Power converters
Definitions and classifications
Converter topologies

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"Introduction to Accelerator Physics"
19th September – 1st October, 2010
Варна - Varna - Bulgaria
- Power converter definition

- Power converter topologies: *commutation*
  Sources, switches, … semiconductors

- Special case for magnet powering
  (Voltage source - Current source)

- Pulsed power converters

- Control and precision

- Conclusion

In 1 hour ????
Schematic of Cockcroft and Walton’s voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.

Voltage multiplier: switches...
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.

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

Ровер Цонвертер  
(written in Cyrillic)
"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
Pulsed Klystron modulators for LINAC’s (ex. Linac 4)

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

Peak power: 2 MW
Average power: 4 kW
**LHC orbit corrector: [±60A,±8V]**

Magnet: \( L = 7 \) H; \( R = 30 \) m\( \Omega \) (60m of 35 mm\(^2\))

\( T = L/R = 300 \) s

\( U_{\text{static}} = R.I = 1.8V \)

6 V for the \( dl/dt \) with \( L = 7 \) H (\( V = RI + L \, dl/dt \))

\( \Rightarrow dl/dt_{\text{max}} < 1A/s \)

Small signal: \( f^{CL_B} \approx 1 \) Hz : \( \Delta I = 0.13 \) A \( \approx 0.25 \% \) \( I_{\text{max}} \)

\( (L \omega \Delta I = 7 \times 2\pi \times f^{CL_B} \times 0.13 \approx 6 \) V \)

"The power converters involved in feedback of the local orbit may need to deal with correction rates between 10 and 500 Hz";

\( f^{CL_B} \approx 50\)Hz (\( \Delta I = 2\% \): \( U_{\text{max}} = 2500 \) V ????

(\( U_{\text{max}} = 8V \Rightarrow \Delta I \approx 50 \) 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"

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Need of more specification data

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

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

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

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

Topologies

Electrical energy transfer

Control

Source

Power Converter

Source

\[ V_i \rightarrow I_i \rightarrow \text{Power Converter} \rightarrow I_o \rightarrow V_o \]
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)
Energy conversion: transfer of energy between two sources

Introductive example

Transfer of energy between
- DC source $U_i$, $I_i$
- DC source: $U_o$, $I_o$
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 = (U_i – U_o) . 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

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

\[
P_T = 0
\]

Linear mode switch mode

(saturated-blocked)
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)
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.
Power Converter topology design: the problem

the interconnection of sources by switches

Fundamental rules and source natures

Power converter topologies

switch characteristics

$I_k$ $V_k$
Switch: *semiconductor device functioning in commutation*

*The losses in the switch has to be minimized*

*Zon very low*  
*Zoff very high*

Switch: at least two orthogonal segments  
*(short and open circuit are not switches)*
Once upon a time…. not so far

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

### Turn-off Devices
- Transistors
  - MOSFETs
  - Darlington
  - IGBTs
- Thyristors
  - Line commutated
  - Fast
  - Bi-directional
  - Pulse

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

### Diodes
- Fast
- Line commutated
- Avalanche
From mercury arc rectifier, grid-controlled vacuum-tube rectifier, inignitron,.....

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 to frequency of the electrical network
50 Hz (60 Hz)
Power Converter for magnets

AC
3 phase mains (50 or 60 Hz)
Voltage source

Power Converter
Topologies

Voltage source

Current source

DC
magnet, solenoid,…

Achieving high performance: COMPROMISE
Operating Modes

1 Quadrant mode

2 Quadrants mode

4 Quadrants mode

Complexity

Output Source
Converter classification

DC 1 → Inverter → AC 1

Chopper

DC 2 → Rectifier → AC 2

f_1 ≠ f_2 frequency direct converter (cycloconverter)
f_1 = f_2 AC controller (transformer)
General power converter topologies

AC Voltage Source

Rectifier

DC Current Source

Filters
Direct Converters: Rectifiers
Main power converters

12 x [6kA, ± 2 kV]
Two Quadrant Phase Controlled Rectifiers for high current SC magnets

3 Phase
50Hz
Supply
18 kV

[13kA, ± 200 V]
Direct Converters: Rectifiers

AC Voltage

DC Current

"AC" Current

\[ V_k \]

\[ I_k \]
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)

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

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

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

AC link

Thyristor line controller at reasonable current (or voltage)
[100 kV, 40A] klystron power converter

