A Glance into the Future of Transformers … and Beyond

Pat Bodger and Wade Enright

Department of Electrical and Computer Engineering
University of Canterbury, Christchurch

Abstract:

An overview of the research and developments into new transformer design, undertaken in the Department of Electrical and Computer Engineering, University of Canterbury, is presented. Initially, single phase, 50 Hz, l1/0.23kV pole mount distribution transformers were fitted with either silicon or amorphous steel cores. The transformer tanks were filled with either standard transformer oil or liquid nitrogen and tested for loss performance. Next a partial core transformer was 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.

A commercial manifestation of a partial core transformer is demonstrated in a parallel resonant compensation test method. Initially this uses a HV inductance that supplies reactive power to the insulation of a hydro generator stator. As a further development, the inductor was turned into a resonant transformer by the addition of a LV primary. The magnetising reactance was matched to the generator stator insulation capacitance. A second tunable resonant transformer was then designed. Finally, a high temperature super-conducting transformer (HTST) has been designed and built. The transformer windings are configured to allow different arrangements, namely internal primary, external primary and autotransformer.

1. INTRODUCTION

The thrust of research in the Department of Electrical and Computer Engineering at the University of Canterbury has been to test the effectiveness of using different materials in a transformer, at different temperatures and in different configurations. Initial research [1] illustrated the improved mechanical properties of a selected paper insulation immersed in the liquid nitrogen. 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 [2].

A partial core transformer was then designed [3-6], built and tested for its performance in air and while immersed in liquid nitrogen [7]. The transformer was a mock up of a proposed high temperature superconducting transformer, but with aluminium windings. The partial core was a slug of laminated silicon steel.

A commercial manifestation of a partial core transformer is demonstrated in a parallel resonant compensation test method [8,9]. Initially this used a HV inductance that supplied reactive power compensation to a hydro generator unit stator. As a further development, the inductor was turned into a resonant transformer by the addition of a LV primary. The magnetising reactance was matched to the generator stator insulation capacitance. A second tunable resonant transformer was then designed.

Finally, a high temperature super-conducting transformer (HTST) has been designed and built. The transformer windings are configured to allow different arrangements, namely internal primary, external primary and autotransformer.

2. SILICON STEEL CORE TRANSFORMERS

Two single phase, 50Hz, 10kVA, 11/0.23kV, silicon steel core, copper winding, transformers were procured from a local transformer manufacturer. One was filled one with standard transformer oil and the other filled with liquid nitrogen. The transformers were initially subjected to an over-voltage test of 6.6kV to test the gross capability of the insulation. Capacitance and dissipation factor equipment was connected and measurements made at 6.35kV, according to [10]. The results are presented in Table 1.

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.

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.

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	0.90	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 liquid nitrogen filled 10kVA transformers

The core losses do not significantly increase with the temperature change. 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 especially 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, with amorphous cores, were procured and 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. This indicates the consistency in winding design and dielectric quality of the mediums. Measurable values for the dissipation factors of both the oil and liquid nitrogen filled 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.

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 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. 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. PARTIALCORE TRANSFORMER

A conventional single phase power transformer has 2 windings linked by a closed or full core of ferromagnetic material. A coreless transformer has no steel. 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. It is referred to here as a partial or open core. Such a transformer has about 25% of the material used in a full core transformer. It thus has reduced core losses.

A silicon steel partial core transformer was wound with aluminium windings [11]. 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. The windings were placed around a former in a helical arrangement, with each layer as a separate entity. This allows for ultimately testing a number of arrangements for the winding.

The as-built transformer was tested while operating in air and in liquid nitrogen. The open circuit test results are presented in Table 5. 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.

Operating medium	Air	LN2
Primary voltage (V)	240	240
Primary current (A)	30	30
Secondary voltage (V)	119	119
Primary real power (W)	400	450

Table 5: Open circuit test measurements.

Operating medium	Air	LN2
Primary voltage (V)	4.2	4.2
Primary current (A)	8	56
Secondary current (A)	16	110
Primary real power (W)	34	230

Table 6: Short circuit test calculations and measurements.

The performance of the transformer under short circuit tests is presented in Table 6. 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 performance of the transformer under load conditions is presented in Table 7. 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.

Operating medium	Air	LN2
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 7: Load test calculations and measurements

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. RESONANT INDUCTOR

A generator stator testing requirement involved a 50Hz, 11kV, 40MW generator at the Matahina power station in New Zealand. The design specification called for a 50Hz ac test voltage of 23kV for 1 minute. The stator capacitance was estimated to be between

A HV resonant inductor was designed and built as shown in Figure 1. The generator stator insulation was measured at 0.56μF. Under test, the stator insulation drew 4.1A at 23kV.

The supply current was reduced to 0.75A, significantly below that which would have been necessary without the inductor in circuit. Thus a VA gain of 5.5 from the supply to the load was obtained. This allowed the use of a lower VA rating HV test supply transformer, supply variac, with smaller station supply and protection considerations.

