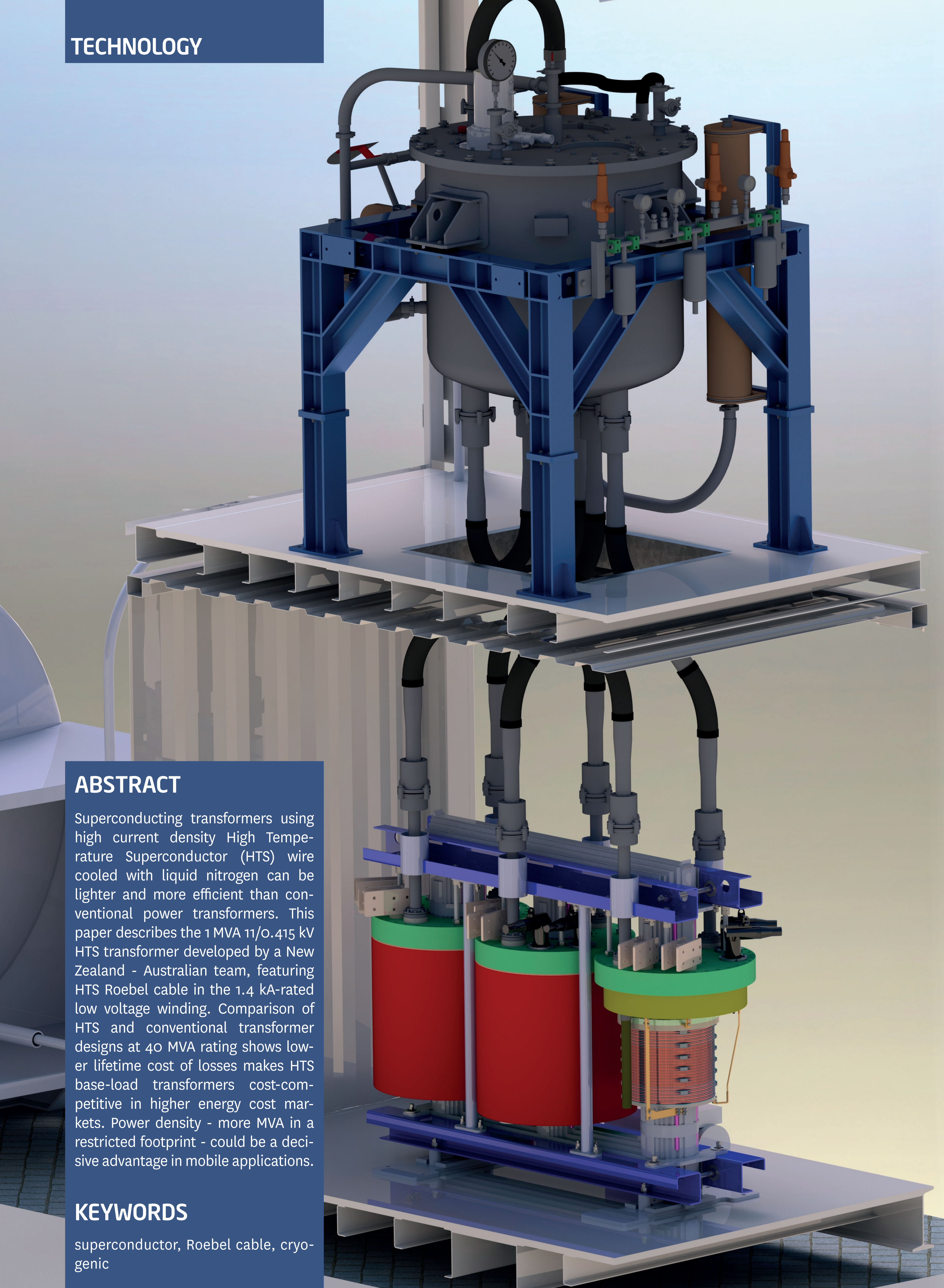

ABSTRACT

Superconducting transformers using high current density High Temperature Superconductor (HTS) wire cooled with liquid nitrogen can be lighter and more efficient than conventional power transformers. This paper describes the 1 MVA 11/0.415 kV HTS transformer developed by a New Zealand - Australian team, featuring HTS Roebel cable in the 1.4 kA-rated low voltage winding. Comparison of HTS and conventional transformer designs at 40 MVA rating shows lower lifetime cost of losses makes HTS base-load transformers cost-competitive in higher energy cost markets. Power density - more MVA in a restricted footprint - could be a decisive advantage in mobile applications.