DC operation
General power converter topologies

1. Rectifier
2. AC Link
3. DC Link

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

- 50 Hz transformer
- Optimal voltage output
- Galvanic isolation

CV1
- Diode bridge
  - 6 or 12 pulses
- PWM Converter
  - Hard commutation

CV2
- Magnet
New PS Auxiliary Power Converters

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

![Multi-Turn Extraction: Current/Voltage waveforms](image)

![Current Loop Bandwidth ≈ 1kHz](image)
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

Passive high-current
Output stage

CV1
AC
50 Hz

CV2
DC

CV3
AC
20 - 100 kHz

Magnet
DC
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
High and medium power

Phase Controlled Rectifiers

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

Low and Medium power

Switch-mode power converters

- Mosfets, IGBTs, IGCTs,... turn-off semiconductors
- HF transformers and passive filters
- excellent for 1-quadrant converter
- 4-quadrant converters but with energy dissipation (very complex structure if energy has to be re-injected to mains)
Power converter: Operational domains for accelerators

Amp
10^5
10^4
10^3
10^2
10
1

Volt
10^6
10^5
10^4
10^3
10^2
10
1

Forward

Soft-commutated converters

Thyristor rectifier (Direct)

Buck

AC controller

Power converter operational domains for accelerators.
**Pulsed converters**

**Synchrotrons:** injections and extractions
- Beam is injected, accelerated and extracted in several turns;

**Linac’s and transfer lines**
- Beam is passing through in one shot, with a given time period;

**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

- **MAINS**
- **CAPACITOR BANK**
- **POWER CONVERTER**
- **ACTIVE FILTER**
- **DISCHARGE UNIT & ENERGY RECOVER SWITCHING MATRIX**
- **LOAD (MAGNET)**

**Components:**
- **CAPACITOR BANK**
- **CURRENT REGULATOR**
- **GAIN**
- **TIMING UNIT**

**Signals:**
- **Ucharge**
- **Iload**
- **Iload.ref**

**Control:**
- Start / Stop Charge
- Start / Stop Active Filter
- Start Discharge / Start Recovery

**Timing:**
- Start Charge
- Stop Charge
- Start Pulse
- Measure

**Pulse Patterns:**
- Active filter “on”

**Graphs:**
- Load (Iload) vs. Time
- Ucharge vs. Recovery
High current, high voltage discharge capacitor power converters

CNGS

150 kA for the horn
180 kA for the reflector
Pulsed Klystron modulators for LINAC’s (Linac 4)

- **Characteristics:**
  - Output voltage: 100 kV
  - Output current: 20 A
  - Pulse length: 700 µs
  - Flat top stability: better than 1%
  - 2 Hz repetition rate

Peak power: 2 MW
Power Converter % Load

Load characteristics are vital.

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

Digital (or analogue) Current loop

Voltage loop

\[ I_{\text{ref}} + \varepsilon_I \rightarrow \text{Reg.} \rightarrow F(s) \rightarrow \text{DAC} \rightarrow G(s) \rightarrow \varepsilon_V \rightarrow V \rightarrow B \]

\[ V_{\text{ref}} \]

\[ I_{\text{measured}} \]
Power converter: Performance requirements

Overshoot

Bandwidth

I_{ref} \rightarrow I \rightarrow I_{meas.} \rightarrow \text{Accuracy, Reproducibility, Stability, Resolution}
- **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**

**Glossary**

**Precision**

- **Precision**
  
  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.

\[ I_{\text{ref}} \pm \Delta I_{\text{ref}} \]

\[ I_{\text{meas.}} \pm \Delta I^* \]

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

\[ I_0 = 1019.9 \text{ Amps} \]

- Current offset in Milliamps
- Current offset in ppm of 20 kA
- Time in Seconds

**Graph:**
- Reference
- Measured
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,...)
EMC: ELECTROMAGNETIC COMPATIBILITY

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
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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: I_{max} (and I_{min})

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

Cryostat containing 154 Main Dipoles

Current source Power Converter
13kA, 10V flat top, ±180V boost
Time Constant = 23000 seconds (6 hours 23 minutes)

Total inductance = 16.6H. Total stored energy = 1.2GJ

2x Energy extraction systems.
Maximum rate of discharge = 120A/sec.
CAS - CERN Accelerator School: Power converters for particle accelerators  
26 - 30 Mar 1990, Switzerland

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