University of Southern Queensland

Faculty of Engineering and Surveying

DEVELOPMENT OF A HIGH VOLTAGE DLA TEST APPARATUS

A dissertation submitted by

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Abstract

An important part of any High Voltage Power System Component is its electrical insulation. The integrity of the electrical insulation of a power system component is often determined through non-destructive condition monitoring tests. One such condition monitoring test is known as the Dielectric Loss Angle (DLA) test. This project is concerned with the development of a DLA test apparatus capable of testing at voltages up to 24,000Volts, primarily for testing high capacity generators.

Based on research undertaken, a DLA test apparatus was successfully developed. The apparatus was developed as two separate components; the high voltage power supply and the DLA measuring equipment. The power supply was adapted from an existing setup, with improvements made to protection and control. The measuring equipment was developed by purchasing a suitable measuring instrument and integrating it with an existing reference device.

The DLA test apparatus was put through a series of experimental tests in order to prove the apparatus was fit for purpose. The experimental tests suggested the apparatus provides accurate measurements, however some small discrepancies in the results have left room for further experimental tests and research.

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Date

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Contents

Chapter 2 – Literature Review

Chapter 3 – Design requirements

Chapter 4 – Conceptual Designs

List of Figures

List of Tables

Abbreviations

CT	Current Transformer
DLA	Dielectric Loss Angle
DDF	Dielectric Dissipation Factor
GST	Grounded Specimen Test
HV	High Voltage
HV & ES	High Voltage & Electrical Services
LV	Low Voltage
NATA	National Association of Testing Authorities
UST	Ungrounded Specimen Test
VT	Voltage Transformer

Chapter 1 – Introduction

1.1 Introduction

An important part of any high voltage power system device is its electrical insulation. Determining the integrity of such insulation can be partially achieved by conducting a test commonly known as the Dielectric Loss Angle (DLA). The development of a tests apparatus for conducting DLA testing is the basis of this project. This chapter will explain the background of the project and also define the key objectives. An outline of the remainder of this dissertation will also be presented.

1.2 Background

A high-voltage (HV) power system is made up of many different components operating at various voltage levels. These components such as generators, motors, transformers, bushings and cables all contain some form of insulation that is appropriate to the application and voltage level. Determining the condition of this insulation can help to establish the life expectancy of the power system equipment in question (James and Su, 2008). One tool used to help determine the insulation quality of HV equipment is non destructive test called D*ielectric Loss Angle* (DLA) or also known as *Dielectric Dissipation Factor* (DDF) or Tan Delta ($\tan\delta_x$).

Silcar HV&ES conducts DLA testing for its clients and was looking to expand and improve its testing capabilities. Prior to the project, Silcar HV&ES operated two Doble M4100 units that are capable of testing at up to 12kV and another set of test apparatus capable of DLA testing at up to 30kV. The intent of the project was to develop a test apparatus capable of performing DLA testing up to at least 24kV. It appeared that no so such apparatus was readily available that would meet Silcar's requirements and therefore further research was required.

The test apparatus was to be developed using new and existing equipment. Factors including safety, cost, practicality and standards were to be considered for this project. On completion of this project, it was hoped that Silcar will have two sets of DLA equipment capable of testing at up to 24kV.

In order for this project to be justified, an adequate amount of preliminary research was conducted. This background research can be broken into two major categories;

- Purpose of DLA testing
- Methods of DLA testing

Researching the purpose of performing DLA testing is important to ensure this type of testing was necessary and that any alternatives were considered. It would have been unwise to pursue the development of a DLA test apparatus if improved methods of insulation condition assessment were available. The research conducted has supported the need for DLA testing on high voltage power system equipment, details of which can found in section 2*.2 Purpose of DLA Testing*.

Also, the researching of various methods of conducting DLA testing has provided a sound basis for the development of a DLA test apparatus. This knowledge was important in making an informed decision about the development of a new test apparatus that would best suit the requirements of Silcar and its clients. Details of this research can be found in chapter *2.3 Methods of DLA Testing.*

1.3 Project Objectives

The primary aim of this project was to develop a high voltage DLA test apparatus from new and existing equipment. In order to achieve this, a specific set of objectives was needed:

- Research current techniques and apparatus used in industry to perform DLA testing on high voltage equipment.
- Itemise Silcar HV&ES existing equipment and determine whether any of it can be used in constructing the new test apparatus.
- Develop at least two conceptual designs to present to Silcar HV&ES management.
- Upon approval of design, purchase and/or manufacture any required equipment and construct apparatus.
- Conduct testing of new apparatus to insure it is fit for purpose.

