CERN
European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Power converters

Definitions and classifications
Converter topologies

Frédérick BORDRY
CERN

"Introduction to Accelerator Physics"
28 October - 9 November, 2012
GRANADA - SPAIN

Menu

- Power converter definition and classification

- Power converter topologies:

  line commutated and switch mode based

  Sources, power switches (semiconductors), commutation rules,...

- Special case for magnet powering

  (Voltage source - Current source)

- Pulsed power converters

- Control and precision

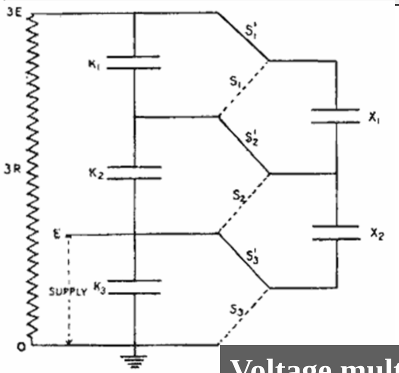
In 1 hour ????

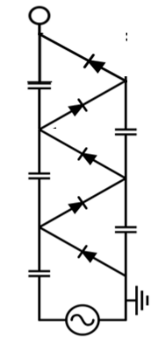
High energy physics and power converters

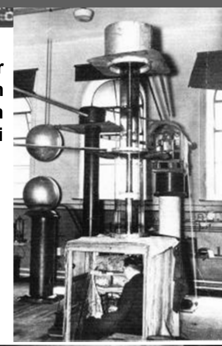
The « Nobel prize » power converter :

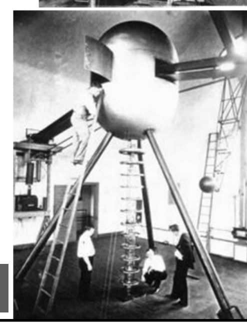
[Cockroft & Walton] who in 1932 used this voltage multiplier to power their particle accelerator, performing the first artificial nuclear disintegration in history. They used this cascade circuit for most of their research, which in 1951 won them the Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles".

Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S, 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."

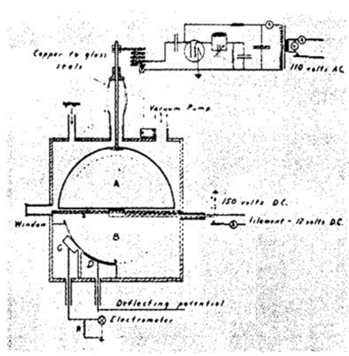
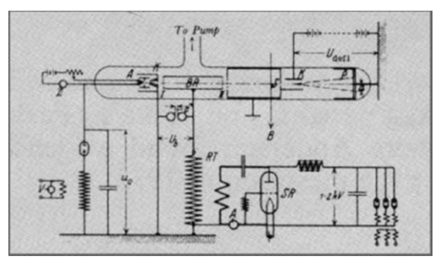


Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.



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 !)

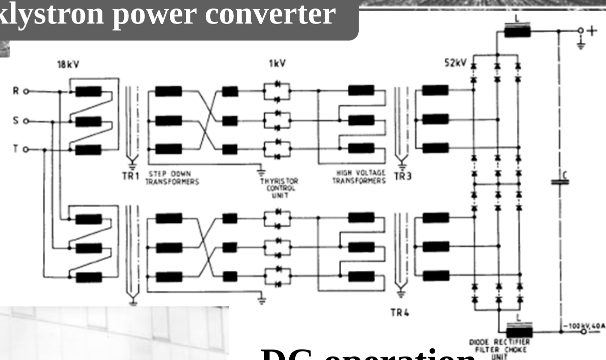
Power converters specifications

"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

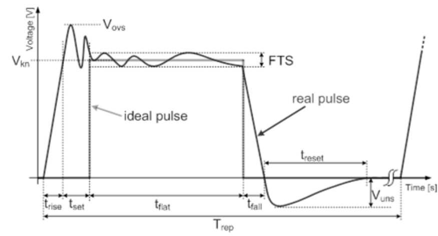
DC Power: 4 MW



DC operation

Pulsed klystron modulators for LINAC 4

Specification	symbol	Value	unit
Output voltage	V_{kn}	110	kV
Output current	I_{out}	50	A
Pulse length	$t_{rise}+t_{set}+t_{flat}+t_{fall}$	1.8	ms
Flat-Top stability	FTS	<1	%
Repetition rate	$1/T_{rep}$	2	Hz



Peak power : 5.5MW
Average power: 20kW

LHC orbit corrector : [±60A,±8V]

Magnet : L=7 H ; R = 30 mΩ (60m of 35 mm²)
T = L/R = 300 s => $f^{OL}_B \cong$ 0.5 mHz

U_{static} = R.I = 1.8V

6 V for the dI/dt with L= 7 H

(dI/dtmax ≅ 1A/s) OK

Small signal : $f^{CL}_B \cong$ 1 Hz : ΔI = 0.1 A = 0.15 % Imax

"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 = 1% : Umax = 2400 V ?????...)

(U_{max}= 8V => ΔI = 30 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.
Don't worry it's not urgent. Next month is OK "
(Email received 05.12.08)

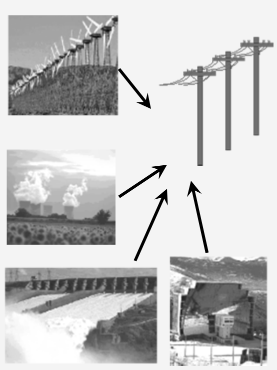
Need of more specification data:

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

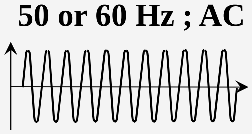
- Output voltage and current reversibility
- Precision (short and long term)
- Ripple (load definition)

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.

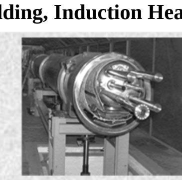
Control

Traction and auxiliary

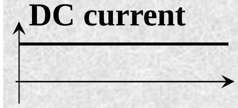
Domestic Appliance

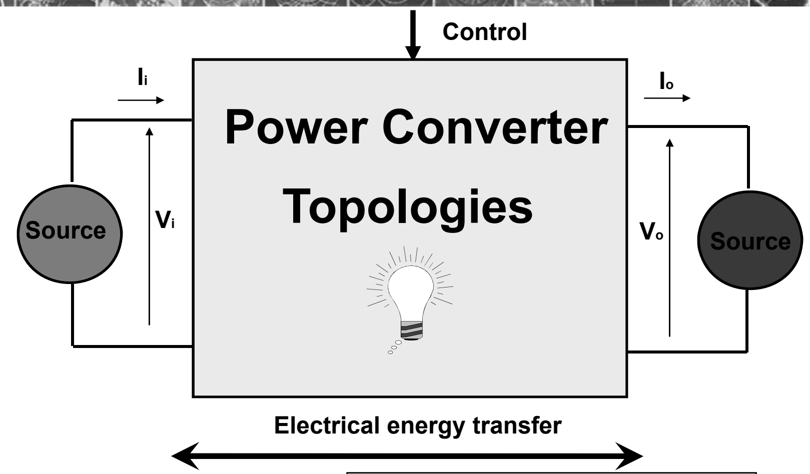
Medical applications

Industrial applications, Welding, Induction Heating, ….



DC current





Power Converter Design

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

Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

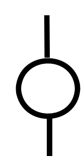
Source definition

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.

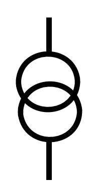
Two types of sources:

Voltage source



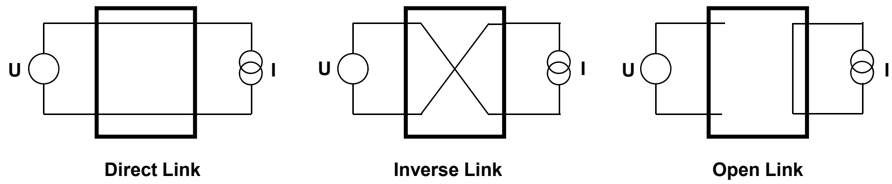
which imposes a voltage independently of the current flowing through it. This implies that the series impedance of the source is zero (or negligible in comparison with the load impedance)

Current source



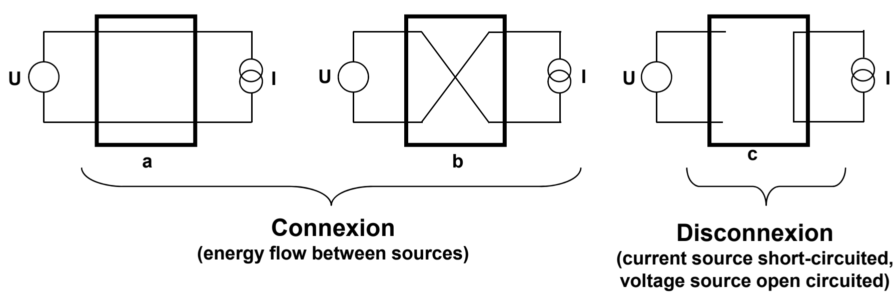
which imposes a current independently of the voltage at its terminals.
This implies that the series impedance of the source is infinite (or very large in comparison with the load impedance)

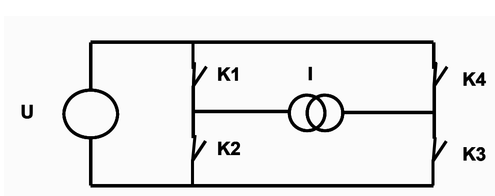
Commutation



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.

