Electro-mechanical testing of a liquid nitrogen filled power transformer.

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Abstract

To remove the environmental and safety hazards associated with power transformers, the authors have investigated the use of liquid nitrogen as a replacement for transformer oil. This paper details tests performed to determine new design rules and efficiency expectations of liquid nitrogen filled power transformers (Enviro-Transformers). The tests include dielectric strength testing of liquid nitrogen and mechanical strength testing of standard transformer insulating materials submerged in liquid nitrogen. Efficiency and dissipation factor tests were performed on two industry standard 10 kVA, 50 Hz, 11/0.24 kV single-phase transformers. One transformer was filled with oil and operated at room temperature, the other was filled with liquid nitrogen and operated at 77 ^{o}K.

1 INTRODUCTION

Traditional power transformers contain thousands of litres of mineral oil. These oil-filled transformers pose a significant environmental and safety risk due to oil spills and fire respectively. Such hazards result from combustible gases, produced when oil is heated, which can cause the transformer to explode, releasing thousands of litres of burning oil and asphyxiating smoke. Transformer explosions can cause significant financial loss including the loss of consent to operate the plant.

Before a non-oil filled transformer can be designed, the performance of the insulation must be determined. The electrical strength of the Enviro-transformer is obtained from liquid nitrogen and an insulating paper immersed in liquid nitrogen. The mechanical strength of the Enviro-transformer is determined by the tensile properties of the paper insulation. The first step in the design procedure was to determine the dielectric strength of liquid nitrogen. This was performed to BS 5874:1980[1] which is the standard used in testing the dielectric strength of insulating oils. Suzuki and Fallou have performed dielectric strength tests on liquid nitrogen [2,3], however, Suzuki's electrode design was not the same as that prescribed by the standard, and Fallou's electrode design was not published.

The life of a transformer is determined by the mechanical strength of its solid insulation. It is necessary to find a solid insulation material that has adequate mechanical strength at liquid nitrogen temperatures. In this research both Kraft and Nomex® paper were tested.

2 ELECTRICAL STRENGTH DESIGN CONSIDERATION

Power transformer design relies on liquid dielectrics as both coolant and insulating material. Liquid dielectrics are useful as they have higher densities than gaseous dielectrics, and can completely fill the space to be insulated more easily than solid dielectrics. Moreover, they are self-healing when a discharge occurs and can be circulated to dissipate heat generated within the system.

To determine the dielectric strength of liquid nitrogen, a set of electrodes were designed to the specifications of BS 5874:1980 and submerged in boiling liquid nitrogen at atmospheric pressure. These electrodes were spherical in shape with a diameter of 13mm. The electrode gap separation was 2.5mm. A 50Hz, a.c. waveform was increased at 2kV/s until breakdown occurred. Each test was repeated 6 times. Electrical breakdown voltages were also determined with gap separations of 1 and 2 mm. The results from these tests are presented in Table 1. Because the tests were performed with the liquid nitrogen boiling, they gave worst-case values.

Gap separation (mm)	Breakdown voltages (kV rms)		
	Average	Minimum	Maximum
1	27.9	25.4	30.5
2	47.4	40.9	54.1
2.5	49.5	45.9	53.5

Table 1 Breakdown voltage for liquid nitrogen

The results obtained are comparable with in-service dry transformer oil. Transformer oil, when tested to this standard, i.e. 2.5mm gap separation, has average breakdown voltages of >60kV for new dry oil, >40kV for good oil and <20kV for bad oil. Therefore, standard oil filled transformer electric strength design principles can be used in the design of the Enviro-transformer.

The electrical breakdown strength of liquid nitrogen is reduced by impurities within the liquid. These can include ice, dust and nitrogen gas bubbles. Dust and ice particles have a different value of permittivity to liquid nitrogen and hence experience a force within an electric field [4]. If the permittivity of a particle is larger than the permittivity of the liquid, which is normally the case, then this force will act to draw a particle into the strongest part of the field. The difference in the permittivity of the particle will also cause a field concentration about the surface of the particle. This causes other particles to be attracted towards it until a conducting path is formed or the field concentration at the surface causes the localised breakdown of the liquid, which leads to total breakdown. To reduce the chances of ice and dust particle contamination the transformer needs to be contained within a sealed cryogenic container.

Nitrogen gas bubbles within liquid nitrogen contain a greater electric field stress than the surrounding liquid. If this field is large enough, then electrical breakdown can occur within the bubble. This will cause more gas to be produced, which will lead to the total electrical breakdown between the electrodes. Research by Suzuki has shown that increasing the pressure of the liquid nitrogen increases the breakdown strength. He found that this phenomenon tended to saturate at a pressure of 5 atmospheres. This is because the number and size of gas bubbles is reduced. A reduction in the number and size of nitrogen gas bubbles, and hence an increase in electrical breakdown strength, can also be obtained by supercooling the liquid to near the freezing point of liquid nitrogen, 63^{o}K.

