Partial Core Transformer for Energisation of High Voltage Arc-Signs

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Abstract: A high voltage partial core resonating transformer has been designed and constructed such that its magnetising current reactance is matched to the reactive current drawn by the capacitance of an arc-sign. The supply only provides the real power losses of the transformer plus any reactive power mismatch between the magnetizing reactance and the capacitance of the arc-sign. A mathematical model of the transformer is developed using a reverse design modelling technique. The model is then used to design a 50Hz, 8kVA, 230V/80kV, partial core transformer to meet the required electrical demand of the load. The transformer was constructed and tested. The transformer successfully resonated with the load and provided 68VAr of compensation when operating at 10kV while being supplied from a domestic 230V, 10A, power outlet. The completed transformer has a finished weight of 69kg and has been successfully used for powering an arc-sign at an exhibition of electric sculptures.

1 INTRODUCTION

A partial core transformer has a central core with the primary and secondary windings wrapped around 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]. A partial core resonating transformer has a characteristically low magnetizing reactance. Through careful design, the reactance of the transformer can be matched to a capacitive load. This has seen effective industrial use in the testing of generator stators [4, 5]. A parallel resonant circuit is formed where the reactive current drawn by the load is provided by the magnetisation of the transformer. The supply only has to provide the real power losses of the transformer plus any mismatch between the magnetizing reactance and the capacitance of the load.

Lightning arc drawings or "arc-signs" are presently being developed in the department. These arc-signs require a very high voltage to obtain their arcing effect. A power source capable of very high voltage is required. This paper describes the design, fabrication and testing of a partial core resonating transformer which is capable of supplying the very high voltages required by arc-signs whilst being able to be operated from a single phase, 10A, 230V, domestic power socket.

2 PARTIAL CORE TRANSFORMER ARRANGEMENT

The usual transformer winding arrangement is to have the LV winding on the inside to reduce its length and hence the copper losses due to its relatively high current. The transformer designed for the arc-sign application 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]. A cross sectional view of a partial core resonating transformer is presented in Fig. 1.

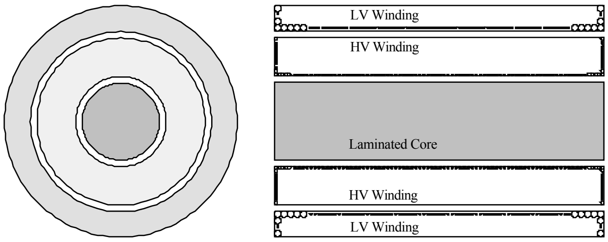

Fig. 1: Cross section and end elevation of a partial core resonating transformer.

By design, partial core transformers are generally long and thin in shape to obtain the required value of magnetising current reactance as given by (1).

$$X_m = \frac{\omega N_1^2 \mu_0 \mu_{rT} A_{core}}{l_{core}} \tag{1}$$

where:

ω	is the supply frequency in rads/sec
N_1	is the number of primary turns
μ_0	is the permeability of free space
μ_{rT}	is the effective permeability of magnetic flux path through the laminated core material and the air return path
A_{core}	is the cross-sectional area of the core
l_{core}	is the length of the core

The fundamental advantage of a partial core transformer it that there is a significant reduction in size and weight when compared to the conventional full core equivalent. This creates some design challenges but generally they are easy and inexpensive to manufacture.

3 ARC-SIGN APPLICATION

The basic arrangement of an arc-sign is presented in Fig. 2. 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.

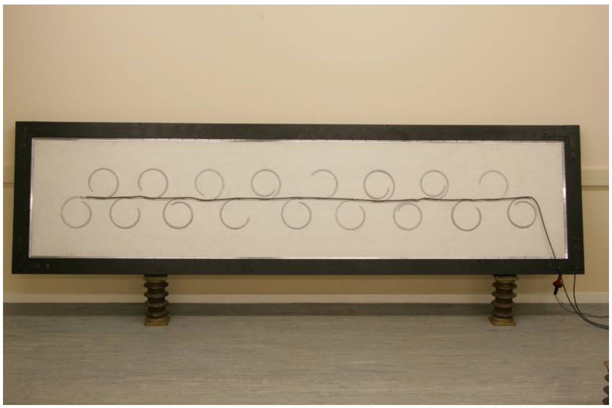

Fig. 2: The arc-sign showing the top electrode and insulation layer.

