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Development of a 1 MVA 3-Phase Superconducting Transformer using YBCO Roebel Cable

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***Abstract*—We present design details for the planned construction of a 3-phase 1 MVA 11 kV/415 V transformer using YBCO Roebel cable (YBCO - Yttrium Barium Copper Oxide second generation high temperature superconducting coated conductor). The YBCO Roebel cable is a promising technology for carrying high currents. It simplifies manufacture of the winding while managing AC loss. We present the transformer winding design which follows a simple layout with the low-voltage windings utilizing a 15 strand x 5 mm (15/5) Roebel cable in a single-layer 20 turn solenoid. The target rated current capacity of the cable is 1500 A rms at 77 K. The high-voltage winding will be in the form of a stack of double pancake coils arranged on a composite former outside the low-voltage windings. The coils will be immersed in sub-cooled liquid nitrogen with a target maximum operating temperature of 70 K. The development methodology is described along with the results of experiments and modeling to validate the performance characteristics of the windings. Experiments on heat transfer from the windings are presented.**

***Index Terms*—Cables, Cryogenics, Superconducting Transformers.**

I. INTRODUCTION

One of the greatest obstacles to the successful implementation of High Temperature Superconductors (HTS) in AC power devices, and transformers in particular, is the challenge of minimizing the inevitable AC loss [1,2]. The consequences of excessive AC loss are unacceptably high cryogenic cooling load and heightened risk of conductor instability and failure.

A major contributor to AC loss in HTS tapes is hysteretic loss produced by the normal component of the AC field. This loss scales with conductor width at moderate field amplitudes and so can be reduced by using narrower conductors requiring parallel conductors to achieve high current capacity. Reduction of magnetic AC loss using striations to divide the conductor into a number of narrower strips [3] has been demonstrated, but these gains may be negated unless the strips can be transposed to eliminate circulating coupling currents. High current and limitation of AC loss using continuously transposed strands can be achieved using YBCO Roebel cable. This technology has been developed by a number of research groups [4-5]. General Cable Superconductors Ltd. has developed a manufacturing facility to produce cable lengths up to 400 m or more.

Here we report the base design and initial work to demonstrate the utility of using YBCO Roebel cable for the high-current secondary windings of a 1 MVA, 3 phase distribution transformer.

II. OVERVIEW

The goal of the project is to demonstrate the utility of YBCO Roebel cable in a transformer application; to develop a fully integrated cryogenic system; and gain experience in the operation of a superconducting transformer in an electricity distribution network.

The transformer rating was determined by the capacity of available cable, standard distribution level voltages, and a desire to avoid the complication of high voltage design. The parameters are listed in Table I.

TABLE I TRANSFORMER DESIGN PARAMETERS

Parameter	Value
Primary Voltage	11,000 V
Secondary Voltage	415 V
Max. Operating Temperature	70 K, liquid nitrogen cooling
Target Rating	1 MVA
Primary Connection	Delta
Secondary Connection	Wye
LV Winding	20 turns 15/5 Roebel cable
LV Rated current	1390 A rms
HV Winding	918 turns of 4 mm YBCO wire
HV Rated current	30 A rms

High risk aspects for application of the cable in the transformer include conductor stability, short circuit performance, and in-rush currents. Stability of the conductor

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was identified as a major risk, complicated by the difficulty of predicting AC loss in the windings and the potential impact of non-uniform critical current.

III. HTS CONDUCTOR SELECTION

Earlier HTS transformer projects had suffered from excessive AC loss [6,7]. A criterion for selecting the conductors in this project was the degree to which AC winding-loss could be reduced. This indicated a wire technology with non-magnetic substrate, narrow width conductor, and sufficient copper thickness for stability without introducing significant eddy current loss. To handle the high current required for the low voltage winding YBCO Roebel cable became the only choice, while standard production 4 mm YBCO wire was acceptable in terms of AC loss for the low-current winding for transformers of ~1 MVA rating. Roebel cable also met ease of winding and mechanical strength considerations.

