Power converters
Definitions and classifications
Converter topologies

Frédérick BORDRY
CERN

"Introduction to Accelerator Physics"
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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

- Conclusions

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)
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 !)
"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?
DC Power: 4 MW

[40A, 100 kV,] klystron power converter

DC operation
## Pulsed klystron modulators for LINAC 4

### Specification

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<td>$1/T_{rep}$</td>
<td>2</td>
<td>Hz</td>
</tr>
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</table>

### Peak power: 5.5MW

### Average power: 20kW
Magnet: \( L = 7 \, \text{H} \); \( R = 30 \, \text{m} \Omega \) (60m of 35 mm²)

\[ T = \frac{L}{R} = 300 \, \text{s} \Rightarrow f_{OL_B} \approx 0.5 \, \text{mHz} \]

\[ U_{\text{static}} = R.I = 1.8 \, \text{V} \]

6 V for the \( dl/dt \) with \( L = 7 \, \text{H} \)

\( dl/dt_{\text{max}} \approx 1 \, \text{A/s} \) OK

Small signal: \( f_{CL_B} \approx 1 \, \text{Hz} \): \( \Delta I = 0.1 \, \text{A} = 0.15 \% \, I_{\text{max}} \)

“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} \approx 50 \, \text{Hz} \) (\( \Delta I = 1\% \): \( U_{\text{max}} = 2400 \, \text{V} \) ????)

\( U_{\text{max}} = 8 \, \text{V} \Rightarrow \Delta I = 30 \, \text{ppm} \, I_{\text{max}} \) at 50 Hz
"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 ,....
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.

50 or 60 Hz; AC

Control

DC current

Energy source

Applications

Traction and auxiliary

Domestic Appliance

Medical applications

Industrial applications, Welding, Induction Heating, ....
Power Converter

Topologies

Electrical energy transfer

Power Converter Design

- performance
- efficiency
- reliability (MTBF), reparability (MTTR),
- effect on environment (EMI, noise,...)
- low cost
Source definition: any element able to impose a voltage or a current, independently of, respectively, the current flowing through, or the voltage imposed at its terminals.

A source could be a generator or a receptor.

Two types of sources:

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

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

Voltage source

Current source

Turn On impossible

Turn Off impossible
Commutation 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.
Active components used as switches to create a succession of link and no link between sources to assure an energy transfer between these sources with high efficiency.
Direct link configuration: Direct voltage-current converters

**Connexion**
(energy flow between sources)

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

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

- Transistors
  - MOSFETs
  - Darlingtons
  - IGBTs

- Thyristors
  - Line commutated
  - Fast
  - Bi-directional
  - Pulse

- Diodes
  - Fast
  - Line commutated
  - Avalanche

Turn-off Devices
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)

From 1985
High frequency power semiconductors: MosFet, IGBTs, GTOs, IGCTs,…..

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

Link between frequency of the electrical network 50 Hz (60 Hz)
Effective(*) switching capabilities

(*)
Voltage de-rating: 1.6;
Current de-rating: ~1.3;
(i.e., power de-rating: $1.6 \times 1.3 \approx 2$)
Power Converter for magnets

AC
3 phase mains (50 or 60 Hz)

Voltage source

Control

DC
magnet, solenoid,…

Current source

Voltage source

Load

Current source

Power Converter

Topologies

Achieving high performance: COMPROMISE
Operating Modes

1 Quadrant mode

2 Quadrants mode

4 Quadrants mode
General power converter topologies
Direct Converters: Rectifiers

- AC Voltage
- DC Current

"Thyristors" + -

Diagram showing circuit components and waveforms.
Main power converters
12 x [6kA, 2 kV]
Two Quadrant Phase Controlled Rectifiers
for high current SC magnets

3 Phase 50/60 Hz Supply

+15°

-15°

LHC main bending power converters
[13 kA, 190 V]
Direct Converters: Rectifiers

AC Voltage

Rectifiers

"AC" Current

Filters

Fk

Direct Converters: Phase Controlled Rectifiers

😊 very high power capability
😊 moderate prices and competitive market
😊 simple structure, well understood (but care needed with high currents)

😊 three phase transformer operates at low frequency (50 or 60 Hz)
😊 variable power factor from 0 to 0.8
😊 harmonic content on input current
😊 response time is large (ms)
😊 current ripple is large (passive or active filters)

passive (active) filters operating at low frequency

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

Application:
- very high currents with low voltages
- (very high voltages with low currents)
Direct Converters: AC link (AC line controller)

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)

DC
[100 kV, 40A] klystron power converter

DC operation
General power converter topologies

![Diagram of power converter topologies]