KEYWORDS

superconductor, Roebel cable, cryogenic

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Superconducting transformers – Part I

Liquid nitrogen, super-high current density – the future of the grid?

1. Introduction

Transformers using High Temperature Superconductor (HTS) wire instead of copper conductor, and liquid nitrogen instead of dielectric oil, have been in development for almost two decades now. What are the prospects that HTS transformers will find a place in the electricity grid of the future? After giving a brief background to high temperature superconducting wire and the basic technology of HTS transformers, we describe the design and construction of our recently completed demonstration transformer featuring superconducting Roebel cable low voltage windings. The agreement of measurement and modelling of the load loss of this transformer allow us now to predict the load loss of larger HTS transformers with confidence. A clearer picture emerges of the outlook for this technology.

> **Compared to conventional oil-immersed transformers, HTS transformers can be smaller, lighter, more efficient, and have overload capability without reduction in lifetime**

1.1. High temperature superconductors

The discovery of a new class of High Temperature Superconductor (HTS) materials in 1987 inspired the vision of a power grid populated with superconducting devices: motors and generators, transformers, cables, fault current limiters, and magnetic energy storage. Although the future has seemed to be rather a long time coming, HTS versions of all these devices have since been demonstrated. A roadmap by Wolsky [1] reviews progress to 2013 and includes extensive references.

The HTS materials of most interest for grid applications, named BSCCO (Bismuth Strontium Calcium Copper Oxide) and REBCO (Rare Earth Barium Copper Oxide) for the initial letters of their constituent elements, make the transition to the superconducting state with its vanishing DC electrical resistivity at critical temperatures above the normal boiling point of liquid nitrogen, 77 kelvin (-196 °C). Fig. 1 contrasts the temperature variation of the resistivity of copper and REBCO HTS conductor, plotted on a log scale. At room temperature, the HTS material behaves like a highly resistive metal, with resistivity almost 1,000 times that of copper. While the resistivity of copper drops more than a factor of seven in cooling to liquid nitrogen temperature, at about 90 K the apparent resistivity of the superconductor falls abruptly to immeasurably low levels.

HTS materials are radically different from normal metals like copper. Brittle ceramics, they have nonetheless been fabricated into flexible wires. Their electrical properties in the superconducting state are strikingly non-metallic. The relationship between current *I* and electric field *E* in the con-

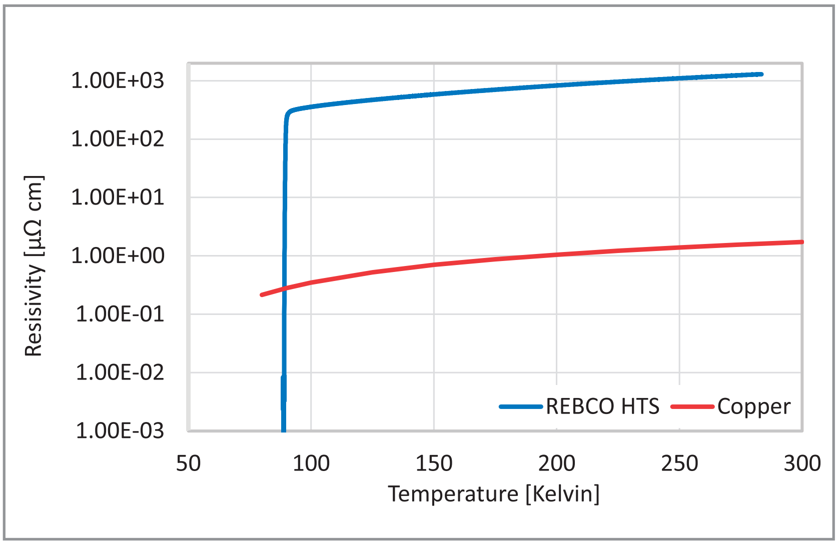

Figure 1. Variation of resistivity of HTS conductor with temperature compared to copper