Direct link configuration : Direct voltage-current converters

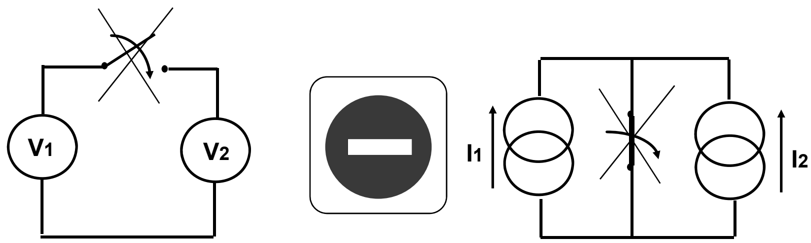




- K1 and K3 closed => a
- K2 and K4 closed => b
- K1 and K4 (or K2 and K3) closed => c

Commutation rules

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



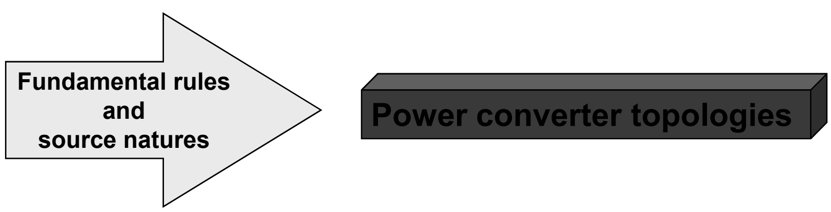
Turn On impossible **Turn Off impossible**

Interconnection between two impeding networks can be modified only if :

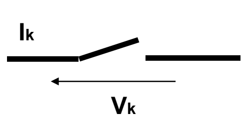
- **the two networks are sources of different natures (voltage and current)**
- **the commutation is achieved by TWO switches. The states of the two switches must be different.**

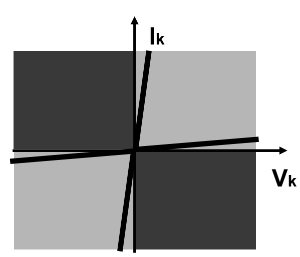
Power Converter topology synthesis: the problem

the interconnection of sources by switches



switch characteristics





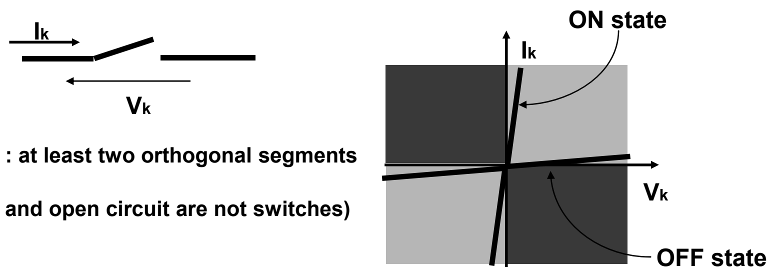
Switch characteristics

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

The losses in the switch have to be minimized

Zon very low

Zoff very high

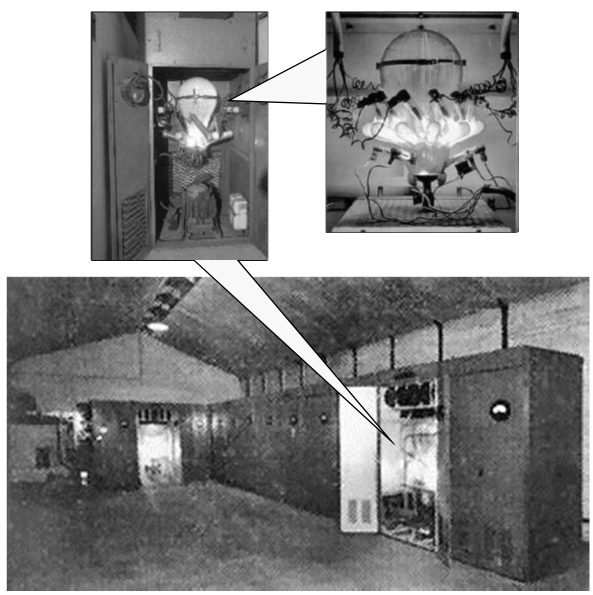


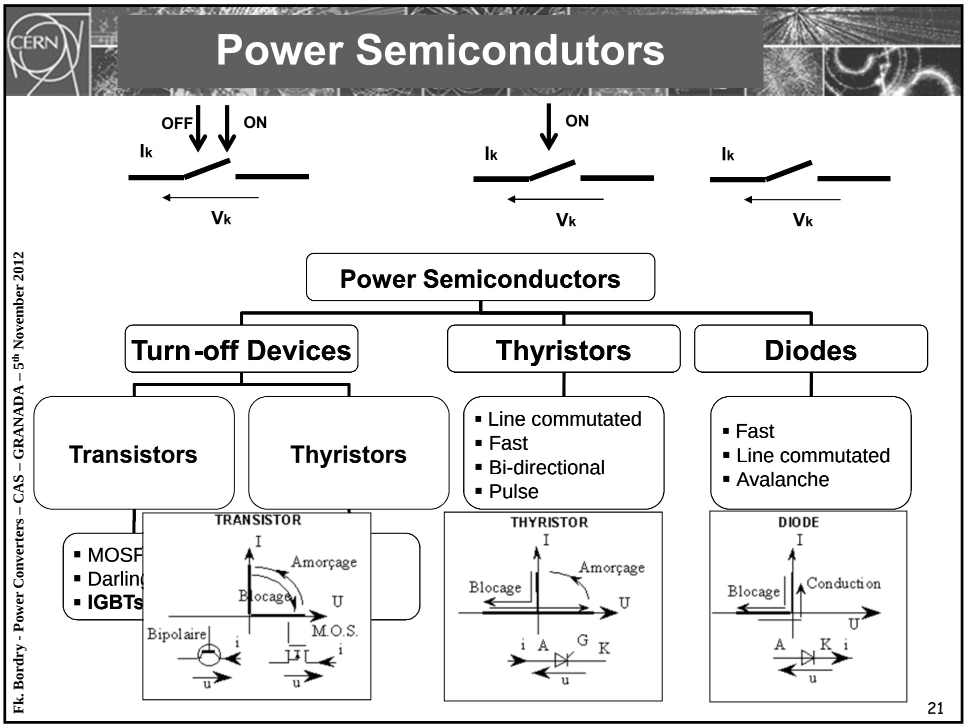
Switch : at least two orthogonal segments

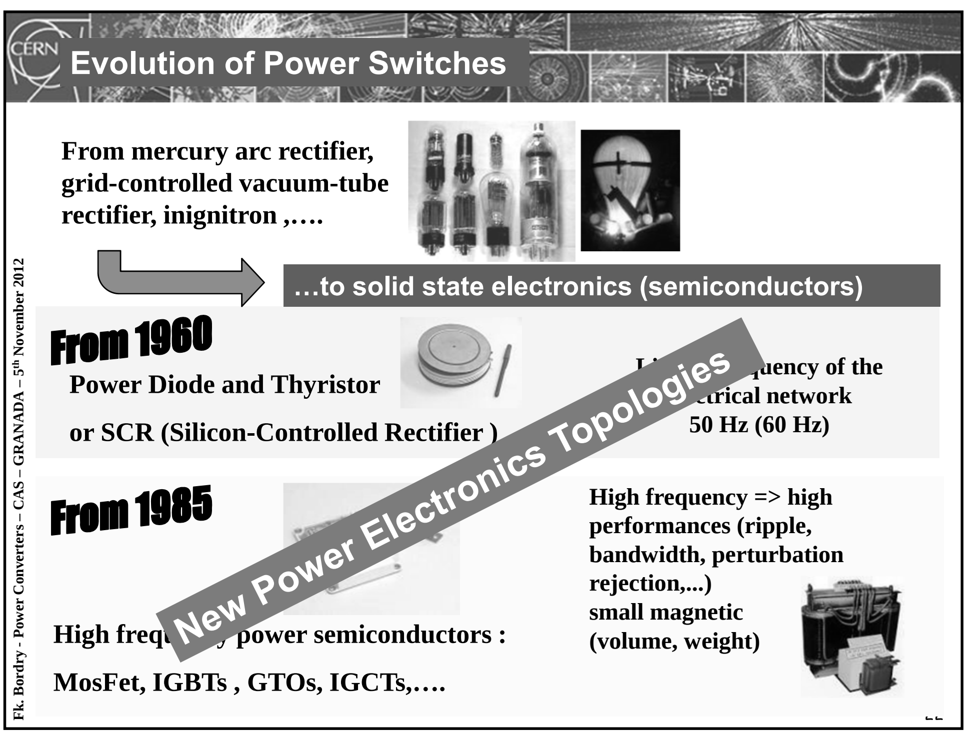
(short and open circuit are not switches)

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.

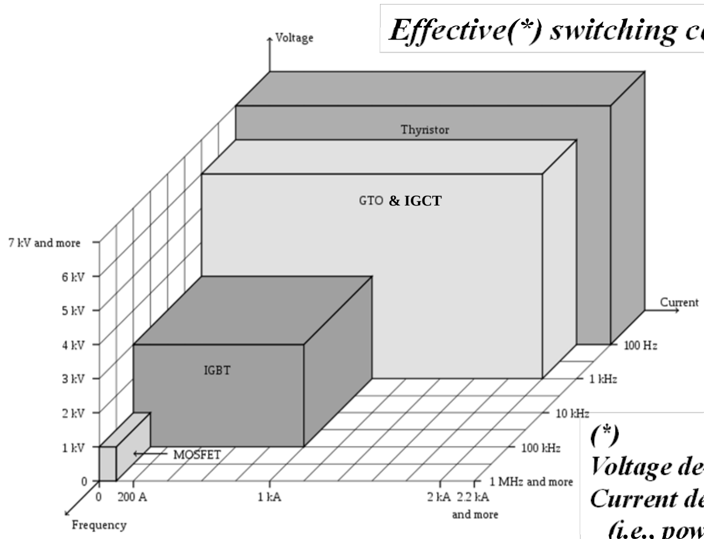



Power Semicondutors
OFF
ON
Ik
Vk
Power Semiconductors
Turn-off Devices
Thyristors
Diodes
Transistors
Thyristors
▪ Line commutated
▪ Fast
▪ Bi-directional
▪ Pulse
▪ Fast
▪ Line commutated
▪ Avalanche
▪ MOSF
▪ Darling
▪ IGBTs
TRANSISTOR
Amorçage
Blocage
Bipolaire
M.O.S.
THYRISTOR
DIODE
Conduction
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
21


Evolution of Power Switches
From mercury arc rectifier, grid-controlled vacuum-tube rectifier, inignitron ,….
…to solid state electronics (semiconductors)
From 1960
Power Diode and Thyristor
or SCR (Silicon-Controlled Rectifier)
50 Hz (60 Hz)
From 1985
High frequency => high performances (ripple, bandwidth, perturbation rejection,...)
small magnetic (volume, weight)
MosFet, IGBTs , GTOs, IGCTs,….
New Power Electronics Topologies
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