A test was performed to observe the voltage and current characteristics of the arc-sign when it is operating in its energized state. The waveforms from the test are presented in Fig. 3 and were recorded when the arc-sign was operating at 8.2 kV. The voltage waveform on the upper channel is sinusoidal whilst the current waveform on the lower channel is also sinusoidal with the exception of current spikes occurring at the voltage peaks, giving rise to power arcs. At this voltage, the power arcs appearing on the surface of the sign represent a momentary (micro-seconds) short circuit of the power supply. The current appears to lead the voltage by approximately 63°. However, the current clamp had an error of ± 20°. Taking this into account, the actual phase angle could be approximately 90° leading, indicating a purely capacitive load. The results of this test showed that very little real power was dissipated by the arc-sign, even when power arcs were being formed on the sign's surface.

Making the assumption that the arc-sign can be modelled as a purely capacitive load, the supply voltage was varied. The current on the HV side of the transformer was measured. The effective capacitance at any voltage could thus be calculated.

An arc-sign with a calculated capacitance of 10.6nF gave a voltage dependent capacitance as presented in Fig. 4. These results show that the capacitance of an arc-sign will increase with the supply voltage but will eventually resolve to a constant value. Possible reasons for the change in capacitance are:

- The polarity of each of the electrodes causes an attraction of the top and bottom electrodes and hence causes the distance between them to decrease.
- The power arcs and streamers occurring from the edges of the top electrode cause the area of the top electrode to increase.

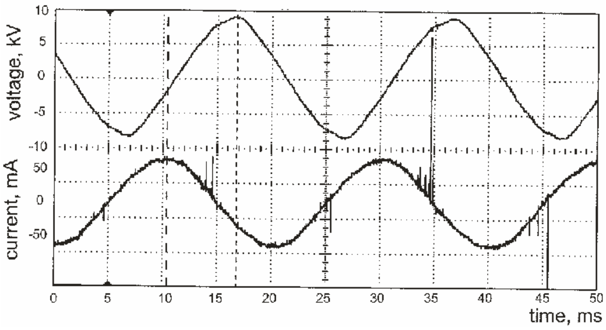

Fig. 3: Energized arc sign operating at 8.2 kV as power arcs are starting to appear.

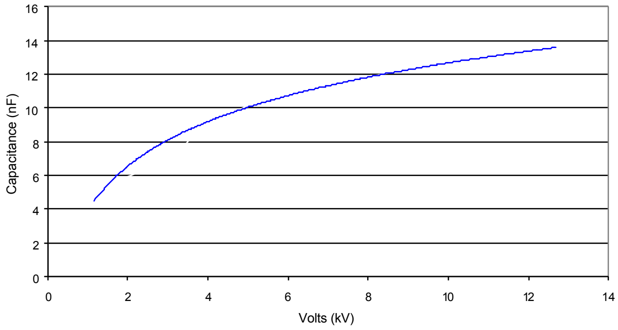

Fig. 4: Arc-sign capacitance change with supply voltage.

4 TECHNICAL SPECIFICATION FOR TRANSFORMER

An 8kVA, oil insulated, full core Ferranti transformer was currently used as the power supply for the arc-sign. This transformer weighed approximately 190kg. The electrical specifications of the Ferranti transformer were adopted as the electrical specifications for the partial core transformer. Using this as the benchmark, the specifications for the partial core transformer which was manufactured are summarized in Tab. 1.

Tab. 1: Electrical design specification for transformer.

Apparent Power	8 kVA
Frequency	50 Hz
Primary Voltage	230 V
Secondary Voltage	80 kV
Max primary current	36.4 A
Max secondary current	0.1 A

To achieve the 8kVA, 80kV design, the secondary current of the transformer is limited to 100mA. This therefore puts a restriction on the size of the load that the transformer can supply without causing the secondary winding to overheat. The minimum value of capacitive reactance to limit current flow to 100mA is 800,000Ω. This was the value of load impedance that the transformer was designed for.

5 MATHEMATICAL MODEL

The reverse approach to transformer design [1–3] takes the materials which are actually available to be used in the construction of the transformer as specifications. The material type and dimensions are used to derive the components of an equivalent circuit model of the transformer and hence determine the performance of the transformer. If this is not the required result then the process is repeated with different material characteristics or dimensions until the required result is achieved.

