Switched Mode Converters
(4 Quadrants)

Yves THUREL
CERN
4 Quadrant basic background

4Q. Conventions
4Q. Working area / loads
4Q. Basic schematics

4 Quadrant topologies Review

Principle schematics (main ones presented)
Advantages / Drawbacks
Some realizations

4 Quadrant practical realization & example

LHC Specifications
LHC Topology choice explained
LHC Converter principles
Technical points highlighted (loops, circulating current, …)
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4 Quadrant Operation: Definition (applied to R-L circuit)

1 Quadrant mode

Control of the decreasing current is still possible within drastic conditions and limits. (\(R_{\text{CIRCUIT}}\) acts as discharger.)

2 Quadrant mode

Current is controlled (being always in the same sense), when increasing or decreasing.

4 Quadrant mode

No theoretical operation limitation.
4 Quadrant Operation: Loads Typical Cycle (R-L)

\[ V_{\text{CIRCUIT}} = R.I + L.dI/dt \]

**KEY FEATURES**

- \( L = 1H \)
- \( R = 7m\text{Ohms} \)
- \( dI/dt_{\text{MAX}} = 5\text{A.s}^{-1} \)
- \( I_{\text{MAX}} = 600\text{A} \)

\[ L.dI/dt = 5\text{V} \]
\[ R.I_{\text{MAX}} = 4.2\text{V} \]
\[ V_{\text{MAX}} = 9.2\text{V} \]
4 Quadrant Operation: Load Influence on topology

**“Pulsed” Machine**
- High Power to be absorbed / Often ➔ High Energy
- Cycle Period

**“Slow” Machine: LHC Type / Magnet or orbit Correctors**
- 12h or more run
- Power to be absorbed / sometimes ➔ Low Energy
- Operation close to 0V / 0A
4 Quadrant Operation: Load Impact on cost & design parameters

**Circuit Characteristics**
- \( L = 1 \text{H} \) (LHC Machine)
- \( \frac{dl}{dt} = 10 \text{A.s}^{-1} \) (LHC Machine)
- \( I = [-600 \text{A}; +600 \text{A}] \) (LHC Machine)
- \( P_{\text{Cable}} < 15 \text{kW} \) (LHC Tunnel)

**20 mOhms**
(V: Output Voltage Power converter)

\[\begin{align*}
V [\text{V}] & \quad 13.2 \text{ kW} \\
I [\text{A}] & \quad 22 V_{\text{MAX}} \\
\end{align*}\]

\[\begin{align*}
-1.25 \text{ kW} \\
-30
\end{align*}\]

**Circuit Key Features**
- \( L \cdot \frac{di}{dt} = 10 \text{V} \)
- \( 10 \text{mOhms} < R_{\text{cable}} < 21 \text{mOhms} \)
- \( 6 \text{V} < R_{\text{cable}} \cdot I_{\text{MAX}} < 12 \text{V} \)

**10 mOhms**
(P: Output power Power converter)

\[\begin{align*}
V [\text{V}] & \quad 9.6 \text{ kW} \\
I [\text{A}] & \quad 16 V_{\text{MAX}} \\
\end{align*}\]

\[\begin{align*}
-2.5 \text{ kW} \\
-30
\end{align*}\]

<table>
<thead>
<tr>
<th>Circuit Key Features</th>
<th>20 mOhms</th>
<th>10 mOhms</th>
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<tr>
<td>( P_{\text{MAX}} )</td>
<td>13.2 kW</td>
<td>9.6 kW</td>
</tr>
<tr>
<td>( P_{\text{ABSORBED}} )</td>
<td>1.25 kW</td>
<td>2.5 kW</td>
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<tr>
<td>Cable Losses</td>
<td>14.4 kW</td>
<td>7.2 kW</td>
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<tr>
<td>Price</td>
<td>➔</td>
<td>➔</td>
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4 Quadrant Operation: Receptor mode

**Goals:**
- Absorbing magnet energy
- Still regulating magnet reverse voltage, i.e. \( \text{d}I/\text{d}t \)

**Solutions:**

**Ideal Magnet**
- No Resistance

**Energy Receptor**
- Concepts

- Variable resistor (active)
- Voltage source added for 0 A transition: No voltage can be obtained when 0 Amp in the magnet.

