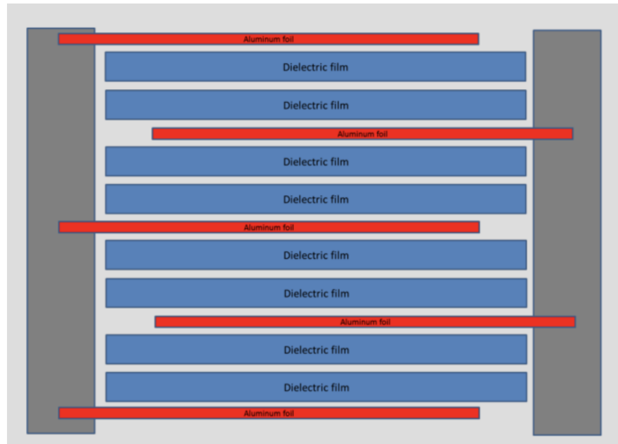


Capacitor Technologies

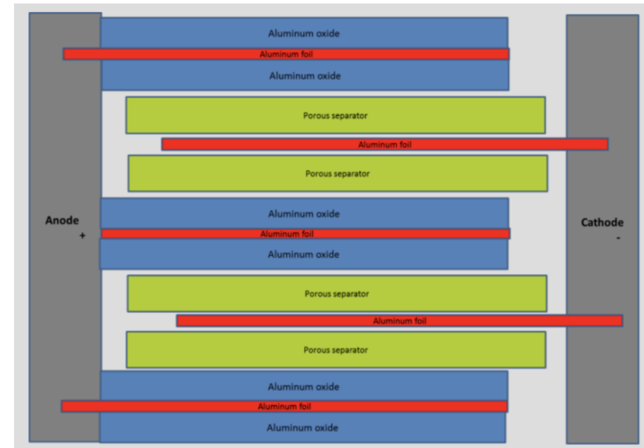
5 main capacitors technologies used in power converters:



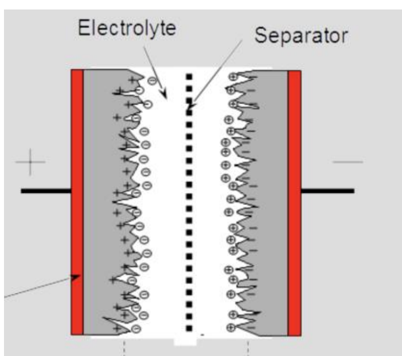
Metalized Film



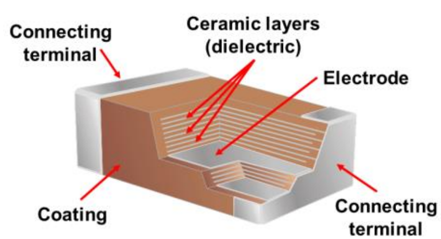
Film Foil



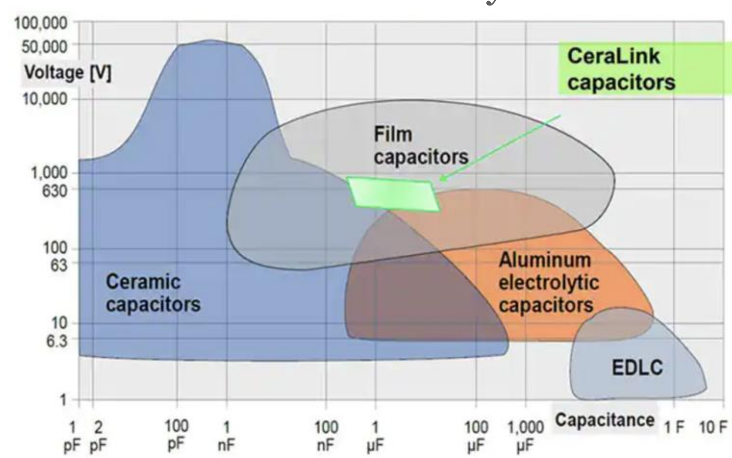
Electrolytic



Electrochemical Dual Layer



Ceramic



Source: TDK Corporation

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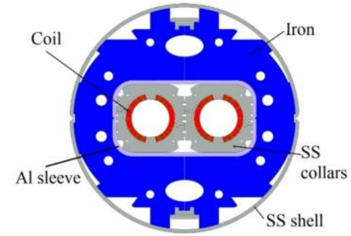
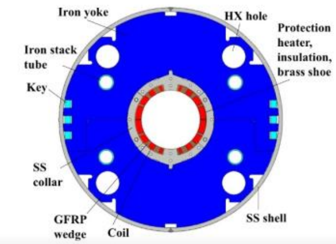
Specificities for Powering Magnet

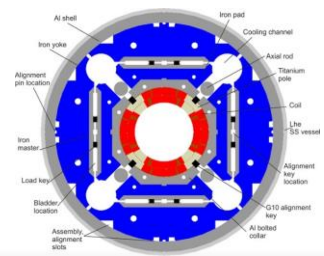
What Type of Magnets are Powered?

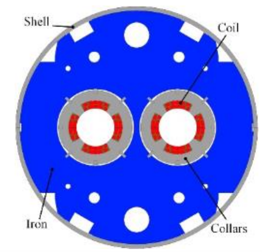
Dipole: Main beam bending, beam separation, recombination, orbit corrections, etc.



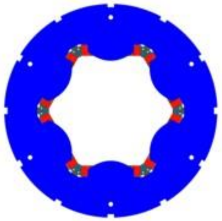


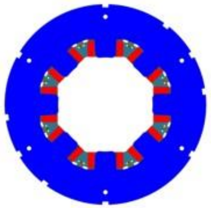
Quadrupole: beam (de)focusing.

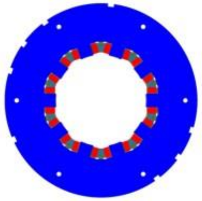


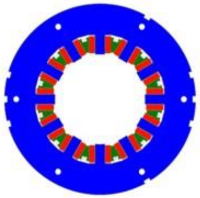


Higher Order Correctors: Chromaticity correction, landau damping, etc.

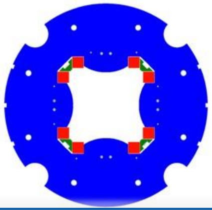








Skew correctors: horizontal & vertical coupling corrections



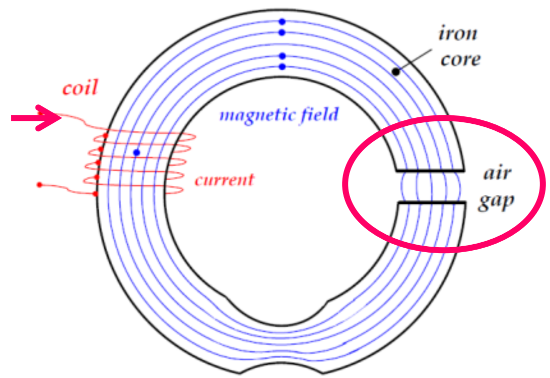
What is Special in Powering Magnets?

In a synchrotron, the beam energy is proportional to the magnetic field.

The magnet field is generated by the current circulating in the magnet coils.

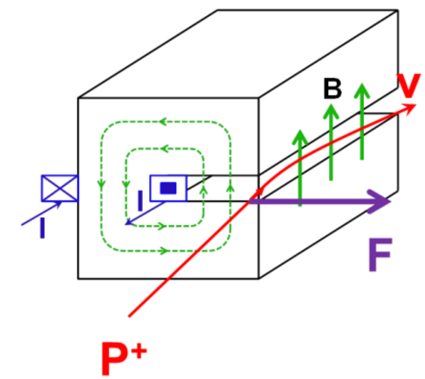
The dipole magnets shall have a high field homogeneity which means a high current stability. The good field region is defined typically within $\pm 10^{-4}$ $\Delta B/B$.

Magnet current

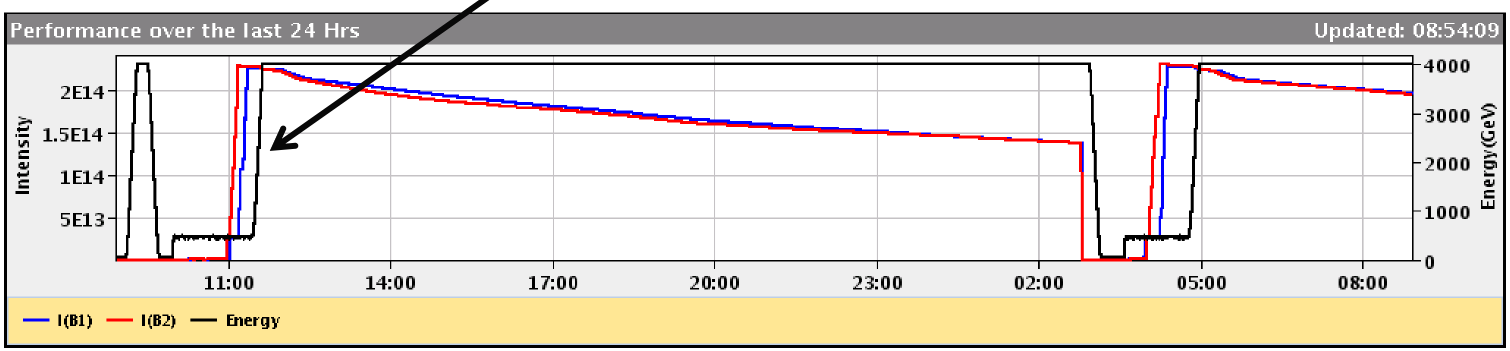


Magnetic field in the air gap

$$NI = \mathcal{R} \times \Phi$$



LHC vistar : Beam Energy = Dipole Current



What is Special in Powering Magnets?

In most synchrotrons, the magnets are current controlled since field measurements is difficult.

The beam energy is imposed by the current of the dipole magnet.

