PARTIAL CORE TRANSFORMERS FOR HV TESTING AND POWER SUPPLIES

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Abstract

Partial core transformers have different characteristics from full core transformers as the flux path is a combination of steel and air. They are also easier to fabricate, transport and assemble on site. A number of useful partial core transformers have been designed. One commercial manifestation is demonstrated in a parallel resonant compensation test method. This uses the magnetising inductance to supply reactive power to the insulation of a hydro generator stator. A partial core high temperature super-conducting transformer (PCHTST) has also been designed and built as a proof of concept model. A third high voltage partial core transformer has operated at open circuit conditions at 80 kV. It has been designed for sphere flashing for testing purposes and has been used as a supply for a HV display arc-sign. A 20 kV ac model has been combined with a two stage multiplier circuit to give 60 kV dc to charge capacitors. A further option gave 4000 A continuously for high current primary injection testing.

Introduction

A partial core transformer has a central core with the primary and secondary windings wrapped round it [1]. The limbs and yoke of a conventional full core transformer are absent in a partial core transformer. Partial core transformers are designed using a Reverse Design Transformer Modelling Technique [2, 3].

One commercial manifestation of a partial core transformer is demonstrated in a parallel resonant compensation test method [4, 5]. 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 tuneable resonant partial core transformer was then designed, built and used in service.

A partial core high temperature super-conducting transformer (PCHTST) has also been designed and built [6]. The transformer windings are configured to allow different arrangements, namely internal primary, external primary and autotransformer. Other transformers have also been built for specific purposes.

This paper gives an overview of the partial core transformer concept and summaries of the most significant developments made.

Partial Core Concept

A conventional single phase power transformer has two windings linked by a closed or full core of ferromagnetic material. By contrast, 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. Such an arrangement, shown in Figure 1, is referred to as a partial or open core.

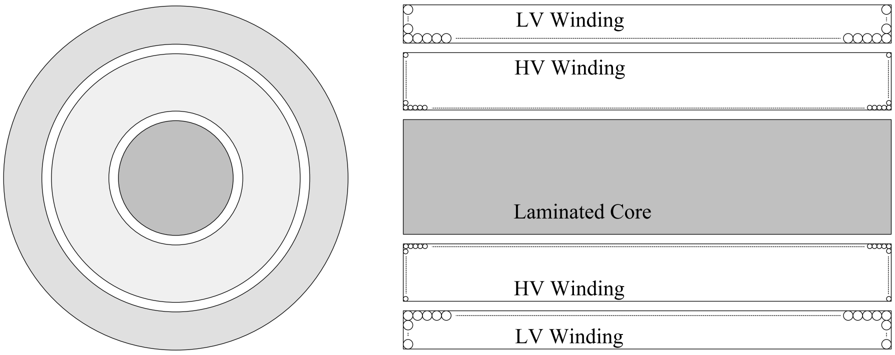


Figure 1
Cross Section and End Elevation of a Partial Core Resonating Transformer

Partial core transformers have different characteristics from full core transformers as the flux path is a combination of steel and air. For identical supply voltage, core cross-sectional area and number of turns on the excitation, the theoretical flux density is the same for both a full core and a partial core transformer. However, the flux path reluctance is much higher in the latter leading to a lower magnetizing reactance and higher magnetizing current. However, by controlling the number of turns, partial core transformers can be designed for useful purposes. They are also easier to manufacture than full core transformers since core and windings are not physically interlinked like a chain.

The fundamental advantage of a partial core transformer is that there can be a significant reduction in size and weight when compared to the conventional full core equivalent. Realising useful partial core transformers creates some design challenges, but once designed they are generally easy and inexpensive to manufacture.

Resonant Inductor

As a prelude to the development of useful partial core transformers, a stator testing requirement involved a 50 Hz, 11 kV, 40 MW generator at the Matahina power station in New Zealand. The design specification called for a 50 Hz ac test voltage of 23 kV for 1 minute. The stator capacitance was estimated to be between 0.217 and 0.422 µF per phase, although at the time of designing, these were not firm. These capacitance values equate to reactance's of approximately 14,700 and 7,500 Ω respectively. There was no available equipment in New Zealand to undertake these tests.