1.4 Methodology

The overall success of this project was mainly to be evaluated by the ability of the DLA test apparatus to perform the intended task consistently and accurately. This was to be achieved through experimental testing within a controlled environment. Testing was also to be performed using other proven DLA test apparatus that have calibration certicficates traceable to The National Association of Testing Authorities (NATA) and the results compared. As many experimental tests as practicable were to be performed under different conditions to ensure the apparatus would perform accurately and consistently in the field.

1.5 Dissertation Outline

Chapter 2 – Literature Review

This chapter presents the research undertaken prior to the design stage. The theory and purpose of DLA testing is presented, as well as methods used in industry to conduct these tests.

Chapter 3 – Design Requirements

Based on the research presented in chapter 2 and the specific needs for Silcar HV&ES, a set of requirements for the apparatus design have been developed. This chapter will present these design requirements and reasons behind them.

Chapter 4 – Conceptual Designs

One of the project objectives was to develop at least two conceptual designs for the test apparatus. Two proposed designs for both the power supply and measurement equipment are outlined in this chapter.

Chapter 5 – Final Design Implementation

In this chapter the final DLA test apparatus design is presented. Details of the constructed apparatus can be found here.

Chapter 6 – Experimental Testing Analysis

The methodology for proving the test apparatus was through experimental testing and comparisons to other proven test apparatus. The results and analysis of the experimental tests are discussed in this chapter.

Chapter 7 – Conclusions

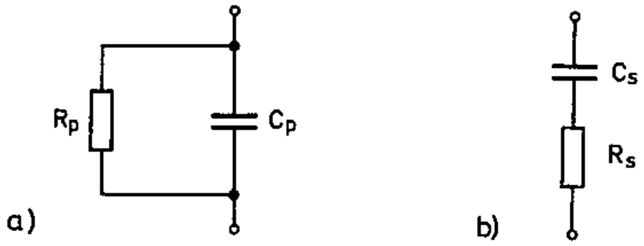
The overall success of the project is reflected upon here. Suggestions for potential future work required in this subject area are discussed.

Chapter 2 - Literature Review

2.1 Theory of DLA testing

An understanding of the theory of DLA testing was to be established before any development work could be undertaken. A solid understanding of the theory has helped to ensure any development of a test apparatus is achieving the desired outcomes.

According to James and Su (2008) an ideal insulator can be considered as pure capacitance, but in practice can never be achieved. Instead all insulation contains losses and can be considered as parallel or series RC circuits as described by Kind (1978).



a) Parallel equivalent circuit
b) Series equivalent circuit

Figure 2.1: Equivalent circuits for a dissipative dielectric for alternating voltage (Kind 1978, p. 56)

The result of this equivalent circuit is that when an AC source is supplied to an object, the current leads the voltage by an angle slightly less than 90˚ as would be the case for a purely capacitive load. The difference between the actual lead angle of the current and that of 90˚ is known as the loss angle and represented by the symbol δ. The Dielectric Dissipation Factor is the tangent of this angle or tanδ. Figure 2.2 shows this relationship in a phasor diagram, although the angle of δ shown is much greater than what would typically be seen.

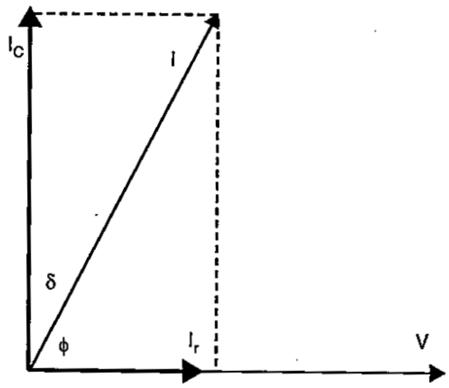


Figure 2.2: Phasor diagram for practical dielectric (James and Su 2008, p. 35)

