



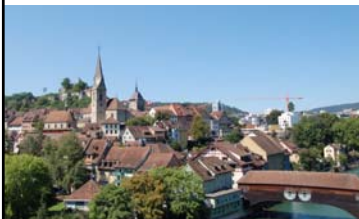
CAS on Power Converters

Definition of Power Converters I&II

...a basic introduction

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CERN

Baden (CH)
8th May 2014



The CERN Accelerator School



Outline

- Power electronic converter definitions
- Power electronics applications
- Principles in power electronics
- Power converter elements and rules
- Main topologies overview
- Galvanic insulation
- Implications of technology limitations
- Power converter design procedure
- Conclusion

in 2 hours...



Power electronic converter definitions

- Different people, different definitions...(majority from F. Bordry)

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! (A former CERN Power Converter Group secretary view)



Power electronic converter definitions

- Different people, different definitions...(majority from F. Bordry)

That which feeds the magnets (a visitor)

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

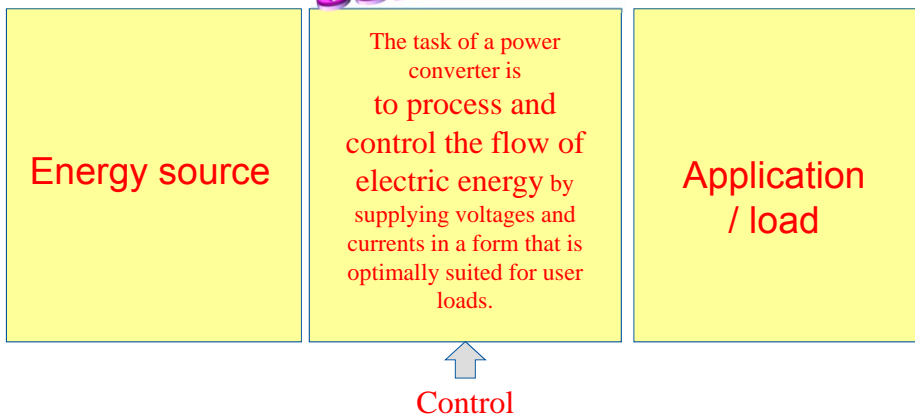
A standard piece of equipment available from industry off-the-shelf (a higher management person, not in in this room !)

An electrical energy amplifier (current Electric Power Converter Group secretary)



Power electronic converter definitions

Power converter



Power electronics applications - general

- Applications in a wide power (P) range. Examples:
 - $P \sim W$: battery-based portable equipment
 - $10W < P < 1kW$: computers & office equipment
 - $1kW < P < 10MW$: variable speed drives (motors & generators)
 - $10MW < P < 1GW$: high power transmission systems (HVDC, UPFC, etc.)



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Power electronics applications - Evolution

From mercury arc rectifier, grid-controlled vacuum-tube rectifier, ignitron ,....



...to solid state electronics (semiconductors)

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)

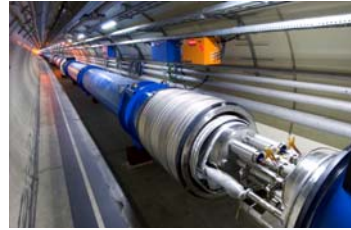
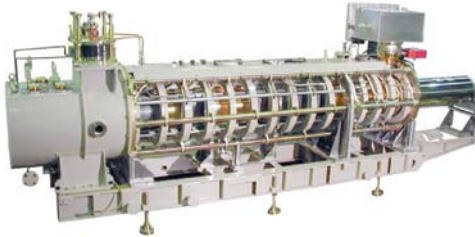


Power electronics applications - Accelerators

- Supply of several accelerator's equipment:

- Normal conducting and superconducting magnets
- Electronic tubes for RF production (klystrons, tetrodes, etc.)
- Particles sources (protons, electrons, ions)
- All auxiliary / standard DC supplies (measurements, control electronics, etc.)

} ~6000 dedicated converters at CERN

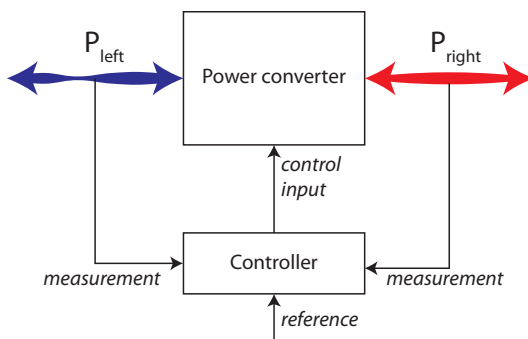


All the energy used to accelerate and guide the particle beams passes through power electronics converters!



Basic principles in power electronics

- Control is most of the time needed (precision), but one could set the reference directly on the control input
- Depending on converter type, power can go in one or both directions
- Low losses = high efficiency η : small size and weight!



- If power flows from left to right

$$\eta = \frac{P_{right}}{P_{left}}$$

- If power flows from right to left

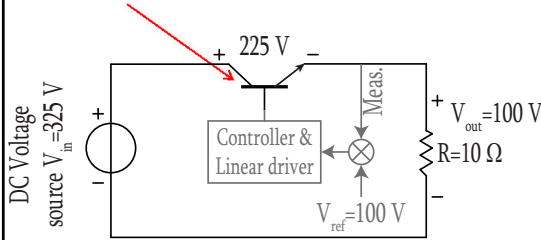
$$\eta = \frac{P_{left}}{P_{right}}$$



Basic principles in power electronics

- Old times: Linear voltage/current regulation for DC-DC conversion
- A step-down voltage regulator example – 325 V in – 100 out – 10A:

Transistor (T) operated in its active region



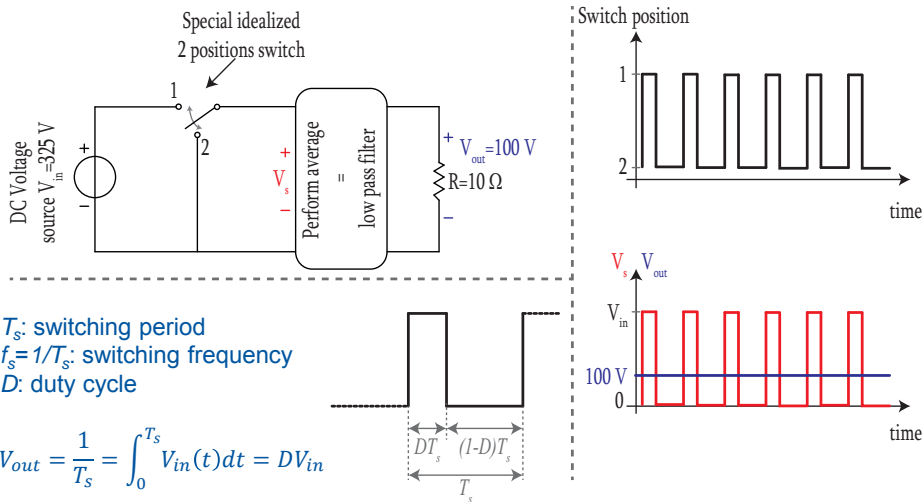
- Analysis:
 $P_{in} = 325 \text{ V} \times 10 \text{ A} = 3.25 \text{ kW}$
 $P_{out} = 100 \text{ V} \times 10 \text{ A} = 1 \text{ kW}$
 $P_T = P_{in} - P_{out} = 2.25 \text{ kW}$
 Efficiency:
 $\eta = \frac{P_{out}}{P_{in}} = \frac{1}{3.25} = 0.3 \rightarrow 30\%$

- Used until 1960s (still used in special applications: audio, high precision, HF, ...)
- Drawbacks: low efficiency – dissipate losses – step-down only – no DC insulation



Basic principles in power electronics

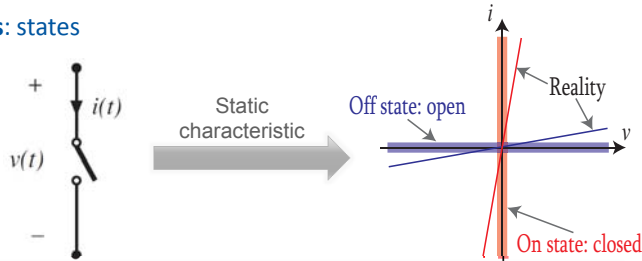
- Modern power converters: switching principle (On – Off states only)



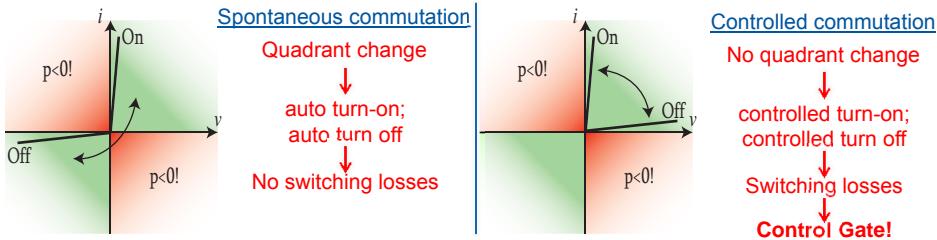
Basic principles in power electronics

- The use of switches: states

Two switch states:
 Closed (On) : $v=0$
 Open (Off) : $i=0$
 In each state $p=vi=0$
 No losses in ideal switch!