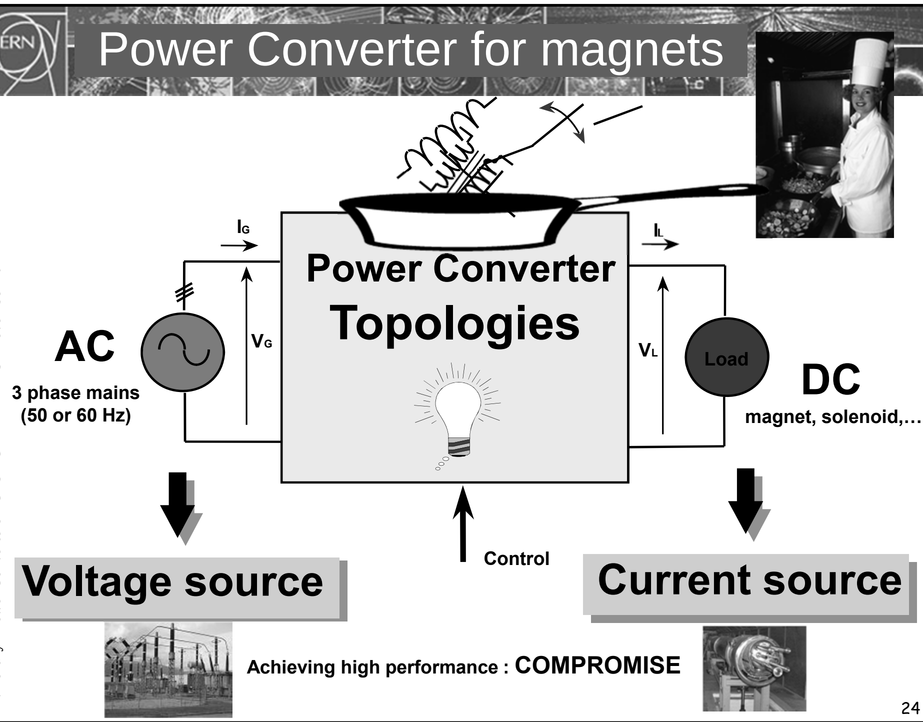
Power semiconductor switches capabilities

Effective(*) switching capabilities

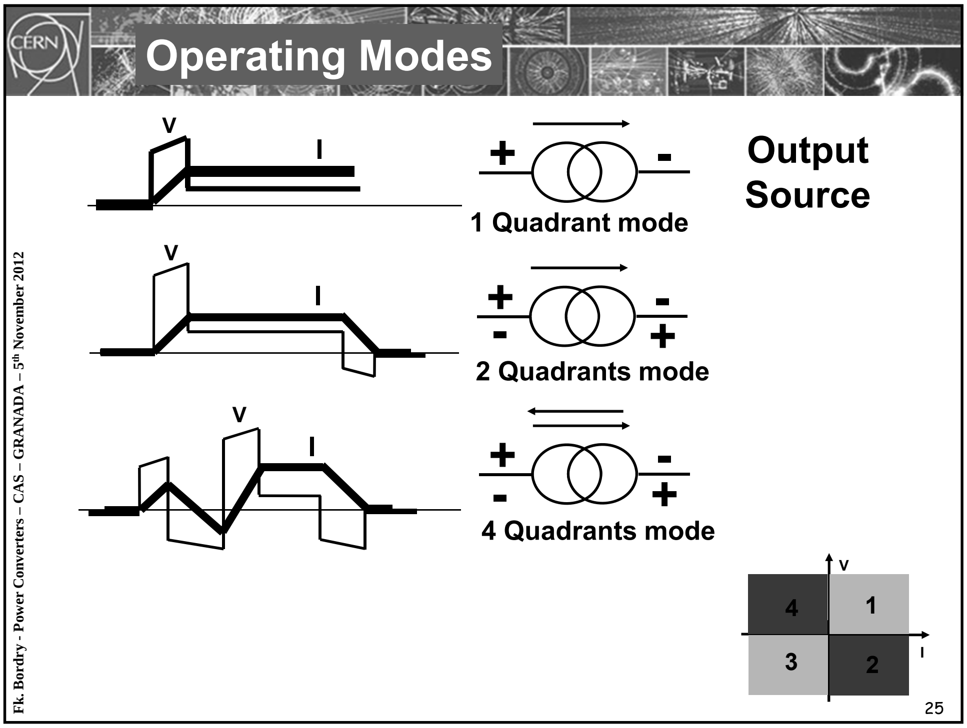


(*)
Voltage de-rating: 1.6;
Current de-rating: ~1.3;
(i.e., power de-rating: 1.6 x 1.3 ≈ 2)

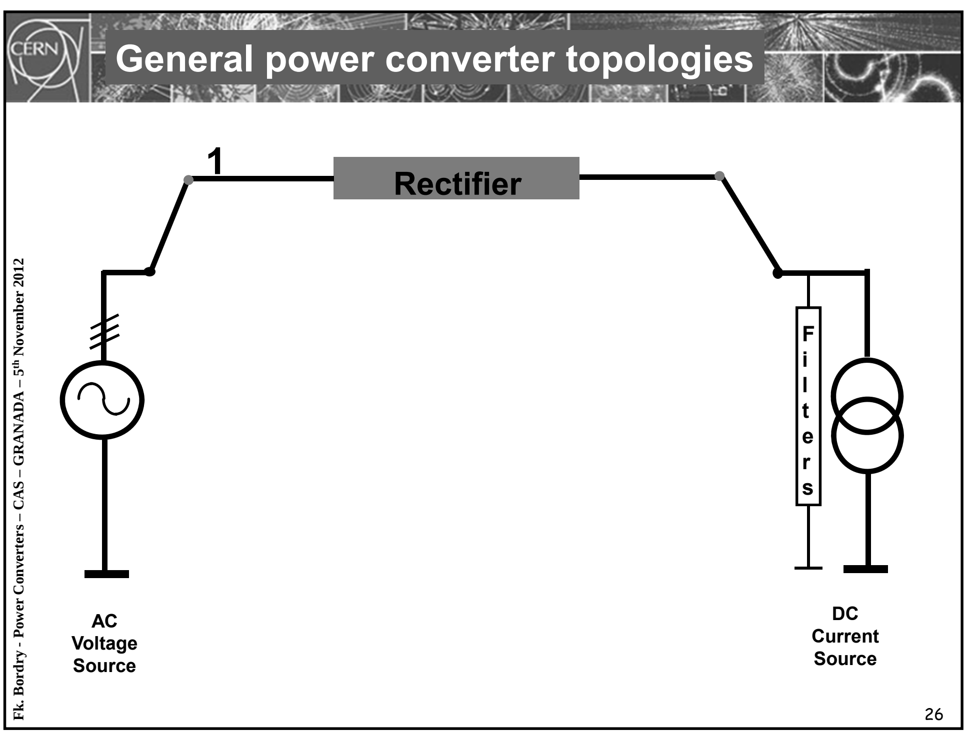
Power Converter for magnets



Achieving high performance : **COMPROMISE**

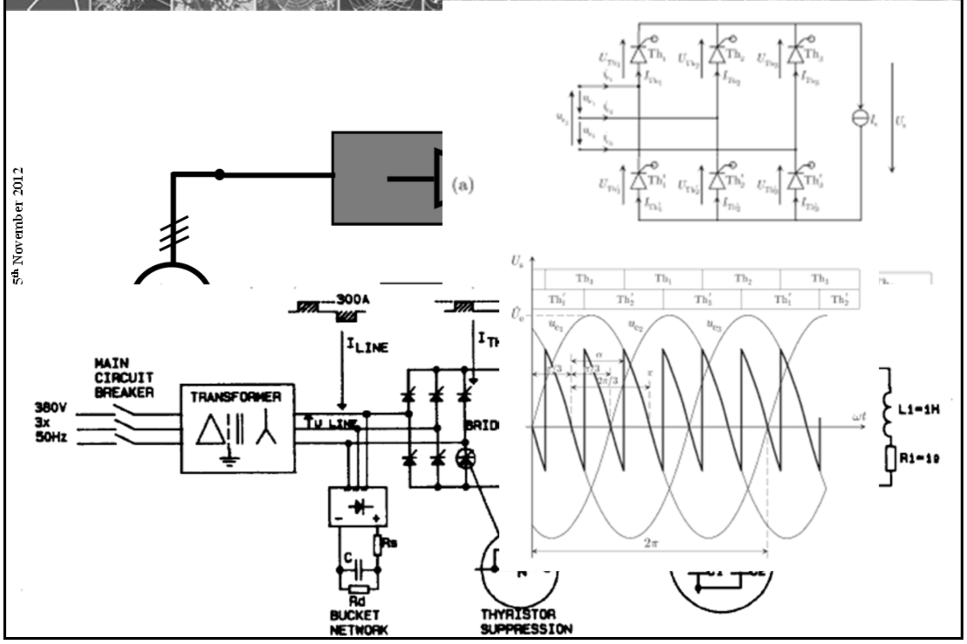


Operating Modes
V
I
1 Quadrant mode
V
I
2 Quadrants mode
V
I
4 Quadrants mode
Output
Source
v
4
1
3
2
I
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
25

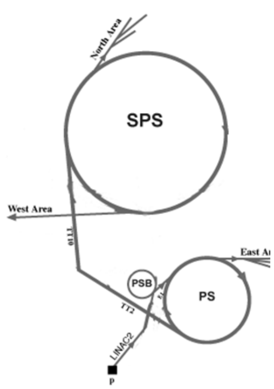


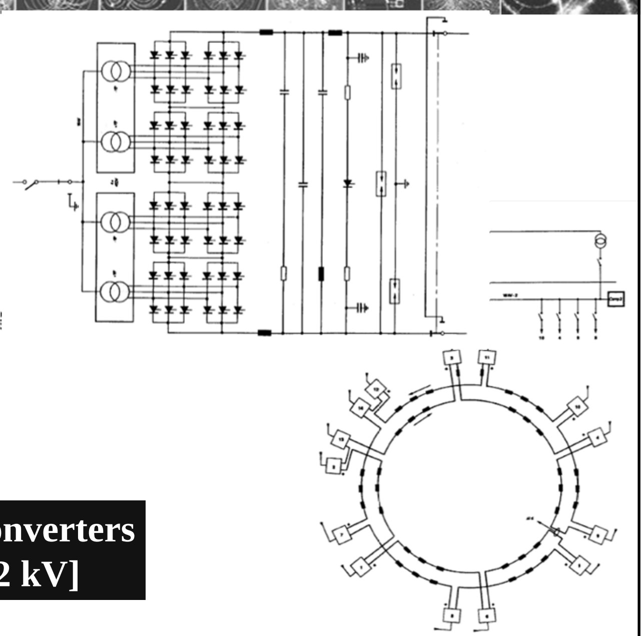
General power converter topologies
1
Rectifier
Filters
AC
Voltage
Source
DC
Current
Source
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
26

