CERN

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CERN, *for* CAS Power Converters 2014 @ Baden CH

Switched Mode 4 Quadrant Power Converters

My main motivation and goal for this presentation

You being able to:

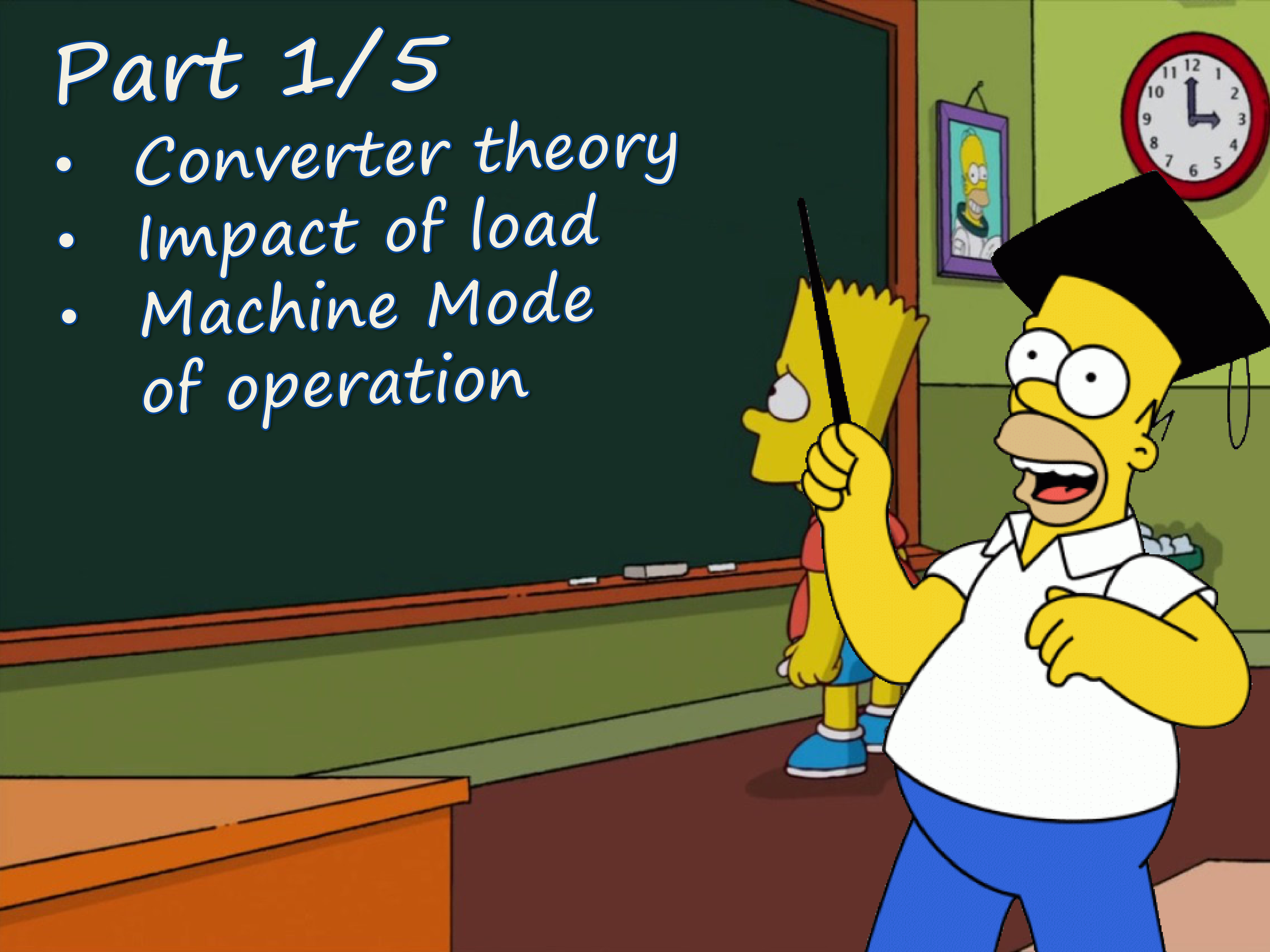
- Recognize when you actually NEED a 4-Quadrant converter.
- Review load characteristics to OPTIMIZE solutions with.
- Integrate a GLOBAL and SAFE technical solution, dealing with
  - Machine requirements like EMC, cycle types, installation requirements
  - Load PROTECTION system like energy extraction.

Get a general overview of technical solutions.

- Strong focus on solutions in operation @ CERN.

Get a feeling about the known limitation.

Show you some CERN practical realizations and results.


Part 1/5
• Converter theory
• Impact of load
• Machine Mode of operation

4-Quadrant Power Converter: when and for what?

A standard converter is often 1-Quadrant converter. Why?

- Simply because we very often need power we immediately use.
- Remember manufacturer communicate on power (Watts) standard converters can transmit, rarely on energy (J).
- Energy a 1-Quadrant converter has to manage itself is its losses.

A 4-Q converter is different from a standard one. Why?

- A tiny 1-Quadrant converter can transmit high amount of energy from energy source (mains) to the load (it just takes time).
- A 4-Quadrant converter can modify the load energy level, increasing or decreasing it. This means removing the load stored energy by:
  - Sending it back to network, storing it or
  - Dissipating it.

4-Quadrant Power Converter: Which load?

A 4-quadrant Power Converter can inject energy to the load and can also received stored energy from the load.

2 types of loads - in electronic field - able to store energy:

- Capacitor $Ej_{load} = 1/2 \cdot C \cdot V_{load}^2$
- Inductor $Ej_{load} = 1/2 \cdot L \cdot I_{load}^2$

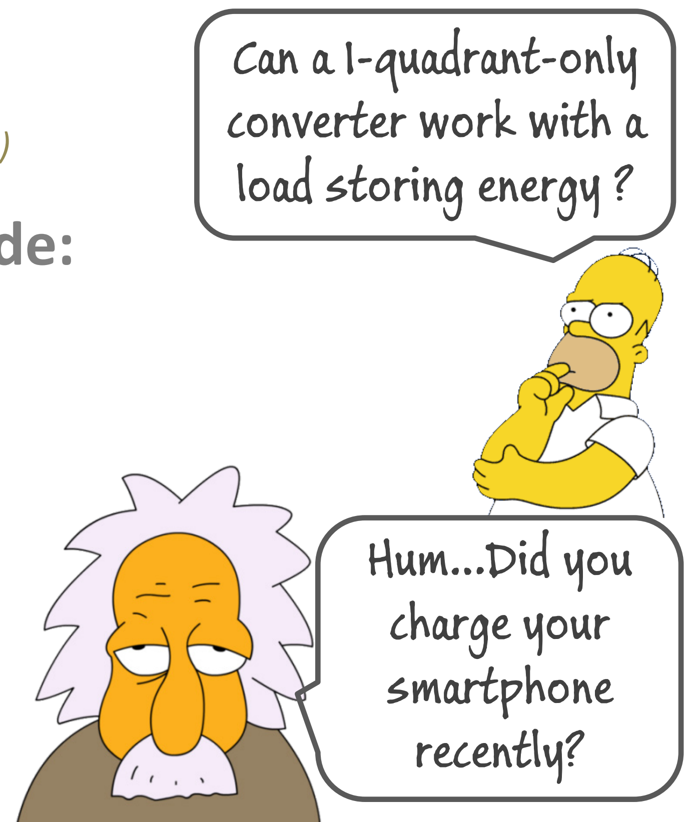
  (accelerator natural preference one)

2 modes of operation from Converter side:

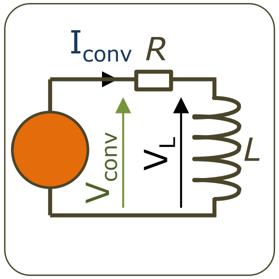
- Generator Mode (energy flows from converter to load)

  ➔ $V_{converter} \cdot I_{converter}$ = Positive quantity.
- Receptor Mode (energy flows from load to converter)

  ➔ $V_{converter} \cdot I_{converter}$ = Negative quantity.



1-Quadrant Converter vs Inductive load (R-L)



$$dI/dt = V_L / L$$

$$V_L = V_{conv} - R \cdot I_{conv}$$

$V_{L.max} = [V_{conv.max} ; I_{conv.min}]$
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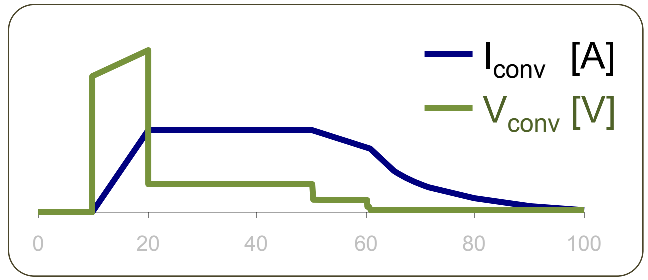
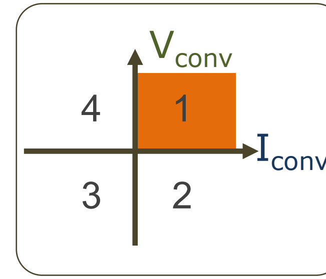


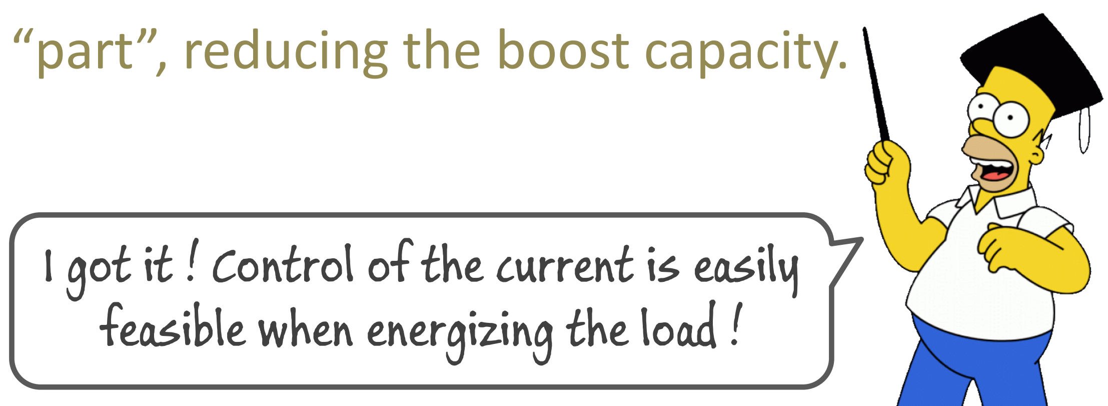


1.Q Converter delivers Energy to load, but **cannot absorb it.**

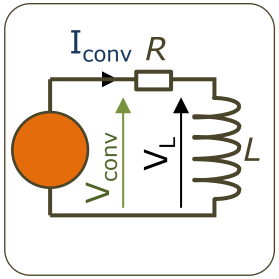
- Current control (its dI/dt) while load energy is increased, is possible, only limited by $V_{converter\ max}$ and level of current.

Maximum voltage delivered by converter takes into account:

- $L \cdot dI/dt$ boost voltage directly applied to inductance.
- $R \cdot I_{max}$ cable losses "part", reducing the boost capacity.



1-Quadrant Converter vs Inductive load (R-L)



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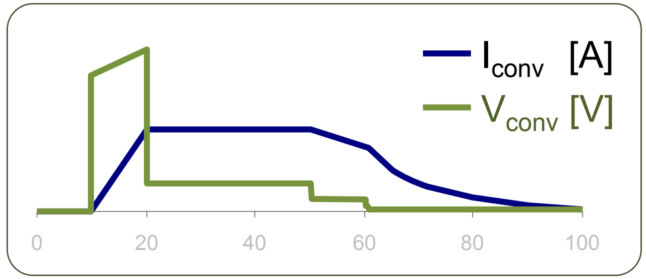
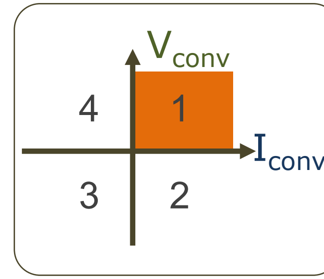




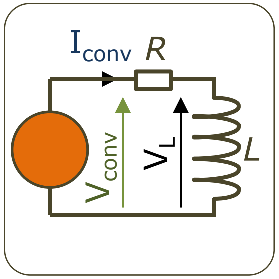
Removing energy from the load can be obtained choosing who, among load or converter, will power cable resistance.

- [dI/dt = 0; constant current] is obtained when $V_{conv} = R.I_{conv}$.

dI/dt to the load is given by $1 / L \cdot (V_{conv} - R \cdot I_{conv})$.

- Maximum rate for ramping down the current is obtained when $V_{conv} = 0$, and I_{conv} is maximum.
- As current indeed decreases, dI/dt constantly decreases (exponential decay), with severe constraints for overall current control loop.

1-Quadrant Converter vs Inductive load (R-L)



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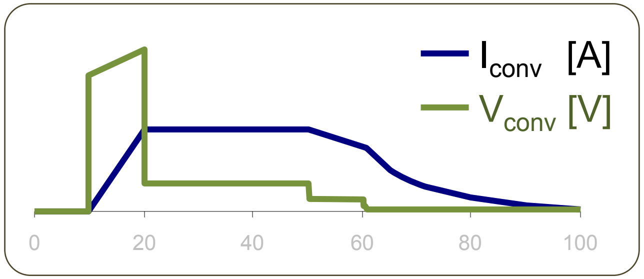
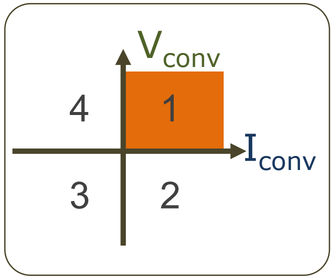


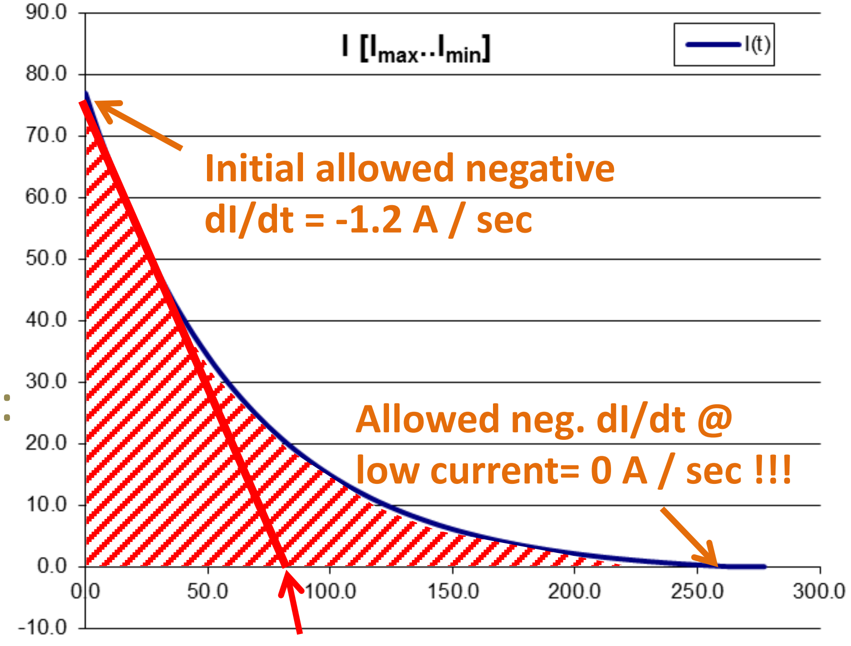


Let's just fix **once for all** the limitation to be cope with:

- For converter being ultimately controlled as a final current source, major issue of 1-Q converter is the limitation on dI/dt when ramping down, with severe limitation given simply by:

  ➔ $dI/dt_{neg.\ critical} = - R / L \times I_{conv}$

So simple that ignoring it is not allowed, and this would cost a lot !



A 1-Q converter cannot follow this reference !!

I_{conv} becomes too low to "get negative voltage across inductor"

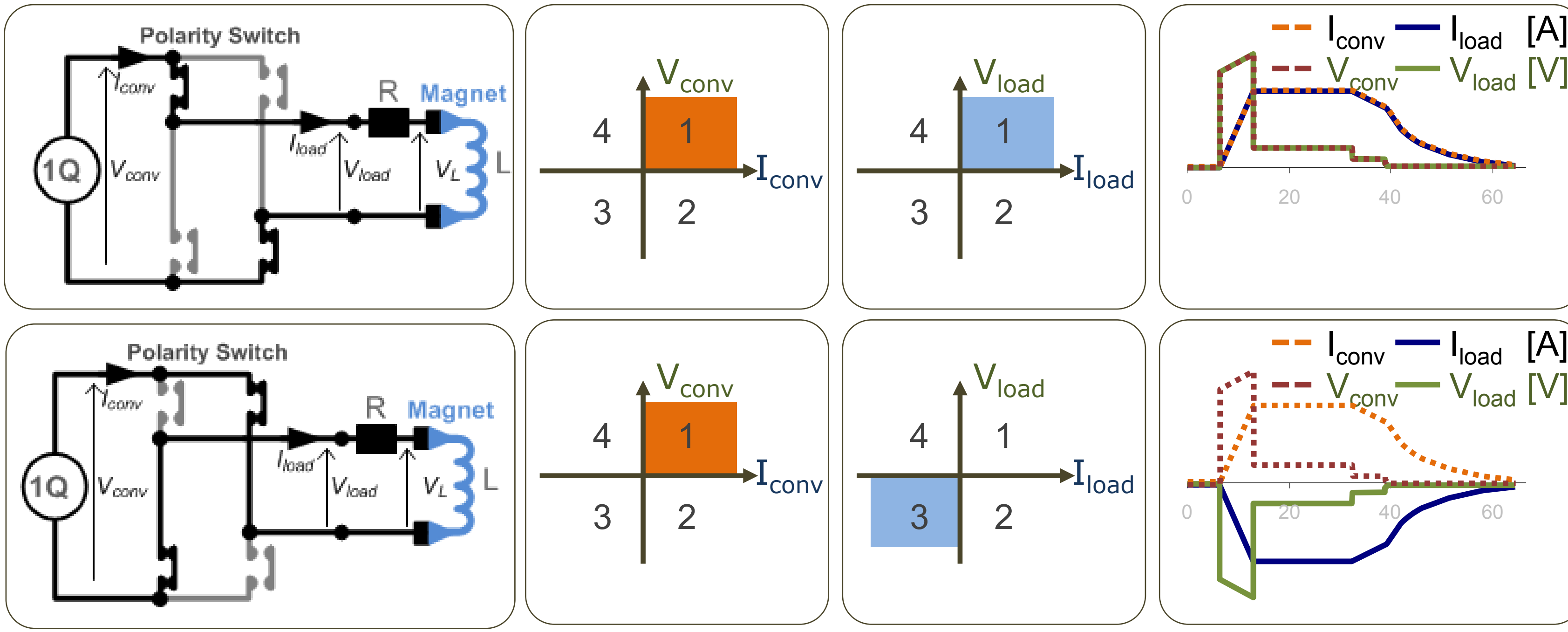
2-Quadrant Converter vs Inductive load (R-L)

Ok. WAIT A MINUTE. Which 2 quadrants? 2 in Diagonal? 2 in Vertical or horizontal?

Clarify before going further !

2-Quadrant Converter vs Inductive load (R-L)

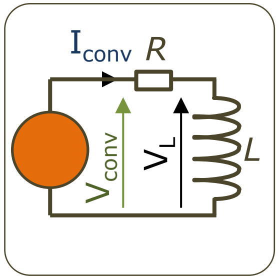
- System: 1-Quadrant converter + Polarity switch inverter example.



- V and I can be both positive or negative, great! But, energy is always and only delivered to the load. ($V_{conv} \cdot I_{conv} > 0$).
- This type of system should be assimilated to a 1-Q converter.

This is a common trap for final user ! Bad surprise in perspective !

2-Quadrant Converter vs Inductive load (R-L)



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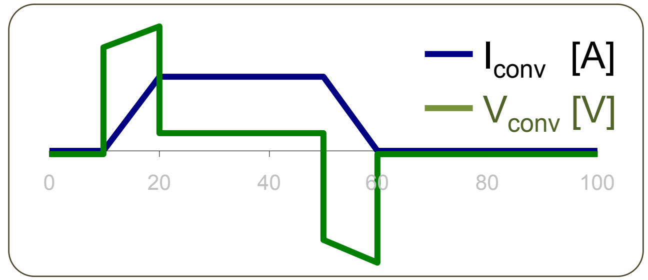
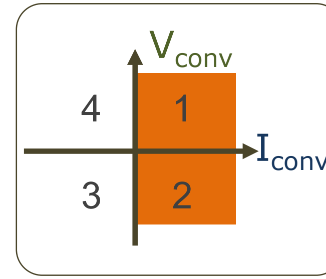
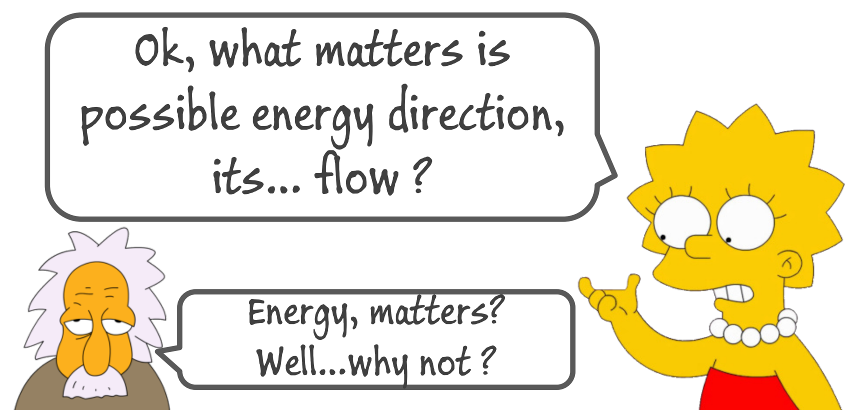
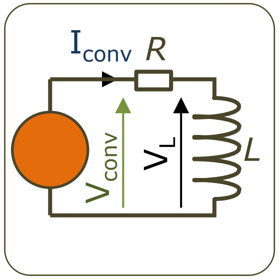




- V can be positive or negative, when current is *only* positive (*typical thyristor converter case, with energy sent back to mains*).
- *Only*? Yes, but energy can *here* be removed from the load in a controlled way - *as long as connection to network is present (thyristor*).
- Control of the current is then possible when increasing or decreasing it, current keeping same direction.



