HiLumi
HL-LHC PROJECT

# COMPARATIVE STUDY OF TWO-QUADRANT DC/DC STAGE IN POWER SUPPLY FOR SUPERCONDUCTING MAGNETS

**E. Coulinge** - J-P. Burnet - S. Pittet

CERN - Electrical Power Converter (EPC)
Low Power Converter (LPC)

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# OUTLINE

**Introduction**

- From LHC to HL-LHC
- HL-LHC operation

**Output DC/DC stage**

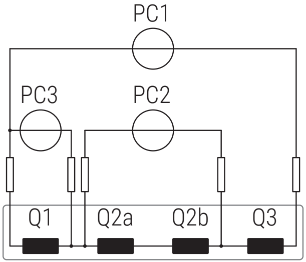
- 2-quadrant 18 kA converter
- 2 kA sub-converter modulation strategies
- 2 kA sub-converter loss map
- 2 kA sub-converter performance comparison

**Conclusions**

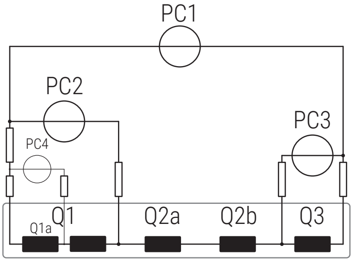
- Ongoing activities

# FROM LHC TO HL-LHC

▲ Actual 1-quadrant 6 kA converter



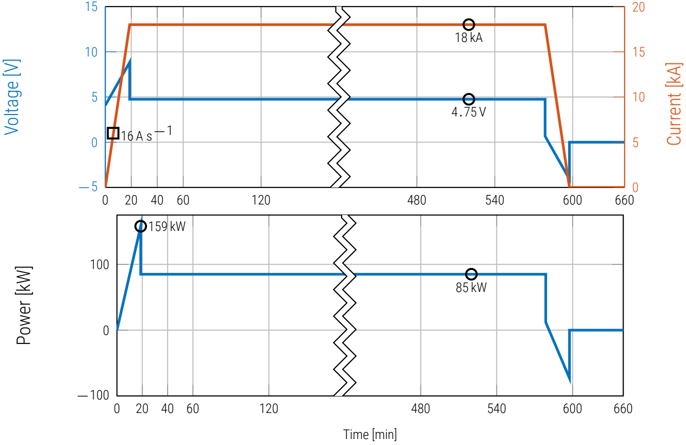

▲ LHC powering scheme




▲ HL-LHC powering scheme

# HL-LHC OPERATION

- Minimal resistance to the load:
  - Superconducting link
- Cycling operation:
  - Constraint on ramp-down time
- Minimal power taken from the grid:
  - Philosophy for new developments



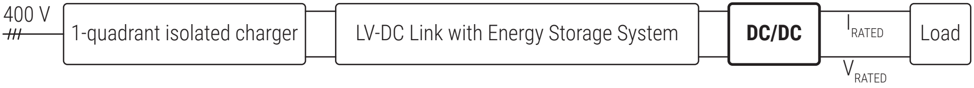

- Key numbers:

$I_{RATED}$ = 18 kA
$V_{RATED}$ = ±10 V

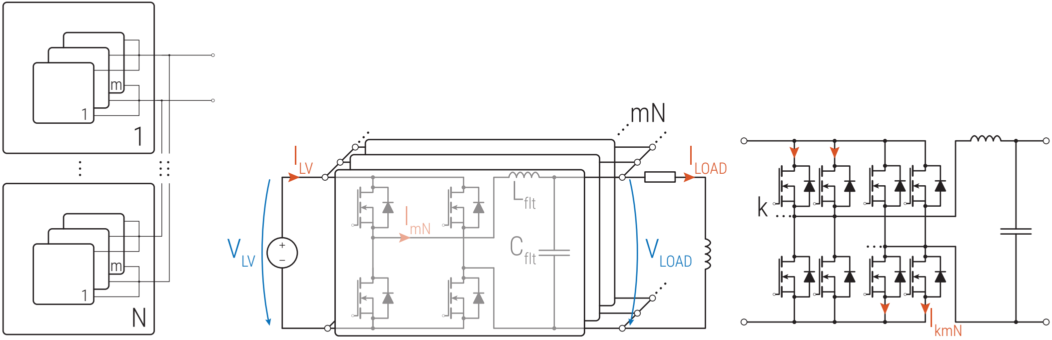
$L_{LOAD}$ = 255 mH
$R_{LOAD}$ ≲ 0.26 mΩ
$P_{LOAD[peak]}$ = 159 kW

