Driving and protecting superconducting hybrid magnets

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Introduction - Objective

The 45 T hybrid magnet system will consist of two nested magnets: an insert Resistive magnet based on the Florida-Bitter plate technology generating 33 T and a Super Conductive (SC) outsert magnet with warm bore generating a background field in the centre of the bore of 12 T.

Hybrid magnet system characteristics:

Resistive magnet inductance	**4.95 mH ±2%**
Resistive magnet resistance	**13.75 mΩ -10/+0%**
Superconducting magnet inductance	**266 mH ±2%**
Mutual inductance	**11.3 mH ±2%**
Calculated coupling factor	**0.311 ±2%**
Calculated turns ratio	**7.33 ±2%**
Current leads maximum series resistance (both)	**50 µΩ**

Tabel.1 Hybrid magnet system characteristics

Design aspects

Driving requirements

For the present and future designs of the Resistive magnet the existing power converter needs to be upgraded to approx. 22 MW.

A new power converter will supply the new Super Conductive magnet at approx. 20 kA and low voltage. The available full load voltage will be such to charge the magnet within half an hour.

Magnet type	*Insert (Resistive)*	*Outsert (Super Conductive)*
Maximum field	**33 T**	**12 T**
Maximum voltage	**550 V**	**±10 V (defined by external cabling)**
Rated current	**40 kA**	**20 kA**
Stability and ripple (8h)	**< 20 ppm with active filter**	**< 50 ppm**

Tabel.2 Hybrid magnet driving requirements

Outsert Magnet Power Converter

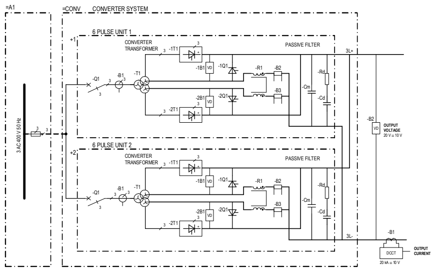

Fig.1 New Power Converter for outsert Super Conductive Magnet (20 kA)

Protection needs

The safety devices contain redundant high current high speed switch-OFF DC circuit-breakers, dump resistors and a semiconductor make switch.The control of the switches is coordinated with the control of the new outsert converter.

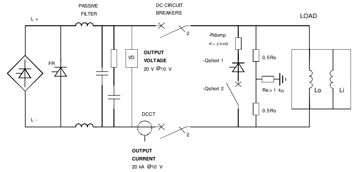

Fig.2 Overview of outsert power supply with protective devices to SC magnet Lo

- The rate of voltage change across the insert magnet will be amplified to the outsert Super Conductive magnet by the turns ratio with its coupling factor
- 500 V change across the insert magnet will become 1140 V across the SC outsert magnet
- The danger for a quench will be strongly enhanced by the rate of change of the current
- To prevent this coordination between the fault handling of the two power converters is needed

Fast dump and Slow dump circuit

The protection philosophy consists of:

- FAST DUMP
- Switch OFF DC circuit breakers
- Switch OFF Slow Dump circuit breaker
- The DC current will be transferred into a fast dump resistor capable to reduce the load current as quickly as possible, but allowing for no more peak voltage across than 2.5 kV and will lead to an outer magnet current decay of approx. 9.4 kA/s.

- SLOW DUMP
- Switch OFF DC circuit breakers
- Switch ON Slow Dump Thyristor switch
- The fast and slow dump resistors operate in parallel causing a current decay of 184 A/s.

Specification of the safety devices

Rated current of series connected DC circuit breakers	**20 kA**
Differential peak voltage for fast dump resistor	**2.5 kV**
Stored energy to be dumped in fast dump resistor	**53.2 MJ**
Applicable I^2t for connection to fast dump resisitor	**426 MA²s**
Differential peak voltage for slow dump resistor	**49 V**
Stored energy to be dumped in slow dump resistor	**52.16 MJ**
Applicable I^2t for connection to slow dump resisitor	**21.3 GA²s**

Tabel.3 Specification of the safety devices

Implementation – Test results

High current high speed switch-OFF DC circuit breakers

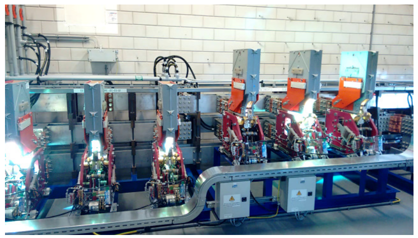

Fig.3 Visible arcing during high speed high DC current (20 kA) switch-OFF

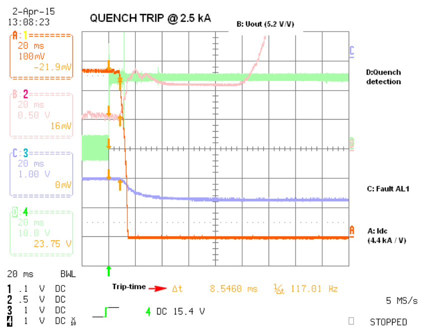

Fig.4 Test result: opening speed: 5 ms mechanical, 8.5 ms max. with arcing

Hybrid magnet protection coordination

At the instant of DC circuit-breakers opening (even during arcing) the voltage across the dump resistor will induce a voltage into the insert magnet circuit through the mutual coupling, which will lead to a SC magnet overcurrent.

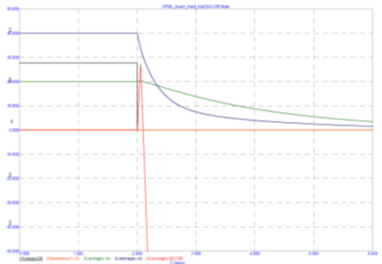

Fig.5 Hard stop of insert power supply. Blue: DC current insert magnet, black: voltage 22 MW insert power supply (drop to zero), red: (over)current in SC outsert magnet

SC outsert magnet overcurrent is prevented by delaying the decrease of DC voltage of the insert power supply until the DC circuit breakers of the outsert power supply are opened. For a worst case approach 25 ms shall be taken as total delay time before the outsert load current is fully commutated into the dump resistor

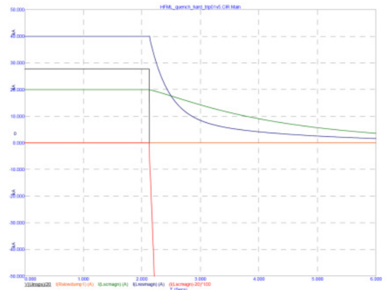

Fig.6 Delayed hard stop of insert power supply. Blue: DC current insert magnet, black: voltage 22 MW insert power supply (drop to zero), red: current in SC outsert magnet (without overcurrent).

End achievements

Design and construction of a hybrid magnet drive and protection system

- Hybrid magnet drive and protection coordination
- High speed high DC current switch-off
- Extremely precise high current injection
- Human machine interface

Energizing Ambitions