4-Quadrant Power Converter



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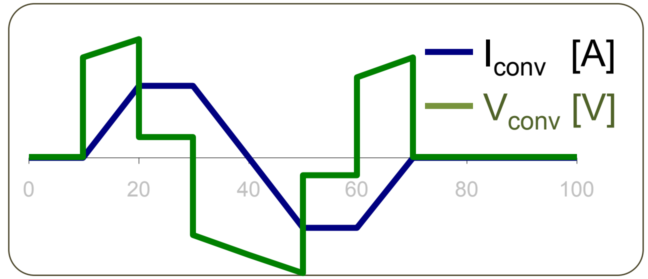
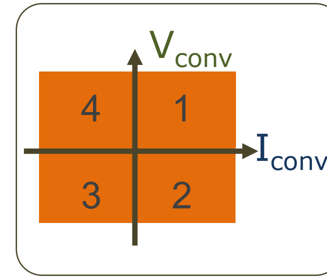


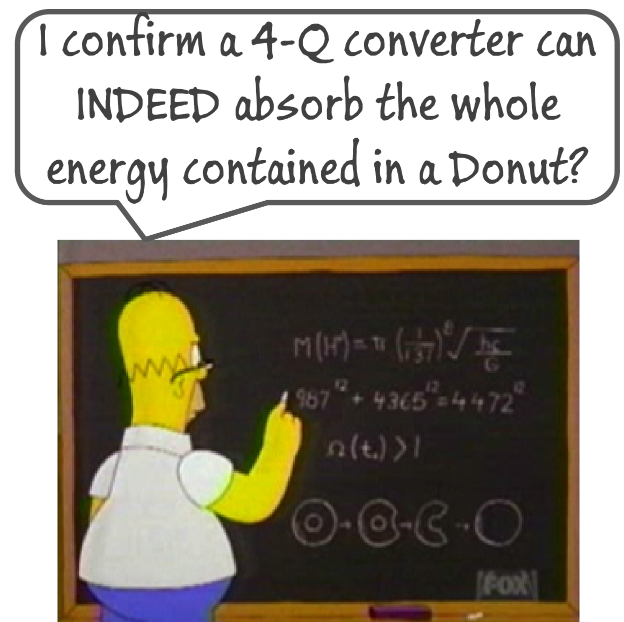


Almost no "topological" limitation regarding any load.

- Complex design, very different topologies with pro and cons.
- Energy transfer possible at any point.

Choice of topologies mainly comes from:

- Power level, Performances, Environment.
- Machine use (Pulsed, or slow DC).
- Load nature and time constant (superconductive loads).

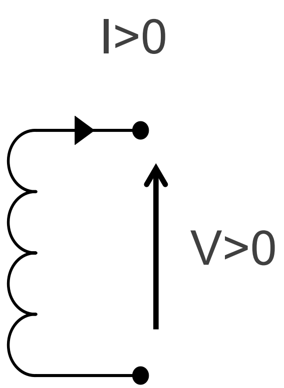


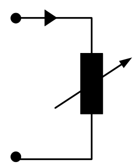
4-Quadrant Operation: Topologies

Goals:

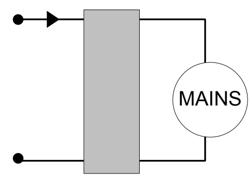
- Choosing adequate topology for removing defined amount of load energy, Regulating magnet current (access to dI/dt).

Solutions:

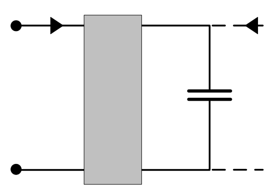




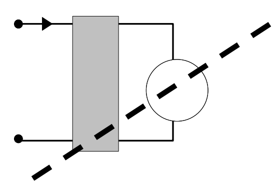
Variable resistor (active), controlling the dissipation level, i.e. the dI/dt.



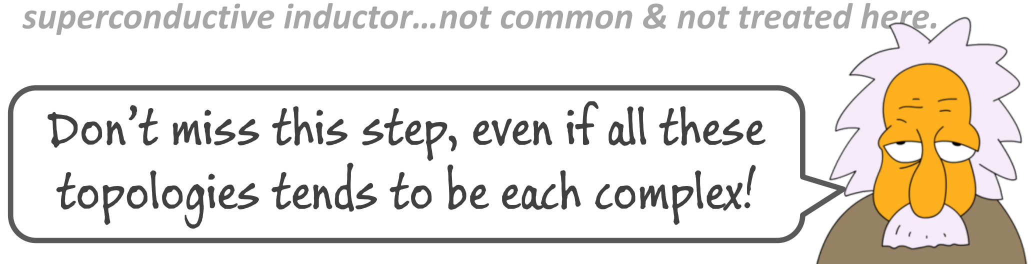
Converter sending back energy to mains controlling the Ej transfer.



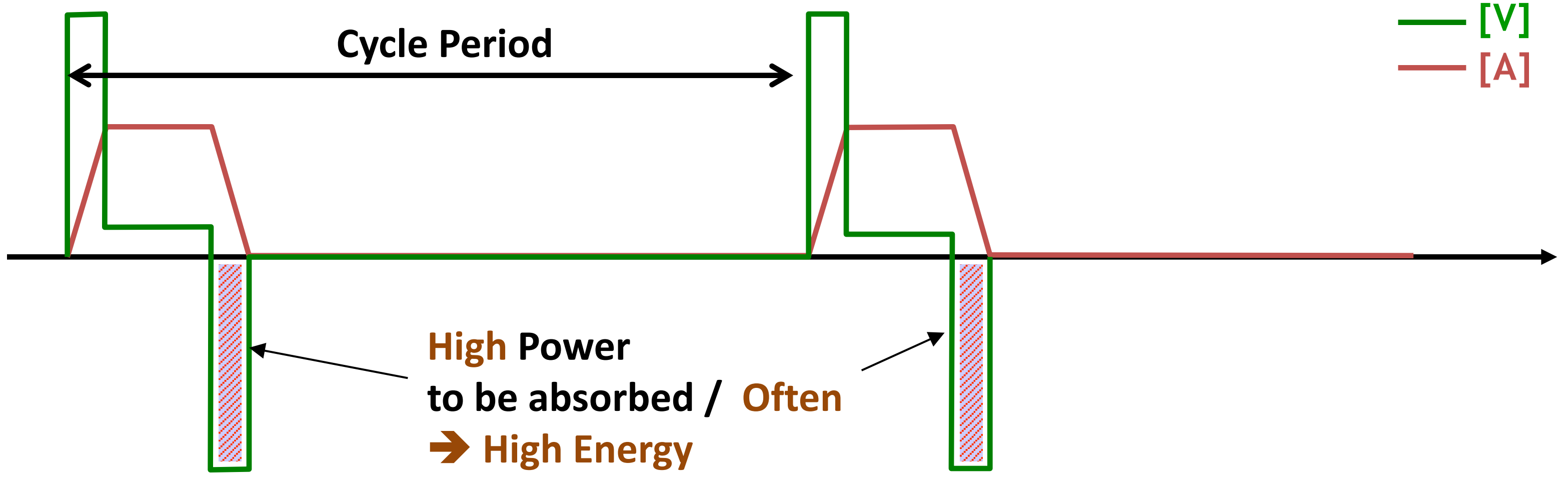
Converter storing the magnet energy in a capacitor, controlling the Ej transfer.



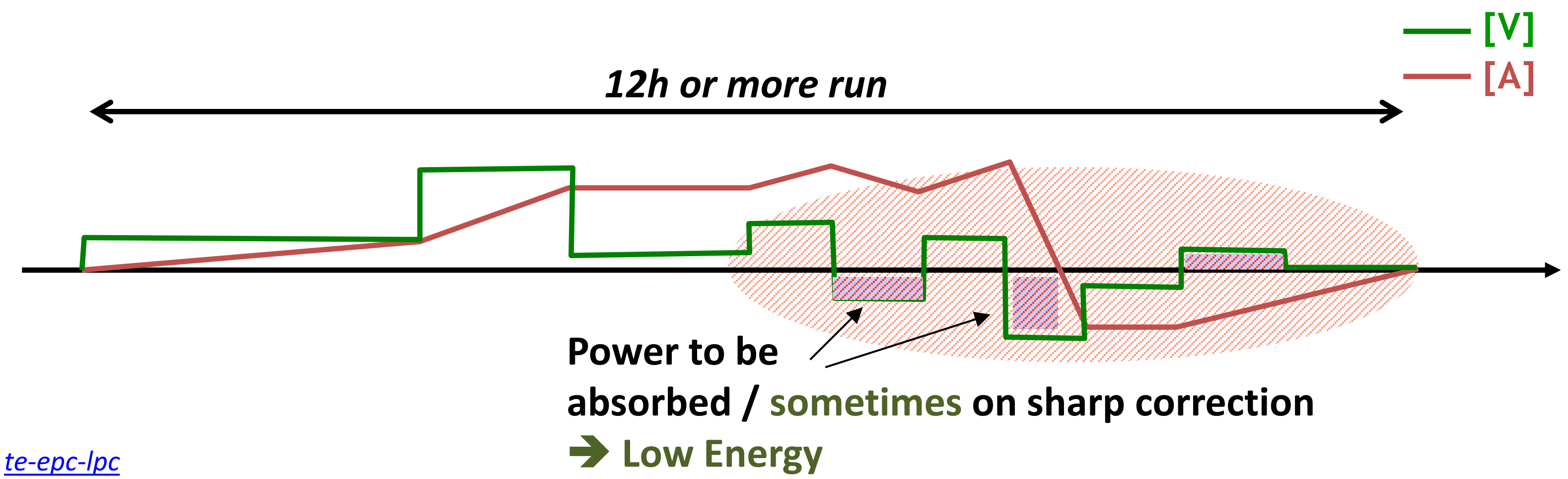
Alternative solutions which could be: rotative machine, or superconductive inductor…not common & not treated here.



"Pulsed" Machine



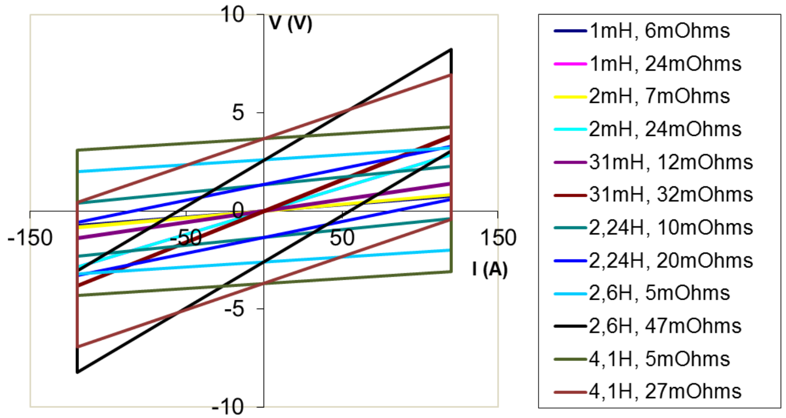
"Slow" Machine: LHC Type / Magnet or orbit Correctors

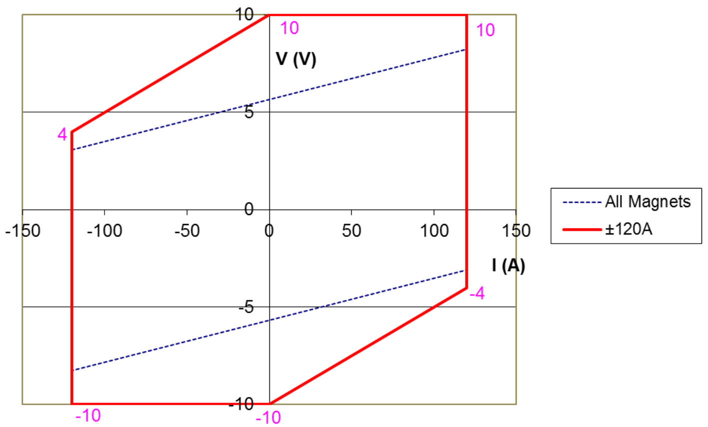


Load resistor impacts highly the receptive quadrant area

In case of dissipative 4-Quadrant solution, energy to be evacuated directly in the converter costs money , weight, reliability (number of power semiconductors being used)

- CERN generally limits the power & energy its 4-Q. converter accept.
- Typical operation & cycles from operational data are set once for all.





➔Result of optimization process is a non-full 4-Q converter, but a cost, weight and technical effective compromise adapted to operation needs.

Impact on the resistance value on design & losses

Circuit Characteristics

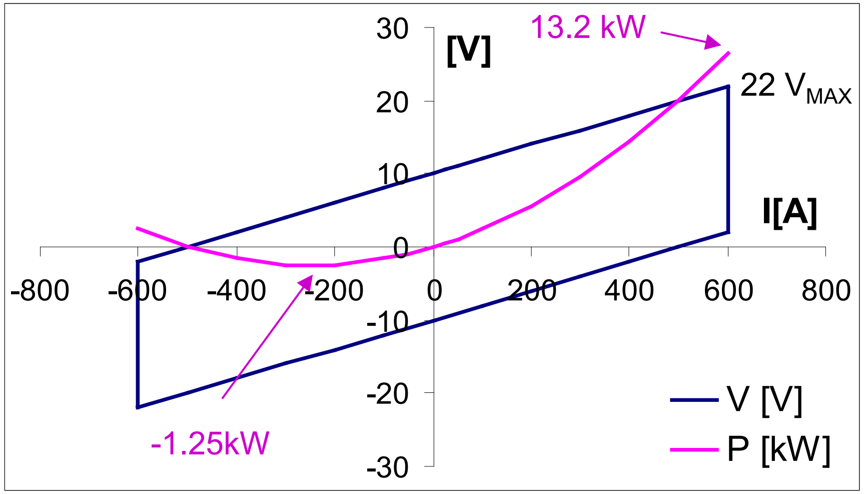
- L = 1 H, dI/dt = 10 A/s
- I = [-600 A; +600 A]
- P_{Cable} < 15 kW

Circuit Key Features

- L · di/dt = 10 V
- 10 mOhms < R_{cable} < 21 mOhms

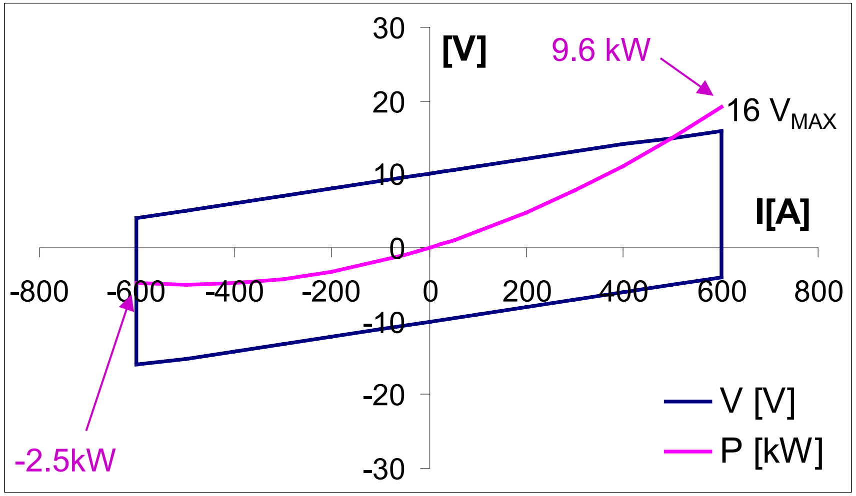
  6 V < $R_{cable} \cdot I_{MAX}$ < 12 V

Choice 1: R.cable = 20 mOhms



P_{MAX}	13.2 kW	*100 %*
$P_{ABSORBED}$	1.25 kW	*100 %*
Cable Losses	14.4 kW	*100 %*

Choice 2: R.cable = 10 mOhms



P_{MAX}	9.6 kW	*73 %*
$P_{ABSORBED}$	2.5 kW	*200%*
Cable Losses	7.2 kW	*50 %*

- Max. power absorbed is divided by 2x, when power in generator mode is only 1.37x higher, at the cost of higher cable power losses.

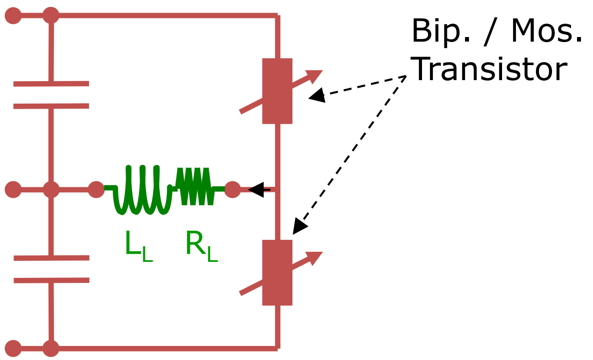

Part 2/5
• Topology review on CERN topologies
• Pro & Cons
Review?... Isn't it the good moment to sleep

4-Quadrant Topologies: principles

2x Thyristor bridges in anti//

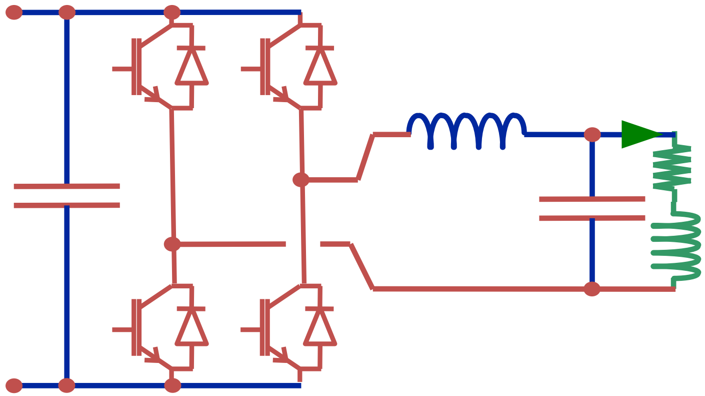
- Very well known.
- Load energy returned to mains.

Linear dissipative Stage



- Basic background known.
- 4-Q operation to be explained later.
- Dissipation in transistors, acting as programmable resistor.

Switching Stage

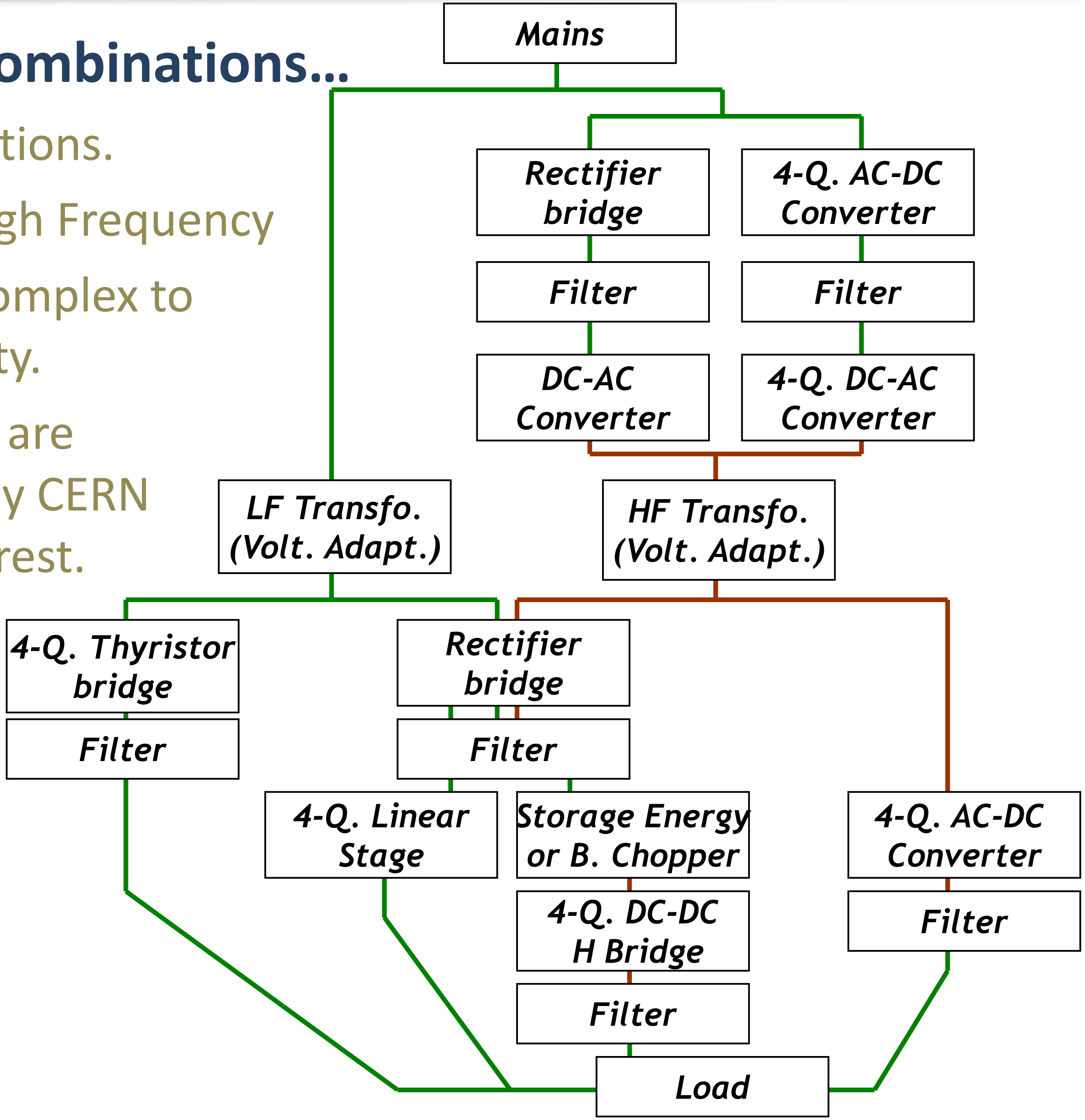


- Conventional 4-Q H bridge (+L-C Filter).
- Power returned to capacitor or dissipated in add. brake chopper.