A HV resonant inductor was designed and built as shown in Figure 2. A core size of 715 mm length and 125 mm diameter was determined. The copper winding wire was 1 mm in diameter. These values were obtained through a process of design/performance evaluation using a computer program created for the purpose [5]. A total of 13 layers of 1mm diameter wire were used in the HV winding. The number of turns was 8,814. Taps were made from layer 9. The measured values of reactance ranged from about 4,700 to 11,900 Ω for 9 to 13 layers respectively. Each layer was insulated with 0.35 mm thick Nomex, which is rated for a breakdown voltage of about 18 kV. The neutral end of the winding was placed next to the core.

Figure 2
Resonant Inductor in use at Matahina

The generator stator insulation was measured at 0.56 μF, corresponding to about 5700 Ω. This was almost twice the design value. Fortunately, the flexibility and relative conservatism in the resonant partial core transformer design allowed an appropriate tap selection to accommodate the actual load. Under test, the stator insulation drew 4.1 A at 23 kV, implying some over-compensation of reactive current by the inductor. Nevertheless, the supply current was reduced to 0.75 A, 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 and variac, with smaller station supply and protection considerations.

Resonant Transformer

The usual transformer winding arrangement is to have the LV winding on the inside next to the core. A partial core resonant transformer has the LV winding wrapped around the HV winding. The LV winding shields the HV winding from electric field coupling to grounds external to the transformer and reduces corona from the windings [4].

The partial core resonant inductor of Section 3 was modified to be its own supply transformer [4], by placing a LV winding around the HV winding. This was made from a single layer of 68 turns of 5.0 by 2.5 mm rectangular aluminium wire. The wire size was selected more by what would best cover the HV winding to reduce leakage, than for current density optimisation, although the number of turns was selected to give a turns ratio of 100, to allow the transformer to be excited from a 230 V supply. The neutral connection to the HV winding was made at the outer layer and the core left floating at the high voltage.

The interlayer insulation material was Nomex/Mylar/Nomex (NMN) 5-10-5. This is paper/polyester film laminate of thickness 0.5 mm, with a nominal dielectric strength of 22 kV. The maximum voltage on the insulation at rated secondary voltage was 4.6 kV. This gave a factor of safety of almost 5 times. A photo of the completed HV winding is presented in Figure 3.

Figure 3
Completed HV Winding

Figure 4
Encapsulating the HV Winding with Sylgard

After completion of the HV winding, the section of overhanging Nomex is filled with Sylgard high voltage insulating compound, under vacuum. This process is presented in Figure 4.

The heavy gauge of the LV winding wire was held in place by fibreglass reinforced packing tape. A photo of the completed LV winding is presented in Figure 5.

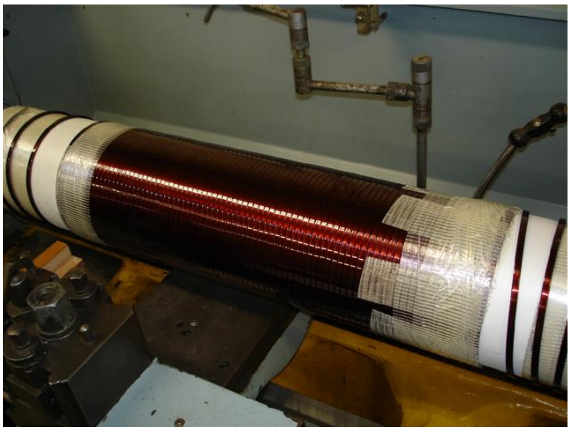


Figure 5
Completed LV Winding

This transformer, weighing approximately 120 kg, replaced the entire 6 tonne HV circuit shown in the background of Figure 6.

Figure 6
Manapouri Resonant Transformer in front of Equipment
Previously used at Tekapo Power Station.

