Modelling and measurement of AC loss in a superconducting transformer

2LPo2C-01: 128

Enric Pardo[1], Mike Staines[2], Zhenan Jiang[2], Neil Glasson[3], Bob Buckley[2]

1 Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

2 Robinson Research Institute, Victoria University of Wellington, Wellington, New Zealand

3 Callaghan Innovation, Christchurch, New Zealand

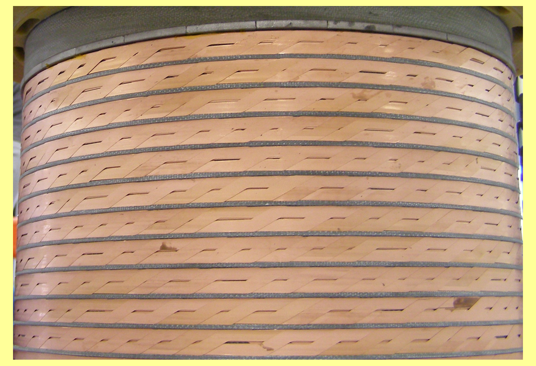
AC loss in superconducting windings:

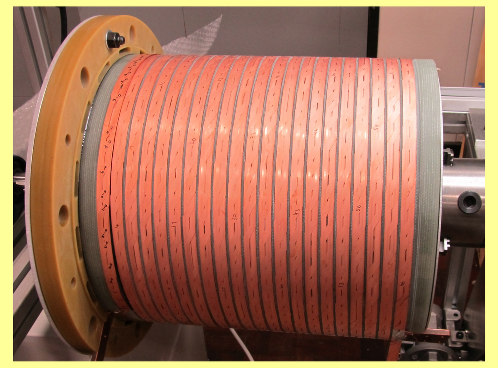
- Reduces efficiency
- Increases cost of cooling system
- Reduces thermal stability

IS YOUR TRANSFORMER DESIGN FEASIBLE?

Modelling required

Roebel cable in LV winding



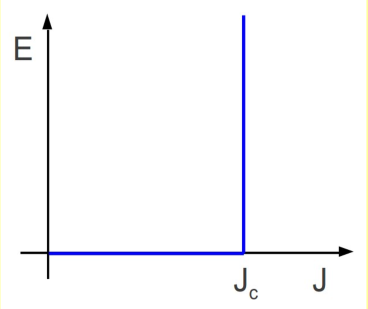


Numerical model

Minimum Magnetic Energy Variation

Assumes critical-state E(J) relation

Interaction of magnetization currents taken into account



application to coils:

- E. Pardo 2008 SuST **21** 065014
- J. Souc *et al.* 2009 SuST **22** 015006
- E. Pardo *et al* 2012 SuST **25** 035003
- E. Pardo 2013 SuST **26** 105017

Axi-symmetrical model of coil made of Roebel cable

Assumed cable cross-section:

We approximate Roebel cable as two stacks of tapes

1 MVA 11 kV/415 V 3-phase transformer modelling and measurement

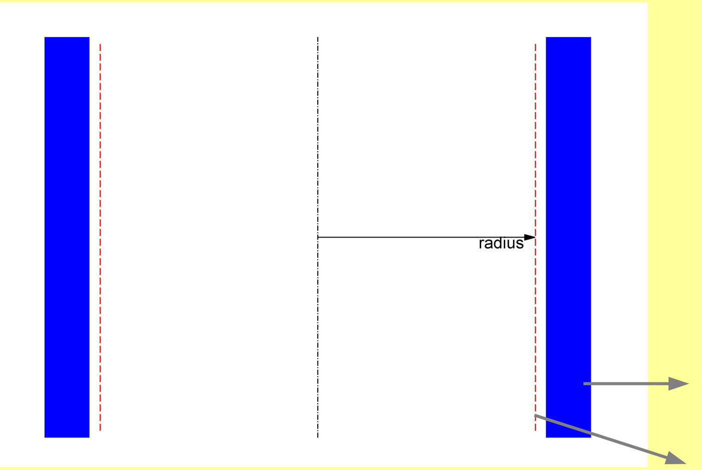
Full transformer parameters

	HV	LV
Voltage rms [V]	11000	240
Rated current amplitude [A]	42.9	1964
Internal diameter [mm]	345	310
No. turns axial direction	48	20
No. turns radial direction	19	1
Total turns	912	20
Conductor width [mm]	4	12.1
Axial gap between turns [mm]	2.130	2.1
Roebel strand number	-	15
Strand width [mm]	-	5
Gap between Roebel stacks [mm]	-	2.1
Superconducting layer thickness [μm]	-	1.4

