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Lutchman, Poonam

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EVALUATION OF AN EFFICIENT TRANSFORMER CORE DESIGN

APPENDICES

Poonam Lutchman

Appendix report for the dissertation on the Evaluation of an Efficient Transformer Core Design submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements of the degree of Master of Science in Engineering.

Johannesburg 2012

Abstract

The following report presents the appendices associated with the Evaluation of an Efficient Transformer Core Design dissertation report submitted for the MSc in Engineering. This report should therefore be read in conjunction with the dissertation main report. This appendix report is subdivided into various sections where the manufacturing process of the hexa-transformer, the test procedure, internal inspection and amorphous material are discussed in depth. A summary of these sections are presented in the main report of the thesis. The various permissions received for use of material and drawings from both Eskom and Hexaformer AB in Sweden is also presented.

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1. INTRODUCTION

The dissertation on the Evaluation of an Efficient Transformer Core Design analyses the hexa-transformer for use in the Eskom Distribution network in South Africa. The hexa-transformer is a three phase symmetrical triangular core transformer; it is made from nine rolls of electrical steel, it achieves a 50% no-load loss reduction when compared to conventional E-core transformers. This report is an appendix to the High Efficiency Transformer Core Design's main report. It presents the transformer manufacturing process of the hexa-transformer, the test procedure; and the internal inspections are discussed in depth. This report should be read in conjunction with the dissertation main report.

2. APPENDIX A - MANUFACTURING PROCESS

The manufacturing process details were obtained from Hexaformer AB in Sweden [1]. The details are explained below.

The Core: The inner core ring is wound using electrical steel. Two outer rings are added using half width bands of the same electrical steel. See Figure 1 below.

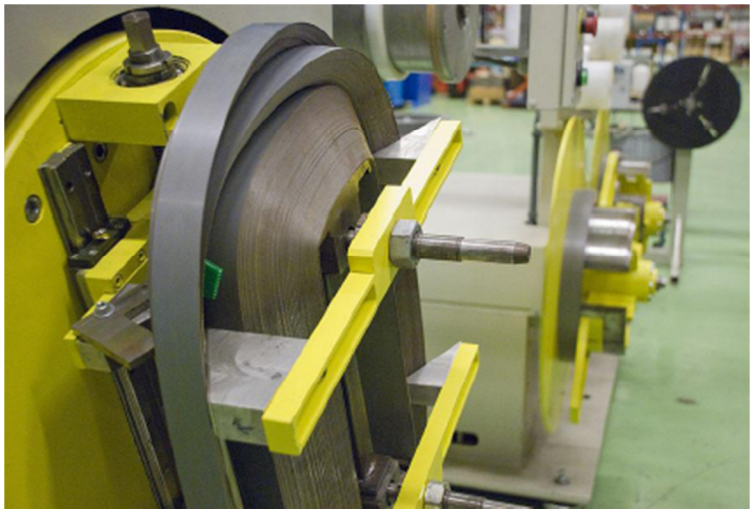


Figure 1: Core ring winding using electrical steel

The three separate core sections, each consisting of three bands are assembled into a cage core using clamps as shown in Figure 2 and Figure 3 below.



Figure 2: Core assembly of the hexaformer



Figure 3: Use of clamps for core assembly

The complete core is heated to aneal the steel. This takes about 12 hours. The magnetic properties are restored through the reorientation of grains. The anealed core is dropped into electric quality varnish in order to glue the assembly together. See Figure 4 below.

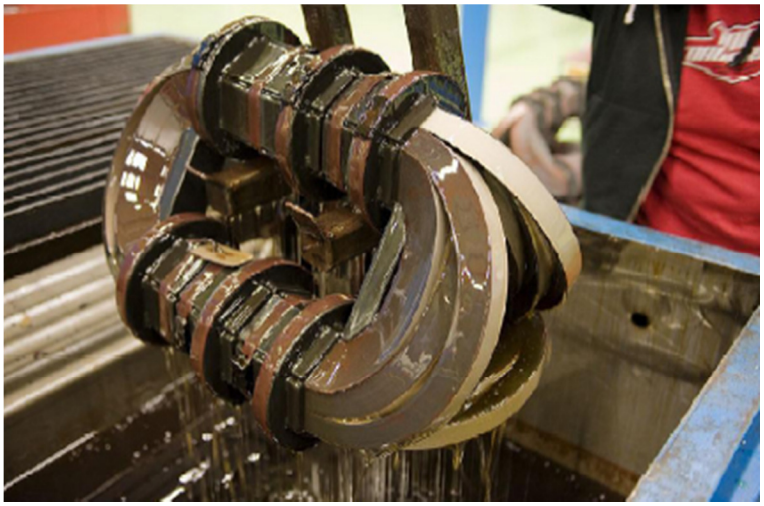


Figure 4: Hexaformer core glued using varnish

The varnish is hardened and all clamps are removed. And reused.

A special test coil is used for measurements for certification of no load losses and no load currents. All three legs are measured.



Figure 5: In Line Test of Core Losses

Coil Winding: The winding is done via a winding tube (bobbin) preparation. The tubes are split and then assembled into each core leg.



Figure 6: Winding tube preparation

The low voltage winding is wound on the first Bobbin. Edge cords are applied for insulation. Insulating paper is applied between each winding. High conductivity electrolytic copper enamelled rectangular wire is used for the winding.

A layer of ducting of pressboard material is applied to secure appropriate insulation and cooling. The thickness of which is dependent on the transformer voltage level.



Figure 7: Inter- layer insulation

The high voltage winding is wound in a similar manner to that of the low voltage winding.



Figure 8: High voltage winding

A protective insulation layer is applied for each winding. See Figure 9 below.



Figure 9: Outer Layer insulation

Assembly: In order to assemble the frame of the transformer the low voltage connectors are pulled out from the coil and the core and windings are mounted on the lower frame.



Figure 10: Frame assembly

The Low Voltage Windings (LVW) are connected to the bushings as shown in Figure 11 below.

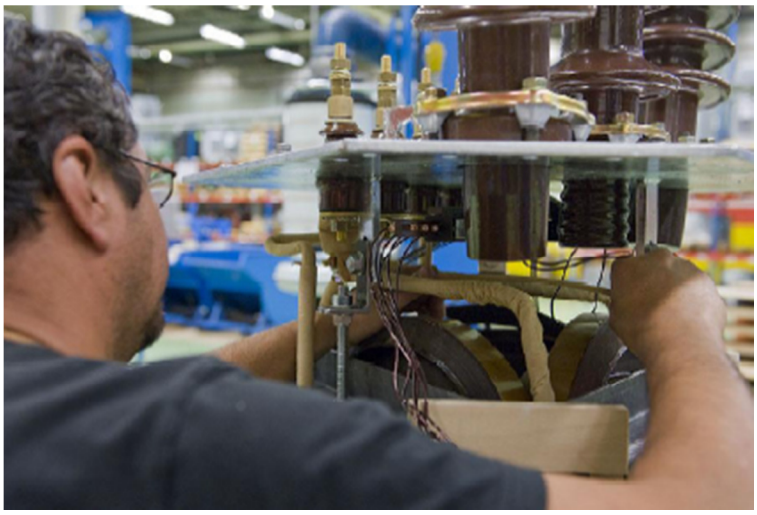


Figure 11: LVW connections

The High Voltage Windings (HVW) are also connected to the busings and the tap changer. As with the LVW these connections are done manually as illustrated in Figure 12 below.



Figure 12: HVW connections

After the assembly, the insulation and other electrical properties are tested for production quality.

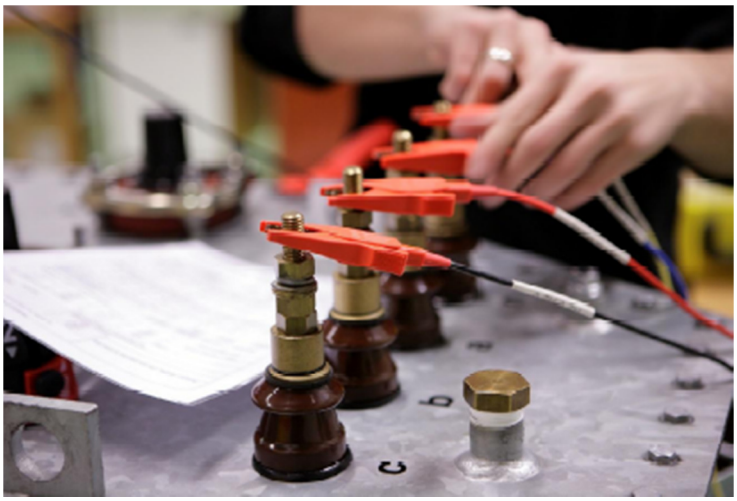


Figure 13: Intermediate in-line electrical test

Oil Filling: The active part (core and windings) assembled with the lid is dried for 12 hours before mounted into the transformer tank.



Figure 14: Tank assembly

The transformer oil is purified of air and moisture in a vacuum filter before being poured into the transformer tank. The transformer is filled with this oil under vacuum, illustrated in Figure 15 below.



Figure 15: Oil filling

3. APPENDIX B – HEXATRANSFORMER TESTING

A 100 kAV unit was purchased from Hexaformer AB in Sweden for testing purposes. The main aim was to evaluate the efficiency of the device.

The hexa-transformer was tested in collaboration with Powertech Distribution Transformers situated in Cape Town. Testing was done in accordance with the following standards:

- IEC 60076- Power Transformers
- IEC 60567 – Oil-filled electrical equipment
- IEC 60599 – Mineral oil – Guide to interpretation dissolved and free gas analysis
- SANS 780 – Distribution Transformers

The aim of the initial tests was to verify electrical efficiency and core integrity. The tests also covered the routine tests needed by Eskom distribution in order to install the transformer in the network for further monitoring.

3.1 TESTS CONDUCTED

The following tests were conducted during the initial testing phase.

Table 1: Transformer Tests

Routine	No-load Test
	Exciting current test
	Applied potential test
	Insulation resistance test

3.1.1 Insulation Resistance Test

The insulation resistance measurement is always done first to determine whether any serious errors were made during the installation and also to confirm whether the transformer is ready for further testing.

Winding insulation resistance is measured by a MW-meter and stopwatch. The winding that is being measured is connected between the first two points of the instrument. The third connecting point serves to connect the windings outside of the measuring circuit. Refer to Figure 16 below [2].

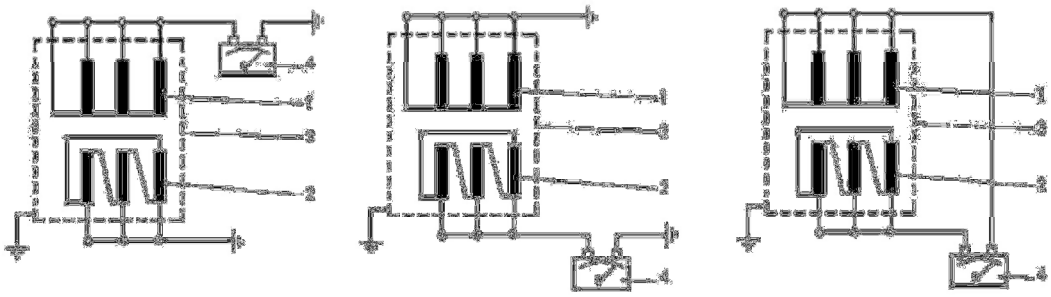


Figure 16: LV-winding-earth (left); LV-winding-earth (mid); HV-winding-LV-winding (right)

3.1.2 No-load test

The aim is to measure no-load loss at specified excitation voltage and specified frequency.

Under no-load conditions, a transformer will continue to drain sources of electrical energy. The chief source of this drain is core loss, which occurs in the magnetic core through a combination of hysteresis and eddy current loss, among others. Core-loss is calculated by applying the rated voltage and frequency to a transformer under no-load conditions. The resultant current is then measured, from which the loss of energy can be extrapolated.

3.1.3 Measurement of magnetising currents

The purpose of this test is to detect inter-winding faults that cannot be clearly recognized.