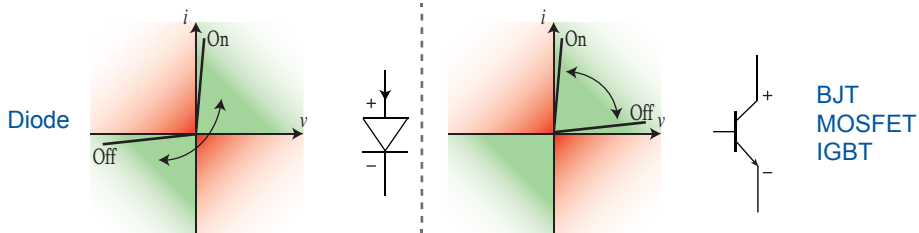


- state change – transition (example of 2 segments switches)

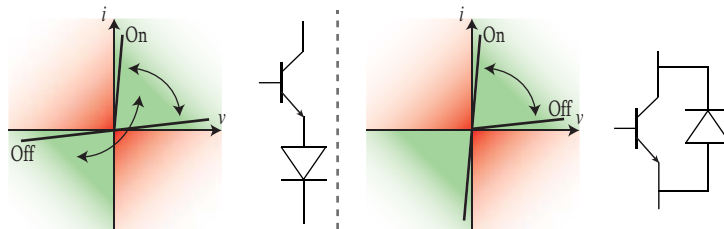


Modern power converter elements - switches

- 2 segments switches

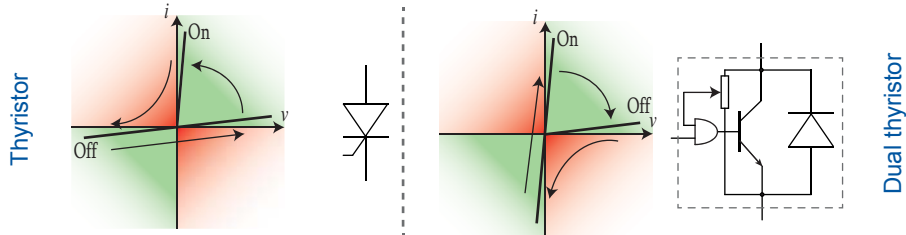


- 3 segments switches

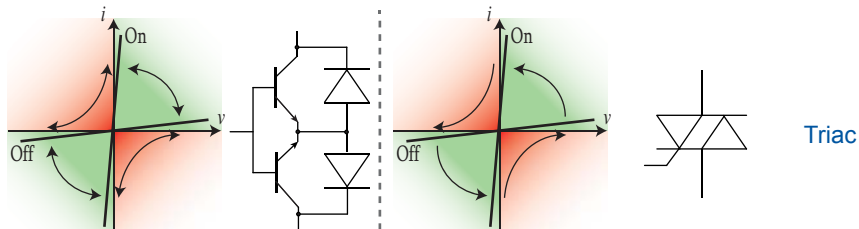


Modern power converter elements - switches

- Some other 3 segments



- 4 segments switches



Modern power converter elements - sources

- Lossless elements are welcomed in power electronics converters:
...if possible avoid resistors or semiconductors operated in their active region!
- Sources definition

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)



A source could be a generator or a receptor!



Modern power converter elements - sources

The principle of operation of a converter is based on the switch mode action of its switches. Commutations of these switches generate very fast current and/or voltage transients so that the transient behaviour of the sources is fundamental.

A source is a voltage source if the voltage across its terminals can't undergo a *discontinuity* due to the *external* circuit variation.

A source is a current source if the current flowing through it can't undergo a *discontinuity* due to the *external* circuit variation.



Modern power converter elements - sources

Instantaneous impedance :
the limit of the impedance $Z(s)$ when the Laplace operator s tends towards infinity.

New definitions:

Voltage Source has a zero instantaneous impedance

Current Source has an infinite instantaneous impedance

Example:


- Capacitor: $Z(s) = 1 / (C.s)$, $\lim_{s \rightarrow \infty} Z(s) = 0 \Rightarrow$ voltage source

- Inductance : $Z(s) = L.s$, $\lim_{s \rightarrow \infty} Z(s) = \infty \Rightarrow$ current source




Modern power converter elements - sources

L





$E_L = \frac{1}{2}LI^2$

I state variable




$di/dt \neq \infty$






“ Current source “

C





$E_c = \frac{1}{2}CV^2$

V state variable




$dV/dt \neq \infty$





“ Voltage source “



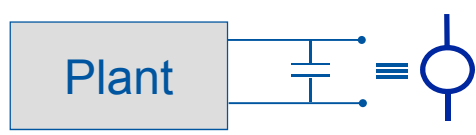
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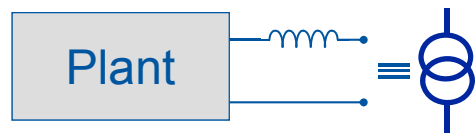
Modern power converter elements - sources

- Modifying / improving source nature

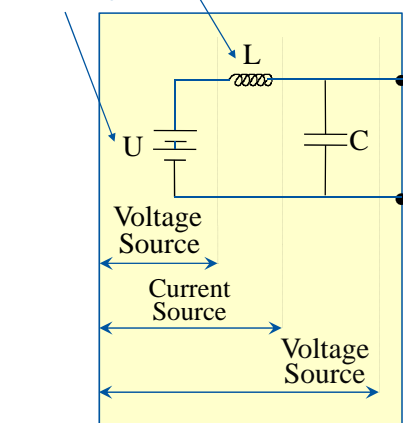
Plant




Plant



Battery **Cables**



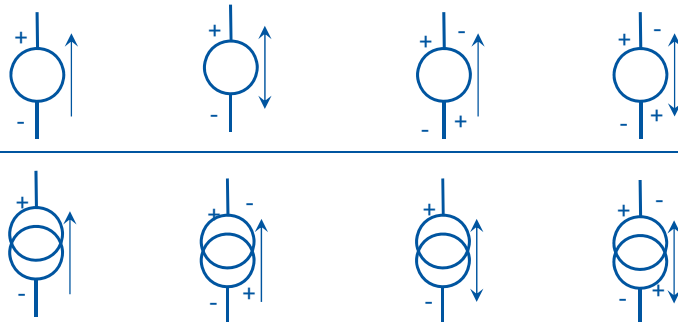


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Modern power converter elements - sources

- There are 8 type of sources



Unidirectional source

voltage : if the voltage, across its terminal, can't change sign

current : if the current, flowing through it, can't reverse

Bidirectional (reversible) source :

voltage : if the voltage, across its terminal, can change sign

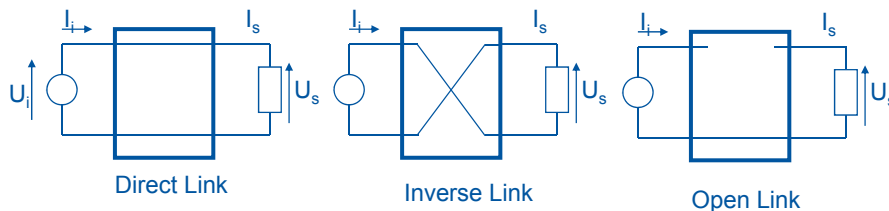
current : if the current, flowing through it, can reverse



Modern power converter – interconnection rules

- In power electronics we switch/commutate sources, that's it!

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.

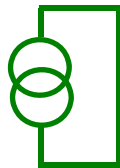


Modern power converter - interconnection rules

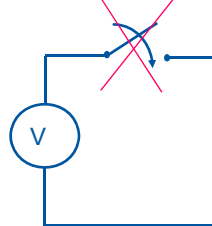
Voltage source



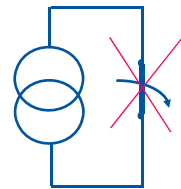
Current source



Turn On impossible

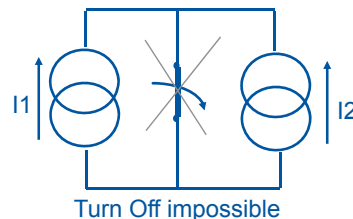
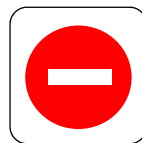
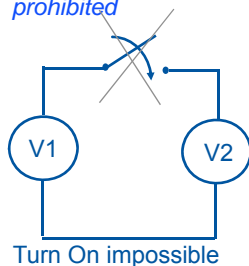


Turn Off impossible



Modern power converter - interconnection rules

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



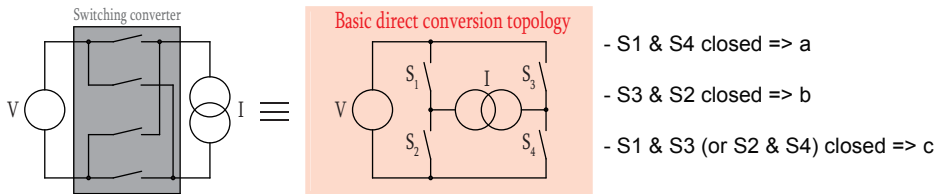
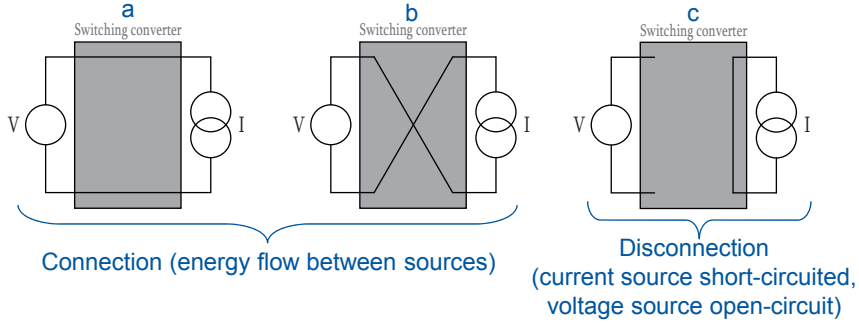
Interconnection between two impeding networks can be modified only if :

- 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.



