An Experimental High Temperature Superconducting Transformer: Design, Construction and Testing

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Abstract

In 2005, the development of a 50Hz, 15kVA, 230V:115V partial core high temperature superconductor (HTS) transformer was completed. The transformer was designed purely as a proof of concept, rather than as a unit that would be put into service. The transformer windings were layer wound using Bi2223 HTS tape from American Superconductors. The transformer failed while endurance testing under full load with the internal primary winding failing to open circuit. This prompted an investigation into the cause of failure. Results from the investigation suggested the cause of failure to be insufficient cooling of the windings.

This paper presents a new experimental full core HTS transformer with an alternative winding design to enable greater cooling for the HTS wire. The design involves the use of cooling channels allowing direct contact of the HTS wire to the liquid nitrogen coolant.

A mock up transformer was constructed first using copper wire of similar dimensions to the HTS wire. The idea was to construct two similar windings, while using the same core, but using two different winding material types so that a direct performance comparison could be made between the two.

Open circuit, short circuit and loaded tests were performed on the copper mock up transformer submerged in liquid nitrogen. Test results gave an efficiency of 88% in liquid nitrogen, and a 17% voltage regulation at 11kVA load. In terms of mechanical integrity, the copper mock-up transformer withstood all stresses subjected to it when submerged in liquid nitrogen.

Following successful testing of the copper mock up transformer, a set of HTS windings were constructed using Bi2223 superconductors. The transformer was a full core, 50Hz, 15kVA, 230V:230V two winding transformer. Open circuit, short circuit and loaded tests were performed on the HTS transformer while submerged in liquid nitrogen. Test results gave an efficiency of 97%, and a 13% voltage regulation at 14kVA load.

1. Introduction

Early superconductors required temperatures of only a few Kelvin to work and their application was very limited. The discovery of high temperature superconductors (HTS) in 1986 [1] paved the way for the application of these materials into power system devices. Wire made from bismuth strontium calcium copper oxide (BSCCO) and more recently yttrium barium copper oxide (YBCO) has been used in many power system devices such as fault current limiters [2][3], power cables [3] and power transformers [5][6].

A HTS conductor will only be superconducting so long as the magnetic field density, temperature and conductor current are below critical limits. If the limits are exceeded, the conductor will change from a superconducting state to a resistive state. If this happens, the HTS conductors may not be able to handle the current flowing due to their small cross sectional area and may blow like a fuse unless the current is otherwise interrupted.

This paper presents an experimental partial core HTS transformer that was built at the University of Canterbury [7]. The transformer was tested under no load, short circuit and full load conditions. A full load endurance run was performed which resulted in the transformer failing. Following an investigation which determined that the cause was thermal related, a new winding design was developed.

A full core copper mock-up was then designed and tested followed by a HTS winding design. The design, construction and testing of these transformers are also presented in this paper.

2. The HTS partial core transformer

In 2005, a new type of HTS transformer was designed and built at the University of Canterbury [7]. The transformer was a partial core design where the outer limbs and connecting yokes of the core were absent, (Figure 1). This means that the magnetic circuit consists of the central core steel and the surrounding air resulting in a high magnetic reluctance.

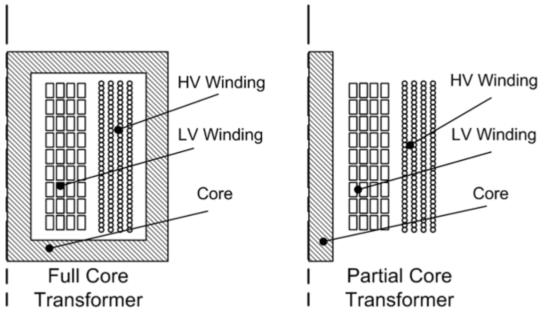


Figure 1. A cross-sectional view of the differences between full core and partial core transformers

An advantage of this design is that the construction of the transformer is easier and the overall weight is reduced, making construction and transportation costs less. A disadvantage of this design is that the magnetising current is high due to the high reluctance of the magnetic circuit. This high magnetising current results in higher copper losses and a larger cross-sectional area is required for the windings.

