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Prospects for HTS transformers in the grid: AC loss and economics

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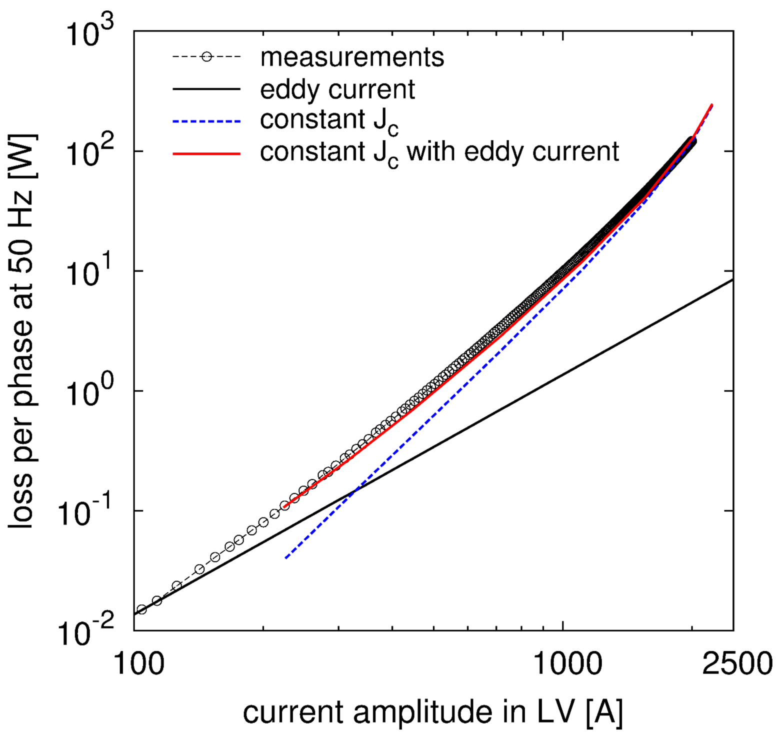
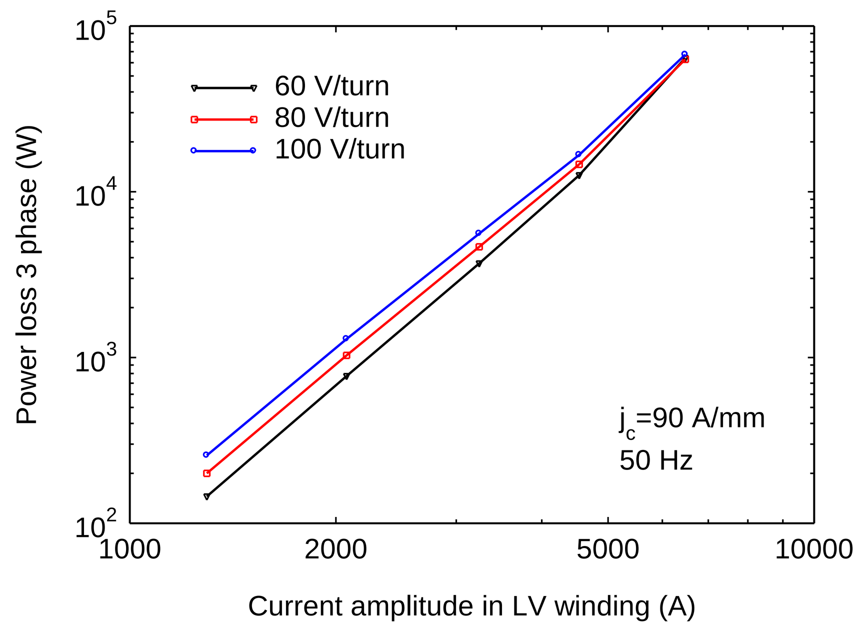
Validated modelling of loss in 40 MVA 110/11 kV windings reveals where HTS is competitive with conventional transformers

Accurate modelling of AC loss in the windings of a 1 MVA 11/0.4 kV HTS transformer validates application of the modelling to higher ratings, closer to commercial viability.