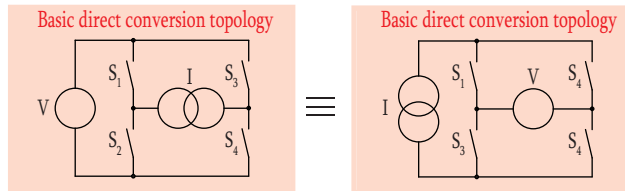
The 3 basic topologies

- Direct conversion: linking sources of different nature



The 3 basic topologies

- Direct conversion basic topologies



- Indirect conversion: linking sources of same nature

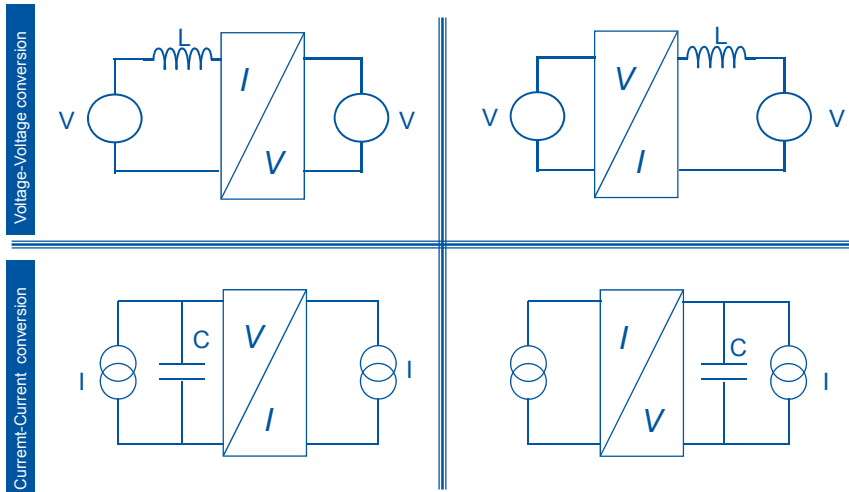
...need intermediate element

- modification of source nature
- use of two direct link structures
- indirect structure



The 3 basic topologies

- Indirect conversion basic topologies



input

Output

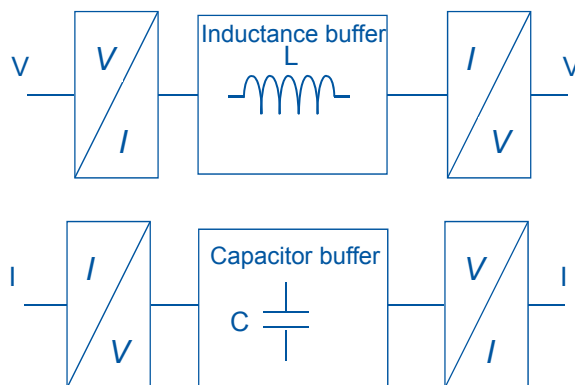
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The 3 basic topologies

- Indirect conversion basic topologies

...using two direct converters



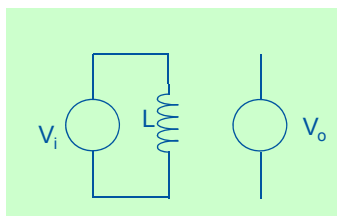
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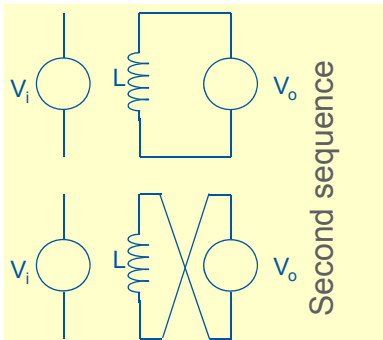
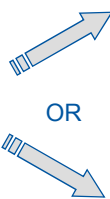
The 3 basic topologies

- indirect conversion basic topologies:

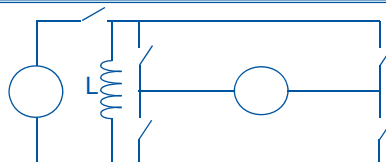
Voltage-Voltage Indirect Converters



First sequence



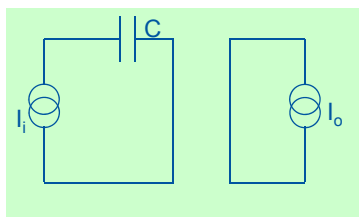
Voltage-Voltage Indirect Converters
basic configuration



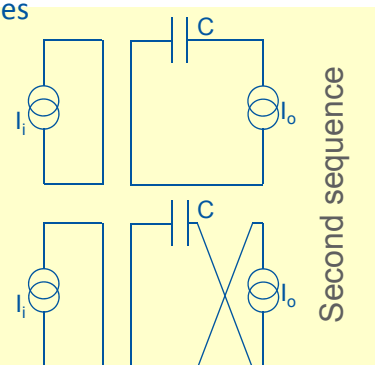
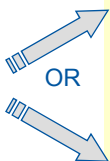
The 3 basic topologies

- indirect conversion basic topologies

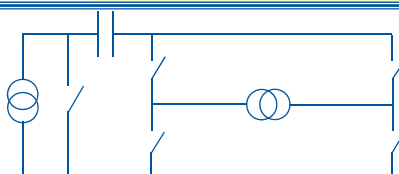
Current-Current Indirect Converters



First sequence



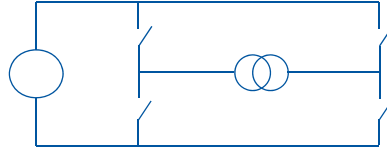
Current-Current Indirect Converters
basic configuration



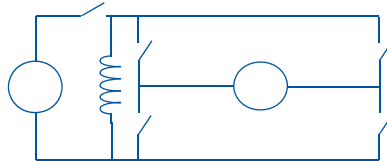
The 3 basic topologies

- Finally:

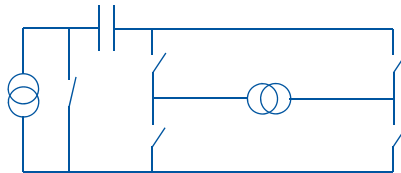
V to I



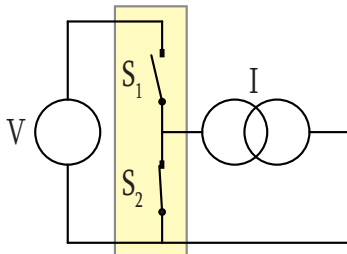
V to V



I to I



Power converter topologies: Elementary commutation cells



Rules (reminder)

- Do not create discontinuity on V & I
- Do not short the voltage source!
- Do not open the current source!

➔ S_1 & S_2 are complementary!

S_1 : On & S_2 : Off, or S_1 : Off & S_2 : On, no other possibilities !

State transition of a switch implies state transition of its complementary switch

The reversibility's of the voltage and current sources determine the static characteristics of the switches.

The switches need to have static characteristics with the same number of current and voltage segments.



Power converter topologies

- Converters main classification

Very used in particles accelerators

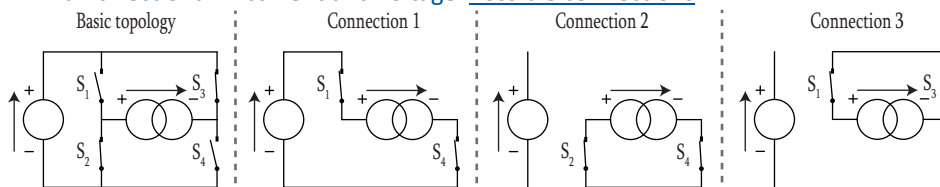
Conversion type	family
DC/DC	Chopper
AC/DC	Rectifier
DC/AC	Inverter
AC/AC	Cyclo- (& matrix) converter
AC/DC/AC	DC-link converter
DC/AC/DC	AC-link converter

Here we concentrate on the red ones...
With a systematic approach!



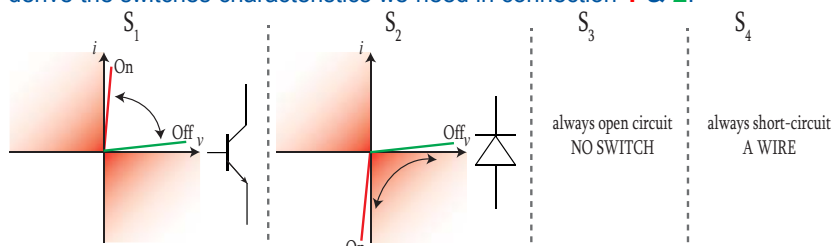
Power converter topologies – DC/DC conversion

- Lets derive the converter between a voltage and a current source, both unidirectional in current and voltage. Possible connections:



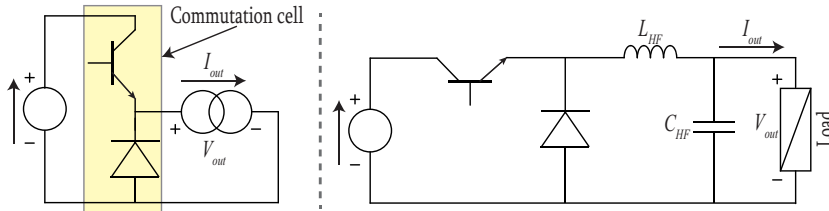
Connection 2 same as connection 3 : just select one, lets take connection 2.

Now derive the switches characteristics we need in connection **1 & 2**:

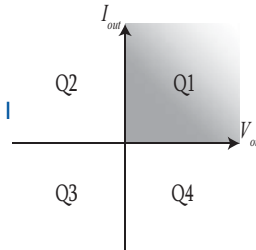


Power converter topologies – DC/DC conversion

- One find what it is called the **Buck converter** (voltage step-down)

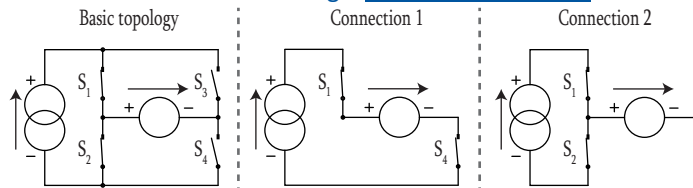


- Current source ensured by L_{HF}
- L_{HF} - C_{HF} filter attenuates switching harmonics
- This is a one quadrant converter – positive output V & I
- The output voltage can be stepped-down only
- Buck converters are part of the so-called chopper family

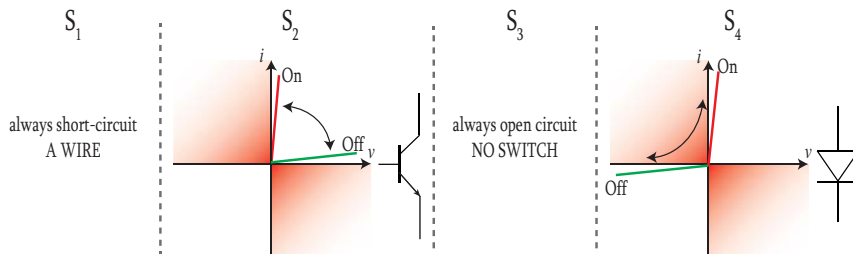


Power converter topologies – DC/DC conversion

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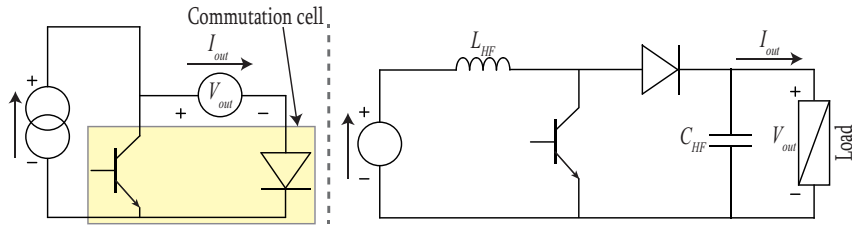