M. Staines *et al.* 2012 SuST **25** 104002

M. D. Glasson *et al.* 2013 IEEE TAS **23** 5500206

Air-core transformer for testing (1 phase)



Same superconducting windings as full transformer

Total AC loss measured by electrical means (lock-in amplifier technique)

superconducting HV winding

superconducting LV winding

LV winding modelling for constant J_c

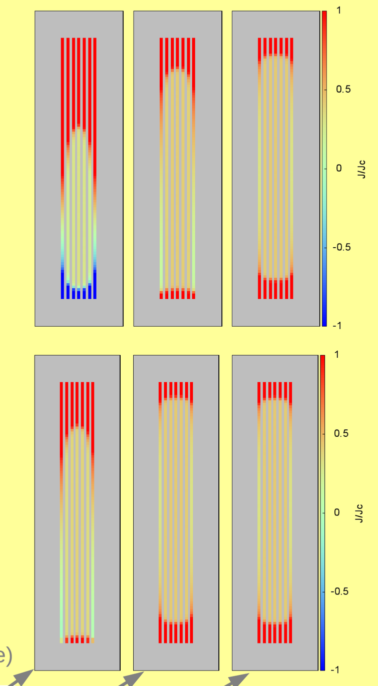
J_c taken from measured cable critical current I_c=2350 A at 70 K

stand-alone coil (no current in HV winding)

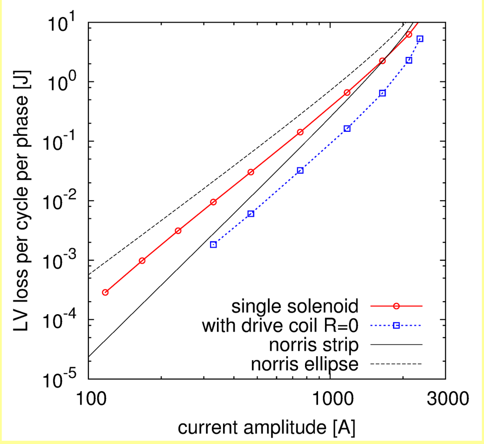
High magnetization currents at top turns

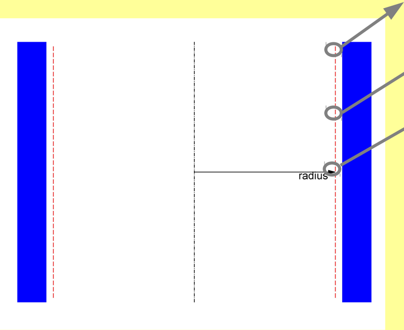
coil in transformer (LV in short circuit)