An equivalent circuit for a partial core transformer with the secondary winding referred to the primary is presented in Fig. 5.

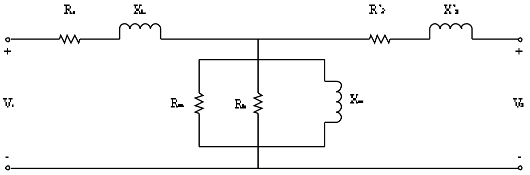

Fig. 5: Transformer equivalent circuit model [1].

Each of the equivalent circuit parameters is calculated either directly from the input data or from the intermediate calculations [1-3].

6 SIMULATED PERFORMANCE EVALUATIOAN

The materials chosen for construction of the transformer, their dimensions and physical characteristics are presented in Tab. 2.

Tab. 2: Materials used in transformer design.

Core	
Material	Laminated silicon steel
Length	700 mm
Diameter	72 mm
Stacking factor	0.96
Lamination thickness	0.5 mm
Core/ inside winding insulation thickness	2 mm
Number of layers of core/ inside winding insulation	1
Relative permeability	1500
Resistivity of core material at 20^{0}C	16.0E-08 ohm-m
Coefficient of thermal resistivity	0.006 ohm-m/^{0}C
Operating temperature	50 ^{0}C
Material density	7833 kg/m3
Inside Winding (HV)	
Material	Copper
Layers	37
Thickness of inter layer insulation	0.5 mm
Wire diameter	0.375 mm
Resistivity of material at 20^{0}C	1.70E-08 ohm-m
Coefficient of thermal resistivity	3.9E-09 ohm-m/^{0}C
Operating temperature	50 ^{0}C
Material density	8954 kg/m3
Inside-Outside Interwinding Space	
Thickness of interwinding insulation	0.5 mm
Number of layers of interwinding insulation	1
Outside Winding (LV)	
Material	Aluminium
Layers	2
Thickness of inter layer insulation	0.5 mm
Width along axis for rectangular wire	7.10 mm
Radial thickness of rectangular wire	3.55 mm
Resistivity of material at 20^{0}C	2.67E-08 ohm-m
Coefficient of thermal resistivity	0.00432 ohm-m/^{0}C
Operating temperature	50 ^{0}C
Material density	2700 kg/m3

6.1. Core design

The core of the transformer was constructed from several laminations of core material. A circular core cross-section was chosen over a rectangular core to minimize the HV winding material length and hence resistance and cost. This winding has high volts per layer and a circular core allows uniform electrical stress. Also, extra mechanical stress would be placed on the winding by the sharp corners of a rectangular core.

6.2. LV Winding Design

The low voltage winding only needs to be of a cross-sectional area large enough to carry the primary current. This is much smaller than the referred secondary current due to the magnetisation reactance compensating for the load capacitance. A current density of 1–2 A/mm^2 is desirable with non-forced cooling wire.

6.3. HV Winding Design

The high voltage winding was also sized to maintain the current density at approximately 1–2 A/mm^2. The very high voltage ratio given by the design specification requires a very high number of secondary turns to step the voltage up to 80 kV.

7 TRANSFORMER CONSTRUTION

7.1. Transformer Core

The transformer core was constructed from pieces of 0.5mm thick laminated silicon steel sheet to form a solid cylindrical shaped core. The lamination widths and quantities which were assembled to construct the core are presented in Tab. 3.

Tab. 3: Lamination stack widths and numbers required to form the circular core.

Lamination width	Quantity
20	10
30	20
46	20
56	20
62	20
67	20
70	20
71	10

For this transformer, a modification to the core was made as compared to those used on previous designs. This was an attempt to reduce eddy current heating in the end of the core laminations caused by horizontal flux cutting the core as it emerged into the air. This heating had been observed in previous partial core resonant transformers [4, 5]. The core was constructed in three sections to produce a cylindrical core 75mm in diameter and 700mm in length. The centre section of the core is 600mm in length and is constructed by using one piece of silicon steel for each lamination. A total of 140 strips were used. The two end pieces of the core are each 50mm long. Each layer of lamination was constructed from thin strips of silicon steel, 10mm wide. Thus, each end section contains 720 pieces of silicon steel, super-glued together to form the cylindrical cross section. A photo of the completed core is presented in Fig. 6.