- **Rectifier**
  - Voltage Source
  - Current Source
  - Voltage Source

- **AC Link**
  - CV1
  - CV2

- **DC Link**
  - CV1
  - CV2

- Filters
  - Current Source
Galvanic isolation at AC input source (50Hz transformer)

- 50 Hz transformer
- Optimal voltage output
- Galvanic isolation

Diode bridge

6 or 12 pulses

PWM Converter

Hard switching

CV1

CV2

Magnet
New PS Auxiliary Power Converters

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

Multi-Turn Extraction: Current/Voltage waveforms

Current Loop Bandwidth ≈ 1kHz
Indirect AC-DC-AC-DC converter

Three cascade power conversion stages:

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

HF transformer to provide the galvanic isolation
LHC Switch-Mode Power Converters

AC 50 Hz  DC  AC 20 - 100 kHz  DC  Passive high-current Output stage

CV1  CV2  CV3  Magnet

Voltage loop:
bandwidth few kHz

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

- light weight, reduced volume (HF transformers and filters)
- good power factor (0.95)
- high bandwidth and good response time
- Soft commutation gives low losses and low electrical noise
- small residual current ripple at output
- More complex structure, less well understood, limited number of manufacturers
LHC: 1-quadrant converter: modular approach

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

MTBF and MTTR optimization
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;

Direct Energy transfer from mains is not possible:
Intermediate storage of energy
Peak power: could be > MW (average power kW)
Block schematic of a fast pulsed converter
High current, high voltage discharge capacitor power converters

CNGS horn and reflector power converters

Charging Unit
10kV - 20A

Thyristors Bridge

Diodes Bridge

Start Charging
Stop Charging

Discharge Circuit 1

Capa
Thyristors Discharge

Pulse 1
Delay 50ms
Pulse 2

Capa
Thyristors Discharge

Discharge Circuit 2

Polarity Changer Earthing

Power Cables (~1000m)

Experimental Area

150 kA for the horn
180 kA for the reflector

CNGS cycles
Pulsed klystron modulators for LINAC 4

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Peak power: 5.5MW
Average power: 20kW
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Test phase: Water cooled dummy loads 2.5T each!
Load characteristics are vital.

Transfer function is a must!
Example: LHC power converter control

Digital (or analogue)
Current loop

Voltage loop

I

Iref

ε_I

Reg.

DAC

G(s)

ε_V

F(s)

V

Vref

B

I measured
Power converter: Performance requirements

Overshoot
Bandwidth

I_{\text{ref}} \rightarrow I \rightarrow B \rightarrow \text{Imeas}

Accuracy  Reproducibility  Stability  Resolution
### Glossary

#### Precision

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

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

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

Accuracy, reproducibility and stability are defined for a given period.

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

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

$\begin{align*}
I^*_{\text{ref}} & \pm \Delta I^*_{\text{ref}} \\
I^*_{\text{meas.}} & \pm \Delta I^*
\end{align*}$

Smallest increment that can be induced or discerned.
Results of Resolution Test with the LHC Prototype Digital Controller

$I_0 = 1019.9$ Amps

![Graph showing current offset in milliamps and current offset in ppm of 20 kA over time in seconds. The graph compares reference and measured values.](chart.png)
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, ...)

\[ V = R \cdot I + L \cdot \frac{dI}{dt} \]
\[ \Rightarrow H(s) = \frac{1}{(L/R \cdot s + 1)} \]
"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 (dl/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

Load specs
(L, R, C values, precision, ...)
Load examples:
- Magnet (high current)
- Klystron (High Voltage)
- Particles source (HV)
- RF equipment (HV)

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

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
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
Energy conversion: transfer of energy between two sources

**Introductive example**

Transfer of energy between
- DC voltage source $U_i$
- DC source (nature is not defined): $U_o$, $I_o$
Linear solution

\[ U_i = 24\,\text{V} \; ; \; U_o = 10\,\text{V} \; \text{and} \; I_o = 600\,\text{A} \]

\[ P_o = U_o \cdot I_o = 10 \cdot 600 = 6'000\,\text{W} \]

\[ P_T \text{ (power dissipated by the switch)} = U_T \cdot I_T = (U_i - U_o) \cdot I_o = (24 - 10) \cdot 600 = 8'400\,\text{W} \]

Converter efficiency \( = \frac{P_o}{P_T + P_o} = 42\% \) !!!!!