3 MECHANICAL STRENGTH DESIGN CONSIDERATIONS

Kraft paper is traditionally used in transformers for mechanical strength. Nomex® paper has been used in recent years for transformers with high operating temperatures. Both Nomex® and Kraft paper were tested for mechanical strength in liquid nitrogen. It was found that the mechanical strength of Kraft paper at 77^oK reduced to the point where it is not suitable for liquid nitrogen transformer applications. Nomex® paper was tested in both transformer oil at room temperature and in boiling liquid nitrogen. Nomex 414 was used in these tests, with a thickness of 0.24mm, and cut into 25mm wide strips. The paper was clamped and then stretched until failure. Each test was repeated five times. Results from these tests are shown in Table 2. Figure 1 shows a force/elongation graph for Nomex 414 paper in oil and liquid nitrogen. The vertical lines in this graph, indicate where each paper yielded. These results show that the mechanical strength of Nomex® in liquid nitrogen is greater that that of Nomex® at room temperature in transformer oil.

	Nomex® in oil (300^oK)		Nomex® in liquid nitrogen (77^oK)	
	Elongation (mm)	Force (N)	Elongation (mm)	Force (N)
Average	21.1	460	11.5	505
Minimum	18.3	400	10.7	452
Maximum	24.3	500	13.2	525

Table 2 Breaking force required for Nomex® in oil at room temperature and in liquid nitrogen

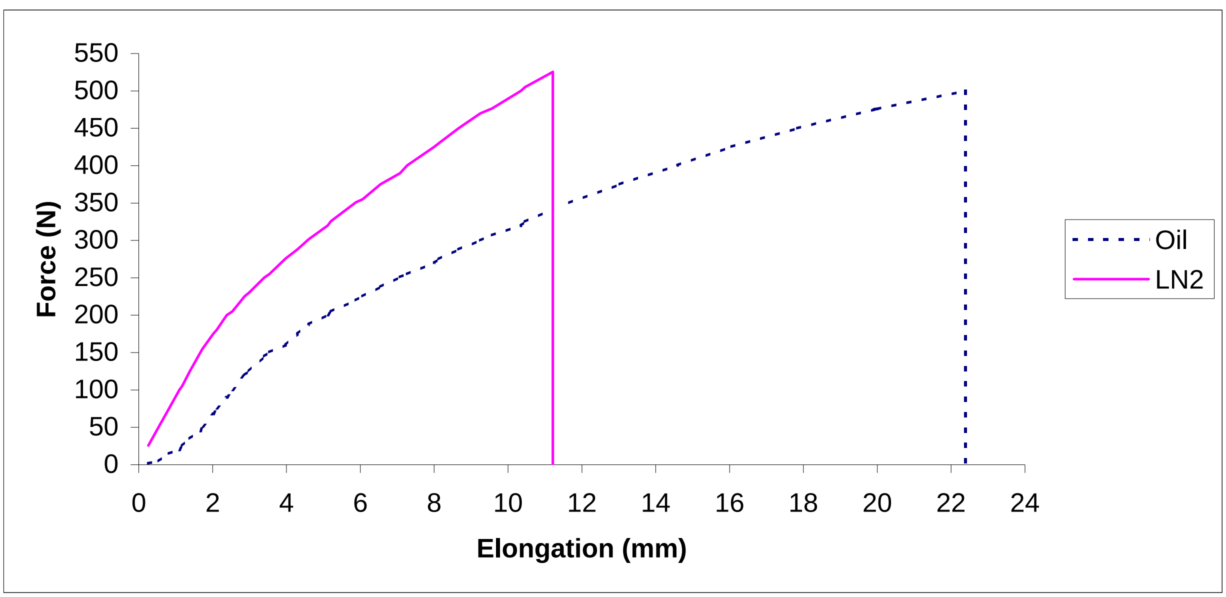

Figure 1 Graph of Force Vs Elongation for Nomex® in oil and liquid nitrogen

4 TRANSFORMER LIFE

The life of a transformer is determined by the condition of its solid insulating material, as it provides both the electrical and mechanical strength of the transformer. Thermal loading, environment and electrical and mechanical stresses determine the life of traditional oil filled transformers. Because liquid nitrogen is a relatively inert liquid, the chemical deterioration of a suitable insulating paper impregnated with liquid nitrogen is very slow. Therefore the life of an Enviro-transformer is determined by the electrical and mechanical stresses only. The results from section 3 have shown that Nomex® has a greater mechanical strength in liquid nitrogen than in transformer oil, therefore a longer mechanical stress life can be expected. Studies of cryogenic insulation indicate that electrical aging obeys the inverse power law, $(\text{stress})^n$ x (time to failure) = constant, of BS EN 60505 [5] [6-9]. The value of the exponent n is rarely in excess of 10 for insulation operated in transformer oil. However, studies have found that the value of n at cryogenic temperatures ranges between 17 and 130. This is because of the very low chemical deterioration of insulating paper in liquid nitrogen.