To allow for comparison between the three-section partial core which was constructed and a conventional single section partial core, a section of core 100mm long was constructed in the same manner as the centre section of the three-piece core (from 140 pieces of lamination). This replaced the two end sections of core. The wider pieces of lamination should have larger eddy currents due to the diverging magnetic flux and hence greater core losses. The sections of core material were fixed together using fibreglass reinforced packing tape as an interim measure while testing the transformer's performance. A more permanent solution is to bind the laminations with a fibreglass tape/resin coating.

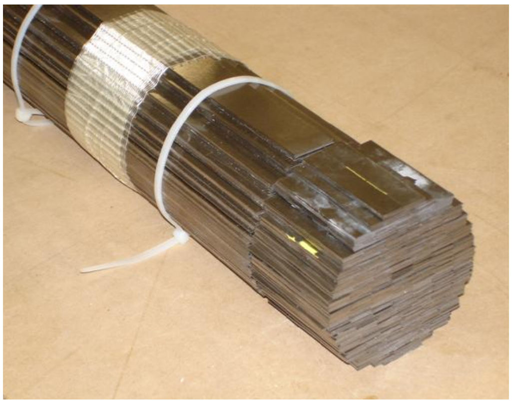

Fig. 6: One end of the completed transformer core.

7.2. High Voltage Winding

The high voltage winding was created by winding 37 layers comprising 1600 turns per layer of 0.375mm diameter copper wire onto a fibreglass former to give a total of 59,200 turns for the winding. The insulation material was Nomex/Mylar/Nomex (NMN) 5-10-5. This is paper/polyester film laminate with a dielectric strength of 22kV and a nominal thickness of 0.5mm. The maximum voltage on the insulation at rated secondary voltage was 4.6kV. This gave a factor of safety of almost 5 times.

The fibreglass former was covered with a layer of un-calendered Nomex 410 to allow the first winding layer to grip onto the Nomex rather than the smooth surface of the former. The HV end of the winding was started on the inside to place maximum separation between the HV lead out and the LV winding. Placing the LV winding on the outside also shields the HV winding from electric field coupling to grounds external to the transformer and reduces corona from the HV winding. Each layer of 1600 turns was wound onto the former and the initial and final 20 turns of each layer were fixed in place using a coating of hot glue to fasten the windings to the insulation layer below it. One layer of Nomex was wound between each layer of copper with a 100mm circumferencial overlap to allow for interlayer voltage creepage distance. There was also a 110mm overhang of the Nomex at each end of the winding to provide an adequate creepage distance for the potential difference of 80kV across the end of the winding. A photo of the completed HV winding is presented in Fig. 7.

After completion of the HV winding, the section of overhanging Nomex was filled with Sylgard high voltage insulating compound. Sylgard is an RTV-curing silicone rubber that repels water and contaminants. The uncured Sylgard was placed in a vacuum to remove any air from the mixture and was then poured into one end of the transformer. A vacuum was applied to the opposite end of the transformer to draw as much of the compound into the transformer body as possible. The second end of the transformer was encapsulated by pouring Sylgard into that end of the transformer and then a vacuum was applied to the same end to draw air out of the gaps between the sheets of insulation, thus allowing the Sylgard to flow into the vacant space. The Sylgard was left to cure over a period of 24 hours.

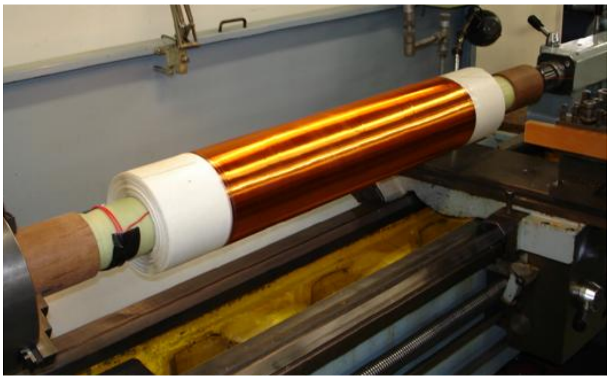

Fig. 7: Completed HV winding.

