A low voltage, mains frequency, partial core, high temperature, superconducting transformer

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ABSTRACT

A high temperature super-conducting transformer (HTST) has been built. It has been designed to operate in liquid nitrogen, an environmentally benign element that represents little fire and personnel safety risk. The transformer is based on the concept of a partial or open core, where the magnetic circuit is incomplete. The partial core was a slug of laminated silicon steel. This concept has been the result of intensive study and the development of analytical models that have allowed a design somewhat different than what has been attempted elsewhere in the world of superconducting transformers. The transformer was designed purely as a device to prove that the concept works, rather than as a unit that would be put into service. The transformer windings were configured to allow different arrangements, namely internal primary, external primary and autotransformer. The nominal ratings are single phase, 50 Hz, 15kVA, 230V:115V.

1. INTRODUCTION

High temperature super-conductors (HTS) are designed to operate in liquid nitrogen, an environmentally benign element that represents little fire and personnel safety risk. A HTS conductor is only superconducting in liquid nitrogen, so long as the magnetic field density, temperature and conductor current are below critical limits or a combination thereof. If these limits are breached, the HTS conductor will move from the superconducting to a resistive state. In the resistive state, the conductors are not able to handle the current and will blow like a fuse unless the current is otherwise interrupted.

The use of HTS conductors in transformers is attractive in that they are seen to offer reductions in size due to high current densities and increases in efficiencies due to the reduction in winding losses. However, to date, commercial realisation of HTS transformers (HTST) has not occurred. This is primarily due to the approach of substituting HTS tape for copper material without full consideration of redesigning the overall composition of the HTST.

In this paper, an alternative HTST transformer is presented. The transformer is based on the concept of a partial or open core, where the magnetic circuit is incomplete. The partial core is a slug of laminated silicon steel. This concept has been the result of intensive study and the development of analytical models that have allowed a design somewhat different than what has been attempted elsewhere in the world of superconducting transformers.

2. TRANSFORMER LOSSES

Electric power transformers have significant energy losses, costing customers millions of dollars per annum. These losses are generally referred to in their steady operational power form. There are dielectric losses [1] associated with the insulation of the transformer and proximity losses [2] associated with coupling of the transformer magnetic field with nearby metallic objects. However, the most important losses are winding or copper losses which reflect the heating of the windings due to the load current, and core losses which are a combination of hysteresis and eddy current heating of the core material.

The dielectric loss of the insulation is a function of the applied voltage, excitation frequency, insulation capacitance and loss tangent. In conventional transformer design, the first two parameters affecting the dielectric loss are a result of the transformer specifications. The next depends on the winding design and its dimensions. Only the loss tangent is a variable and through the selection of high quality insulation and good maintenance practice, this is generally kept to a low value. Its increase with age and deterioration is more of interest in predicting catastrophic failures than in reducing the dielectric loss. In practice, dielectric losses are considered negligible.

Proximity losses are essentially eddy current losses due to emfs induced in metals near to a transformer. This may include substation structures, circuit breakers, other transformers, the tank of the transformer itself, etc. These losses are a function of voltage and frequency of the supply (transformer specifications), the medium of the magnetic coupling between the transformer and the metal, and the distance between the transformer core and the metal. In a full core transformer design, the inclusion of high permeability material effectively confines the magnetic flux to a designed path such that the leakage flux is small and the coupling to the external metal, through unity permeability insulation, is poor. In practice, while metal transformer tanks get hot, this is usually ascribed to the convectional transfer of winding and core losses through the cooling medium (usually oil) to the tank. Indeed, transformer cooling methods often take advantage of this flow of heat and enhance the resultant dissipation of heat through radiation to the atmosphere by the inclusion of fins or radiators, and forcing air on to these to increase the cooling. The proximity cooling is generally ignored as being too low to measure relative to the winding and core losses.

In fully loaded transformers, the winding losses are dominant. Consequently, when transformer manufacturers consider obtaining high efficiency, most attention is given to reducing these losses. Conventional materials such as copper and aluminium have finite resistivity for all practicable temperatures. There is only so much that can be done in reducing the resistance of a winding through its dimensions. The winding cross-section is directly related to the load current, although the current density is more important and this depends on the cooling method. But effective cooling does not reduce winding losses; it just dissipates them better. It does allow less material to be used which is a capital cost saving rather than an operational issue. Winding length is dependent on the rated voltage although the number of volts per turn is important here. Again material reductions can be achieved, but at the expense of an increase in core size and hence core losses.

One potential solution to the winding loss issue is the application of superconducting tape to power transformers. This will reduce these losses directly through the reduction of material resistivity. Theoretically, the resistivity of a superconductor is zero, so regardless of the size and shape of the winding, there will be no losses. This allows an opportunity to design innovative transformer configurations, but to date those who have attempted superconducting transformer designs have remained very conventional and have essentially substituted classic materials with superconducting equivalents. While this has lead to significant reductions in transformer size, opportunities have been lost to develop even better options.