Higher performance requirements could lead to:

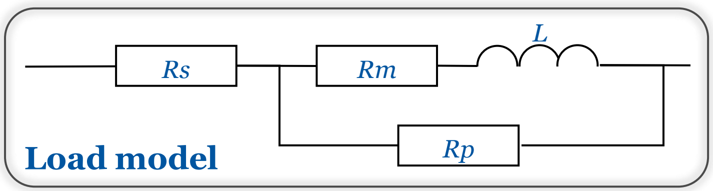
- Operator can apply, real time feedback system on orbit, tune, chromaticity, etc.
- Real-time magnetic field measurement and control

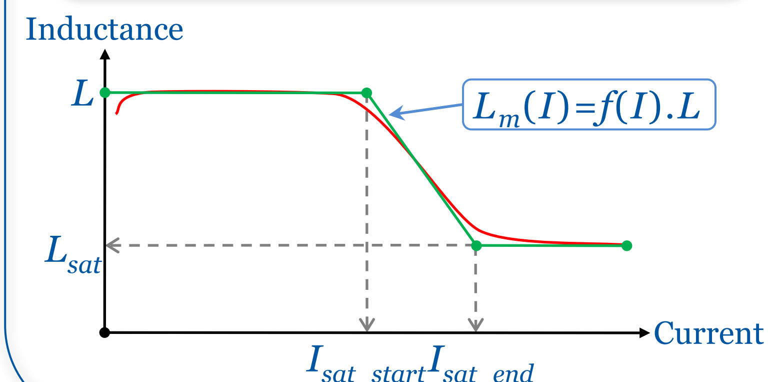
Magnet Parameters and Operation

Magnet parameters seen by <u>power converters</u>:

- Inductance, in H
- Resistance, in Ω
- Current limits
- Voltage limits (insulation class)
- di/dt limits

much better, magnet model including saturation effect.



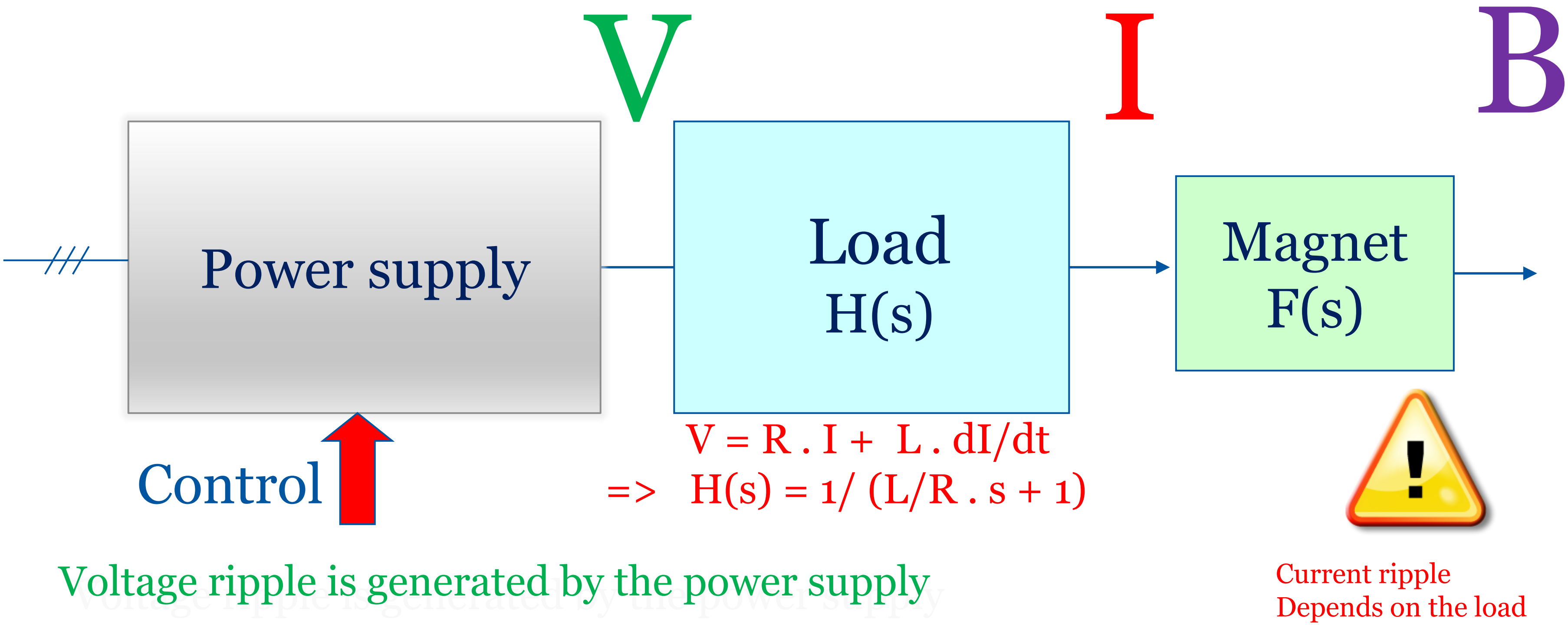


The way that the magnets will be operated has to be defined from the beginning.

- Type of control: Current / B-field
- Maximum – minimum current
- Complete cycle
  - Injection current
  - Maximum dI/dt, ramp-up
  - Maximum flat top current
  - Maximum dI/dt, ramp-down
  - Cycle time
- Degauss cycle / pre-cycle
- Standby mode

Power Converter Ripple

Magnetic field ripple impacts beam stability and has to be fixed by the accelerator physicists.
From the B-field ripple, we can determine the current ripple and then, fix the voltage ripple.



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

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

Voltage ripple is generated by the power supply

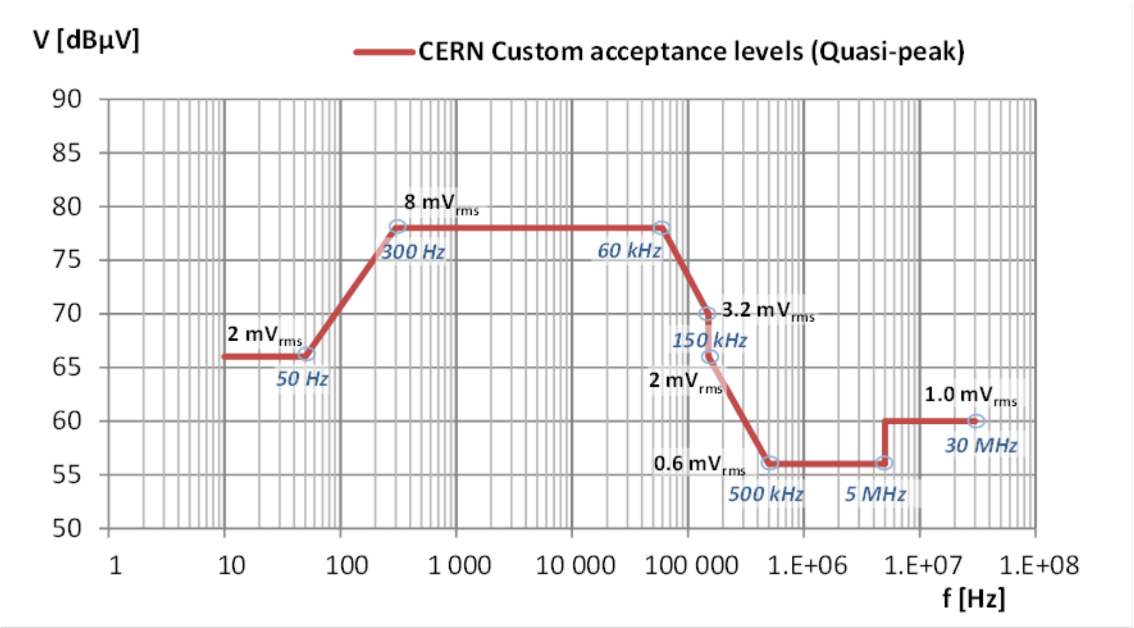
Current ripple is defined by load transfer function (cables & magnet)

B-Field ripple is depends on magnet transfer function (vacuum chamber,…)

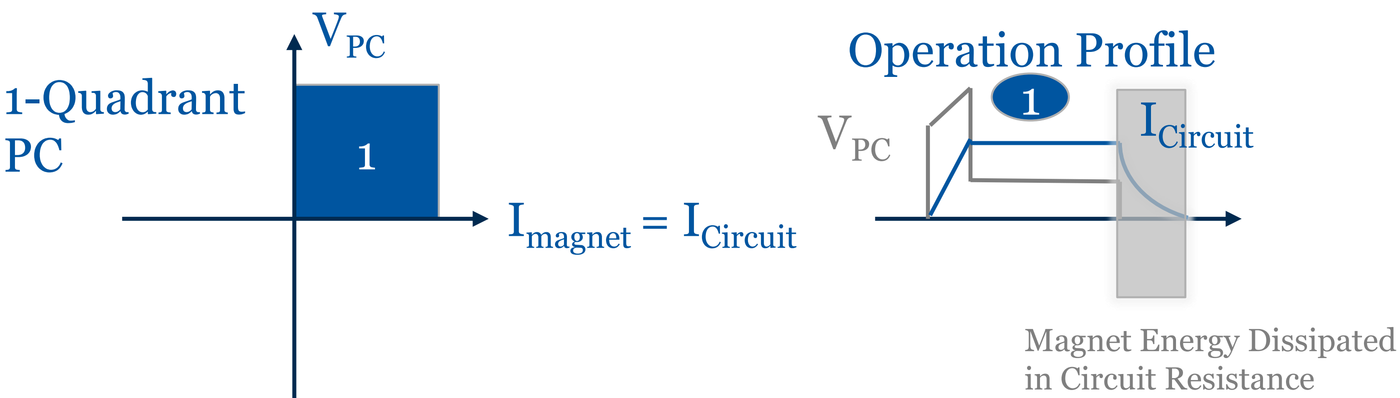
Power Converter Ripple Specification

The voltage ripple must be specified for all frequencies.