To test the effectiveness of the resonant transformer, 10 capacitors of an inverted Marx HV impulse generator were connected in parallel to give a nominal load capacitance of 0.65 μF. This equated to an impedance of 4,900 ohms, which was almost equivalent to the transformer magnetising impedance for 9 layers, and corresponded to the tests undertaken on site with the resonant inductor.

The transformer showed linear behaviour through to rated high voltage. However, to get 23 kV on the HV winding, 285V was needed to be applied to the LV winding, to give a voltage ratio of 81. The HV winding current was measured at 4.9 A, equivalent to the Matahina stator and consistent with a load impedance of 4,700 Ω. The LV winding current was 55 A. This gave input volt-amperes of 15.7 kVA for a load value of 113 kVAr, or a gain of 7.2.

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. The calculated open circuit current of 490 A would give rise to a current density of 39 A/mm^2, which would soon overheat the winding.

The electrical circuit for resonant testing using a partial core transformer is shown in Figure 7.

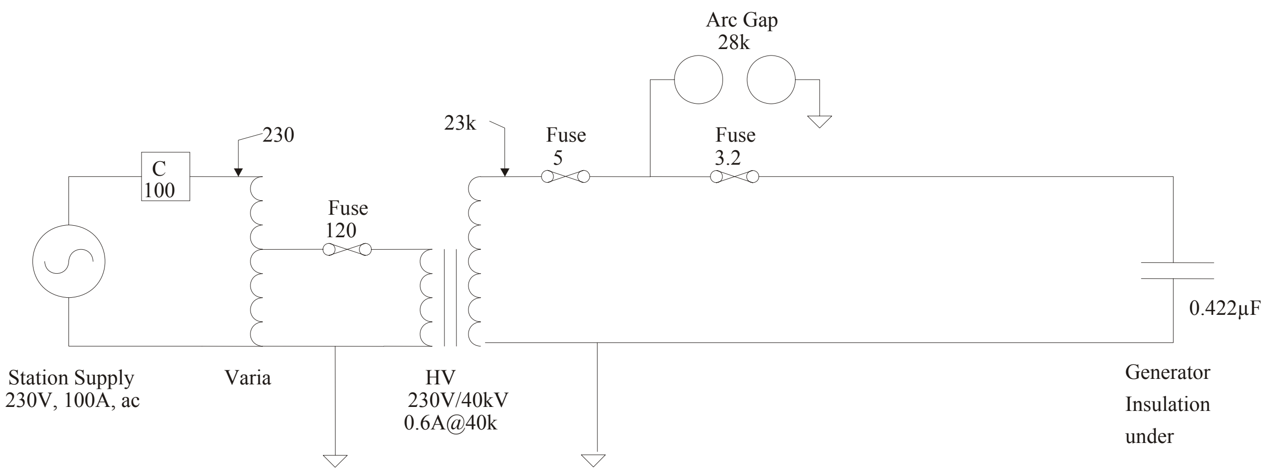


Figure 7
HV ac Insulation Test Set using a Partial Core Resonant Transformer

Tuneable Resonant Transformer

A partial core resonant transformer was designed to test a 50 Hz, 13.8 kV, 135 MVA generator stator at the Manapouri underground power station, at 31.5 kV. The stator capacitance was estimated to be 1.083 µF. The completed resonant transformer is shown at the front of Figure 6.

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

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

A resonant transformer kitset consisting of three partial-core transformers which share a common core has since been designed to supersede the Matahina and Manapouri transformers. Optimisation techniques were applied to a finite element model to minimise the transformer metal weight. The design is complete and the transformers have been built. Initial test results have confirmed the validity of the model. The first transformer is a direct replacement for the Manapouri resonant transformer. The advantages are increased performance and a reduction of metal weight by nearly 45%. The two transformers are compared in Figure 8.

