Techno-Commercial Aspects of Superconducting Transformers – A Case Study

B. Dheeraj Reddy, K. Dinesh Kumar, R. Sudha

Abstract- On invention of High Temperature Superconductors (HTS), there is a widespread talk that superconducting transformers can now be used extensively. But there are problems like lack of a suitable superconductor, cryogenic coolers and behavior of these transformers on faults and starting transients. This paper describes the problems with superconducting technology. A comparative study has been done with a conventional distribution transformer (DTR) and the outcome is tabulated. The results show, that superconducting transformers can give an additional efficiency of 0.3 to 0.5% at double the cost of conventional transformer with an unacceptable payback period. Hence HTS Transformers are used where they are essential and viable. A final purpose of this paper is given to create a method of analysis that allows others to conduct quantitative or optimised modelling about the future HTS transformers.

Index Terms - Distribution Transformer (DTR), Fault Current Limiter (FCL), Superconductor, Superconducting Transformers (SCT), High Temperature Superconductivity (HTS).

I. INTRODUCTION

The announcement in April 1986, by Muller and Bednorz (IBM) of superconductivity in the perovskite structure Lanthanum-Barium-Copper oxide at 30K, was an important step towards a wider application of superconductivity [1].There is significant activity around the world regarding applications of HTS materials to cables, motors, generators, fault current limiters, energy storage devices and transformers. However a HTS conductor will be superconducting as 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.

At present HTS transformers are designed with a maximum overall efficiency of 99.9% against the maximum possible value of 99.3% with a conventional transformer. However there are certain known difficulties like leakage of coolant, maintaining temperature and pressure of coolant and their inability to withstand high starting and fault currents. The superconducting windings require special consideration for the induced electromagnetic forces in order to limit them below the permissible tensile stresses.

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II. MERITS OF HTS TRANSFORMERS

HTS transformers can be used for various applications such as for quenching techniques and in traction systems[2] indoor applications.The up to date study and research confirms that superconducting transformers can raise the efficiency of Transformer from 99.3 % to 99.9%, which means superconducting transformers can save 70 to 80% of energy loss per year. Reduced size and free from fire accidents are the other major benefits. The merit of SCT's is a possibility as a fault current limiter by the utilization of normal transition of superconducting winding.

III. PROBLEMS WITH HTS TRANSFORMERS

Coolant: Liquid nitrogen cooling system requires continuous supervision and maintenance. The cost of the coolant is also very high compared to the oil cooling in traditional transformer.

Cost implications: The capital cost of SCT's is double than that of conventional DTR. The payback period of SCT is discussed later and is not economical.

Operation under abnormal conditions: SCT's cannot withstand faults for a longer time and have high recovery time. This requires operation in parallel with a conventional transformer.

Starting problems: Inability to withstand for high starting currents which calls for single pole circuit breakers.

Mechanical Forces: Distribution transformers will not be immediately affected by deformation caused by mechanical force during high current flow but SCT's will not carry high currents with deformed windings which lead to immediate failure of the transformer.

IV. MATERIALS

The fundamental requirement for electrical power applications is a strong and flexible high-temperature superconducting wire capable of carrying large currents in magnetic fields. The amount of current a wire can carry before losing its superconductivity due to heating or magnetic fields is called the critical current.

For the high temperature superconductors, following two types, are being mainly developed.

Yttrium compounds (YBCO)

$Y_1Ba_2Cu_3O_{7-x}$ (123) $T_c = 92$ K

$Y_2Ba_4Cu_7O_{15-y}$ (247) $T_c = 95$ K

Bismuth compounds (BISCCO)

$Bi_2Sr_2Ca_1Cu_2O_y$ (2212) $T_c = 80$ K

$Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_y$ (2223)(Fig 1) $T_c = 110$ K

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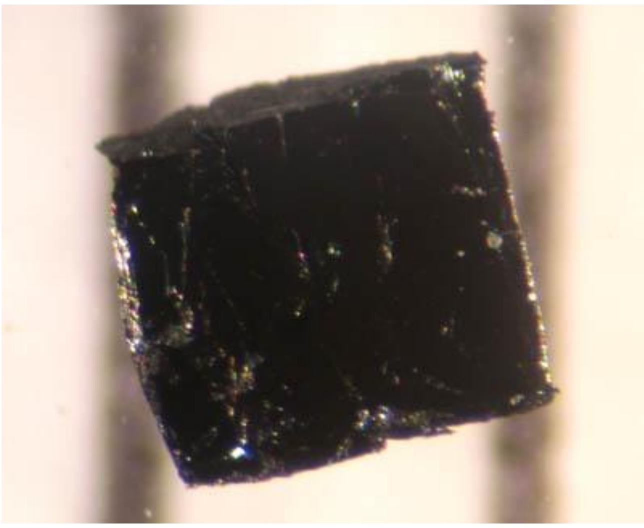