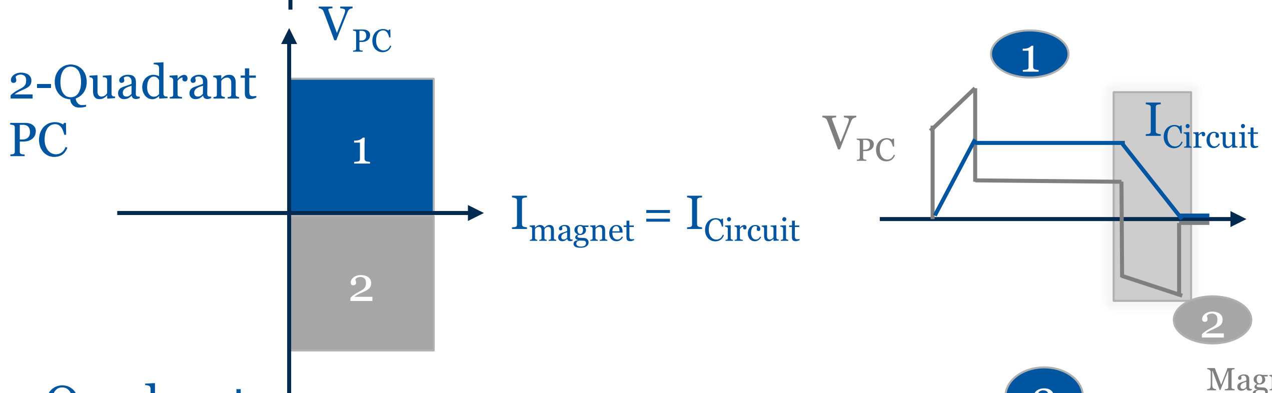
<50Hz: for regulation performance of the power converter
50-1200Hz: for grid disturbance rejection definition
1-150kHz: for power converter switching frequency and filters definition
>150kHz: for Electro Magnetic Compatibility (EMC) definition



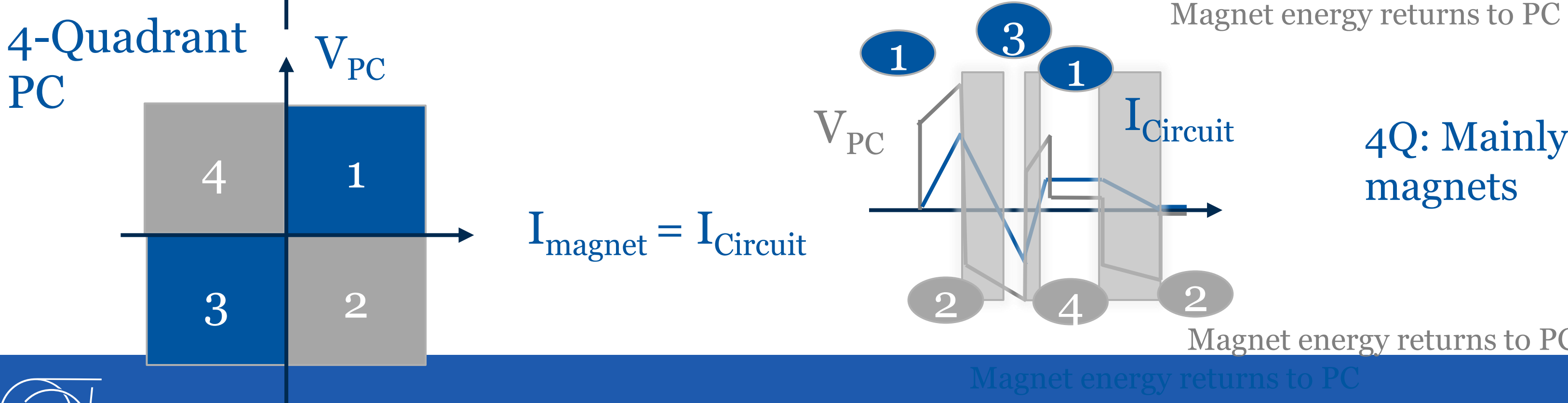
Powering Quadrants and Energy Management



1Q: Mainly main magnets with low inductance or circuit high resistance



2Q: Mainly main magnets with high inductance or circuit low resistance

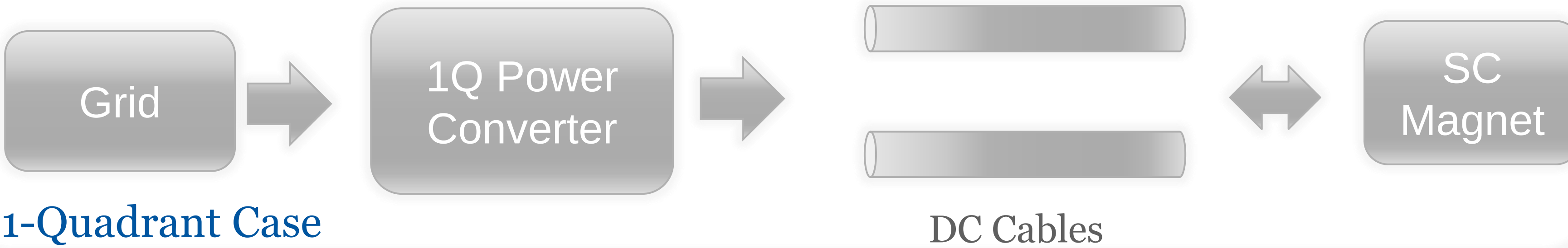


4Q: Mainly corrector magnets

Magnet energy returns to PC

New Energy Management for SC Magnets

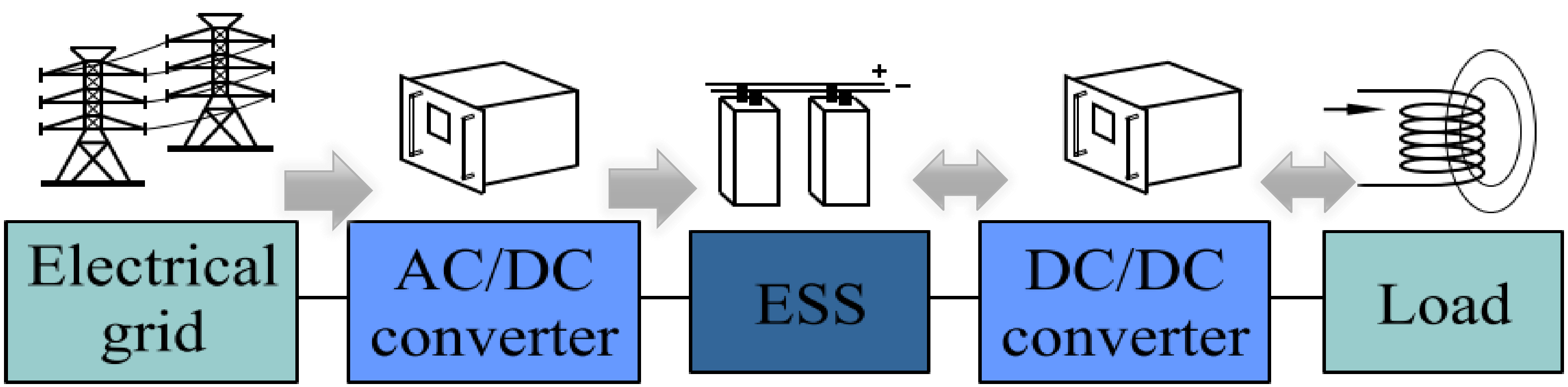
Topology where magnet energy extracted as DC cable heating (long discharges, high cable resistances, etc.)