Fortunately, with the application of HTS wire, the issue of a high magnetising current is reduced. The HTS wire has very low conductor losses and a small cross-sectional area, thus allowing for a compact and light partial core transformer. Also of interest is that the problematic magnetising current reduces with the square of the number of turns, as described in

$$X_m = \omega L = \omega \frac{N^2}{\Re}, \tag{1}$$

where;

X_m = Magnetising reactance,
ω = $2\pi f$ (f = frequency),
L = Magnetising inductance,
N = Number of turns,
$\Re$ = Reluctance of the magnetic circuit.

Small increases in HTS wire length, i.e. number of turns, can give a significant reduction in magnetising current.

However, the disadvantage of this approach is the high cost of the HTS wire at present, although cost is likely to reduce in the future as the technology matures.

2.1. Transformer Design

The HTS partial core transformer was designed as a 50Hz, 15kVA, 230V:115V three winding transformer. This design allowed for the basic transformer operation and performance to be found without the added complexity of having extra high voltage windings. The three winding arrangement was to allow for the investigation of multiple winding configurations. Liquid nitrogen was used as the coolant for the HTS windings. The design details of the transformer are given in Table 1.

The core was constructed using high permeability, grain orientated silicon steel. The core was designed as a parallel stacked circular core with 420 laminations.

The windings were layer wound using 1G-HSP wire from American Superconductors with dimensions of 0.23 ×4.3 mm. This tape is based on BSCCO superconductor, a generation one HTS technology, where many superconducting filaments are encased in a silver alloy matrix using a powder in tube process. The HTS wire was insulated using NOMEX® tape.

Table 1. Dimensions of the partial core transformer

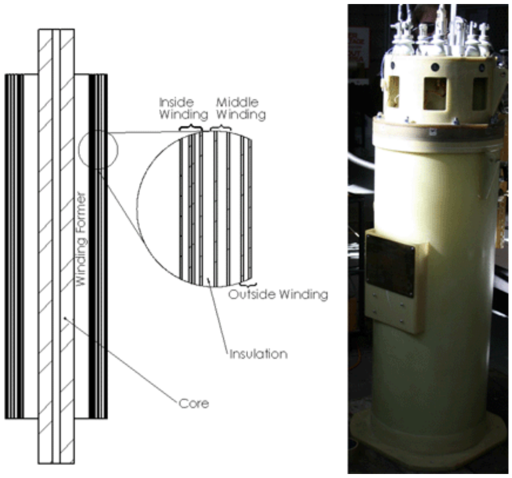
	Parameter	Dimension
Core	length	484 mm
	diameter	80 mm
	lamination thickness	0.23 mm
Inside winding	terminal connection	A1 – A2
	layers	4
	turns per layer	80
	winding height	384 mm
	conductor length	122 m
Middle winding	terminal connection	a1-a2
	layers	2
	turns per layer	80
	winding height	384 mm
	conductor length	69 m
Outside winding	terminal connection	a3-a4
	layers	2
	turns per layer	80
	winding height	384 mm
	conductor length	77 m

Copper lead-outs were used to connect the HTS windings to the transformer bushings. These lead-outs consisted of two 1.2 ×5 mm copper conductors that were soldered to the HTS windings.

Because the copper lead-outs were much thicker than the HTS conductors, it was necessary to pad the windings out to make room. Several layers of NOMEX® 410 insulation paper were used on either side of the HTS layers to allow room for the copper lead-outs. It was assumed that because the windings would be superconducting, the winding losses would be small and direct contact with the liquid nitrogen would not be necessary. Figure 2 shows a diagram of the winding layout and a photograph of the completed transformer.

2.2. HTS partial core test results

A series of electrical tests were performed on the completed transformer. These were an open circuit test, a short circuit test, a full load test and a full load endurance run. The test results are outlined in Table 2. The open circuit test was performed with all three windings open circuit, the short circuit test and load test were performed with the two 115 V windings connected in series.



(a) **(b)**

Figure 2. The HTS partial core transformer (a) Diagram of the winding layout with respect to the core, also showing detail of the relative layer spacing (b) Photograph of the HTS partial core transformer

The open circuit test results show a voltage imbalance between the two 115 V windings. This is because the leakage flux increases the further the windings are from the core. Also of note is the high magnetising current in the open circuit test. This is due to the relatively high reluctance of the magnetic circuit resulting in a low magnetising reactance (Equation 1).

The short circuit test results show small real power losses compared to the apparent power of the test, indicating that the leakage reactance is much larger than the winding losses.

