TOWARDS A USABLE MAINS FREQUENCY PARTIAL CORE TRANSFORMER

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Abstract

A partial core transformer has been designed, built and tested for its performance in air and while immersed in liquid nitrogen. The transformer was designed as a mock up of a proposed high temperature superconducting transformer, but with aluminium windings. The partial core was a slug of laminated silicon steel.

Open circuit and short circuit tests were conducted to determine the performance of the transformer. These yielded discrepancies between the calculated and measured values of many parameters, but 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. Full load tests conducted on the transformer showed a high level of efficiency and low regulation, even at ambient temperatures.

1. INTRODUCTION

A power transformer is designed to transfer electrical energy from one ac system voltage to another with a high efficiency (of the order of 98-99%) and low voltage regulation (typically less than 10%). These performance characteristics are achieved through a combination of the spacial dimensions of the transformer, and the materials that are used in its fabrication.

A conventional single phase power transformer has 2 windings linked by a closed or full core of ferromagnetic material. When one winding is excited under ac conditions, a magnetic flux flows in the core. Its magnitude is related to the core material permeability, number of turns in the winding, primary/secondary winding separation, core length and core cross-sectional area.

A high permeability core effectively confines the flux to flow inside the core, rather than have it pass through the air. This reduces leakage flux. It furnishes a low reluctance path for the magnetic flux to link both windings, and produces a coupling factor close to unity. The high permeability of the ferromagnetic core also allows the generation of a high core flux density using a relatively low magnetising current. The core material is usually laminated into high resistance paths to reduce eddy current power losses and produce uniform core flux density. The material is also produced to give low hysteresis losses.

The windings of a transformer are usually made of copper or aluminium. These are relatively inexpensive, low resistivity materials, which give low power losses per unit length. The use of a ferromagnetic core allows for designs with high voltages per turn for the windings, which minimizes the lengths of the winding material used, accentuating the low losses.

The imperfection of the performance characteristics of fullcore transformers provides the motivation to eliminate or reduce the factors that cause them. One option is to to eliminate the core. No core means no hysteresis and eddy current losses. Also, since the core is essentially air, the device exhibits a linear magnetization curve, without saturation and inherent operational constraints due to resonance. In a coreless transformer, the coupling between windings can be very high. This is due to the flux channelling effect of multiple layer windings. They effectively constrain the flux into an inner tube, regardless of the material that is present in the core space. The flux then loops around the windings.

Magnetization is controlled by the physical design of the windings. The current that is needed to excite the transformer at rated voltage may be a significant percentage of the total full load current. This is controlled to some degree, by reducing the voltage per turn, which increases the winding length. However, more winding length means greater heat losses and increased leakage inductance due to the increased spacial separation of the windings. This has the consequence of a reduction in efficiency and an increase in regulation.

A compromise between a conventional full core and a coreless transformer is to include laminated ferromagnetic material only into the space enclosed by the windings, i.e. the outer limbs and yokes of a full core transformer are absent. The core does not form a closed path. Such a transformer has about 25% of the material used in a full core transformer. It thus has reduced core losses.

The magnetization of a partialcore transformer can be controlled through setting the voltage per turn on the exciting winding. For the same core flux density as a fullcore transformer, the voltage per turn on the windings is low. This means an increase in the winding length, and hence losses and leakage flux. To minimise these, the partial core transformer should be made long and thin to reduce the winding length and the spacial separation of the primary and secondary. An alternative is to consider reducing the winding losses by changing their operating temperature. To this end liquid nitrogen has been explored as an alternative insulation medium [1]. The use of materials that are superconducting in liquid nitrogen also offer a significant reduction in winding losses.

In this paper, the design of a prototype partial core transformer, fabricated of conventional core and winding materials, is presented. Its performance is determined for operation at ambient and cryogenic temperatures. The transformer is designed to be a mock-up of a proposed high temperature superconducting (HTS) transformer, rather than have its performance optimised for its own sake.

2. PARTIALCORE TRANSFORMER DESIGN

To model partial core transformers, a reverse design approach was used [2]. This program takes the characteristics and dimensions of the materials to be used, and derives the parameters of a Steinmetz model of a transformer [3]. From this model, open circuit, short circuit and load performance can be calculated. The partial core model was modified to accommodate designs where the transformer components were immersed in liquid nitrogen [4].

The particular HTS tape under consideration had cross-sectional dimensions of 0.305 by 4.1 mm [5]. Its rated engineering critical dc current density is 79 A/mm^2. The tape also had a minimum bend radius of 70 mm. 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 value of 50 A/mm^2 was chosen, giving the tape a current rating of 62.5 A.

To provide insight into the likely performance and effectiveness of the partial core design, an aluminium winding option was developed. This had core dimensions similar to what is ultimately proposed for the HTS transformer, but by necessity has much thicker winding material. A transformer with a relatively low voltage rating and low turns ratio was selected to simplify design and testing, and to minimise the cost of materials. The nominal voltage ratings were 240/120 V, so that at full load the current in the secondary winding will be approximately twice that of the primary. Thus 2 conductors in parallel are used in the secondary winding.

In refining the design of the aluminium winding partial core transformer, a circular former was chosen to increase the minimum rolling radius of the windings. A convenient fibreglass tube was purchased. Its internal diameter of 78mm set the dimensions of the core. The windings were placed around the former in a helical arrangement, with each layer as a separate entity. This allows for ultimately testing a number of arrangements for the winding.

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

The dimensions of Table 1 yielded a design of 76 turns per layer, to give a primary winding of 304 turns and a secondary winding of 152 turns.