Now derive the switches characteristics we need in connection **1 & 2**:

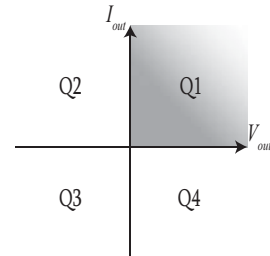


Power converter topologies – DC/DC conversion

- One find what it is called the **Boost converter** (voltage step-up)

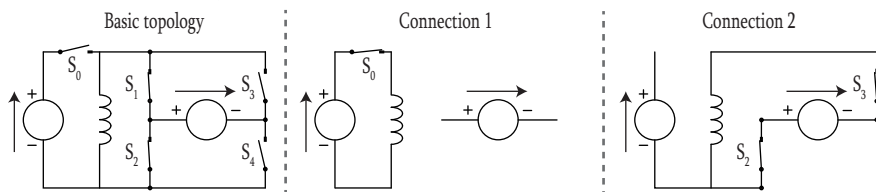


- Current source ensured by L_{HF}
- L_{HF} - C_{HF} filter attenuates switching harmonics
- This is a one quadrant converter – positive output V & I
- The output voltage can be stepped-up only
- Boost converters: chopper family
- Drawback: transistor dimensioned for V_{out}

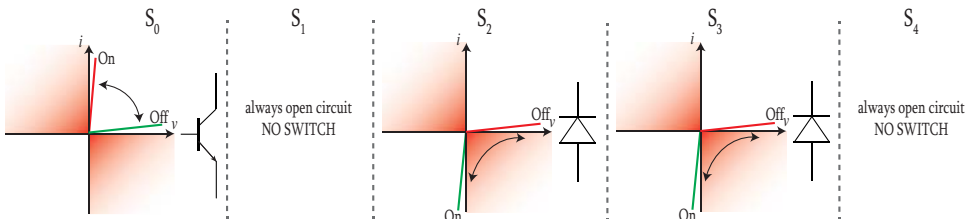


Power converter topologies – DC/DC conversion

- Lets derive the converter between two voltage sources, both unidirectional in current and voltage. Possible connections:

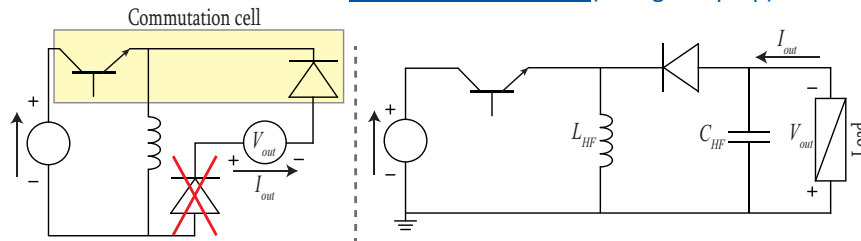


Now derive the switches characteristics we need in connection **1 & 2**:

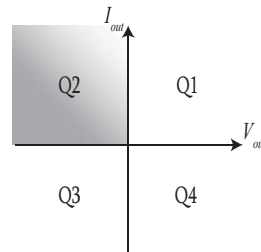


Power converter topologies – DC/DC conversion

- One find what it is called the **Buck-Boost** converter (voltage step-up)



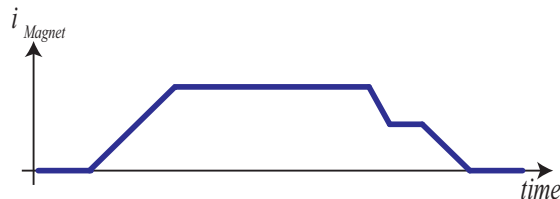
- Current source ensured by L_{HF}
- L_{HF} - C_{HF} filter attenuates switching harmonics
- This is a one quadrant converter – inverted voltage
- The output voltage can be stepped-up or down
- Buck-Boost converters: chopper family
- Drawback: inverted voltage \rightarrow isolated version
- Limitations: Transistor blocking voltage $V_{in}+V_{out}$



Power converter topologies – DC/DC conversion

- Homework: with the same method you find the converter between two current sources, both unidirectional in current and voltage (the “Ćuk” converter)
- **Exercise**: You have to propose the converter topology for the following application:

1. Feed a magnet with the following current shape:

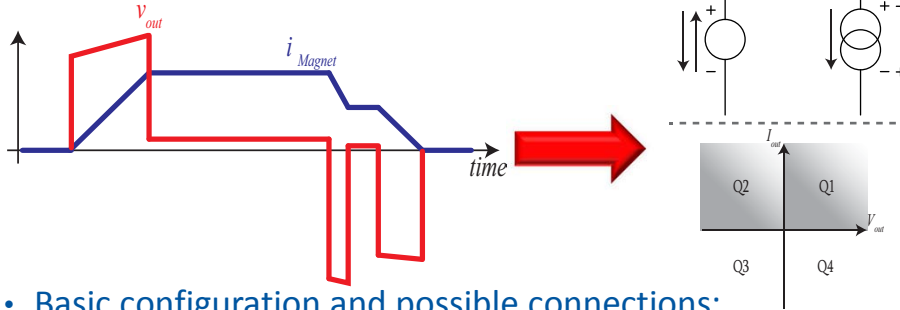


2. We have a DC voltage source which can be bi-directional in current if we add a capacitor in parallel to it...

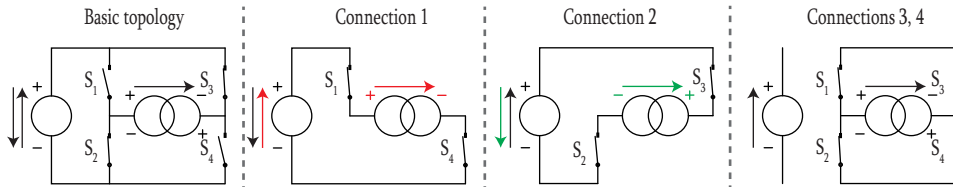


Power converter topologies – DC/DC conversion

- Define the output sources nature:

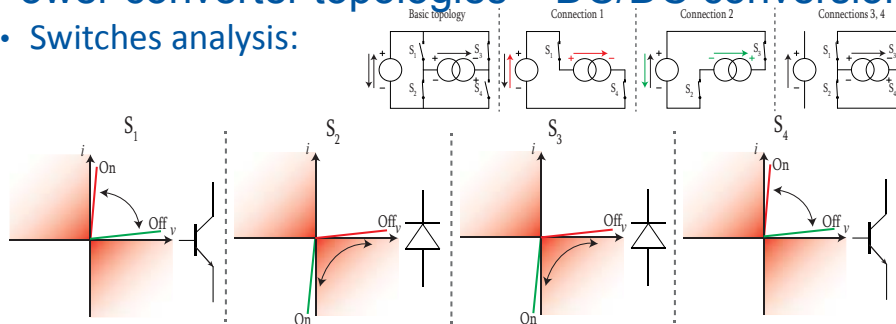


- Basic configuration and possible connections:

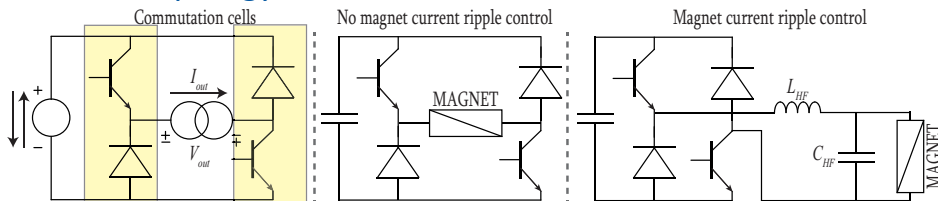


Power converter topologies – DC/DC conversion

- Switches analysis:

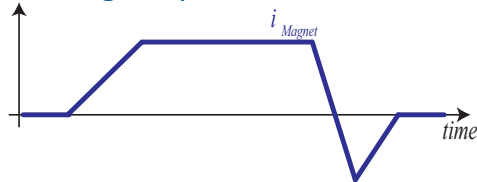


- Final topology:

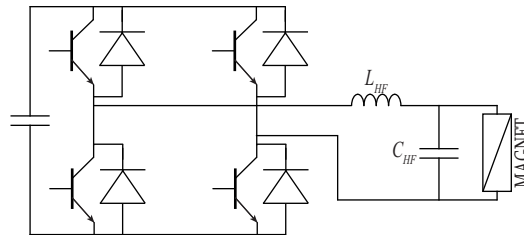


Power converter topologies – DC/DC conversion

- **Homework:** Demonstrate that for supplying a magnet with the following shape:



- You need the following converter structure:



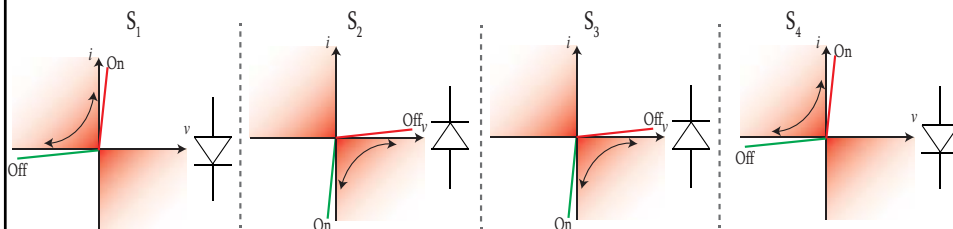
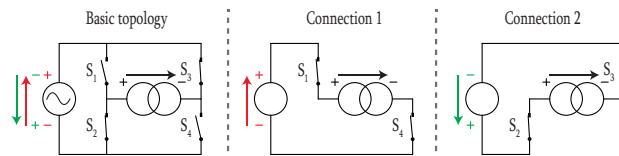
Is this a DC/DC converter only?