No-load currents should be measured separately for the HV and LV sides. The on-load or off-load charger must be set to the extreme position when the winding with the tapping range are measured. This is to ensure that the highest ratio is obtained. Refer to Figure 17 below [2]:

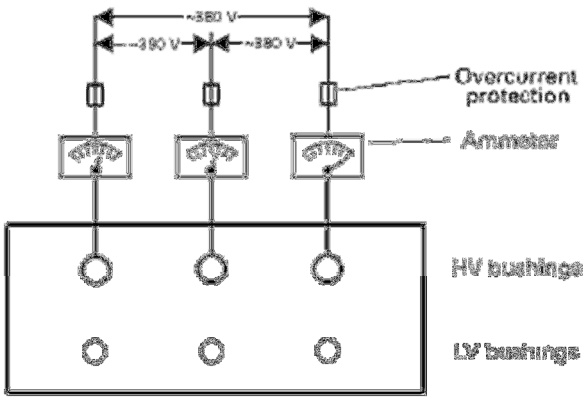


Figure 17: Test circuit for no-load current measurement of HV winding

3.1.4 Winding Resistance

The winding resistance measurement provides an indication whether the winding connections are in order.

The winding resistance is dependent on temperature. Measurement should therefore be done in conjunction with a reference temperature.

A battery or preferably a constant-current unit of 12 to 24 V (car battery) is required. The voltmeter should be connected at point 1, ammeter at point 2 as shown in Figure 30. Upper limit of DC measuring current: Up to 10 % of the rated winding current. Lower limit of DC measuring current: 1.2 times the peak value of the no-load current. After switching on the voltage source, wait until the measuring current reaches its stable value. Long waiting times may be expected for large low-voltage windings. Note that the voltmeter is not connected when the DC measuring current is switched on and off. The same applies to the diverter switch. The voltmeter and the ammeter must be read simultaneously. The ohmic resistance of each winding is measured between the corresponding bushing of each phase and all taps of the tapping range.

The quotient of the voltage drop at the winding and the DC measuring current flowing through it yields the ohmic winding resistance. The values measured must be compared with the test report of the works acceptance test (maximum deviations: ± 5 %) to enable faults to be clearly analysed. Refer to Figure 18 below [2].

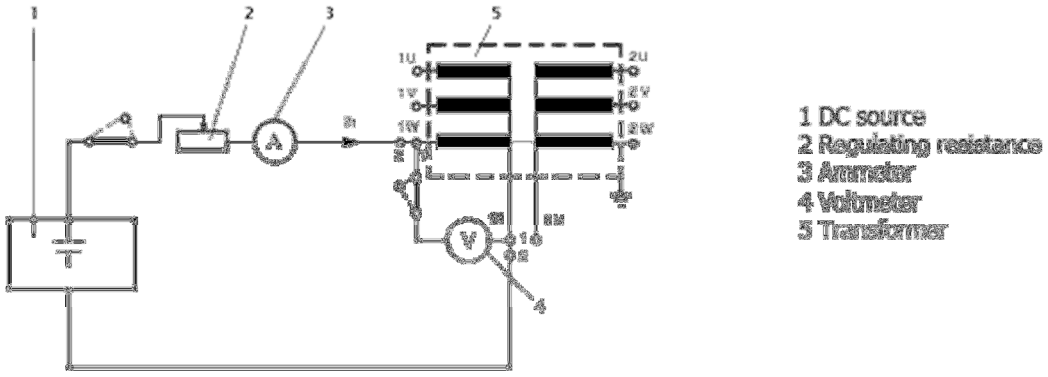


Figure 18: Single-line diagram for resistance measurement

3.1.5 Impedance Voltage, Short-Circuit Impedance and Load Loss

Measurements of impedance losses and impedance volts may be made simultaneously. Short-circuit one of the windings of the transformer. Apply voltage at rated frequency to the other winding and adjust it to achieve rated currents in the windings. With current and frequency adjusted to the rated values as nearly as possible, take simultaneous readings on the ammeter, voltmeter, wattmeter, and frequency meter. Proper corrections must be made for instrument transformers and the instruments.

The I^2R losses of the two windings are calculated from the ohmic resistance measurements (corrected to the temperature at which the impedance test was made) and the currents, which were used in the impedance measurements. Subtracting these I^2R losses from the impedance watts gives the stray losses of the transformer. Refer to Figure 19 below.

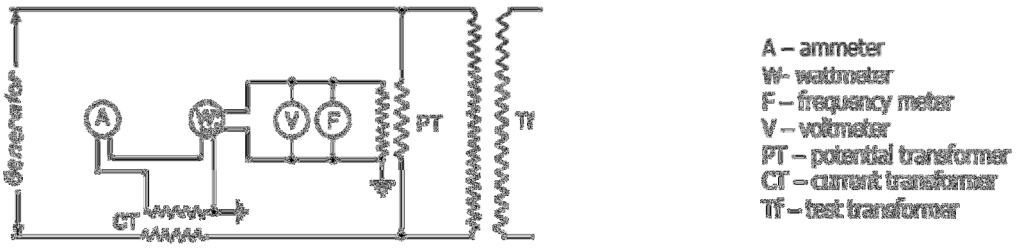


Figure 19: Load-loss and impedance-voltage testing connections

3.1.6 Applied potential tests

The applied potential test is used to see how well the transformer's insulation deals with voltages higher than the rated voltage, for given periods of time. The applied potential test checks the insulation between individual windings; and between windings and ground by applying voltages to each of these areas. This test is intended to test the turn-to-turn, layer-to-layer and line-to-line insulation. A 400 Hz source is used and applied for 7200 cycles.

3.2 TEST RESULTS

The hexa-transformer was tested in Powertech Distribution Transformers in Cape Town, South Africa. The testing equipment details are given in Table 2 below.

Table 2: Hexaformer test details

Date Used:	Operator Name:	Test Location:	Specifics:	Instrument Details:	Date of Calibration:	Serial No:
17.02.10	W. Brandt	Main test bay	Resistance Test	Tinsley 5896	03.06.09	0075665/6
17.02.10	W. Brandt	Main test bay	Iron and Copper Loss	Norma 04355	12.01.10	A46020306A
17.02.10	W. Brandt	Main test bay	Flash and Vector Test	Fluke 177	14.01.10	86100478

Details of these records and the transformer test certificates can be found in Section 3.8 of this report.

The results of the tests performed at Powertech Transformers on the hexa-transformer is summarised in Table 3 below.

Table 3: Eskom/Powertech test results

Test		Eskom/Powertech Results
Ratio Test	TAP 1	47.66
	TAP 2	46.52
	TAP 3	45.39
	TAP 4	44.25
	TAP 5	43.11
No-Load Loss (W)		178
Mag Current (%)		0.35% (0.478A)
Resistance Test (Ω)	AB	17.308
	BC	17.31
	CA	17.312
	ab	0.017967
	bc	0.017936
	ca	0.018016
Ambient Temperature (℃)		21
Ret Temperature (℃)		75
Load Loss (W)		1569
Reactance (%)		3.37
Impedance (%)		3.72
Test Amps (A)		5.25
Test Volts (V)		398.4
Test Wats (W)		1330
Applied Voltage test at 75%		Supply 21 kV for 60 sec. to HV with LV earthed. Supply 2.5 kV for 60 sec. to LV with HV earthed.

The induced voltage test on the LV side was performed at 840 V for 15 seconds. The applied voltage test was performed at 75%. The HV side was energised by 21 kV for one minute with a short circuit on the LV. Thereafter the LV was energised by 2.5 kV.

3.7 ANALYSIS

The above test results were compared to those of the manufacturer who is Hexaformer AB and also to those of the Chalmers University of Technology in Sweden. The Chalmers University of Technology conducted tests on a 100 kVA, 11/0.42kVA Hexa-transformer unit and an E-core transformer unit of the same rating. Their Results are summarised in Table 4 and Table 5 [3].

Table 4: No-load Test Results

Type	Voltage	Im (A)	No load Power (W)
E-core	420	0.46	191
Hex core	420	0.27	156
%difference	0	41	18

Table 5: Magneto-static calculations

Type	Voltage	P core loss (W)	L (H)	M (kg)
E-Core	403	85	1.6	182
Hex core	401	64	1.73	161
% difference	0.5	25	6	12

From Table 4 and Table 5 above it can be seen that the Hexaformer transformer yields improved transformer parameters. The Hexaformer was found to have 25% lower core loss, 40 % smaller magnetising currents and 12 % lower weight.

The test objective was to verify the hexa-transformer efficiency and manufacturing test results. A summary of both the manufacturing tests and the verification tests conducted at Powertech Transformers are presented in Table 9 below. The results were quite similar to that of the manufacturer. No-load losses of 178 W was measured, this verified the test results by Hexaformer in Sweden. However it was the measured magnetising current was 0.478 A, Hexaformer measured 0.28 A. Lower load losses were measured compared to that of the manufacturer. This could be due to a difference in temperature and the use of different equipment. Both test results however indicated that the hexa-transformer exhibits lower losses than an E-core transformer as illustrated in Table 6 below.

Table 6: Eskom/Powertech results comparison with Hexaformer AB

Test		Guaranteed Values	Tolerances (SANS 780)	Hexaformer Result	Eskom Power-tech
Ratio Test	TAP 1	47.63	±0.5%	47.66	47.66
	TAP 2	46.50	±0.5%	46.52	46.52
	TAP 3	45.36	±0.5%	45.39	45.39
	TAP 4	44.23	±0.5%	44.25	44.25
	TAP 5	43.09	±0.5%	43.11	43.11
No-Load Loss		170	15%	178	178
Mag Current			30%	0.2%(0.28A)	0.35%(0.478A
Resistance Test (Ω)	AB			17.34	17.31
	BC			17.34	17.31
	CA			17.35	17.33
	Ab			0.01793	0.01797
	Bc			0.1797	0.01794
	Ca			0.01791	0.1802
Ambient Temp (℃)				20.2(℃)	21(℃)
Retention Temp (℃)				75	75
Load Loss				1645(℃)	1569(℃)
Reactance				4.03	3.37
Impedance				4.35	3.72
Test Amps				5.25	5.25
Test Volts (V)				470	398.4
Test Wats				1416	1330

Table 6 summarises the test results of three 100 kVA 11/0.415 KV E-core transformers tested by Powertech Transformers on the same day as the hexa-transformer. The no-load losses were measured in the range of 325 – 345 W, the average being 337 W.

Table 7: E-core results

Test		Guaranteed	E-core	E-core	E-core
Ratio Test	TAP 1	48.66	48.66	47.66	47.66
	TAP 2	47.29	47.29	46.52	46.52
	TAP 3	45.91	45.91	45.39	45.39
	TAP 4	44.53	44.53	44.25	44.25
	TAP 5	43.16	43.16	43.11	43.11
No-Load Loss		300	345	325	341
Mag Current			2.9%	2.7%	2.8%
Resistance Test (Ω)	AB		18.94	19.08	19.13
	BC		18.91	19.21	19.01
	CA		18.99	19.15	19.08
	Ab		0.025890	0.025740	0.025750
	Bc		0.026120	0.026050	0.025840
	Ca		0.026010	0.025970	0.025780
Ambient			40	40	40
Retention Temperature			75	75	75
Load Loss		1700	1804	1812	1806
Reactance			4.30	4.26	4.25
Impedance			4.66	4.63	4.62
Test Amps			3.2	3.2	3.2
Test Volts (V)			316.5	310.9	303.6
Test Wats			634	624	609

3.8 TEST AND CALIBRATION CERTIFICATES

3.8.1 Hexaformer Test Certificate from Hexaformer AB

Hexaformer
Evolution in Energy Transformation

TESTREPORT

Acc. To SS EN 600 76-1

kVA	Volts	Amps	Connection group
100	11000 ± 2 x 2,5 %	5,25	Dyn 11
	420	137,5	

3-phase transformer , 50 Hz Type : 100 11 T1QM	No. : VSE 09 - 0209

INSULATION TEST :

Low voltage to high voltage, core and ground :	3 kV during 1 minute.
High voltage to low voltage, core and ground :	28 kV during 1 minute.
Induced overvoltage test :	2x Un 150Hz 40 seconds.