The cable was manufactured by General Cable Superconductors. Carefully selected 12 mm wide YBCO tapes were sourced from SuperPower® and punched into serpentine strands with a 300 mm transposition length. The width of each strand is 5 mm. Tapes were selected for good two-dimensional superconducting homogeneity as determined by the uniformity of the remanent field distribution measured by in-line scanning using a Hall sensor array. The punched strands were assessed further for quality by measuring transport Ic. Selected strands were then assembled into a cable in a custom built cabling machine.

Fig 1. Close up photographs of YBCO Roebel cable.

The 1 MVA design requires the cable in the low voltage winding to be a 15/5 configuration (15 strands 5 mm wide), 20 m per phase, with a critical current at the operating temperature in excess of 2000 A. The first 20 m cable has been delivered.

Transport and magnetization AC loss measurements have been made on single 4 mm strands and Roebel cable that allow for an estimate of the AC loss of the windings [8,9]. For the HV winding, for which $I/I_c \sim 0.25$ at 70 K we use an average of the Norris strip and ellipse predictions scaled by a factor of 50 - an empirical factor to take into account the coil self-field [10]. The cable in the LV coil will operate much closer to its critical current. Because of this transport loss should dominate. The Norris strip model has been shown to predict the AC loss of a Roebel cable at high I/I_c [11]. Estimating I_c for the cable at 70 K is difficult, involving extrapolating strand Ic and the self-field reduction of cable I_c relative to the sum of the strands. Assuming a cable assembled from strands with 180 A critical current we estimate the total loss in the low and high voltage windings at the rated current of 1390A is about 200 W/phase.

IV. TRANSFORMER DESIGN

A. *Background*

An electrical design for a prototype 1 MVA, 3-phase, 11 kV/420 V, Dyn connected, 50 Hz, 5% impedance transformer has been developed using YBCO Roebel cable (LV) and standard 4 mm wire (HV). The transformer will be manufactured and tested to IEC60076 and installed as a demonstration unit in the distribution network in Auckland of lines company Vector. The iron core will be fabricated by Wilson Transformers, coils wound by HTS-110, cryogenics designed by IRL, and core-coil assembly and final testing completed by ETEL Ltd.

B. *Low voltage winding*

The low voltage coils will use a 20 m length of 15/5 Roebel cable per phase as a single layer solenoid winding on a fiberglass composite former with a machined helical groove. The groove supports and axially restrains the cable on the former. This winding will allow sub-cooled liquid nitrogen to freely circulate across its surface.

C. *High voltage winding*

The high voltage windings will take the form of 24 double pancakes per phase. The 4 mm wire will be insulated with spiral-wrapped polyimide tape. Each double pancake will have 38¼ turns. The pancakes will not be epoxy encapsulated for a number of reasons. First, recent research indicates that epoxy impregnation of YBCO pancake assemblies can result in serious performance degradation [12]. Second, there is concern that voids within the epoxy will present a weaker impulse withstand. Third, encapsulation is likely to be detrimental to the heat transfer performance of the winding.

D. *Electrical Performance*

The warm core has a cruciform, 6-stepped core section of high grade core steel. The net utilization factor will be close to 88% and no-load loss can be limited to 708 W for the smaller core allowed by a single 3-phase cryostat (Fig. 2). During a short circuit event, the HTS is assumed to quench immediately and transfer current to the 40 µm thick copper stabilizer layer. The resistance offered by the copper is 12.6% (effective impedance is 13.7%). This provides significant resistive current limiting, resulting in the following tangential stresses due to radial forces: HV = 100 MPa; LV = -227 MPa. These stresses are within the 0.2% proof strength of >500 MPa for YBCO coated conductor [13]. Axial forces on the conductors are controlled by careful design of the winding formers and winding clamping arrangement.

Thermal performance during short circuit has been investigated using a transient temperature-resistance-current model. The transformer will not withstand 2 seconds as prescribed in the standards, and will need to be isolated sooner to prevent a damaging temperature rise.