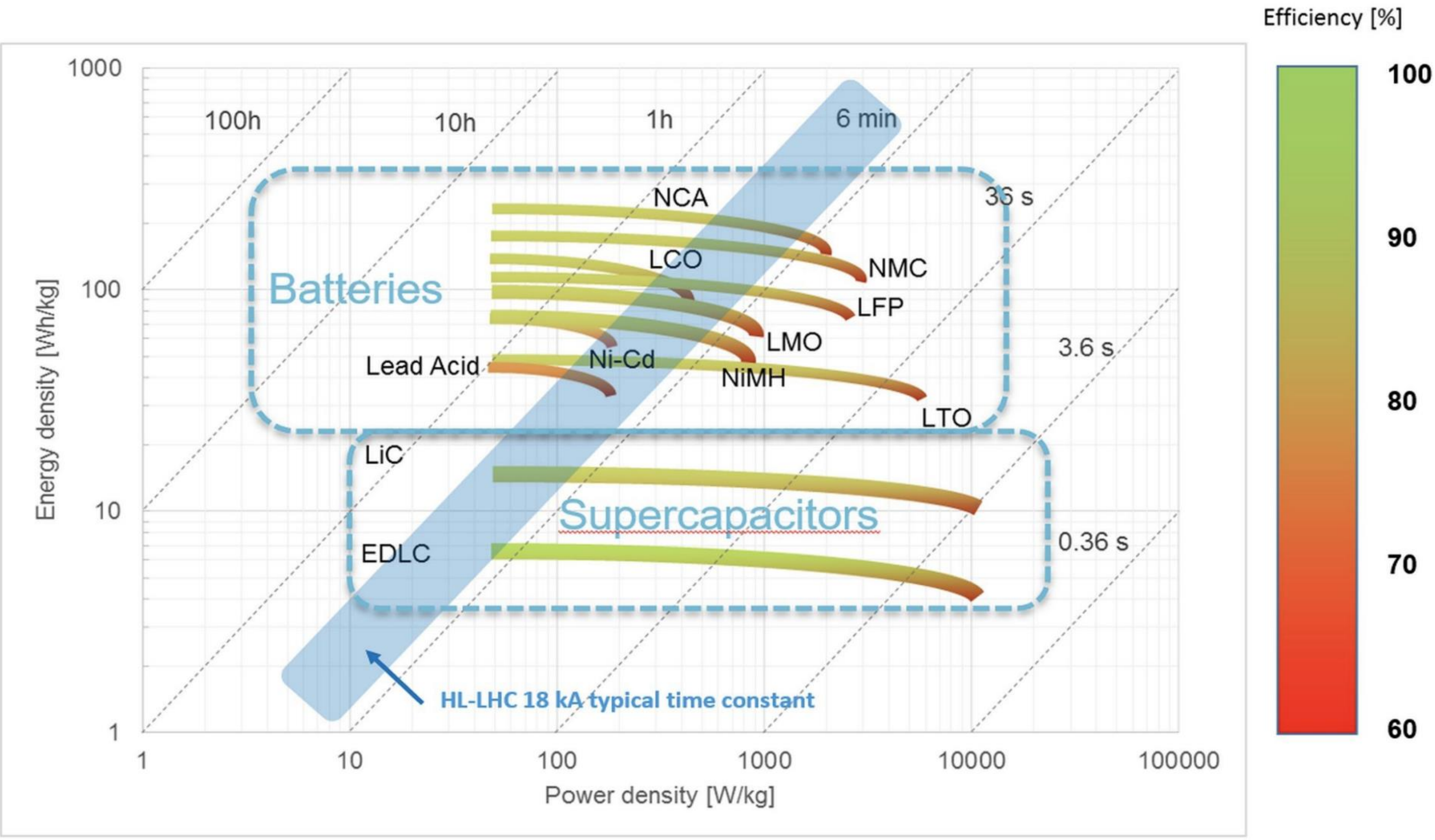
1-Quadrant Case

2 and 4-Quadrant Case

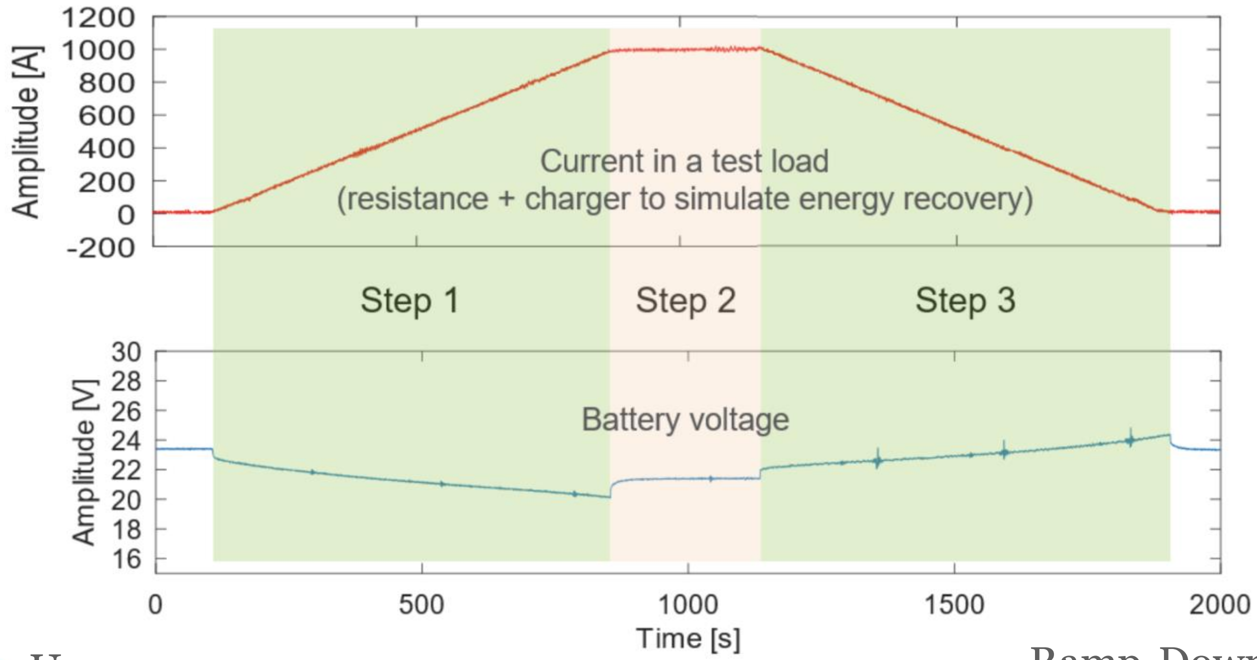
The energy to be transferred to the magnets is stored in capacitors or batteries (Energy Storage System - ESS) or in some cases dissipated inside PC via resistors



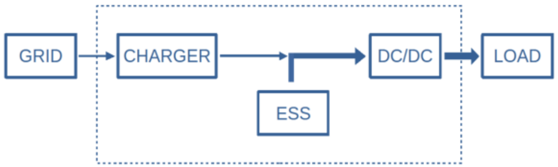
Energy Storage System Technologies



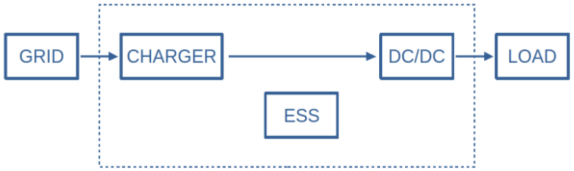
New Concept for Energy Management



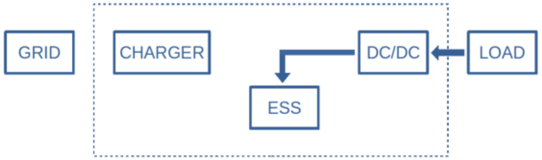
Ramp-Up



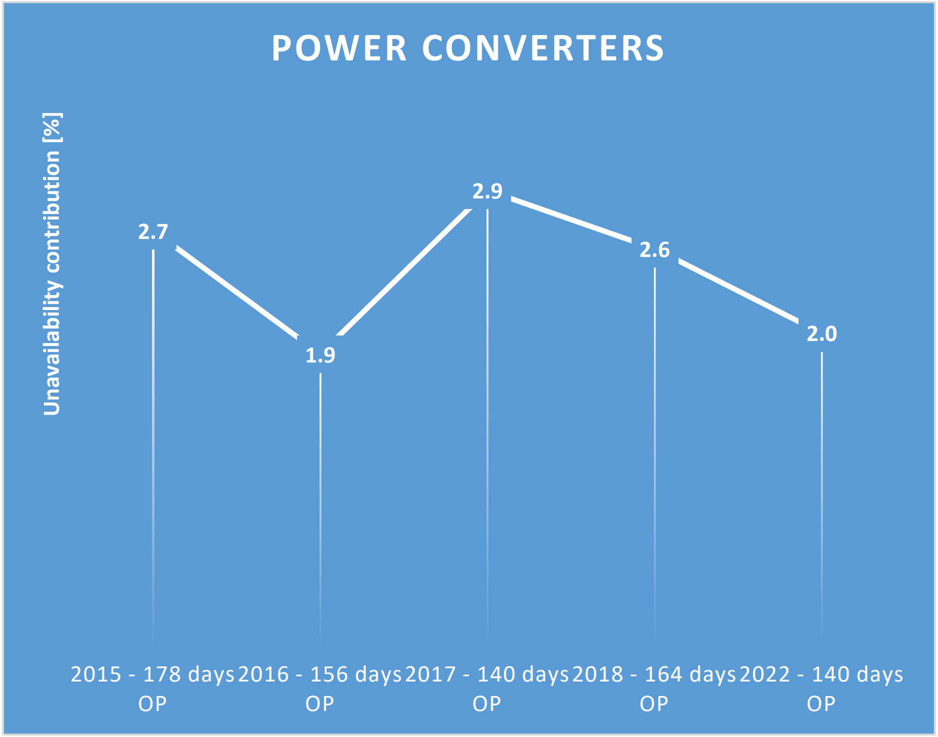
Flat-Top



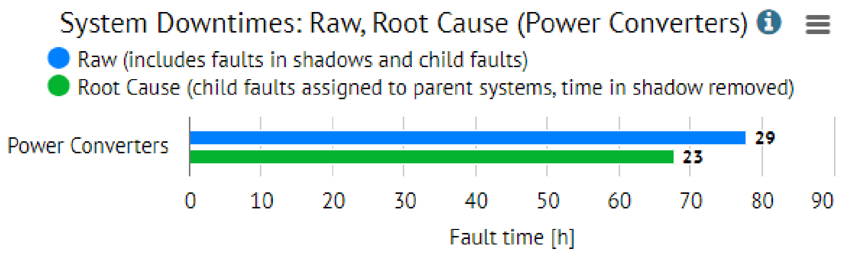
Ramp-Down



Availability of Power Converters



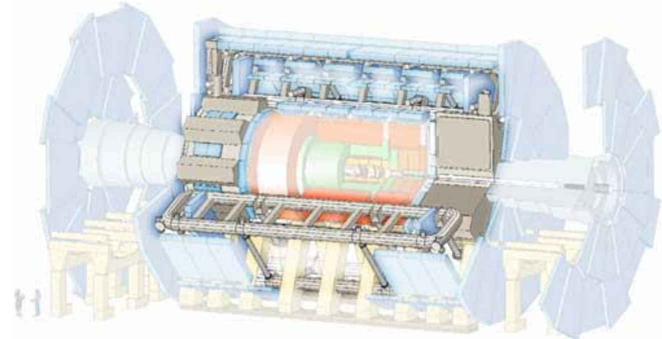
Unavailability of Power Converters in the LHC