Power converter topologies – AC/DC conversion

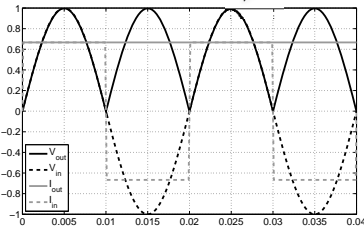
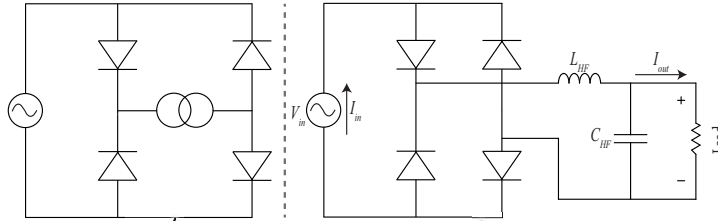
- Line commutated AC/DC converters: full wave rectifiers (single phase)

In full wave rectifiers we use diodes – turn-on and turn-off natural commutation provided by the AC line.



Power converter topologies – AC/DC conversion

- Line commutated AC/DC converters: full wave rectifiers (single phase)



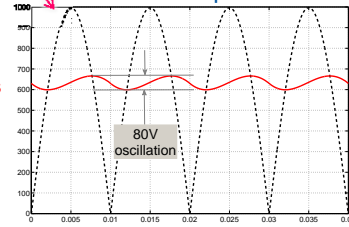
Maximal average output voltage:

$$V_{out,max} = \frac{2}{\pi} \hat{V}_{in}$$

Ripple factor defined as the absolute maximal oscillation over nominal average value (one definition).

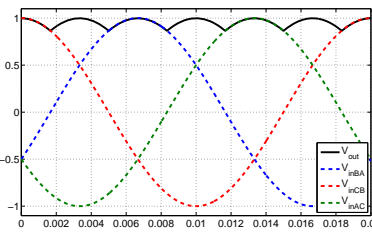
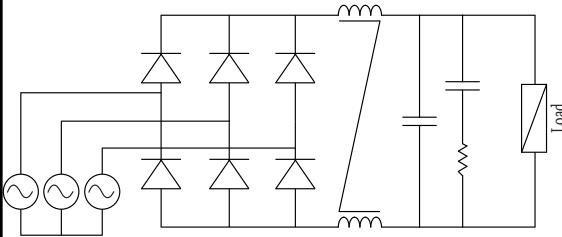
Example on right: $R=80V/636V=12.6\%$

Voltage ripple is attenuated with the low pass filter



Power converter topologies – AC/DC conversion

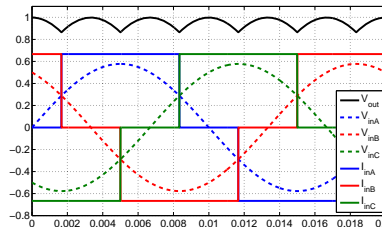
- Line commutated AC/DC converters: full wave rectifiers (three-phase)



Much smaller voltage ripple compared to single phase
Higher maximal average output voltage:

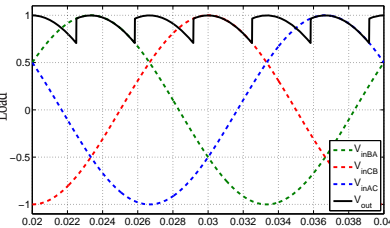
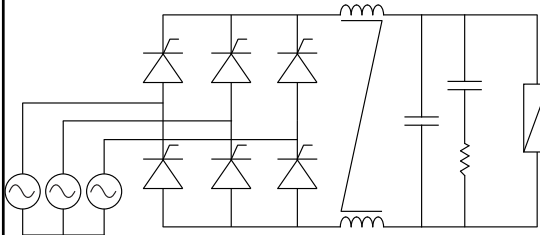
$$V_{out,max} = \frac{3}{\pi} \hat{V}_{in,L-L}$$

As in single phase, fundamental harmonic voltage and current are in phase, $\cos(\phi)=1$ and power factor near unity.



Power converter topologies – AC/DC conversion

- Line commutated AC/DC converters: controlled rectifiers (three-phase)



Can control the bridge output voltage by changing the firing angle α :

$$V_{out} = \frac{3}{\pi} \hat{V}_{in,L-L} \cos(\alpha)$$

Bi-directional output voltage, 2 quadrants converter.

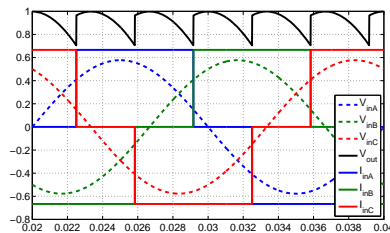
Current is shifted by α (fundamental)

AC side active and reactive power (neglecting harmonics):

$$P = 3 * V_{phase} * I_{line} * \cos(\alpha)$$

$$Q = 3 * V_{phase} * I_{line} * \sin(\alpha)$$

Huge reactive power at low DC voltages...



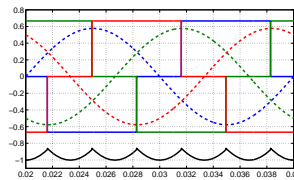
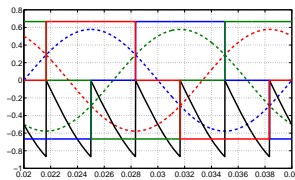
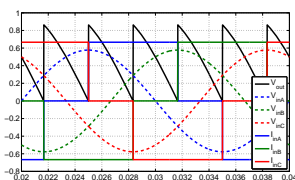
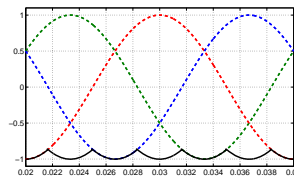
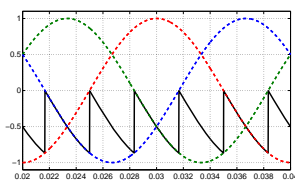
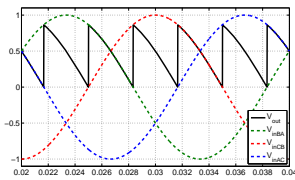
Power converter topologies – AC/DC conversion

- Line commutated AC/DC converters: controlled rectifiers (three-phase)

$\alpha = 60^\circ$

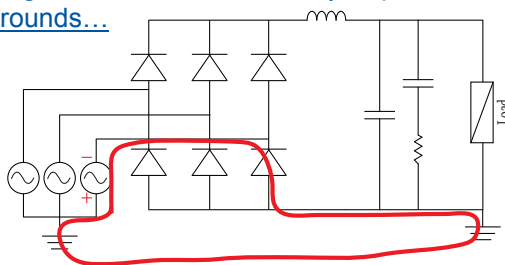
$\alpha = 120^\circ$

$\alpha = 180^\circ$

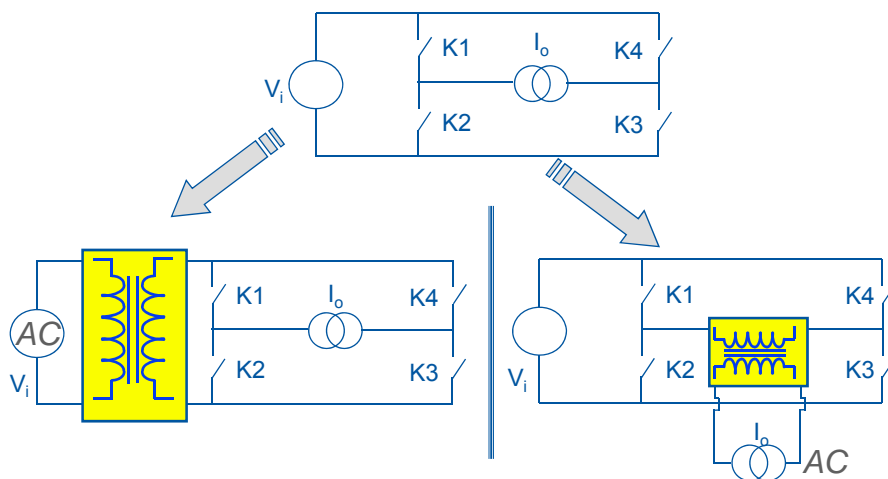


Power converter topologies – isolation

- Ground connections are used to guarantee personnel safety and determine the insulation to ground levels of each active part of the circuit
- Galvanic isolation is used to separate two or more electric circuits with grounds at different potential. It is an effective method of breaking ground loops (EMC). Personnel safety is increased by preventing accidental current from reaching ground through a person's body
- Sometimes galvanic isolation is trivially required to separate the circuit and grid grounds...

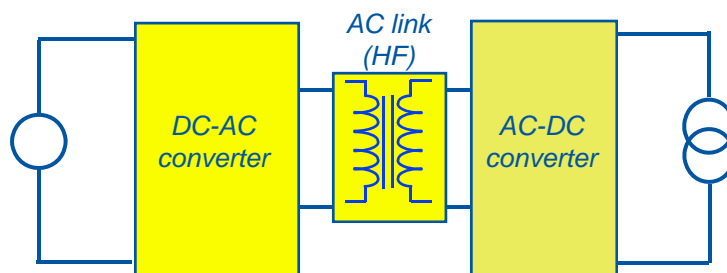


Power converter topologies – isolation



Power converter topologies – isolation

- AC link – voltage or current link

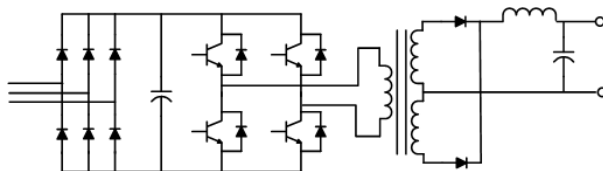
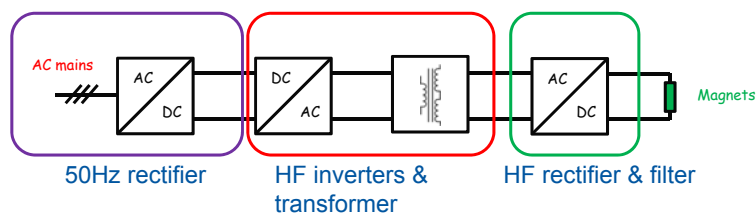


A HF AC link is interesting since the transformer iron core can be drastically reduced. For a constant maximal magnetic induction B , the iron core section is inversely proportional to the AC frequency.