Insulation design is based on an FEM impulse design program. Calculated turn-to-turn, inter-disc and HV-LV impulse voltages stresses are consistent with withstand voltage stresses for a liquid nitrogen-fiberglass composite barrier system [14].

E. Heat Transfer

Effective heat transfer from the windings into the liquid nitrogen is a vital consideration to manage AC loss and rapid recovery from fault currents. Experiments have been conducted to determine the optimal winding configuration for maximum heat transfer to guide selection of the winding insulation employed [15]. These experiments were conducted using 5 mm x 0.3 mm copper tapes assembled in a variety of different configurations to represent single conductors, stacks of conductors, and pancake windings. Heat input was varied by controlling the current and the temperature rise in the copper was determined by the measured change in resistance. Notable outcomes are:

- Heat transfer occurs entirely in a non-boiling regime for the range of heat loads anticipated within the transformer during normal operation.
- The expected temperature increase in the LV windings for the calculated AC power dissipation is of the order of 1 K.

F. Transformer Cryostat

The transformer design requires a warm core. Although this makes the cryostat more complex it is vital to minimize the thermal load within the cryogenic envelope. The estimated core loss is of the order of 700 W. Assuming a cooling penalty of 25:1 an extra 17.5 kW of cryocooler power would be required if the core was housed within the cold zone.

The transformer cryostat will be manufactured from a fiberglass composite with properties that approximate proprietary G10.

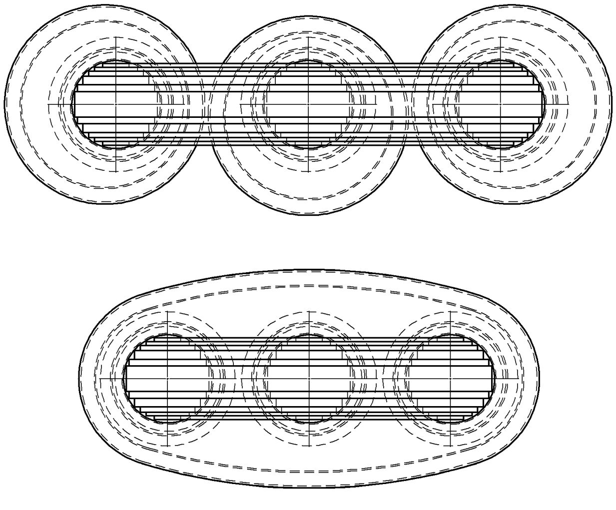

Fig. 2. Plan views of alternative cryostat configurations for a three phase transformer. Three individual cryostats (top) offers simple manufacture. A common cryostat for all three phases (bottom) allows a more compact design and reduced heat leak through bushings and liquid nitrogen connections.

A major consideration is to decide if each phase is to be housed in a separate cryostat or if the more challenging cryostat housing should be adopted with all three winding assemblies in the same cryostat. Having three individual cryostats is attractive as it offers lower manufacturing risk. A common cryostat offers significant advantages in terms of reduced transformer dimensions and reduced heat leak through current leads because electrical interconnections can be made within the cold zone thereby reducing the number of high current bushings from 6 to 4. A common cryostat will allow a greatly simplified cooling system.

Fig. 2 illustrates the comparative sizes of transformers designed with 3 individual cryostats and a single common cryostat. Clearly the single common cryostat is smaller and offers the attractive option of a smaller core design, less loss and lower weight. To manage the risks associated with the construction of the cryostat we will first manufacture an individual single phase cryostat followed by the development of a common cryostat. The single phase cryostat will be used to test single phase windings.