The advent of high temperature superconductor (HTS) ceramics, especially BSCCO, and their incorporation into usable tapes has brought huge reductions in cost over low-temperature superconductors. Additionally, the use of liquid nitrogen for cooling instead of liquid helium, has made practical superconducting transformers realisable and cost effective. Liquid nitrogen is significantly cheaper than liquid helium, although the efficiency of generation of the liquid nitrogen through the use of compressors is poor. But the HTS tapes are simple in construction and relatively inexpensive to procure. Unfortunately, to date, no manufacturer has produced a tape that has no losses under ac conditions. The ceramic material that is superconducting is imbedded in a matrix of silver, through a powder in tube manufacturing technique. The silver is useful as a quenching medium in the event of an over-current due to a system fault, whereby the critical current limit of the ceramic may be exceeded. Under these conditions the ceramic comes out of the superconducting state and becomes relatively non-conducting. The current migrates to the silver matrix with a resistance lower than the ceramic in the non-superconducting state. This phenomenon can be used for limiting the fault current, but in reality, tape size is selected on continuous operation of the transformer with the ceramic in the superconducting state. The fault current must be interrupted with a circuit breaker because the sudden increase in heat generated in the silver would melt it, even if it is immersed in liquid nitrogen.

Of most importance to the continuous operation of superconducting tape under ac conditions is that there are internal eddy currents in the silver, which has a finite resistivity even at 77K. In addition, there are hysteresis losses in the ceramic filaments. The net result is that there are small but finite winding losses when using presently available HTS tapes. This fact alone has effectively halted the introduction of HTS transformers on to the market. Traditional power transformer designs are just not compatible with HTS tape specifications. This incompatibility threatens to jeopardise the realisation of industrial HTS power transformers unless an alternative design approach is forth coming.

Even with the use of HTS tapes as winding conductors, there is still the consideration of the core losses. These are voltage and frequency dependent and therefore constant for any energised transformer, regardless of load. The losses are both eddy current and hysteresis. The former can be reduced by having very thin laminations such as those used in amorphous cores, where up to 70% reduction in losses is achievable. But this comes at the expense of maximum flux density and hence core size. Hysteresis losses are material dependent but are most related to the bulk of the core. In many practical transformers the hysteresis losses constitute about 70% of the total core losses.

For distribution level transformers, core losses may dominate the winding losses of even a conventional copper winding transformer. Winding losses and core losses are equal at maximum efficiency for a transformer. This is usually designed to occur for a relatively high load factor. For lightly loaded transformers, the core losses dominate. This is the general operational state of most distribution transformers, where utilities tend to oversize installed transformer ratings in anticipation of load growth. Coupled with their ubiquitous nature as compared to transmission system transformers where system configuration and loadings are much more predictable, distribution transformer core losses are the single biggest loss in a system. The most effective way of reducing core losses is to decrease the core size. But this means increasing the winding turns to control the magnetisation.

What is needed is an approach to transformer design which addresses all the above considerations. In addition, the world is looking for ways to ameliorate the impact technology is having on human safety and environmental contamination. The use of materials and configurations that reduce these concerns is also a design requirement. A new electric power transformer design which addresses these design considerations has been developed. This transformer has been coined a partial core high temperature superconducting transformer (PCHTST).

3. TRANSFORMER DESIGN

The design of the transformer has involved computer modelling and empirical experimentation activities. A feasible HTS transformer design has been derived using a program developed from traditional transformer design theory and a reverse as-built design approach [3-6]. This has proved to be about 10% accurate in modelling mains frequency transformer and inductor units, where empirical data helps form the simulation models [7-11]. This computer program has been altered to account for the rectangular profile of HTS conductors and uses critical current as a parameter for the HTS tape rather than resistivity. It does allow for a calculation of the ac losses for the tape and hence a calculation of the efficiency of the transformer.

The program modifications have been validated through a process of design and build of a number of experimental units. A mock superconducting transformer was built using aluminium tape for its windings [12]. Empirical data recorded was checked against the program predictions with very high correlation on most parameters, especially under load.

This program has now been used to design a nominal single phase, 50Hz, 230/115V, 15 kVA, HTS power transformer. Such a design allows for the proving of the magnetic coupling concepts involved and basic transformer operation and performance, without the additional complexity of having extra high voltage windings.