Fig 1. Bi2223 HTS piece

YBCO wires allow larger critical current density than BSCCO and hence YBCO are much more economical as they large help in reducing AC loss in HTS transformer.
Presently, magnets made of BSCCO [3] type superconductors seem to be more feasible from the current engineering point of view. However the critical current density of BSCCO superconductors, at the liquid nitrogen temperature, is greatly reduced in the presence of magnetic fields. Therefore, it is difficult to achieve the field of 0.2 to 0.3 T necessary for transformers. High temperature superconducting tapes like BSCCO when used in high voltage application require insulation. Adjacent tapes have voids which lead to partial discharge of voltage and cause damage which ultimately leads to breakdown. When HTS tapes are used in cryogenic temperature partial discharge aging might be the primary source of aging.
The new materials developed recently like brittle ceramics are not easily formed into long flexible conductors; high current levels require near-perfect crystallinity; and the downside of high transition temperature performance drops rapidly in a magnetic field. Despite these formidable obstacles, high-temperature superconducting wires are manufactured for demonstrations of transmission cables, motors and other electrical power components. The question arises whether the advantages of superconducting wire, such as efficiency and compactness, can outweigh the cost disadvantage.

V. TESTING

As stated in [4], a series of electrical tests were conducted on the high temperature superconducting partial-core transformer (HTSPCTX) to determine its performance. These tests include an open circuit test, short circuit test, load test and load endurance test. When the HTSPCTX was placed on a full load endurance run, a catastrophic failure occurred (fig 2). Approximately 1 minute 30 seconds into the test the secondary voltage collapsed and a surge in nitrogen gas venting was observed, at which point power was removed from the transformer. The emergency venting rupture disc prevented excessive build-up of nitrogen gas in the chamber. Also, radial buckling [4] was found on the inner winding layers. It is believed that this buckling has been caused by thermal expansion of the HTS wire rather than short circuit forces referred to in traditional transformer.

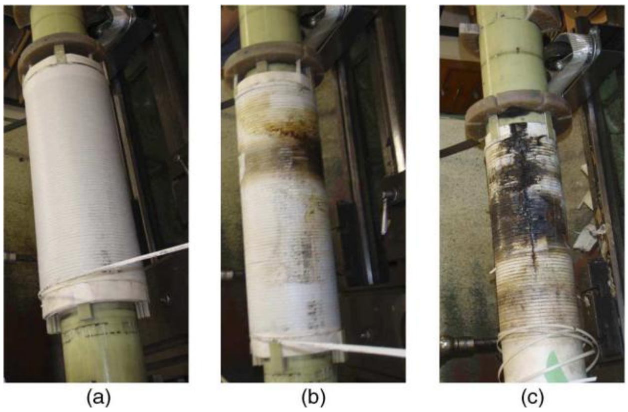

Fig 2. Photographs of unwinding the HTSPCTX after the failure. (a) Outside Winding; (b) middle winding; (c) inside winding

VI. FAILURE ANALYSIS

The initial inspection revealed that contamination of the insulation with a black substance. The burn profile indicated that the superconductor quenched due to lack of cooling. The detailed inspection shows extensive thermal damage over a significant area of the primary winding. The contamination over the insulation mainly due to nitrogen bubbling was occurring in the cooling system. It was presumed that the failure was because the HTS tape quenched due to a combination of the transport current, magnetic field and temperature of the windings. With the HTS in a resistive state, the losses dissipated would have increased the temperature in the inner windings where the cooling was poorest. Eventually the increase in temperature would result in the insulation failing, shorted turns in the windings and final breakdown of the HTS.

VII. SOLUTION

The transformer selected for testing has a rating of 65A (92 A) peak. During full load endurance test the transformer operated close to the critical value. The test results show poor performance of HTS tape rated for 92A in a perpendicular field near the critical value. So reasonable margins should be made between the ratings of these two values. It is suggested that the critical current value is approx. 75% (fig.3) of the maximum peak load current.

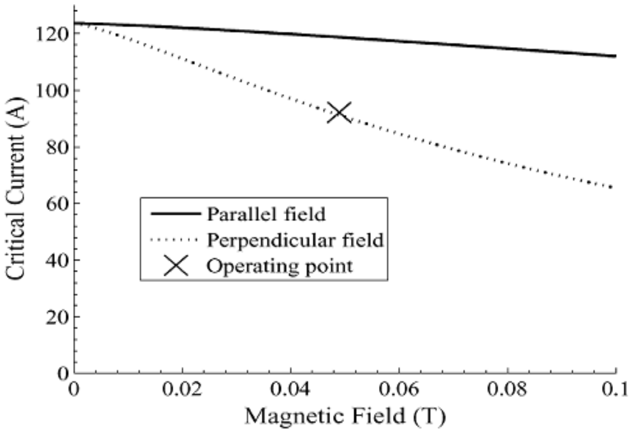

Fig. 3 Predicted critical current at 77 K of the Bi2223 HTS tape with increasing magnetic field.

A Continuously transposed Coil (fig. 4) [5] cable made of copper carries large current while keeping AC losses within an acceptable limit. This helps in increasing critical current limit.