2.2 Purpose of DLA testing

As stated earlier, DLA testing is used as a non destructive diagnostic tool for insulation in power system equipment. James and Su (2008) believe knowledge of the insulation condition of much power system equipment is critical for asset management, especially for planning maintenance and estimating service length for new and existing equipment. Although specifically referring to rotating plant, the critical need for condition monitoring supported by Farahani et al. (2005). They believe the most important aspect of a high voltage rotating machine is the insulation, due its significant impact on the life expectancy, maintenance and cost of the machine. Farahani et al. (2005) therefore recommend that the condition of insulation be assessed through non destructive testing. Steed (2001) suggests many advantages of condition monitoring including:

- A reduction in maintenance costs.
- Reduced likelihood of destructive failures.
- Provide quality control measures.
- Provide plant life expectancy estimates, used to aid maintenance decisions.

The advantages of condition monitoring are well documented and it would seem the importance of condition monitoring is widely supported throughout the power industry, with many of Silcar's clients using routine condition monitoring of the insulation of their high voltage assets.

It is evident that condition monitoring of power system equipment is necessary and is widespread throughout the power industry. This then leads to next question, is DLA testing the best form of condition monitoring of insulation? The answer to this is not simple. This is because many different types of power system equipment exist, containing different types of insulation. Due to the large variety of power system equipment, the discussion will be limited to rotating machines and power transformers as these are the main types of equipment tested by Silcar HV&ES.

2.2.1 Power Transformers

According to the relevant Australian standard for power transformer insulation, AS60076-3 (2008) there is no requirement for DLA testing to be performed on power transformers, instead it recommends a variety of other tests. This however contradicts what is written in IEEE std 62-1995, that recommends this testing. This IEEE standard is focussed on diagnostic field testing which makes it very relevant for the testing performed by Silcar HV&ES. This is supported by what is seen by Silcar during on-site routine testing of large power transformers (typically transformers larger than 10MVA) where many asset owners/managers request DLA testing as part of routine transformer testing.

Rojas (2006) supports the importance of DLA testing as it can effectively highlight contaminated and faulty insulation. He suggests that oil-paper insulation systems (as found in power transformers) have flat capacitance and loss curve, meaning the capacitance loss angle is not affected by the applied voltage level. Rojas (2006) believes that DLA testing is historically performed at high voltages to reduce noise and that more work could be done on developing test methods that can operate at low voltages, within electrically noisy environments. It therefore seems that DLA testing is a worthy test for diagnostic testing of power transformers, but testing at higher voltages has little advantage, other than noise suppression. This would indicate the new apparatus proposed for this project with a potential output of up to 24kV, will have no advantage over the 12kV test sets currently being used, but would provide another option for testing.

2.2.2 Rotating machines

According to Farahani et al. (2005) the most important aspect of a high voltage rotating machine is the insulation, due to its significant impact on the life expectancy, maintenance and cost of the machine. Among other diagnostic insulation tests, Farahani et al. (2005) suggest that DLA testing provides important information about the condition of the insulation. This is also supported by standard IEEE std 62.2(2004), which recommends performing a tip-up test and IEEE has another standard, IEEE std 286 (2000) entirely devoted to tip-up tests on rotating machines. According to both these IEEE standards, voids in the insulation used in the stators of rotating machines produce partial discharges (PD) when subject to high AC voltage and the higher the voltage the more PD occurs. This PD increases the loss in the insulation and therefore the test requires the test voltage to be at least as high as the nominal phase to ground voltage of the machine and as high as the phase to phase voltage.

Many of Silcar HV&ES clients operate high capacity machines (usually generators) that operate at voltages up to 24kV. Developing another DLA test set capable of achieving these voltages will provide Silcar with a greater capacity to perform these tip-up tests on high capacity machines.

2.3 Methods of DLA testing

The basic requirement for DLA testing is a power supply to provide the required voltage to the test object and some form of measuring circuit to determine the dissipation factor of the object under test. Different methods for power supplies and measurement circuits will be discussed below.