The results from the load testing show how the partial core design can produce a capable power transformer. The efficiency and voltage regulation results under full load are comparable to full core transformers of similar ratings.

During the endurance run, a catastrophic failure occurred. About 1 minute 30 seconds into the test, a surge in nitrogen gas was observed with a collapse of the secondary voltage. The power was removed from the transformer and resistance tests were performed on the windings. The primary winding, A1-A2, was found to be open circuit.

Table 2. Test results for the partial core HTS transformer

Open Circuit Test	
Parameter	**Measured**
Inside winding voltage (V)	230
Inside winding current (A)	19
Middle winding voltage (V)	113
Outside winding voltage (V)	111
Inside Winding Real Power (kW)	0.2
Short Circuit Test	
Parameter	**Measured**
Inside winding voltage (V)	25
Inside winding current (A)	65
Outside winding current (A)	65
Inside winding real power (W)	80
Inside winding apparent power (VA)	1625
Load Test	
Parameter	**Measured**
Inside winding voltage (V)	230.9
Inside winding current (A)	65
Inside Winding Real Power (kW)	13.8
Outside winding voltage (V)	223.6
Outside winding current (A)	61
Outside winding real power (kW)	13.6
Real power loss (kW)	0.2
Efficiency (%)	98.6
Voltage regulation (%)	3.2

2.3. Failure investigation

An investigation was conducted to determine the cause of the transformer failure [8]. The investigation involved a visual inspection of the transformer. This inspection revealed black contaminants on the insulation and a small area of burnt insulation was found on the primary, A1-A2, winding where the open circuit was measured (Figure 3).

Following the initial inspection, it was hoped that the damaged area would be able to be repaired. In order to do this it was necessary to unwind the transformer. It was during the unwinding of the transformer that the full extent of the damage was discovered. Figure 4 shows the damage found on the inner winding layers. It is believed that the damage originated from the inner most winding layer.

Results from that investigation suggested that insufficient cooling of the inner windings caused the windings to go out of their superconducting state and a thermal failure occurred. In hindsight the authors believe that the packing should have used axial fibreglass to allow for better contact of the liquid nitrogen with HTS wire.

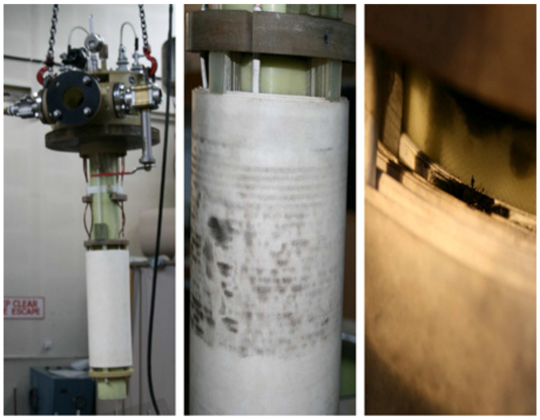

(a) (b) (c)

Figure 3. Photographs of the initial visual inspection of the failed HTS partial core transformer (a) The transformer before the failure (b) Contaminants found on the insulation after the failure (c) close up of the small area of burnt insulation.


(a) (b) (c)

Figure 4. Photographs of the unwinding of the failed transformer (a) outer layer of the middle winding (b) outer layer of the inside winding (c) innermost layer of the inside winding

3. New winding design

Following the failure of the partial core HTS transformer and the subsequent investigation into the cause of that failure, a new design for the windings was developed [9]. This design was to incorporate cooling channels in the winding area to enable greater contact of the liquid nitrogen with the HTS windings and prevent another thermal failure. It was decided that two full core transformers would be designed, a copper mock-up and a HTS design, using a combination of mathematical modelling and computer aided design software. The two transformers would share the same core and have the same winding dimensions so that their performance could be compared directly. Due to financial constraints, the transformers were designed to be completely submerged in liquid nitrogen rather than designing a winding Dewar.

3.1. Core design

Because the two windings were sharing the one core, the challenge was to design the core so that it could be easily pulled apart and put together again. The core was designed to minimise the weight and core losses.

The core was constructed from high permeability, grain orientated silicon steel. It was designed as a circular core of parallel stacked laminations, with a square limb and yokes to keep construction simple, (Figure 5).