The particular HTS tape from American Superconductors has cross-sectional dimensions of 0.305 by 4.1 mm. Its rated engineering critical dc current density is 79 A/mm^2. Hence the critical current is approximately 100A. When a dc HTS tape is used in a transformer application, it will be subjected to alternating currents and magnetic fields. These will reduce the engineering critical current density. In the design, a target value of 50 A/mm^2 was chosen, giving the tape a current rating of 62.5 A. The tape also had a minimum bend radius of 70 mm.

Full details of the design of the partial core HTS transformer are given in Table 1.

Table 1: Dimensions of the partial core transformer

COMPONENT	PARAMETER	DIMENSION
Core	length	345mm
	diameter	80mm
	lamination thickness	0.3mm
Inside winding	layers	4
	wire width	4.1mm
	wire thickness	0.305mm
Outside windings	layers	2
	parallel conductors	2
	wire width	4.1mm
	wire thickness	0.305mm

The dimensions of Table 1 yielded a design of 80 turns per layer, to give an inside winding of 320 turns and two outside windings of 160 turns each.

For the core, a stacking factor of 0.95 and a relative permeability of 2000, were estimated, based on previous design experience [4]. The number of laminations was 253. These were cut to yield a stepped, circular core. Using the modelling equations previously developed for partial core transformers, the effective relative permeability of the flux path was calculated to be about 19. While this is substantially less than that for a fullcore transformer, it is significantly many times more than the value of unity for a coreless transformer. This has the effect of reducing the magnetising current. The calculated peak flux density was 0.68T. This is deliberately well below the saturation level of the silicon steel, typically of the order of 1.8T, to try and avoid core end radial flux exceeding a critical level when the transformer is loaded and forcing the HTS conductors out of the superconducting region.

The equivalent circuit parameters for the Steinmetz model, for the transformer operating in liquid nitrogen, are given in Table 2. It can be seen that the core loss resistance, being a parallel combination of the hysteresis and eddy current loss resistances, is very high relative to the magnetising component. This latter component dominates the open circuit characteristics of the transformer. With the transformer operating in liquid nitrogen, the model predicts a resistance drop, but not to significant levels. The winding reactances are low, indicating the relatively low leakage flux.

Table 2: Transformer equivalent circuit parameters for a liquid nitrogen temperature of -195^{0}C.

COMPONENT	PARAMETER	VALUE (ohms)
Core	eddy current resistance	38400
	hysteresis resistance	12000
	core resistance	9200
	magnetising reactance	10
Inside winding	Resistance/current^2	1.2E-6
	reactance	0.07
Outside windings in parallel	Resistance/current^2	1.3E-7
	reactance	0.07

4. FABRICATION

The HTS conductor was initially insulated with Nomex tape. The conductor was then wound on a composite former and insulated with 1mm Nomex insulation between each layer. The composite former was a double skin sandwich construction with a vacuum space between the skins. This allowed the core to run at normal temperatures while the windings were immersed in liquid nitrogen.

This entire assembly was placed inside a double skinned/vacuum or permulite composite tank that provided insulation to the outside.

The HTS transformer was built with the ends of all three windings accessible to enable the location of the primary and secondary windings to be varied as well as two-winding and auto-transformer designs to be compared. The winding ends were connected to copper leads and brought out to terminals through a gaseous nitrogen headspace which cooled the leads and reduced conduction of heat from the outside into the liquid nitrogen.

5. PRE-OPERATIONAL TESTS

Attempts to measure the dc resistance of the conductors proved fruitless with the standard equipment available. To obtain quantifiable results, calorimetric methods would need to be used.

Extensive testing of the HTST was undertaken prior to its performance being determined. A 60 sec, 1 kV Meggar test confirmed the integrity of the winding insulation. The insulation resistances were 8.2, 5.7 and 4.7 MΩ for the inside and two outside windings respectively.

Power factor and capacitance tests performed at 1kV yielded values ranging from 0.16 - 27% and 25 – 2037 pF depending on the configuration. These were considered acceptable.

6. PERFORMANCE RESULTS

Having obtained the equivalent circuit parameters, the performance of the transformer could be calculated. In addition, the as-built transformer was tested while operating in liquid nitrogen.

Excitation was applied to the inside winding. The transformer exhibited virtually linear voltage/current characteristics. The open circuit test results at rated voltage are presented in Table 3. There is good if not perfect agreement between the calculated and measured values of all quantities. The difference in excitation current is mainly due to the higher measured value of magnetisation reactance of about 12Ω. The secondary voltage is close to the nominal rated value of 115 V. This implies that the flux coupling between the windings is likely to be high and that there may be very little leakage. However, it is recognised that the open circuit voltage is not a perfect indicator of flux leakage, as a transformer with poor voltage regulation could still have an open circuit voltage close to the nominal rated voltage.

There is a major difference between the calculated and measured values of core power losses. This is believed to be mainly due to the losses in the copper leads from the terminals to the HTS tape.