Direct Converters : Rectifiers

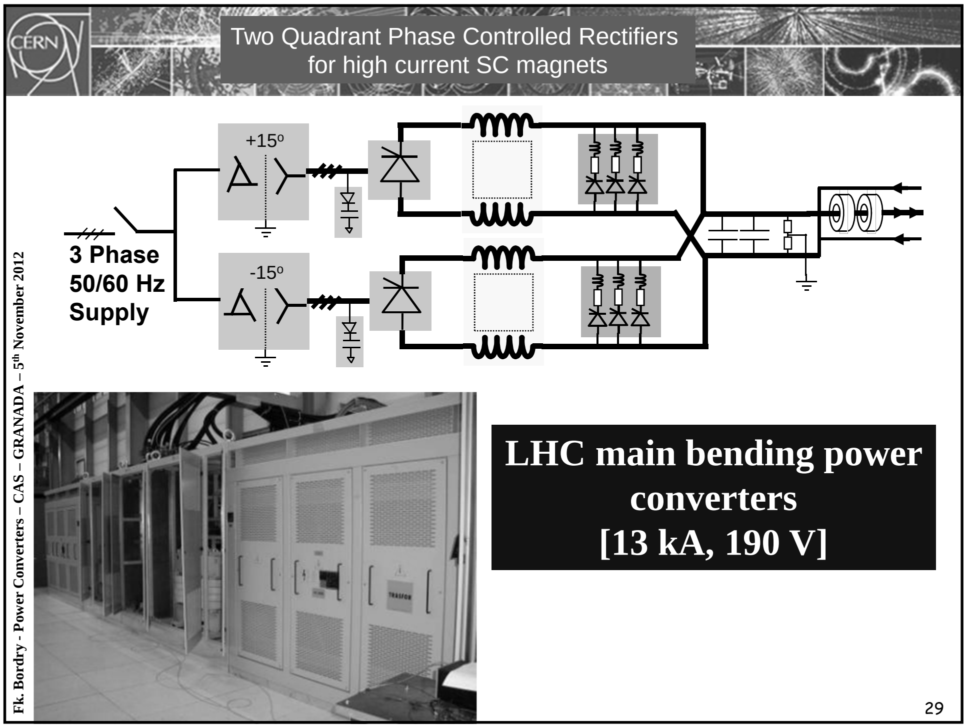


SPS Main power converters

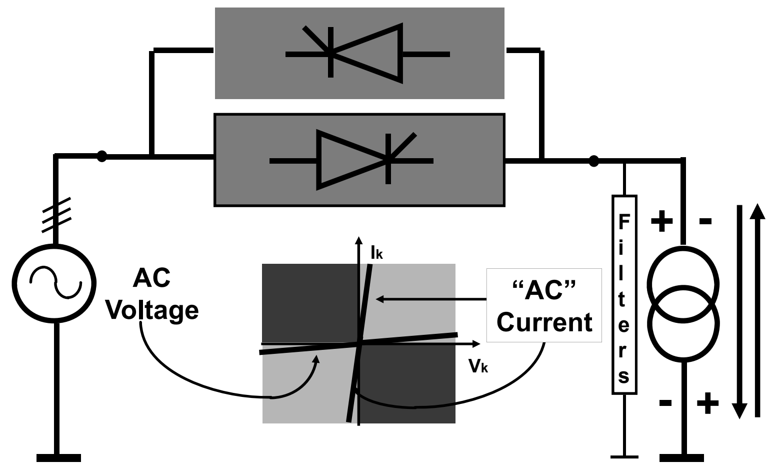




Main power converters
12 x [6kA, 2 kV]


Two Quadrant Phase Controlled Rectifiers
for high current SC magnets
+15º
-15º
3 Phase
50/60 Hz
Supply
LHC main bending power converters
[13 kA, 190 V]
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
29

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

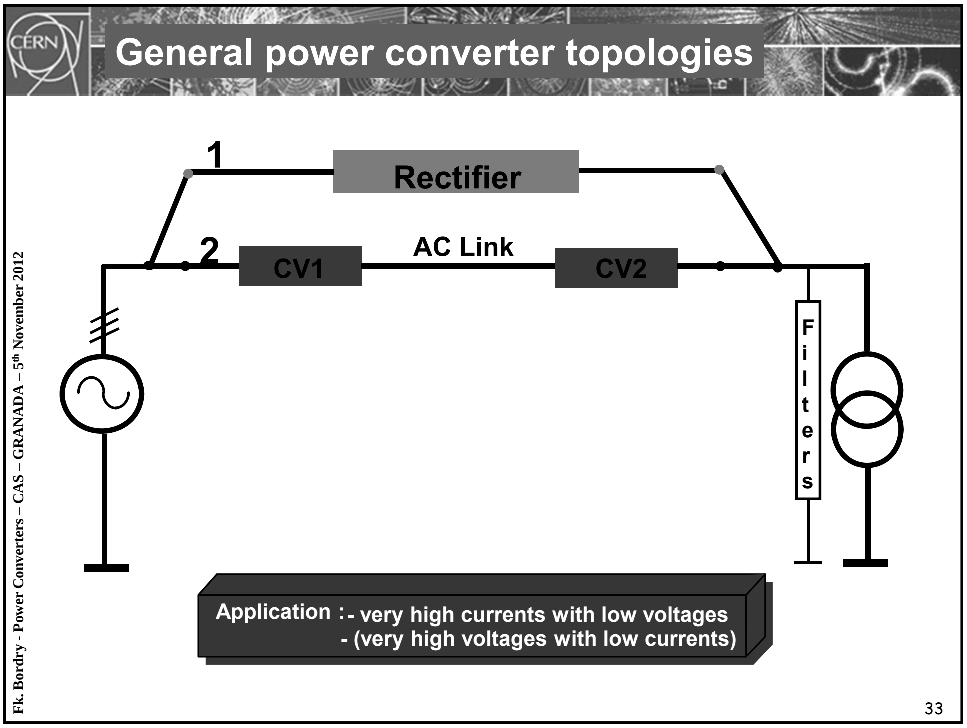
☹ harmonic content on input current

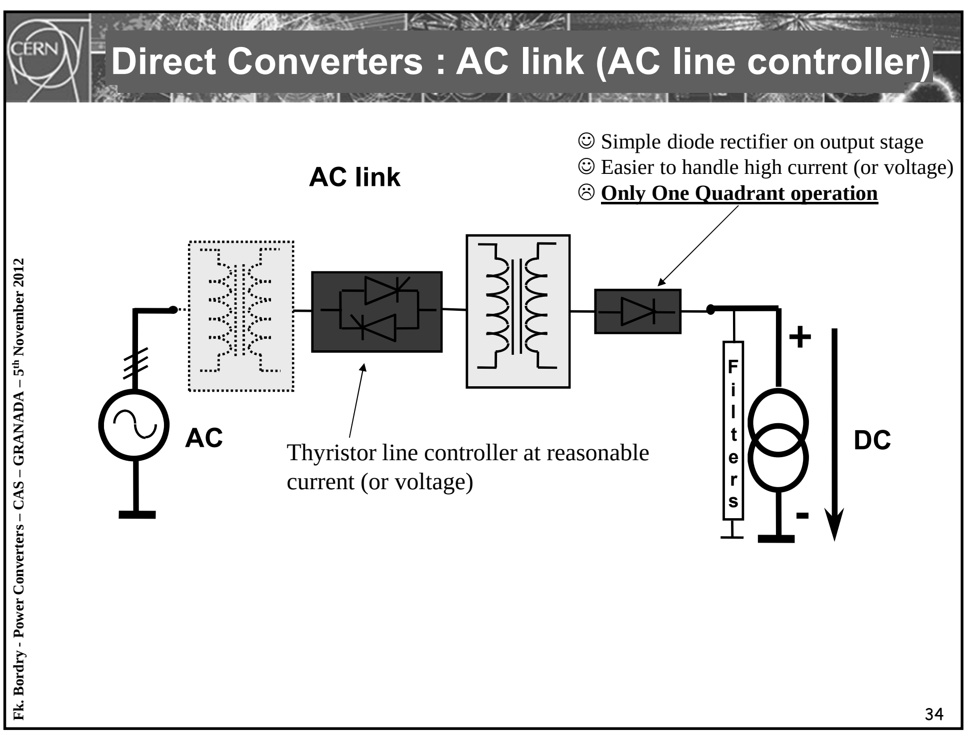
☹ response time is large (ms)

☹ current ripple is large (passive or active filters)

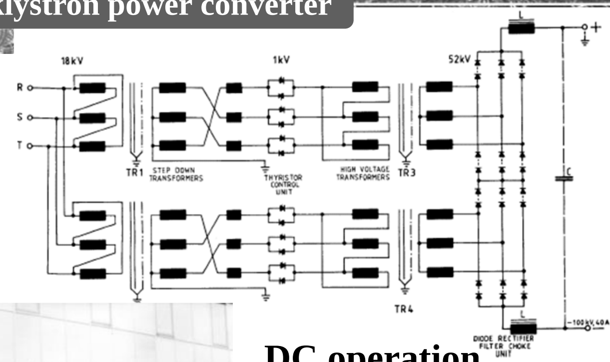
⇒ passive (active) filters operating at low frequency

Increase of pulse number (3,6,12,24,48) but complexity (cost, control,...)