[Pardo et al (2015) AC loss modelling and measurement of superconducting transformers with coated-conductor Roebel-cable in low-voltage winding, *Supercond. Sci. Technol.* to be published]



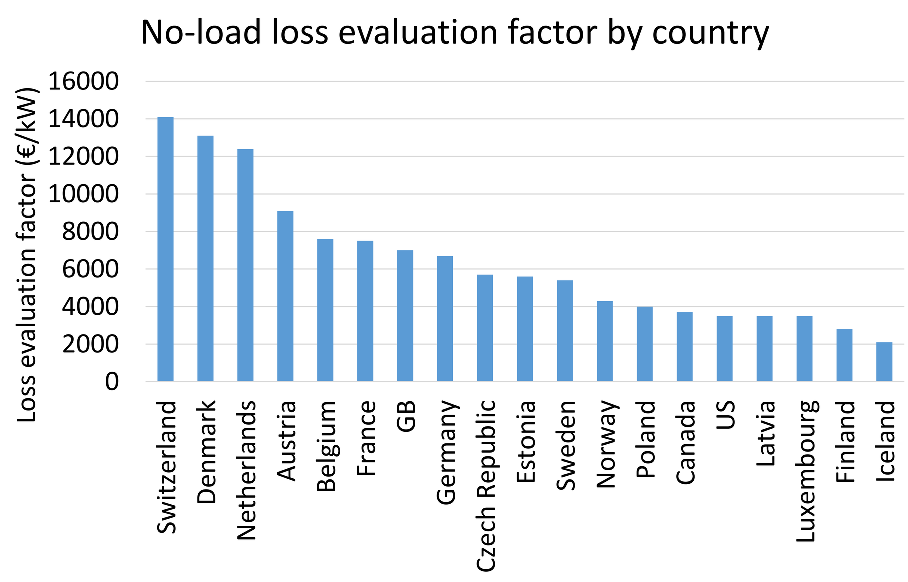


Modelling of the AC loss in the windings of a 40 MVA 110/11 kV HTS transformer shows that designs with lower volts per turn have lower total loss, even though they use more wire.

Transformer economics: Total Cost of Ownership (TCO) is the sum of purchase price, cost of installation, and capitalised lifetime maintenance and running costs. The key parameter for quantifying the lifetime cost of losses in a transformer is the **no-load loss evaluation factor,** A, lifetime cost per kW of continuous loss.

$$Lifetime\ Cost\ of\ Losses = A.NL + B.LL$$
$$B = (Load\ Factor)^2.A$$

NL = No-load loss, LL = Load Loss, B = Load loss evaluation factor



A survey of loss evaluation factors for tenders to an ABB transformer plant in 2011. Source: Fogelberg et al, Energy efficient transformers and reactors - Some incentive models and case studies to show the long term profitability of such designs, CIGRE Session paper 2012, A2-204

The loss evaluation factor varies widely, influenced more by assumed investment lifetime and discount rate than by wholesale energy cost. A mid-range value for European markets is about 7 €/W, 8.5 US$/W.

Cryocoolers for HTS transformer applications

The required cooling power is ~ 2-5 kW. The figure of merit is the TCO per watt of cooling power, calculated here for an operating temperature of 65 K for A=8.5 US$/W.

Our study system uses a single Stirling Cryogenic SPC-4, which has the required cooling power when the AC loss in the windings is below 2 kW, achievable with wire jc ≥ 120 A/mm at the operating temperature.

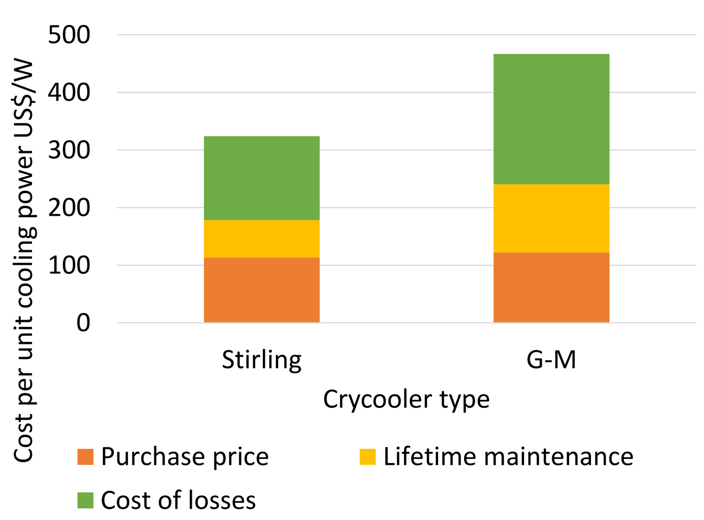


Table 1	Transformer design specifications
Electrical	Delta-star connected 3 phase, 40 MVA, 10 % impedance 60 volts/turn, Peak core flux density = 1.7 T, n1(HV turns) = 1898, n2 = 106 Winding currents i1 = 121 A, i2 = 2100 A rms
Conductor	j_c 120 A/mm width at 65 K (60 A/mm at 77 K); $i = I_m/I_c = 0.35$ HV: 13.31 km 4 mm width LV: 662 m of 16x4.5 mm Roebel cable (75% yield, 50 $/m mfg cost)
Cryostat	Foam/vacuum insulated Current lead loss 375 W at rated current, 800 W total loss incl. leads
Cooling	Stirling Cryogenic SPC-4 2.8 kW cooling power at 65 K, 47 kW input power Back-up cooling: pumped liquid nitrogen from 4000 l storage tank