4-Quadrant Topology Simplified Tree

A large panel of combinations…

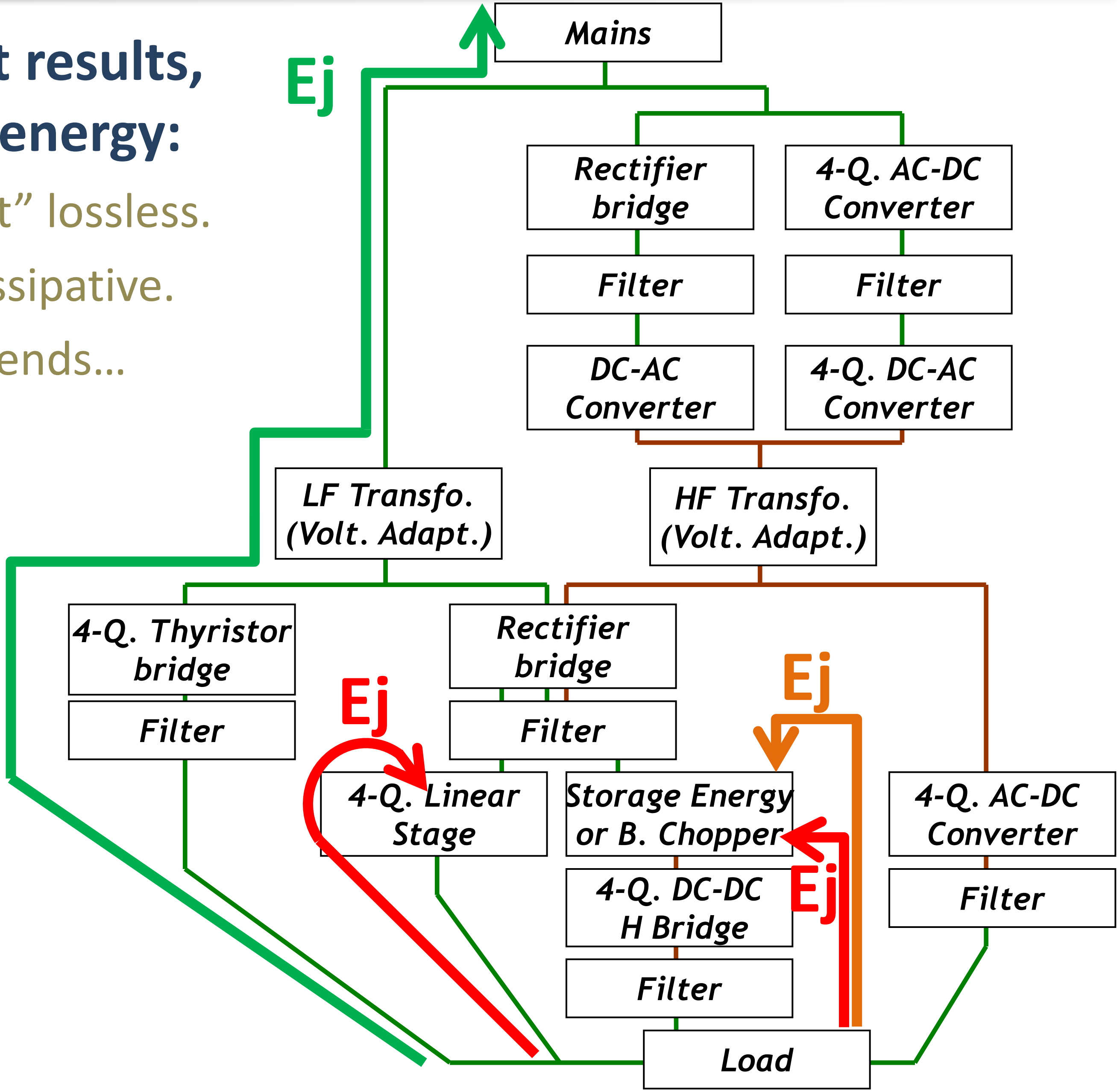
- Several combinations.
- From 50Hz to High Frequency
- From medium complex to insane complexity.
- Not all solutions are represented, only CERN solutions of interest.



4-Quadrant Topology Simplified Tree

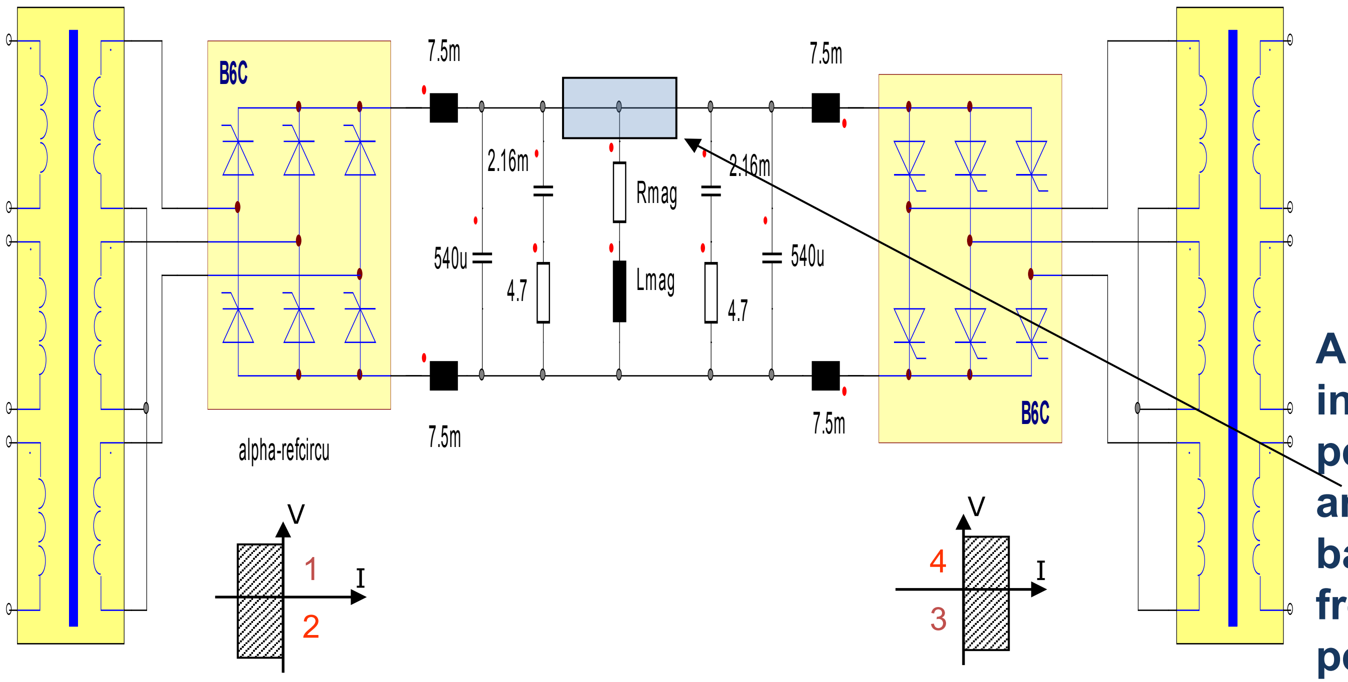
…with different results, regarding load energy:

- Some "almost" lossless.
- some fully dissipative.
- Some…it depends…

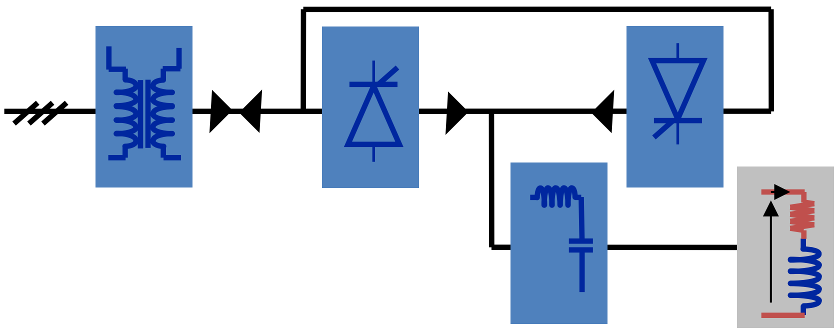


Schematic

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



Active Filter increase dynamic performance (low amplitude bandwidth, low frequency ripple, perturbation…)



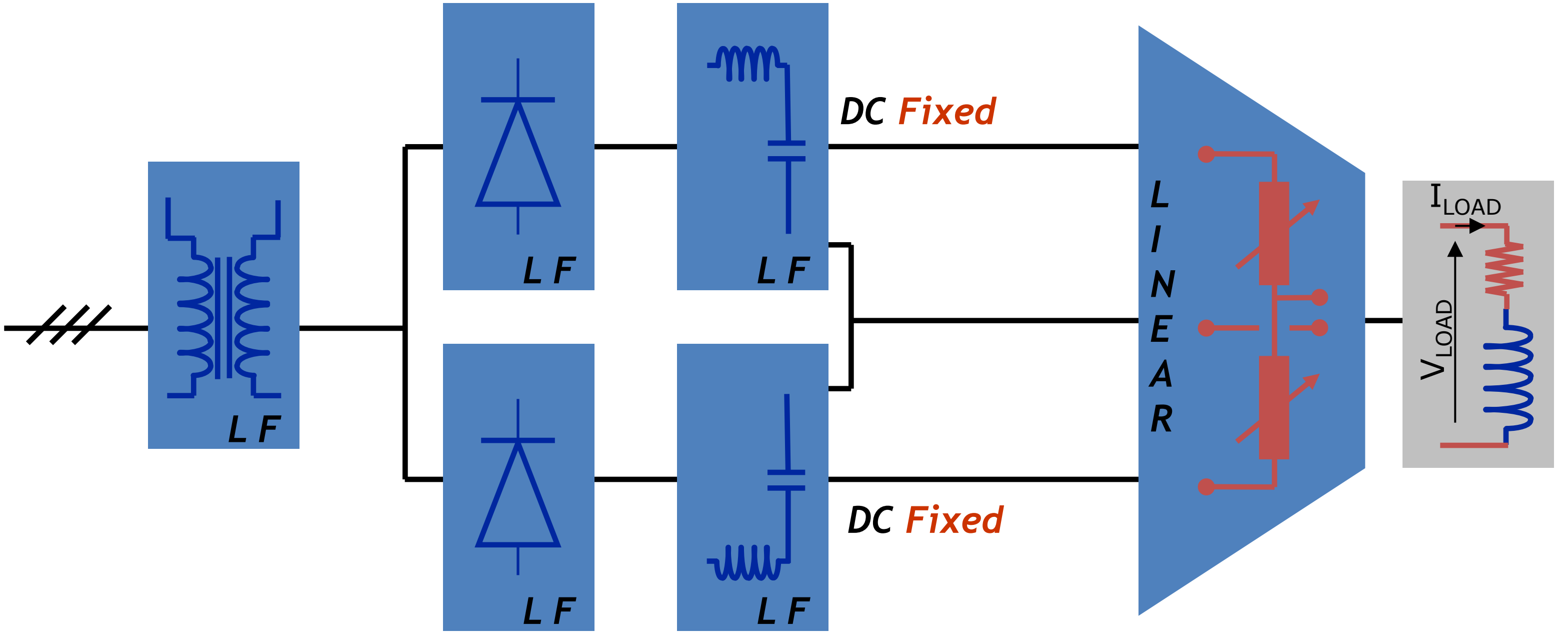
Advantages

- Very high power possible.
- Load energy returned to mains.
- High Efficiency.
- Very well known topology, and rather simple design.
- EMC relatively *easy* to handle (low frequency operation)

Drawbacks

- Low Bandwidth (add. active filter can help for small signal range).
- Poor AC mains perturbation rejection (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.

Schematic / Principle



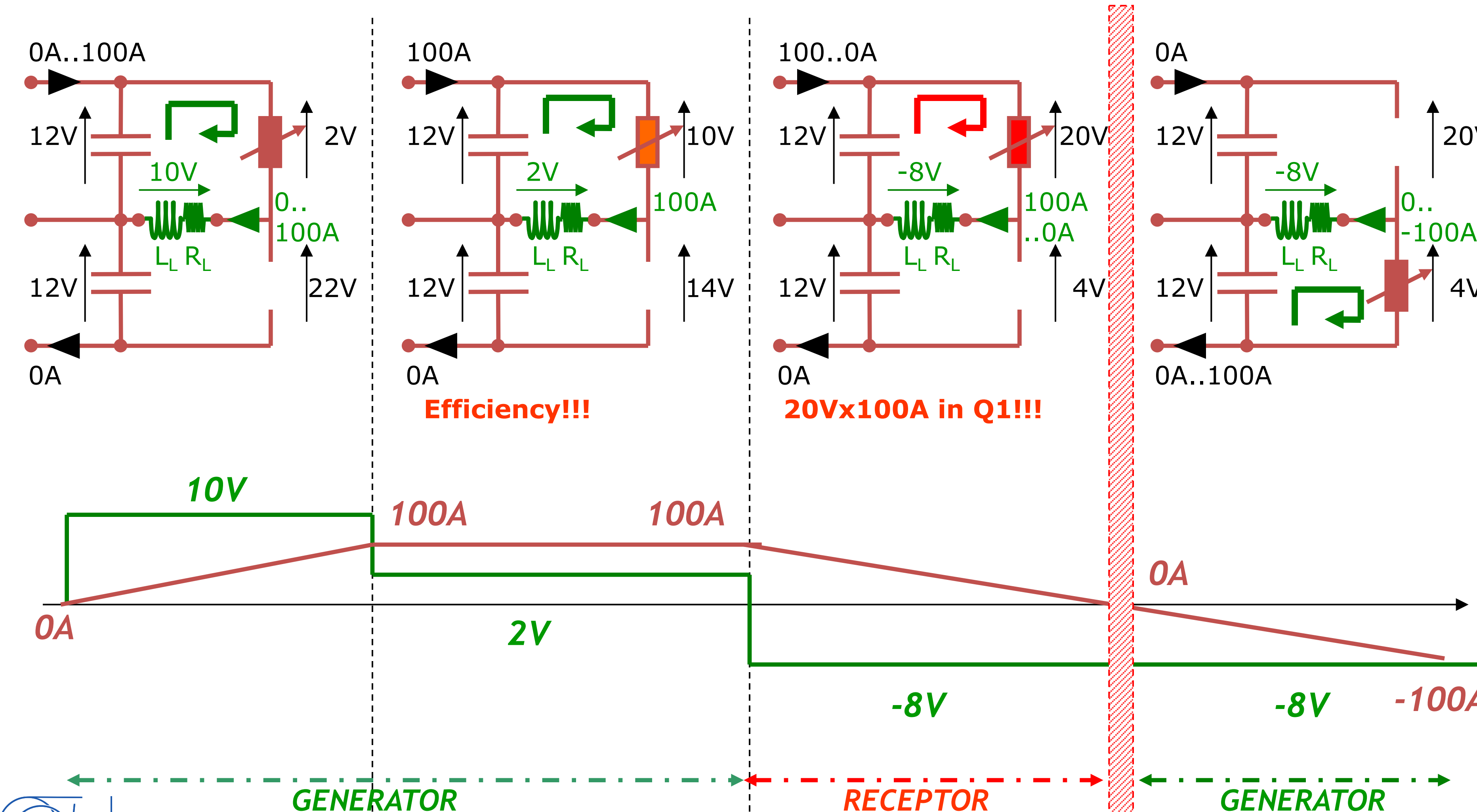
50 Hz transfo.
Optimal voltage output
(Galvanic Isolation)

Rectifier +
Double Output Low Frequency Filter

4-Q Linear Stage
(Dissipate Magnet Energy)

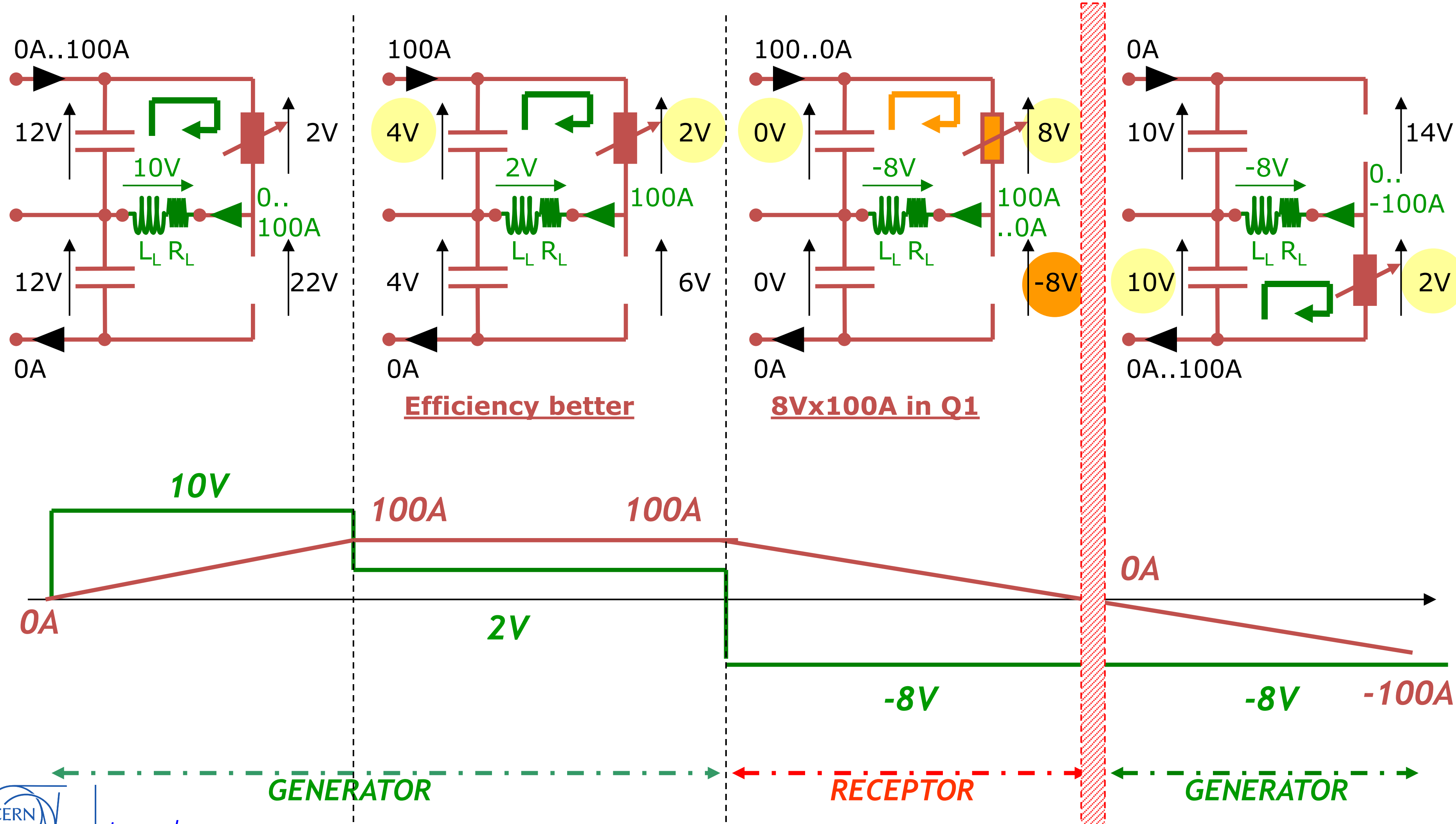
2. 4-Q Linear Stage: basic principle

Highlight: using double DC fixed voltage outputs



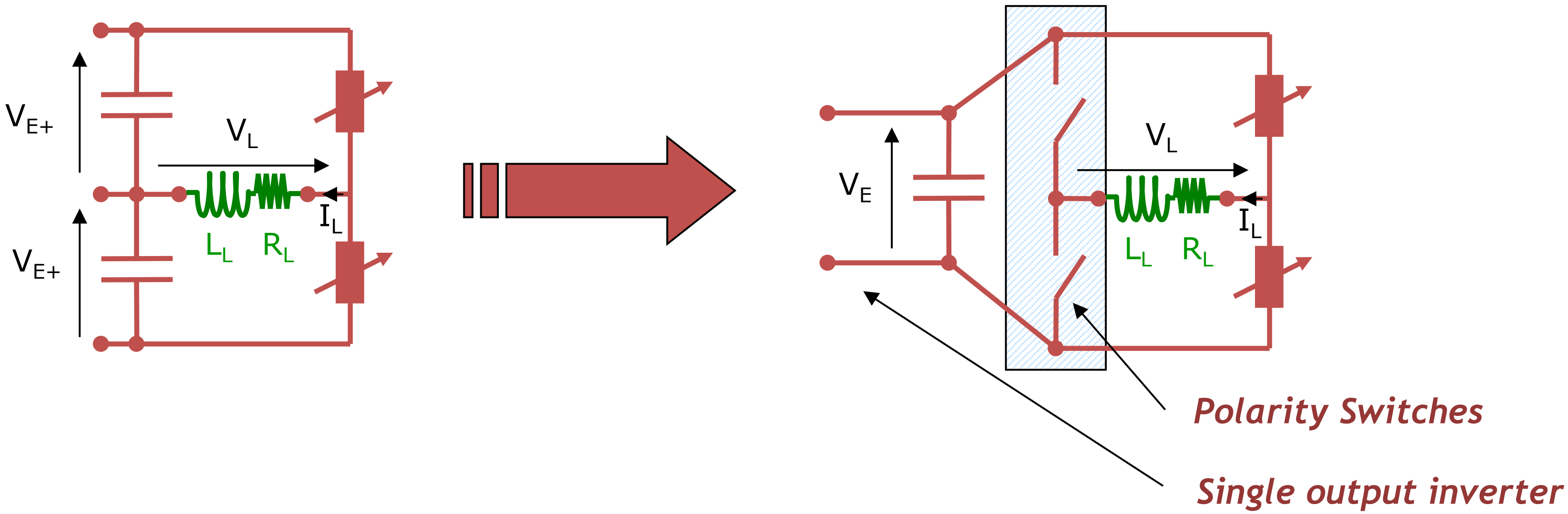
Highlight: using double DC variable voltage outputs

for better efficiency an losses reduced in receptor mode, *adequate if DC Bus fast enough*



2. 4-Q Linear Stage: basic principle (variation)

Highlight: using single DC variable voltage output



Remark:

- This solution is easier, from the inverter/input side, but leads to polarity new transitions which can be source of distortion, and finally lead to a complex 4-Quadrant stage.