General power converter topologies
1
Rectifier
2
CV1
AC Link
CV2
Filters
Application : - very high currents with low voltages
- (very high voltages with low currents)
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
33

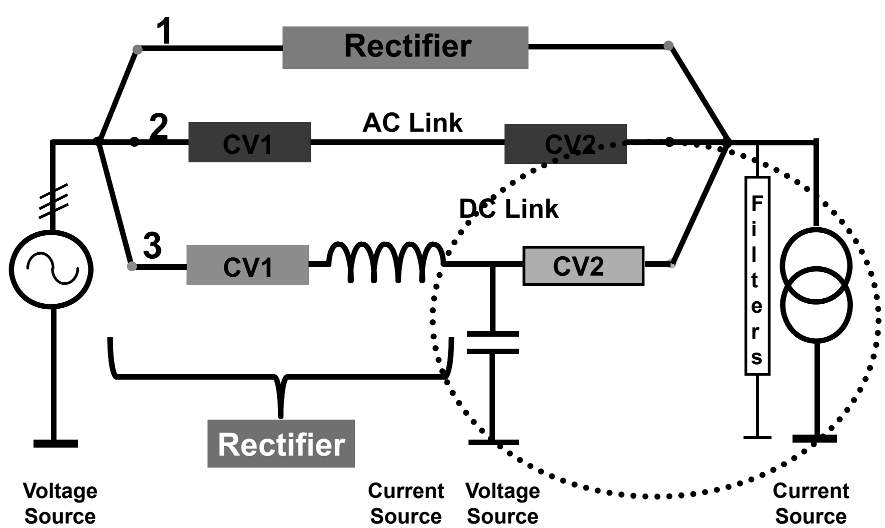

Direct Converters : AC link (AC line controller)
AC link
☺ Simple diode rectifier on output stage
☺ Easier to handle high current (or voltage)
☹ Only One Quadrant operation
AC
Thyristor line controller at reasonable current (or voltage)
Filters
+
-
DC
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012
34

[100 kV, 40A] klystron power converter



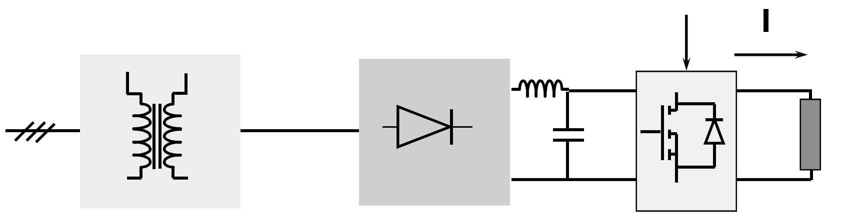
DC operation

General power converter topologies



Galvanic isolation at AC input source (50Hz transformer)

Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012



50 Hz transformer
Optimal voltage output
Galvanic isolation

CV1
Diode bridge
6 or 12 pulses

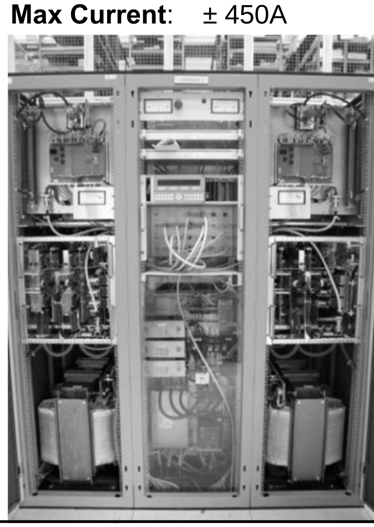
CV2
PWM Converter
Hard switching

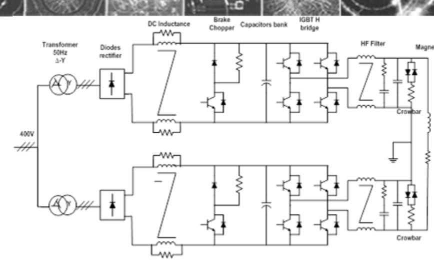
Magnet

New PS Auxiliary Power Converters

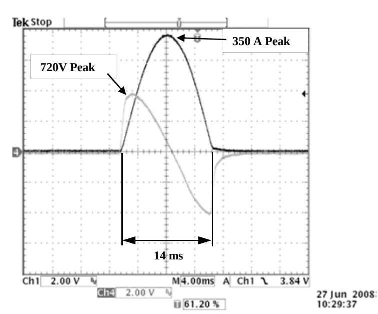
Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

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





Multi-Turn Extraction: Current/Voltage waveforms



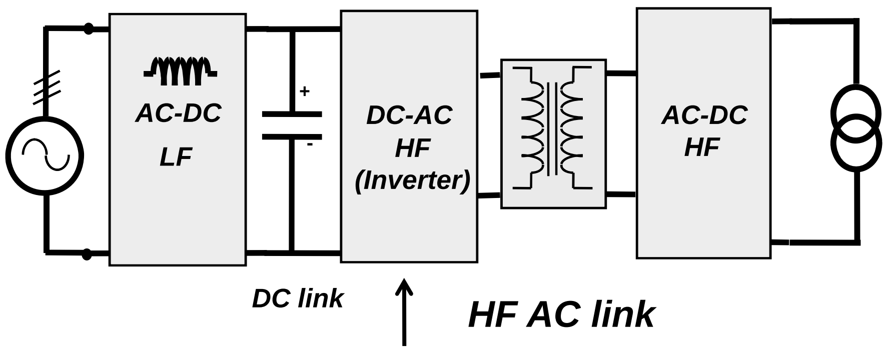
Current Loop Bandwidth ≈ 1kHz

Indirect AC-DC-AC-DC converter

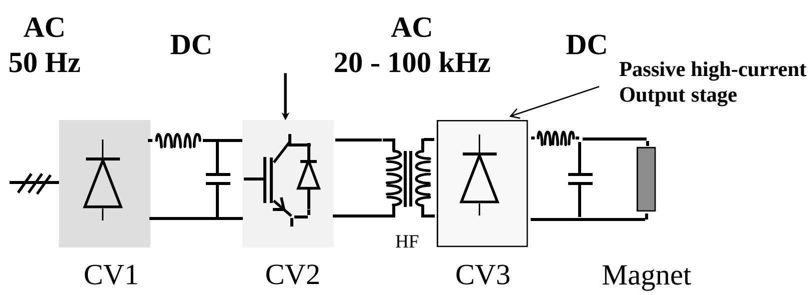
Three cascade power conversion stages:

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

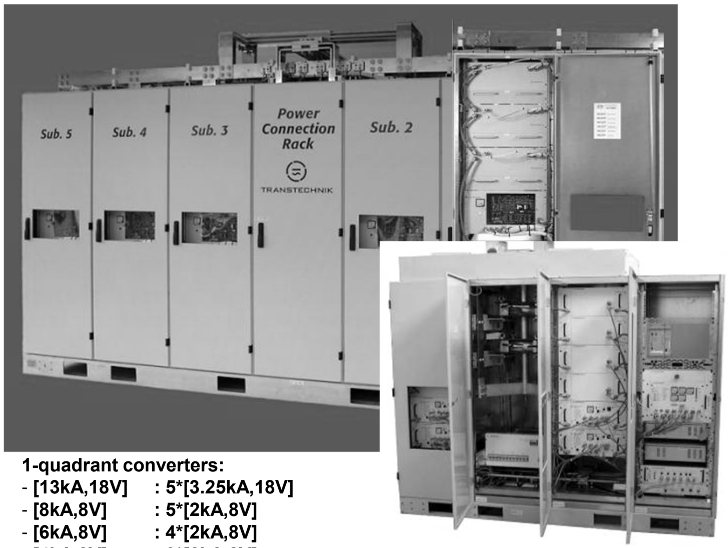


Voltage loop:
bandwidth few kHz

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

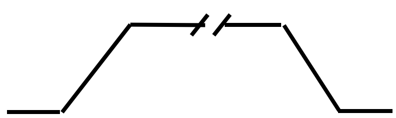


1-quadrant converters:
- [13kA,18V] : 5*[3.25kA,18V]
- [8kA,8V] : 5*[2kA,8V]
- [6kA,8V] : 4*[2kA,8V]
- [4kA,8V] : 3*[2kA,8V]

[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

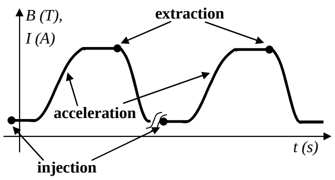
Switch-mode power converters

- 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)

Pulsed converters

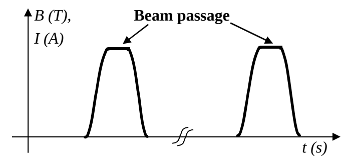
Synchrotrons

• 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;



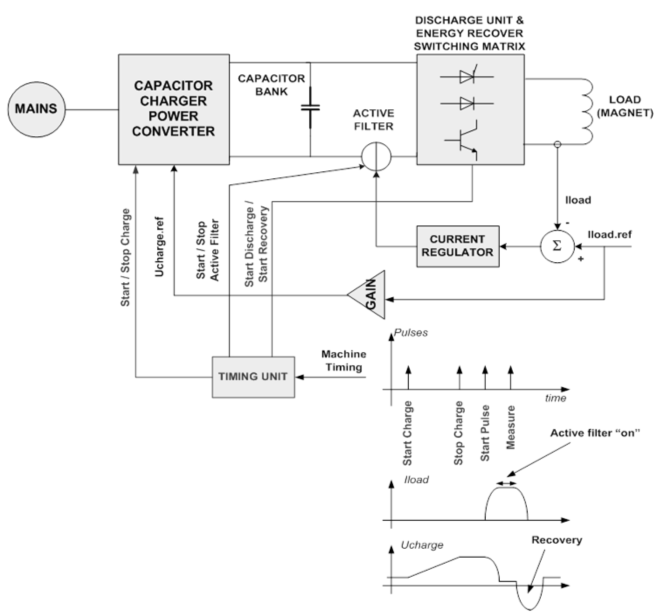
Rise and fall time < few ms

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

Fk. Bordry - Power Converters – CAS – GRANADA – 5^{th} November 2012

43

Block schematic of a fast pulsed converter

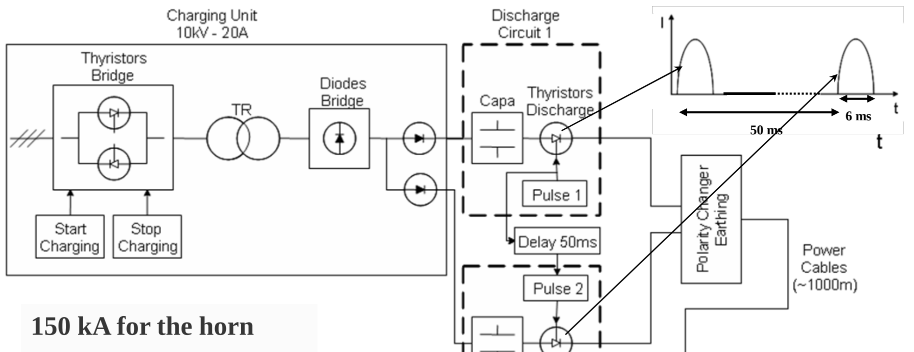


Fk. Bordry - Power Converters – CAS – GRANADA – 5^{th} November 2012

44

High current, high voltage discharge capacitor power converters

CNGS horn and reflector power converters

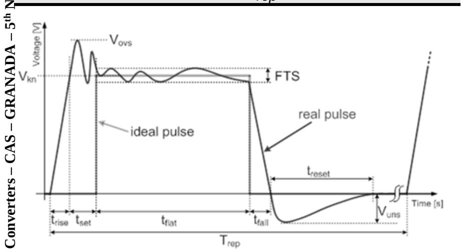


150 kA for the horn

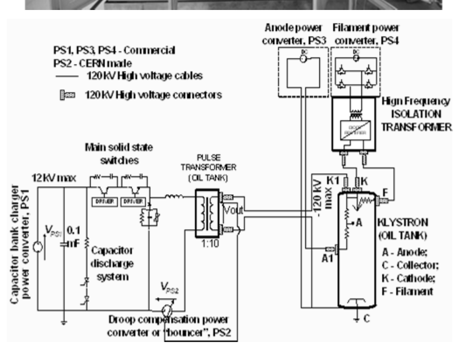
180 kA for the reflector

Pulsed klystron modulators for LINAC 4

Specification	symbol	Value	unit
Output voltage	V_{kn}	110	*kV*
Output current	I_{out}	50	*A*
Pulse length	$t_{rise}+t_{set}+t_{flat}+t_{fall}$	1.8	*ms*
Flat-Top stability	*FTS*	<1	*5*
Repetition rate	$1/T_{rep}$	2	*Hz*

