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Fault tolerant HTS transformers: increasing the fault withstand time and recovery current

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A 45 kVA fault current limiting transformer demonstration:
33% resistive fault impedance + 1 second fault withstand time + recovery under load

Aim of the project - to demonstrate:

- Fault withstand times significantly greater than 5 to 10 cycles achieved to date (IEC60076-5 stipulates 2 s)
- Recovery after the fault is isolated while carrying rated current
- High j design: > 20 A rms/mm

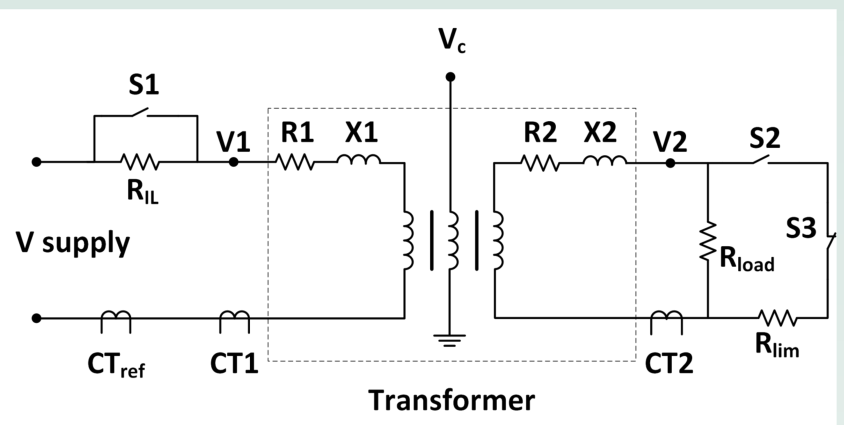
How?

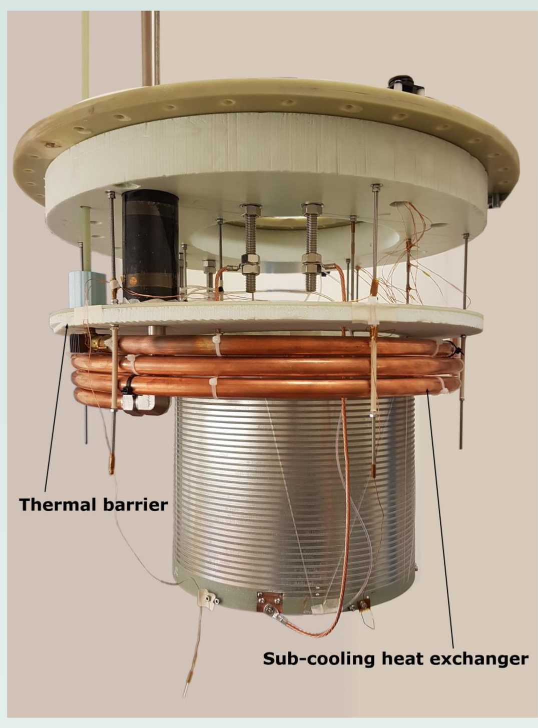
- Thicker laminated HTS wire: 0.4 mm
- Favourable normal state resistance
- Polymer coating on wire to maximise boiling heat transfer
- Operation in sub-cooled liquid nitrogen

Table 1 Transformer design specifications

Electrical	Single phase 45 kVA, 450 / 450 V 12 volts/turn (wound on central limb of 1 MVA 3-phase transformer core) 38 turns single layer primary and secondary, total wire length 75 m
HTS Wire	American Superconductor Type 8700 brass-laminated ReBCO tape 4.4 x 0.4 mm I_c = 109 A at 77 K, 240 A (estimated) at 65 K Normal state resistance 0.02 Ω/m at 90 K (R_s = 88 μW/square), 0.04 Ω/m at 300 K
Cryostat	Single phase vacuum insulated Two temperature zones: surface liquid at 77 K, subcooled zone at 65K