- Converter magnet-mains, giving back energy to mains.

- Converter magnet-capacitor, storing the magnet energy.

- This capacitor is charged by the magnet and the needed generator converter

**Alternative (not very used) solutions could be:**
- Rotative machine, or (supraconductor) inductor...not treated here.
4 Q Stage: Main topologies

2x Thyristor bridge in anti-parallel

Very well known
Power returned to mains

Linear dissipative Stage

Basic background known, (push-pull stage)
4Q operation to be explained later
Dissipation in the transistors, acting as programmable resistor

Switching Stage

Conventional H bridge (L-C Filter)
Power returned to capacitor or dissipated in brake chopper.
**4Q Stage: Linear basic principle**

...Combined with double* DC fixed voltage output

(* The 2 voltages are always the same)
4Q Stage: Linear basic principle

...combined with double* DC variable voltage output
for better efficiency an losses reduced in receptor mode

(* The 2 voltages are always the same)
4Q Stage: Linear basic principle (variation “linear” H bridge) …combined with single DC variable voltage output

Remark:

This solution is easier, from the inverter side, but leads to polarity new transitions which can be source of distortion, and finally lead to a complex 4 quadrant stage
4Q Stage: Switching basic principle

**H Bridge: 2 modes**

It is possible to work in Buck Mode so that both
- $\Delta I$ is reduced (HF output voltage ripple)
- Losses are reduced

**Note:**
transition between these 2 possible modes can be source of distortions.

$$V_{\text{MEAN}} = (2\cdot \alpha - 1) \cdot V_E$$
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Technical points highlighted (loops, circulating current,...)
Realizations
**Topologies:** Key points, (how to classify them, how to select them?)

- **Power Range,** Dissipative or Not, Efficiency
- **AC Mains Pert. Rej., EMC, BF & HF Ripple**
- **Distortion, Bandwidth**
- **Size, Weight, Cost**
- **Number of CPTS, Design Complexity, MTBF, Use of Commercial Part**

*TOPOLOGY CHOICE ????
Topologies: Thyristor (Principle)

50 Hz transfo.
Optimal voltage output
*(Galvanic Isolation)*

Thyristor bridge

Thyristor bridge

Low freq.
Output Filter
Topologies: Thyristor (schematics Example)

Basic schematic

- [0,0] & [V] axis required circulating current between the 2 bridges

Adding a circulating current between the 2 thyristor bridges helps!!!
Topologies: Thyristor (Discussion)

Advantages

• Huge power possible
• Not Dissipative: power returned to mains
• High Efficiency
• Very well known topology
• Rather simple design
• No High frequency signal (low frequency operation): EMC easy to handle

Drawbacks

• Low Bandwidth (addition of active filter can help a bit in small signal)
• Poor AC mains perturbation rejection (speed loop limited by L-C filter)
• Distortion (crossing axes, and point [0,0]) requires some additional circuit for high precision converter: Circulating current
• Size, weight of transformer and filtering elements
Topologies: 50Hz + Linear (Principle)

- 50 Hz transfo. Optimal voltage output (*Galvanic Isolation*)
- Rectifier + Double Output High Freq. Filter
- Linear Stage (*Dissipate Magnet Energy*)
Topologies: 50Hz + Linear (Principle variation)

50 Hz transfo.
Optimal voltage output
*(Galvanic Isolation)*

Diode bridge

Low freq.
Output Filter

H Bridge
Linear Stage
*(Polarity Changer / Dissipate Magnet Energy)*

DC Fixed
Topologies: 50Hz + Linear (Discussion)