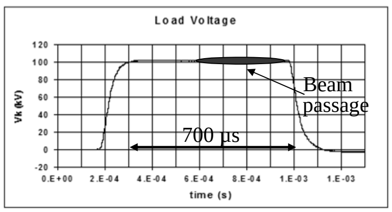


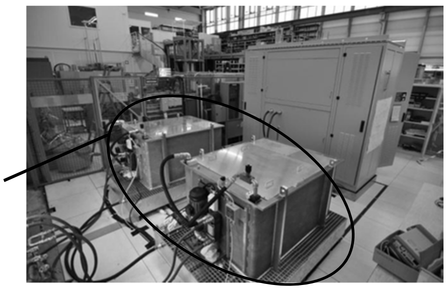
Peak power : 5.5MW
Average power: 20kW



Pulsed klystron modulators for LINAC 4

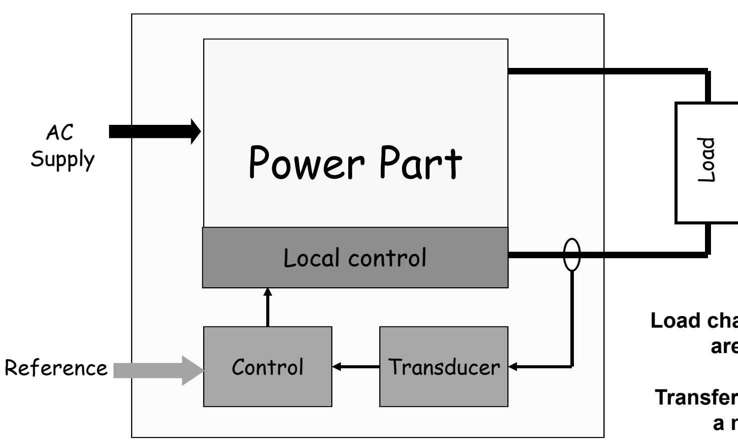
Specification	symbol	Value	unit
Output voltage	V_{kn}	110	*kV*
Output current	I_{out}	50	*A*
Pulse length	$t_{rise}+t_{set}+t_{flat}+t_{fall}$	1.8	*ms*
Flat-Top stability	*FTS*	<1	*5*
Repetition rate	$1/T_{rep}$	2	*Hz*





Test phase: Water cooled dummy loads 2.5T each!

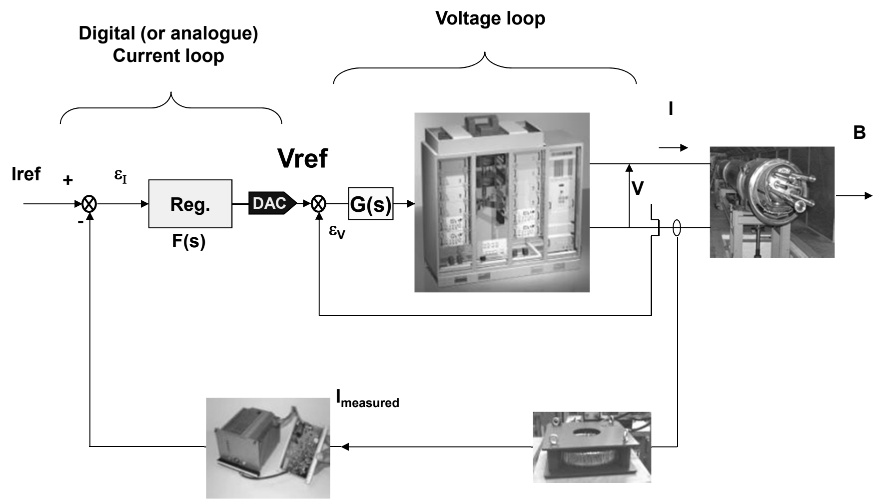
Power Converter % Load



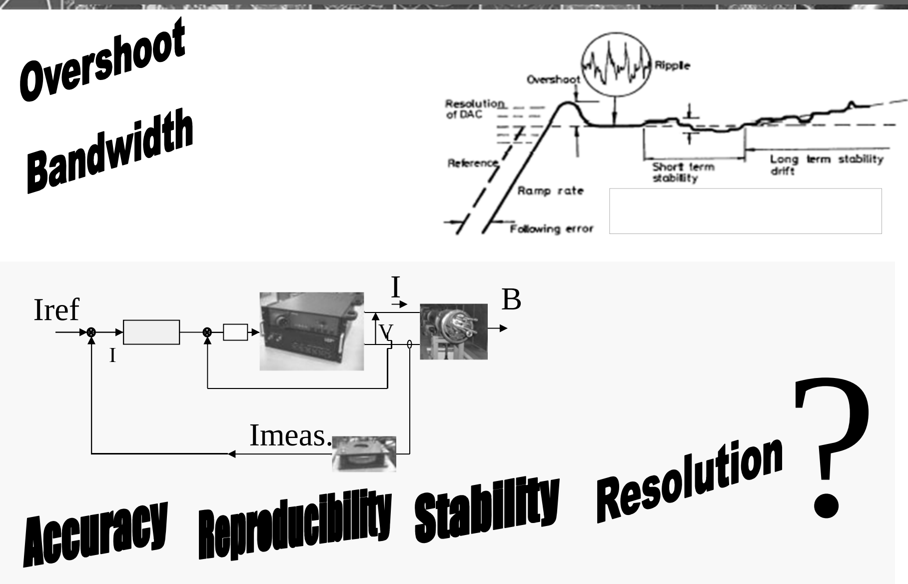
Load characteristics are vital.

Transfer function is a must !

Example :LHC power converter control



Power converter :Performance requirements



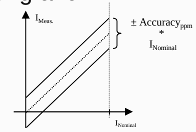
Glossary

Precision

– Accuracy

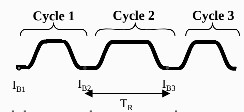
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

* requires definition



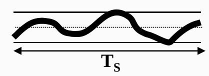
– Reproducibility

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.



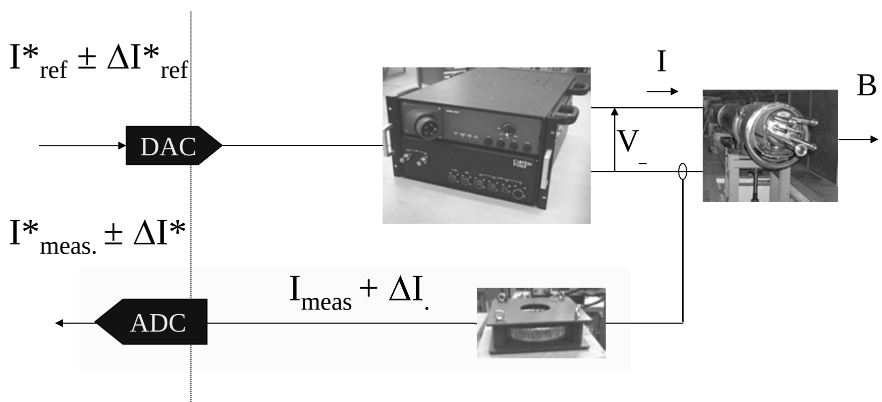
Accuracy, reproducibility and stability are defined for a given period

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

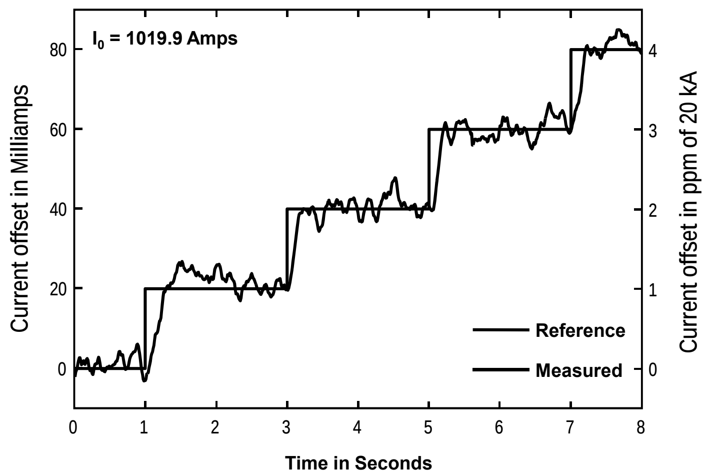
Resolution

Smallest increment that can be induced or discerned.

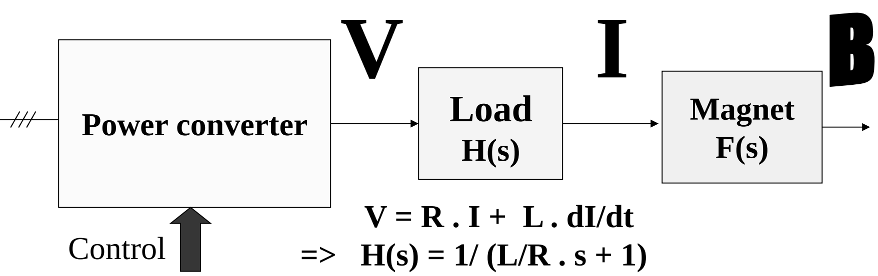
The resolution is expressed in ppm of $I_{Nominal}$.
Resolution is directly linked to A/D system



Results of Resolution Test with the LHC Prototype Digital Controller



RIPPLE



V = R . I + L . dI/dt

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

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,…)

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: ΔV(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…..