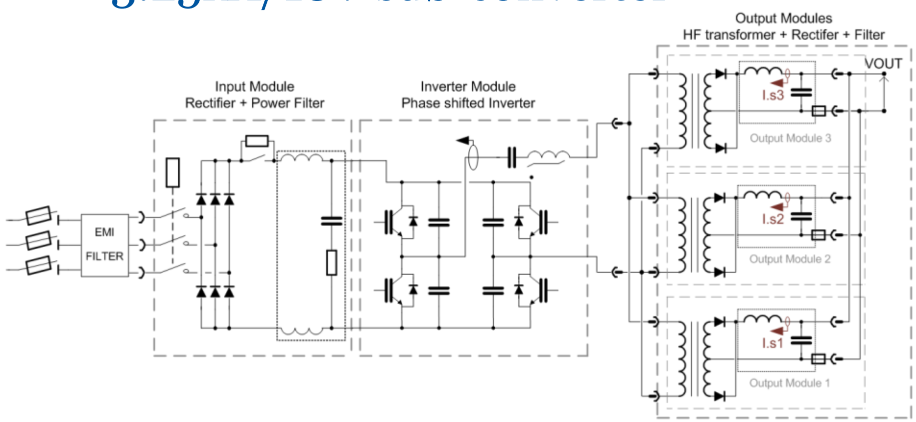
Converters Fault Time in the LHC, 2022

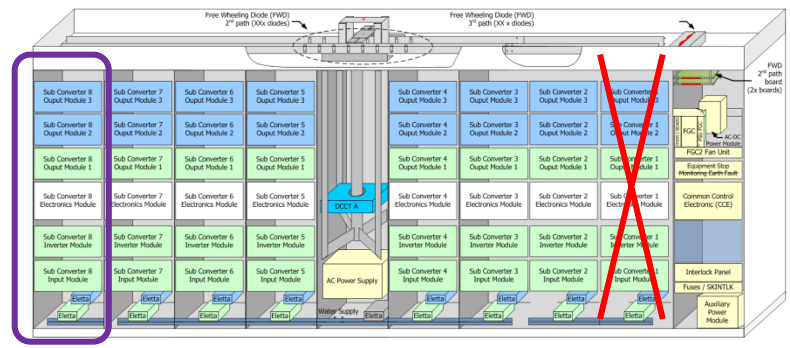
Redundancy to Maximize Availability

Example: Atlas toroid magnet power supply 20.5kA/18V



3.25kA/18V sub-converter





3.25kA/18V

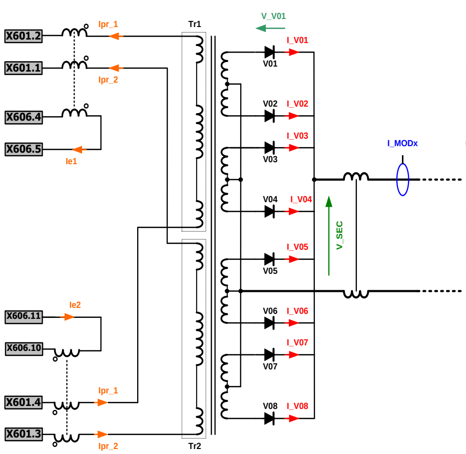
Redundancy implementation, n+1 sub-converters

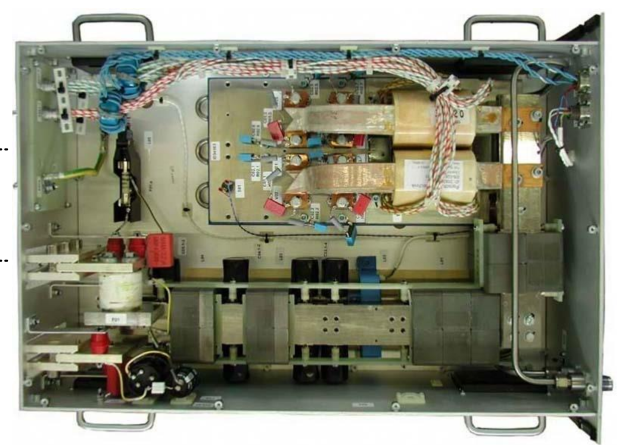
Can work with only n sub-converters

8 sub-converters in parallel

Other methods are available to reduce down time: Radiation Tolerant Electronics, increase MTBF (via reliable systems) and decrease MTTR (plug and play systems), etc.


Sub. 8
Sub. 7
Sub. 6
Sub. 5
Power
Connection
Rack
TRANSTECHNIK
Sub. 4
Sub. 3
Sub. 2
Sub. 1
Electronics
Rack


X601.2
X601.1
X606.4
X606.5
Ipr_1
Ipr_2
Ie1
Tr1
V_V01
I_V01
V01
V02
I_V02
I_V03
V03
V04
I_V04
I_V05
V05
V06
I_V06
I_V07
V07
V08
I_V08
V_SEC
I_MODx
X606.11
X606.10
Ie2
X601.4
X601.3
Ipr_1
Ipr_2
Tr2



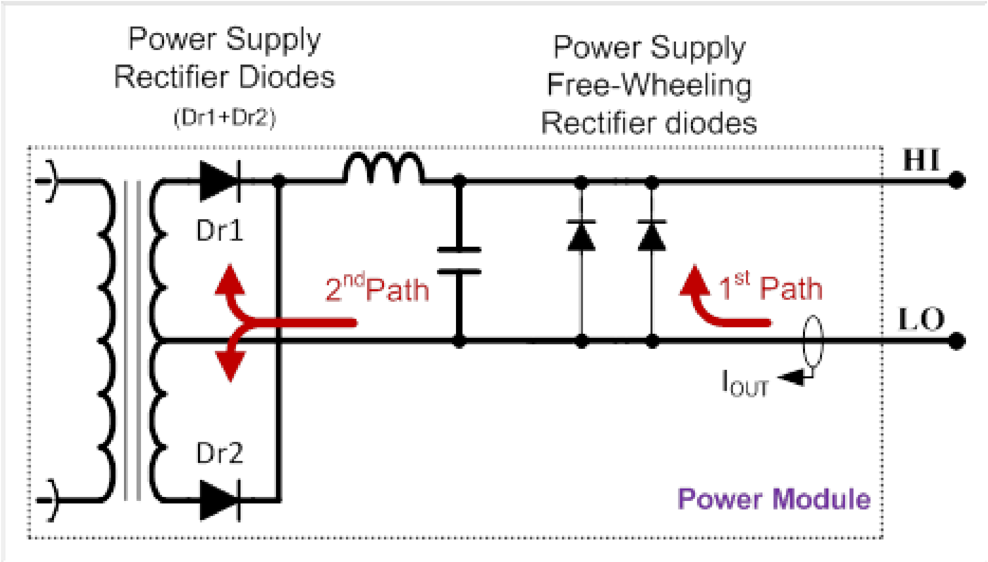

PWC-T

Magnet and Circuit Protection

Superconducting magnets have their quench protection system which is connected to the interlock system.

This interlock system shall request a power abort to the power converter.

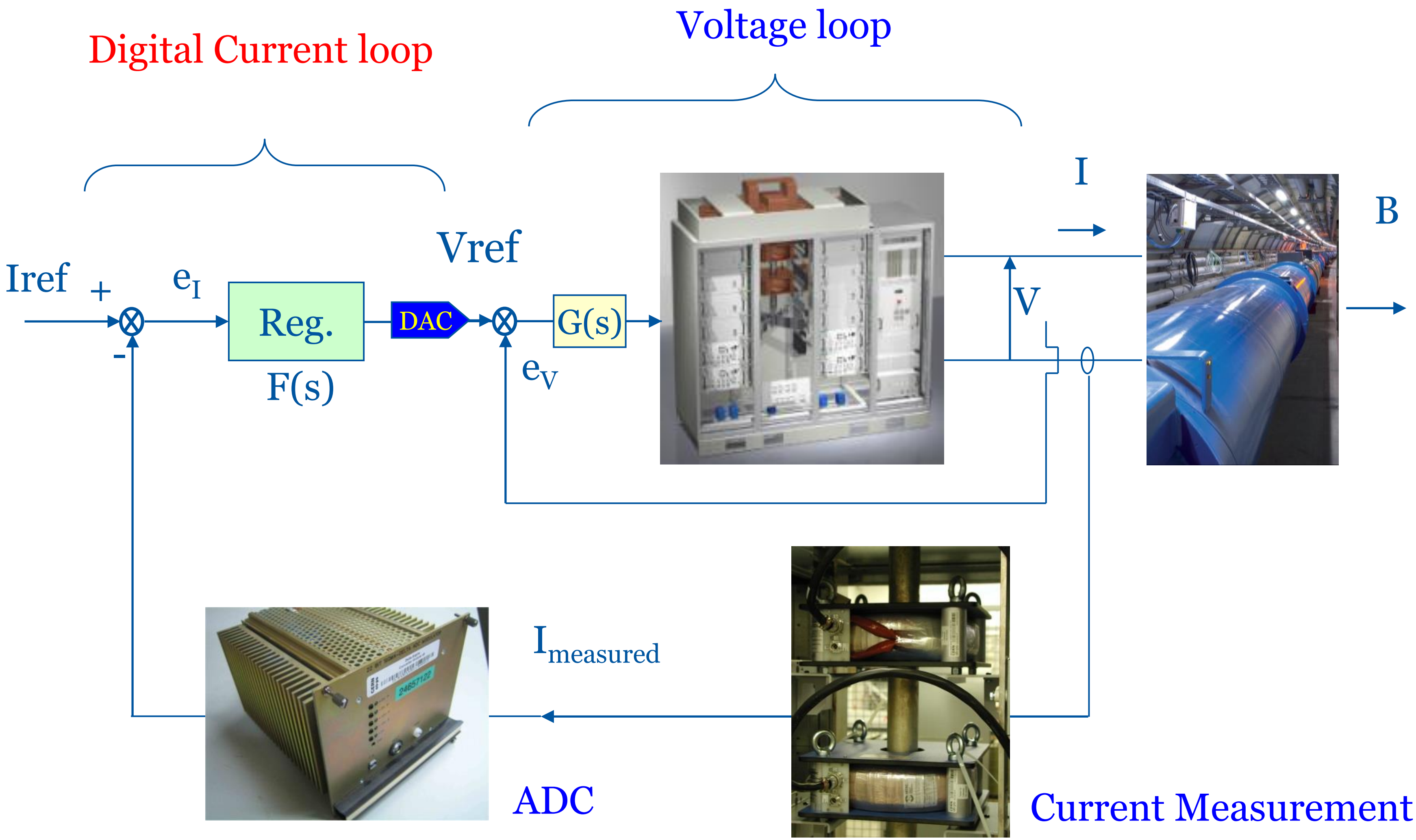
Magnets are inductive load, the circuit cannot be opened ! The power converter shall assure a freewheeling path to the current.