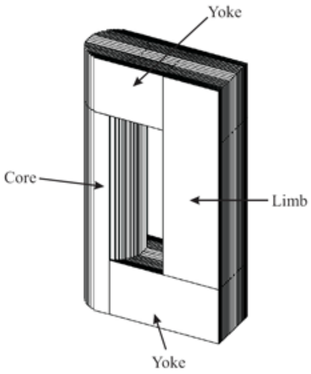


Figure 5. The full core assembly

The design data for the core is given in Table 3. The reason for the low staking factor was due to the use of polyurethane for gluing the lamination sections together. These sections, comprising of ten laminations, enabled the core to be assembled and disassembled easily, Figure 6.

Table 3. Full core design data

Parameter	Dimension
Core length	784 mm
Core diameter	75 mm
Winding window height	200 mm
Winding window width	42 mm
Lamination thickness	0.23 mm
Stacking factor	0.85
Operating temperature	77 K

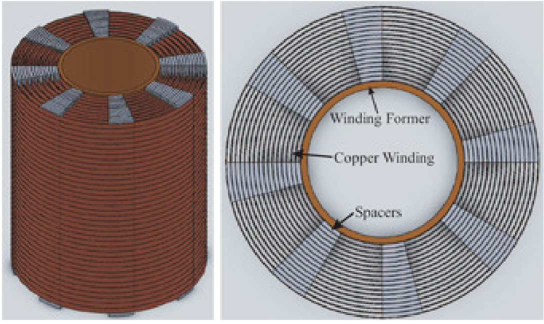
Figure 6. The full core assembly with the top yoke removed.

3.2. A full core copper mock-up

The winding design data for the copper mock-up is given in Table 4. The priority of the design was to ensure enough cooling of both windings. Working with the materials available in the university, 2mm thick composite fibreglass spacers were used for the inter-layer insulation. The spacers were placed radially around the winding as depicted in Figure 7. As the number of layers increased, the width of the spacers was also increased to ensure a firm circular/round winding with no kinks in any of the turns.

Table 4. Copper mock-up design data

Parameter	Dimension
Inside winding dimensions	
Winding height	190 mm
Number of layers	8
Turns per layer	37
Conductor length	92.6 m
Wire width	4.83 mm
Wire thickness	0.30 mm
Wire insulation thickness	0.11 mm
Insulation layer space	2 mm
Operating temperature	77 K
Parameter	**Dimension**
Outside winding dimensions	
Winding height	190 mm
Number of layers	8
Turns per layer	37
Conductor length	125.6 m
Wire width	4.83 mm
Wire thickness	0.30 mm
Wire insulation thickness	0.11 mm
Insulation layer space	2 mm
Operating temperature	77 K



(a) **(b)**

Figure 7. Diagram for the winding and spacer arrangement for the copper mock-up (a) Trimetric view of winding assembly (b) top view of winding assembly

To prevent inter-turn short circuits, the copper wire was insulated with NOMEX® tape. The windings were wound on a composite former made with an epoxy-resin lacquered fabric. Both these materials were tested under liquid nitrogen conditions to observe shrinkage or other adverse effects. No significant shrinkage was observed. A photograph of the completed copper mock-up transformer is presented in Figure 8.

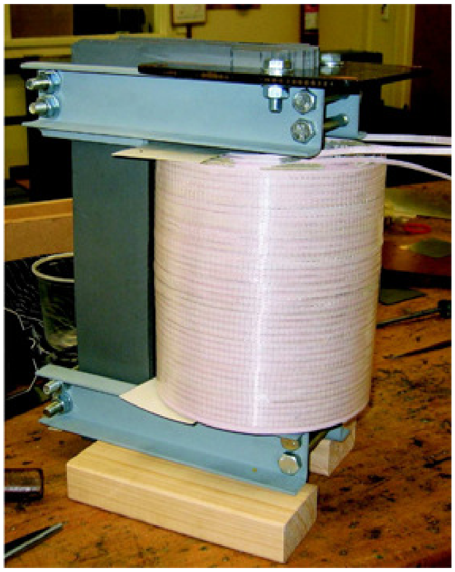


Figure 8. Photograph of the completed copper mock-up transformer

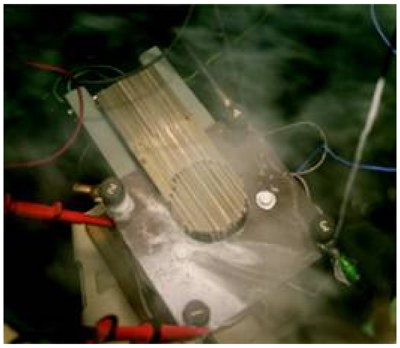


Figure 9. Photograph of the copper mock-up transformer being tested under liquid nitrogen

3.2.1. Copper mock-up test results

A series of electrical tests were performed on the copper mock-up transformer while submerged in liquid nitrogen, Figure 9. Open circuit, short circuit and loaded tests were performed. The results are presented in Table 5.