Power converter topologies – isolation

- A typical example...



Awesome! We are done, we are able to perform any electrical conversion with power electronics!



Ok then, let's find the topology of a 1MV, 100kA DC/DC converter...



Implications of technology limitations

- Switches are limited in blocking voltage and conducting current
- At high frequencies inductors behaves also as capacitors, and capacitors behave as inductors...
- Losses are always a nightmare, in switches, inductors, and capacitors.
 - Switching frequencies primarily limited by losses (not only)...not easy to reach very small ripples at high power

Other topologies have been developed, and still are under development, to face the technological limitations of power electronics components.

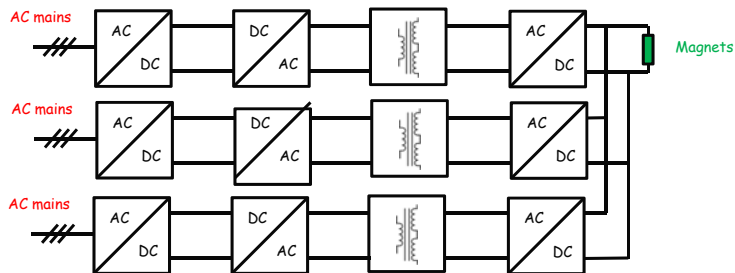
R&D in this domain primarily oriented toward new topologies and optimisation of known ones.



Implications of technology limitations

When the power demand increases above the rating of the power semiconductor, the only solution is to build a topology with parallel or series connection of sub-systems

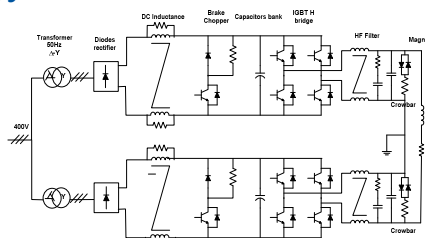
Parallel association of converters



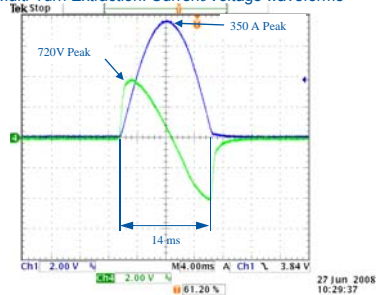
Implications of technology limitations

Series association of converters

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



Multi-Turn Extraction: Current/Voltage waveforms

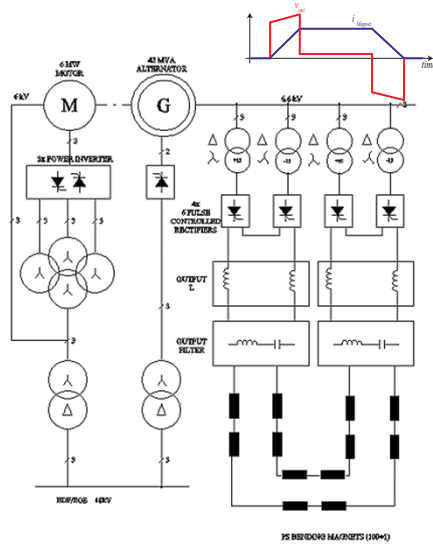


Implications of technology limitations

Series association of converters



CERN - PS



- Generator inertia stores energy to be delivered to magnets
- The motor provides the average active power dissipated by the entire system



Implications of technology limitations

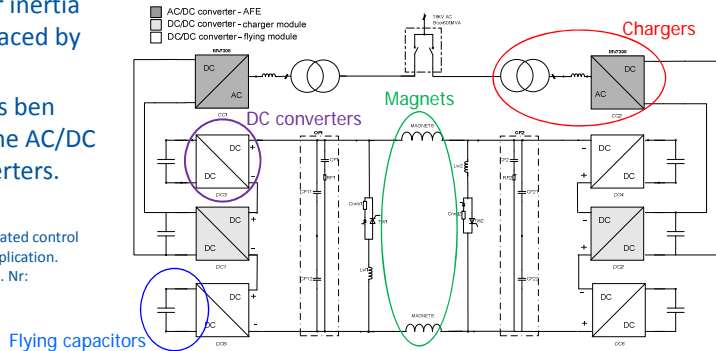
New CERN PS main converter: Series association of converters

Instead the energy to be transferred to the magnets can be stored in capacitors

- DC/DC converters transfer the power from the storage capacitors to the magnets.
- 6 capacitors banks (4 flying) are not connected directly to the mains. They are charged via the magnets
- Only two AC/DC converters (called chargers) are connected to the mains and supply the losses of the system and of the magnets.
- The generator inertia has been replaced by capacitors
- The motor has been replaced by the AC/DC charger converters.

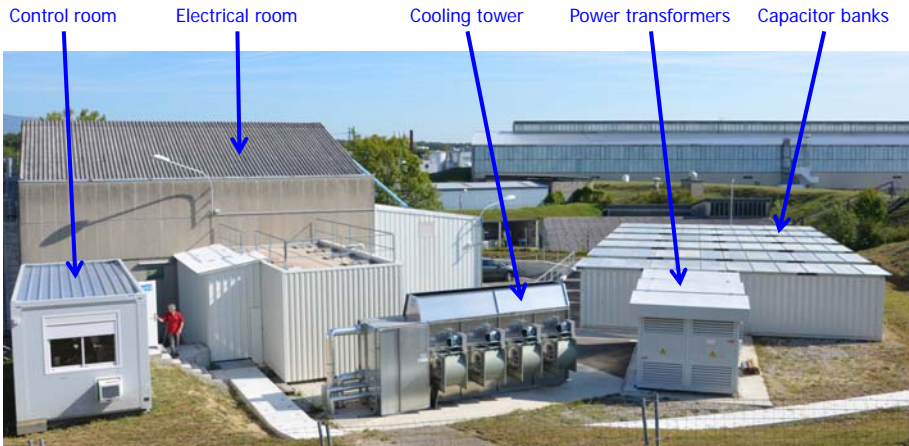
Patent

The global system with dedicated control has been filed as a patent application. European Patent Office, Appl. Nr: 06012385.8 (CERN & EPFL)



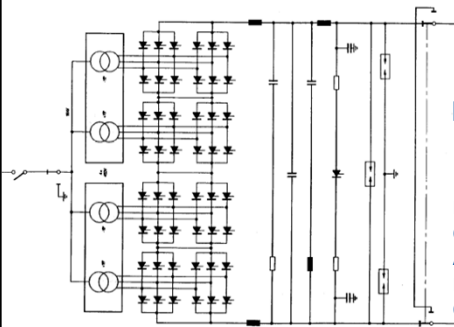
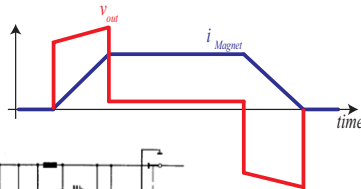
Implications of technology limitations

POPS 6kA/±10kV



Implications of technology limitations

- Series and parallel association of converters: SPS main power converter (6kA)



Remember that for thyristor rectifiers:

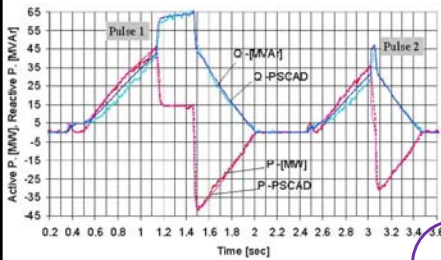
$$V_{out} = \frac{3}{\pi} \hat{V}_{in,L-L} \cos(\alpha)$$

Bi-directional output voltage, 2 quadrants converter.
 Current is shifted by α (fundamental)
 AC side active and reactive power (neglecting harmonics):
 $P = 3 * V_{phase} * I_{line} * \cos(\alpha)$
 $Q = 3 * V_{phase} * I_{line} * \sin(\alpha)$ → Huge reactive power at low DC voltages...



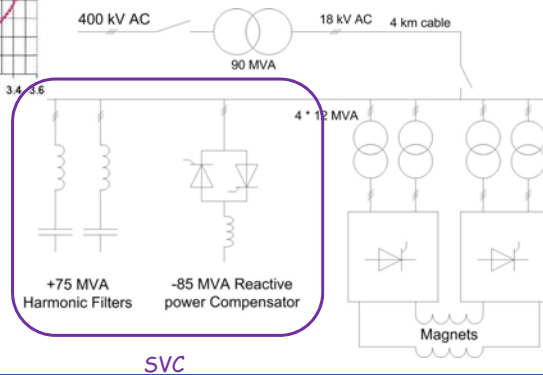
Implications of technology limitations

- Indeed...



Reactive power, especially at current flat-top, is enormous. Must be compensated: SVC!

The Static Var Compensator (SVC) produces reactive power and filters harmonic currents in order to reduce reactive currents.