Power Converter Design: Typical R&D procedure

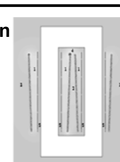
Efficiency, cost, volume, EMI,…, specs

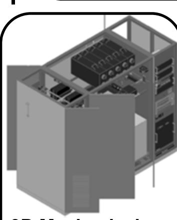
Utility grid specs (Voltage, power quality,…)

Specs analysis for topology selection (1,2,4 quadrants, active/passive converter – closed/open loop regulation, switches technology, …)

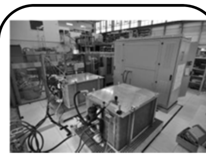
Numerical verification of selected topology (dedicated numerical simulations for general converter functionality)

Components design and/or specifications (analytical or numerical approaches)





3D Mechanical integration & construction



Laboratory tests

On site commissioning

Load specs (L, R, C values, precision, …)

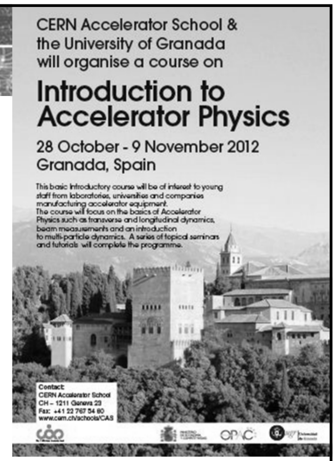
Load examples:
- Magnet (high current)
- Klystron (High Voltage)
- Particles source (HV)
- RF equipment (HV)

The end

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

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

2014: Next Specialised CAS Course on Power Converters for particle accelerators

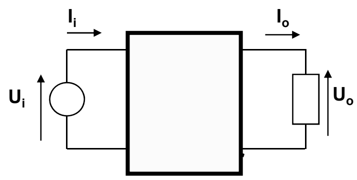


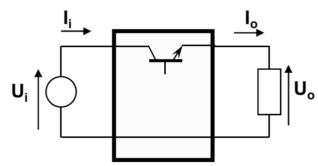
Reserved slides

58

Energy conversion : transfer of energy between two sources

Introductive example



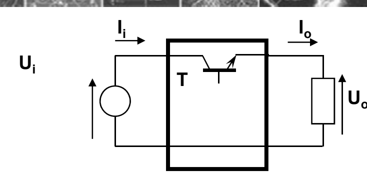


Linear solution

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

- $U_T \approx 0$ if $I_T \neq 0$
- $I_T = 0$ if $U_T \neq 0$ } **$P_T \approx 0$ (if power switches are ideal)**

~~Linear mode~~ ⇒ **switch mode**
(power switches either saturated or blocked)

Reactive Components of Power Converters

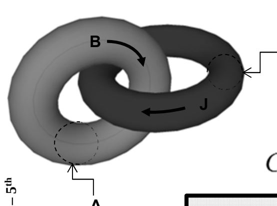
Inductors & Capacitors Functionalities in Power Converters
- Electrical Energy storage
  (POPS, SMES, indirect-link converters)
- Adaptation of converter I/O sources
  (DC or AC current & voltage filters, Bouncers ...)
- Phase control of power flow through HF resonant LC stage
- Implementation of non dissipative commutation
  (ZCS or ZVS snubbers)

Transformer Functionalities in Power Converters
- Galvanic Isolation
- High Voltage or Low Voltage converters
  (Klystrons or Magnets)

Reactive Components can degrade:
- Converter Efficiency
- Converter Power Density: W/m^3 & W/kg
- Converter Control Bandwidth: Filter Time constants

Reactive Components of Power Converters

Basic Dimensional Analysis of Reactive Components



Transformer Apparent Power (VA)

$$S = \sum VI = f.K_u.K_v.B.J.A_e.S_{Cu} \propto f.B \cdot J.[L]^4$$

Transformer Losses (W)

$$MagLosses \propto B^{\approx 2}.[L]^3$$
$$CopperLosses \propto J^2.[L]^3$$

Transformer Temperature Rise

$$TempRise = \frac{Losses}{h.S_{ext}} \propto [L]$$

Transformer Apparent Power at Constant Temp Rise $(B.J \propto [L]^{-1})$

$$S(VA) \propto f.[L]^3 \propto f.Volume$$

Inductor Stored Magnetic Energy (J)

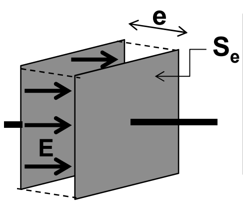
$$W_{mag} = \frac{1}{2}LI^2 = K_u.B.J.A_e.S_{Cu} \propto B \cdot J.[L]^4$$

Inductor Stored Magnetic Energy at Constant Temp Rise $(B.J \propto [L]^{-1})$

$$W_{mag}(J) \propto [L]^3 \propto Volume$$

Reactive Components of Power Converters

Basic Dimensional Analysis of Reactive Components



Capacitor Stored Magnetic Energy (J)

$$W_{el} = \frac{1}{2}CV^2 = K.\varepsilon.E^2.S_e.e \propto \varepsilon.E^2.[L]^3$$

$$W_{el}(J) \propto [L]^3 \propto Volume$$

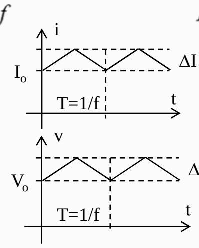
Basic Dimensional Analysis of Converter I/O Filters

Inductor Current Filter L

$$V = L \cdot \frac{\Delta I}{\Delta t} \propto \frac{Volume}{I_o^2} \Delta I_{ppm} . I_o . f$$

$$\Delta I_{ppm} = \frac{\Delta I}{I_o} \qquad \Delta t \propto \frac{1}{f}$$

$$Volume \propto \frac{V . I_o}{f . \Delta I_{ppm}}$$



Capacitor Voltage Filter C

$$I = C \cdot \frac{\Delta V}{\Delta t} \propto \frac{Volume}{V_0^2} \Delta V_{ppm} . V_o . f$$

$$\Delta V_{ppm} = \frac{\Delta V}{V_o} \qquad \Delta t \propto \frac{1}{f}$$

$$Volume \propto \frac{V_o . I}{f . \Delta V_{ppm}}$$

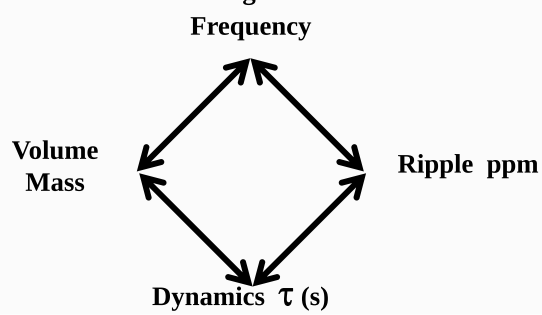
Reactive Components of Power Converters

Trade-off on dynamic performance

Main Time Constant of LC Filter

$$\tau = \sqrt{L.C} \propto \frac{1}{f . \sqrt{V_{ppm} \cdot I_{ppm}}}$$

Main Design Trade off

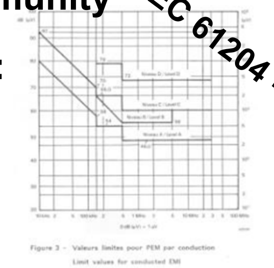


EMC : ELECTROMAGNETIC COMPATIBILITY

COMPATIBILITY : Emission - Immunity

IEC 61204 -3

Norms for the power converters :



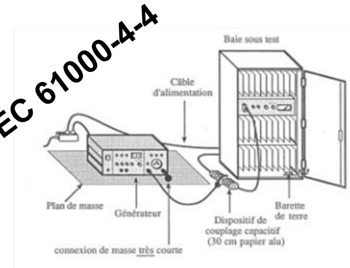
Emission :

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



Classification of switches

- **According to the degree of controllability:**
- **Diodes: On and Off states controlled by the power circuit (uncontrolled).**
- **Thyristors: Turned On by a control signal but turned off by the power circuit (semi-controlled).**
- **Transistors: Controllable switches. Can be turned On and Off by a control signal.**
- **For analysis purposes power switches are usually considered ideal: Instantaneous, lossless, and infinite current and voltage handling capability.**

Diodes

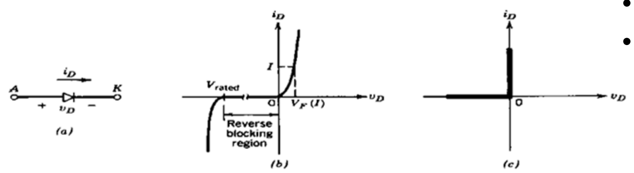
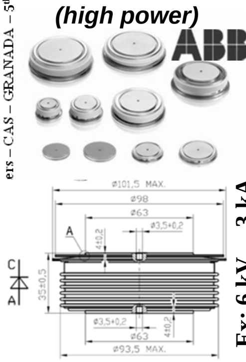


Figure 2-1 Diode: (a) symbol, (b) i–v characteristic, (c) idealized characteristic.

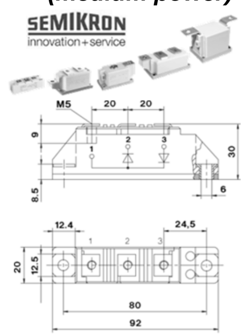
- 2 terminals device.
- An ideal diode turns On when forward biased and Off <u>when its forward current goes to zero</u>.

***press-pack case* (high power)**



Ex: 6 kV$_{pk}$, 3 kA$_{av}$

***modules case* (medium power)**



Ex: 1.8 kV$_{pk}$, 80A$_{av}$

***Other cases* (low power)**

IXYS

SOT-227 Minibloc case Ex: 1000V$_{pk}$, 2x30A$_{av}$

TO-220 case
Ex: 600V$_{pk}$, 30A$_{av}$

DO-203 Stud case
Ex: 800V$_{pk}$, 110A$_{av}$

67

Thyristor (Silicon Controlled Rectifier - SCR)

3 terminals device.

3 main operating regions.

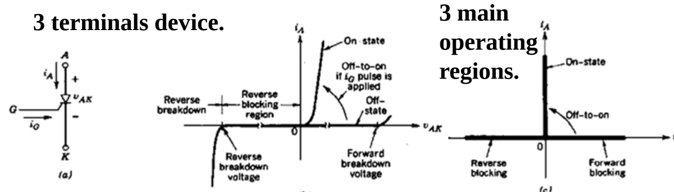
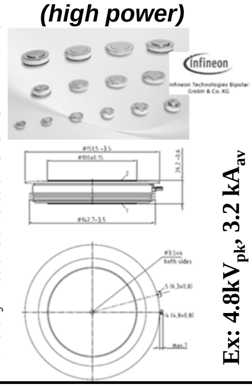


Figure 2-3 Thyristor: (a) symbol, (b) i–v characteristics, (c) idealized characteristics.