Open circuit test results show how the full core design reduces the magnetising current compared to that of the partial core design. Also of note is a small reduction in the secondary voltage due to the primary leakage reactance.

The short circuit test results show that even at cryogenic temperatures, the resistance of

Table 5. Copper mock-up test results at liquid nitrogen temperature

Parameter	Measured
Open Circuit Test	
Primary voltage (V)	230
Primary current (A)	0.12
Primary real power (W)	19
Primary apparent power (VA)	28
Primary power factor	0.7
Secondary voltage (V)	226
Voltage ratio	0.98
Short Circuit Test	
Parameter	**Measured**
Primary voltage (V)	35.3
Primary current (A)	30.6
Primary real power (W)	410
Primary apparent power (VA)	1080
Primary power factor	0.38
Secondary current (A)	30.9
Current ratio	1.01
Load Test	
Parameter	**Measured**
Primary voltage (V)	229
Primary current (A)	49.3
Primary real power (kW)	10.2
Primary apparent power (kVA)	11.3
Primary power factor	0.9
Secondary voltage (V)	189
Secondary current (A)	49
Secondary real power (kW)	9
Secondary apparent power (kVA)	9.3
Secondary power factor	0.97
Efficiency (%)	88
Voltage regulation (%)	17

the copper windings is enough to cause 400 W of losses. The current density during the short circuit test was approximately 20 A/mm^2, a value much higher than could be sustained by the transformer operating in air at room temperature.

The load test shows how the large leakage flux caused by having 2 mm spacing between each layer has resulted in a relatively large voltage regulation. The resistance of the windings has also affected the efficiency of the transformer. The current density for this test was about 34 A/mm^2.

3.3. HTS full core transformer

The spacers and insulation design of the superconducting winding is the same as the copper mock-up. The main difference is the wire width, which is 0.73mm less than the copper tape. However, these windings still have the same number of turns per layer as for the copper version. The design data for the HTS transformer is given in Table 6.

Table 6. Design data for the HTS transformer

Parameter	Dimension
Inside winding dimensions	
Winding height	190 mm
Number of layers	8
Turns per layer	37
Conductor length	92.6 m
Wire width	4.10 mm
Wire thickness	0.30 mm
Wire insulation thickness	0.11 mm
Insulation layer space	2 mm
Operating temperature	77 K
Parameter	**Dimension**
Outside winding dimensions	
Winding height	190 mm
Number of layers	8
Turns per layer	37
Conductor length	125.6 m
Wire width	4.10 mm
Wire thickness	0.30 mm
Wire insulation thickness	0.11 mm
Insulation layer space	2 mm
Operating temperature	77 K

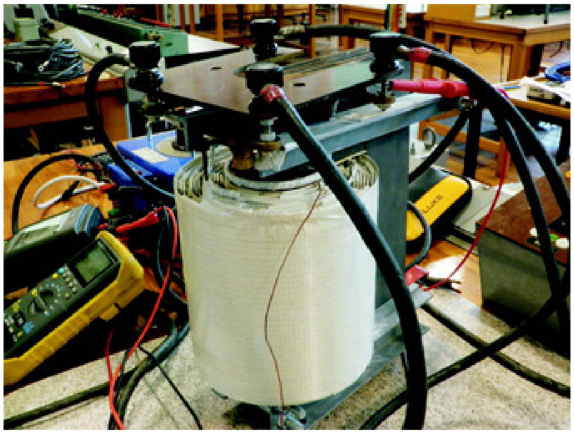


Figure 10. The completed HTS full core transformer

Copper lead-outs were used to connect the HTS windings to the terminals. The lead-outs were soldered to the HTS wire using the same technique as used for the partial core HTS transformer of Section 2.