Implications of technology limitations

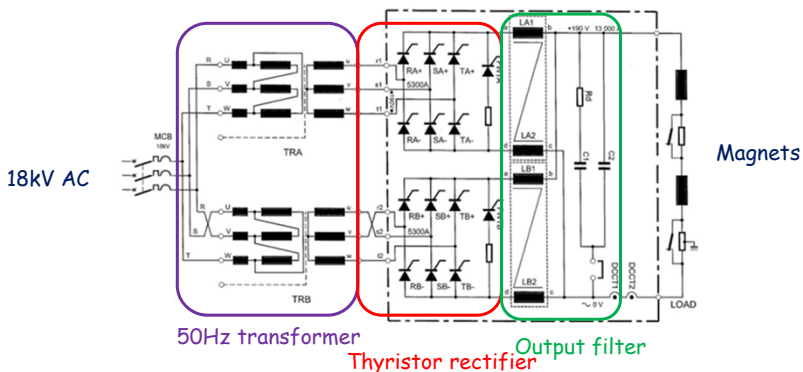
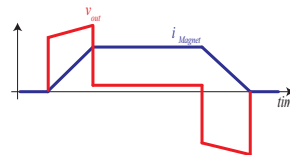
SVC role on the 18kV

- Compensate reactive power (Thyristor Controlled Reactor)
- Clean the network (harmonic filters)
- Stabilize the 18kV network ($>\pm 1\%$)



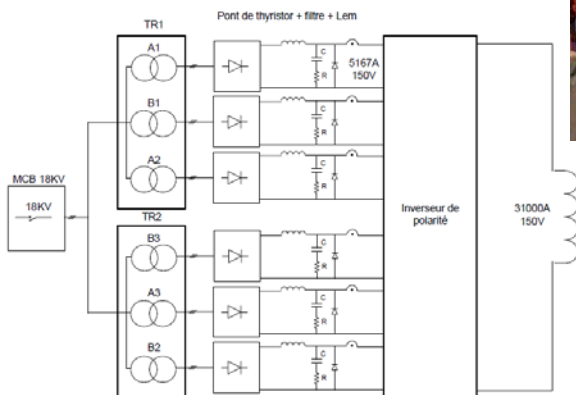
Implications of technology limitations

- parallel association of LHC 13kA / 18V converter



Implications of technology limitations

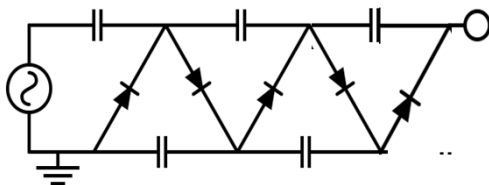
- parallel association: ALICE dipole 31kA/180V



Implications of technology limitations

The « Nobel prize » power converter :
 [Cockroft & Walton] who in 1932 used this Greinacher multiplier (1913) to power their accelerator, performing the first artificial nuclear disintegration in history. In 1951 they won the Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles".

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

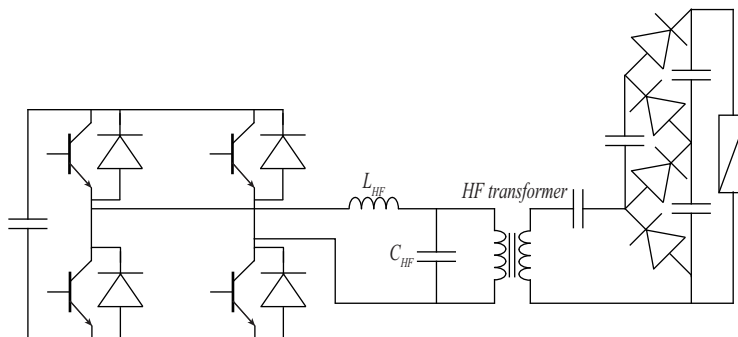


Voltage multiplier : switches...



Implications of technology limitations

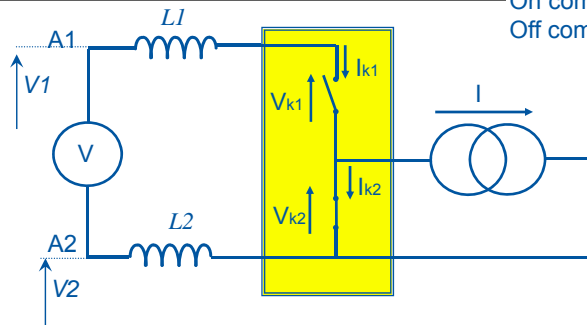
- This multiplier is still used
- HV / low current power supply
- HV capacitor chargers (similar)



Implications of technology limitations

- Commutation cell with parasitic components: real nature of the sources

commutation cell with inductive voltage source



On command : OK

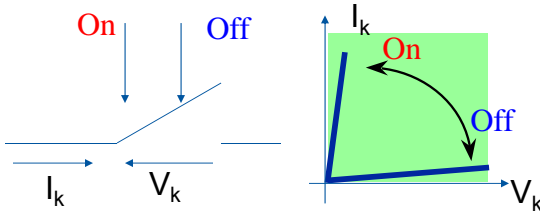
Off command : **overvoltage**



Implications of technology limitations

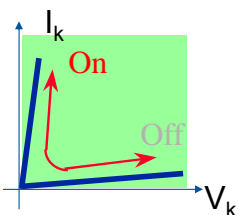
- Hard commutation

(two segments switches)



High commutation losses
=> frequency limitation

To limit the losses :
high dI/dt and/or dV/dt
=> EMI problem



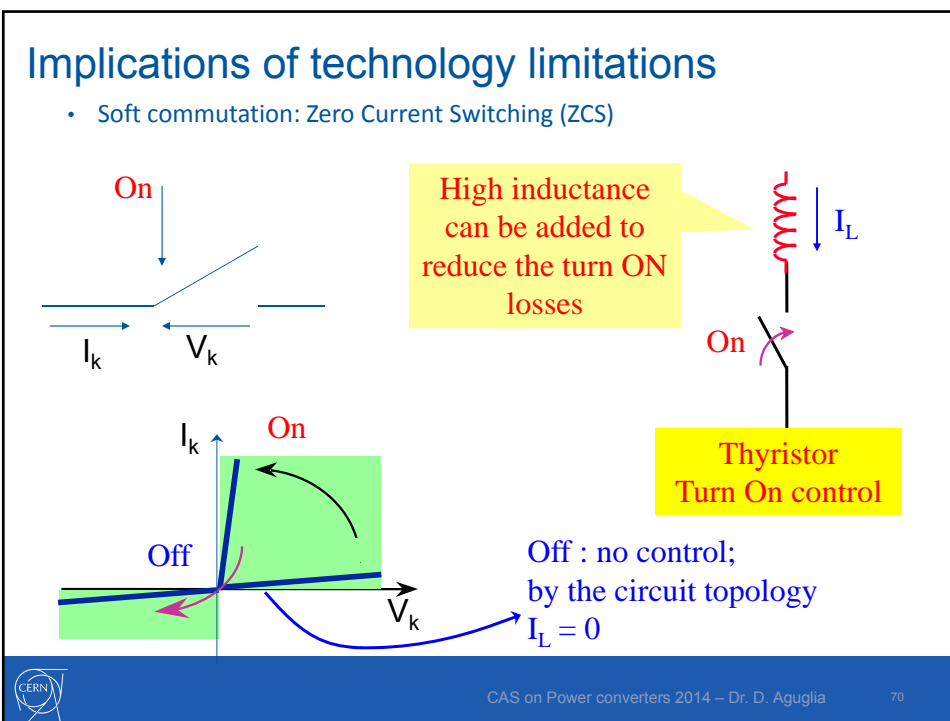
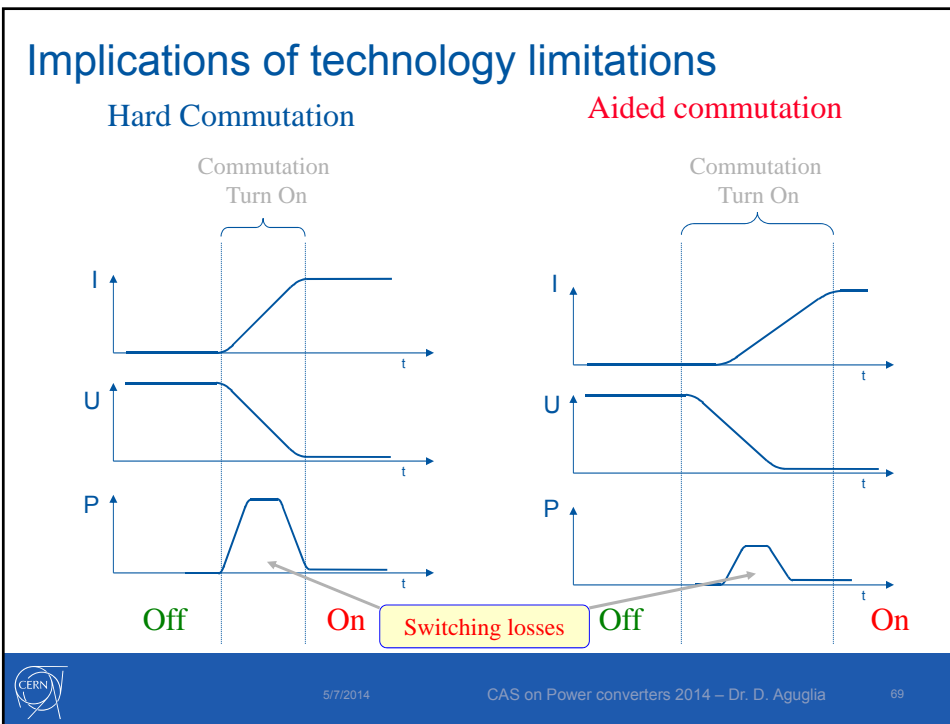
Aided commutation : addition of aided commutation network (snubber)

Series Inductance : turn On

Parallel capacitor : turn Off

Should discharge the snubber before the next commutation ! (losses, extra components,...)