Advantages

- Schematics and topologies are very well known
- Simple schematics
- Adding circulation current helps
- Bandwidth (10 kHz)

Drawbacks

- Dissipative
- Efficiency very low in generator mode
- Size, weight of transformer and filtering elements
- Often realized with several transistors in // (MTBF and avalanche failure)
Topologies: 50Hz + Switching (Principle)

50 Hz transfo.  
Optimal voltage output  
(Galvanic Isolation)

Diode bridge

Low freq. Output Filter  
(Magnet Energy $\Rightarrow 1/2.C.V^2$)

Add. Brake Chopper  
(Optional)  
(Dissipate Magnet Energy)

PWM Converter  
Hard Commutation

High freq. Output Filter
Topologies: 50Hz + Switching (Schematics Example)

Basic schematic

- 50Hz Transfo + L - C Filter
- Rectifier bridge: High Frequency Hard commutation Bridge
  Commercial part possible
- Brake chopper: absorb magnet energy if Vcap. too high
- High Frequency LC Filter (2 cells)
Topologies: 50Hz + Switching (Discussion)

Advantages

- Huge power possible
- Part of magnet energy re-used
- Very well known topology—possible to use commercial standard elements
- High bandwidth (10 kHz)
- Good AC mains perturbation rejection
- No distortion of the signal (if H bridge not changing mode)

Drawbacks

- H bridge hard commutation @ high current
- 50Hz LC-Filter can be un-damped by H bridge negative equivalent resistor
- Size, weight of transformer and filtering elements
- Hard commutation EMC to cope with
- Low voltage high current not ideal (loss of the switching H bridge, $f_{\text{switching}}$ limited)
- HF filtering Ripple difficult (if buck mode not used), at “only $f_{\text{switching}}$”
Topologies: Switching + Linear (Principle)

- High Freq. Bridge
- Low freq. Filter
- High Freq. Soft Commutation Inverter
- High Freq. Transfo.
- Rectifier + Double Output High Freq. Filter
- Linear Stage
Topologies: Switching + Linear (Principle variation)

3Ph Diode Bridge
Low freq. Output Filter
High Freq. Soft Commutation Inverter
High Freq. Transfo.
Rectifier + Single Output High Freq. Filter
H Bridge Linear Stage
(Polarity Changer)
Topologies: Switching + Linear (Schematics Example)

Basic schematic
Topologies: Switching + Linear (Discussion)

Advantages

• Medium power possible
• Addition of 2 distinct well known topologies
• High bandwidth
• Good AC mains perturbation rejection
• No distortion of the signal (if circulating current used)
• HF filtering Ripple at 2x f\textsubscript{switching} possible
• Efficiency OK, (no switching Loss at secondary side)
• EMC OK, since Soft commutation possible

Drawbacks

• Dealing with Inverter Loop & Circulation current Loop can lead to some complexity
• Double output voltage requires additional power components (L-C Filtering + Rectifiers)
• Dissipative (No energy back to anywhere, except Output transistors!!!)
Topologies: Switching + Switching Type 1 (Principle)

- 50 Hz transformer
- Optimal voltage output
- Galvanic isolation
- Diode bridge
- Low freq. Output Filter
- Add. Crowbar
- PWM Converter
- Hard Commutation

I_{LOAD} \rightarrow V_{LOAD}
Topologies: Switching + Switching Type 1 (Discussion)

Advantages

• High power possible
• Part of magnet energy re-used
• Very well known topology
• High bandwidth
• Good AC mains perturbation rejection
• No distortion of the signal (if H bridge not changing mode)

Drawbacks

• Secondary H bridge hard commutation @ high current (Losses EMC to cope with )
• Low voltage high current not ideal (loss of the switching H bridge, $f_{\text{switching}}$ limited)
• 2 HF filtering levels
• Complexity (2 inverters, Gate drives) & Cost
• Efficiency low
• HF filtering Ripple difficult (if buck mode not used), at “only $f_{\text{switching}}$”
Topologies: Switching + Switching Type 2 (Principle)

Diode bridge  Low freq.  Add. Output Filter  Crowbar

High Freq.  Soft Commutation  Inverter

High Freq.  Soft Commutation  Transfo.