> **Measurement and modelling of the load loss of the prototype transformer allow us now to predict the load loss of larger HTS transformers with confidence**

ductor is a power law: $E/E_0 = (I/I_c)^n$. For REBCO HTS the exponent n is 30 or above, compared to the linear (i.e. n=1) relationship for metals. The effective peak current carrying capacity, the critical current I_c, at which the voltage drop $E = E_0 = 1$ μV/cm, is indeed the critical parameter determining the performance of an HTS wire.

An example makes the potential for near-lossless DC electrical transmission clear. A copper conductor at 75 °C carrying 100 A at a current density of 1 A/mm^2 has a voltage drop of 215 μV/cm and dissipates 2.15 W/m. An HTS wire with a critical current of 140 A carrying the same current will dissipate only 0.4 μW/m, falling by roughly a factor of 10 for each 8 % increase in I_c.

Critical current increases markedly as the temperature drops, approximately doubling between 77 K and 65 K, not far above the freezing point of liquid nitrogen at 63.15 K. I_c depends also also on magnetic field strength and orientation, complicating the electrical design of windings. Unlike metals such as copper, where high conductivity is intrinsic and associated with freedom from defects and impurities, high critical current is achieved by building in “flux-pinning” defects, e.g. nano-sized non-superconducting grains, to hinder the movement of magnetic flux.

As manufacturers have become more skilled at defect engineering, the performance of the wire has improved. The best production wire can achieve extraordinarily high current density. A fairly standard HTS wire profile, a tape 4 mm wide by 0.1 mm thick (of which only 1-2 % is the superconductor), can carry more than 250 A at 77 K. The current density of more than 600 A/mm^2 compares to typical current density in copper transformers of 3 A/mm^2 or less.

While HTS conductors can carry DC currents less than the critical current with virtually no resistance, when they are subjected to AC currents and magnetic fields, there is electrical loss due to the work expended moving magnetic field in and out of the conductor against the flux-pinning forces. This is not ordinary resistive electrical loss. In fact it is hysteretic, like magnetisation loss in transformer cores, 20 % higher at 60 Hz compared to 50 Hz. This “AC loss” can be an obstacle to AC applications of HTS conductors. In HTS cables, it is manageable because the AC magnetic flux is predominantly in a favourable low-loss orientation in the plane of the HTS tape. In rotating machines, the use of HTS wire is restricted to DC rotor windings; HTS wire designed for low loss in the high AC magnetic field in stator windings has not yet been developed. In transformers, while AC loss is a constraint, HTS transformers can nevertheless be designed with load losses that are a fraction of those of conventional power transformers.

2. Background to HTS transformers

Thanks to the high current density of HTS wire, compared to conventional oil-immersed transformers, HTS transformers can be smaller, lighter, and more efficient. Windings can be designed with lower reactive impedance, with benefits throughout the power system [2], provided fault currents can be limited. The windings can provide the required fault current limiting resistively, if only for a limited time, because of the sharp increase in the resistance of the HTS conductor when current exceeds the critical current.

HTS transformer windings operate immersed in liquid nitrogen dielectric at temperatures 77 K to 65 K, enclosed in a thermally insulated tank or cryostat cooled by a low temperature refrigerator or cryocooler, or by tanker-delivered liquid nitrogen supply. Liquid nitrogen eliminates the fire and environmental hazard of the mineral oil dielectric in conventional transformers. Liquid nitrogen is an excellent electrical insulator, with breakdown voltage comparable to transformer oil [3]. Liquid nitrogen offers a further benefit: the potential for overload capability without reduction in lifetime because the inert dielectric and low rate of chemical reaction means insulation is very resistant to ageing at cryogenic temperatures [4].