MEASUREMENT OF RATIO AND CONNECTION GROUP CONTROL :

Position	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5		
A-B : a-n	47,66	46,52	45,39	44,25	43,11	-	-
B-C : b-n	47,66	46,52	45,39	44,25	43,11	-	-
C-A : c-n	47,66	46,53	45,39	44,25	43,12	-	-

MEASUREMENT OF RESISTANCES AT : 20,2 °C , TAP 3

Position	Ω	Average	Position	mΩ	Average
A - B	17,34	17,34	a - b	17,93	17,94
A - C	17,34		a - c	17,97	
B - C	17,35		b - c	17,91	
			a - n	9,11	

MEASUREMENT OF NO-LOAD LOSSES :

Position	Un (V)	I 1 - I 2 - I 3 (A)			P 1 - P 2 - P 3 (W)			I 0 (A)	P 0 (W)
a - b - c	420	0,271	0,288	0,273	56,85	62,36	58,69	0,28	178

MEASUREMENT OF LOAD LOSSES AT : 20,2 °C , TAP 3

Position	U1 - U2 - U3 (V)			In (A)	P 1 - P 2 - P 3 (W)			Uk (V)	Pk (W)
A - B - C	469,0	470,1	470,9	5,25	475,0	480,5	460,3	470	1416

		MEASURED :	GUARANTEED :	DEVIATION :
No-load losses	(W)	178	170	4,6%
No-load current	(%)	0,20	-	
Load losses at 75°C	(W)	1645	1600	2,8%
Impedance voltage	(%)	4,35	4	8,9%
Total losses	(W)	1823	1770	3,0%

Västervik : 2009-11-11
This test is carried out by :
Benny Lärking
Accepted : DJowce

CUSTOMER / COMMENT :

This product is free from pcb (<1ppm) according to IEC 60296,DIN 51527-T1

3.8.2 Hexaformer Test Certificate from Powertech Transformers

DESTA POWER MATLA
ROUTINE TEST CERTIFICATE

DPM Desta Power Matla

CUSTOMER:	-			SER. No.:	VSE 09-0209
KVA:	100	VOLTAGE:	11000 / 420 V	Ph: 3 Ph	O/No.: -
VECTOR:	Dyn11	CURRENT:	5.25 / 137.46 A	Hz: 50 Hz	REPORT No.: -
TAPS:	± 2.5, ± 5.0	COOLING:	ONAN		TEST DATE: 17-Feb-10

TESTS		GUARANTEED VALUES	TOLERANCES (SANS 780)	TRANSFORMER SERIAL NUMBERS (MEASURED VALUES) 1			
RATIO TEST	TAP 1	47.6314	±0.5%	47.6500			
	TAP 2	46.4973	±0.5%	46.5200			
	TAP 3	45.3632	±0.5%	45.3800			
	TAP 4	44.2292	±0.5%	44.2500			
	TAP 5	43.0951	±0.5%	43.1100			
	TAP 6						
	TAP 7						
NO LOAD LOSS (W)		170	+ 15%	176			
MAG. CURRENT (%)		-	+30%	0.35%			
RESISTANCE TEST (ohms)	AB	-	-	17.3080			
	BC	-	-	17.3100			
	CA	-	-	17.3120			
	ab	-	-	0.017967			
	bc	-	-	0.017936			
	ca	-	-	0.018016			
AMB.TEMP. (°C)			-	21			
REF. TEMP. (°C)		75	-	75			
LOAD LOSS (W)		1600	+ 15%	1589			
REACTANCE (%)		0	-	3.37			
IMPEDANCE (%)			± 10%	3.72			
TEST AMPS (A)		-	-	5.25			
TEST VOLTS (V)		-	-	398.4			
TEST WATTS (W)		-	-	1330			

APPLIED VOLTAGE TESTS	Supply 28kV for 60 sec. to HV with LV earthed. Supply 2.5kV for 60 sec. to LV with HV earthed.				
INDUCED VOLTAGE TESTS	100% increased voltage for 15 sec. @ 400 Hz.				
INSULATING MEDIUM	Oil tested to SABS 555 (flash tested at a minimum of 70kV).				
VECTOR TEST	Done in conjunction with ratio test.				
MEASUREMENT OF PAINT THICKNESS	Comply with:	SANS 780	X	SCSSCAAPS	X
TEST FOR EFFECTIVENESS OF SEALING	Comply with:	SANS 780	X		
TEST FOR PHASE DISPLACEMENT	Comply with:	SANS 780	X		
NOTES					

FORM No. 2.8.1.057 REV 1

TESTED BY:	Neville Bennit	WITNESSED BY:		DATE:	17-Feb-10

3.8.2 E-core Transformer Test Certificates

CAPE TOWN
ROUTINE TEST CERTIFICATE

DPM Deals Power Matla

CUSTOMER.			SER. NO 10693702/01/10693702/03
kVA. 100	VOLTAGE 11000/415	PH. 3	O/NO
VECTOR Dyn11	CURRENT. 5.2/ 139.1	C/S. 50	COOLING ONAN
TAPS. +-3% TO +-6% IN 3% STEPS			TEST DATE 17/02/10

TESTS		GUARANTEE VALUES	TRANSFORMER SERIAL NUMBERS				
			10693702/01	10693702/02	10693702/05		
RATIO TEST +- 0,5% ON RATIOS HV Ph-Ph / LV Ph-n	TAP 1	48.66	48.66	48.66	48.66		
	TAP2	47.29	47.29	47.29	47.29		
	TAP3	45.91	45.91	45.91	45.91		
	TAP4	44.53	44.53	44.53	44.53		
	TAP5	43.16	43.16	43.16	43.16		
	TAP6						
	TAP7						
NO LOAD LOSS (W)		300	345 @415.0 v	325 @415.0 v	341 @415.0 v		
MAG. CURRENT (%)			2.90	2.70	2.80		
RESISTANCE TEST (ohms)	AB		18.94000	19.08900	19.13000		
	BC		18.91000	19.21000	19.01000		
	CA		18.99000	19.15000	19.08000		
	ab		0.025890	0.025740	0.025750		
	bc		0.026120	0.026050	0.025840		
	ca		0.026010	0.025970	0.025780		
AMB. TEMP. (°C)			40.0	40.0	40.0		
REF. TEMP 75. (°c) LOAD LOSS (W)		1700	1804	1812	1806		
REACTANCE (%)			4.30	4.26	4.25		
IMPEDANCE (%)		3.0-4.5	4.66	4.63	4.62		
TEST AMPS (A)			3.2	3.2	3.2		
TEST VOLTS (V)			316.5	310.9	306.6		
TEST WATTS (W)			634.0	624.0	609.0		

APPLIED VOLTAGE TESTS:	H.V. to L.V. earthed at 28.0 kV for 60 sec.
INDUCED VOLTAGE TESTS.	L.V. to H.V. earthed at 2.5KV for 60 sec
INSULATING MEDIUM:	100% increased voltage for 60 sec. @ 100 C/S
VECTOR TEST.	Oil tested to SABS 555 (flash tested at a minimum of 55 kV)
NOTES.	Done in conjuction with ratio test

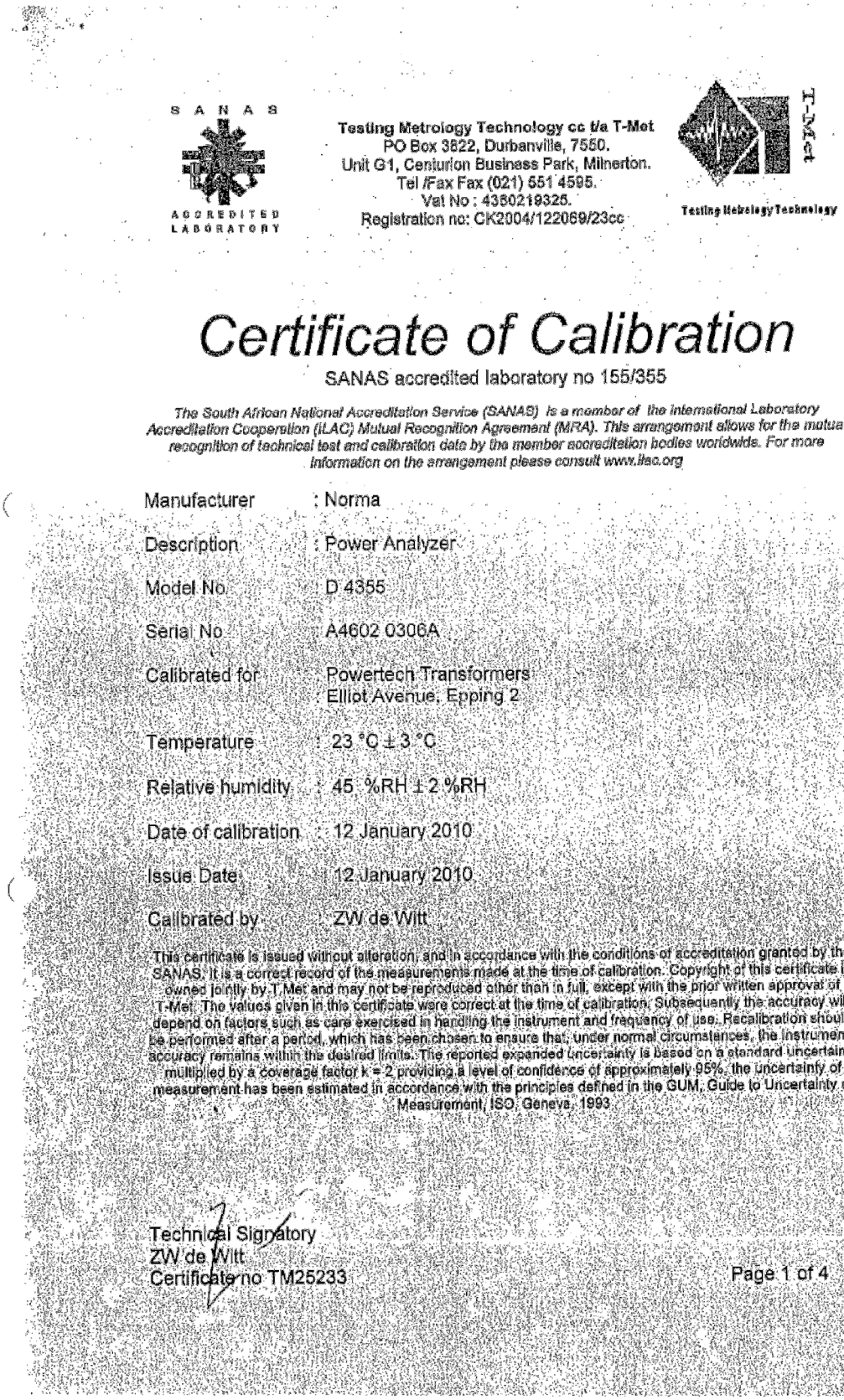
ISO 9002

WITNESSED BY: | TESTED BY: | DATE:

FORM No 2.5 : 05 REV

3.8.3 Equipment Calibration Certificate by Powertech Transformers

3.8.3.1 Norma Power Analyser



SANAS ACCREDITED LABORATORY

Testing Metrology Technology cc t/a T-Met
PO Box 3822, Durbanville, 7550.
Unit G1, Centurion Business Park, Milnerton.
Tel /Fax Fax (021) 551 4595.
Vat No : 4350219325.
Registration no: CK2004/122069/23cc

T-Met
Testing Metrology Technology

Certificate of Calibration

SANAS accredited laboratory no 155/355

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Manufacturer	: Norma
Description	: Power Analyzer
Model No	: D 4355
Serial No	: A4602 0306A
Calibrated for	: Powertech Transformers Elliot Avenue, Epping 2
Temperature	: 23 °C ± 3 °C
Relative humidity	: 45 %RH ± 2 %RH
Date of calibration	: 12 January 2010
Issue Date	: 12 January 2010
Calibrated by	: ZW de Witt

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Technical Signatory
ZW de Witt
Certificate no TM25233

Page 1 of 4

Certificate of Calibration

1. Standards and equipment

Ref No	Make	Model	Description	Serial Number
50	Fluke	5500A	Calibrator	7270009
106	Fluke	5220A	Amplifier	5150020
37	Sangomo Weston	S67.1.541	Wattmeter	AP91742
35	Hart Scientific	1620 (2626-H)	Thermo hygrometer	A53650
268	Array	M3500A	Multimeter Logger	TW00001075

2. Procedure

2.1 The UUT (Unit under test) was calibrated in terms of the manufacturers' accuracy specification, referenced to the manufacturers recommended procedure.