Table 7. HTS full core transformer test results at liquid nitrogen temperature

Open Circuit Test	
Parameter	**Measured**
Primary voltage (V)	226
Primary current (A)	0.26
Primary real power (W)	34
Primary apparent power (VA)	57
Primary power factor	0.59
Secondary voltage (V)	232
Voltage ratio	1.03
Short Circuit Test	
Parameter	**Measured**
Primary voltage (V)	40.2
Primary current (A)	35
Primary real power (kW)	0.07
Primary apparent power (kVA)	1.41
Primary power factor	0.05
Secondary current (A)	33.5
Current ratio	0.96
Load Test	
Parameter	**Measured**
Primary voltage (V)	230
Primary current (A)	62
Primary real power (kW)	12.5
Primary apparent power (kVA)	14.3
Primary power factor	0.87
Secondary voltage (V)	204
Secondary current (A)	61
Secondary real power (kW)	12.0
Secondary apparent power (kVA)	12.4
Secondary power factor	0.97
Efficiency (%)	97
Voltage regulation (%)	13

Due to the poor voltage regulation of the copper mock-up transformer, some extra turns were used on the secondary winding of the HTS transformer. The completed transformer is illustrated in Figure 10.

3.3.1. HTS test results

A series of electrical tests were performed on the HTS transformer while submerged in liquid nitrogen. Figure 11 shows the Dewar where the transformer was placed during testing. Open circuit, short circuit and loaded tests were performed. The results of the testing are summarised in Table 7. The load test was performed for more than 3 minutes with no measurable increase in winding temperature. This suggests that the cooling channels are beneficial to the ability of the superconducting windings to continue to be superconductive under high transport currents and magnetic fields.

Figure 11. The Dewar used for containing the liquid nitrogen during testing

Open circuit test results show a slightly higher power loss and a slightly larger current than that of the copper mock-up. This could be due to the reassembly of the core being slightly different compared to when it was used with the copper mock-up. The test also shows an increase in secondary voltage due to the extra turns on the final secondary layer that was added to compensate for the loaded volt-drop of the copper mock-up.

The short circuit test results show a dramatic reduction in the real power losses compared to the copper mock-up, from 410W to 70W, even though the current density was much higher (28 A/mm^2 compared to 20 A/mm^2). This demonstrates the HTS windings ability to transport very high current densities with low losses while superconducting.

The load test results show an improvement across the board compared to the copper mock-up. The efficiency has been greatly improved over the copper transformer from 88% to 97% even though the load has been increased from 9 kW to 12 kW. The voltage regulation, at 13%, is still quite large compared to conventional transformers of similar ratings. This is due to the excess leakage flux caused by the 2 mm spacers.

4. Future work

The successful testing of the new full core HTS winding design demonstrated that the cooling channels are beneficial in preventing thermal failure. The next step is to perform a full load endurance run on the prototype full core HTS transformer for at least a 24 hr period.

Following a successful endurance test, the partial core HTS transformer will be redesigned to allow for cooling channels in the windings. The problematic leakage flux that was present in the full core prototype will be somewhat minimised by the longer aspect ratio of the partial core design.

5. Conclusions

Construction of a 50Hz, 15kVA, 230V:115V partial core, HTS transformer was completed in 2005 using Bi2223 HTS tape from American Superconductors. The transformer failed while endurance testing under full load with the internal primary winding failing to open circuit. An investigation into the cause of failure suggested insufficient cooling of the windings.

A new experimental full core HTS transformer was designed with windings enabling greater cooling for the HTS wire. The design involved the use of cooling channels allowing direct contact of the HTS wire to the liquid nitrogen coolant.

A copper mock-up transformer was constructed using copper wire of similar dimensions to the HTS wire. Open circuit, short circuit and loaded tests were performed on the copper mock up transformer submerged in liquid nitrogen. Test results gave an efficiency of 88% in liquid nitrogen, and a 17% voltage regulation at 11kVA load. In terms of mechanical integrity, the copper mock-up transformer withstood all stresses subjected to it when submerged in liquid nitrogen.

A set of HTS windings were then constructed using Bi2223 superconductors. The transformer was a full core, 50Hz, 15kVA, 230V:230V two winding transformer. Open circuit, short circuit and loaded tests were performed on the HTS transformer while submerged in liquid nitrogen. Test results gave an efficiency of 97%, and a 13% voltage regulation at 14kVA load.

6. Acknowledgements

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