There is a cooling energy penalty associated with refrigeration: for each kW of dissipation in a cryostat at 77 K, 15 kW of power or more will need to be supplied, depending on the cryocooler efficiency.

To avoid the cooling penalty on core losses the core is typically kept at room temperature, outside the cryostat; this means the cryostat containing the windings encircles the core limbs. To avoid presenting a closed conducting path, Glass-fiber Reinforced Epoxy (GRE) composite cryostats are typically used. Separate cryostats for each phase have generally been favoured for simplicity of construction, even though a single cryostat for all three phases is more thermally efficient. The bushings and current leads to the HTS windings introduce an unavoidable heat leak. For high current low voltage windings, this can be a major fraction of the cryostat thermal load, minimised by enclosing all windings and three phase interconnects in a single cryostat.

Around a dozen HTS power transformers with rating 500 kVA and above have been built and tested over the last two decades, see [1] for references. ABB demonstrated a 630 kVA 18.7/0.42 kV three-phase transformer as early as 1997. The transformer operated connected to the grid in Geneva for a year

> **A copper conductor at 75 °C carrying 100 A at a current density of 1 A/mm^2 dissipates 2.15 W/m; an HTS wire with a critical current of 140 A carrying the same current will dissipate only 0.4 μW/m**

without major problems. In 2001, Siemens demonstrated a single-phase 1 MVA 25/1.4 kV traction transformer which included a Roebel cable low voltage winding made with BSCCO wire. Other HTS transformer demonstrations have featured ratings to 4 MVA, high voltage windings rated to 66 kV, and have been operated continuously for more than two years.

> **HTS transformer windings operate in liquid nitrogen, which is an excellent electrical insulator – it eliminates the fire and environmental hazard of the mineral oil and has the potential for overload capability without reduction in lifetime**

3. The New Zealand - Australian HTS transformer

In early 2015, testing was completed on a 1 MVA three-phase transformer developed in a partnership between Robinson Research Institute of Victoria University of Wellington, Callaghan Innovation, Melbourne-based manufacturer Wilson Transformer Company, and others. The objectives of the project were to demonstrate a transformer using REBCO conductor throughout, with high current HTS Roebel cable in the LV winding, and a closed-cycle cooling system, and to accurately measure and validate modelling of the load loss in the HTS windings so that the losses of larger transformers could be predicted with confidence.

3.1 Specifications and construction

The specifications and design of the transformer are summarised in Table 1.

Table 1. Specifications and design parameters for the HTS transformer

Transformer design parameters	
Rated capacity	1 MVA
Rated frequency	50 Hz
Rated voltage (primary/secondary)	11 kV/ 0.415 kV
Rated current (primary/secondary)	30 A/1390 A rms
Connection	Δ-Y
Operating temperature	70 K
Primary winding	
Winding geometry	Double pancake
Conductor	REBCO 4 mm tape
Number of pancakes	48
Total turns	918
Inside diameter	344 mm
Height of winding	292 mm
Secondary winding	
Winding geometry	Solenoid
Conductor	REBCO 15/5 Roebel cable
Number of layers	1
Total turns	20
Inside diameter	310 mm
Height of winding	296 mm
Transformer core	
Type	three-phase three-limbs
Material	grain-oriented silicon steel
Diameter	225 mm
Effective sectional area	350.6 cm²
Window height	910 mm
Centre distance between limbs	590 mm
Flux density	1.54 T
Turn potential	11.98 V
Weight	1493 kg
No-load loss	1183 W