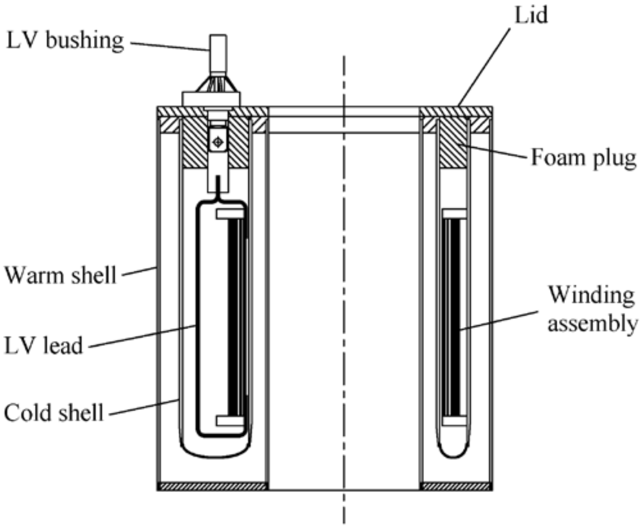

Fig. 3. Design of individual cryostat. Note that the eccentric cryostat design affords plenty of space for bushings and liquid nitrogen connections, while still allowing a reasonably compact assembly of a 3-phase core.

G. Cryogenic cooling system

The primary requirement for the cooling system is that it must reliably provide sufficient cooling power to accommodate all the thermal loads including: heat leaks, AC winding-loss, current lead I^2R loss, and rapid recovery after a fault. Based on the assumptions above a baseline cooling-load was estimated to be 840 W. The relative contributions to this load are listed in Table II. AC winding-loss is the largest contributor (70%). Assuming a 25:1 refrigeration penalty the estimated total transformer losses, including core losses, are about 2%.

To meet this target the cooling system must be efficient and controllable over a wide range of loads. The AC loss increases significantly as the operating current in the secondary winding

TABLE II Calculated Cold Space Heat Loads

Parameter	Value
Cryostat Heat Leak	20 W total
Current Lead Heat Leak	220 W total
Primary Winding AC Loss	30 W/Phase at 70 K
Secondary Winding AC Loss	170 W/Phase at 70 K
Total Heat Load	840 W at 70K

approaches the critical current density of the HTS conductor. “Real world” transformers are likely to be operated somewhat less than the rated load for extended periods. This is particularly true for larger power transformers where capital cost and importance dictate conservative sizing [16]. Therefore the cooling system must be sized to handle the maximum rated loading of the transformer, and also be controllable to efficiently operate at a fraction of that cooling power. This is particularly important given that standards governing transformer efficiency typically specify that efficiency is measured at 50% of the rated load [17].

Cryomech Inc. refrigerators are best suited for continuous constant cooling power operation. They can be cycled on and off, but with no more than 6 starts per hour [18]. Such “on-off” operation would be practical but will require careful system design possibly using a large buffer volume and multiple cryocoolers to produce an efficient and stable system.

Refrigerators from Stirling Cryogenics can be frequency controlled down to 60% of maximum cooling power without significant impact on efficiency. Further control over cooling power may be achieved by using multiple coolers and cycling them on and off as required. A Stirling Cryogenics based system utilizing two cryocoolers, could thereby be controlled almost continuously over the load range from 30% to 100% of full load. Stirling Cryogenics machines can be cycled on and off up to 10 times per hour [19].

The cooling system must satisfy noise level standards for transformers. The utility company has specified that 66 dBA is the target maximum sound power level [20]. Sound pressure levels quoted for the cryocoolers under consideration are in the range of 70 dBA to 76 dBA measured at 1m. Sound power and sound pressure can be related by standard formulae [21]. Calculated sound power values are higher than the quoted sound pressure values. This means that the noise produced by these cryocoolers will need to be attenuated with an enclosure.

V. SUMMARY

An electrical design has been described for a 1 MVA three-phase grid-connected transformer using YBCO Roebel cable for the high-current windings and standard 4mm tape for the high-voltage winding. AC winding loss has been estimated and along with estimates of other contributions to the loss allowing for a total transformer loss estimate of 2%. Next steps include measurements to confirm the loss estimates, design of the cryostat(s), the cooling system, and winding support and restraint structures.

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