2. Topology: 50Hz + 4-Q Linear

Advantages

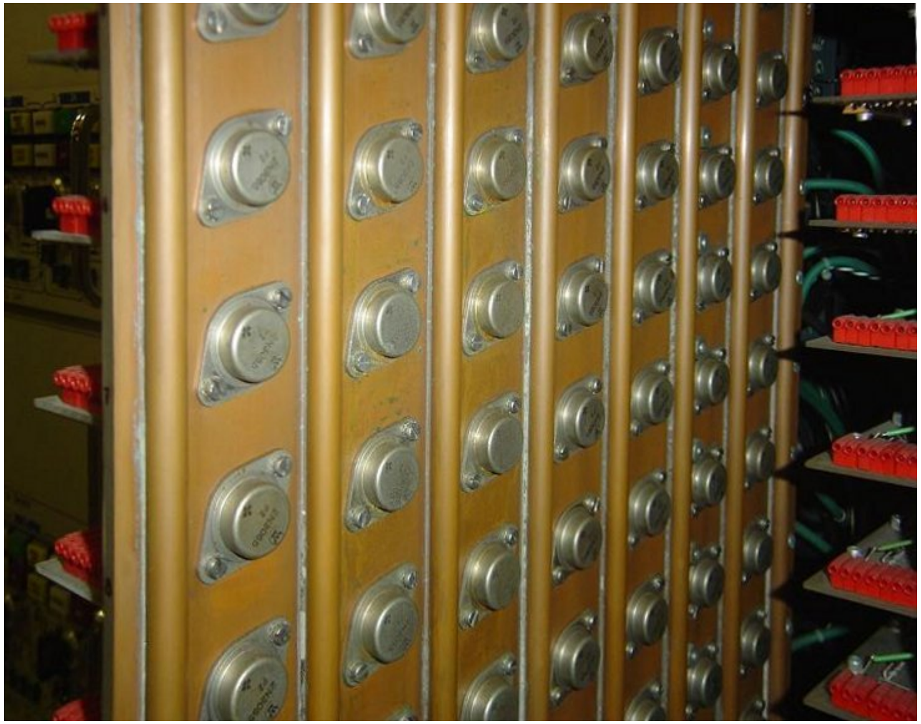
- Schematics and topologies are very well known.
- Simple schematic.
- Bandwidth (10 kHz relatively easily).

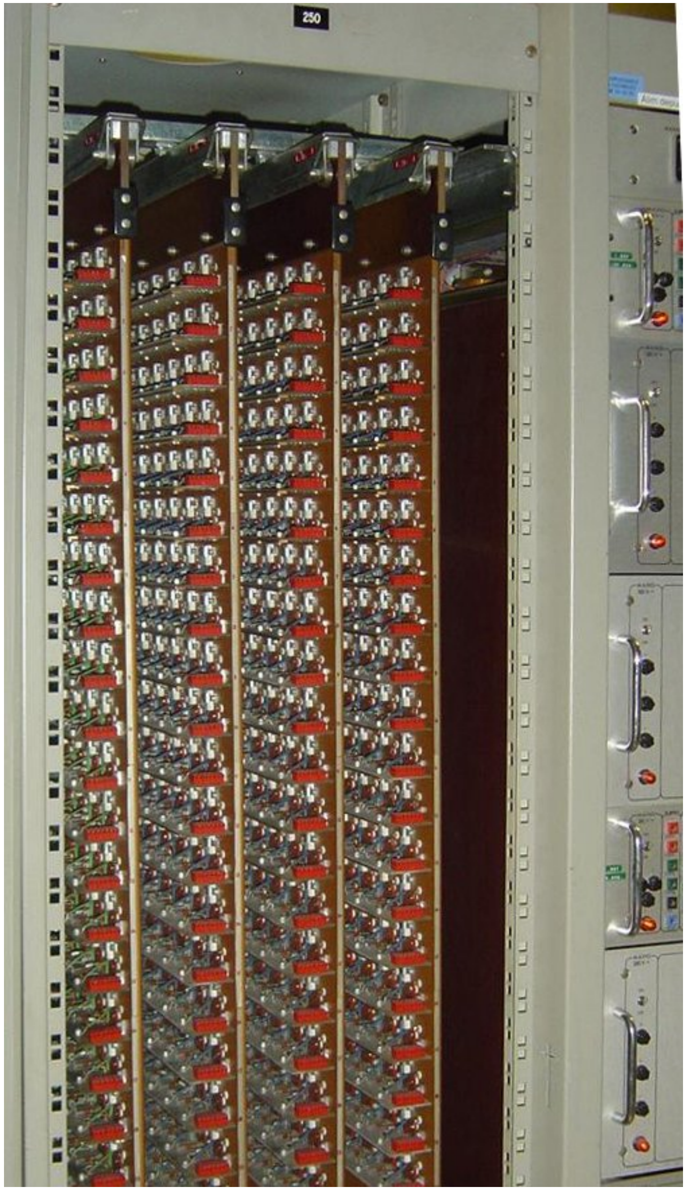
Drawbacks

- Energy recovered from the load is entirely lost & has to be handled.
- Efficiency very low in generator mode, sometimes increased using thyristor instead of diode bridge providing a variable DC bus at a cost of a strongly limited speed (50Hz).
- Size, weight of transformer and filtering elements.
- Distortion of the voltage @ 0A (circulating current can fix it).
- 4-Quadrant stage often realized with many transistors in parallel on old designs (50Hz tagged) with MTBF and avalanche failure issues.

Drawbacks *illustrated*

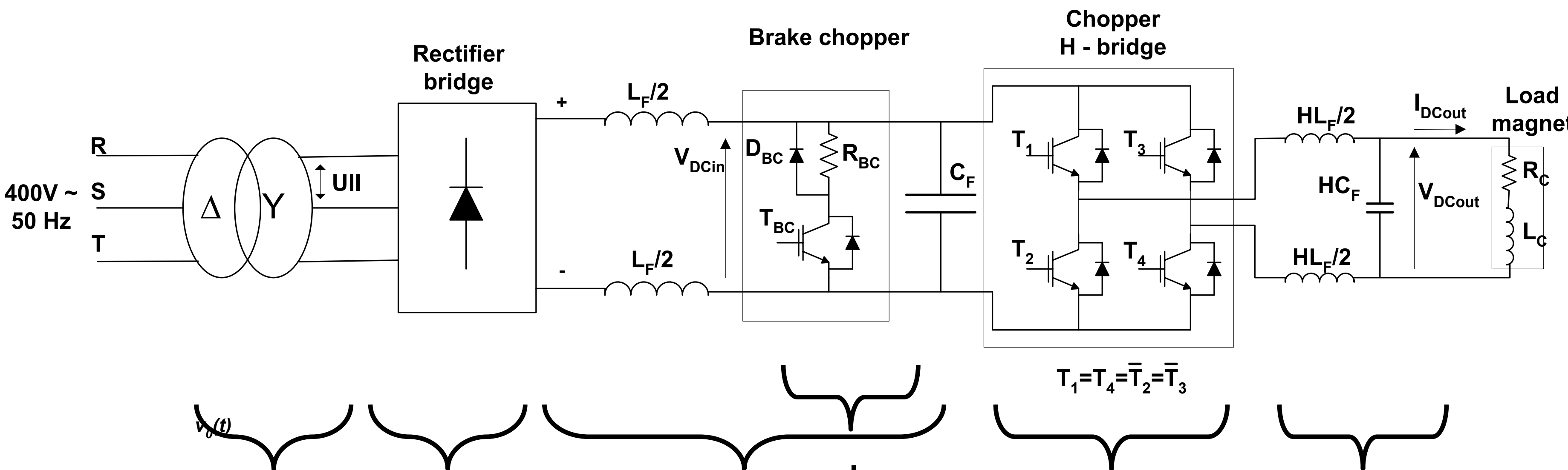
- "Sometimes realized with many transistors in //".





3. Topology: 50Hz + 4-Q Switching

Schematic



50 Hz transformer
Optimal voltage output
(Galvanic Isolation)

Diode bridge

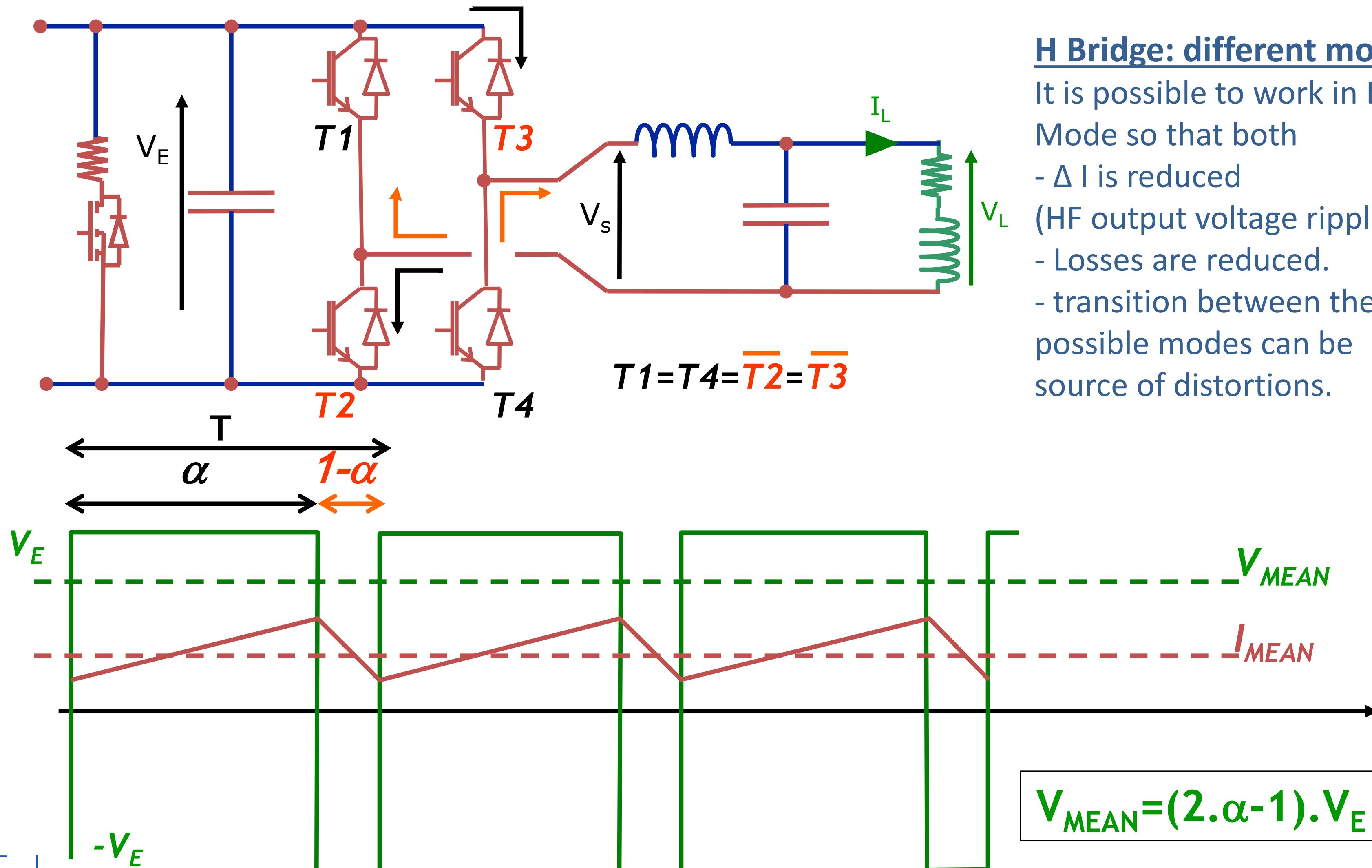
Low Frequency Output Filter
(Magnet Energy ➔1/2· C· V²)

Additional Brake Chopper (Optional)
(Magnet Energy ➔ Heat if in excess)

4-Q Switching Stage

High Frequency Output Filter

Highlight: Using natural reversibility of full (or H) bridge



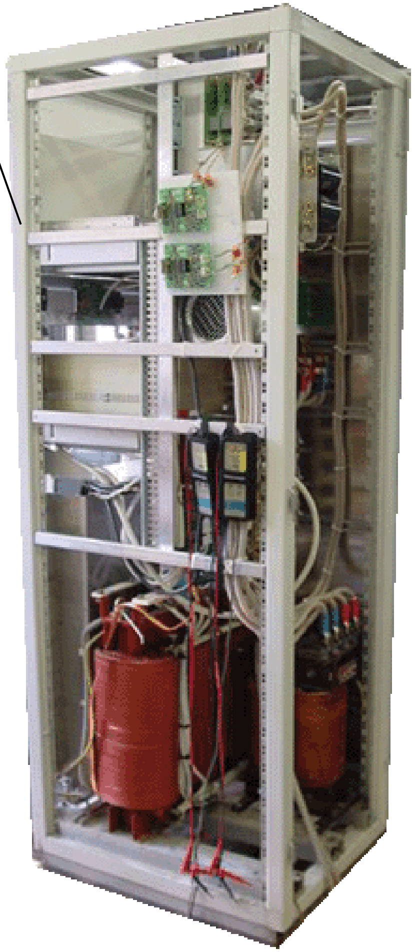
H Bridge: different modes

It is possible to work in Buck Mode so that both
- Δ I is reduced (HF output voltage ripple).
- Losses are reduced.
- transition between these 2 possible modes can be source of distortions.

$$V_{MEAN}=(2.\alpha-1).V_E$$

3. Topology: 50Hz + 4-Q Switching

±150A
±200V



Advantages

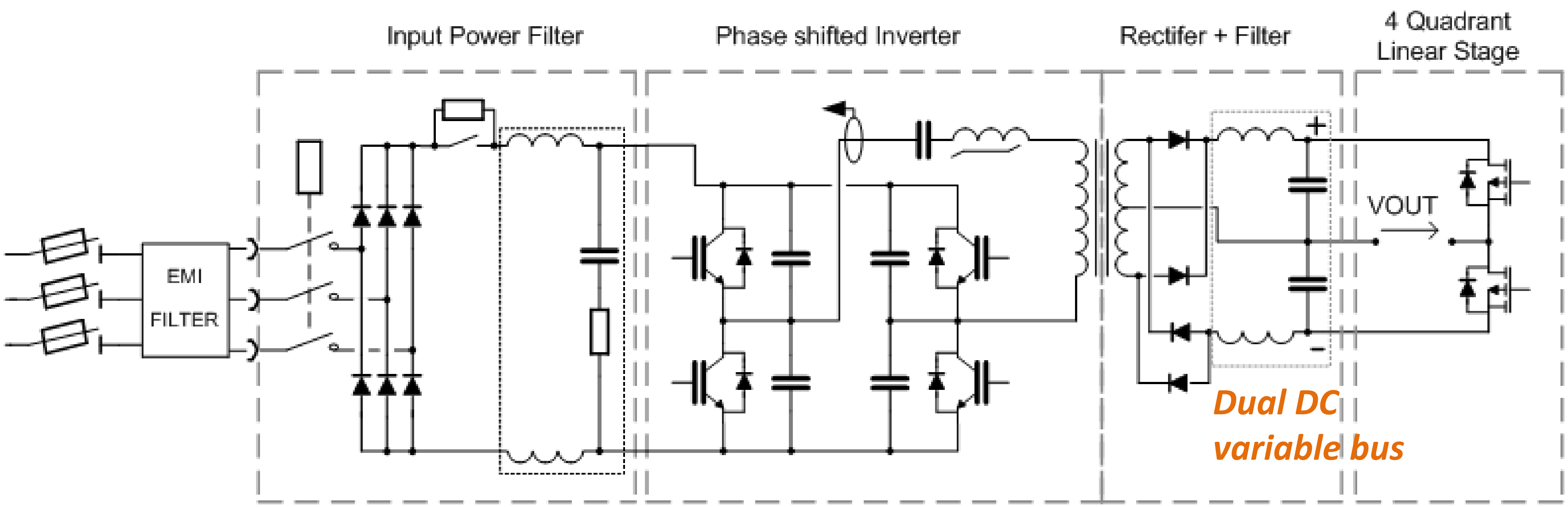
- High power, with part of magnet energy re-used.
- Well known topology → commercial elements.
- High bandwidth (10 kHz) (good AC mains rejection).
- No distortion (if H bridge not changing mode).

Drawbacks

- 4-Q H bridge switching load current (conduction & commutation losses).
- 50Hz LC-Filter un-damped by H bridge neg. resistor.
- Size, weight of transformer and filtering elements.
- EMC issues with H bridge "*close*" to the load.

4. Topology: Switching + 4-Q Linear

Schematic



300Hz L –C Filter

HF Transformer

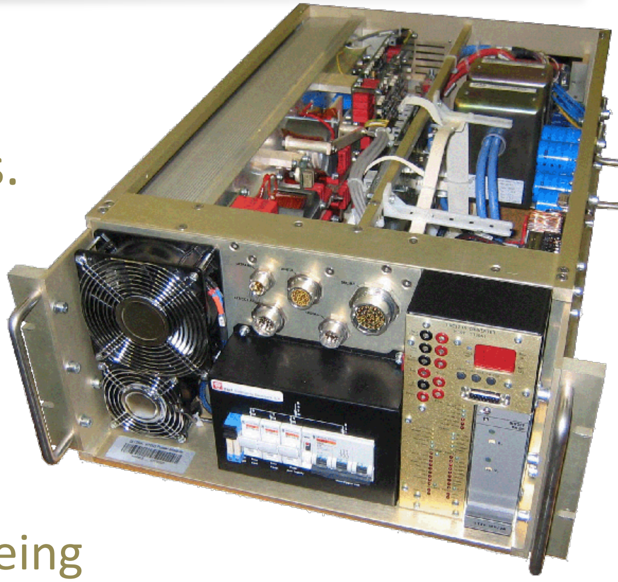
4-Q Linear Stage

High Frequency Soft commutation H Bridge

HF Filter + Rectifier

To be noticed: Dual DC Bus must at least follow the output voltage reference (speed) not to saturate the 4-Q linear stage !!

4. Topology: Switching + 4-Q Linear



Advantages

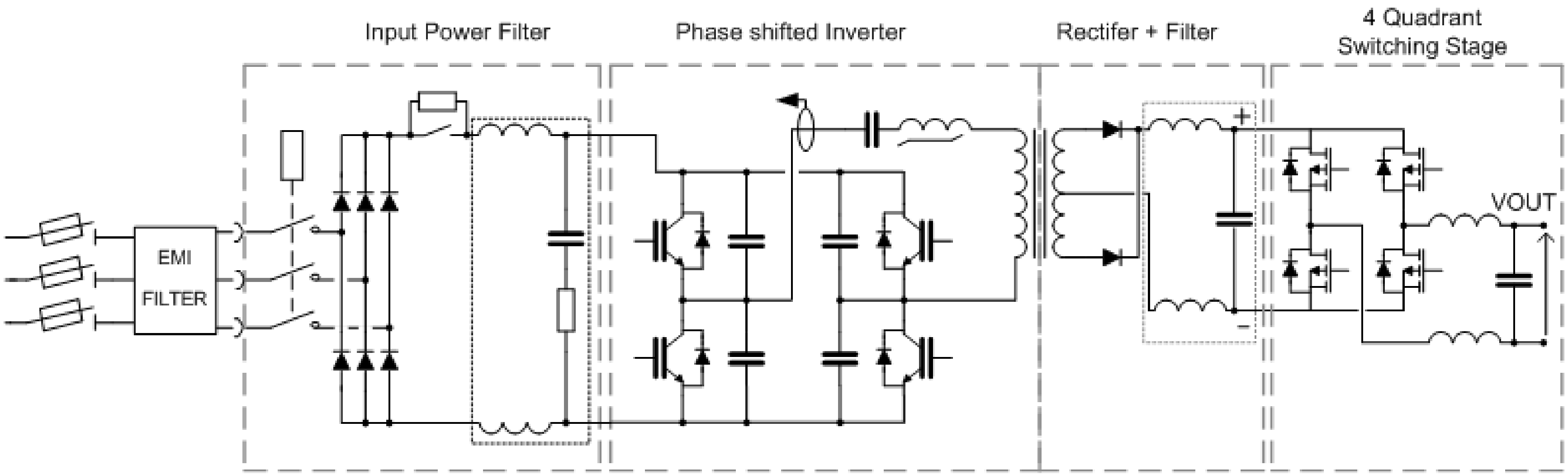
- Addition of 2 distinct well known topologies.
- High bandwidth with good AC mains perturbation rejection capability.
- Addition of a fast input DC bus makes possible to achieve correct efficiency:
  generator mode optimized, with on-transistor being almost transparent, 4-Q stage generating few conduction losses.
- EMC OK (soft commutation & 1x high frequency switching stage).

Drawbacks

- Energy recovered from the load is entirely lost & has to be handled.
- Distortion of the voltage @ 0A (circulating current can fix it).
- Dealing with Inverter, 4-Q Linear Stage and Circulation current loops can lead to some complexity and some limitations.

5. Topology: Switching + 4-Q Switching

Schematic



300Hz L –C Filter

High Frequency Soft commutation H Bridge

HF Transformer

HF Filter + Rectifier

4-Q Switching Stage

HF Filter + Rectifier

5. Topology: Switching + 4-Q Switching

Advantages

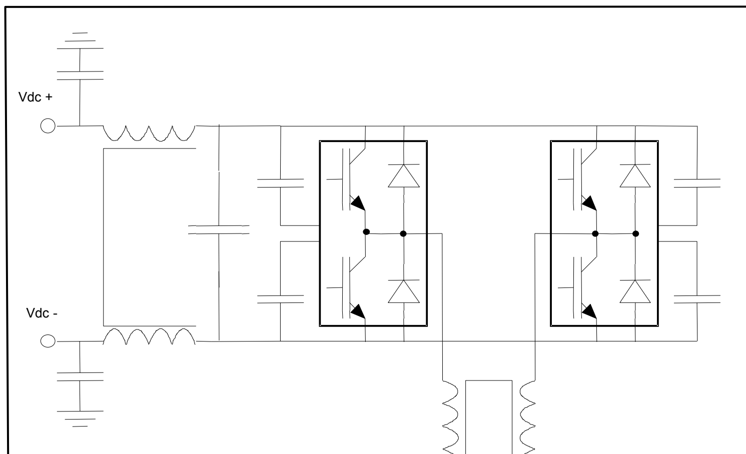
- Part of magnet energy re-used, making this suitable for pulsed application.
- Very well known topology.
- High bandwidth, with good AC mains perturbation rejection capability.
- No distortion of the signal.