Because of the very high value of n, the difference in the value of electrical stress that produces a life of 50 years and 1 hour is very small. Hence the life of the insulation, and therefore the transformer, will be determined by transient overvoltages. The impulse breakdown strengths of Nomex® in liquid nitrogen obtained from Bulinski [6] and Weedy [7] are shown in table 3. Both sets of tests were performed with a butt gap. A butt gap is the space between overlapping layers of tape. Partial discharges occur due to the breakdown of the liquid nitrogen within this space. Bulinski used a pressure of 0.4 MPa whereas Weedy used a pressure of 0.1 MPa. These results also show that the dielectric strength of the insulating paper increases with increased liquid nitrogen pressure.

Bulinski [6]		Weedy [7]	
Number of layers and thickness	kV/mm	Number of layers and thickness	kV/mm
4 x 0.125 mm	105	6 x 0.08 mm	86.3
6 x 0.125 mm	109	6 x .14 mm	79.4

Table 3 Breakdown strength of nomex in liquid nitrogen

5 EFFICIENCY

The results from the previous three sections imply that traditional oil filled transformer principles can be used in the design of the liquid nitrogen filled transformer. If an Enviro-transformer is to be economically viable, its efficiency must be close to that of a traditional transformer. Short circuit and open circuit tests were performed to determine the windings and core losses, and hence the efficiency, of two industry standard 10 kVA, 50 Hz, 11/0.24 kV single-phase transformers. One transformer was oil-filled and operated at room temperature, the other was filled with liquid nitrogen. Results from these tests are shown in Table 4.

	Enviro-transformer		Traditional oil filled transformer	
	Open circuit test	Short circuit test	Open circuit test	Short circuit test
Power	75 W	44 W	65 W	149 W

Table 4 Open and short circuit test on liquid nitrogen and oil filled transformers

In the Enviro-transformer, copper losses have deceased to 29.5% of that in the traditional oil filled transformer. The iron losses however have increased to 115% of that of the traditional transformer. To avoid the increased iron losses, the Enviro-transformer design would require the core to be outside the cryostat. This means that the core would be operated at room temperature and only the windings would be cooled via liquid nitrogen. Cryogenic refrigeration units investigated presently have an efficiency ratio of 1:11. However, this technology was not matched to Enviro-transformer applications. Furthermore, the standard pole-mounted transformer winding design is not matched to Enviro-transformer applications. Improvements in purpose built Enviro-transformers and refrigeration units may produce efficiencies close to that of traditional oil filled transformer designs. An Enviro-transformer design would have the aided financial advantages of reduced maintenance and the removal of transformer oil storage and processing.

6 INSULATION ELECTRICAL STRENGTH

Dissipation factor, Tanδ, tests were performed at a voltage of 6.35 kV. The LV terminals were short-circuited and connected to the tank. The insulation tested was the high voltage to low voltage insulation and the high voltage to tank insulation. Tanδ and capacitance results are given in Table 5.

Enviro-transformer		Oil filled transformer	
Capacitance (pF)	Tanδ	Capacitance (pF)	Tanδ
628	0.00391	1118	0.00753

Table 5 Capacitance and Tanδ for liquid nitrogen and oil filled transformers

The dissipation factor reduces to approximately half using liquid nitrogen in comparison to transformer oil. Tanδ should be less than 0.02 for power transformers, with lower values indicating superior insulation. Combining this result with the zero percentage of oxidating agents implies that the paper should have a superior life to oil filled transformers. The change in capacitance is due to winding shrinkage and the change in the permittivity of the insulating materials.

7 CONCLUSIONS

Test results from a liquid nitrogen filled power transformer "the Enviro-transformer" have been presented. This includes dielectric strength of liquid nitrogen, mechanical strength of Kraft and Nomex® paper in liquid nitrogen, and efficiency and dissipation factor comparisons between an Enviro-transformer and a traditional oil filled transformer.

The dielectric strength and mechanical strength tests produced results equivalent to that of an oil filled transformer This is an important result because the design of the Enviro-transformer can follow well-known and proven traditional oil filled transformer principles.

If cryogenic cooler technology efficiencies can match this loss reduction then the Enviro-transformer concept is viable. As well as offering significant environmental benefits due to the elimination of transformer oil, the Enviro-transformer should offer a superior life span. Therefore, in spite of the higher losses, the Enviro-transformer may be a viable option where environmental or health risks are high.

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