$I_{uncertainty}$ = 18 mA (1 ppm)

# 2-QUADRANT 18 KA CONVERTER



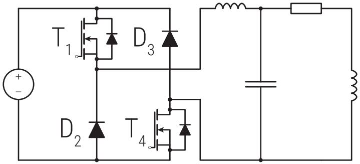

- Paralleling is needed to reach 18 kA
- Converter modularity:
  - The *converter* is divided in *N sub-converters* rated 2 kA each, $N + 1 = 9 + 1$
  - The *sub-converter* is divided in *m branches*, *m* to be defined
  - Each *sub-converter* composed of a charger, an energy storage system and an output DC/DC will be integrated in a rack
  - The *branch* is composed by *k devices* in parallel, *k* to be defined

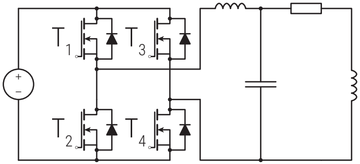



▲ Topology and modularity concept

# 2 KA SUB-CONVERTER MODULATION STRATEGIES

- 2-quadrant operation required:
  - Four different modulation strategies are compared:
    - 2-quadrant with diode (2Q)
    - 2-quadrant with synchronous rectification (2QSR)
    - 4-quadrant with bipolar modulation (4QBI)
    - 4-quadrant with unipolar modulation (4QUNI)
  - Different performances
  - Different controllability




| Mode | $T_1$ | $D_2$ | $D_3$ | $T_4$ |
|---|---|---|---|---|
| $V_{LOAD} \geq 0$ | $d$ | $1-d$ | blk | on |
| $V_{LOAD} \leq 0$ | off | cond | $1-d$ | $d$ |

▲ 2-quadrant operation with diode

| Mode | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|
| $V_{LOAD} \geq 0$ | $d$ | $1-d$ | off | on |
| $V_{LOAD} \leq 0$ | off | on | $1-d$ | $d$ |

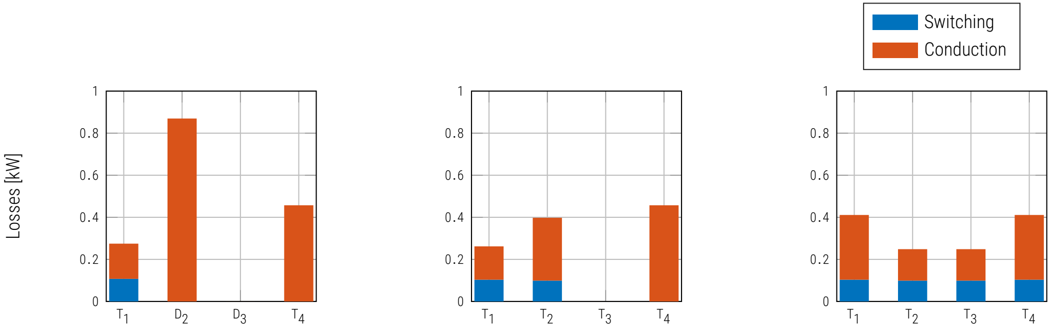
▲ 2-quadrant operation with synchronous rectification

| Mode | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|
| bipolar | $d$ | $1-d$ | $1-d$ | $d$ |
| unipolar | $d$ | $1-d$ | $d$ | $1-d$ |