4

Control, Measurement and Precision

Power Converter Cascade Control

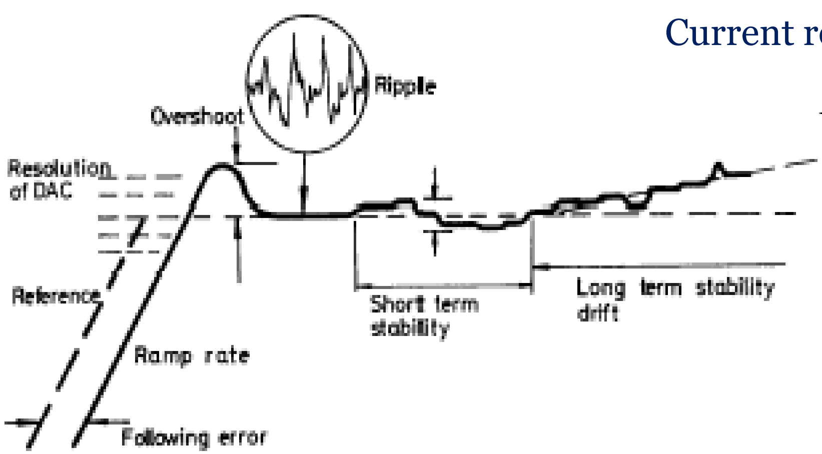


Current Regulation/Control

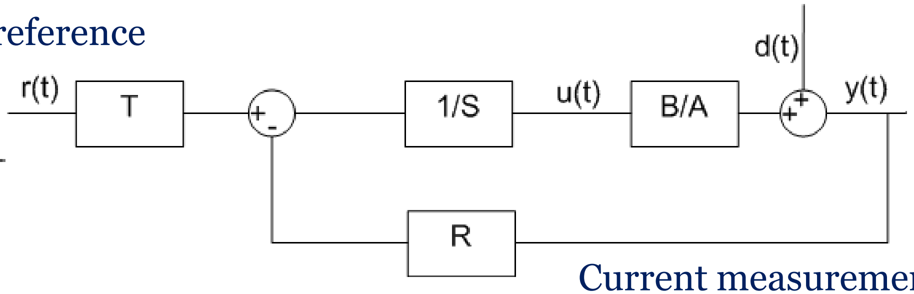
Performance of the current regulation is critical for a machine and can be a nightmare for operators!

References should be synchronized between all power converters of the machine, otherwise the beam is unstable.

RST controller provides very powerful features: manage the following error and provide stable current regulation.



Current reference



Current measurement

High-Precision Definition

Accuracy

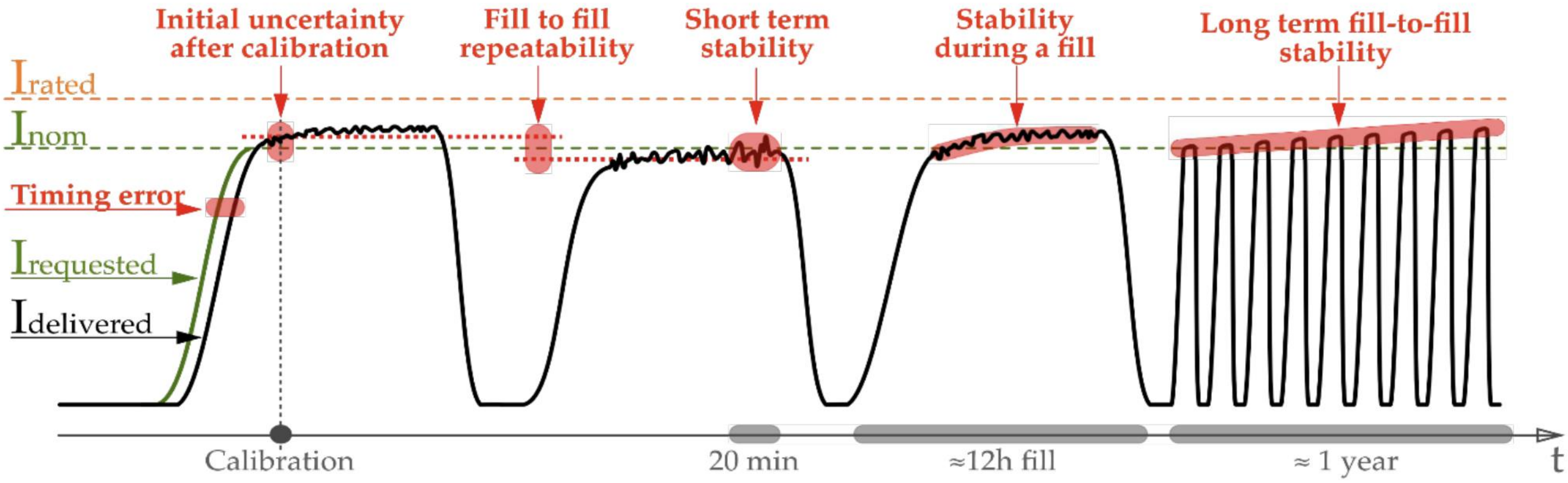
The closeness of agreement between a test result and the accepted reference value. (ISO)

Reproducibility/ Repeatability

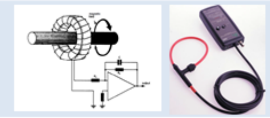
Uncertainty when returning to a set of previous working values from cycle to cycle of the machine.

Stability

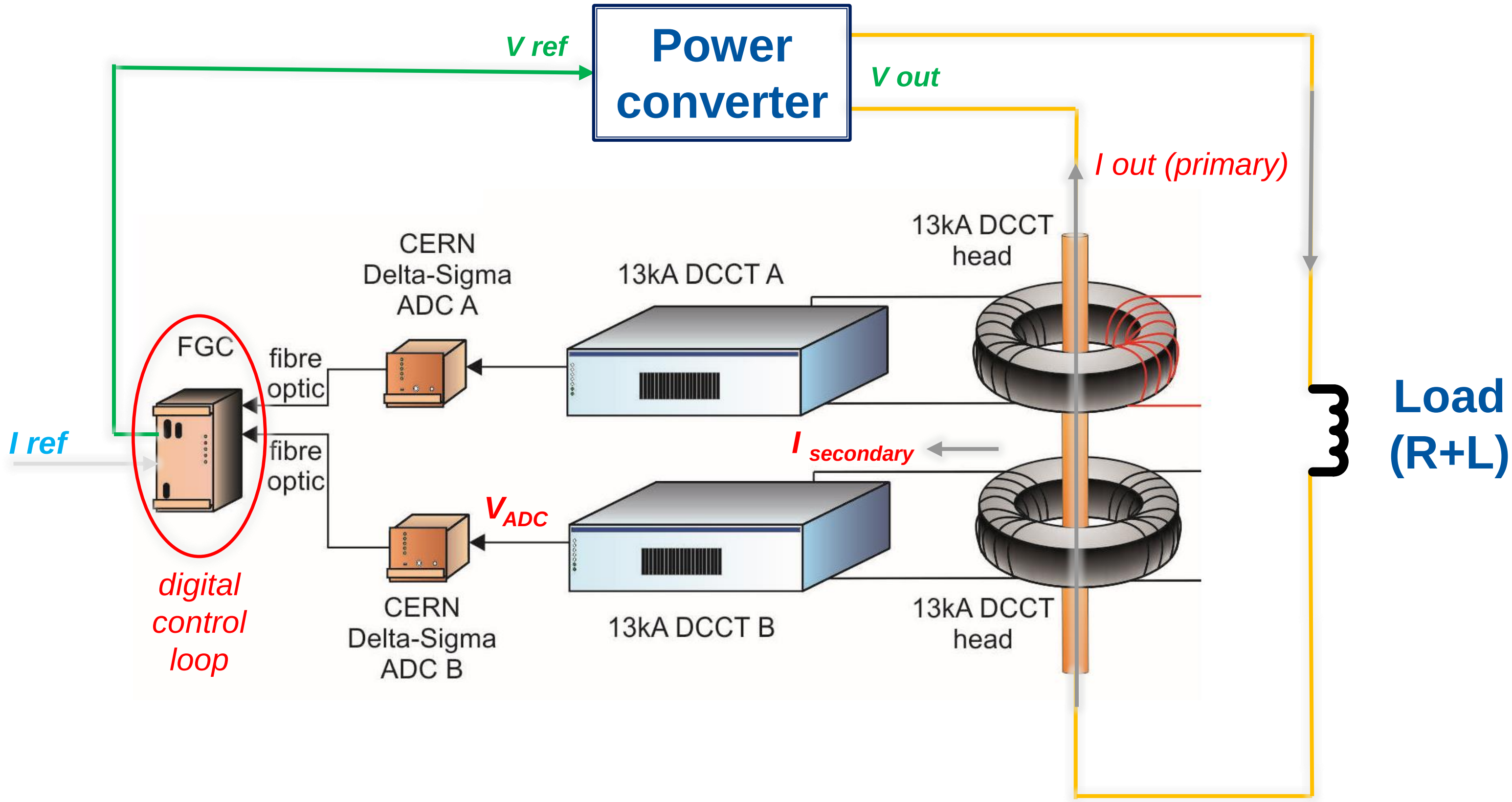
Maximum deviation over a period with no changes in operating conditions.