Test set-up





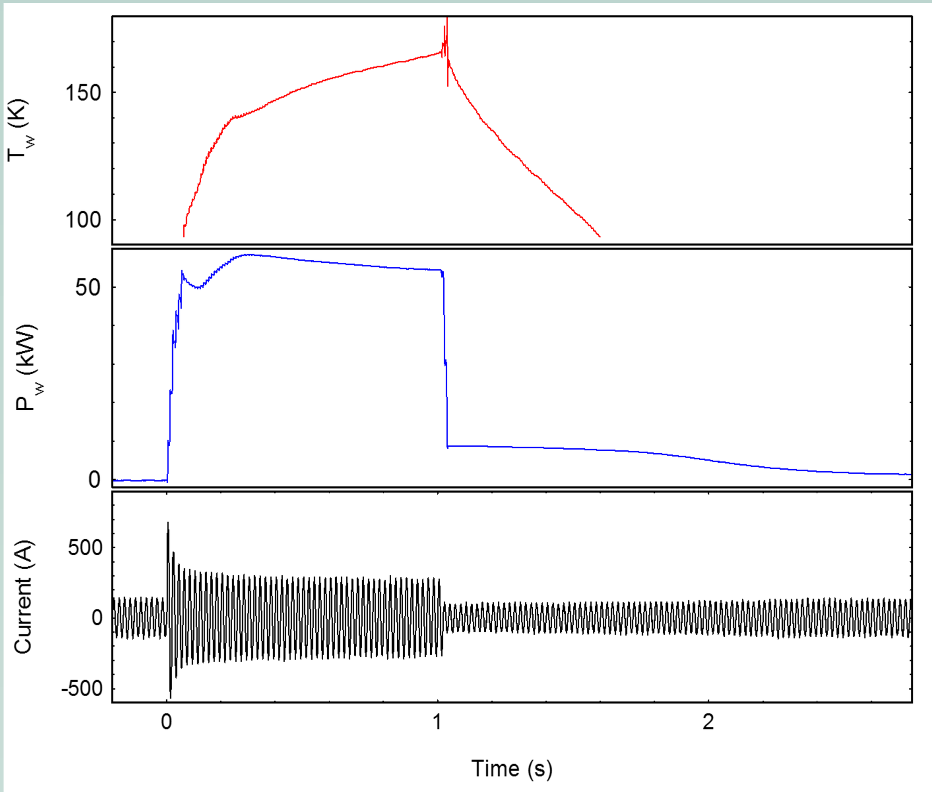
A third winding measuring the core voltage V_c allows us to separately measure the power in the primary and secondary windings.

$$P_1 = (V_1 - V_c)I_1 = I_1^2(R_1 + jX_1);\;\; P_2 = (V_c - V_2)I_2 = I_2^2(R_2 + jX_2)$$

A sliding average over one period of the 50 Hz waveform eliminates the active power to give the power dissipated in the winding.

The average winding temperature can be determined using a calibration curve for the wire resistance.

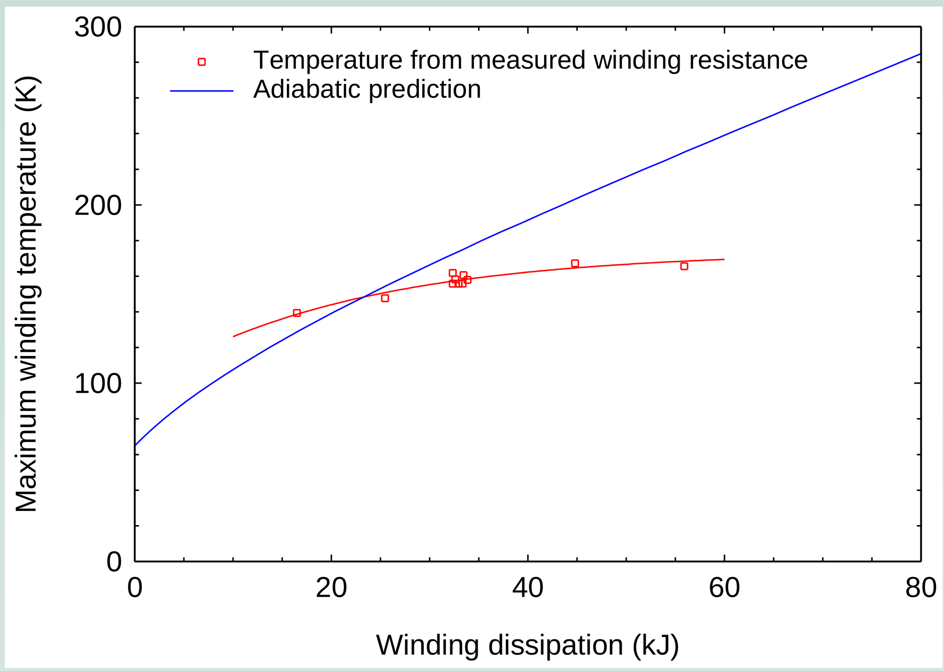
Test results: 1 s short duration



Test results for short circuit of 1 s duration with load current of 93 A. The dissipation in the windings, P_w, during the fault is ~ 60 kW. Average winding temperature reaches 165 K. Maximum winding temperature should not exceed 170 K based on extrapolation to longer fault times. This implies the boiling heat transfer is equal to the power dissipated in the windings, ie. $\dot{q}$ ~ 1.7x10^5 Wm^{-2}.