7.3. Low Voltage Winding

Two separate LV windings were wound onto the outside of the HV winding. Each winding consists of a single 80 turn layer of 7.1mm x 3.55mm rectangular cross section enamelled aluminium wire. The two windings are connected in series by an external link to achieve the 160 turns required for 230V operation. No additional insulation was required between layers of the LV winding because of the modest interlayer voltage. 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 Fig. 8.

The completed transformer including the core weighs 69kg. This is a significant reduction in weight in comparison to the 190kg full core equivalent.

At the completion of the transformer construction, a suitable mounting arrangement was constructed to allow safe operation of the transformer for testing. A photo of the completed transformer and mounting arrangement is presented in Fig. 9.

8 TRANSFORMER TESTING

Tests were performed on the constructed transformer to ascertain its performance under open circuit, short circuit and loaded circuit conditions. These are all standard transformer tests and must be completed to determine the correct operation of the transformer before it can be placed into service. The tests also allow for a comparison between the calculated and actual transformer performance. Due to space reasons, only the loaded-circuit test is presented here.

The transformer was load tested with the arc-sign previously presented in Fig. 2, which has a de-energized capacitance of 7nF, corresponding to 450kΩ of capacitive load reactance, or 3.32Ω when referred to the transformer primary. A sine wave set was used to eliminate any external harmonics in the power supply from the testing. The primary voltage to the transformer was controlled using a 10A variac. The voltage across the arc-sign was increased to 10kV. The arc-sign capacitance increased with the applied voltage until the lagging primary current came into phase with the primary voltage. At 10kV, the measured power factor on the primary of the transformer was 0.91.

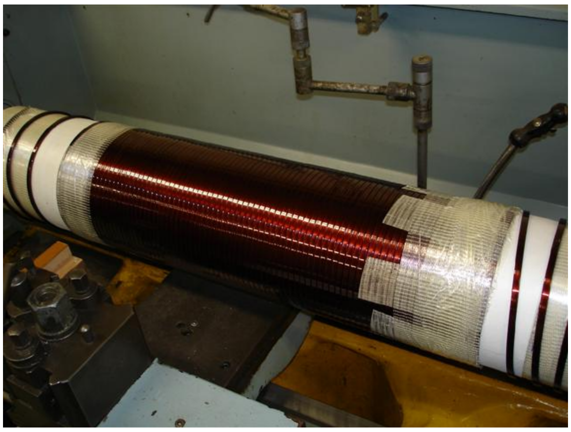

Fig. 8 : Completed LV winding.

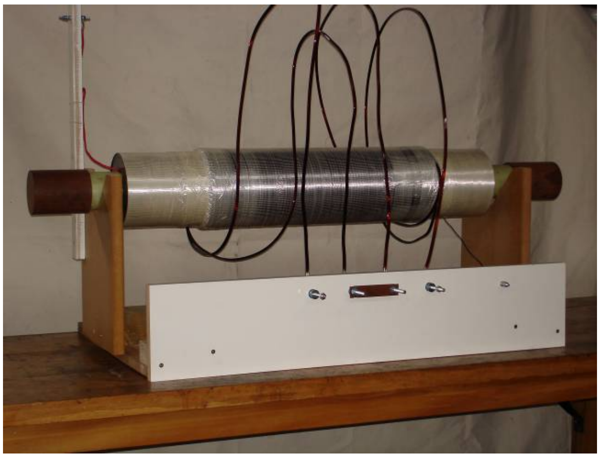

Fig. 9 : Completed transformer.

A waveform showing the primary voltage on channel 1 and primary current on channel 2, whilst operating at 10kV is presented in Fig. 10. At this voltage, streamers started to appear on the surface of the sign. The voltage waveform is sinusoidal while the waveform of the primary current contains a large third-harmonic component with power arcs superimposed on it. The harmonic currents are attributed to the non-linear load characteristic of Fig. 4. While resonating at 10kV, the transformer magnetising reactance is providing reactive power compensation. The results for the loaded-circuit test are presented in Tab. 4.