4Q Converter  Soft Commutation

I_{LOAD}  V_{LOAD}
Topologies: Switching + Switching Type 2 (Schematic Example)

See Paper from CERN & LEEI for detailed explanation.
Topologies: Switching + Switching Type 2 (Discussion)

Advantages

• Fully reversible with energy sent back to mains (thyristor bridge to be added)

• High frequency power converter (low volume and high dynamic performance)

• High bandwidth

• Good AC mains perturbation rejection

• No distortion of the signal (if H bridge not changing mode)

• Soft commutation possible on the 2 H-Bridges

• High efficiency

Drawbacks

• Complex control
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LHC: Specifications

- **Electrical Characteristics**
  - Low Output Voltage / High Output Current
  - High Efficiency (Losses in Tunnel must be as low as possible)
  - High bandwidth
  - No need for returning power to mains (slow machine)
  - Operation close to [0V-0A]
  - Low BF ripple (magnet current precision) & Low HF Ripple (EMC)

- **Mechanical Characteristics**
  - To be installed in LHC tunnel
  - Must be possible to change it as a plug-in module
  - Low volume and low weight

- **Electrical Environment**
  - Good immunity to mains perturbation (phase loss of 100ms)
  - Very low level of distortion tolerated (high precision)
  - EMC behavior must be very good (IN & OUT)
  - To be integrated in a few ppm current loop regulation

- **Other key points**
  - 15 years of operation (MTBF)
  - Principle as simple as possible (operation)
LHC ±120A ±10V: EMC Highlighted

Magnet loads are several magnets in series (hundreds of meters "load")
IEC478.3 C applied INPUT and OUTPUT side

Digital & Analog signals exchanged between Power converter & High Precision Current Controller
LHC ±120A ±10V Topology Choice

Minimum 50Hz Components for size & weight reduction (tunnel installation)

Switching based topology

High precision environment:
- EMC must be as good as possible
- No distortion / operation [0V-0A]

Linear base topology
LHC ±120A ±10V Topology Choice

Input Module, Bd: 70Hz
Phase shifted Inverter
Rectifier + Filter
4 Quadrant Linear Stage

BREAKER & CONTACTOR
INPUT FILTER & SOFT-START
SOFT COM. INVERTER, 50kHz..100kHz
ISOLATION & RECTIFIER + FILTER
4Q.L.S.
LHC ±120A ±10V Topology Choice

**AC-DC**
- 3 phases + Neutral (used for auxiliary power supply)
- 1400V Rectifiers
- 70Hz Input filter (damped with C-4C) to give a flat 540V DC (around -20dB on 300Hz)
- Soft start based on “R + switch”.

**High Frequency Soft commutation Inverter**
- Fixed switching frequency (50..100kHz).
- ZVS operation with Phase Shifted command.
- ZCS for lagging leg
- IGBT Bridge
- “Voltage” or “current” mode possible
LHC ±120A ±10V Topology Choice

Rectifier + DC Filter
- HF Ripple at 2x inverter $F_{\text{switching}}$
- Schottky rectifiers.
- Double LC cell at 5..10 kHz.

4 Quadrant Linear Stage
- Linear Regulation based on Mosfets.
- Mosfet used as
  - polarity switch in generator mode
  - programmable resistor to dissipate Magnet energy.
- Use of 4QLS as an active filter
- Use of 4QLS to pre-load inverter (continuous mode)
- Circulating current always present but value depending from load current (no mode change transition, both DC/DC outputs always minimum loaded)
LHC ±120A ±10V Topology Choice

Highlights on 4QLS

• A double power source programmable via inverter \((V_E)\)

• 2 MOSFETS, Q1 & Q2, used as switch and programmable resistor. (high level of power possible)