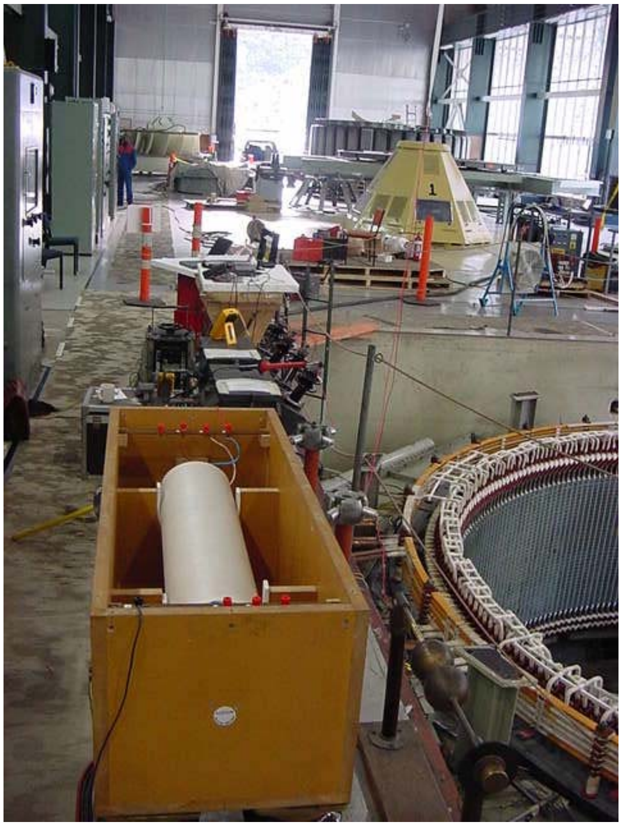

Fig. 1 Resonant inductor in use at Matahina

6. RESONANT TRANSFORMER

The partial core resonant inductor was modified to be its own supply transformer [8]. The inductor was altered by placing a LV winding around the HV winding. The neutral connection to the HV winding was made at the outer layer and the core left floating at the high voltage. The LV winding thus shielded the HV winding for electric field coupling to grounds external to the device. This reduced corona from the windings.

This transformer cannot be operated on open circuit as the LV winding was not designed to take the high magnetising current under steady state conditions.

However, this transformer, weighing approximately 120 kg, replaced the entire 6 tonne HV circuit shown in the background of Fig. 2.

7. TUNABLE RESONANT TRANSFORMER

A resonant transformer was designed to test a 50Hz, 13.8kV, 135MVA generator stator at the Manapouri underground power station, at 31.5kV. The stator capacitance was estimated to be 1.083μF. The completed resonant transformer is shown in Figure 2.

Fig. 2 Manapouri resonant transformer in front of equipment previously used at Tekapo power station.

The tunable resonant transformer was used on site at the Manapouri power station to test the initial batch of installed generator stator bars. The test voltage was 36.5kV and the capacitance of the installed stator bars was measured at 0.49μF. During the test, a flashover occurred on the stator. The resonant transformer showed no damage from this full circuit condition at high voltage, proving the electrical and mechanical integrity of the winding system.

In a follow up test, the Matahina resonant transformer was reinsulated to operate 32kV and inserted as an inductor in parallel with the Manapouri resonant transformer. Each complete phase of the generator stator of 1.06μF was tested. The stator current was 10.6A to give a reactive power of 339kvar. The Matahina and Manapouri resonant transformers had currents of 4.0A and 7.1A respectively. The primary was excited at 443V and took 70A, to give a VA rating of 31kVA and an output to supply VA ratio of 11.

8. HIGH TEMPERATURE SUPERCONDUCTING TRANSFORMER

A single phase, 50Hz, 230/115V, 15 kVA, HTS power transformer has been designed and built. The particular HTS tape from American Superconductors has cross-sectional dimensions of 0.305 by 4.1 mm. A target current density 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.

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 autotransformer 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. The transformer is shown in Figure 3.

Fig. 3 Partialcore High Temperature Superconducting Transformer

The open circuit test results at rated voltage showed that the secondary voltage was close to the nominal rated value of 115 V.

9. 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. Liquid nitrogen significantly reduces winding losses. This is an expected result as the resistivity of copper (or aluminium) is temperature dependent.

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.

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. 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.

As a further development of transformers, the capacitance of generators can be compensated by the use of inductive reactance in a parallel resonant circuit. A test apparatus has been designed around the partial core concept. The generator stator insulation capacitance is provided by the transformer magnetisation. This means that the supply only has to provide the real power losses of the transformer and in practice any mismatch between the magnetisation current and the stator capacitance. The primary winding can thus be downsized to conduct only this supply current.

To test the resonant concept in practise, a high voltage inductor was designed and used in the testing of a generator at a New Zealand power station, Matahina. It supplied 115kvar of reactive power compensation at 23kV. The inductor weighed 120kg. The inductor was subsequently modified by the addition of a low voltage primary. The required high voltage of 23kV could be obtained from energising the primary at 285V at 60A or at a rating of about 1/7th the load.

A further resonant transformer was then designed for a 334kvar capacitor load to test Manapouri power station generator stators at 31.5kV. The transformer has a finished weight of approximately 300 kg. On site, the resonant transformer was used to supply 36.5kV to the initial batch of installed stator bars at 0.49µF. This is the equal to a capacitive load of 205kvar. It also withstood a stator flashover proving the electrical and mechanical integrity under short circuit. In a follow up test, the Matahina resonant transformer was reinsulated to operate 32kV and inserted as an inductor in parallel with the Manapouri resonant transformer. Each complete phase of the generator stator of 1.06µF was tested. The output to supply VA ratio was 11.

A partial core, high temperature superconducting transformer has also been designed, built and tested for its performance while immersed in liquid nitrogen. The tests indicated 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.

10. REFERENCES

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