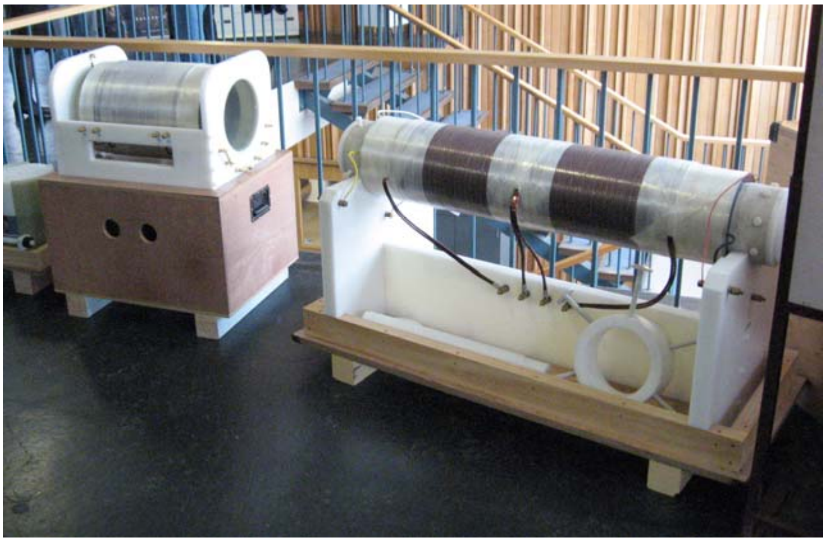


Figure 8
Partial Core Resonant Transformers – New (170kg, left), Original (300kg, right).

The new transformer exhibits more voltage current linearity at rated load capacitance, as shown in Figure 9.

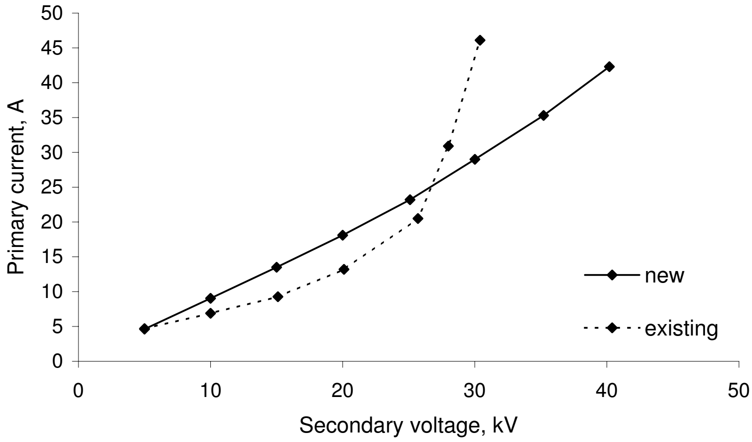


Figure 9
Partial Core Resonant Transformers – Laboratory Capacitive Load Test, 1.1uF

High Temperature Superconducting (HTS) Transformer

A single phase, 50 Hz, 230/115 V, 15 kVA, partial core, HTS transformer has been designed and built as a proof of concept device. The particular HTS tape from American Superconductors has cross-sectional dimensions of 4.1 mm by 0.305 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 design led to a partial core length of 345 mm and diameter of 80 mm. Each layer of the windings had 80 turns to give an inside winding of 320 turns and two outside windings of 160 turns each. The HTS conductor was insulated with Nomex tape. The conductor was then wound on a composite former and insulated with 1 mm Nomex 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 ends of all three windings were accessible to enable the location of the primary and secondary windings to be varied, as well as two-winding and auto-transformer 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 10.

Figure 10
Partial Core High Temperature Superconducting Transformer

Excitation was applied to the inside winding. The transformer exhibited virtually linear voltage/current characteristics. The open circuit test results at rated voltage are presented in Table 1. The secondary voltage is close to the nominal rated value of 115 V.

Each outside winding was short circuited separately while the other was kept at open circuit. The performance of the transformer under one indicative short circuit test is presented in Table 2. The winding real power losses are most likely due to the copper leads which connect the terminals at ambient temperature to the HTS conductors at liquid nitrogen temperature.

Table 1
Open Circuit Test Measurements for Partial Core HTS Transformer.