• A command which works according to:

\[
V_{OUT} = + (V_E - R_{HIGH} \cdot I_{HIGH})
\]

\[
V_{OUT} = - (V_E - R_{LOW} \cdot I_{LOW})
\]

\(R_{HIGH} \& R_{LOW}\) are equivalent MOSFET resistance
LHC: 4QLS without circulation current

• Remember a limitation of the linear stage…

• Main Loop (VOUT linear regulation loop) cannot provide needed step for biasing MOSFET (-3V to +3V)

• Playing with fixed bias is a bad idea!!! Discrepancies on V<sub>GS</sub> ON ±1V !!!
LHC: 4QLS with circulation current

- Adding 2x circulation current loop

  - To avoid 0A distortion crossing, a circulating current can help, biasing MOSFET gates.

  - These additional loops (one per MOSFET) must not perturb main loop. (must be slower)

  - $I_{\text{circulation}}$ can vary

  \[
  \begin{align*}
  V_E & \quad V_{GS\, \text{HIGH}} & \quad V_{DS\, \text{HIGH}} \\
  V_E & \quad V_{GS\, \text{LOW}} & \quad V_{DS\, \text{LOW}}
  \end{align*}
  \]

  \[
  \begin{align*}
  I_{\text{HIGH}} & \quad I_{\text{LOW}} & \quad I_{\text{OUT}}
  \end{align*}
  \]
LHC: 4QLS with circulation current

different approaches:

• Circulating current always present, changing its value depending on output current
  • Its control is easy (reference is only smoothly changing with \( I_{\text{OUT}} \))
  • Inverter reference must always be set so that this circulating current is possible leading to higher losses in receptor mode.
  • No changing mode (Gate of each side MOSFET always biased)

• Circulating current only present when close to a potential transition
  • This solution saves a lot of energy when recovering, since inverter doesn’t inject power in MOSFET when absorbing power.
  • \( \frac{dI}{dt} \) Limitation exists, since if too fast, circulating current doesn’t have time to appear and MOSFET Gate are not well biased.
LHC: 4QLS / Inverter Reference

- Inverter REF is built according to
  - VBIAS MIN. not to saturate MOSFET (i.e. saturate Loop)
  - VBIAS OPT. For 4Q Linear stage acting as active filter (better rejection of mains disturbances and 300 Hz)
  - VMIN coupled to I circulation MIN to always minimum load inverter (Conduction mode un-changed)
  - Inverter Loop must be faster / transparent than 4Q stage loop
**LHC: 4QLS MOS working Area (Example)**

**Practical case of Circulation current always ON, at the same value: 5A.**

**RDSON variations limited by circulating current.**

**Dissipate Power is:**

- 21V x 120A in recovering MOSFET instead of 10V x 120A required by the load.
- Only valid if not often the case.
**LHC: 4QLS MOS Model (FB180SA10 I.R.)**

*MOSFET is difficult to control directly from the main loop to the gate. Indeed gain is from virtually 0 if saturated to thousands when almost OFF.*

*Settings like:*

- Circulating current value
- Difference voltage issued from the inverter output voltage
- Number of MOSFET in // are the key to maintain a stable efficient analog loop.
LHC: Practical Results

**DISTORTION?:**
Crossing axis is OK. No distortion, achieved thanks to circulating current.

**CONTROL:**
Bandwidth in generator & receptor quadrant
Crossing 0A is OK, being unchanged.
LHC: Realizations

LHC $\pm 120A \pm 10V$
- 330 Converters
- Correctors
- CERN Internal Design

LHC $\pm 60A \pm 8V$
- 800 Converters
- Orbit Correctors
- Below Dipoles, in a radiation zone
- CERN Internal Design
CIRTEM

LHC ±600A ±10V
• 440 Converters
• 1x 6U Module

TRANSTECHNIK

LHC ±600A ±40V
• 50 Converters
• 2x 6U module
Thank you for your attention.
Reference

Care with test invisible so that alignment is ok