Suppressed magnetization currents



LV winding as part of transformer creates lower loss than as stand-alone coil

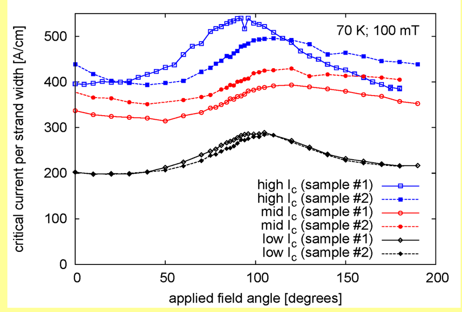


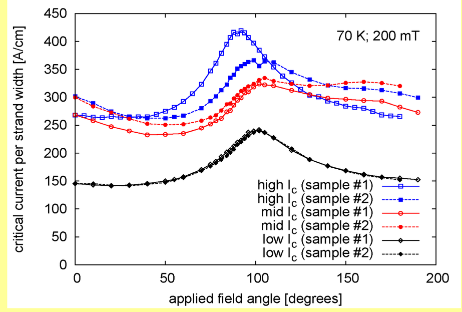


Modelling of complete one phase for $J_c(B,\theta)$

Strands I_c present low anisotropy

SuperPower tape



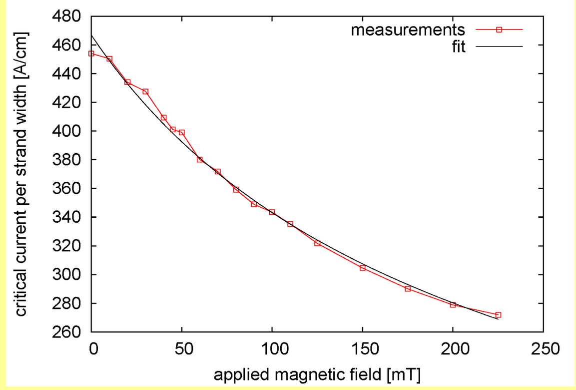


3 groups of strands: high I_c, mid I_c and low I_c

Roebel cable contains:

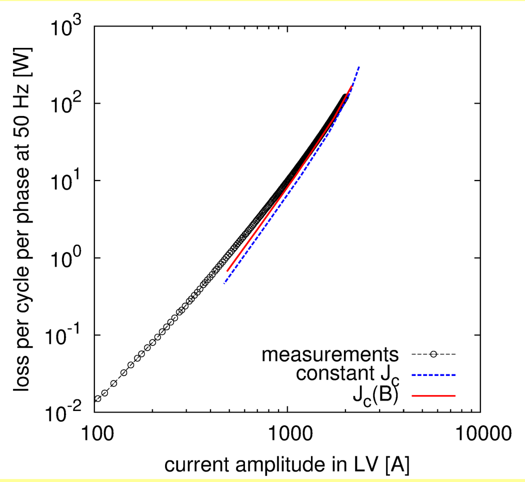
- 4 high I_c
- 7 mid I_c
- 3 low I_c

Assume isotropic J_c and take Jc(B) of most typical strands (mid Ic sample #1) at perpendicular applied field.



J_c(B=0) scaled to average J_c of strands at self-field

Model agrees with measurements with short-circuit LV

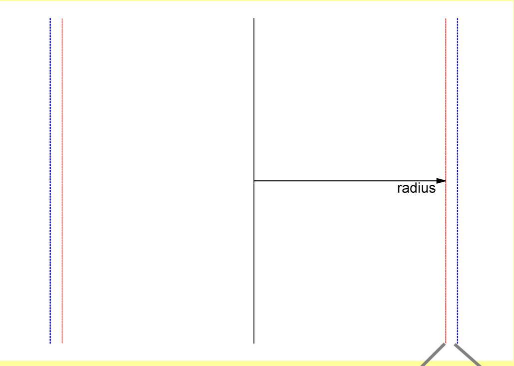


Discrepancies mainly due to approximated J_c(B)

40 MVA 110 kV/11 kV 3-phase transformer modelling

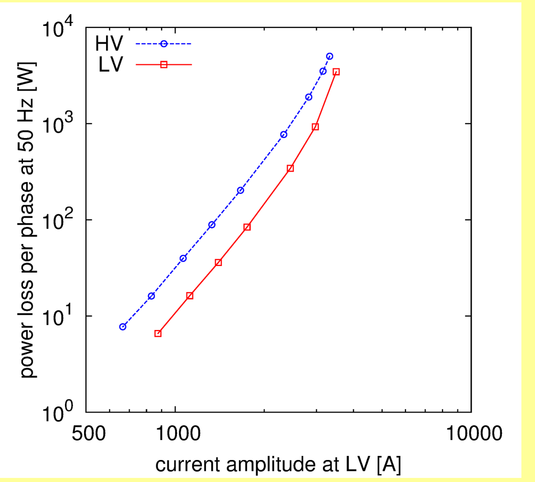
Transformer concept

One phase cross-section



	HV	LV
Voltage rms [V]	110000	6350
Rated current amplitude [A]	171.4	2969
Internal diameter [mm]	880	830
No. turns axial direction	114	64
No. turns radial direction	10	1
Total turns	1140	64
Conductor width [mm]	4	10
Axial gap between turns [mm]	2.2	1
Roebel strand number	-	16
Strand width [mm]	-	4.5
Gap between Roebel stacks [mm]	-	1
Superconducting layer thickness [μm]	-	1.4