Parameter	Measured Value
Inside winding voltage (V)	230
Inside winding current (A)	19
Outside winding voltage(s) (V)	113 and 111
Inside winding real power (W)	200

Table 2
Short Circuit Test Measurements for Partial Core HTS Transformer.

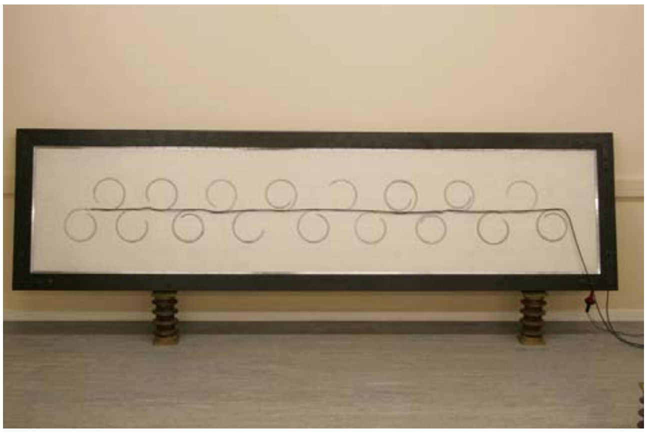
Parameter	Measured Value
Inside winding voltage (V)	25
Inside winding current (A)	65
Outside winding current (A)	65
Inside winding real power (W)	80

Energization of High Voltage Arc-Signs

Lightning arc drawings or "arc-signs" have been developed in a collaborative study in the Departments' of Electrical and Computer Engineering and Fine Arts at the University of Canterbury. These arc-signs require a high voltage to obtain their arcing effect. The basic arrangement of an arc-sign is presented in Figure 11 [7].

The configuration consists of a top electrode which forms the design, a sheet of insulating film (NMN 5-10-5), and a thin sheet conductor which forms the bottom electrode. Essentially, the arc-sign is a parallel plate capacitor of very small value. Many of these signs have been constructed and the appearance and capacitance of each varies with the design of the top electrode.

At rated voltage, power arcs can appear on the surface of the sign. They represent a momentary (μsec) short circuit of the power supply. Very little real power is dissipated by the arc-sign, even when power arcs are being formed on the sign's surface. The operation is near to an open circuit state.



(a) De-energised

(b) Energised (close-up)

Figure 11
The Arc-sign Showing the Top Electrode and Insulation Layer

The core of the partial core transformer designed to supply the arc-sign was 700 mm in length, with a circular cross-section of 85 mm diameter [8]. The high voltage winding was created by winding 37 layers comprising 1600 turns per layer of 0.375 mm diameter copper wire onto a fibreglass former to give a total of 59,600 turns for the winding. 0.5 mm Nomex insulation was used between layers.

Two separate LV windings were wound onto the outside of the HV winding. Each winding consists of a single 80 turn layer of 7.1 mm x 3.55 mm rectangular cross section enamelled aluminium wire. The two windings are connected in series by an external link to give the very high turns ratio required for an output voltage of 80 kV from a 230 V supply.

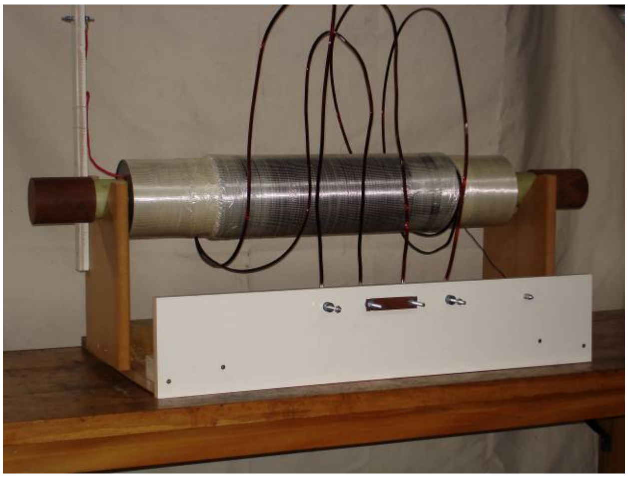


Figure 12
80kV Transformer

The completed transformer including the core weighs 69 kg. A photo of the transformer and mounting arrangement is presented in Figure 12.