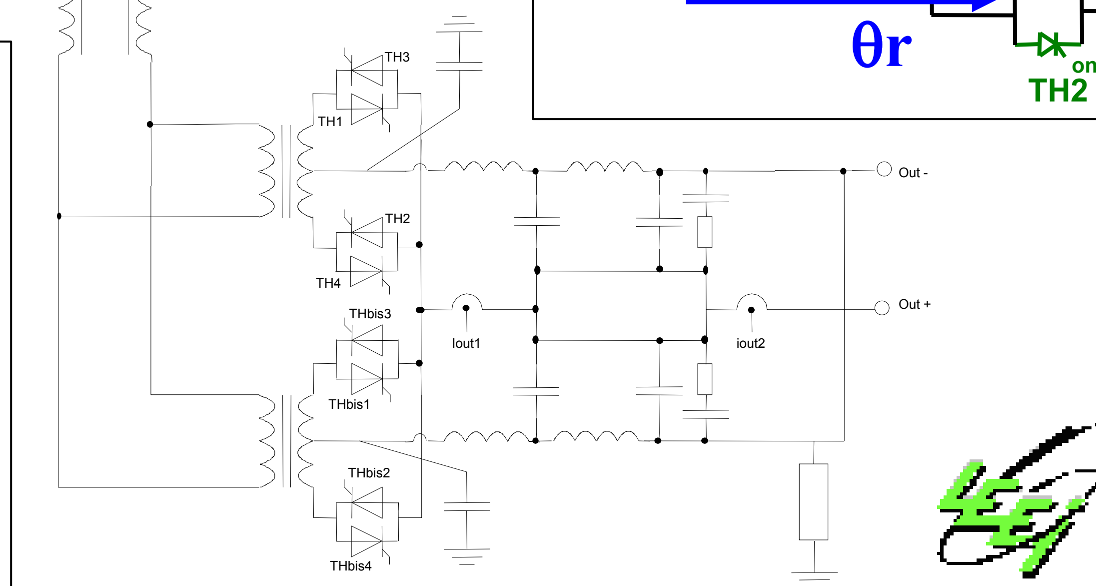
Drawbacks

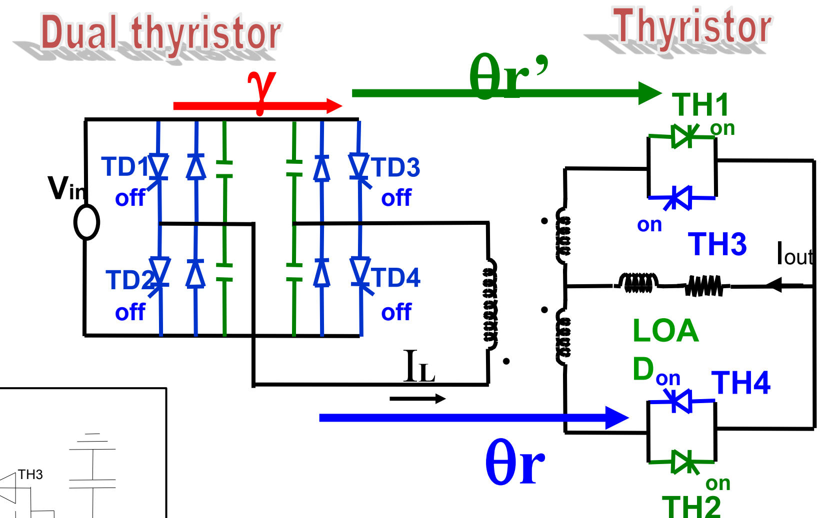
- 4-Q H bridge switching load current (conduction & commutation losses), with a total of 2 switching stages in series.
- EMC challenging, 2x high frequency switching stages.
- 2 high frequency filtering levels, number of components (duplication of the switching stages with drivers, control etc…)

Schematic (with Energy sent back to mains capability)

Exploring switching solutions for a "fully reversible" converter.







See Paper from CERN & LEEI for detailed explanation.

5.a Topology: Switching + 4-Q Switching (2)

Advantages

- Theoretically possibility demo of fully reversible with energy sent back to mains (AC thyristor bridge to be added to the prototype).
- High frequency power converter (low volume and high dynamic performance).
- High bandwidth, with good AC mains perturbation rejection.
- No distortion of the signal.

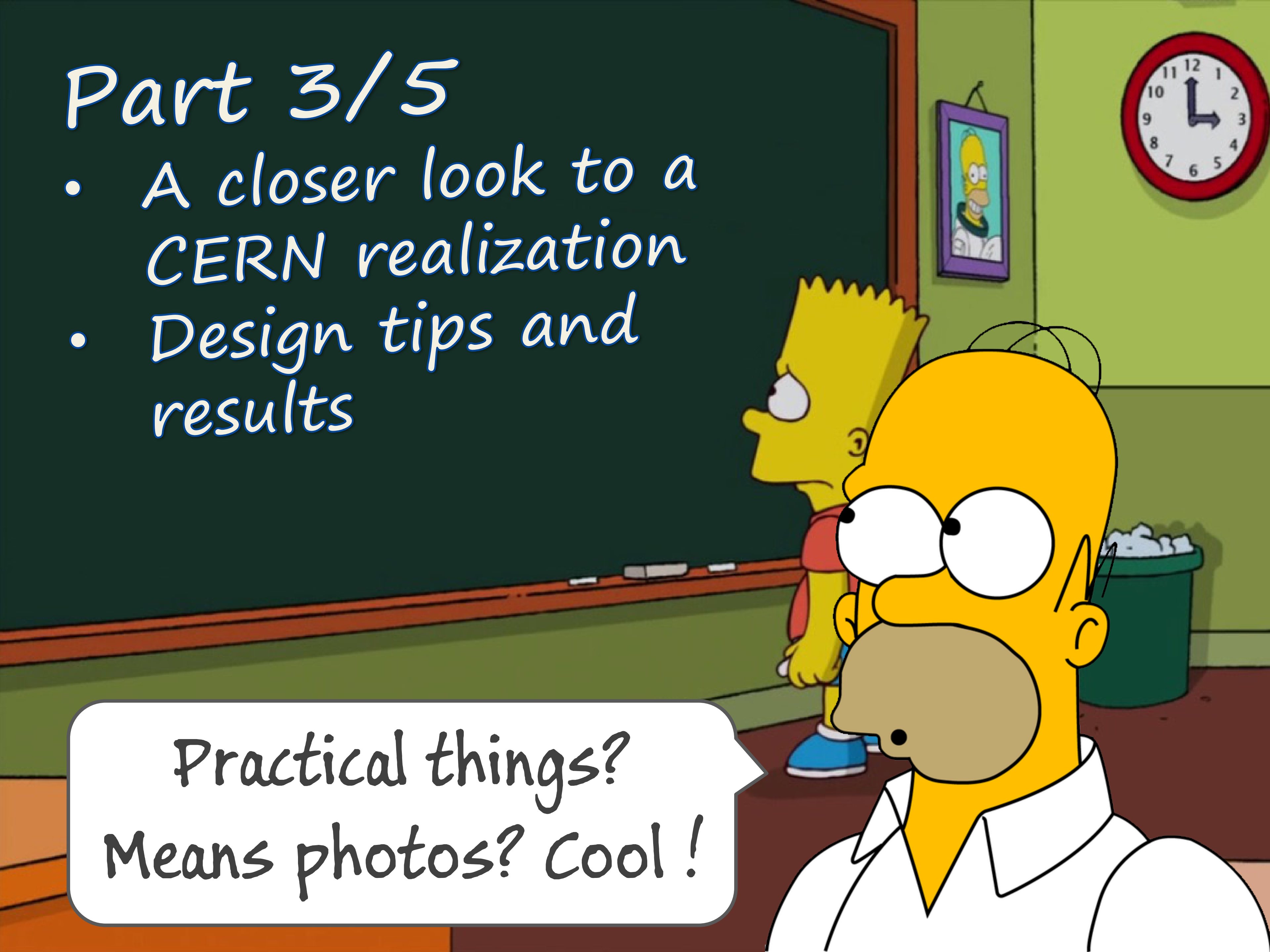
Drawbacks

- Complex control & topology.
- *This converter stayed at design prototype stage, and was not deployed in any machine at CERN since judged too complex / risky.*

±600A
±12V

Part 3/5

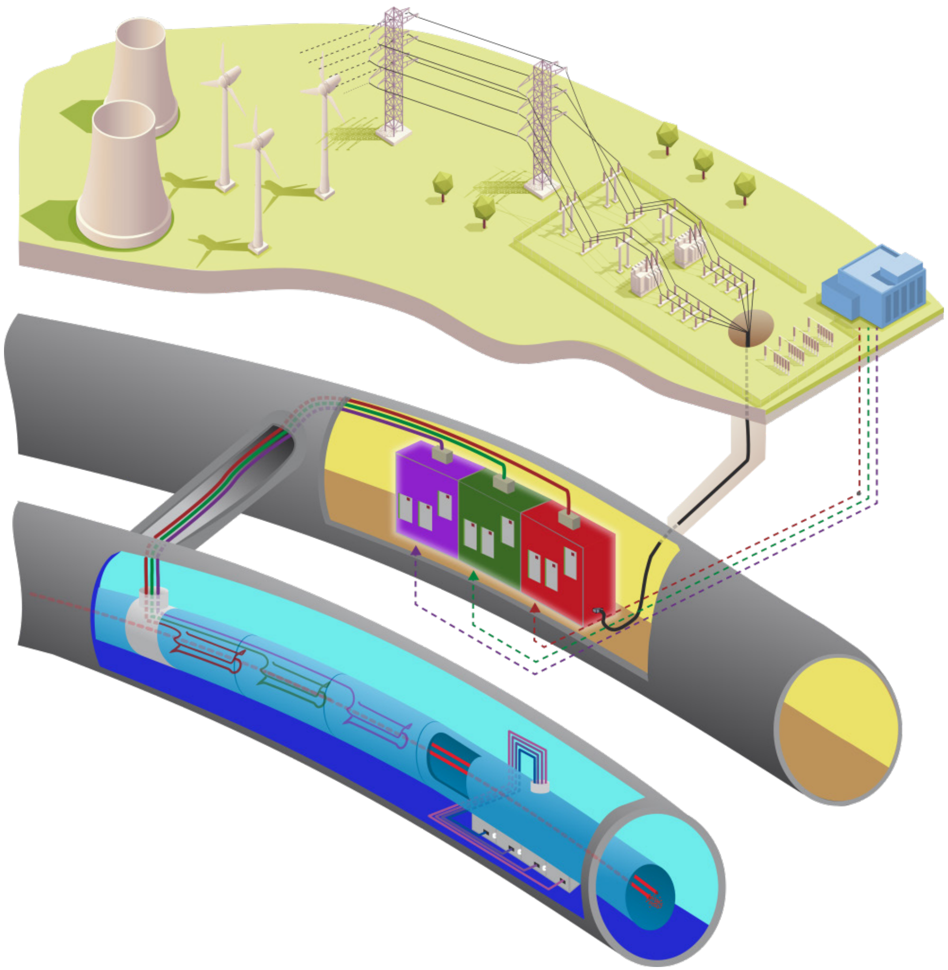
- A closer look to a CERN realization
- Design tips and results



LHC Machine, using 4-Quadrant converters

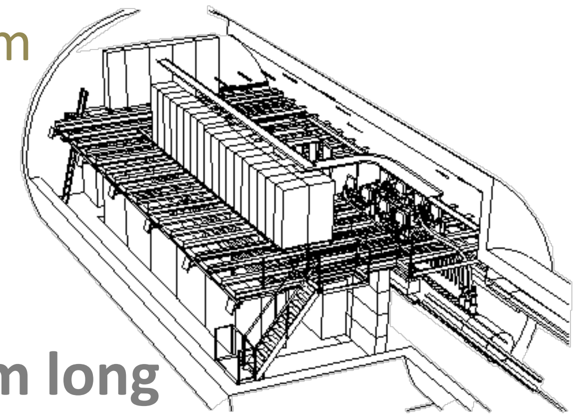
With its superconductive loads, LHC required around 1500 4-Quadrant converters ending up with 4 different types.

- Correctors of a slow machine in the range of [60A; 600A], with no strong interest in energy recovery.
- Installation in a tunnel, with a strong interest in low level of losses. (medium current < 600A)
- Large quantities, difficult and long access to the converters, with strong interest in high reliability.



LHC Machine, using 4-Quadrant converters

Noise emitters and sensitive clients installed close to each other.



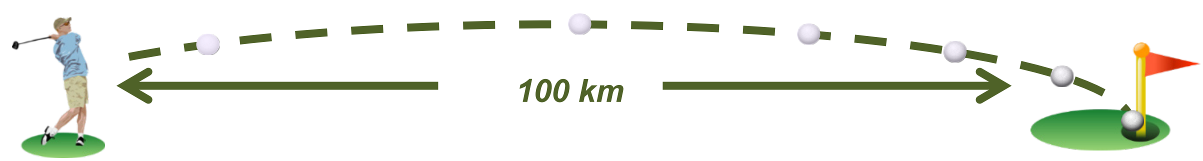
- Installation of several sensitive to noise system (Analog down to nanovolt quench systems) in tiny areas (UA, RR), close to converters.
- Low EMC noise emission is of great interest.

Load being magnet chain of more than 2 km long

- Easy coupling (electrical and magnetic) between windings in cryostats requiring low noise (EMC) generators.

Converters operating at current precision at the level of ppm.

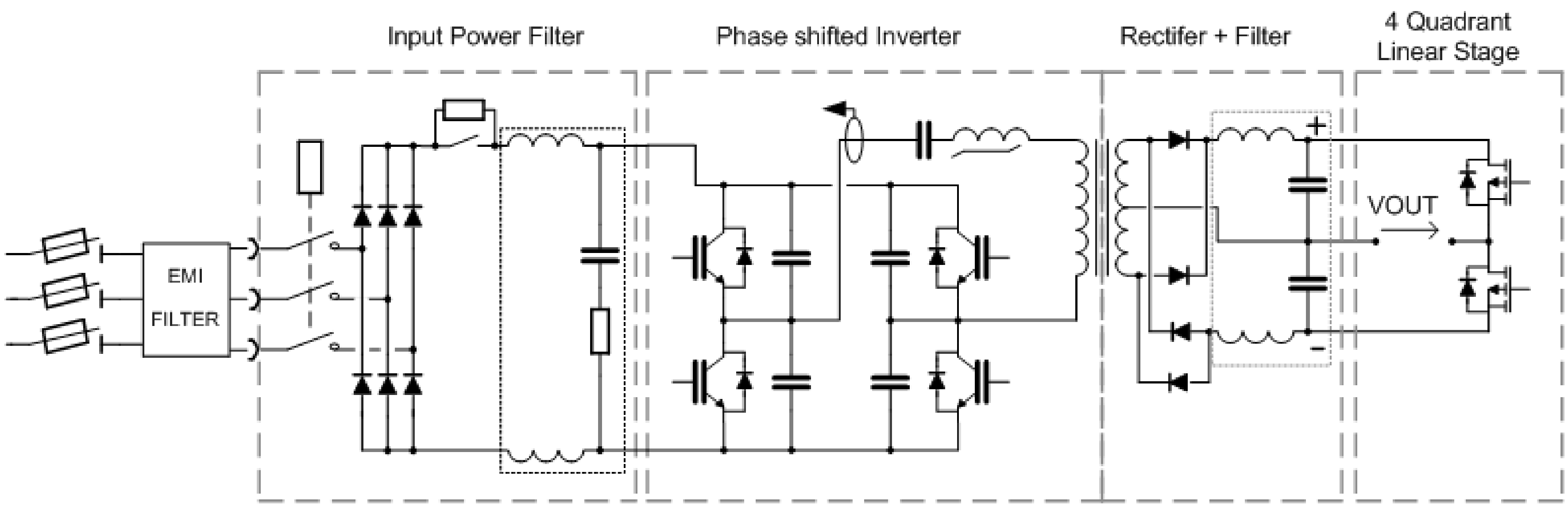
- Being precise at the "one part per million level" means achieving this … with every shot!



→ Low EMC noise emission is a key parameter for LHC.

General approach each designer adopted was:

➔ Switching stage + 4-Quadrant linear stage.



Main advantages initially expected *and indeed* obtained:

- **High Efficiency possible** (soft commutation inverters, 4-Quadrant stage not leading to high level of losses in generator mode).
- **Very low level of output noise**, differential and common mode.

LHC Machine, using 4-Quadrant converters

4 large families, 3 external companies: CIRTEM, EEI, TRANSTECHNIK , in addition to CERN teams.

LHC60A-08V
4-Quadrant
730 Units
CERN Design

LHC120A-10V
4-Quadrant
300 Units
CERN Design

LHC600A-10V
4-Quadrant
400 Units
EEI-CIRTEM

LHC600A-40V
4-Quadrant
40 Units
Transtechnik

LHC ±120A CERN Design & Results

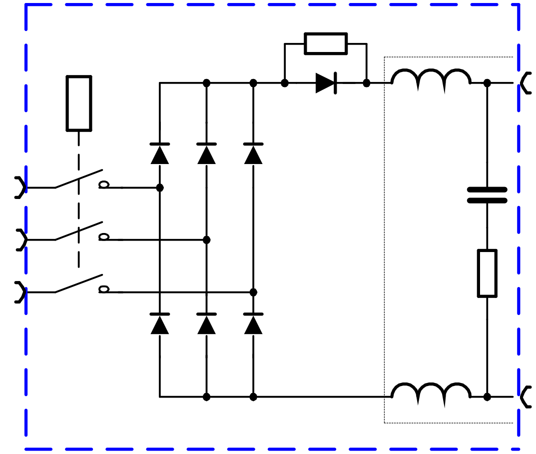
A CERN design in detail:

LHC ±120A ±10V Converter

- ±120A ±10V.
- Air cooled converter.
- 50 kHz inverter switching frequency
- 1 kHz voltage bandwidth.
- Load time constant range [0.1; 1050] seconds.
- 300x installed in LHC.

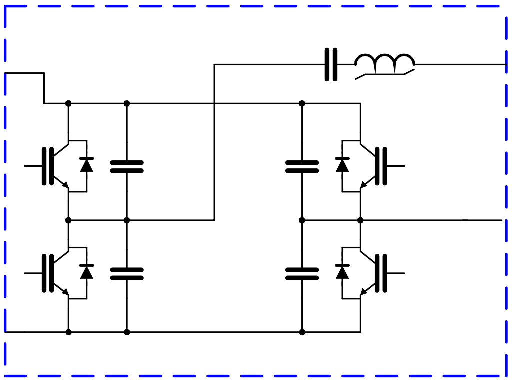
LHC ±120A Topology Choice

AC-DC



- 3 phases + Neutral.
- 1400V Rectifiers (AC rectification) .
- 70Hz Input filter (damped with C-4C) to give a flat 540V DC (around -20dB on 300Hz).
- Soft start based on "R + switch".

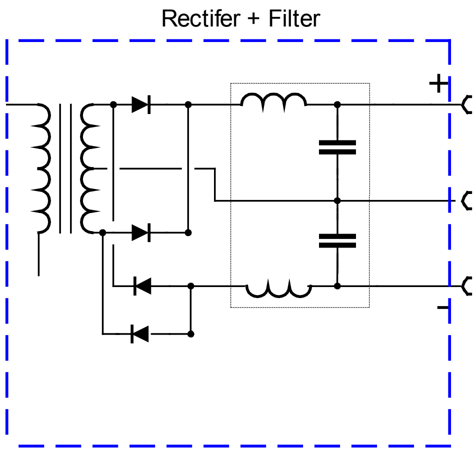
High frequency soft commutation inverter



- Fixed switching frequency (50..100kHz).
- ZVS operation through Phase Shifted.
- ZCS for lagging leg possible (saturable inductor)
- 1.2kV IGBT Full Bridge.
- "Voltage" or "current" regulation mode possible.

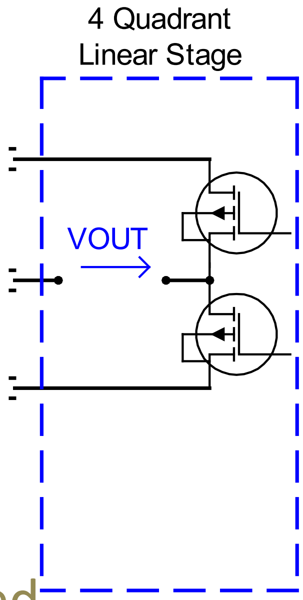
LHC ±120A Topology Choice

Rectifier + DC Filter



- Schottky rectifiers.
- High frequency ripple can be easily filtered.
- Double LC cell at 5..10 kHz cut off frequency.

4-Quadrant Linear Stage (4-QLS)



- 4-Q Linear Stage based on several Power Mosfets mounted in parallel for each leg (top and bottom).
- Use of 4-QLS as an active filter.
- Use of 4-QLS to pre-load inverter (continuous mode).
- Circulating current always present but value depending from load current (no mode change transition, both DCDC outputs always minimum loaded.