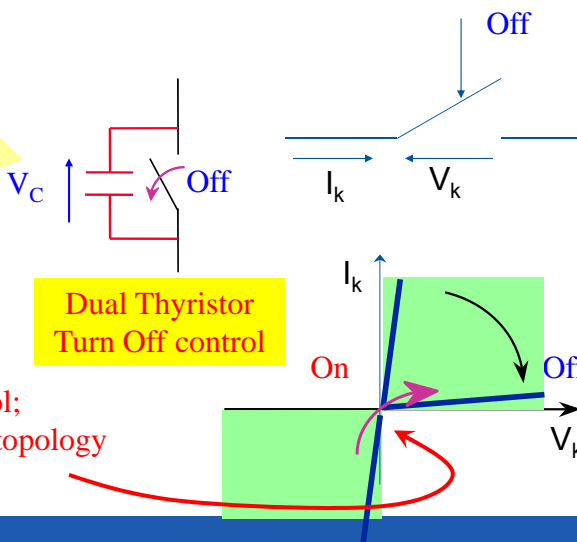




Implications of technology limitations

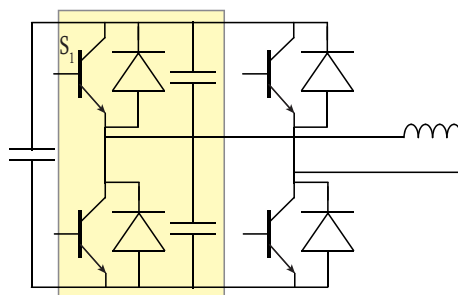
- Soft commutation: Zero Voltage Switching (ZVS)

High capacitance can be added to reduce the turn OFF losses



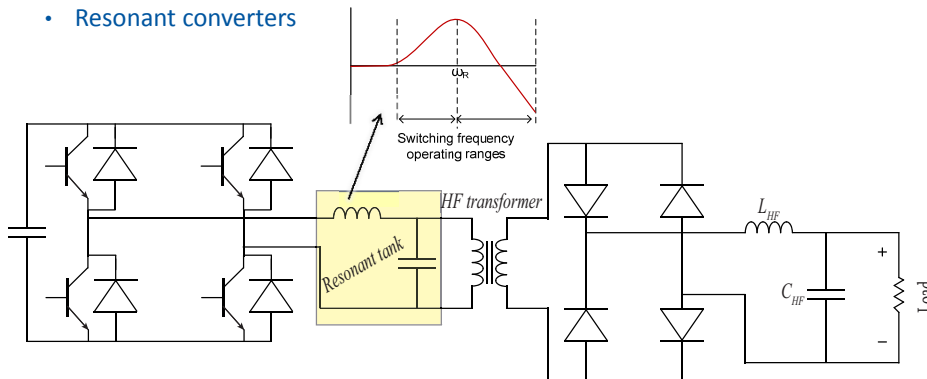
Implications of technology limitations

- Soft commutation: Zero Voltage Switching (ZVS)
- Small capacitors can be add in parallel to the transistor
- When turning off S1, current is deviated into the parallel capacitor which starts charging. Voltage across S1 rises up slower and commutation losses are drastically reduced
- Very good for lowering EMI



Implications of technology limitations

- Resonant converters



- Variable frequency or phase-shift operation
- Tank resonance can be exploited to step-up or step-down voltage
- Load dependency



Power converter design procedure

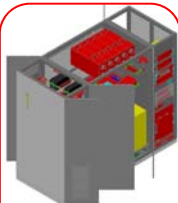
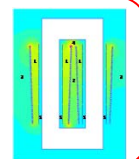
Efficiency, cost, volume, EMI, ..., **specs**

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)

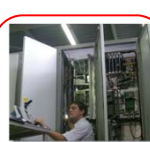
Components design and/or specifications
(analytical or numerical approaches)



3D Mechanical integration & construction



Laboratory tests



On site commissioning

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

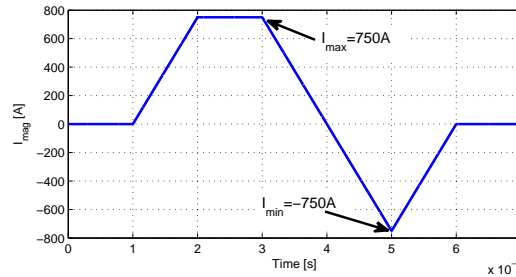
Load examples:

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



Power converter design procedure

- Example: Inverse reasoning from spec...
- We have to feed a magnet: $L_{\text{mag}}=500\mu\text{H}$, $R_{\text{mag}}=3\text{m}\Omega$
- The required current is:



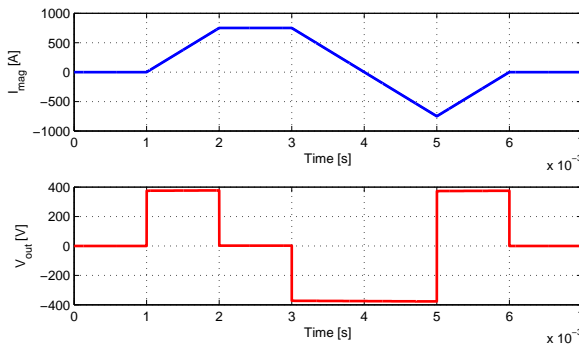
- What kind of converter you need?
- Converter association?
- Switches technology?

Need of some kind of simplified pre-design evaluation

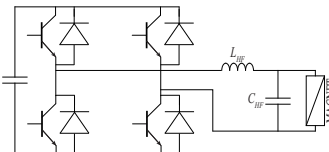


Power converter design procedure

- Example: Inverse reasoning from spec...
- First step is to derive the output voltage of the converter. If required add cables inductance and resistance...



- Ok, something like this:



- Probably only one bridge is enough, current ok...1200V or 1700V IGBT? Well DC bus at 600 to 700V should be ok...then 1200V IGBT (can switch faster!)



Power converter design procedure

- Example: Inverse reasoning from spec...
 - Talking about switching...we forgot to ask what is the maximum allowable current ripple to the magnet guy!
- (Following discussion comes from personal experience, may be different for you!)
- Magnet Guy: I need 10ppm max ripple in the magnetic field!
 - PowerEng: Well, ok, but what is the ripple in current then?
 - Magnet Guy: I need to check, is this spec so important?
 - PowerEng: It is one of the most important! It goes from easy to unfeasible!
 - Magnet Guy: Please make a proposal of what you think is reasonable for you, you know, in the past that magnet was supplied by a nice, ripple-free, capacitor discharge “supply”, now you come with your new stuff and insert harmonics everywhere and our magnet has to filter them...(he is partially right...).
 - PowerEng: I understand...give me a week and will get back to you, cheers!



Power converter design procedure

- Example: Inverse reasoning from spec...
- Ok, ripple can be filtered, but the filter will slow down the dynamics and I don't know if we can follow the current shape precisely...
- Oh no!!!! What's the precision (stability) they want!
- Magnet guy: 1% is fine!
- First hint on ripple: must be lower than 1%! (be careful, in some cases the specification of stability or ripple may be a function of frequency)
- Ok, let's fix the ripple to 0.5%, should be ok.
- How do we evaluate this quickly? Trial & error method? Optimization? No, we didn't follow all courses yet...let's do something terribly simplified!

Assume a sinusoidal current ripple of 5%, then the max voltage ripple to be applied to the magnet is:

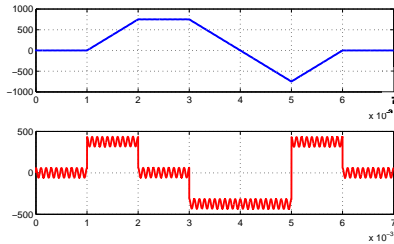
$$V_{out,rip} = i_{max} \times ripple \times 2\pi f_{sw} L_{mag} = 750[A] \times 5\% \times 2\pi f_{sw} 500[\mu H]$$

$$= 0.0118 f_{sw}$$

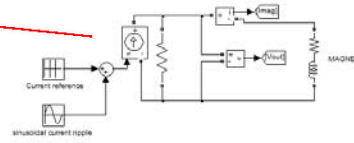


Power converter design procedure

- Example: Inverse reasoning from spec...
- Ok, if $f_{sw}=10\text{kHz}$, $V_{out.rip}=118\text{V}$. Can be easily simulated!



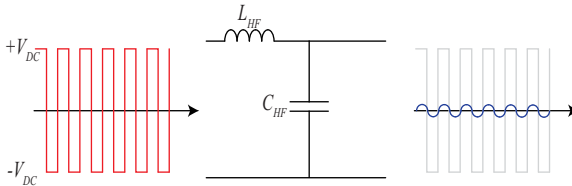
From extremely simple simulation



- How do I select the filter?

At switching frequency f_{sw} , the filter must attenuate at -26dB

$$20 \log_{10} \left(\frac{V_{out,rip}}{4/\pi \cdot 2V_{DC}} \right) \quad 4/\pi \text{ from Fourier}$$



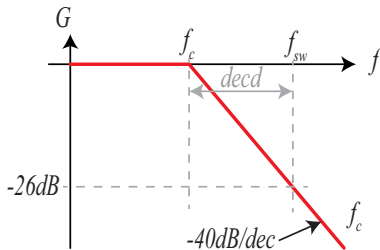
Power converter design procedure

- Example: Inverse reasoning from spec...
- How many decades down will the filter cutting frequency be?

$$dec_d = \frac{26\text{dB}}{40\text{dB}} = 0.65 \text{ decades}$$

- Where is this frequency?

$$f_c = f_{sw} \times 10^{-dec_d} = 2.24 \text{ kHz}$$

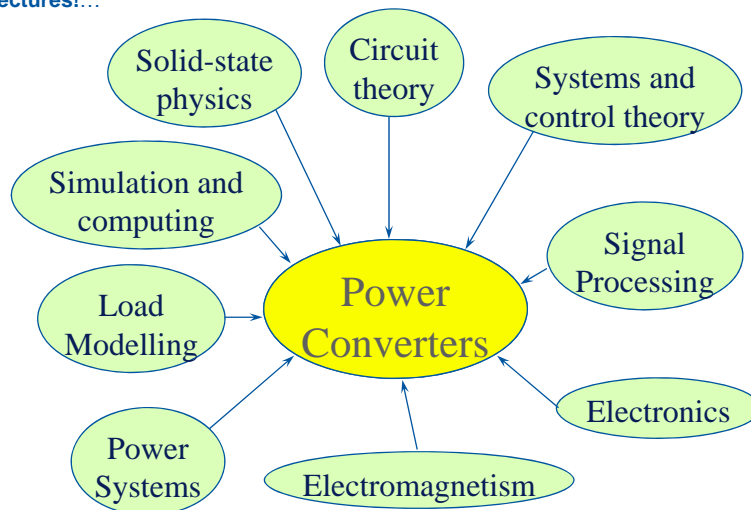


Enough open-loop bandwidth?
 ...probably not, what actions are required? Increase f_{sw} ? Interleave then? Increase filter order? Ask for a more precise spec to magnet guy?...live discussion...



Conclusion

- multi-domain and integrated approach - which justifies the importance of next lectures!...



Thank you for your attention!