2.2.1 The functions and ranges were calibrated by generating known signal levels from the calibrators using a direct measurement method

3. Results

3.1.1 Input Current (50 Hz)
Voltage @ 230 V / Power Factor @ 1.000)

UUT Range	Applied Input	Lower Limit	L1 Reading	L2 Reading	L3 Reading	Upper Limit	Measurement Uncertainty
5 A	0.1000 A	99.9 mA	100.06 mA	100.03 mA	100.05 mA	100.1 mA	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	0.5000 A	499.0 mA	499.47 mA	499.44 mA	499.56 mA	500.1 mA	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	1.0000 A	990 mA	998.69 mA	999.26 mA	998.15 mA	1009 mA	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	2.0000 A	1.960 A	1.9970 A	1.9989 A	1.9979 A	2.040 A	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	3.0000 A	2.940 A	2.9978 A	2.9986 A	2.9979 A	3.060 A	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	4.0000 A	3.920 A	3.9969 A	3.9987 A	3.9968 A	4.080 A	$\pm 5 \cdot 10^{-3} \cdot I$
5 A	4.5000 A	4.410 A	4.4956 A	4.4984 A	4.4959 A	4.590 A	$\pm 5 \cdot 10^{-3} \cdot I$
30 A	0.1000 A	99.9 mA	100.03 mA	100.08 mA	100.08 mA	100.1 mA	$\pm 5 \cdot 10^{-3} \cdot I$
30 A	0.5000 A	499.0 mA	499.42 mA	499.45 mA	499.56 mA	500.1 mA	$\pm 5 \cdot 10^{-3} \cdot I$
30 A	1.0000 A	0.990 A	0.998 mA	0.9994 mA	0.9989 mA	1.009 A	$\pm 5 \cdot 10^{-3} \cdot I$
30 A	2.0000 A	1.960 A	1.9970 A	1.9983 A	1.9971 A	2.040 A	$\pm 5 \cdot 10^{-3} \cdot I$

Certificate of Calibration

3.2 Input Voltage (50 Hz) -Current @ 1.000 A / Power Factor @ 1.000

UUT Range	Applied Input	Lower Limit	L1 Reading	L2 Reading	L3 Reading	Upper Limit	Measurement Uncertainty
400 V	100.0 V	99.0 V	100.06 V	100.09 V	100.06 V	101.0 V	$\pm 5 \cdot 10^{-3} \cdot U$
400 V	110.0 V	108.9 V	110.07 V	110.09 V	110.06 V	111.1 V	$\pm 5 \cdot 10^{-3} \cdot U$
400 V	120.0 V	118.8 V	120.02 V	120.09 V	120.08 V	121.2 V	$\pm 5 \cdot 10^{-3} \cdot U$
400 V	200.0 V	198.0 V	200.04 V	200.06 V	200.08 V	202.0 V	$\pm 5 \cdot 10^{-3} \cdot U$
400 V	220.0 V	217.8 V	220.06 V	220.09 V	220.10 V	222.2 V	$\pm 5 \cdot 10^{-3} \cdot U$
400 V	240.0 V	237.6 V	240.03 V	240.12 V	240.10 V	242.4 V	$\pm 5 \cdot 10^{-3} \cdot U$

3.3 Power (kW)

UUT Range	Applied Input	Lower Limit	L1 Reading	L2 Reading	L3 Reading	Upper Limit	Measurement Uncertainty*
110.00 V 0.100 A PF @ 1.0	11.0 W	10.67 W	11.002 W	11.006 W	11.003 W	11.33 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 0.100 A PF @ 0.5	5.50 W	5.34 W	5.508 W	5.505 W	5.508 W	5.67 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 0.500 A PF @ 1.0	55.0 W	53.9 W	54.10 W	54.01 W	54.10 W	56.1 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 0.500 A PF @ 0.5	27.5 W	26.59 W	27.510 W	27.501 W	27.510 W	28.05 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 1.000 A PF @ 1.0	110 W	107.8 W	109.86 W	110.02 W	109.89 W	112 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 1.000 A PF @ 0.5	55.0 W	53.9 W	55.010 W	55.014 W	55.014 W	56.0 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 4.500 A PF @ 1.0	495 W	485 W	494.83 W	495.62 W	495.65 W	505 W	$\pm 5 \cdot 10^{-3}$ W
110.00 V 4.500 A PF @ 0.5	247.5 W	242 W	247.86 W	248.08 W	248.83 W	252 W	$\pm 5 \cdot 10^{-3}$ W
220.00 V 1.000 A PF @ 1.0	220 W	216 W	219.86 W	220.09 W	219.70 W	224 W	$\pm 5 \cdot 10^{-3}$ W
220.00 V 1.000 A PF @ 0.5	110 W	108 W	110.03 W	110.08 W	110.03 W	112 W	$\pm 5 \cdot 10^{-3}$ W
220.00 V 4.500 A PF @ 1.0	990 W	970 W	989.01 W	990.04 W	989.02 W	1009 W	$\pm 5 \cdot 10^{-3}$ W
220.00 V 4.500 A PF @ 0.5	495 W	485 W	495.44 W	495.86 W	495.44 W	505 W	$\pm 5 \cdot 10^{-3}$ W

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ZW de Witt
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3.4 Power Factor

UUT Range	Applied Input	Lower Limit	L1 Reading	L2 Reading	L3 Reading	Upper Limit	Measurement Uncertainty*
-1.0 to 1.0	-0.200	-0.198	-0.19994	-0.19994	-0.19996	-0.202	± 1 LSD
-1.0 to 1.0	-0.400	-0.396	-0.39994	-0.39993	-0.39994	-0.404	± 1 LSD
-1.0 to 1.0	-0.600	-0.594	-0.59967	-0.59965	-0.59967	-0.606	± 1 LSD
-1.0 to 1.0	-0.800	-0.792	-0.79974	-0.79976	-0.79974	-0.808	± 1 LSD
-1.0 to 1.0	-1.000	-0.990	0.99998	0.99998	0.99998	-1.010	± 1 LSD
-1.0 to 1.0	0.200	0.198	0.20087	0.20084	0.20080	0.202	± 1 LSD
-1.0 to 1.0	0.400	0.396	0.40076	0.40070	0.40076	0.404	± 1 LSD
-1.0 to 1.0	0.600	0.594	0.60082	0.60063	0.60003	0.606	± 1 LSD

3.5 Power (kVA) with PF @1

UUT Range	Applied Input	Lower Limit	L1 Reading	L2 Reading	L3 Reading	Upper Limit	Measurement Uncertainty*
110.00 V 1.000 A PF @ 1.0	110.0 W	108.9 W	109.90 W	110.06 W	109.89 W	111.1 W	$\pm 1 \cdot 10^{-3} \cdot U$
110.00 V 4.500 A PF @ 1.0	495.0 W	490.1 W	495.03 W	495.97 W	495.64 W	499.9 W	$\pm 1 \cdot 10^{-3} \cdot U$
220.00 V 1.000 A PF @ 1.0	220.0 W	217.8 W	219.79 W	220.10 W	219.80 W	222.2 W	$\pm 1 \cdot 10^{-3} \cdot U$
220.00 V 4.500 A PF @ 1.0	990.0 W	980.1 W	989.40 W	990.50 W	999.80 W	999.9 W	$\pm 1 \cdot 10^{-3} \cdot U$

4. Comments

4.1 The calibration was performed on-site.
4.2 Bold - highlights indicate out of tolerance values.

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3.8.3.2 Fluke Tester

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ACCREDITED LABORATORY

Testing Metrology Technology cc t/a T-Met
PO Box 3822, Durbanville, 7550.
Unit G1, Centurion Business Park, Milnerton.
Tel /Fax Fax (021) 551 4595.
Vat No : 4360219325.
Registration no: CK2004/122069/23cc

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Testing Metrology Technology

Certificate of Calibration

SANAS accredited laboratory no 155/355

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Manufacturer	: FLUKE
Description	: True RMS Multimeter
Model No	: 177
Serial No	: 86100478
Asset No	: Unknown
Plant No	: Unknown
Calibrated for	: Powertech Transformers : Elliot Avenue, Epping 2
Temperature	: 23 °C ± 3 °C
Relative humidity	: 48 % RH ± 5 %RH
Date of calibration	: 14 January 2010
Issue Date	: 14 January 2010
Calibrated by	: ZW de Witt

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Technical Signatory
ZW de Witt
Certificate no TM25311

Certificate of Calibration

1. Standards and equipment

Ref	Make	Model	Description	Serial no
50	Fluke	5500A	Calibrator	7270009
268	Array	M3500A	Multimeter Logger	TW00001075
328	Leeds and Northrup	4045-B Series	Standard Resistors	EQ328
8	Fluke	80K-40	HV Probe	6524073
53	TMet	W Mare	Precision Res Box	9601

2. Procedure

2.1 UUT (Unit under Test) was calibrated in terms of the manufacturer's typical calibration procedure.

2.2 The functions and ranges were calibrated by generating known signal levels from the calibrators and using the unit to measure known components and or conditions.

2.1.1 Calibration Procedure Number TM P1 001 was used

3. Results

3.1 DC Voltage

3.1.1 Pre/Post Adjustment

Step	Range	Applied Input	Tolerance	Displayed Reading	Measurement Uncertainty
Pre cal	6.0 V	5.000 V	4.9935 V to 5.0065 V	4.999 V	± 1 LSD
Post cal	6.0 V	5.000 V	4.9935 V to 5.0065 V	4.999 V	± 1 LSD

3.2 DC Volts

UUT Range	Applied Input	Lower Limit	Displayed Reading	Upper limit	Measurement Uncertainty
600 mV	30.00 mV	29.8 mV	30.0 mV	30.1 mV	± 2 LSD
600 mV	600.0 mV	599.3 mV	599.6 mV	600.6 mV	± 1 LSD
600 mV	-300.0 mV	-299.5 mV	-299.9 mV	-300.4 mV	± 1 LSD
6 V	5.0000 V	4.993 V	4.999 V	5.007 V	± 1 LSD
60 V	30.000 V	29.95 V	30.00 V	30.04 V	± 1 LSD
60 V	-30.000 V	-29.95 V	-29.99 V	-30.05 V	± 1 LSD
600 V	300.000 V	299.6 V	299.9 V	300.3 V	± 1 LSD
1000 V	1000.0 V	997 V	999 V	1003 V	± 2 LSD
1000 V	-1000.0 V	-997 V	-999 V	-1003 V	± 2 LSD

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3.3 AC Volts

UUT Range	Applied Input	Lower Limit	Displayed Reading	Upper limit	Measurement Uncertainty
600 mV	300.00 mV @ 45 Hz	296.7 mV	297.1 mV	303.3 mV	± 2 LSD
600 mV	300.00 mV@ 1 kHz	293.7 mV	296.5 mV	306.3 mV	± 10 LSD
6 V	5.000 V@ 500 Hz	4.947 V	4.991 V	5.053 V	± 10 LSD
6 V	5.000 V @ 1 kHz	4.897 V	4.951 V	5.103 V	± 10 LSD
60 V	50.00 V @ 45 Hz	49.47 V	49.92 V	50.53 V	± 1 LSD
60 V	50.00 V @ 1 kHz	48.97 V	50.05 V	51.03 V	± 2 LSD
600 V	100.00 V @ 1 kHz	97.7 V	100.3 V	102.3 V	± 1 LSD
600 V	300.00 V @ 1 kHz	296.7 V	300.1 V	303.3 V	± 1 LSD
600 V	600.00 V @ 50 Hz	587.7 V	599.2 V	612.3 V	± 1 LSD
1000 V	1000.0 V @ 50 Hz	987 V	997 V	1013 V	± 2 LSD

