# THE PERFORMANCE OF SILICON AND AMORPHOUS STEEL CORE, DISTRIBUTION TRANSFORMERS AT AMBIENT AND CRYOGENIC TEMPERATURES

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**Abstract**

Four, single phase, 50 Hz, 11/0.23kV pole mount distribution transformers were purchased from a manufacturer. The transformers were fitted with either silicon or amorphous steel cores. The transformer tanks were filled with 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 show the reduction of core losses due to the use of amorphous steel over silicon steel, and the effect of immersion of the entire unit in liquid nitrogen.

## 1. INTRODUCTION

Distribution transformers account for the majority of losses in an electric power network. Of these losses, core heating accounts for the substantial portion. They can be considered constant so long as a transformer is in service. By contrast, winding losses are only significant under higher load conditions. On a daily basis, the transformer may experience these conditions only briefly. Also, distribution transformers are often over-rated for their requirements, as load growth and variation may mean an installed capacity much greater than what is actually being used. This means that the winding losses may be well below the nominal short circuit value.

It is of interest to test the effectiveness of different materials in a transformer, in reducing losses. A simple alternative to the use of traditional silicon steel in the core, is the use of amorphous steel. In addition, instead of operating the transformer at normal temperatures and using oil as the insulant, an alternative is to immerse the entire unit in liquid nitrogen. While in the present environment, this practice is unlikely to suggest an economic conversion of traditional transformers, it does reveal knowledge that is useful in considering alternative transformer designs.

Previous research [1] has shown that silicon steel transformers have significantly reduced winding losses at liquid nitrogen temperatures; not an unsurprising result. But most important was the result that the core losses did not significantly change. This is not an obvious result, because the reduction in temperature gives a lower material resistivity which can mean greater eddy currents and losses due to the current squared factor. However, the depth of penetration of these currents into the core material reduces due to the lower resistivity. This means that there is a smaller cross-sectional area for the currents to flow through and hence a higher resistance. It is not apparent as to which option dominates.

The theory on what the real state is, is vague, even in induction heating literature [2], where the whole viability of devices is dependent on skin depth. There is nothing in the transformer literature which addresses this situation, probably because it is not usual practice to dip conventional transformers into liquid nitrogen. All that is left is to observe such results via experiment. Prior to embarking on this, the viability of liquid nitrogen as an insulation system should be confirmed. Again previous research [3] has established this, as well as illustrating the improved mechanical properties of a selected paper insulation immersed in the liquid nitrogen.

This paper reports on the insulation and loss tests associated with both silicon steel and amorphous core distribution transformers, and therefore the improved efficiency of operation of these devices.

## 2. SILICON STEEL CORE TRANSFORMERS

Two silicon steel core, copper winding, transformers were procured from a local transformer manufacturer, with instructions to fill one with standard transformer oil and to leave the other dry. No modifications were made to the oiled filled unit as this was the benchmark to which the other could be compared. The dry transformer was set inside a large steel drum. The space between the drum and the transformer tank was filled with refrigeration foam for thermal insulation purposes. A large hole was cut into the transformer tank lid and a filling tube installed. The high and low voltage bushings penetrated through the foam and drum to give access to the terminals. The transformer was then dried by passing a 16A dc current through the low voltage windings. This heated the windings to a measured 85$^{o}$C. A vacuum pump was attached to the transformer during the drying process to draw off any moisture. The tank was back-filled with dry nitrogen gas and then filled with liquid nitrogen. It was allowed to cool until only minimal vapour was being emitted, indicating that the transformer had reached the desired temperature.

### 2.1 Performance Tests

The two, single phase, 50Hz, 10kVA, 11/0.23kV transformers tested in [1], which have silicon steel cores, were retested to act as a benchmark for the two amorphous core transformers under consideration. The transformers were initially subjected to an over-voltage test of 6.6kV to test the gross capability of the insulation. This voltage is only marginally above the rated value, but was deemed sufficient to establish insulation integrity without running the risk of insulation failure during testing and hence damage to the precision test equipment.

Having established this, capacitance and dissipation factor equipment was connected and measurements made at 6.35kV, according to [4]. The results are presented in Table 1.

The results for the oil-filled unit were similar, as was the capacitance for the unit immersed in liquid nitrogen. However, the dissipation factor of the liquid nitrogen filled unit could not be measured within the accuracy of the equipment. The original value was 0.00391 [1]. The dissipation factor of liquid nitrogen is extremely small, of the order of $10^{-5}$ [4]. However, the dissipation factor of the solid insulation immersed in liquid nitrogen should be higher than this.

The results indicate that liquid nitrogen is a better insulator than oil as far as dielectric loss is concerned. 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 change in capacitance can be an important consideration in the determination of first natural resonant frequencies, the propagation of high frequencies through such transformers, and their propensity towards ferroresonant behaviour.

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.

These results for the oil filled transformer are essentially the same from what had previously been measured [1]. However, there was a significant difference in the results for the nitrogen filled transformer. The open circuit losses dropped from 75W to 62W. The latter figure compares well with the oil filled transformer. The core losses do not significantly increase with the temperature change. The short circuit losses increased from 44W to 57W. There is no obvious explanation for this change. They may be an indication of a longer term change in material state due to the immersion in liquid nitrogen, or perhaps the temperature of the transformer may have been different by a few degrees.

| Transformer Insulation | Capacitance (nF) | Dissipation Factor |
|---|---|---|
| Oil | 1.119 | 0.00670 |
| Liquid Nitrogen | 0.363 | <0.00001 |

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

| 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 | 0.90 | 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

Both transformers were fully operational, so for the sake of comparison, the new results of Table 2 suggest that 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 CORE 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 transformers were ordered from the same manufacturer, with the instructions to replace the silicon steel core with amorphous cores, leaving everything else identical. Perhaps as a consequence of the change in core material, allowing lower generation of heat for the same loading, the delivered nameplate power ratings of these transformers were 15kVA. Alternatively, their may have been some change in the size of the winding wires used. All other ratings were the same as the 10kVA units. The cost of the new units were of the order of 120% of the silicon steel units, which means that on a normalised basis, they are cheaper per unit of installed capacity.

One transformer was delivered filled with oil as before and required no further modifications. The other, dry transformer, was retrofitted with a modified tank top and container with insulation, dried under vacuum and filled with liquid nitrogen.

### 3.1 Performance Tests

Capacitance and dissipation factor tests were conducted on both transformers to test their insulation integrity. The results are shown in Table 3.

These results are very similar to those presented in Table 1, for the 10kVA transformers. This indicates the consistency in winding design and dielectric quality of the mediums. Measurable values have been recorded for the dissipation factors of both the oil and liquid nitrogen filled transformers. These are both low, with the value for liquid nitrogen being significantly lower than that for the oiled 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.

These results show that the core losses are 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.

| 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

| 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

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. Further, this may also be due to some change in the design and fabrication of the transformers, such as winding wire size, which was not conveyed by the manufacturer. Because of continuing research, the transformers have not been dismantled to investigate this possibility.

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. 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 implies that the first natural resonant frequencies and hence potential resonant problems of these transformers will occur at much higher frequencies. 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. 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 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 20% capital cost of the transformer. If it is desirable to not use oil as an insulation, then the liquid nitrogen offers an alternative. At present, due to cryogenic heat exchanger requirements, this may not be cost competitive.

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 losses and gain in efficiency.

## 5. REFERENCES


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