2.3.1 Measurement Circuits

2.3.1.1 Traditional Techniques

The oldest method for High Voltage DLA measurement is through the use of an AC bridge circuit called a Schering Bridge (Fig 2.3). The method was developed by H. Schering in 1919 (Kind & Freser 2001). C_2 represents a standard capacitor that should be almost loss free and C_x represents object under test. Variable elements C_4 and R_3 are used to balance the bridge. The capacitance and dissipation factor ($\tan\delta_x$) can then be calculated according the below formulas suggested by Kind and Freser (2001).

$$\tan\delta_x = \omega C_4 R_4$$

$$C_x = \frac{R_4}{R_3}$$

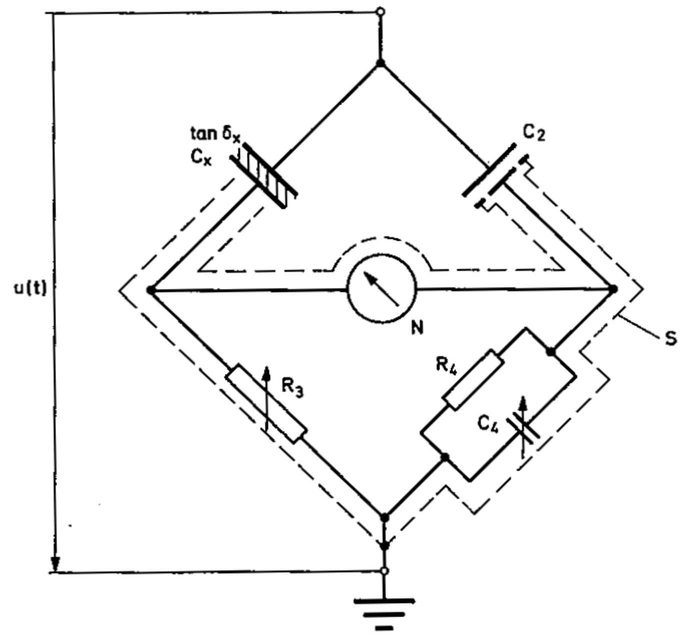


Figure 2.3: Circuit of the Schering Bridge (Kind & Freser 2001, p. 98)

Schwab (1972) describes many variations of the Schering bridge, such as used with high charging currents, earthed test specimens and direct readings with no calculation required. Although a very old technology, Silcar was operating a Schering type bridge as recent as 2004, when the device was condemned due to unrepairable transport damage. This device did have direct readings of tanδ_x and C_x and was capable of testing earthed and unearthed test specimens. The major disadvantage of this type of device is the need for manual balancing of the bridge and manual recording and reporting of results, unlike some modern devices such the Doble M4000, where recording and reporting is automated and no manual balancing is required.

Another similar type device is the transformer-ratio-arm bridge designed by Glynne. Schwab (1972) describes this type of bridge as superior to the Schering bridge as it is more sensitive by a factor of about 100 and it does not require double shielding on leads to eliminate stray ground capacitance. It would therefore seem the logical choice over a Schering type bridge. Silcar currently operates a transformer-ratio-arm bridge, called the Type 2805, manufactured by Tettex AG. Although internally different to the Schering bridge, from an operators point of view it has similar disadvantages, with manual balancing and recording required. The internal circuit diagram of the Tettex AG Type 2805 is shown in figure 2.4. As can be seen in figure 4, an external supply and standard capacitor are required as with the Schering bridge.

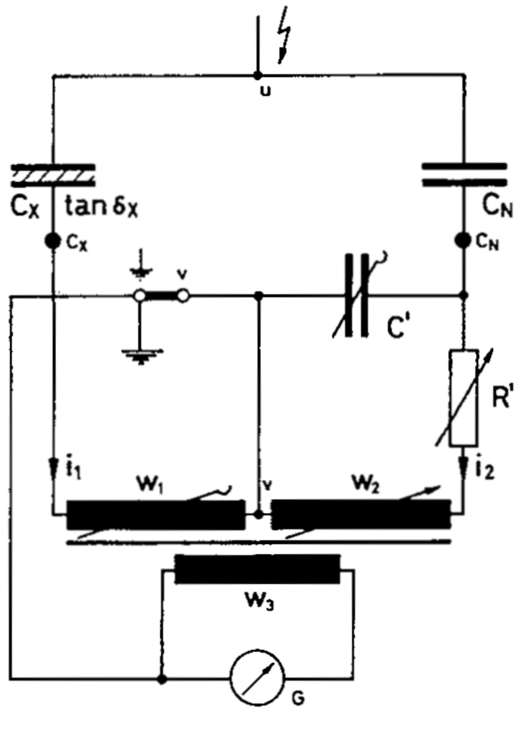


Figure 2.4: Tettex Type 2805 basic circuit (Tettex 1976, p. 11)