Fig 4. Continuously Transposed Cable

The transformer is going to act as a fault current Limiter (FCL) [6], the uniformity of the transition of the transformers winding is crucial to avoid sectional responses of the transformers. These fault current limiters based on high temperature super conductor offers a solution for controlling the problem of fault level at utility distribution and transmission network. Unlike reactor or high impedance transformers, these fault current limiters will limit fault current without adding impedance to the circuit during normal operation [7]. This kind of fault current limiter finds numerous application as it provides various benefits like avoiding equipment damage, equipment replacement, higher circuit breaker rating and split buses.

VIII. CASE STUDY

A case study has been conducted in a continuous process industry having a conventional transformer.

Table 1: Details of existing conventional transformer

Type	3 phase, Oil immersed Distribution type
Rating	1600 KVA
Voltage(Pri/Sec)	6.6 KV / 433 V
Current(Pri/Sec)	150 A / 2130 A
Vector Symbol	Dyn 11
Tap Changer	Off-Circuit with $\pm$2.5% and $\pm$5% Taps
Cooling	ONAN
% Impedance Volts	4.3
Operation	Independent
Iron loss	1.7 KW
Copper loss	17.5 KW at Full Load
Efficiency at 40 % load	99.3%

The continuous observation of load pattern on conventional transformer is as shown in fig. 5.

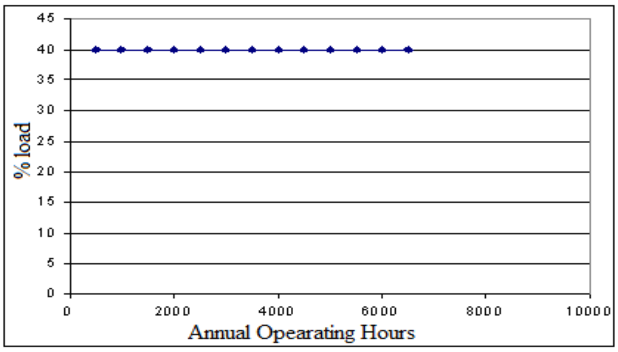

Fig. 5 % Load vs. Annual operating hours

The load is almost constant which helps in easy comparison with Super Conducting Transformer.

A. Comparison of operating parameters

Before proceeding further, the total losses and efficiency of both the transformers at various loads are shown in the Fig.6.

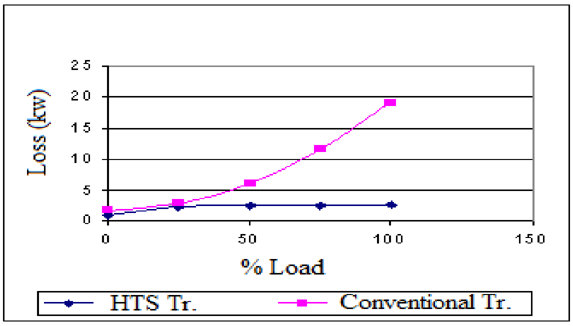

Fig. 6. Losses of both the transformers

The losses in HTS transformer remain almost constant irrespective of the load but in conventional transformer copper losses increase due to increase in load current. However, the efficiency of conventional transformers is already quite high (fig.7); and therefore the efficiency factor alone is not enough in order to introduce SCT's into the existing power system for which other advantages must also be considered.

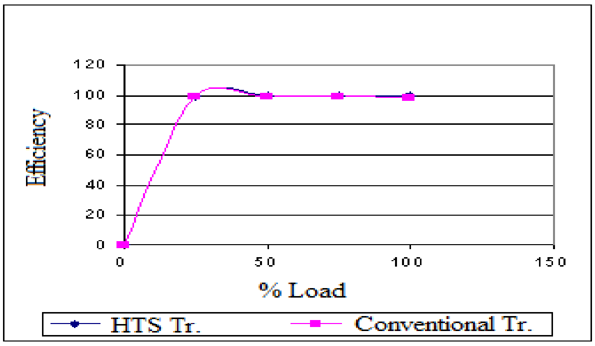

Fig.7 Efficiency of transformers

B. Results

The main parameters are compared in table-2.

Type	HTS	Conventional
Cost (Rs)	16,00,000	8,00,000
Iron loss (KW)	1.0	1.7
Copper loss (KW) @40% load	-	3.0

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Others (KW)	1.0	Nil
Total	2.0	4.7

Table 2: Comparing cost and losses

Difference between total losses = 2.7 KW
Annual energy savings are
2.7 KW * 6500 Hrs. = 17550 KWH
By taking unit charge @ Rs 5/-,
Annual money savings =Rs 88000
Payback period (approx.) = 10 years
This payback period of 10 years is not at all economically viable for a continuously running industry.

IX. CONCLUSION

From the above case study and observations there in depicts that even though Super Conducting transformer offers an additional 0.3% to 0.6% improvement in efficiency, it is may not be acceptable to industries to go for this at double the cost of conventional transformers with a long pay back of unacceptable 10 years. However Super Conducting transformers can be preferred for indoor applications and Industries handling hazardous chemicals due to their fire-risk free property. For other industries, they may wait for further easiness and out coming of energy efficient transformers with efficiency up to 99.6% at an affordable price which can be comparable to Super Conducting transformers.

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