LHC ±120A Topology Choice

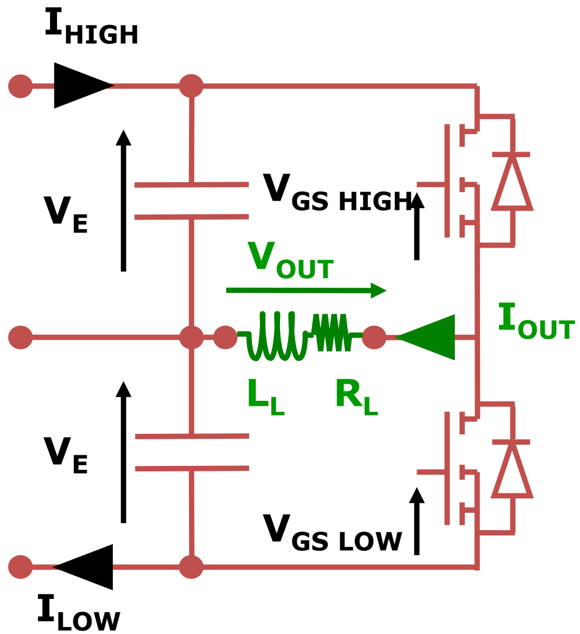
Highlights on 4-QLS:

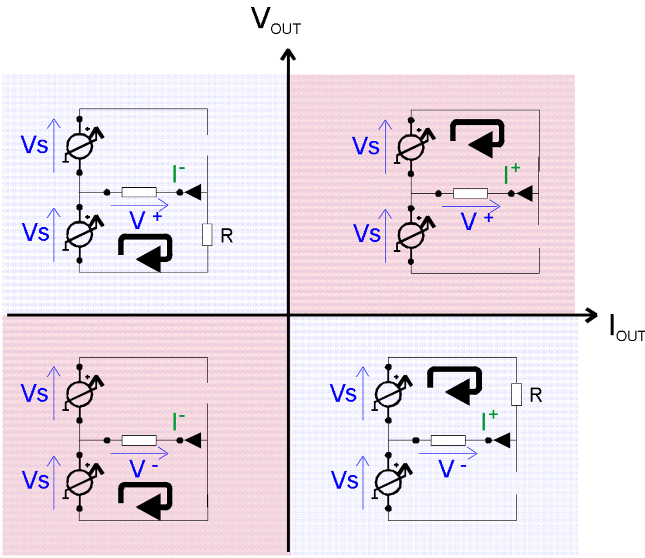
- A double power source programmable via inverter control (Dual VE source).
- 2x equivalent MOSFETS, Top & Bottom leg, used as switch and/or programmable resistor depending on generator /receptor mode.
- A command based on control rules :

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

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

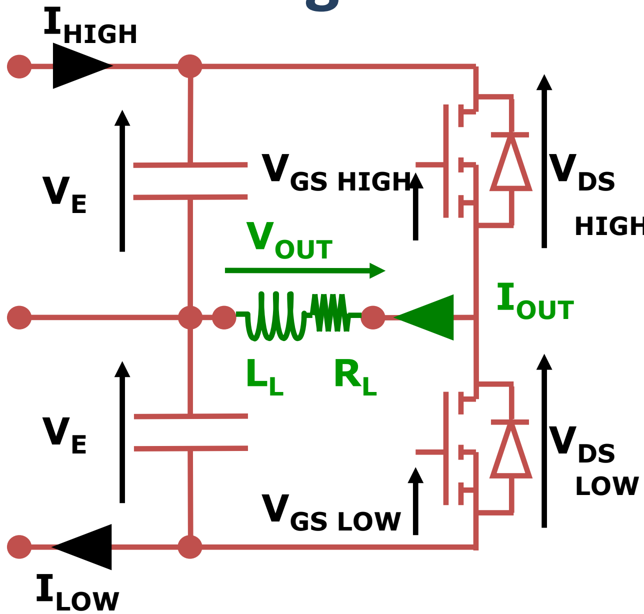
R_{HIGH} & R_{LOW} are equivalent MOSFET resistance

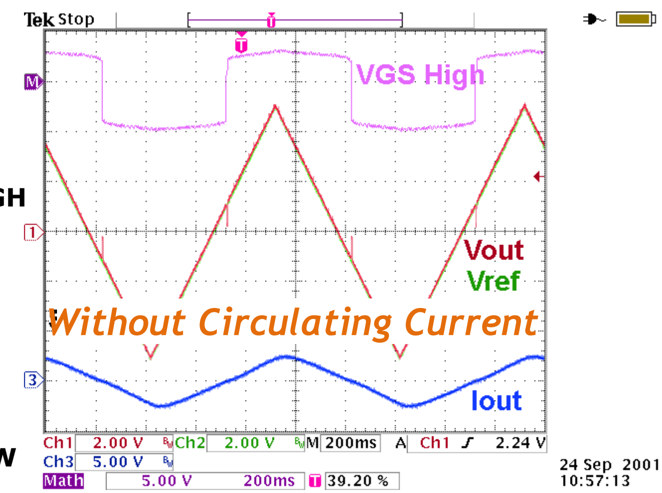


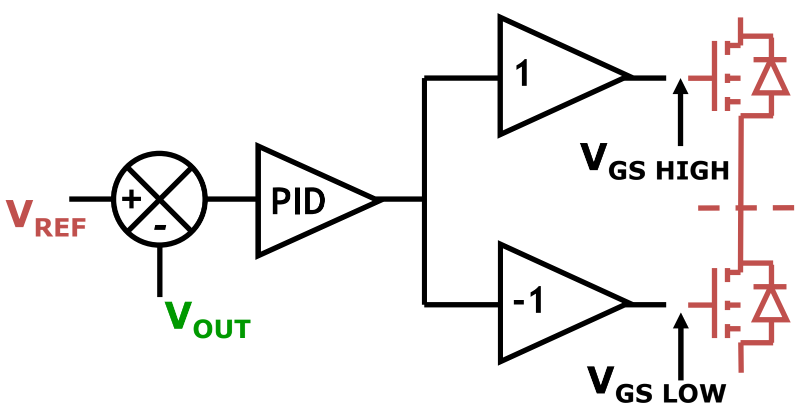


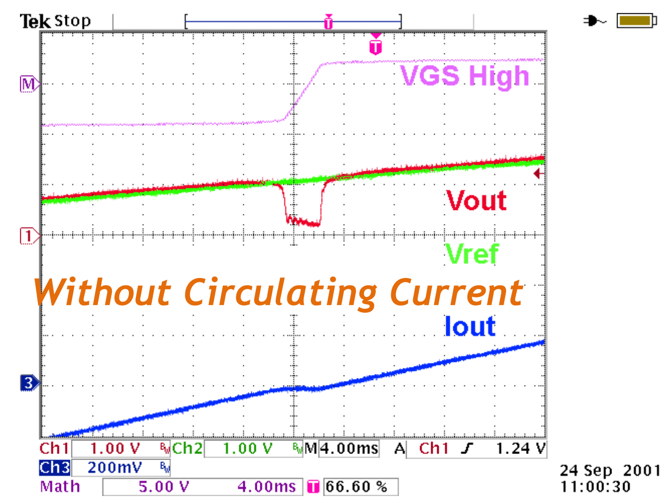
Limitation of the linear stage…

- Main analog loop cannot provide needed step for biasing MOSFET (-3V to + 3V).
- Playing with fixed bias is a bad idea !!! Discrepancies on $V_{GS\ ON}$ ±1V !!!



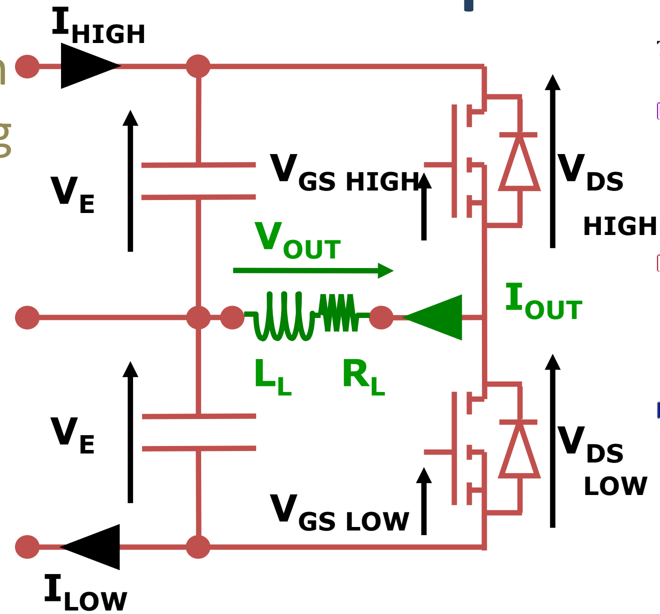


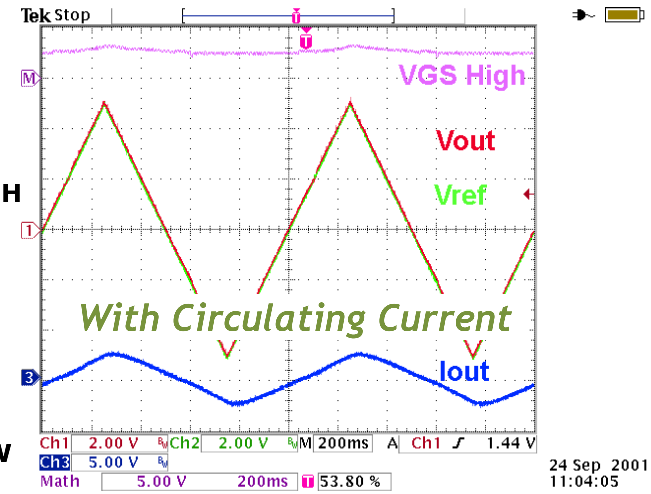


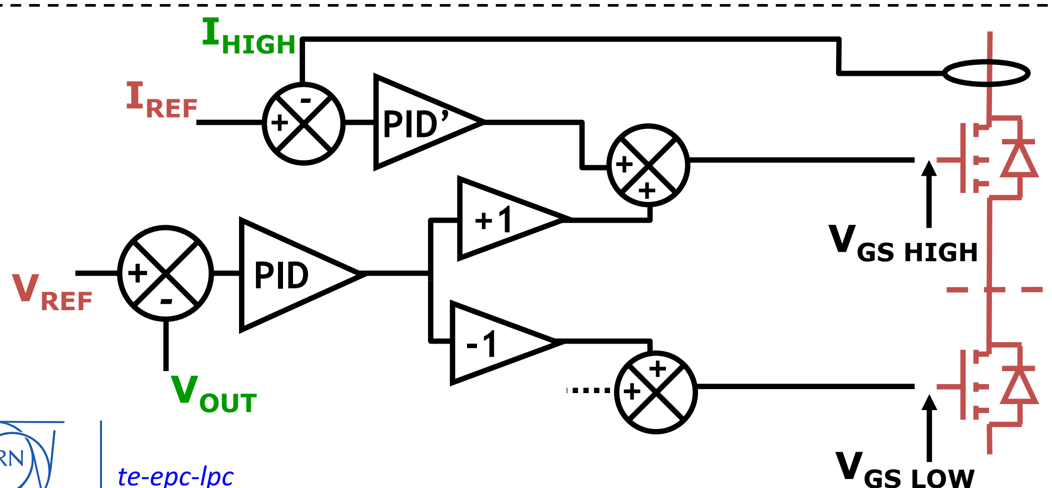


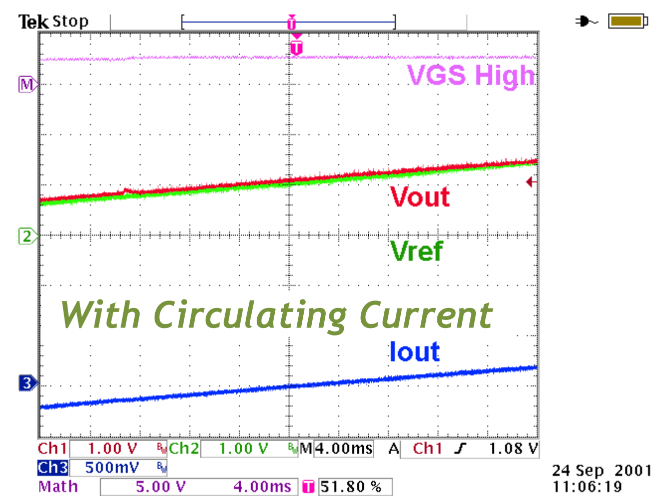
…adding circulation current loop.

- To avoid 0A distortion crossing , a circulating can help, biasing MOSFET gates.
- These additional loops (one per leg) must not perturb main loop.
- $I_{Circulation}$ can vary.









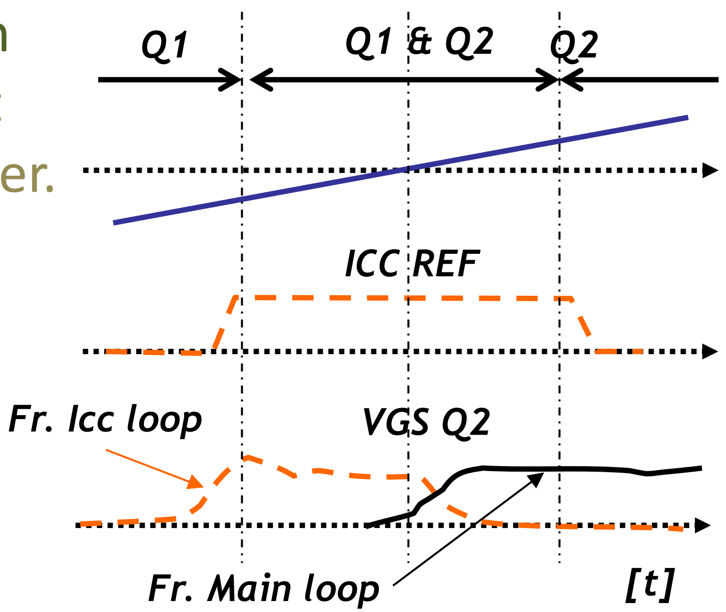
Different approaches:

Circulating current always present, its value changing with I_{out}:

- Easier control (reference is only smoothly changing with I_{out}).
- Inverter / DC Bus reference must always be set for this circulating current being possible, leading to higher losses in receptor mode.
- "Continuous" mode (Gate of each side MOSFET always biased).

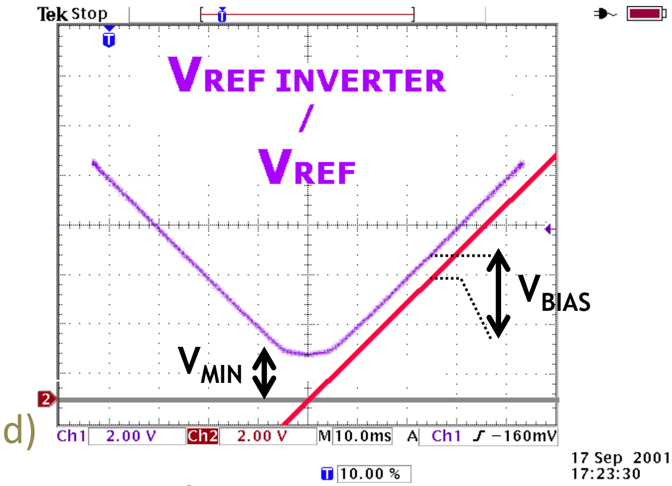
Circulating current present when close to a potential transition:

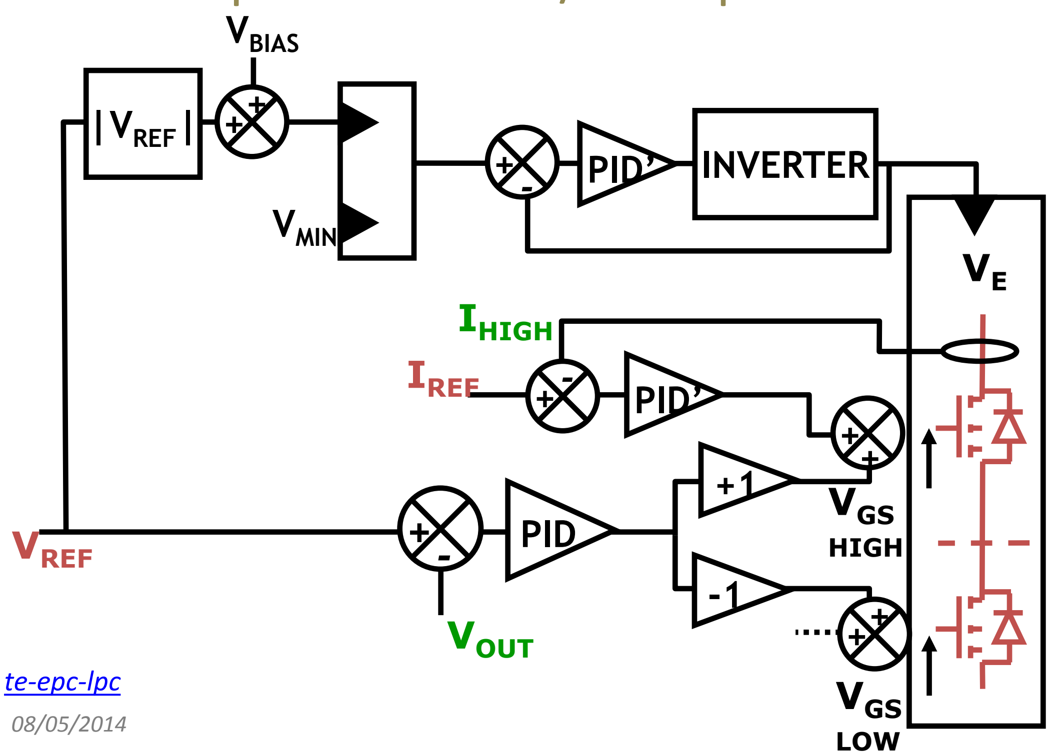
- This solution saves a lot of energy when recovering, since inverter doesn't inject power in MOSFET when absorbing power.
- dI/dt Limitation exists, since if too fast, circulating current doesn't have time to appear and MOSFET Gate are not well biased.

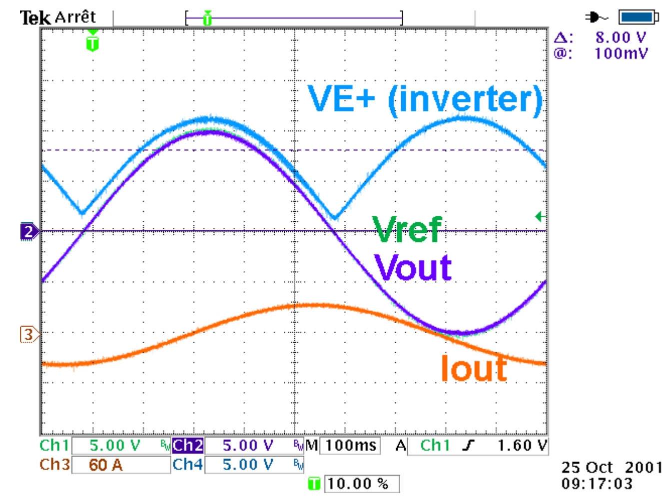


Dual DC Bus REF built according to:

- $V_{BIAS\ MIN}$ not to saturate MOSFET
- $V_{BIAS\ OPT}$ For 4-Q Linear stage with better rejection of mains disturbances and 300 Hz
- V_{MIN} & $I_{circ.\ MIN}$ to ensure minimum load
  (Conduction mode un-changed, 4-Q acting as a dummy load)
- VE Loop to be faster / transparent than 4-Q stage loop



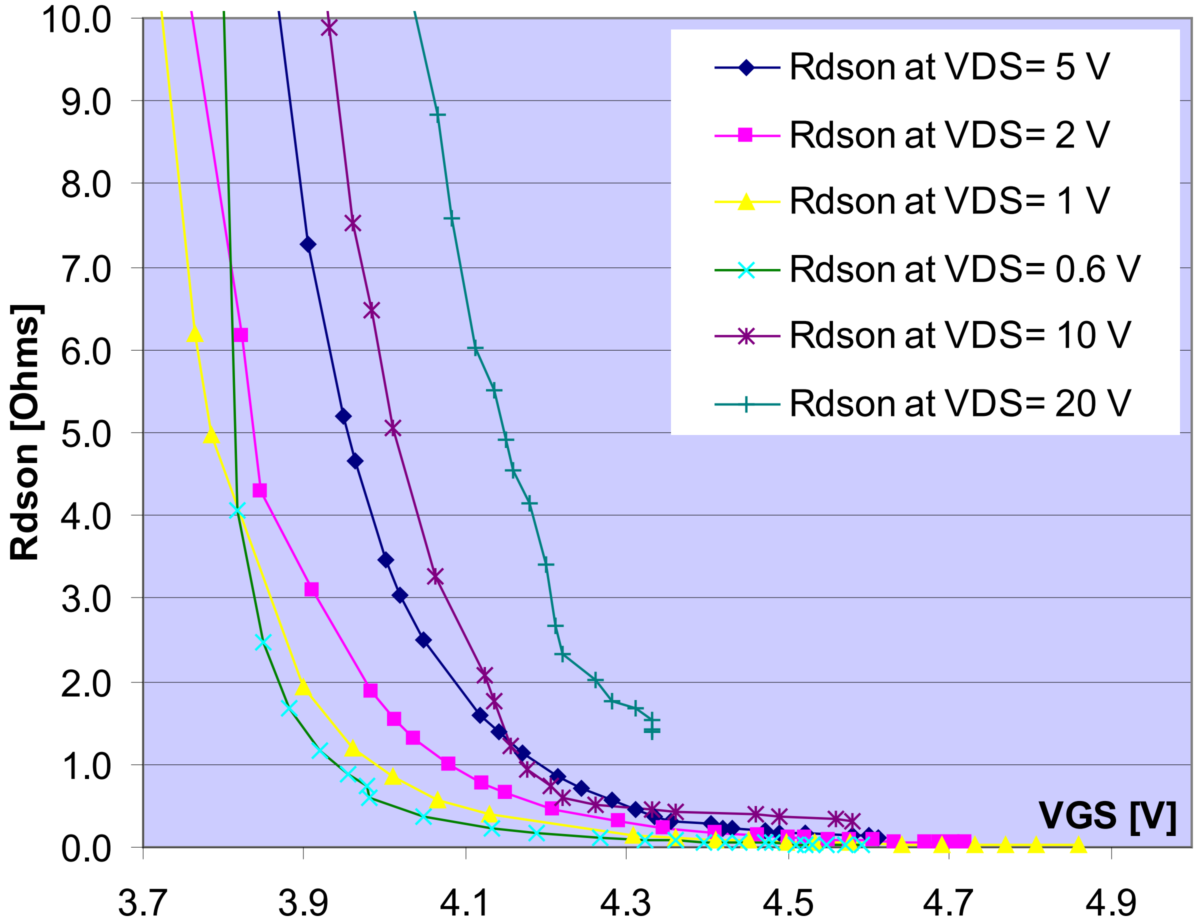




Controlling a MOSFET as a variable resistance: a challenge

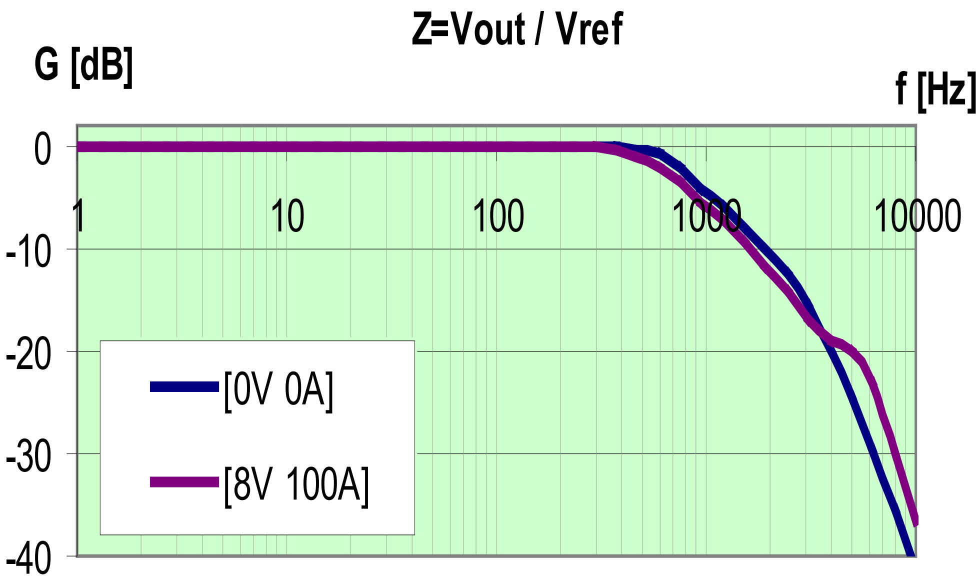
MOSFET is difficult to control directly from the main loop to the gate, as a variable resistance. Indeed gain is from virtually 0 if saturated to thousands when almost opened.