Current Measurement Technologies

	DCCTs	Hall effect	CTs	Rogowsky	Shunts
					
Principle	Zero flux detection	Hall effect	Faraday's law	Faraday's law	Ohm's law
Output	Voltage or current	Voltage or current	Voltage	Voltage	Voltage
Accuracy	Best devices can reach a few ppm stability and repeatability	Best devices can reach 0.1%	Typically not better than 1%	Typically %, better possible with digital integrators	Can reach a few ppm for low currents, <% for high currents
Ranges	50A to 20kA	hundreds mA to tens of kA	50A to 20kA	high currents possible, up to 100kA	From <mA up to to several kA
Bandwidth	DC ..kHz for the higher currents, DC..100kHz for lower currents	DC up to couple hundred kHz	Typically 50Hz up to a few hudreds of kHz	Few Hz possible, up to the MHz	Up to some hundreds of kHz with coaxial assemblies
Isolation	Yes	Yes	Yes	Yes	No
Error sources	**Magnetic** (remanence, external fields, centering) **Burden resistor** (thermal settling, stability, linearity, tempco) **Output amplifier** (stability, noise, CMR, tempco)	**Magnetic** **Burden resistor** **Output amplifier** **Hall sensor stability** (tempco, piezoelectric effect)	**Magnetic** (remanence, external fields, centering, magnetizing current) **Burden resistor**	**Magnetic** **Integrator** (offset stability, linearity, tempco)	Power coefficient, tempco, ageing, thermal voltages

LHC High Precision Measurement System

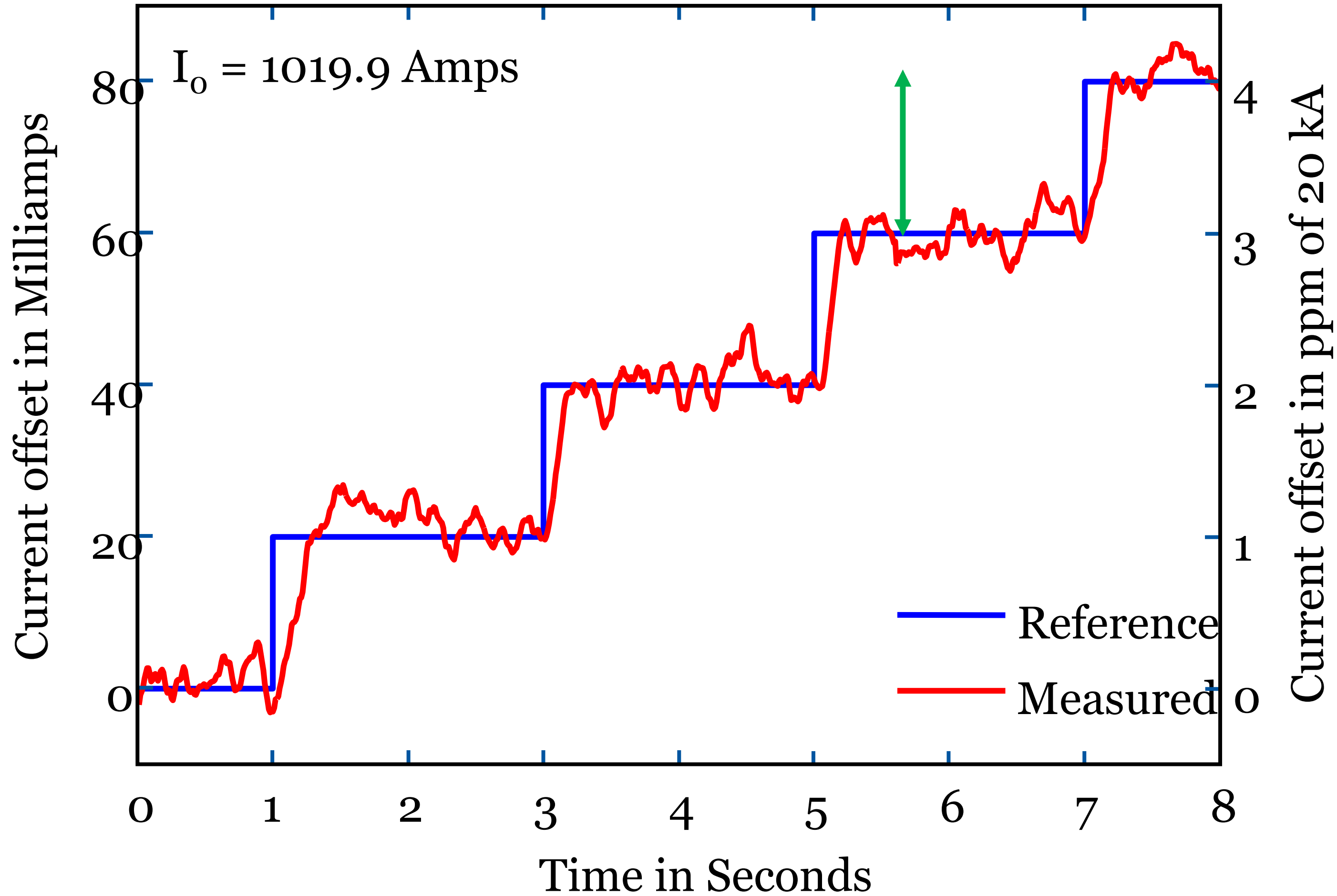


(HL-)LHC Class Specification (for reference)

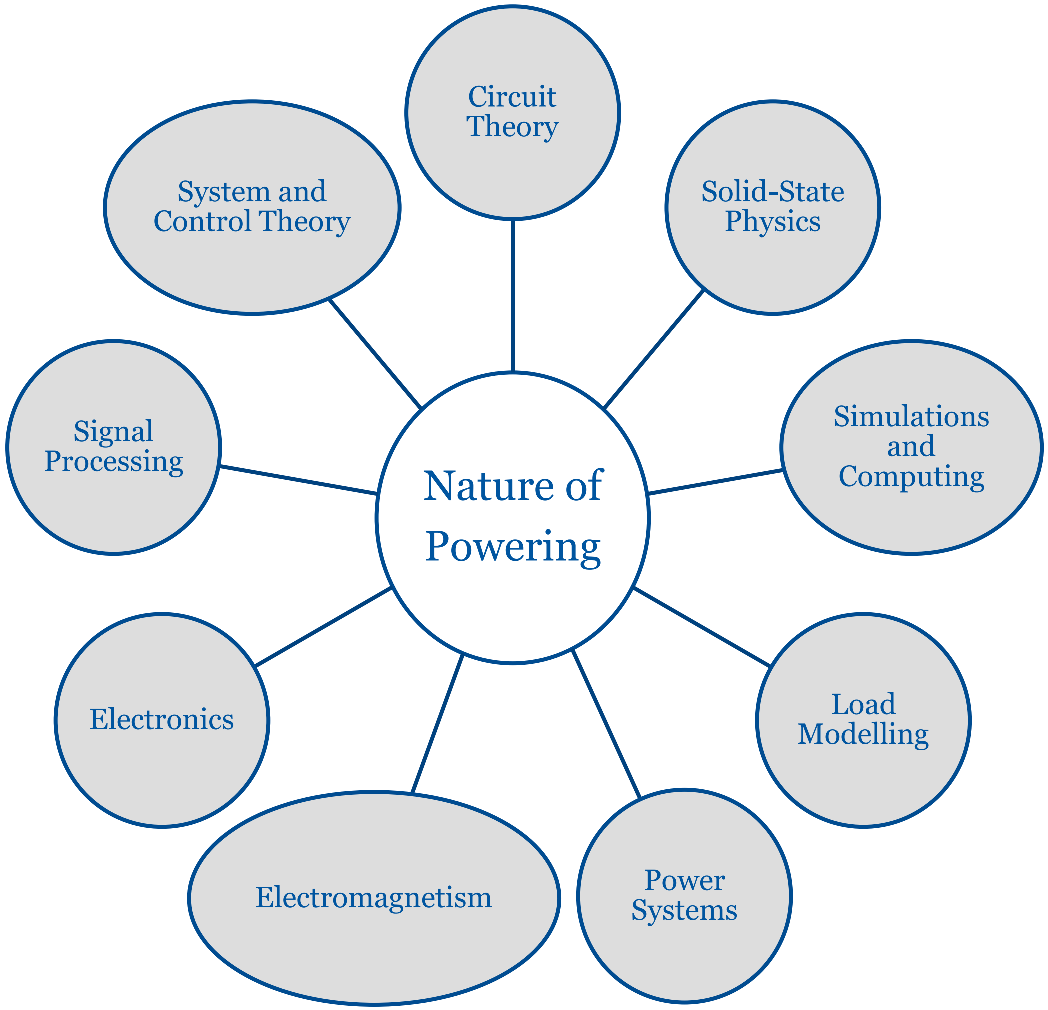
Circuit Name	I_{DCCT} [kA]	Accuracy Class	Stability [ppm of $I_{DCCT.rated}$] expressed as twice the rms value		
			Short Term	During a fill (12h)	Long Term fill-to fill
HL-LHC Inner Triplet	18	0	0.2	1	9.5
LHC Main Dipole	13	0.5-1	0.4	2	9.5
LHC Main Quadrupole	13	1	0.4	2	9.5
Individually Powered Quadrupoles	4-6	2	1.2	15.5	26.5
600 A Correctors	0.6	3	2	34	56
120 A Correctors	0.12	4	5	40	64

LHC Current Measurement Resolution

Best resolution achieved = 1ppm



Summary (1/2)


Circuit Theory
System and Control Theory
Solid-State Physics
Signal Processing
Nature of Powering
Simulations and Computing
Electronics
Load Modelling
Electromagnetism
Power Systems

Summary (2/2)

Powering infrastructure is a key system for particles accelerator magnets

Operators play with power converters to control the beam and the magnet current

The PC performance has a direct impact on the beam quality and magnetic measurements in the test benches.

Cutting Edge Technology is required in many technical fields!