The transformer was load tested with the arc-sign previously presented in Figure 11, which has a de-energized capacitance of 7 nF, corresponding to 450 kΩ of capacitive load reactance, or 3.32 Ω when referred to the transformer primary winding.

The transformer can also be used for flashing sphere gaps used for high voltage testing protection, as it can sustain full voltage short circuits without damage.

High Current Transformer

Primary current injection is mainly used to test current transformers and associated equipment on power transmission and distribution network metering and protection schemes. It is useful to test CTs in situ in the field. Conventional high current transformers are bulky and heavy. This limits the location they can be placed in, resulting in extra secondary cable lengths. With the high current, low voltage output characteristic of these transformers, cable voltage drop is usually the limiting factor of the output current. A smaller, lighter transformer can be placed closer to the equipment under test, reducing the effect of cable voltage drop, resulting in higher current available for testing.

A partial core high current transformer was designed for the purpose [9]. It weighed 39 kg. It can deliver 4,000 A continuously or 11,000 A peak. While the continuous rating met the specifications of a conventional transformer used for the purpose (weighing 147 kg), the peak current was limited due to excessive eddy current heating at the terminals of the secondary winding. Laminating these terminations may be a way of solving this heating problem.

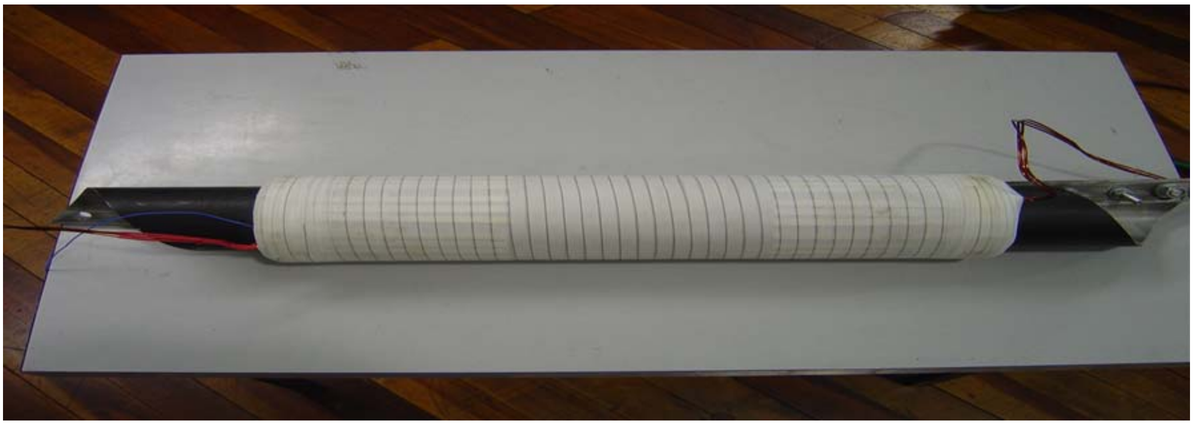


Figure 13
High Current Test Transformer

Conclusions

A number of partial core transformers have been designed, built and tested for their performance under different operating conditions. In one development, 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 115 kVAr of reactive power compensation at 23 kV. The inductor was subsequently modified by the addition of a low voltage primary. The required high voltage of 23 kV could be obtained from energising the primary at 285 V at 60 A or at a rating of about 1/7th the load. The transformer weighed 120 kg.

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

A partial core, high temperature superconducting transformer has 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 a low percentage of this is leakage flux. This supports the viability of the partial core design for real power transformation.

A design has also been presented of a partial core transformer rated to single phase, 80 kV using dry insulation. This transformer operates near to an open circuit condition and was designed specifically to power arc-signs which use high voltage arcing in air for display purposes and as a sphere flashing transformer for HV testing protection.

A final design is a partial core high current test transformer. It can provide 4,000 A continuously.

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