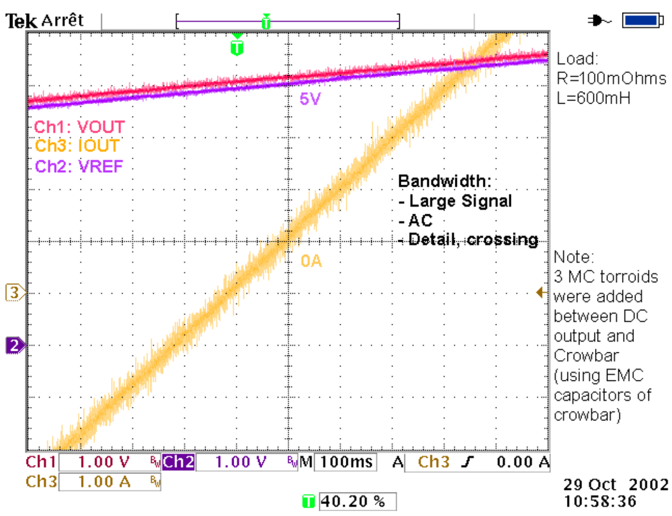
Circulating current and V_{BIAS} value allow to limit the operating equivalent resistance area, for an easier control.



Performances as a voltage source

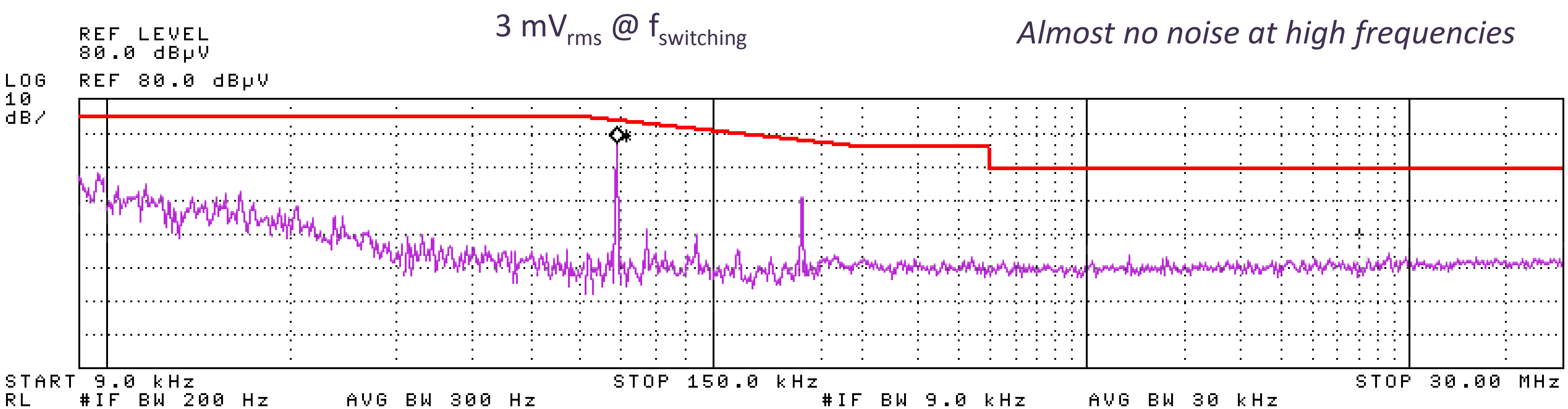
- No distortion @ 0A, thanks to circulating current.
- High bandwidth (could be higher in small signal: 4-Q linear stage)
- Good bandwidth in large signal (Dual voltage source speed + 4-Quadrant linear stage)



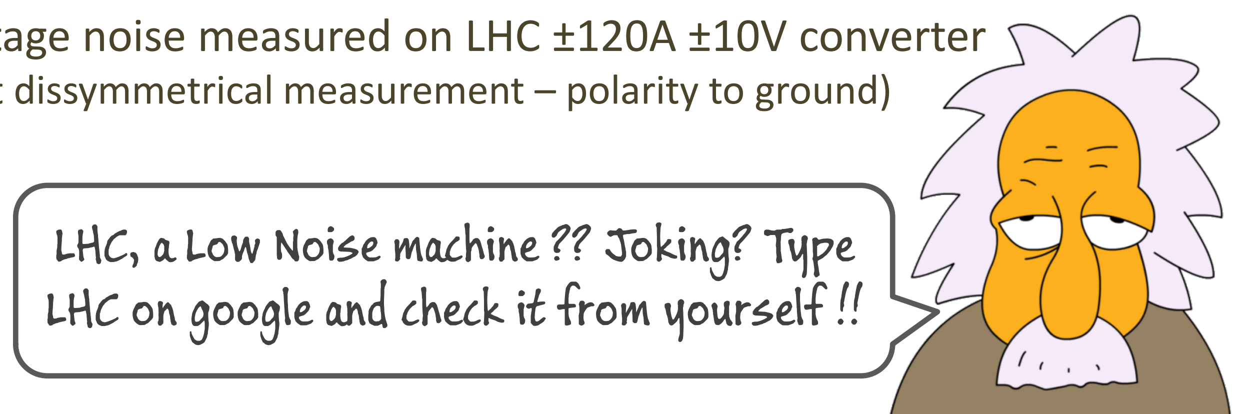


Performances as a low-noise system

- EMC is very well managed, with strong focus on “cleaning inverter side”, being the only noise-generator of the topology presented.
- EMC noise: common mode and differential very low, AC & DC Side.



Output voltage noise measured on LHC ±120A ±10V converter
(output dissymmetrical measurement – polarity to ground)



Part 4/5

- Tips on 4-Q converter family
- Magnet protection
- Testing models

Magnet protection applied to 4-Q family

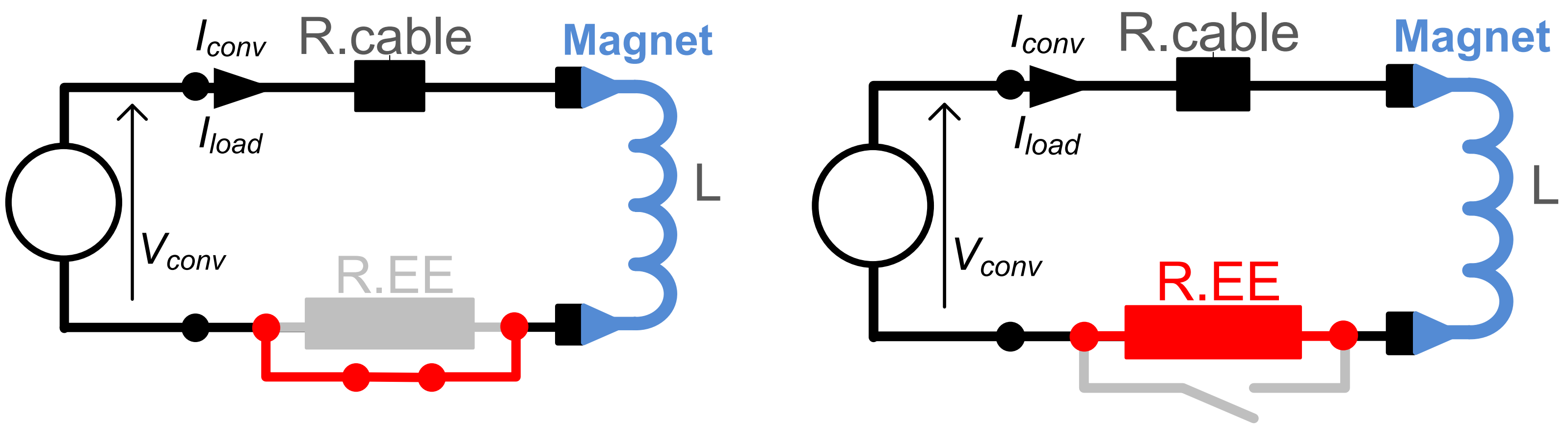
- Magnet protection versus 4-Quadrant converters

Practical issues on 4-Q converters reception

- Qualification of several design (even if close) for a final operation on superconductive magnet, with a wide range of time constant, without any early and easy access to the costly – cryogenic - loads !
- Test of **1500** Converters @ CERN : Need to find some efficient and compact tests giving much information on the converter integrity.

Magnet protection widely spread principle @ CERN

Power Converter must always ensure a safe path for magnet current for the Energy Extraction System to work whatever…



Energy Extraction System: Inactive

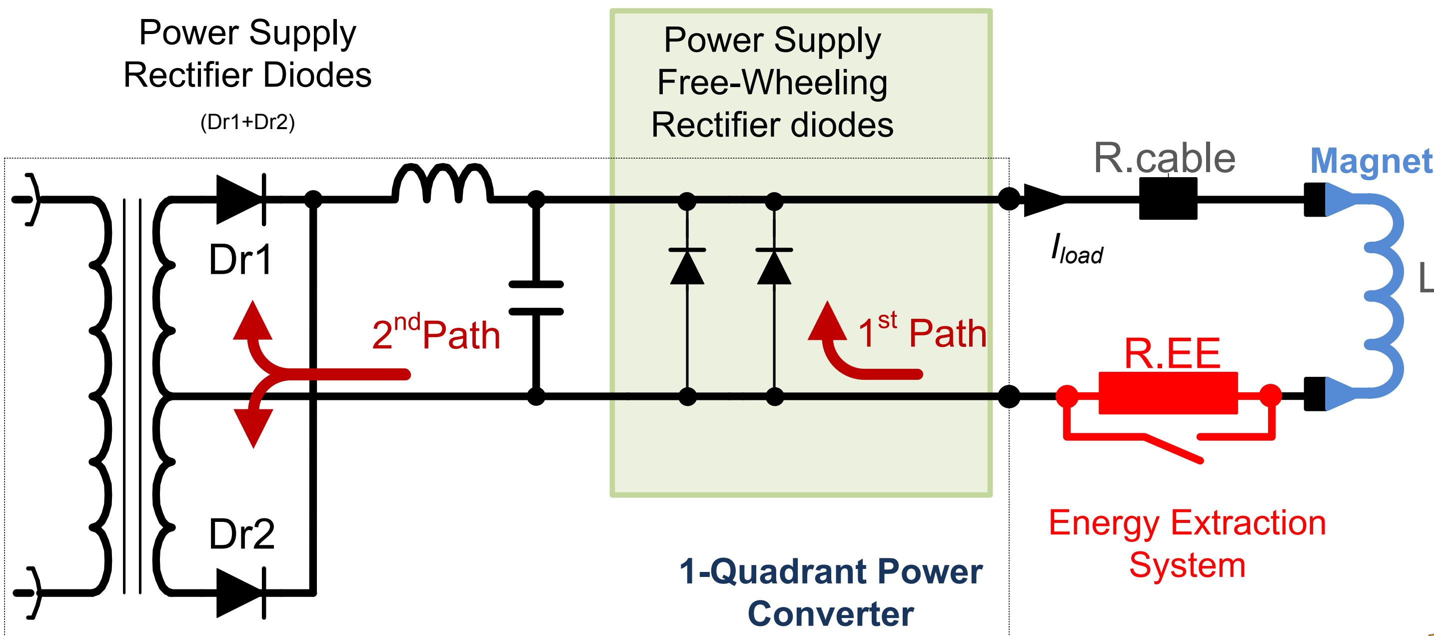
Energy Extraction System: Active

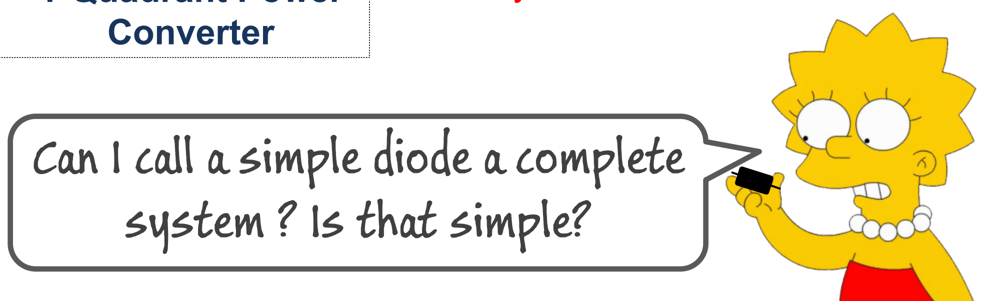
… its state: safe, **faulty**, even **disconnected from mains**!

1-Q Converter typical protection

Safe Path ensured for Power Converter side with a diode only

- Simple, efficient, high MTBF *system*: 1 component only !!!
- Even redundant most of the time with Converter Components

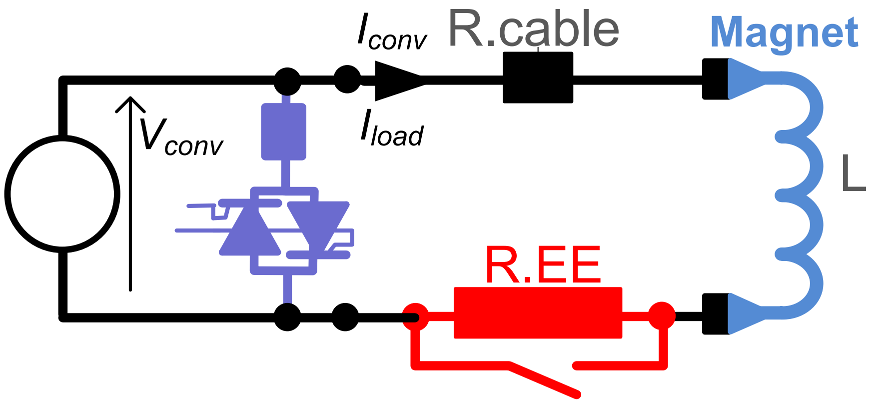


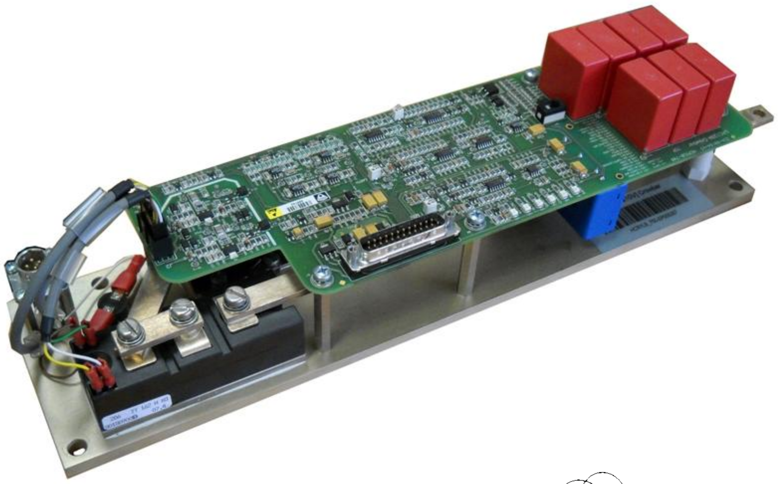


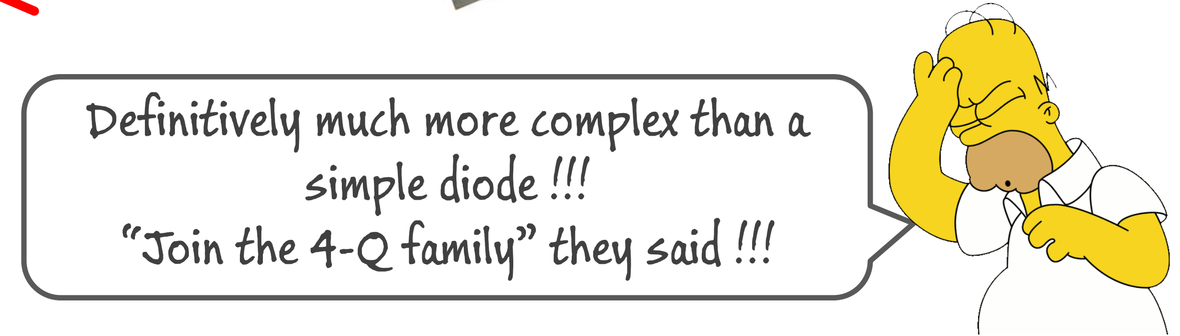
4-Q Converter typical protection

Safe Path ensured for Power Converter side by a "Crowbar"

- Active electronics which must be launched on purpose
- Thyristor (Power Mosfet) self triggered by over-voltage condition
- Converter OFF or FAULTY = non-conductive

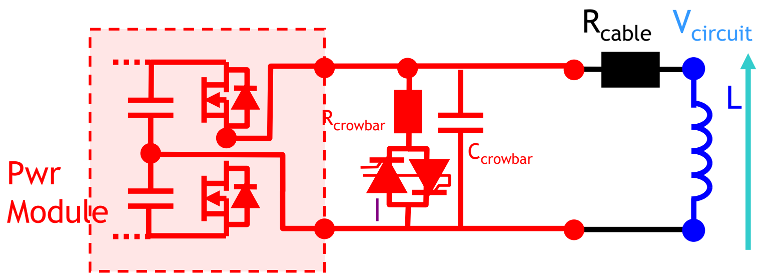


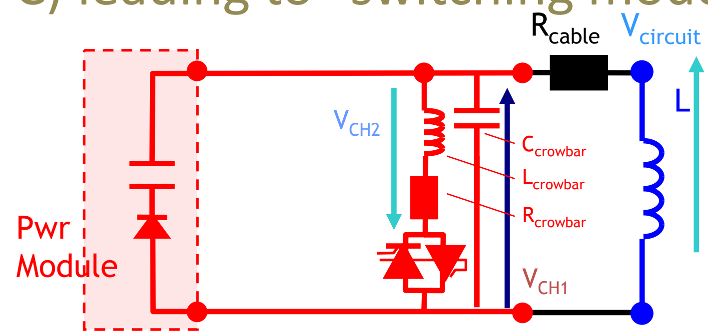


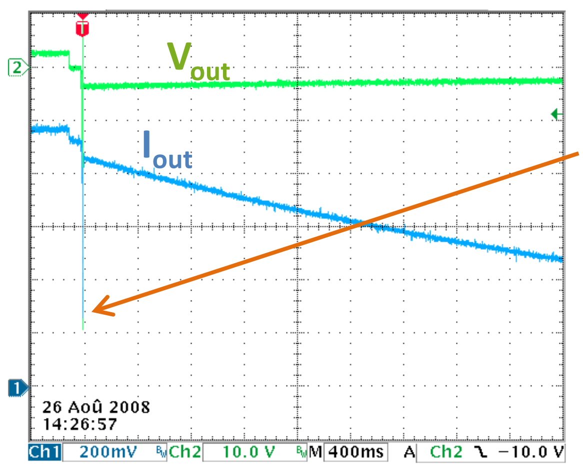


Stressful period when commissioning circuits with crowbar

- Depending on operating conditions, crowbar thyristor can be auto-reset by natural oscillation ($L_{cabling}$-C) leading to “switching mode”.

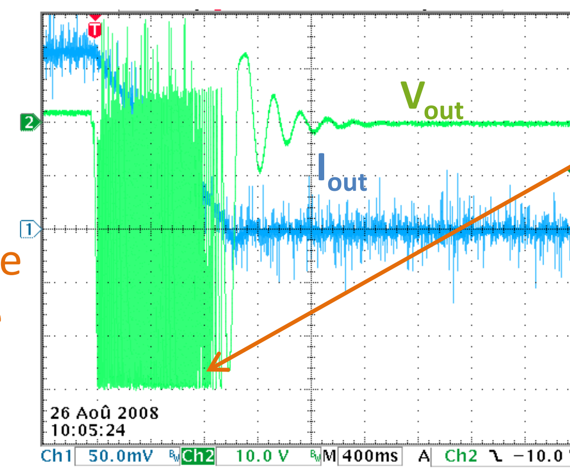






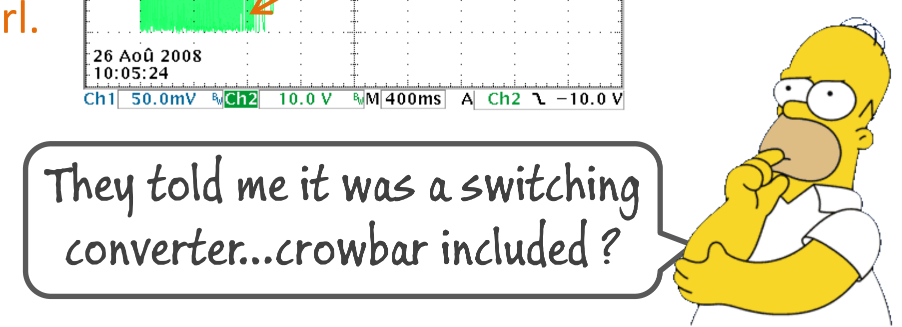
One Spike expected, creating higher voltage to launch the thyristor ctrl.