▲ 4-quadrant bi-/uni-polar modulation

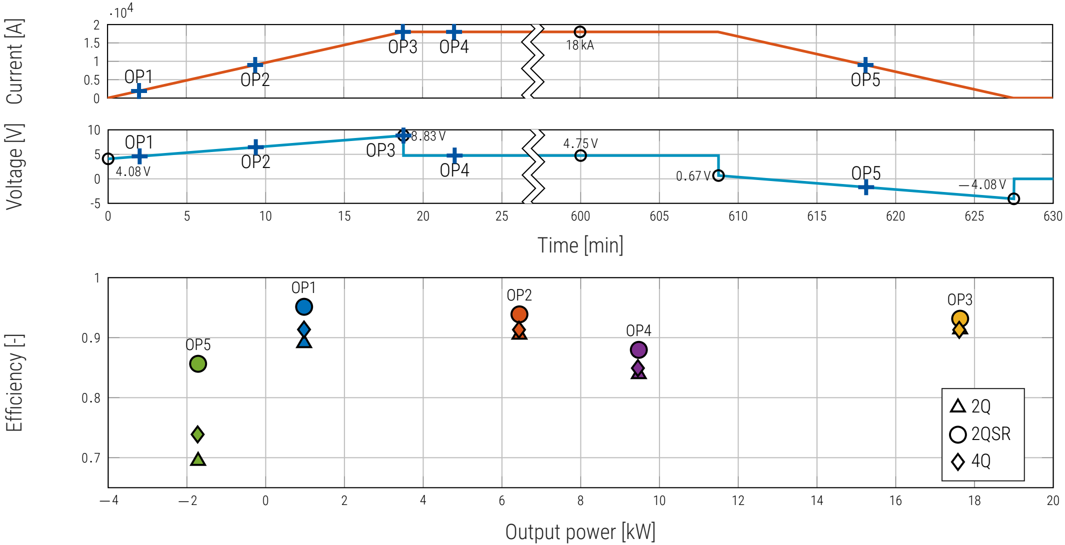
# 2 KA SUB-CONVERTER LOSS MAP

- Depends on the modulation strategy
- Given for one configuration:
  - Operating point: flat-top, 4.75 V; 2 kA; 9.5 kW
  - Switching frequency: 50 kHz
  - Number of MOSFETs:
    - $m \times k = 14$
    - Total for the *sub-converter* $14 \times 4 = 56$
  - Reference device: IXYS GigaMOS 75 V; 500 A@25 °C



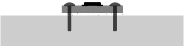
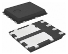

▲ 2-quadrant operation with diode ▲ 2-quadrant operation with synchronous rectification ▲ 4-quadrant bi-/uni-polar modulation

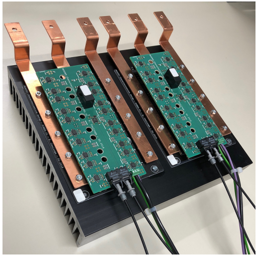
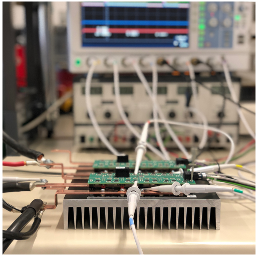
# 2 KA SUB-CONVERTER PERFORMANCE COMPARISON



# ONGOING ACTIVITIES

- MOSFET characterization setup:
  - Follow device selection process:
    - Electrical performances
    - Mechanical integration
  - Selected component:
    - $V_{DSS}$: 60 V
    - $I_{D25}$: 260 A
    - PowerFLAT package
    - Above 95 % efficiency
    - 400+ MOSFETs per *sub-converter*
  - Up to 10 devices in parallel:
    - Setup rated for 200 A
  - Used to verify:
    - Parallel switching of several devices
    - Current sharing
    - Current limit
    - Switching frequency limit
    - Thermal behavior
  - Carried out at EPFL

# CONCLUSIONS

- Modulation strategy comparison:
  - Efficiency
  - Selected modulation is **2-quadrant with synchronous rectification**

- Next steps:
  - Complete MOSFET study using characterization setup:
    - Number of devices
    - Switching frequency
  - Magnetic components
  - Mechanical integration

- References:

  - E. Coulinge, J. P. Burnet and D. Dujic, "High-current low-voltage power supplies for superconducting magnets", 2017 International Symposium on Power Electronics (Ee), Novi Sad, 2017, EDMS 1832844
  - E. Coulinge, J. P. Burnet, D. Dujic and S. Pittet, "Comparative study of two-quadrant DC/DC stage in power supply for superconducting magnets", 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, 2018, EDMS 1918772
  - E. Coulinge, "18 kA Converter for HL-LHC Inner-Triplet, MOSFET Characterization Setup", internal presentation, EDMS 1887908

# THANK YOU

Thank you for your attention


Any questions ?

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