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**

\[ \begin{align*}
    & U_T \approx 0 \text{ if } I_T \neq 0 \\
    & I_T = 0 \text{ if } U_T \neq 0
\end{align*} \]

\[ P_T \approx 0 \text{ (if power switches are ideal)} \]

Linear mode

\[ \text{x} \]

\[ \text{switch mode} \]

(power switches either saturated or blocked)
Power Converter topology synthesis: the problem

The interconnection of sources by switches

Fundamental rules and source natures

Power converter topologies

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)
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

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

**Diode Symbol**

**Diode Characteristic**

**Idealized Characteristic**

---

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

Ex: 6 kV\(_{pk}\), 3 kA\(_{av}\)

---

**Modules case (medium power)**

Ex: 1.8 kV\(_{pk}\), 80 A\(_{av}\)

---

**Other cases (low power)**

**SOT-227 Minibloc case**

Ex: 1000 V\(_{pk}\), 2x30 A\(_{av}\)

**DO-203 Stud case**

Ex: 800 V\(_{pk}\), 110 A\(_{av}\)

**TO-220 case**

Ex: 600 V\(_{pk}\), 30 A\(_{av}\)
Thyristor (Silicon Controlled Rectifier - SCR)

3 terminals device.

3 main operating regions.

- 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)

Press-pack: 4.8kV pk, 3.2 kA av

**modules case**
(medium power)

 Modules: 1.8 kV pk, 500A av

**Other cases**
(low power)

- **TO-93 case**
  - Ex: 1200V pk, 325A av

- **TO-208 Stud case**
  - Ex: 800V pk, 30A av

- **TO-220 case**
  - Ex: 800V 64 pk, 20A av
Controllable switches

- Used in forced-commutated converters \( f_{sw} > 60 \text{ Hz} \)
- 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 is On.

\[ i_T \quad + \quad v_T \quad - \]

Generic controllable switch
MOSFET

- 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.

**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
Insulated Gate Bipolar Transistor (IGBT)

- 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)  
Ex: 4.5kV, 2.4kA

**modules case** (medium power)  
Ex: 1.7kV, 3.6kA

**Other cases** (low power)

- **Semix**  
  Ex: 1200V, 400A  
  (6 IGBT’s)

- **Mini Skiip**  
  Ex: 600V, 50A  
  (6 IGBT’s)

- **Semitop**  
  Ex: 600V, 100A  
  (6 IGBT’s)
Gate-Turn-Off (GTO) thyristor

- 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.

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

*press-pack case (ultra high power)*

Ex: 4.5kV, 4 kA
Comparison of controllable switches

Table 2-1 Relative Properties of Controllable Switches

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Capability</th>
<th>Effective(*) switching</th>
<th>Switching Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT/MD</td>
<td>Medium</td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Low (&lt; ~ 15 kW)</td>
<td>Fast (~0.1µs)</td>
<td></td>
</tr>
<tr>
<td>GTO</td>
<td>High (&lt; ~ 10 MW)</td>
<td>Slow (~ 5µs)</td>
<td></td>
</tr>
<tr>
<td>IGBT</td>
<td>Medium (&lt; ~ 3 MW)</td>
<td>Medium (~0.5µs)</td>
<td></td>
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(*)
Voltage de-rating: 1.6; Current de-rating: ~1.3
(i.e., power de-rating: 1.6 x 1.3 ≈ 2)
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/m³ & W/kg
- Converter Control Bandwidth: Filter Time constants
Basic Dimensional Analysis of Reactive Components

Transformer Apparent Power (VA)

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

Transformer Losses (W)

- MagLosses \( \propto B^2 \cdot [L]^3 \)
- CopperLosses \( \propto J^2 \cdot [L]^3 \)

Transformer Temperature Rise

\[ \text{TempRise} = \frac{\text{Losses}}{h \cdot S_{ext}} \propto [L] \]

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

\[ S (VA) \propto f \cdot [L]^3 \propto f \cdot \text{Volume} \]

Inductor Stored Magnetic Energy (J)

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

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

\[ W_{mag} (J) \propto [L]^3 \propto \text{Volume} \]
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 Reactive Components

#### Capacitor Voltage Filter C

- \( Volume \propto \frac{V_o.I}{f.\Delta V_{ppm}} \)

#### Inductor Current Filter L

- \( Volume \propto \frac{V.I_o}{f.\Delta I_{ppm}} \)
Reactive Components of Power Converters

Trade-off on dynamic performance

Main Time Constant of LC Filter

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

Main Design Trade off

- Frequency
- Volume
- Mass
- Ripple ppm
- Dynamics \( \tau \) (s)
COMPATIBILITY : Emission - Immunity

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
Interdisciplinary nature of power converters

- Solid-state physics
- Circuit theory
- Systems and control theory
- Simulation and computing
- Signal Processing
- Electronics
- Power Systems
- Electromagnetism
- Load Modelling