The transformer uses HTS Roebel cable manufactured by GCS Ltd in New Zealand. The 15 strands of the cable are precision-punched from 12 mm wide HTS tape. The high voltage winding consists of double pancakes – disk windings wound in modules of pairs of disks with the conductor crossover transition from one disk to the second at the inner radius. Each high voltage winding has 24 double pancakes connected in series with soldered HTS jumpers. Each phase uses almost a kilometre of 4 mm HTS wire and 20 m of Roebel cable. The 4 mm wire is insulated with polyimide tape wrapped with 50 % lap, while the Roebel cable is left bare to ensure maximal heat transfer to the liquid nitrogen. The contact resistance between the cable strands is sufficiently high to ensure the cable behaves as a continuously transposed conductor without the need for insulation of the strands. Fig. 2 shows the low voltage and high voltage windings in the process of assembly. Winding tension is chosen to counteract any differential contraction of the wire and composite formers. Both wire and GRE composite contract by around 0.3 % in cooling from room temperature to liquid nitrogen temperature. The design operating temperature is 70 K

> **Around a dozen HTS power transformers with rating 500 kVA and above, and up to 4 MVA, 66 kV have been built and tested over the last two decades – with some examples operating continuously for more than two years**

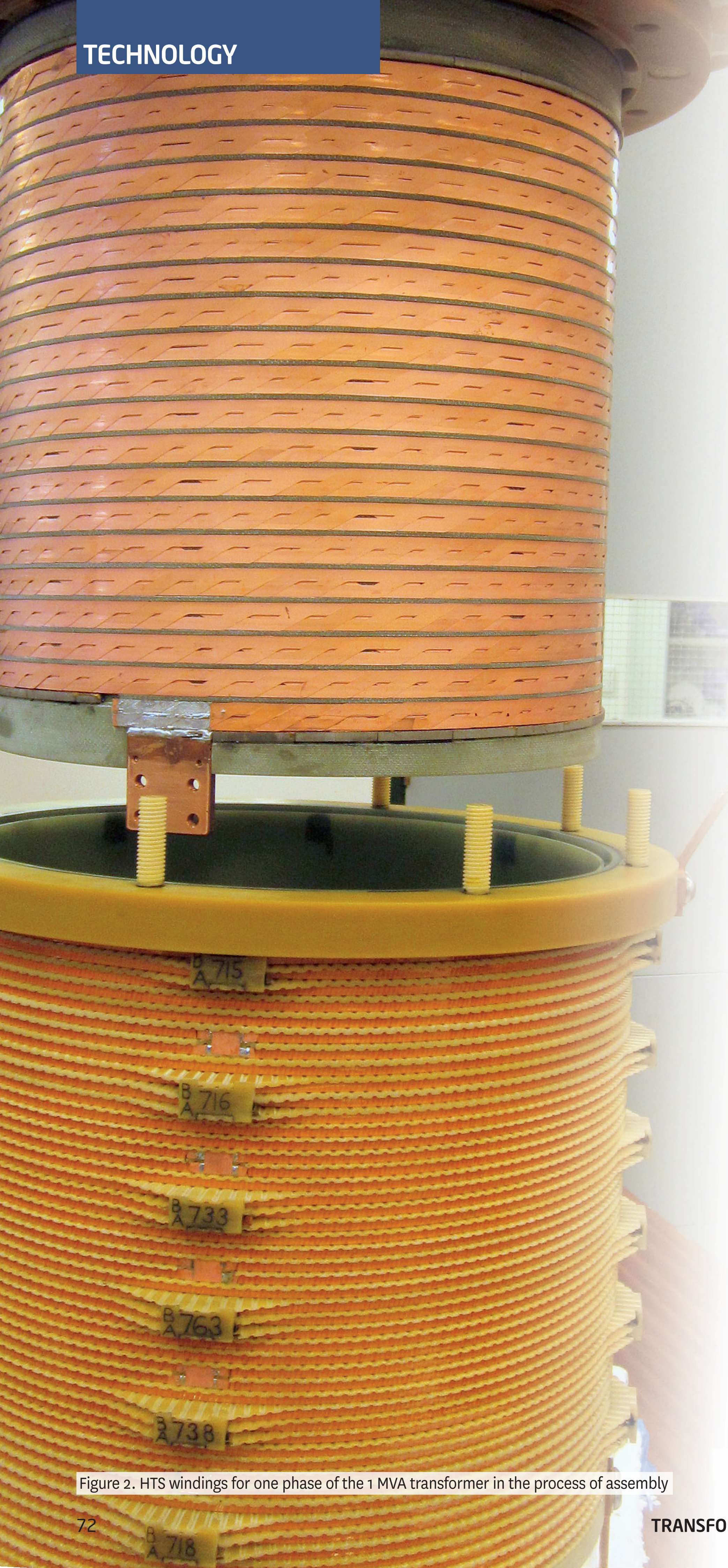

Figure 2. HTS windings for one phase of the 1 MVA transformer in the process of assembly

> **To avoid the cooling penalty on core losses, the core is typically kept at room temperature**

at a pressure around 1.2 atm absolute at the top of the windings.