COMPONENT	**PARAMETER**	**DIMENSION**
Core	length	400mm
	diameter	77mm
	lamination thickness	0.3mm
Primary winding	layers	4
	wire width	5mm
	wire thickness	2.5mm
Secondary winding	layers	2
	parallel conductors	2
	wire width	5mm
	wire thickness	2.5mm

Table 1: Dimensions of the partial core transformer

For the core, a stacking factor of 0.96 and a relative permeability of 2000, were estimated, based on previous design experience [6]. The number of laminations used was 243. 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 25. 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 rms flux density was 0.57 T. This is deliberately well below the saturation level of the silicon steel.

The equivalent circuit parameters for the Steinmetz model, for the transformer operating in air at ambient temperature 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. The winding resistances and reactances are low, indicating the relatively low material resistivity and leakage flux.

COMPONENT	**PARAMETER**	**VALUE (ohms)**	**VALUE (ohms)**
Dielectric		Air	Liquid nitrogen
Core	eddy current resistance	28000	4840
	hysteresis resistance	12000	12000
	core resistance	8350	3430
	magnetising reactance	10	10
Primary winding	resistance	0.24	0.054
	reactance	0.14	0.14
Secondary winding	resistance	0.31	0.068
	reactance	0.14	0.14

Table 2: Transformer equivalent circuit parameters for ambient and liquid nitrogen temperatures.

With the transformer operating in liquid nitrogen, the modelling predicts an eddy current resistance drop, but not to significant levels. This will affect the core loss only. The most striking reduction is in the winding resistance, which has reduced by a factor of about 4.5. In calculating these parameters, the operating temperature of the aluminium in liquid nitrogen was set at -170^{0}C. This was the same as that in [4] which gave good correlation between calculated and measured results for copper partial core transformers.

3. RESULTS

Having obtained the equivalent circuit parameters, the performance of the transformer could be determined. In addition, the as-built transformer was tested while operating in air and in liquid nitrogen. In the latter tests, the transformer was immersed in a liquid nitrogen bath and allowed to stabilise in temperature.

The open circuit test results are presented in Table 3. The secondary voltage is very similar in all cases, and most importantly, it is very close to the nominal rated value of 120 V. This implies that the flux coupling between the windings 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. These highlight that the models currently in use need further refinement. The difference in primary current is mainly due to a higher calculated value of magnetisation reactance.

Operating medium	Air		Liquid nitrogen	
Parameter	Calculated	Measured	Calculated	Measured
Primary voltage (V)	240	240	240	240
Primary current (A)	24	30	24	30
Secondary voltage (V)	119	119	118	119
Primary real power (W)	144	400	47	450

Table 3: Open circuit test calculations and measurements.

The performance of the transformer under short circuit tests is presented in Table 4. When operating the transformer in air, there is very good agreement between the calculated and measured values. The slightly higher measured current accounts for the increase in power losses. However, when the transformer was immersed in liquid nitrogen, there was a major difference in real power, and primary and secondary currents. These indicate lower measured resistance and leakage reactance values respectively. The resistance may be due to aluminium behaving differently than the changes allowed in the model for copper, and indicate that this should be explored more fully. The low leakage reactance is likely to be due an interleaving of the windings of the as-built transformer, whereas the calculated values were determined for separated windings.

Operating medium	Air		Liquid nitrogen	
Parameter	Calculated	Measured	Calculated	Measured
Primary voltage (V)	4.2	4.2	4.2	4.2
Primary current (A)	7	8	14	56
Secondary current (A)	14	16	28	110
Primary real power (W)	26	34	24	230

Table 4: Short circuit test calculations and measurements.

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. A dummy load was constructed of available resistors, which gave slightly less than full load conditions. The performance of the transformer under these conditions is presented in Table 5. The dominant feature of the results is the similarity between calculated and measured values, for the operation of the transformer at both ambient and liquid nitrogen temperatures. This reinforces the accuracy of the modelling for the transformer under operating conditions, as against the open circuit and short circuit tests which are used for determining the circuit parameters. The major discrepancies are with the real power losses and regulation under liquid nitrogen conditions. These may be attributed to the conditions discussed under open circuit and short circuit tests.

Operating medium	Air		Liquid nitrogen	
Parameter	Calculated	Measured	Calculated	Measured
Primary voltage (V)	240	240	237	237
Primary current (A)	42	46	44	49
Primary real power (W)	8400	8700	8700	9300
Secondary voltage (V)	109	109	115	117
Secondary current (A)	70	71	74	76
Secondary real power (W)	7600	7800	8500	8900
Real power loss (W)	820	900	220	400
Efficiency (%)	90	90	98	96
Voltage regulation (%)	9.4	8.8	3.4	0.9

Table 5: Load test calculations and measurements

For this transformer operating in air, the efficiency was 90% and the voltage regulation was less than 10%. The bulk of the real power losses were in the windings, and are therefore related to the load, rather than being standing losses. Under normal operating conditions, the all day efficiency would be higher. Such a transformer, designed for appropriate voltage levels, could be used in service. The economic viability of the transformer would depend on comparing the cost of losses against the saving in the capital costs of such a transformer.

For the transformer operating in liquid nitrogen, the measured efficiency increased to 96% and the regulation reduced to less than 1 %. These are acceptable values for any transformer under full load conditions. 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.

4. CONCLUSIONS

A partial core transformer has been designed, built and tested for its performance in air and while immersed in liquid nitrogen. The transformer was designed as a mock up of a proposed high temperature superconducting transformer, but with aluminium windings. 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 conducted on the transformer showed a high level of efficiency and low regulation, even at ambient temperatures. Such a transformer, suitably designed, is a potential candidate for real operation on a network.

5. REFERENCES

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