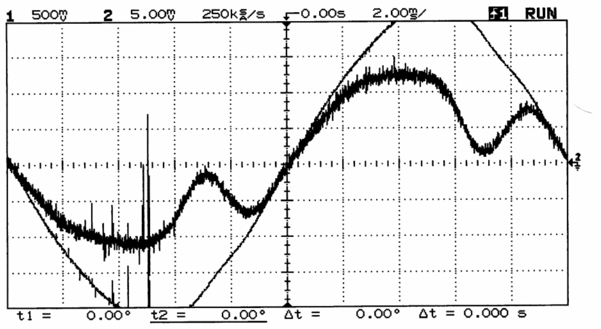

Fig. 10: Primary Voltage and Current of Loaded Transformer while operating in Resonance with arc-sign.

Tab. 4: Results of loaded-circuit test.

Outside (LV) winding voltage	30	V
Inside (HV) winding voltage	10	kV
Outside winding current	5.5	A
Inside winding current	24	mA
Outside winding real power	150	W
Outside winding power factor	0.91	

9 FUTURE APPLICATION

During the testing of the transformer and whilst operating under load using an arc-sign, the transformer was exposed to a number of short-circuits across the HV winding terminals, the highest being at a voltage of 22kV. Under a short-circuit, the transformer impedance is high enough to limit the fault current to a small enough value as to not damage the transformer construction caused by excessive internal heating. The impedance of the transformer is very large due to the large leakage reactance and large series resistance of the HV winding. This makes it suitable for use when testing spark gaps. Spark gaps are used in high voltage testing both as a safety device and to rapidly switch high voltages for pulsed power applications. To set and test spark gap distances, a high voltage power supply capable of withstanding a short circuit of its terminals is required. For the partial core transformer to be used for this application a suitable protection device would need to be attached to the transformer to protect it from a sustained fault current. A circuit breaker with an I^2t characteristic of less than ten times the I^2t characteristic of the transformer would need to be installed to limit the internal heat rise of the transformer under short-circuit.

10 CONCLUSION

Lightning Arc Drawings or arc-signs require a high voltage to obtain their arcing effect. A power source capable of high voltage is thus required. Previously, this has been provided by an 8kVA, 80kV, full core transformer which is very heavy and difficult to move around. However, because of the capacitive characteristic of the arc-sign, a partial core resonating transformer is a much more suitable power supply as the reactive power is generated in a parallel resonance between the transformer and the arc-sign.

The characteristics of an arc-sign and the power supply were determined and used as specifications in the design for a partial core resonating transformer. A reverse design transformer modelling technique was used to develop a mathematical model of the prototype transformer. The reverse design technique takes the construction materials and their dimensions and develops them into an equivalent circuit for the transformer. Simulated tests were performed to determine the suitability of the design. The constructed partial core transformer is 64% lighter than the equivalent full core transformer. It has a finished weight of 69kg.

The final transformer met all the operating requirements by successfully resonating with the arc-sign and providing 69VAr of compensation at 10kV, while being supplied from a domestic 230V, 10A, power outlet. The 80kV open circuit test of a dry partial core transformer was a significant result which allows future setting of spark gaps. The transformer was sucessfully used for powering an arc-sign at an exhibition of electric sculptures.

11 REFERENCES

[1] Liew, M. C., and Bodger, P. S., "Partial Core Transformer Design using Reverse Modelling Techniques", *IEE Proc. Electric Power Applications*, vol. 148, no. 6, pp. 513–519, Nov. 2001.

[2] Bodger, P.S., and Liew M.C., "Reverse as-built transformer design method", *Int. J. Elect. Enging. Educ.*, vol. 39, no. 1, pp. 42–53, Jan. 2002.

[3] Liew, M.C. and Bodger, P.S., "Applying a reverse design modelling technique to partial core transformers", *J. Electrical and Electronics Engineering*, Australia, vol. 22, no. 1, pp. 85–92, 2002.

[4] Bodger, P.S. and Enright, W.G., "A resonant transformer for high voltage testing of generator stators", *Australian Journal of Electrical and Electronics Engineering*, vol. 1, no. 3, pp. 179–185, 2004.

[5] Enright, W.G. and Bodger, P.S., "Short time rated and protected high voltage ac testing of generator stators using parallel resonant circuits", In *Electricity Engineers' Association Conference (EEA),* Best paper: non-member, Christchurch, New Zealand, 18–19 June, 2004, CD-ROM.