The windings are enclosed in vacuum-insulated GRE cryostats (one for each phase) manufactured by Fabrum Solutions, Christchurch, along with other GRE composite bobbins and components. Liquid nitrogen circulates by thermosiphon action from an external cooling system designed and manufactured for the project by Absolut System SAS, Grenoble. The system is shown in Fig. 3 installed in a shipping container mounted above the container housing the transformer. Cooling can be provided by Cryomech AL600 cryocoolers (510 W cooling power at 70 K) and/or liquid nitrogen from a tank.

The transformer core was manufactured by Wilson Transformer Company. The core is a "warm" core (placed in air outside the liquid nitrogen cryostats). Cold-rolled, grain oriented silicon sheet steel laminations 0.27 mm thick were used to build a three-limbed core. The legs have a cruciform shape in six steps. Maximum flux density of 1.54 Tesla and step-lap joints were employed to reduce the core losses.

The bushings for the 11 kV windings were Elastimold K180-S4 bushings rated at 200 A, which we modified for cryogenic service, adding stainless steel tails extending down to the liquid nitrogen level. The cross-section and length of these current leads are designed to achieve minimum heat input to the cryogen at the rated line current of 52.5 A. The low voltage bushings were manufactured with copper conductor sized for minimum heat leak at the rated current of 1390 A. An optimally sized metallic current lead, i.e. with the ideal ratio of length to cross-section, will produce a heat leak at its design current of around 43 W at 77 K operating temperature for each kA of current [5].

Figure 3. Cooling system for 1 MVA HTS transformer

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Authors

Mike Staines is a Senior Scientist at Robinson Research Institute, Victoria University of Wellington, with a PhD in Physics obtained in 1979. Mike has been engaged in HTS research since 1987, working in superconducting materials synthesis, wire development, and measurement of electrical properties, particularly AC loss, of HTS wire and windings. He was Science Leader for the 1 MVA HTS transformer development. His current work focuses on extending the fault current performance of HTS windings, reducing the cost and complexity of transformer cooling systems, and quantifying the value proposition for HTS transformers.

Mohinder Pannu is Strategic Engineering & Projects Manager at Wilson Transformer Co Pty Ltd, developing new product applications for the Power industry. He holds a B.Tech (Hons) in Electrical Engineering from The Indian Institute of Technology and an MBA from Monash Mt Eliza Business School. He has background experience in Power Transformer Design, Quality and Test. He is a member of Cigre Australian Panels A2 and D1.

Neil Glasson is a Senior Research Engineer at Callaghan Innovation, with a PhD in Mechanical Engineering obtained in 1993. Neil has been involved in this transformer project as the lead Engineer since its beginning in 2009. Engineering challenges faced in the project were dominated by the need to efficiently make things really cold - without breaking them – and keep them that way for a long time. Neil came to this role from 10 years as Engineering Manager for a stainless steel fabricator, but had to quickly learn about advanced composite fabrication for this project as many of the components had to not only be compatible with cryogenic temperatures but also be non-conductive. Callaghan Innovation is the government agency charged with accelerating the commercialisation of innovation with New Zealand businesses.

Nathan Allpress is a Mechanical Engineer at Callaghan Innovation, with a BE (Hons) obtained in 2009. Nathan joined the HTS transformer project after working on aspects of HTS Roebel cable manufacture and testing, making use of that experience in the design of the low voltage winding. Other related research projects he has worked on include the development of a small-scale nitrogen liquefaction plant.