3.4 DC Ampere

UUT Range	Applied Input	Lower Limit	Displayed Reading	Upper limit	Measurement Uncertainty
60 mA	3.000 mA	2.94 mA	3.00 mA	3.06 mA	± 1 LSD
60 mA	50.000 mA	49.47 mA	49.99 mA	50.53 mA	± 1 LSD
600 mA	-400.00 mA	-395.7 mA	-399.9 mA	-404.30 mA	± 1 LSD
10 A	-1.0000 A	-0.987 A	-1.000 A	1.013 A	± 1 LSD

3.5. AC Ampere

UUT Range	Applied Input	Lower Limit	Displayed Reading	Upper limit	Measurement Uncertainty
60 mA	3.000 mA @ 45 Hz	2.93 mA	3.00 mA	3.08 mA	± 10 LSD
60 mA	50.00 mA @ 1 kHz	49.22 mA	49.99 mA	50.78 mA	± 5 LSD
600 mA	400.0 mA @ 45 Hz	393.7 mA	399.9 mA	406.3 mA	± 5 LSD
600 mA	400.0 mA @ 1 kHz	393.7 mA	399.6 mA	406.3 mA	± 5 LSD
6 A	2.000 A @ 45 Hz	1.987 A	2.001 A	2.033 A	± 5 LSD
10 A	2.000 A @ 1 kHz	1.94 A	2.00 A	2.06 A	± 1 LSD

3.6. Frequency

UUT Range	Applied Input	Lower limit	Displayed Reading	Upper limit	Measurement Uncertainty
99.99 Hz	10.000 Hz	9.98 Hz	9.99 Hz	10.02 Hz	± 1 LSD
999.9 Hz	100.00 Hz	100.0 Hz	99.98 Hz	100.0 Hz	± 1 LSD
9.999 kHz	1.000 kHz	9995 Hz	999.7 Hz	1000.5 Hz	± 1 LSD
99.99 kHz	20.00 kHz	19.98 kHz	20.00 kHz	20.02 kHz	± 1 LSD
99.99 kHz	50.00 kHz	49.95 kHz	49.98 kHz	50.05 kHz	± 1 LSD

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3.7. Resistance

UUT Range	Applied Input	Lower limit	Displayed Reading	Upper limit	Measurement Uncertainty
600 Ω	190.0 Ω	188.1 Ω	190.1 Ω	191.8 Ω	± 1 LSD
6k Ω	1.900 k Ω	1.882 k Ω	1.900 kΩ	1918 kΩ	± 1 LSD
60 kΩ	19.00 kΩ	18.82 kΩ	19.00 kΩ	19.18 kΩ	± 1 LSD
600 kΩ	190.0 kΩ	188.2 kΩ	189.9 kΩ	191.8 kΩ	± 1 LSD
6 MΩ	1.900 MΩ	1.882 MΩ	1.900 MΩ	1.918 MΩ	± 1 LSD
50 MΩ	19.00 MΩ	18.69 MΩ	18.98 MΩ	19.31 MΩ	± 1 LSD

3.8 Capacitance

UUT Range	Applied Input	Lower limit	Displayed Reading	Upper limit	Measurement Uncertainty
1000.00 nF	200.00 nF	195.6 nF	200 nF	204.4 nF	± 10 LSD
1000.00 nF	500.00 nF	492 nF	501 nF	508 nF	± 10 LSD
10.00 µF	0.500 µF	0.474 µF	0.51 µF	0.706 µF	± 10 LSD

3.9 Continuity

UUT Range	Applied Input	Lower limit	Pass / Fail	Upper limit	Measurement Uncertainty
600 Ω	25 Ω	25 Ω Beeper on	Pass	0.0 Ω Beeper on	± 1%
600 Ω	250 Ω	26 Ω Beeper off	Pass	28 Ω Beeper off	± 1%

3.10 Function Ohms

UUT Range	Nominal Output	Pass / Fail	Measured output	Measurement Uncertainty
50 MΩ	Open Circuit test voltage 1.5 V	Pass	1.24 V	± 1%
100 Ω	Short Circuit current 500 µA	Pass	304 µA	± 1%

4. Comments

4.1 Bold - highlights indicate out of tolerance values

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3.8.3.3 Transformer micro-ohmeter

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TRAC Laboratories

TECHNOLOGY RESEARCH AND CALIBRATION LABORATORIES

SOUTH AFRICAN NATIONAL ACCREDITATION SERVICE LABORATORY No: 101

CERTIFICATE OF CALIBRATION

Certificate number	17537
Date of Calibration	03/06/2009
Date of Issue	03/06/2009
Authorised Signatory	A.E.Loxton

The uncertainties of measurement are based on a standard uncertainty multiplied by a coverage factor of k = 2 which, unless stated otherwise, provides a level of confidence of approximately 95%.

The accuracy of all measurements is traceable to the National Measuring Standards.

The values in this certificate are correct at the time of calibration. Subsequently the accuracy will depend on such factors as the care executed in handling and use of the device, and the frequency of use. Re-calibration should be performed after the period so chosen to ensure that the instrument's accuracy remains within the desired limits.

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TECHNOLOGY RESEARCH AND CALIBRATION LABORATORIES
65 Second Avenue
Alberton North
Tel. (011) 869-4831

CERTIFICATE OF CALIBRATION

Certificate Number	:	**17537**
Calibration of a	:	**Transformer Micro-ohmeter**
Manufacturer & Type	:	**Tinsley 5896B (25A)**
Serial Number	:	**007565/6**
Calibrated for	:	**Desta Power Matla PTY Ltd**
Customer Address	:	**Elliot Avenue, Eping Industrial 2, Cape town**
Procedure Number	:	**014**
Date of Calibration	:	**03/06/2009**
Date of Issue	:	**03/06/2009**
Laboratory Environment	:	**23 ± 2°C, 35 to 60%rh**
Reference Standards	:	Tettex 0,0001Ω Serial No.122670 Yew 0,001Ω Serial No.00201 Yew 0,01Ω Serial No.00271 Yew 0,1Ω Serial No.00325 Yew 1,0Ω Serial No.00854 Yew 10,0Ω Serial No.N71H94 Yew 100,0Ω Serial No.00448 Datron 1071 Digital Multimeter S/No. 16643

Recommended re-calibration date: **June 2010**

Calibration was made against the stated reference equipment with the following results.

RESISTANCE [CHANNEL 1 @ Low Current Setting]

RANGE	APPLIED (Ω)	DISPLAY (Ω)	% ERROR
1mΩ (10A)	1,00008mΩ	0,9991mΩ	-0,10
	0,100000mΩ	0,1003mΩ	+0,30
10mΩ (10A)	10,0002mΩ	10,000mΩ	0,00
	1,0001mΩ	1,002mΩ	+0,19
100mΩ (5A)	99,982mΩ	99,95mΩ	-0,03
	10,000mΩ	10,01mΩ	+0,10
1Ω (1A)	1,00000	0,9998	-0,02
	0,10000	0,1001	+0,10
10Ω (250mA)	9,9999	9,998	-0,02
	1,0000	1,001	+0,10
100Ω (100mA)	100,006	99,99	-0,02
	10,000	10,01	+0,10

Uncertainty of measurement is ± 0,05% of range & 1 least significant digit.

Calibrated by : J.R Taylor

A.E.Loxton
Authorised Signatory

SANAS ACCREDITED LABORATORY

TECHNOLOGY RESEARCH AND CALIBRATION LABORATORIES

65 Second Avenue
Alberton North

Tel. (011) 869-4831

CERTIFICATE OF CALIBRATION

Certificate Number : **17537**
Manufacturer & Type : **Tinsley 5896 Micro-ohmeter**
Serial Number : **007565/6**

RESISTANCE [CHANNEL 2 @ Low Current Setting]

RANGE	APPLIED (Ω)	DISPLAY (Ω)	% ERROR
1mΩ (10A)	1,00008mΩ	0,9997mΩ	-0,04
	0,100000mΩ	0,0999mΩ	-0,10
10mΩ (10A)	10,0002mΩ	10,001mΩ	+0,01
	1,0001mΩ	1,002mΩ	+0,19
100mΩ (5A)	99,982mΩ	99,96mΩ	-0,02
	10,000mΩ	10,01mΩ	+0,10
1Ω (1A)	1,00000	0,9998	-0,02
	0,10000	0,1000	0,00
10Ω (250mA)	9,9999	9,998	-0,02
	1,0000	1,001	+0,10
100Ω (100mA)	100,006	99,99	-0,02
	10,000	10,01	+0,10

Uncertainty of measurement is ± 0,05% of range & 1 least significant digit.

RESISTANCE [CHANNEL 1 @ High Current Setting]

RANGE	APPLIED (Ω)	DISPLAY (Ω)	% ERROR
1mΩ (25A)	1,00008mΩ	0,9993mΩ	-0,08
	0,10000mΩ	0,1000mΩ	0,00
10mΩ (25A)	9,2520mΩ	9,252mΩ	0,00
	1,0001mΩ	1,002mΩ	+0,20
100mΩ (10A)	99,982mΩ	99,92mΩ	-0,06
	10,000mΩ	10,01mΩ	+0,10
1Ω (5A)	0,98930	0,9888	-0,05
	0,09998	0,1001	+0,12
10Ω (1A)	9,8765	9,874	-0,03
	1,0000	1,001	+0,10
100Ω (250mA)	99,915	99,90	-0,02
	10,000	10,02	+0,20

Uncertainty of measurement is ± 0,05% of range & 1 least significant digit.

Calibrated by : J.R Taylor

A.E.Loxton
Authorised Signatory

SANAS
ACCREDITED
LABORATORY

TECHNOLOGY RESEARCH AND CALIBRATION LABORATORIES
65 Second Avenue
Alberton North
Tel. (011) 869-4831

TRAC Laboratories

CERTIFICATE OF CALIBRATION

Certificate Number : **17537**
Manufacturer & Type : **Tinsley 5896 Micro-ohmeter**
Serial Number : **007565/6**

RESISTANCE [CHANNEL 2 @ High Current Setting]

RANGE	APPLIED (Ω)	DISPLAY (Ω)	% ERROR
1mΩ (25A)	1,00008mΩ	1,0004mΩ	+0,03
	0,10000mΩ	0,1001mΩ	+0,10
10mΩ (25A)	9,2520mΩ	9,247mΩ	-0,05
	1,0000mΩ	1,000mΩ	0,00
100mΩ (10A)	99,982mΩ	99,93mΩ	-0,05
	10,000mΩ	10,01mΩ	+0,10
1Ω (5A)	0,98930	0,9890	-0,03
	0,09998	0,1000	+0,02
10Ω (1A)	9,8765	9,875	-0,02
	1,0000	1,001	+0,10
100Ω (250mA)	99,915	99,90	-0,02
	10,000	10,01	+0,10

Uncertainty of measurement is ± 0,05% of range & 1 least significant digit.

Calibrated by : J.R Taylor

A.E.Loxton
Authorised Signatory

4. APPENDIX C – TRANSFORMER CORE AND OIL ANALYSIS

Tests were conducted on various points on the B-H curve in order to determine the integrity of the hexa-transformer core.

4.1 B-H CURVE TESTS

4.1.1 Tests conducted at Powertech Transformers in Cape town

The B-H curve tests were conducted at Powertech Distribution Transformers in Cape Town, South Africa. The test Results are illustrated on Table 8 below.

Table 8: Hexa-transformer B-H curve test results

AMPS				**WATTS**								
A PHASE	B PHASE	C PHASE	AVE.	A PHASE	B PHASE	C PHASE	SUM		Amps	Volts	Watts	
0.422	0.311	0.521	0.418	0.756	0.844	0.848	2.44	10%	0.418	42	2.44	10%
0.428	0.32	0.526	0.424	6.41	6.36	6.09	18.8	30%	0.424	126	18.8	30%
0.444	0.331	0.54	0.438	15.46	14.64	14.44	44.5	50%	0.438	210	44.5	50%
0.459	0.351	0.556	0.455	29.92	25.9	26.41	82.2	70%	0.455	294	82.2	70%
0.49	0.371	0.572	0.477	50.7	40.6	43.3	134	90%	0.477	378	134	90%
0.51	0.381	0.576	0.489	64.2	51	55.1	170	100%	0.489	420	170	100%
0.545	0.405	0.612	0.52	88.3	66.9	77.4	232	110%	0.52	462	232	110%
0.584	0.453	0.642	0.559	102.2	78.5	90.8	271	115%	0.559	483	271	115%
0.73	0.666	0.812	0.735	122.9	97.8	115.4	336	120%	0.735	504	336	120%
1.179	1.236	1.373	1.26	142.4	112.2	148.5	403	125%	1.26	525	403	125%

From Table 8 the voltage/watt curve has been plotted. Refer to Figure 20 below.