Table 3: Open circuit test calculations and measurements.

Parameter	Calculated	Measured
Inside winding voltage (V)	230	230
Inside winding current (A)	22	19
Outside winding voltage(s) (V)	114	113 and 111
Inside winding real power (W)	6	200

The performance of the transformer under one indicative short circuit test is presented in Table 4. For the measured values, each outside winding was short circuited separately while the other was kept at open circuit. There was a major difference in excitation voltage and real power. These indicate higher measured resistance and leakage reactance values respectively. The resistance may be due to the copper leads which connect the terminals at ambient temperature to the HTS conductors at liquid nitrogen temperature. The higher leakage reactance is likely to be due to a spreading of the flux out of the partial core before the core ends of the as-built transformer, whereas the calculated values assume linear flux without leakage in this region.

Table 4: Short circuit test calculations and measurements.

Parameter	Calculated	Measured
Inside winding voltage (V)	10	25
Inside winding current (A)	72	65
Outside winding current (A)	144	65
Inside winding real power (W)	17	80

While both open circuit and short circuit tests are of interest in determining the parameters of a transformer, the real measure of performance is a load test. Unfortunately to date this has not been achieved due to a mechanical failure in the liquid nitrogen containment vessel. However, it is illustrative to look at the predicted performance of the transformer under these conditions. This is presented in Table 5.

Table 5: Load test calculations and measurements

Parameter	Calculated
Inside winding voltage (V)	230
Inside winding current (A)	69
Inside winding real power (W)	14810
Outside winding voltage (V)	114
Outside winding current (A)	130
Outside winding real power (W)	14800
Real power loss (W)	14
Efficiency (%)	99.9
Voltage regulation (%)	0.8

The calculated efficiency is high and the regulation low. The economic viability of the transformer under these conditions would depend on comparing the cost of losses against the capital costs of the transformer and the costs of providing a cryogenic heat exchanger.

7. DISCUSSION

Despite the transformer industry being in operation for about 120 years, the partial core design concept lies outside conventional manufacturing design. Recent scientific discoveries in HTS have been followed by the commercial availability of HTS conductors for practical use. The combination of these ideas makes the research significant in that the developments proposed could revolutionise the power supply industry. There are environmental and safety advantages through the removal of oil, increased life, reduced weight and eventually costs, elimination of winding losses as heat and reduction in core losses, and technical benefits in areas such as current limiting, voltage regulation, reactive compensation, inrush current, harmonic generation and ferroresonance suppression.

From a technical perspective, the PCHTST has addressed the loss issues developed in section 2. The dielectric losses have been reduced relative to a conventional transformer because the overall size of the transformer is small, even compared to other HTS transformer designs. By this factor alone, the capacitance is reduced. Also, the insulation is of a high quality synthetic composite that has been shown to have a low loss tangent while retaining both mechanical strength and electric breakdown capability, even when immersed in liquid nitrogen.

The use of a composite tank has eliminated any tank heating due to eddy currents. In the partial core design, magnetic fields do propagate further from the windings and core of a fullcore transformer. In use, the transformer would need to be effectively separated from any metal outside the transformer. This separation will depend on the transformer size and rating but preliminary finite element analysis suggests that there is a very rapid drop in flux density with distance from the partial core and that coupling to stray metal would not be a significant issue. This has already been proved in another open core device [13] which has been commercialised and is a common issue faced and solved in induction heating units [14].

The use of HTS tapes for windings, even though they exhibit internal eddy current and hysteresis losses, radically reduces winding losses. The partial core concept has reduced the volume of the core and hence the core losses by at least a factor of four over a full core design. Indeed it is possible to design a coreless device using the reverse design techniques such that core losses are eliminated.

The insignificance of the overall losses of the transformer is evident in that the outside of the composite tank remains close to ambient temperature. It requires no forced cooling and the venting of liquid nitrogen is minimal. The calculated and measured losses show that these are no longer issues with the transformer.

The most important characteristics of a PCHTST are its size, reliability, safety and environmental benefits. These need to be weighed against the overall capital and operational costs of the transformer.

8. CONCLUSIONS

A partial core, high temperature superconducting transformer has been designed, built and tested for its performance while immersed in liquid nitrogen. The partial core was a slug of laminated silicon steel.

Open circuit and short circuit tests yielded discrepancies between the calculated and measured values of many parameters. However, these are extremes of operation, and are designed to give impedance values in equivalent circuit models. Nevertheless, these tests did indicate the level of expected standing losses and showed that the magnetic flux coupling between windings for these transformers is very high and that there is a low percentage of this that is leakage flux. This supports the viability of the partial core design.

Full load tests indicate a high level of efficiency and low regulation. Such a transformer, suitably designed, is a potential candidate for operation in a real network.

9. REFERENCES

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