More information :

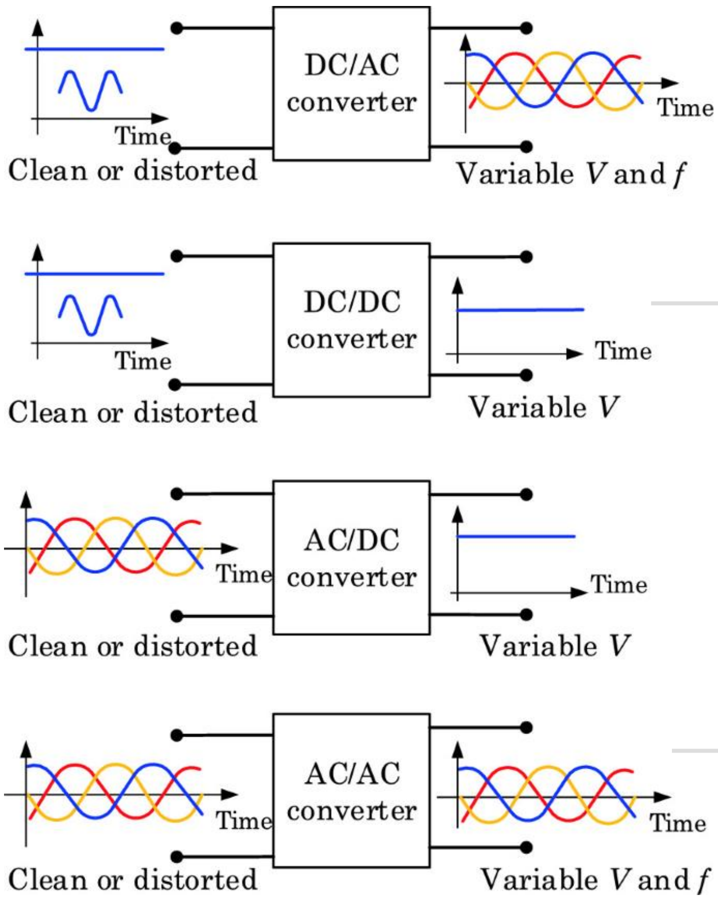
Special CAS on Power Converters

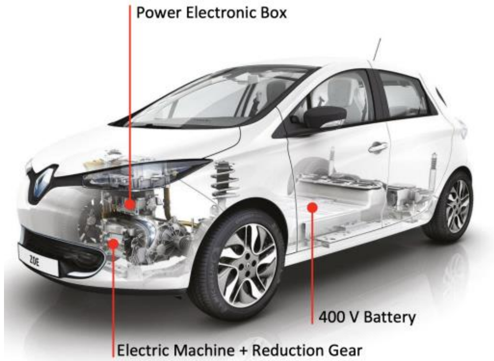
(https://cds.cern.ch/record/1641409)

7 – 14 May 2014 Baden (CH)

Additional Slides

Where do we Find Power Converters?

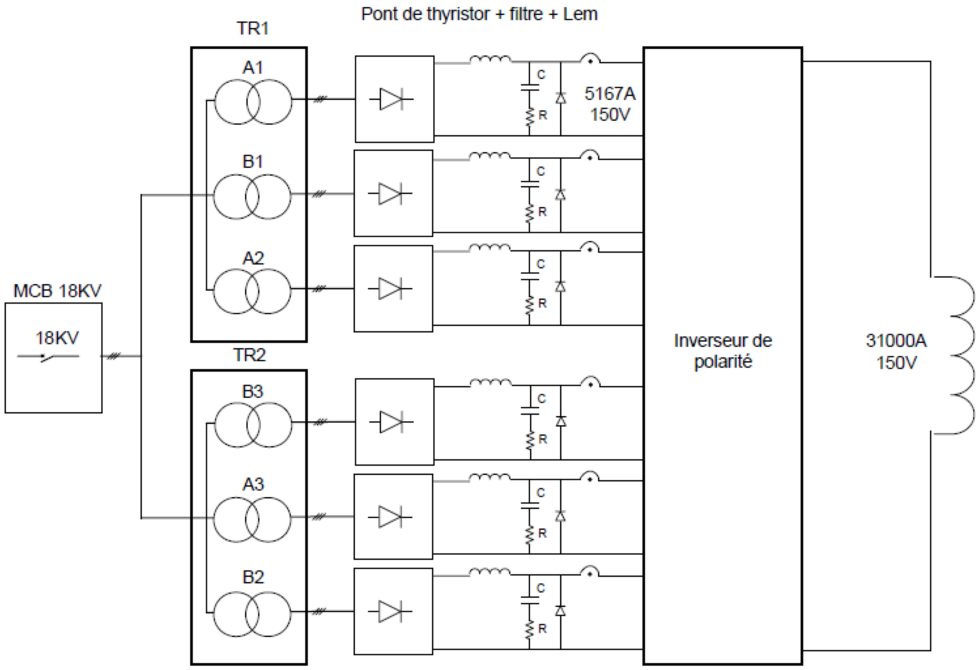


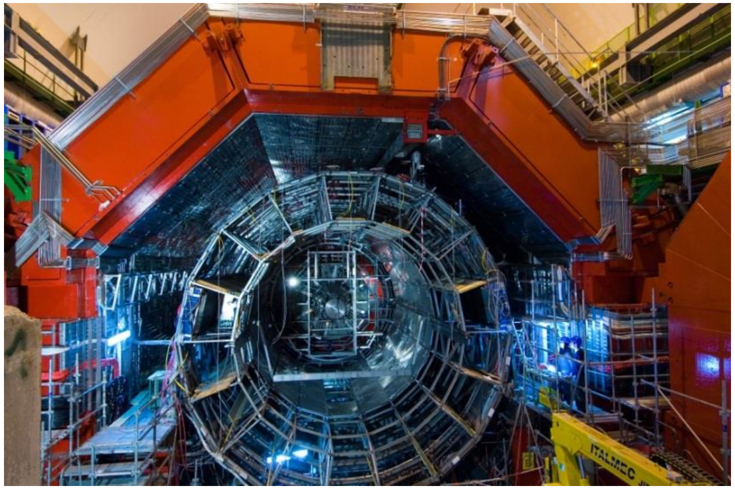


Static Var Compensator at CERN

Parallel Connection with Thyristor Rectifier

Example: Alice (experiment at CERN) Dipole, 31kA/150V





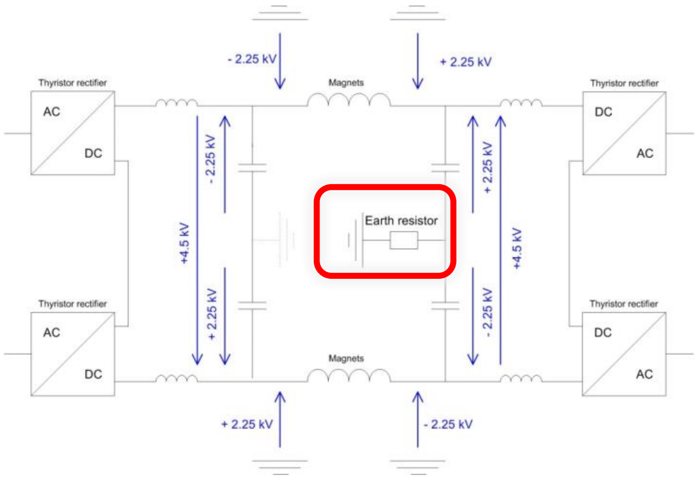
Magnet Grounding

For safety reasons, the magnet shall be isolated from the main grid. Therefore, the power converter needs an insolation transformer in its topology.

The magnets shall be connected to the ground somewhere, they cannot be left floating with parasitic capacitances.

One polarity can be connected directly to the ground, or via a divider for a better voltage sharing.

The ground current shall be monitored and interlocked.

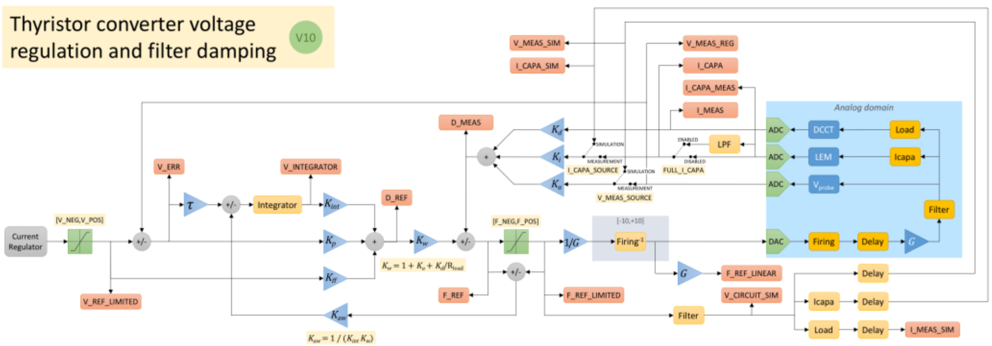


Voltage Regulation

Voltage Regulation can be either digital or analogue

Damping techniques are used to control system resonances

Many techniques are used : state feedback, feedforward and anti-windup control saturation



Processing sequence per iteration :

1. $V_{err} = V_{ref\_limited} - V_{meas\_reg}$
2. $V_{integrator} = V_{integrator} + V_{err}\,\tau$
3. $D_{ref} = V_{ref\_limited}\,K_{ff} + V_{err}\,K_p + V_{integrator}\,K_{int}$
4. $D_{meas} = I_{capa}\,K_i + V_{meas}\,K_u + I_{meas}\,K_d$
5. $F_{ref} = D_{ref}\,K_w - D_{meas}$
6. $F_{ref\_limited} = F_{ref}$ limited to $[F_{neg}, F_{pos}]$
7. $V_{integrator} = V_{integrator} - (F_{ref} - F_{ref\_limited})\,K_{aw}$
8. $V_{dac} = Firing^{-1}(F_{ref\_limited}/G)$

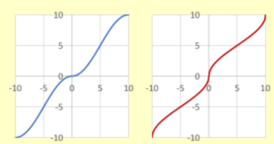
where :

$F_{neg} = 0 \ or \ -10\,G \ \ (1Q \ or \ 2Q)$

$F_{pos} = 10\,G$

$K_w = 1 + K_u + K_d/R_{Load}$

$K_{aw} = 1/(K_{int}\,K_w)$



Example Firing function   Example inverse Firing function

Firing = Physical non-linear response of the firing that respects the mappings -10 → -10, 0 → 0, 10 → 10

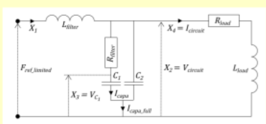
$Firing^{-1}$ = Software inverse firing function to linearize open-loop response

If I_{capa_full} is measured, it can be transformed into I_{capa} :

$I_{capa} = a\,I_{capa} + b(1-a)\,I_{capa\_full}$

where :

$a = e^{-\tau/(b\,C_2\,R_{filter})}$ and $b = C_1/(C_1 + C_2)$



Filter and Load Model use state vector X:

$X_{k+1} = M_a \cdot X_k + M_b \cdot F_{ref\_limited}$

where :

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} I_{filter} \\ V_{circuit} \\ V_{C_1} \\ I_{circuit} \end{bmatrix}$$

$I_{capa} = (X_2 - X_3)/R_{filter}$