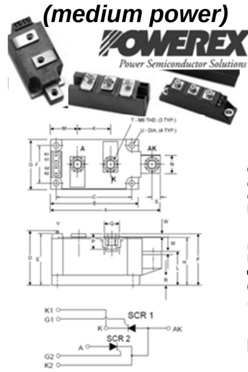
- Latches On by a gate current pulse when forward biased and turns Off as a diode.
- Requires low power gate drives and is very rugged.

***press-pack case* (high power)**



Ex: 4.8kV$_{pk}$, 3.2 kA$_{av}$

***modules case* (medium power)**



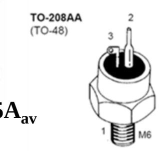
Ex: 1.8 kV$_{pk}$, 500A$_{av}$

***Other cases* (low power)**

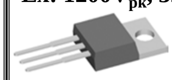
IXYS

TO-93 case

Ex: 1200V$_{pk}$, 325A$_{av}$



TO-208 Stud case
Ex: 800V$_{pk}$, 30A$_{av}$

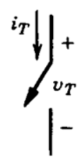


TO-220 case
Ex: 800V$_{pk}$, 20A$_{av}$

68

Controllable switches

- Used in forced-commutated converters (f_{sw} > 60 Hz)
- Different types: MOSFET, IGBT, GTO, IGCT.
- Gate requirements and performance are quite different.
- Generic switch: Current flows in the direction of the arrow when the device in On.



Generic controllable switch

MOSFET

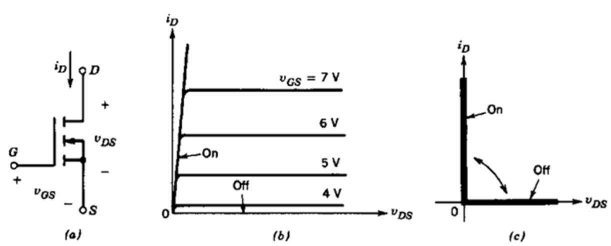


Figure 2-9 *N*-channel MOSFET: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.

International IOR Rectifier

SMD-220 case

Ex: 200V, 70A

TO-247 case

Ex: 200V, 130A

- High input impedance on the gate (voltage controlled) device.
- Fast commutation times (tens to hundreds of ns). Low switching losses;
- Low On state resistance (R_{DS_On}).
- Easy paralleling
- Limited in voltage and power handling capabilities. Great for low voltage (V_{DS}<250V) and low current (I_{DS}<150A) applications.

Insulated Gate Bipolar Transistor (IGBT)

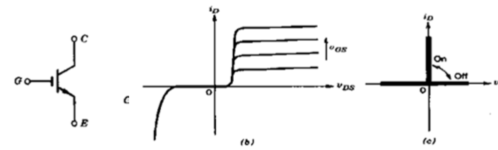
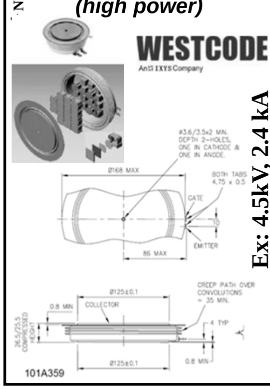


Figure 2-12 An IGBT: (a) symbol, (b) i–v characteristics, (c) idealized characteristics.

- High input impedance for controls (between gate (G) and emitter (E)) thanks to the use of a MOSFET.
- High voltage devices have low "on" state voltage drops, like a BJT
- High current (high power) switching capabilities;
- Fast switching (typ. < 500ns) -> Moderate switching losses

press-pack case
(high power)

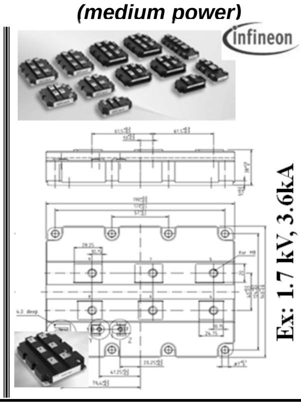
WESTCODE



Ex: 4.5kV, 2.4 kA

modules case
(medium power)

Infineon



Ex: 1.7 kV, 3.6kA

***Other cases** (low power)*

SEMIKRON innovation+service

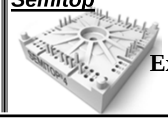
Semix

Ex: 1200V, 400A
(6 IGBT's)

Mini Skiip

Ex: 600V, 50A
(6 IGBT's)

Semitop



Ex: 600V, 100A
(6 IGBT's)

71

Gate-Turn-Off (GTO) thyristor

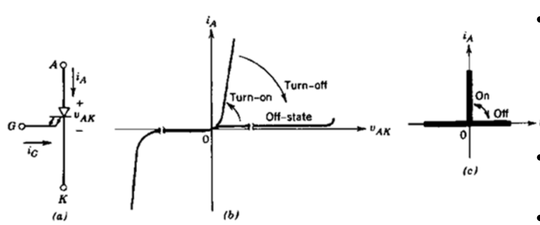
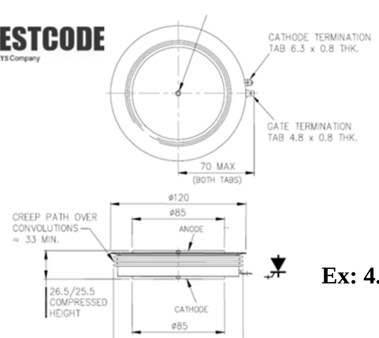


Figure 2-10 A GTO: (a) symbol, (b) i–v characteristics, (c) idealized characteristics.

- Turns on and latches as an SCR but requires a large (I_{AK}/3) negative gate current to turn-off (elaborated gate control circuit);
- Blocks negative voltages but has low switching speeds;
- Still used in ultra high power applications.

press-pack case
(ultra high power)

WESTCODE



Ex: 4.5kV, 4 kA

72

Comparison of controllable switches

Table 2-1 Relative Properties of Controllable Switches

Effective(*) switching

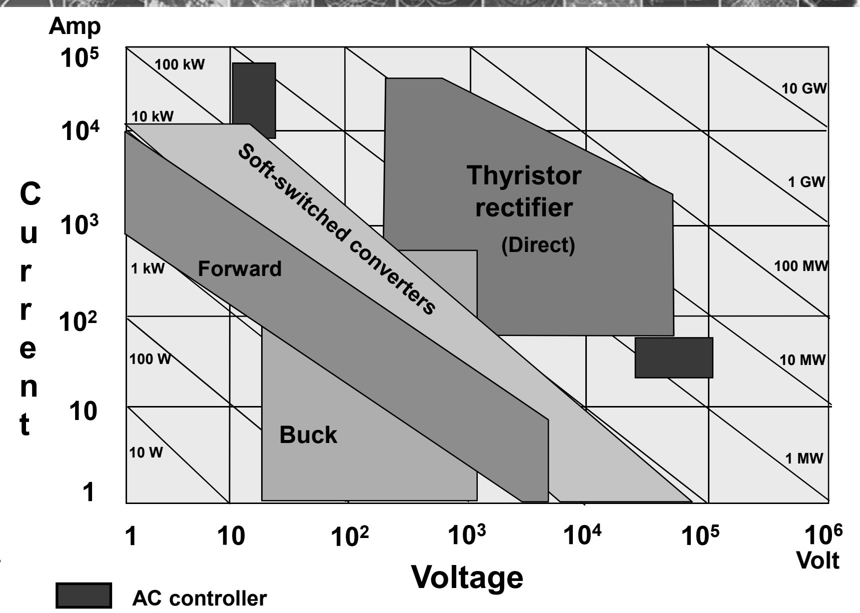
	Device	*Power Capability*	*Switching Speed*
obsolete	~~BJT/MD~~	~~Medium~~	~~Medium~~
Most popular (low power) ⇨	MOSFET	Low (< ~ 15 kW)	Fast (~0.1µs)
	GTO	High (< ~ 10 MW)	Slow (~ 5µs)
Most popular (high power) ⇨	IGBT	Medium (< ~ 3 MW)	Medium (~0.5µs)

(*)
Voltage de-rating: 1.6; Current de-rating: ~1.3
(i.e., power de-rating: 1.6 x 1.3 ≈ 2)

Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

73

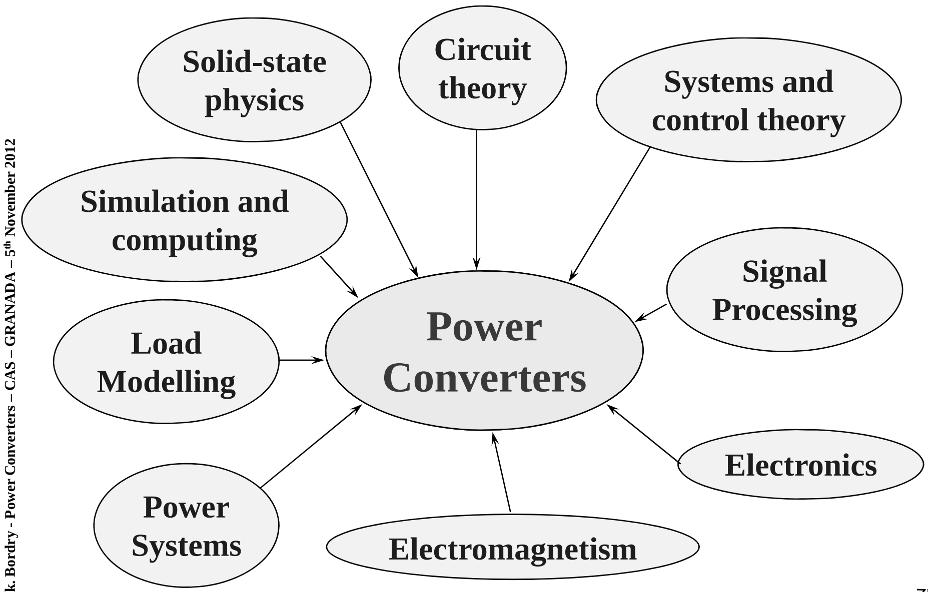
Power converter : Operational domains for accelerators



Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

74

Interdisciplinary nature of power converters



Fk. Bordry - Power Converters – CAS – GRANADA – 5th November 2012

75