Test @ 15A (600A nominal)



N Spikes measured.

Test @ 10A Is crowbar dead?



How to test a 4-Quadrant converter?

In case of a superconductive magnet load, how to ensure the converter will fit the requirements? In receptor mode?

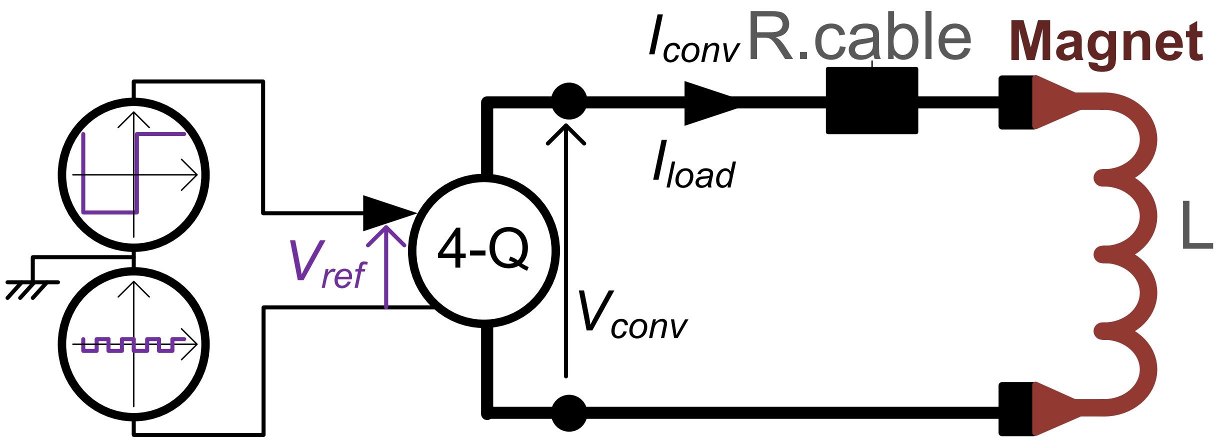
- Finding a superconductive load is not easy or can be available too late in a project.

Some topologies are more sensitive to the quadrant (generator or receptor) they operate regarding their control

- It is mandatory to get a small signal behaviour with a good confidence on a warm magnet despite low inductance value .
- It is important to “really and practically” test the receptor capability of the converter, like if operating on a superconductive magnet with hundreds or thousands of sec of time constants to validate thermal design.

Method of the 2x Signal generators tests

With a moderate time constant load, it is possible to check the control loop in receptive quadrant with a simple measurement.

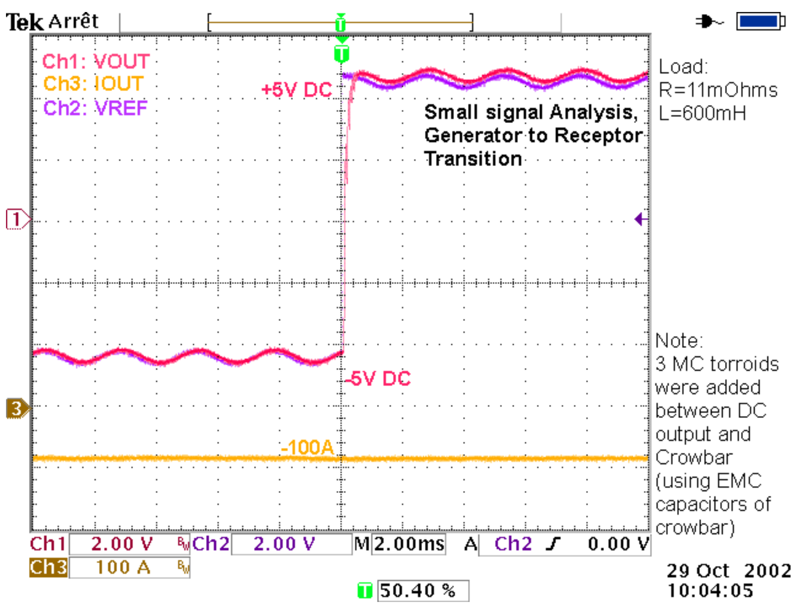


Use 2 signal generators in series, once creating high frequency small signal (sinus or square), with the other signal generator creating slow frequency square signal (amplitude modulated) to generate, at the transition, receptive quadrant conditions.

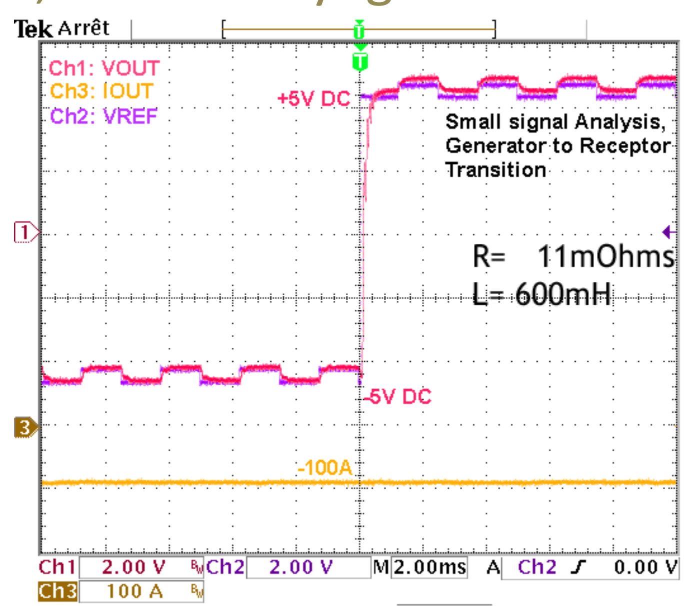
Method of the 2x Signal generators tests

Of course, and zooming on the transition only, no real difference between a warm load and a superconductive magnet (zoom).

- Difference can appear and can come from thermal management.
- This test ensure minimum stability of the converter while receiving energy, working in receptive quadrants, without cryogenic load!



Test on warm magnet (to=0.1 s)

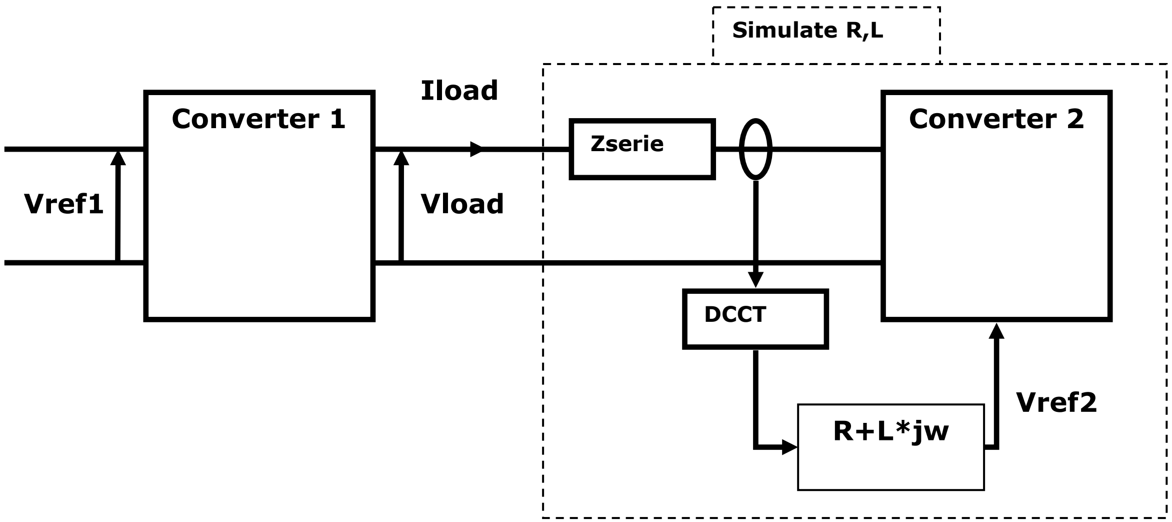


Test on cold magnet (to=60 sec)

Method of the 2x Back-to-Back Power converters

One converter simulate a large time constant load, using its 4-Quadrant “nature”.

- Very elegant and very efficient solution to test thermal management.
- Issues can come if some instability exists in the converter to be tested, since being used as a load as well.



Seems too nice, does it really work ?? If the case, better requires 2 prototypes instead of 1 in the contract, to validate the design…

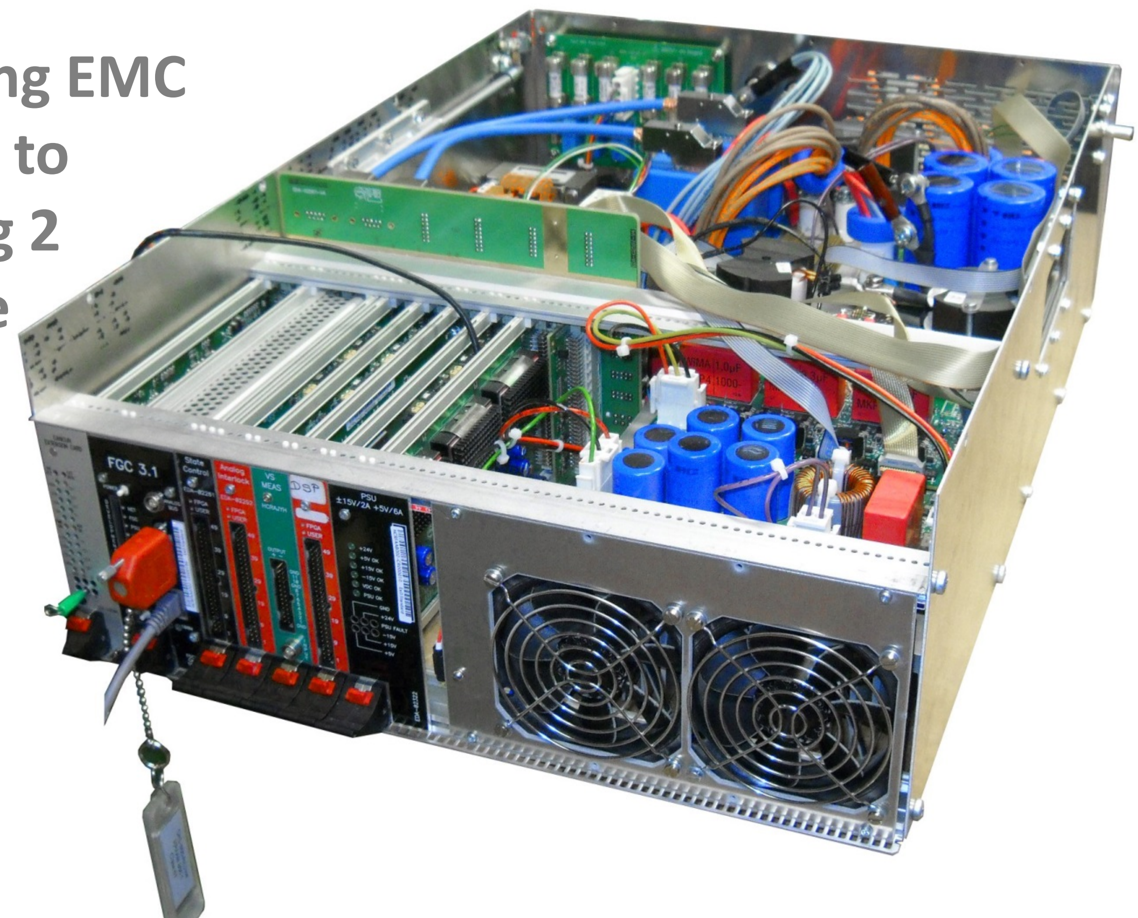
Part 5/5

- Future CERN focus and realizations
- Ideas currently being studied

Switching + 4-Q switching

For pulsed applications, implementing digital regulations, and changing 4-Q H Bridge operation mode for lower high frequency ripple.

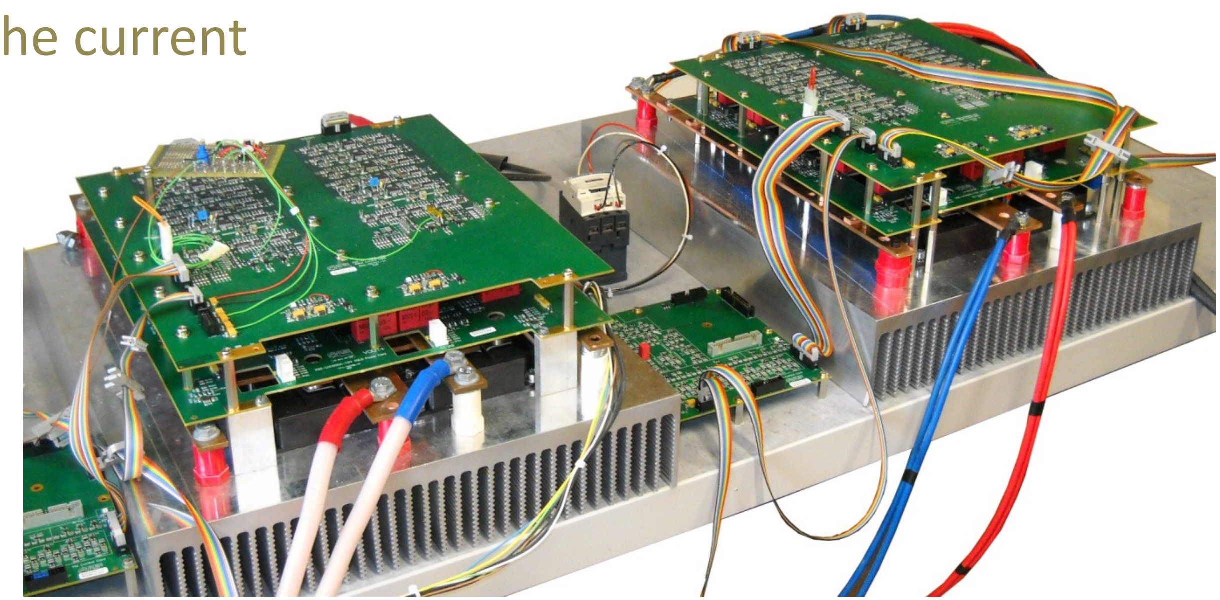
Performances regarding EMC output signature tend to be similar to switching 2 4-Q Linear Stage, once well understood… and with adequate filters in place.



Switching + 4-Q Linear

For LHC radiation tolerant converter upgrade.

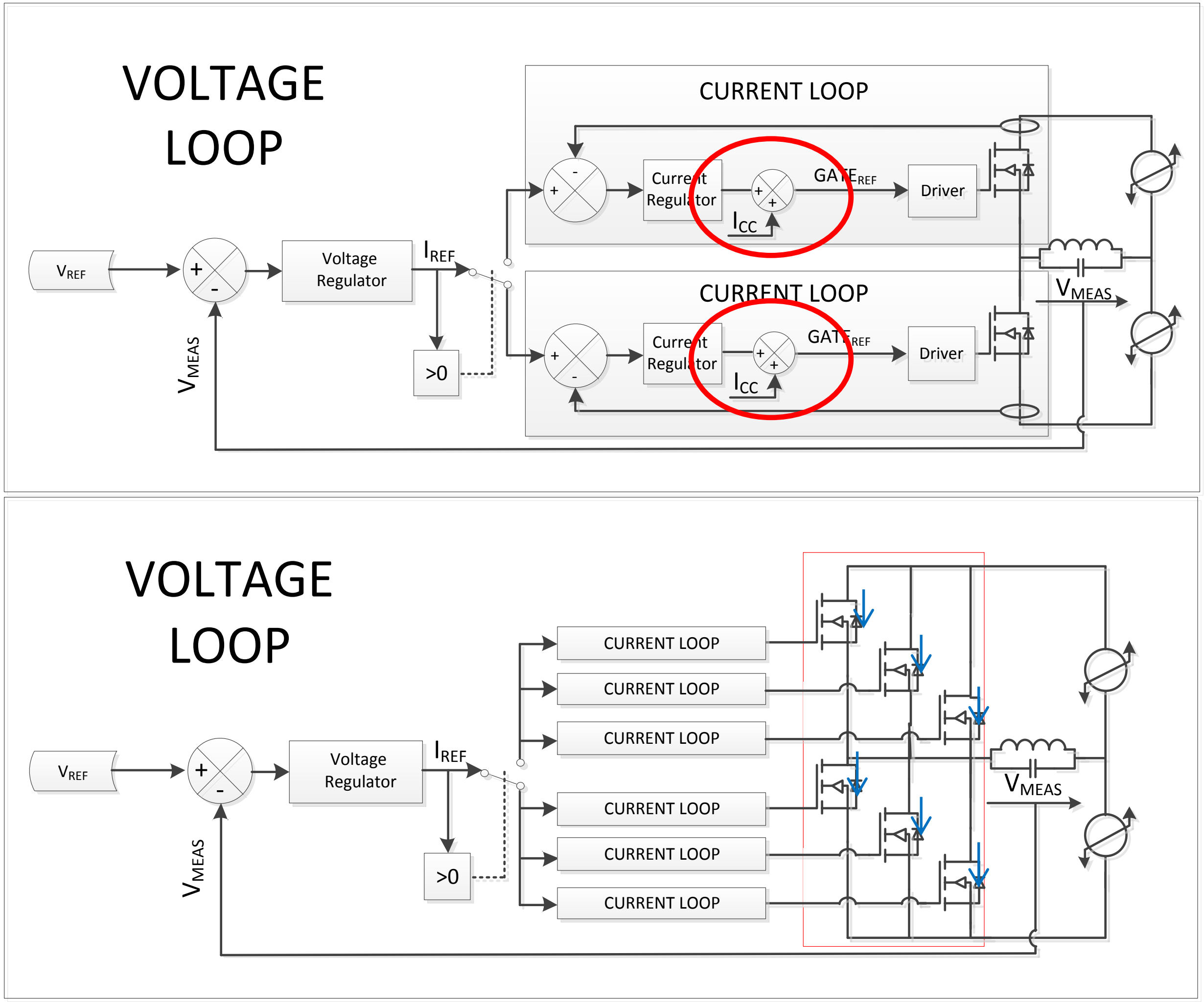
- A linear stage is less sensitive to radiation than H bridge stage (Mosfet being always conductive, then suffered only from total dose degradation, when switching transistor can die on 1x single event).
- Implementing regulation at the level of the 4-Q linear stage, directly controlling the Mosfet as current sources.
- Proposing a redundant solution of 2x 4-Q power modules working in parallel thanks to the current control in the 4-Q stage heart.



Switching + 4-Q Linear

Current sources in 4-Q Linear Stage are ideal for:

- Implementing circulation loop easily.
- Adding Mosfet in parallel inside each 4-Q power module.

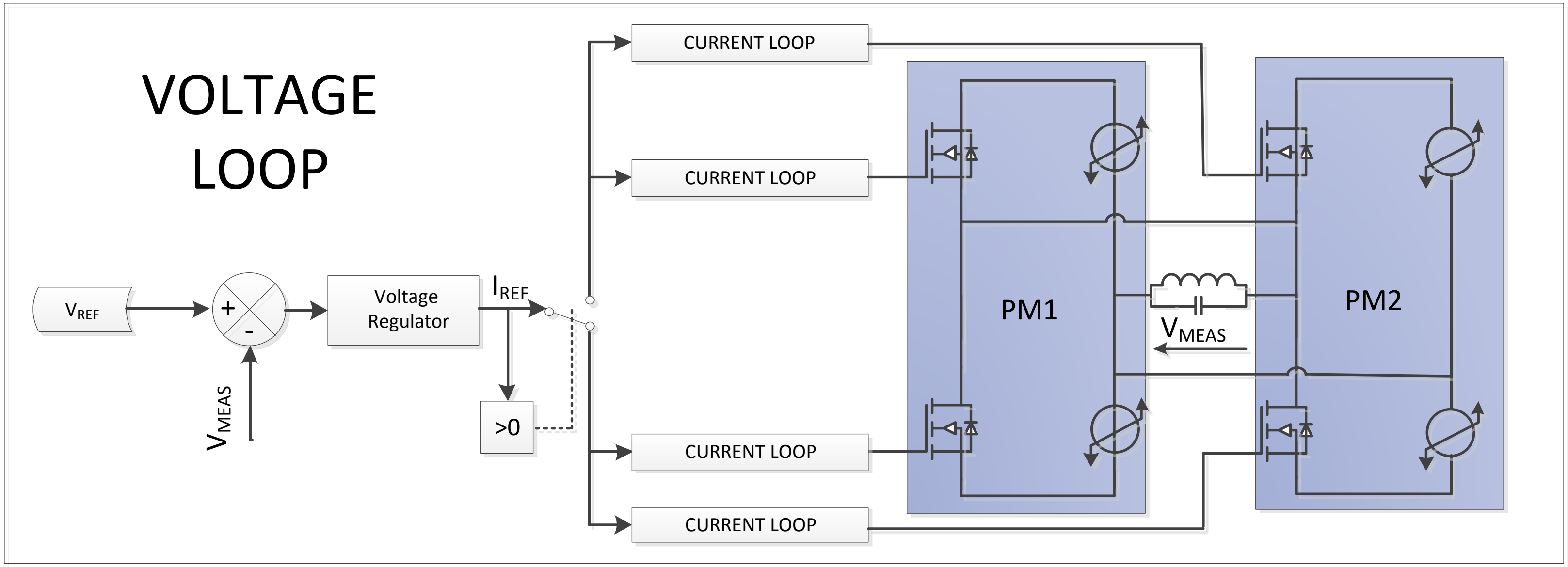


Slides courtesy of Vicente Raul Herrero Gonzales, CERN

Switching + 4-Q Linear

Current sources in 4-Q Linear Stage are ideal for:

- Implementing active sharing for redundancy between 2x 4-Q power modules operating in parallel, sharing the load current information.




Conclusion
Are you still with me?

4-Quadrant converters are specific items

Understanding the final use is a key point to choose the correct topology, and to be able to limit the requirements for a suitable product.

All topologies present drawbacks, which can be managed if the 1st step (clear final use) is correctly done.

These converters will always remain intrinsically more complex and will require more attention: test/qualifying phase is difficult and has to be addressed from the beginning.

Not a lot of companies are capable of designing a high performance converter, since market is relatively small.

And finally

Thank you for your attention !

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