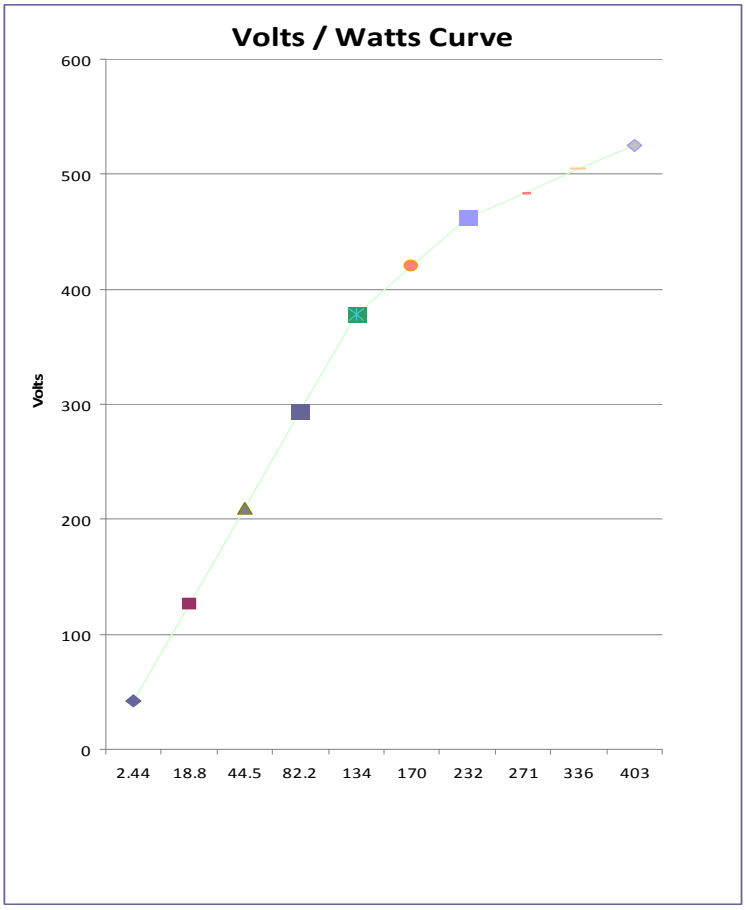

Figure 20: Eskom/Powertech Voltage/watt curve

The magnetization curve is illustrated in Figure 21 below.

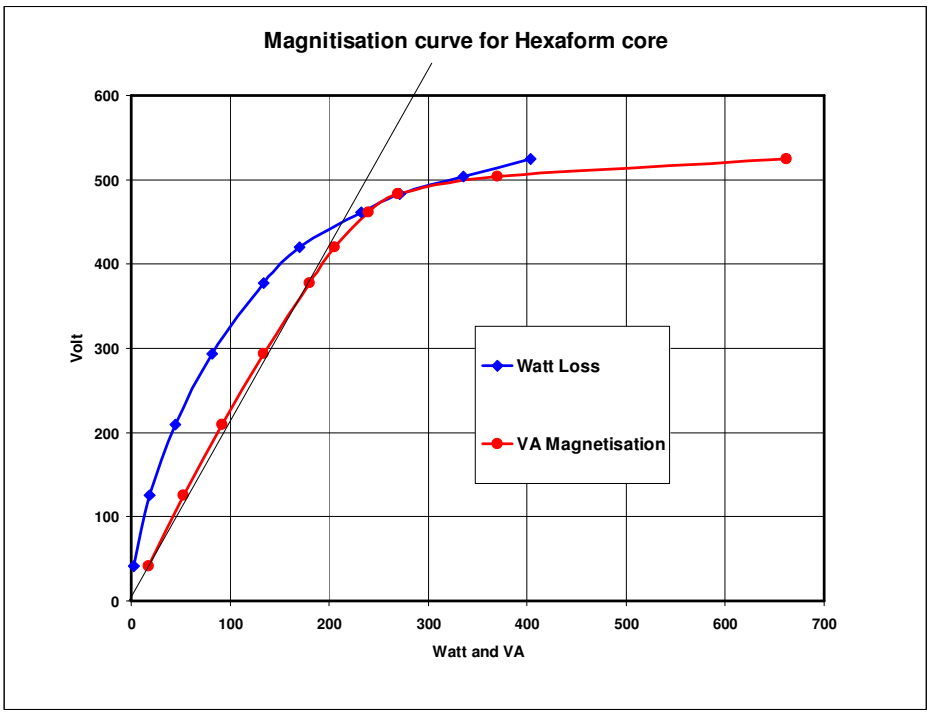

Figure 21: Eskom/Powertech magnetization curve

4.1.2 Tests conducted by Hexaformer AB in Sweden

Tests on the B-H curve were also conducted by Hexaformer AB in Sweden. The results are summarized in the Table 9 below [4].

Table 9: B-H Curve test results (Hexaformer AB)

	AMPS				WATTS								
VOLTS	A PHASE	B PHASE	C PHASE	AVE.	A PHASE	B PHASE	C PHASE	SUM		Amps	Volts	Watts	
42	0.039	0.038	0.037	0.038	0.89	0.85	0.85	2.6	10%	0.038	42	2.6	10%
126	0.091	0.087	0.089	0.089	6.42	6.19	6.33	18.9	30%	0.089	126	18.9	30%
210	0.143	0.139	0.142	0.141	16.07	15.52	15.93	47.5	50%	0.141	210	47.5	50%
294	0.199	0.195	0.199	0.198	29.78	28.87	29.70	88.4	70%	0.198	294	88.4	70%
378	0.251	0.248	0.255	0.251	48.34	46.88	48.61	143.8	90%	0.251	378	143.8	90%
420	0.275	0.272	0.280	0.276	60.26	58.61	61.15	180.0	100%	0.276	420	180.0	100%
462	0.307	0.303	0.313	0.308	75.78	74.13	77.78	227.7	110%	0.308	462	227.7	110%
483	0.354	0.351	0.358	0.354	86.84	86.12	89.21	262.2	115%	0.354	483	262.2	115%
504	0.506	0.502	0.497	0.502	103.62	102.09	103.32	309.0	120%	0.502	504	309.0	120%
525	1.064	1.061	0.998	1.041	133.80	118.77	122.27	374.8	125%	1.260	525	374.8	125%

From Table 12 the voltage/watt curve has been plotted. Refer to Figure 22 below.

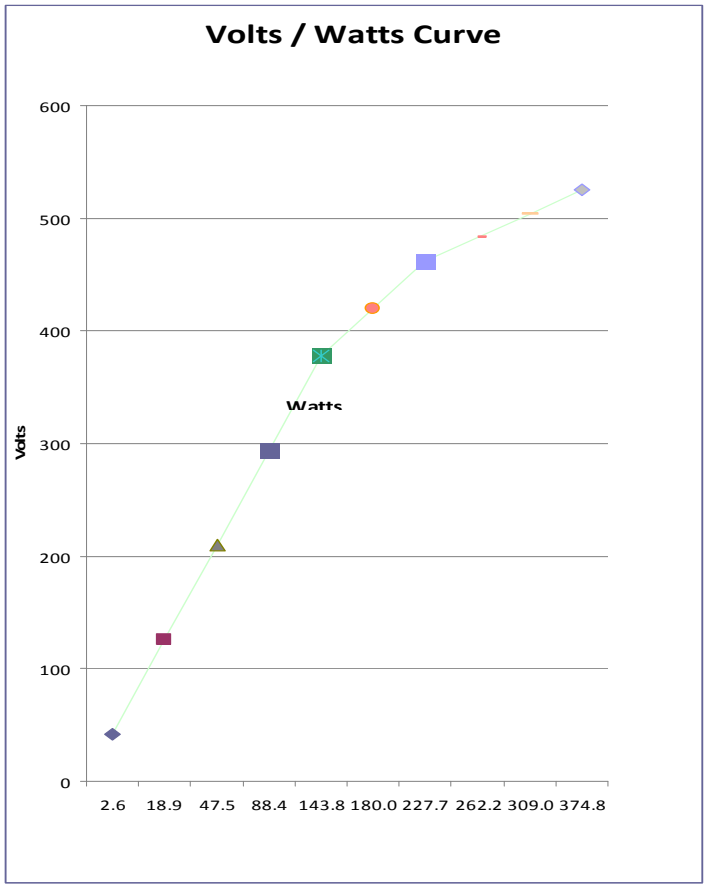

Figure 22: Hexaformer AB Voltage/watt curve

The magnetization curve is illustrated in Figure 23 below.

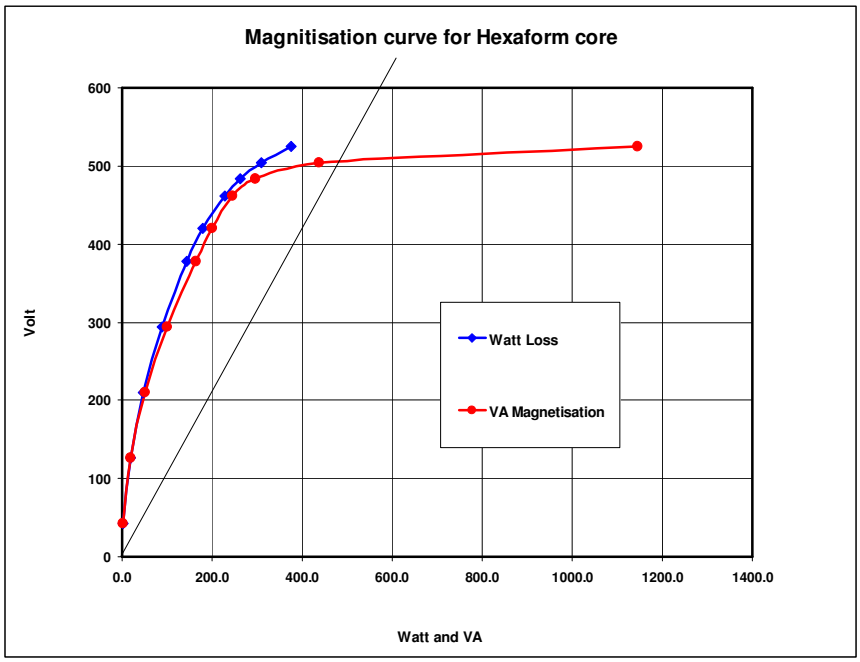

Figure 23: Hexaformer AB magnetization curve

4.1.3 Analysis

The hexa-transformer is designed to be completely symmetric. Hence it is therefore expected that the current on each phase would be the same. The tests conducted at Powertech Transformers indicated that the current in phase C is larger than that of Phases A and B. Other discrepancies include:

- Powertech measured no-load current at 100% (420 V) is 0,489 A, i.e. 0, 36% whereas Hexaformer AB measured 0,20% no-load current;
- There are considerable differences between no-load (magnetizing) currents in all phases (66% between phase B and C at 420 V). This is not possible since the core is completely symmetrical.
- Magnetizing current at 10% load (42 V) is 0,418 A, i.e. 85% from the measured current at 100%, i.e. 420 V (0,489 A).

As a result of the above mentioned discrepancies, Hexaformer AB in Sweden conducted the same measurements on the B-H curve. The results indicate [4]:

- Measured no-load current at 100% (420 V) is 0,276 A, i.e. 0, 20%.
- Differences between no-load (magnetizing) currents in all phases are very small (3% between phase B and C at 420 V).