2.3.1.2 Modern measurement instruments

Through researching various commercially available DLA measurement instruments, it would seem AC bridge circuits are still used in modern equipment, however microprocessors and computer interfaces have made it possible for automatic bridge balancing and results recording. Tettex have two new devices available called the Tettex Type 2877 and Type 2820 offering this automation.

Muhr et al (2006) describe a method for DLA measurement called Vectorial Impedance Measurement in Frequency Domain. The technique still uses a standard capacitor, but instead of using an AC bridge circuit, it uses analogue-to-digital converters and a computer to calculate the DLA using a Discrete Fourier Transform. Test results present by Muhr et al (2006) show this technique is credible, however at this stage a commercially available device utilising this method has yet to be located. Developing a device of this complexity is beyond the scope of this project.

2.3.2 Power Supplies

One of the objectives of this project is to be able to perform DLA tests up to 24kV. The voltage must be variable to allow for tests at different voltages and be able to withstand the load current required to energise the test specimen and measurement instruments.

Kind & Freser (2001) describe the most conventional method for supply high voltage AC is through a single stage voltage transformer, using an variable low voltage auto transformer (variac) to supply the low voltage side of the voltage transformer. This method will be adopted for this project as Silcar HV&ES owns many of these components already, making it the logical choice.

One of the biggest issues with testing large power system equipment is the high capacitive nature means large amounts of reactive load must be supplied by the test supply (Kind & Freser 2001). There are three basic options to combat this problem. One is to have a very high capacity supply capable of supplying a high level of current. This is not very practical because equipment must be larger and a large capacity low voltage (LV) supply is not often available. Another method is to conduct the test at a lower frequency, a method described by Virsberg (1966). At lower frequency, less capacitive current is required. However IEEE (1995) recommend DLA test should be performed at power frequency (50Hz) to simulate normal operating conditions. Silcar HV&ES currently performs all DLA testing at power frequency, so it would be logical to stick with this convention.

The third option is to compensate for the capacitive load, by including variable inductance in the circuit, as described by Kind & Freser (2001) in figure 2.5. This is the method currently adopted by Silcar HV&ES, using variable inductors on the LV side of the supply (option 1 in figure 2.5). This method reduces the kVA required from the power outlet and variac, but the HV transformer has to transmit the full kVA to the load. The Doble M4100 has the option of a variable resonator on the HV side, similar to option 2 in figure 2.5. This enables the HV transformer to also have a reduce power rating. Option 3 and 4 in figure 5 require a special construction transformer, therefore it is probable that options 1 or 2 will be the most economical for this project.

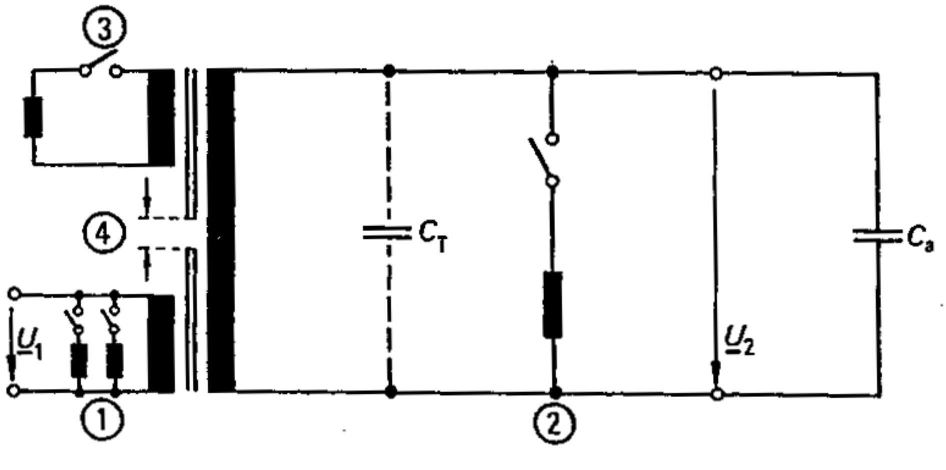


Figure 2.5: Methods for Compensation of the capacitive reactive kVA (Kind & Fresser 2001, p. 8)