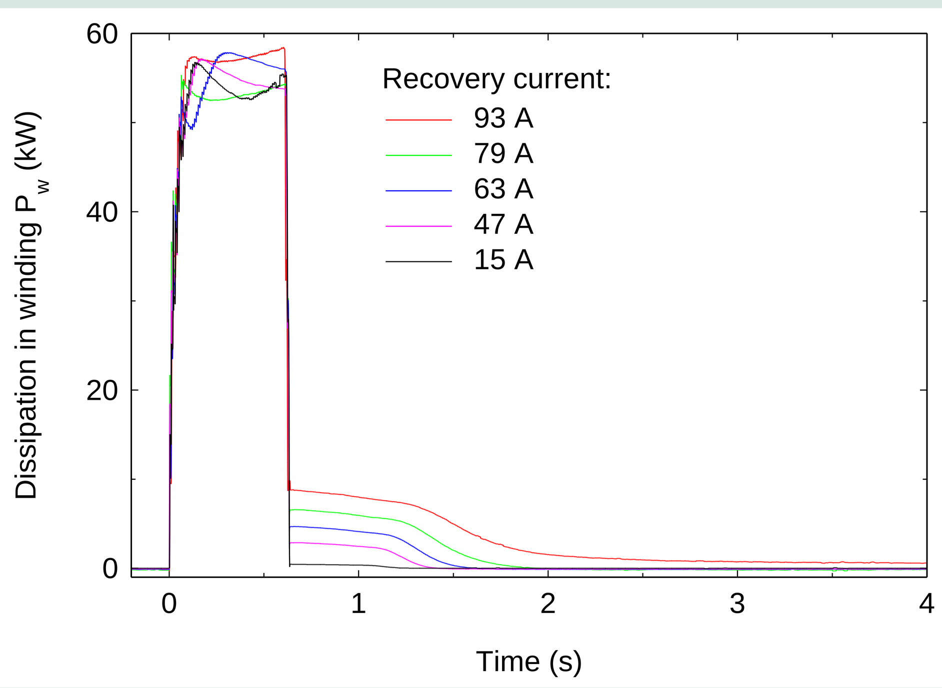
This is within the range we have measured on short samples of coated wire, but several times higher than observed for bare wire.

Winding temperature rise



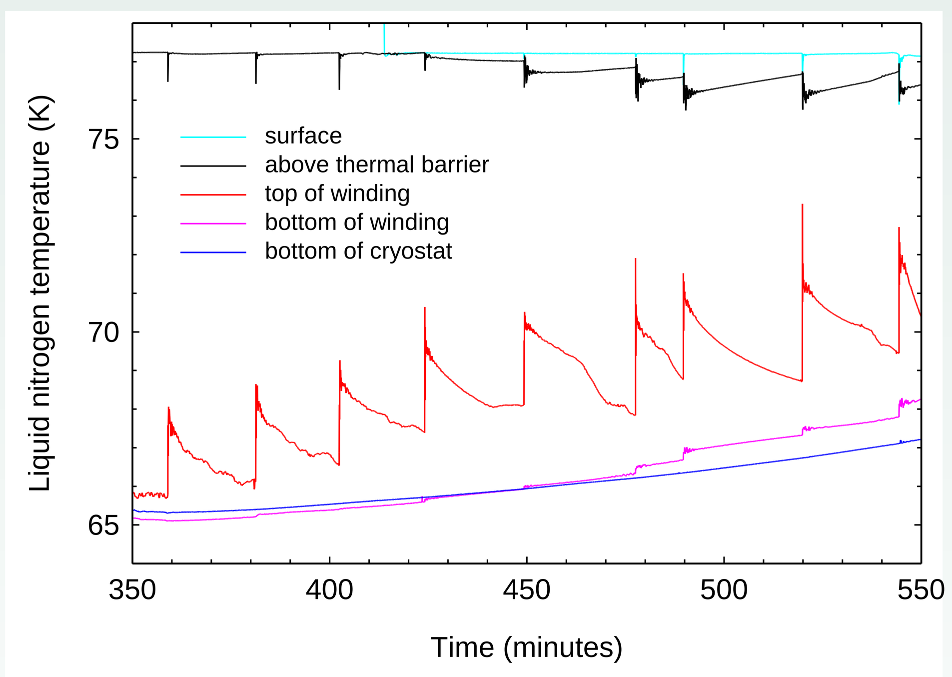
Test results for short circuits of duration 0.3, 0.45, 0.6, 0.8, and 1 s. The temperature rise is close to the adiabatic prediction for shorter fault durations, but significantly reduced by heat transfer for longer durations. In the absence of heat transfer, the predicted maximum temperature for a 1 s short circuit is still < 250 K.

Recovery under load



Test results for short circuits of duration 0.6 s for various load currents. With the removal of the short the windings make a complete recovery to the superconducting state within a second or less for load currents of 79 A or less. For the highest load current, 93 A, the windings cool to a superconducting state but do not immediately regain their base temperature.

Cryogen warming and boil-off



Temperature at different levels in the cryostat during a sequence of nine short-circuit tests. The temperature at the top of the winding jumps ~ 2 K at each test. With not enough time to cool back down between the tests, the base temperature progressively rises from 65-66 K at the outset and the nitrogen becomes stratified. The liquid nitrogen at the surface is hardly affected.
Gas flow rate measurements showed that only 1-2 % of the energy dissipated in a test produces boil-off; vapour from boiling on the windings is efficiently condensed in the subcooled liquid and the energy taken up by the heat capacity of the liquid nitrogen.

Summary

- Fault withstand time > 1 second achieved – allows more time for grid protection systems to isolate the fault
- Fault current limiting with fault impedance of 33% - huge potential benefits for grid stability
- Complete recovery at 79% of rated load within 2 seconds, resistive recovery at 93% of rated load
- Boiling heat transfer during recovery enhanced by coating and subcooled operation