- Magnetizing current at 10% load (42 V) is 0,038 A, i.e. 14% from the measured current at 100%, i.e. 420 V (0,276 A).

There is no explanation for the Powertech results, the no-load loss previously proved to be 50% more efficient compared to a conventional transformer. No-load loss was measured to be 150 W which was as expected. The discrepancies on the B-H curve may be attributed to the test equipment and setup used. Unfortunately the tests could not be repeated.

4.2 OIL TESTING

An oil sample was taken in order to determine the transformer oil characteristics. The following tests were performed:

- Dielectric strength
- Water content
- Tan delta
- PCB Content

Oil samples were taken from the top of the transformer tank. This is illustrated in Figure 24 below:

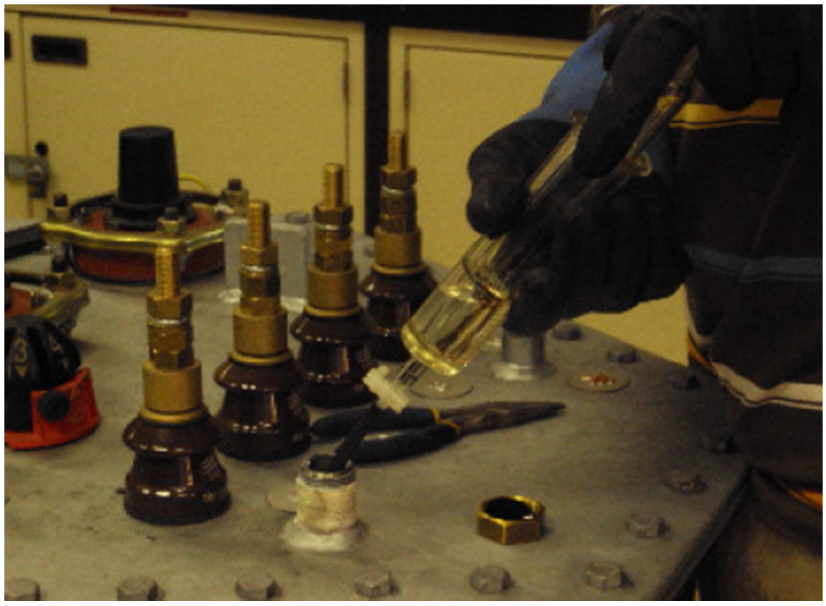

Figure 24: Hexa-transformer oil sampling

4.2.1 Oil Test Results

The results are summarized in Table 10 below:

Table 10: Oil Test Results

Test	**Results**
Electric Strength	79 kV
Moisture reading	2 mg/kg
PCB (ppm)	<1
Tan delta at 90 ℃	0.004

The sample conforms to the ESP 32-406 specification with regards to moisture, electric strength and tan delta. It is also classified as PCB free material which is level 0 according to the SANS 290:2007. The PCB concentration is below 1mg/kg.

4.2.2 Test result certificate from Laboratory

Technical Support Services
Laboratory Services
Private Bag 40175
CLEVELAND 2022
+27 11 629 5329
+27 11 629 5690

Laboratory Services
Task Report

Customer Details

Customer:	TSS CONSULTING	**Task ID**	LS2010-010676
Address:	PRIVATE BAG 40175	**Registered Date**	10 Sep 2010
	CLEVELAND	**Completion Date**	
	2094		

Customer Contact details

Tel No.:	011 629 5360	**Copy To :**	A. LOMBARD
Fax No.:	086 668 5360	**Tel No.:**	011 629 5360
Requestor :	A. LOMBARD	**Fax No.:**	086 668 5360

Report Completed By:

Task Name :	ROUTINE
Task Type :	PET-ADHOCH-TX-OIL
Description :	W,KV,TAN DELTA AND PCB ANALYSES
Task Comment :	SAMPLE RECEIVED IN GOOD CONDITION
Number of Samples :	1
Customer Reference :	DR6001.07/696050
Sample Description :	ELECTRICAL LABORATORY EXPERIMENT

This report include(s) sample(s) from LAB-ELECTRICAL taken on 08 Sep 2010
This report contains the following samples:
2209739

Task Approved By :
Designation :
Tel No. :
Fax No. : +27 11 629 5690

This report relates only to the specific sample(s) tested as identified herein.
The test results do not apply to any similar item that has not been tested.

sanas
Testing Lab No: T0055

Sample	PET-2010-09-08/4416	2209739	LS2010-010676

Site		**Emergency Sample**	
Position		**Work order no.**	
Sample Point		**Sample Container**	Various
Make		**Date Sampled**	08 Sep 2010
Serial Number		**Date Received**	10 Sep 2010
Plant Voltage (kV)		**Date Logged**	10 Sep 2010
Capacity (MVA)		**Date Authorised**	
Oil Volume (l)		**Transformer Point Note**	LAB-ELECTRICAL

Sampling Reason LABORATORY EXPERIMEN
Sample Condition GOOD

Date Sampled				08/09/2010				
Sample ID				2209739				
Analysis	Component	Result 1	Result 2	Result 3	Uncertainty	Accredited	Specification	Method
Transformer Oil Dielectric Strength accredited				Test Authorised by:		Hlengiwe Nzima		
Electric Strength (KV)				79	0	Yes		M201 Rev 5
Moisture in Oil -accredited				Test Authorised by:		Hlengiwe Nzima		
Moisture Reading (mg/kg)				2	0	Yes		M202 Rev6
Polychlorinated Biphenyls in oil Auto				Test Authorised by:		Fikile Bosch		
PCB (ppm)				<1	0	Yes		M221Rev5
Tan Delta at 90 °C				Test Authorised by:		Hlengiwe Nzima		
Tan Delta at 90 °C				0.004	0	No		Ref. IEC 247

Sample Comments:

The sample conforms to the ESP 32-406 specification with regards to moisture, electric strength and tan delta tests.

The sample is classified as PCB free material which is level 0 according to the SANS 290:2007 edition1, as the PCB concentration is below 1mg/kg.

This report relates only to the specific sample(s) tested as identified herein.
The test results do not apply to any similar item that has not been tested.

sanas
Testing Lab No: T0055

The acceptance of an item for test and issue of a certificate of analysis are to the requirements in the Eskom Holdings QA Manual.

1. If published or reproduced by the client a test report shall be reproduced in full, i.e. the reproduction shall contain the printed as well as the typed parts of the report, nothing exempted. In special circumstances an abridged form of the report or certain parts of the report may be published or reproduced, provided that the abridged form or partial version of the report is approved in writing by the responsible Manager before publication or issue.

2. A certificate of analysis relates only to an item submitted for the actual test. It furnishes or implies no guarentee whatsoever in respect of a similar item that has not been tested.

3. While every endeavour will be made to ensure that a test is representative and accurately performed, and that the report is accurate in the quoted results and conclusions drawn from the test, its officers shall in no way be liable for any error made in carrying out the test or for erroneous statement, whether in fact or opinion, contained in a report persuant to a test.

4. Unless otherwise stated, sampling is not carried out by the laboratory.

5. All water samples are preserved according to procedure P511 unless otherwise stated.

6. Unless otherwise specified all analyses on water samples give the dissolved constituents.

7. In the case of any dispute, the data contained in the database shall be regarded as the true data.

8. To ensure integrity of data, the authorised version of the certificate of analysis is available on written request from the laboratory to authorised customers only, the sample number, fax number, contact details customer details must be clearly indicated on the written request. The certificate of analysis, as signed by a SANAS authorised signatory, will be faxed to the fax number after verification of the details as supplied.

9. NB: This note is applicable to preliminary reports only: Please note that preliminary or draft reports have not been approved by a relevant approved technical signatory. The results are subject to change. A final report will follow as soon as possible.

This report relates only to the specific sample(s) tested as identified herein.
The test results do not apply to any similar item that has not been tested.

sanas
Testing Lab No: T0055

5. APPENDIX D - TRANSFORMER INSPECTION

In order to determine the mechanical integrity of the transformer, the transformer was opened and its construction was carefully examined.

5.1 EXTERIOR OBSERVATIONS

The complete tank unit was carefully examined prior to dismantling. The key parameters considered are as follows:

- Bushing sealing materials and technology
- Mounting detail
- Paint and corrosion protection
- Photographic evidence of the complete unit
- Physical attributes

5.1.1 Complete Unit

The tank was inspected. It was observed that the tank walls have fins, this is for additional cooling. It was also observed that the cooling fins on one side of the tank were larger than the others. Refer to Figure 25 below. The mild steel tank is galvanized; Hexaformer AB a uses hot-dip galvanizing process. The transformer has lifting lugs on the cover of the tank, and a drain valve at the bottom for oil sampling.

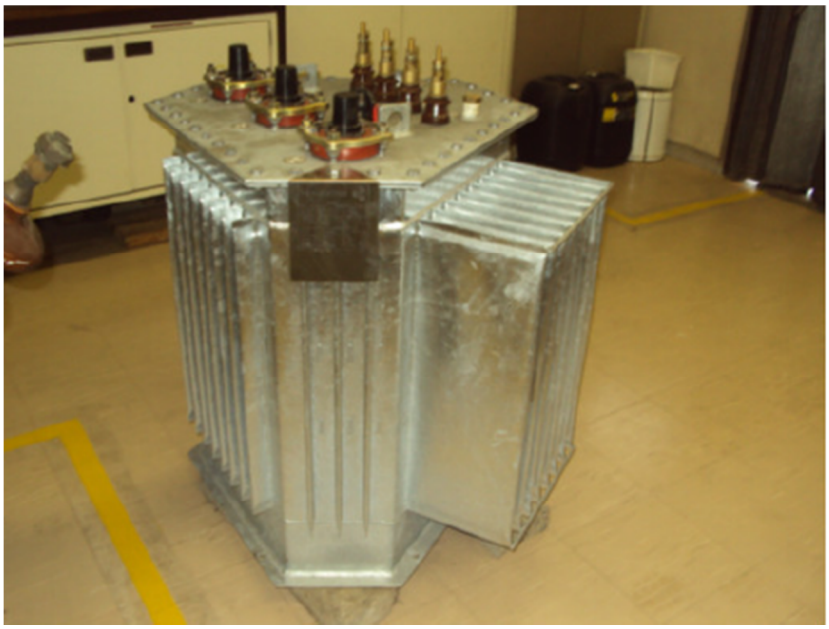

Figure 25: Hexa-transformer complete unit

It can be seen from Figure 25 above that the cooling fins on one side of the tank are larger than the rest. This is to cater for the expansion and contraction of the oil. In hermetically sealed designs the cooling fin design enables a degree of flexibility which is needed to accommodate the expansion and contraction of the oil as it heats and cools, due to load and ambient temperature variations (i.e. the in case of hermetically sealed transformers without conservator the corrugated walls will absorb the changes of oil volume due to thermal expansion).

Hexaformer AB has conducted measurements (temperature rise test) between all phases and confirmed that heat is distributed evenly. Besides, top oil temperature rise and winding temperature rise are a few degrees lower than allowed temperature rise limits according to the standard IEC 60076-2 [4].

5.1.2Transformer Bushings

Porcelain and elastimold bushings are used. Elastimold is only used for high voltage. Refer to Figure 26 and 27 respectively.



Figure 26: Porcelain bushings

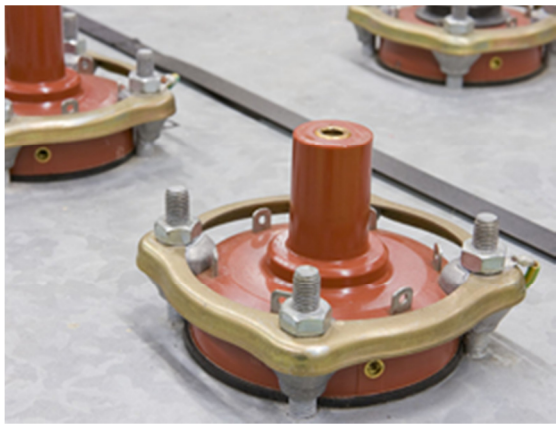

Figure 27: Elastimold bushings

Creepage distance for bushings [4]:

- 1 kV, 250 A – 50 mm
- 10 kV, 250 A – 295 mm

These values are for porcelain bushings. The creepage distance for Elastimold (plug-in type) is not applicable.