AC loss modelling with constant J_c



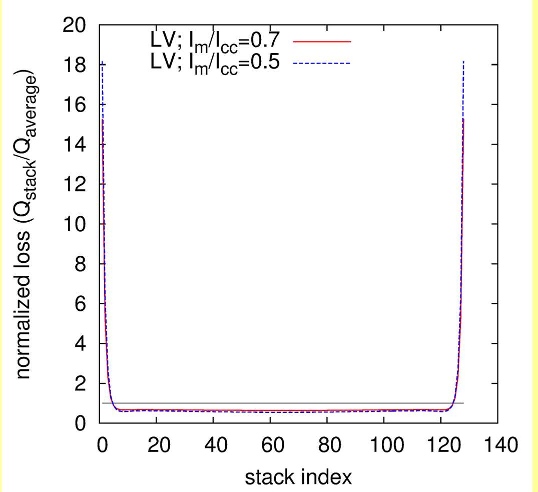
Jc taken from cable critical current I_c=3500A at 70 K

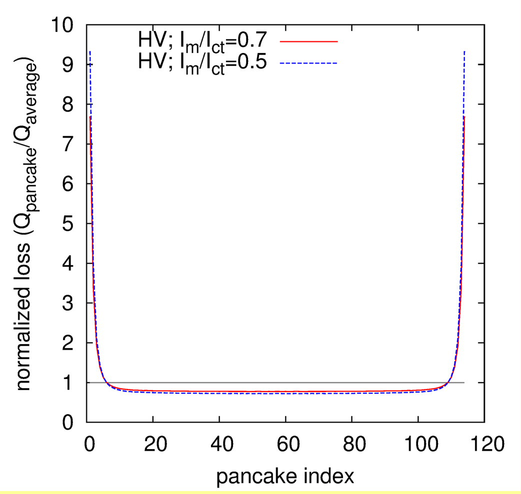
Critical current obtained by load line with present Fujikura tape

HV winding dominates AC loss

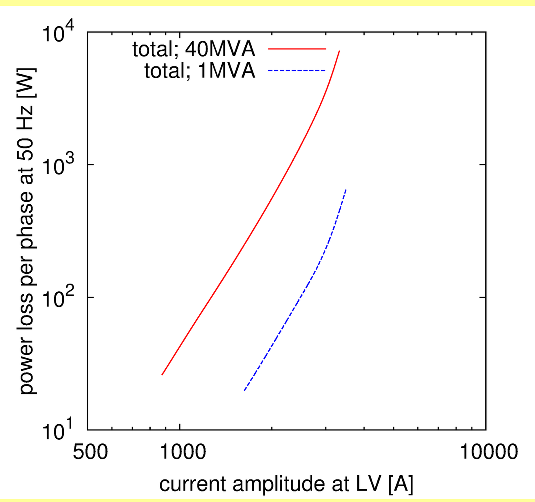
Loss distribution in the axial direction

Loss at central turns or pancakes is not negligible





Transformer modelling results: comparison between 1 MVA and 40 MVA

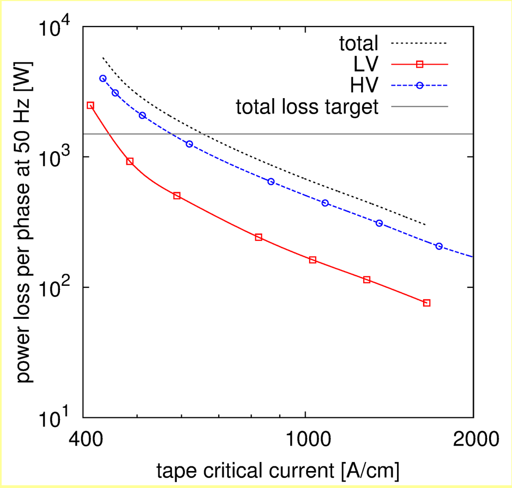


Assumed same I_c for both transformers

1 MVA transformer prototype has lower I_c

AC loss only around 12 times higher for 40 times rating

Tape requirements for transformer feasibility



1.5 kW AC loss goal per phase

equivalent to 135 kW 3-phase conductor loss assuming 30x cooling penalty

Required critical current 656 A/cm at 65 K and 400 mT

Fujikura projecting 700 A/cm 77K s.f. production I_c for 2015

I_c(77K,s.f) ~ I_c(65K,400mT)

[Iijima, ISIS22, 2013]

CONCLUSION

Model agrees with measurements of 1 MVA transformer

40 MVA transformer will have efficiency better than conventional transformers

Critical current required to surpass efficiency of conventional transformers is achievable