Total Cost of Ownership

We plot the TCO as a function of the loss evaluation factor A below. Solid lines assume a 100% load factor e.g. a base-load generator step-up transformer; dashed lines assume the load loss evaluation factor B =0.3 A, typical of a sub-station transformer. Intercepts at A=0 give the purchase price. The conventional transformer costing includes $130K fire protection costs, and the design is optimised for each loss evaluation value. The HTS design is not optimised.

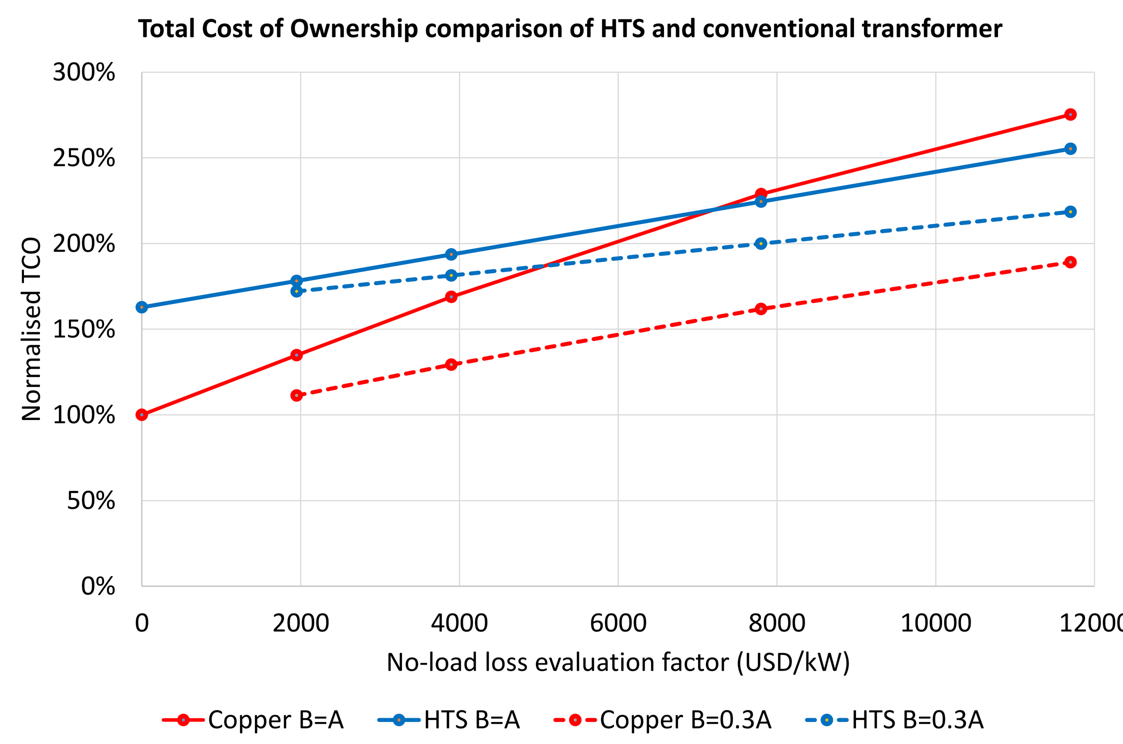


Table 2 Comparison of optimised conventional and HTS transformer designs

	A	B	Current density	Peak flux density	Total mass*
	US$/kW	US$/kW	A/mm²	Tesla	tonnes
Standard	4000	1200	3.0	1.68	72
High efficiency	8500	8500	1.0	1.53	110
HTS				1.70	25

* Includes oil and radiators for conventional, liquid nitrogen and cryostat for HTS

SUMMARY

- HTS transformers are cost competitive with conventional transformers in applications with 100% load factor for loss evaluation factors > European mid-range (at wire cost of 50 US$/kAm)
- Cryocooler and HTS conductor costs will need to fall for HTS to be competitive at 40 MVA rating at load factors typical of substation transformers
- HTS transformers are significantly lighter, < ¼ the mass of a high efficiency conventional transformer, reducing installation cost
- The lower weight of HTS transformers makes mobile transformers an attractive application – more MVA can be delivered within restricted space and weight

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