Testing full-core and partial-core transformers at ambient and cryogenic temperatures

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Abstract:

Single phase, full-core transformers were fitted with either silicon or amorphous steel cores and immersed in either standard transformer oil or liquid nitrogen. Each transformer was subjected to a capacitance and dissipation factor test to determine the integrity of the insulation systems. Open circuit and short circuit tests were then undertaken to determine core and winding losses. Similar tests were also conducted on a silicon steel partial-core transformer. Full load tests on this transformer showed a high level of efficiency and low regulation, even at ambient temperatures.

1. INTRODUCTION

Different materials used in the construction of a transformer affect the efficiency and regulation performance of a transformer. An alternative to the use of traditional silicon steel in the core is the use of amorphous steel. Windings are usually made of copper or aluminium, each with its own characteristics. In addition, instead of operating the transformer at normal temperatures and using oil as the liquid insulation, an alternative is to immerse the entire unit in liquid nitrogen.

Previous research [1] has shown that silicon steel transformers have significantly reduced winding losses at liquid nitrogen temperatures. The core losses did not significantly change. While there are clues to the reasons for this in induction heating literature [2], there is nothing in the transformer literature that addresses this situation, probably because it is not usual practice to dip conventional transformers into liquid nitrogen. The viability of liquid nitrogen as an insulation system was confirmed in [3]. This also illustrated the improved mechanical properties of a selected paper insulation immersed in the liquid nitrogen.

Changing the design of a transformer can also affect the performance of transformers. A new proposal 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 is called a partial core transformer. It has about 25% of the material used in a full core transformer. It thus has reduced core losses through the reduction in material.

This paper reports on insulation and power loss tests associated with both silicon steel and amorphous full-core transformers. The design of a partial core transformer, fabricated of conventional core and winding materials, is also presented. Its performance is determined for operation at ambient and cryogenic temperatures.

2. SILICON STEEL FULLCORE TRANSFORMERS

Two single phase, 50Hz, 10kVA, 11/0.23kV transformer with silicon steel full cores and copper windings were purchased. One was filled with standard transformer oil. The other was thermally insulated and filled with liquid nitrogen. The two transformers were connected to capacitance and dissipation factor equipment and measurements made at 6.35kV, according to [4]. The results are presented in Table 1.

Transformer Insulation	Capacitance (nF)	Dissipation Factor
Oil	1.119	0.0067

Liquid Nitrogen	0.363	0.0039

Table 1: Capacitance and Dissipation factor test results for 10kVA transformers.

The lower capacitance is primarily due to the different dielectric constants of oil and liquid nitrogen, being of the order of 3 and 1 respectively. A secondary effect may be due to shrinkage of the insulation under the colder temperature of liquid nitrogen. The dissipation factor results indicate that liquid nitrogen is a better insulator than oil as far as dielectric loss is concerned.

Open circuit and short circuit tests were also undertaken on these transformers to yield core and copper losses respectively. The results of these tests are shown in Table 2.

Transformer Insulation	**Open Circuit**			**Short Circuit**			
	V(V)	I(A)	P(W)	V(V)	I(A)	P(W)	Isec(A)
Oil	240	1.15	65	368	0.9	145	41.2
Liquid nitrogen	240	1.05	62	345	0.86	57	41.4

Table 2: Open circuit and short circuit test results on oil and nitrogen filled 10kVA transformers

The core losses are virtually identical, indicating that they are independent of temperature. By comparison, the copper losses for the transformer under liquid nitrogen were 39% of the oil filled equivalent. Taking the core losses into account, the overall losses of the liquid nitrogen filled transformer were 57% of the oil filled unit.

3. AMORPHOUS STEEL FULLCORE TRANSFORMERS

Amorphous steel has been specially hardened in its metallurgical process. The steel is rolled to relatively thin sheets of the order of 0.2mm, annealed to red heat temperatures, and then rapidly spray quenched in liquid nitrogen. The result is a steel with crystals in a random (amorphous) state, which has a bright, hard surface. More importantly, the steel has less hysteresis losses, and because of an increase in resistivity, less eddy current losses when subjected to excitation.

Two single phase, 50Hz, 15kVA, 11/0.23kV amorphous full core transformers were filled with oil and liquid nitrogen as before. Capacitance and dissipation factor tests were conducted on both transformers to test their insulation integrity. The results are shown in Table 3.

Transformer Insulation	Capacitance (nF)	Dissipation Factor
Oil	1.003	0.00527
Liquid nitrogen	0.419	0.00211

Table 3: Capacitance and Dissipation Factor test results for the 15kVA amorphous core transformers

These results are very similar to those presented in Table 1 for the 10kVA transformers. The dissipation factors of both the oil and liquid nitrogen filled transformers are low, with the value for liquid nitrogen being significantly lower than that for the oil filled model, indicating the superior dielectric characteristics of liquid nitrogen.