5.1.3 Tank Sealing Material

Sealing material on the lid is a form of Silicon structure. It is a soft seal gasket tape. Refer to Figure 28 below:

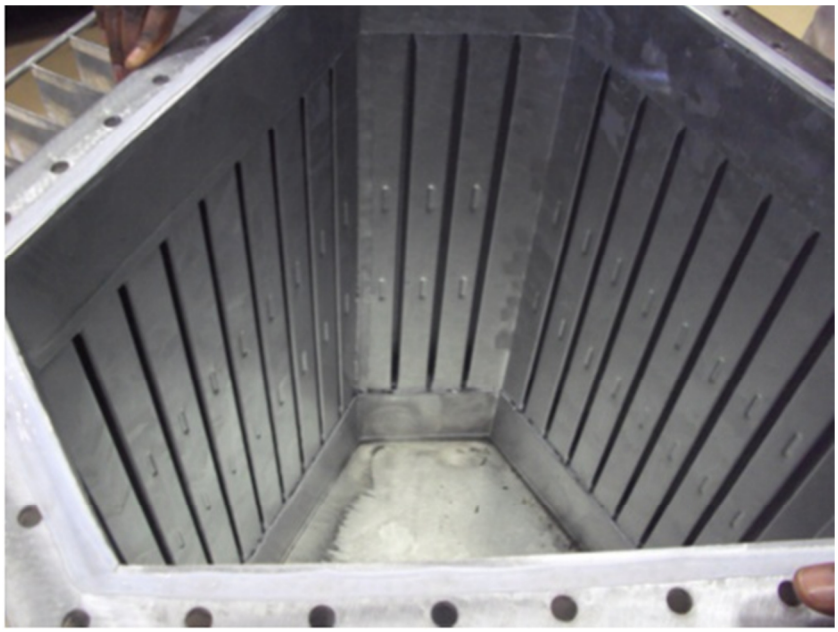

Figure 28: Tank Sealing Material

Description of material:

SOFTSEAL™ is a joint sealant consisting of 100% virgin PTFE which has been fully mono-axially expanded by a unique process. The product is soft and easily pliable and highly compressible. The seal is supplied in tape form with an adhesive backing strip for easy installation [5].

Characteristics: SOFTSEAL™ has a very good adaptability to uneven or warped flanges and does not require a high seating stress to seal effectively. It is ideal for weak flanges or flanges of plastic, glass or enamel etc. SOFTSEAL™ has very good chemical resistance and very little cold flow. It does not get hard and is easy to install and remove [5].

5.1.4 Name plate

The rating plate on the hexa-transformer has the following information:

- Year of manufacture
- Transformer rating and weight
- Transformer rating
- Type
- Serial number

Refer to Figure 29 below for the name plate illustration.

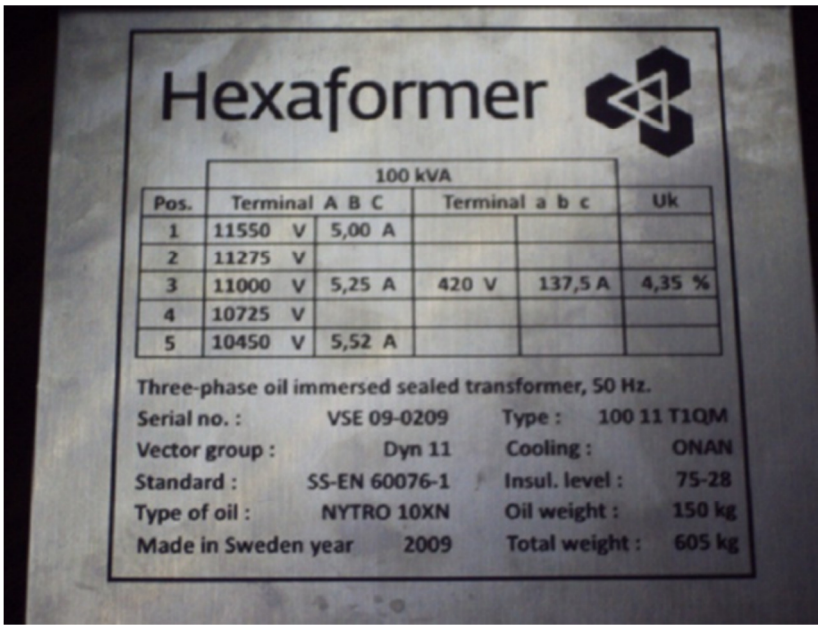

Figure 29: Hexa-transformer nameplate

5.2 INTERIOR OBSERVATIONS

The transformer was slowly opened to examine the core and core windings. The oil was drained prior to opening the unit.

5.2.1 Complete Unit

The unit was completely removed from the tank. Figure 30 below illustrates the complete unit.



Figure 30: Hexa-transformer unit removed from tank

5.2.2 Windings

The core windings are made from copper material. These are connected to the tap changer as illustrated in Figure 31 below.



Figure 31: Copper windings connected to a tap changer

5.2.3 Cross sectional view

The core was cut to obtain a set of windings for further inspection. A cross sectional view of the core is illustrated in Figure 32 below. The hexagonal shape of the core can be seen.



Figure 32: Cross sectional view of the Hexa-transformer core

5.2.4 Paper Insulation

Diamond duct epoxy coated insulation has been used. The paper adhered very well to the windings. Refer to Figure 33 and Figure 34 below.

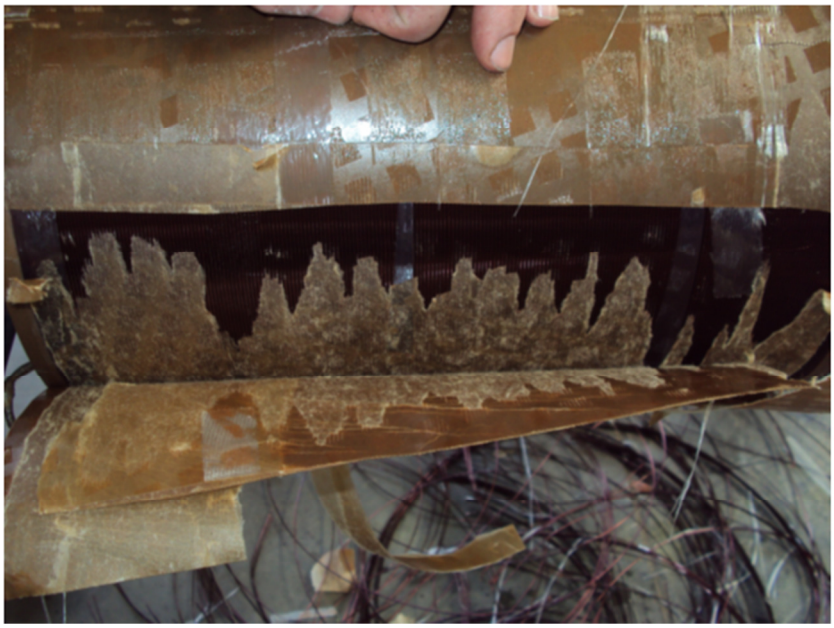

Figure 33: Paper insulation and HV windings



Figure 34: Paper insulation and HV windings

The advantages of using diamond dotted paper are [6]:

- Safe tolerance of axial and mechanical forces
- Internal strengthening of oils
- Helps in faster drying & filling as the liquid insulating agent penetrates the pressboard insulation completely in a short period
- Minimised danger of partial discharges

6. APPENDIX F – AUTHORIZATION

6.1 ESKOM

The document below is an authorization letter from Eskom Sustainability and Innovation [7].

Eskom

Further Studies Committee

Date:
18 January 2010

Enquiries: P Lutchman
Tel +27 11 629 5206

Dear Sir/Madam

Application for further studies : Poonam Lutchman (Unique number 04110060)

Ms Poonam Lutchman is currently employed as an engineer in training in the Generators and Transformers section within the Resources and Integrity department of Sustainability and Innovation. It is hereby requested that consideration be given towards supporting a study towards an MSc in Electrical Engineering. The MSc is a full thesis to be done on a part-time basis at the Witwatersrand University in South Africa. The MSc will focus on transformer core efficiency.

Transformers form an integral part of Eskom's electrical grid. The MSc in transformer core design would be aimed at evaluating the Hexaformer distribution Transformer for use within Eskom. An efficiency of 10 – 15 % has been claimed. This needs to be verified. A 100 kVA transformer used by Eskom has no-load losses of 300 W. This results in 300 kW of losses per fleet of 1000 transformers. The Hexaformer transformer is claimed to have no-load losses of 145 W, half that of a conventional E-core transformer as used by Eskom. This results in savings of half the power lost by Eskom in this size of transformer, namely 100 kVA. The lifespan of the transformer and maintenance considerations are included in the scope of work.

If proven successful, the project has the potential to reduce Eskom's transformer fleet losses substantially. The MSc would also equip Ms Lutchman with the relevant skills needed to tackle a full research project independently and would aid in ensuring a more effective output delivery of research projects. It would aid in her development as follows:
Project Management
Research Aspects
Testing – Laboratories (Eskom, Powertech, Wits)
Transformer Design
Business understanding
Finance and Life Assessment of Transformers

I support the application and hope you will proceed with the process of funding her further studies.

Yours Sincerely

Vikesh Rajpaul
Senior Manager - Resources and Integrity
Sustainability and Innovation

Corporate Services Division
Sustainability and Innovation Department
PO 40175 Cleveland 2022, South Africa
Tel +27 11 629 5312 Fax + 0865323279www.eskom.co.za

Directors: PM Makwana (Acting Chairman) LCZ Cele SD Dube LG Josefsson (Swedish) HB Lee (Korean)
WE Lucas-Bull J Mirenge (Rwandan) JRD Modise AJ Morgan U Nene PS O'Flaherty* (*Executive Director)
Company Secretary: Vacant
Eskom Holdings Limited Reg No 2002/015527/06

6.2 HEXAFORMER AB IN SWEDEN

Authorization from Hexaformer AB in Sweden is provided below [8].

Hexaformer™

Västervik, 2011-09-08

Re: authorisation

To who it may concern,

We hereby authorize Poonam Lutchnam to use the pictures and the test reports provided by Hexaformer for the Master of Science report that she is currently writing.

Yours truly



Richard Arbus

Director of Sales

Hexaformer AB

Hexaformer AB/Hexaformer Produktion AB
Lysingsvägen 18
593 53 VÄSTERVIK
Sweden

Phone: +46-490410100
Fax: +46-490-316 41
sales@hexaformer.com

7. CONCLUSION

This report is an Appendix to the dissertation on the Evaluation of an Efficient Transformer Core Design. A detailed account of the Hexa-transformer manufacturing process has been presented. The transformer test procedure and results were also discussed in greater detail. Authorization letters from Eskom Research and Hexaformer AB for the use of diagrams and test data were presented.

8. REFERENCES

[1] The Hexaformer Oil Filled Transformer Production Steps, obtained from Mr Lars Bengtsson. Hexaformer CEO. Lars.Bengtsson@hexaformer.com, as at 25 May 2009.

[2] Milin A. Transformer Testing. www.matrex-e.com

[3] Lundmark S, Serdyuk V.Y, Gubanski M.S, Larking B, *Comparison between Hexa-and Conventional E-type Core Three-Phase Transformer.* Proceedings of the 2008 International Conference on Electrical Machines.

[4] Hexaformer AB B-H Curve test results obtained from Jovce Doneski, Hexaformer AB. Jovce.Doneski@hexaformer.com.

[5] Softseal self adhesive gasket tape specifications. www.specma.se, seals@specma.se

[6] Diamond dotted paper insulation advantages. http://www.acme.in.th/ele-paper.html, last accessed 10 November 2010

[7] Eskom, department manager, Resources and Plant Integrity. Mr V Rajpaul, Vikesh.Rajpaul@eskom.co.za.

[8] Hexaformer AB. Mr Richard Arbus, Sales Director, Phone +46(0) 490- 410108, Email: Richard.Arbus@hexaformer.com.