Open circuit and short circuit tests were also performed on the two transformers. The results are summarised in Table 4.

Transformer Insulation	Open Circuit			Short Circuit			
	V(V)	I(A)	P(W)	V(V)	I(A)	P(W)	Isec(A)
Oil	240	0.69	19	336	0.95	131	41.5
Liquid nitrogen	240	0.73	20	304	0.95	22	41.5

Table 4: Open circuit and short circuit test results on oil and nitrogen filled 15kVA amorphous core transformers

These results show that the core losses are again unaffected by temperature. This is consistent with the results of Table 2. Most importantly, the core losses have dropped to about 31% of the losses associated with silicon steel cores. This shows the superiority of using amorphous steel to reduce standing losses in transformers.

The winding losses of the liquid nitrogen filled transformer decreased to a very low 17% of that of the oil filled unit. Also, the absolute values of power loss in both units are significantly less than the values recorded in Table 2 for their silicon steel equivalents. This might be explained in part by testing the 15kVA units at a secondary current consistent with a 10kVA rating, thus running the transformers at less than their rated values.

Overall the nitrogen filled transformer has a total 10kVA load loss of 42W which is 28% of that for the oil filled model, and just 20% of that of the oil filled silicon steel unit.

4. SILICON STEEL PARTIALCORE TRANSFORMER

A 50 Hz, 15 kVA, 240/120V partial core transformer [5,6,7] was constructed using aluminium windings and a silicon steel core. The design parameters are given in Table 5.

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 5: Dimensions of the partial core transformer

The 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 6. The performance of both transformers is virtually identical, with slightly more core losses when immersed in liquid nitrogen. The secondary voltages are very close to the nominal rated values of 120V.

Operating medium	Air	Liquid nitrogen
Primary voltage (V)	240	240
Primary current (A)	30	30
Secondary voltage (V)	119	119
Primary real power (W)	400	450

Table 6: Open circuit test calculations and measurements.

The performance of the transformer under short circuit tests is presented in Table 7. When the transformer was immersed in liquid nitrogen, there was a major difference in real power, and primary and secondary currents, as compared to its operation in air. These indicate lower measured resistance and leakage reactance values respectively.

Operating medium	Air	Liquid nitrogen
Primary voltage (V)	4.2	4.2
Primary current (A)	8	56
Secondary current (A)	16	110
Primary real power (W)	34	230

Table 7: 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 less than full load conditions. The performance of the transformer under these conditions is presented in Table 8.

Operating medium	Air	Liquid nitrogen
Primary voltage (V)	240	237
Primary current (A)	46	49
Primary real power (W)	8700	9300
Secondary voltage (V)	109	117
Secondary current (A)	71	76
Secondary real power (W)	7800	8900
Real power loss (W)	900	400
Efficiency (%)	90	96
Voltage regulation (%)	8.8	0.9

Table 8: 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.

5. CONCLUSIONS

Pole-mounted distribution transformers, with silicon and amorphous steel cores, have been filled with oil and liquid nitrogen. These have been tested for the integrity of their insulation, and to ascertain the core and winding losses under the different combinations.

Equivalent liquid nitrogen filled transformers display a lower capacitance than oil filled units. This is due to the low dielectric constant of nitrogen as compared to oil. A lower dissipation factor was also measured. This implies that liquid nitrogen is a superior insulation as regards dielectric losses.

A number of effects have been observed with respect to temperature and the losses associated with the transformers. Liquid nitrogen temperature essentially has no effect on core losses. This is an important result which may indicate that the reduced core material resistivity is balanced by the reduced depth of current penetration in the laminations. This means that full immersion liquid nitrogen techniques can be considered in power transformer design.

Liquid nitrogen significantly reduces winding losses. This is an expected result as the resistivity of copper (or aluminium) is temperature dependent. Moreover, the depth of current penetration in these conductor materials is relatively high when compared to those in core material. These penetration depths are greater than the dimensions of the windings.

Significant reductions in transformer losses can be made by combining the observed effects. The silicon steel alone can be replaced by amorphous steel. The saving in standing losses may pay off the extra capital cost of the transformer. If it is desirable to not use oil as the liquid insulation, then the liquid nitrogen offers an alternative. At present, due to cryogenic heat exchanger requirements, this will not be cost competitive.

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 indicate the level of expected core and winding losses at rated values. Near full load tests conducted on the transformer showed a high level of efficiency and low regulation, even at ambient temperatures. Such a transformer, with suitable voltage ratings, is a potential candidate for real operation on a network.

These tests indicate that a revisit of fundamental transformer design is possible. The selection of winding materials compatible with liquid nitrogen, for example high temperature ceramic superconductors can be considered. This will change the overall structure of the transformer to minimise the power losses and consequent gain in efficiency.

5. REFERENCES

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