2.3.3 Combined power supply and measurement instruments

In recent years test equipment has become commercially available that offers a complete testing package in one unit, combining the power supply and measurement instruments into one unit. Two such units are the Doble M4100 and Tettex Midas, both manufactures claim their units are accurate in electrically noisy environments and offer computer interfaces for the data storage and reporting. These units have an advantage over the bridge and separate power supply method described earlier as less connections are required, and transport is more simple. However these units operate at a maximum output voltage of 12kV and 15kV respectively and therefore were not a suitable option for this project. There does not appear to be any commercially available combine units capable of operating at 24kV with high capacity.

Doble® offers an extension for there M4100 that enables the unit to be used with an external supply. This allows the use of the M4100 measuring circuits at voltages higher than 12kV. Due to fact that Silcar HV&ES already owns two Doble M4100 units, this was a viable option as a measuring device.

Chapter 3 – Design requirements

3.1 Power Supply

When developing the design requirements for the new power supply, there were three main considerations; Load, Control and Safety.

3.1.1 Load

As discussed in chapter 2, this new apparatus will mainly be used for the testing of high capacity generators. In order to perform DLA tip-up tests, the tests must be conducted at various voltages up to the nominal line voltage of the machine. The highest rated machine tested by Silcar, operates at 24kV. This is why one of the objectives of the project is to develop an apparatus capable of testing at up to 24kV.

When energising the winding of a generator, the capacitive load is quite substantial. From previous tests conducted by Silcar, it is known that the capacitance of one phase of a large generator typically ranges from 100,000pF up to 400,000pF. The power supply will be designed for the highest expected load, that being 400,000pF, supplying at 24kV. According to table 3.1, this gives a load current of approximately 3Amps.

Capacitance (pF)	100,000	200,000	300,000	400,000
Xc (Ω)	31,831	15,915	10,610	7,958
I @ 2,000V	0.063	0.126	0.188	0.251
I @ 4,000V	0.126	0.251	0.377	0.503
I @ 6,000V	0.188	0.377	0.565	0.754
I @ 8,000V	0.251	0.503	0.754	1.005
I @ 10,000V	0.314	0.628	0.942	1.257
I @ 12,000V	0.377	0.754	1.131	1.508
I @ 14,000V	0.440	0.880	1.319	1.759
I @ 16,000V	0.503	1.005	1.508	2.011
I @ 18,000V	0.565	1.131	1.696	2.262
I @ 20,000V	0.628	1.257	1.885	2.513
I @ 22,000V	0.691	1.382	2.073	2.765
I @ 24,000V	0.754	1.508	2.262	3.016

Table 3.1: Load currents for different capacitance and supply voltage

A load of 3Amps at 24kV amounts to an apparent power rating of 72,000VA.

$$Apparant\ Power = V \times I = 24000 \times 3 = 72{,}000VA$$

This amounts to current of 173Amps on the 415V supply side.

$$I = \frac{Apparent\ Power}{Volts} = \frac{72{,}000}{415} = 173.5A$$

Considering the power supply will be powered from a 63Amp 415V outlet, 72kVA is too much load, even for this short term tests. It is therefore required that this load requirement be reduced by way of induction regulator/s, either on the LV or HV side of the test transformer, as discussed in chapter 2.3.2.

3.1.2 Control

As the tests are performed at various tests voltages, the power supply must have a variable supply. This will most likely be achieved through the use of a 415V variable autotransformer, also known as a variac. The variac must also meet the load requirements.

3.1.3 Safety

A review of the existing power supply used for HV generator DLA tests, revealed some shortcomings in its safety. The main points were;

- No overload/overcurrent protection other than the fused supply.
- No provision to rapidly switch off circuit in the event of an emergency.
- No overvoltage protection – risk of damage to test specimen.
- Operator required to adjust variac manually – close proximity to hazardous voltages.

In order to eliminate these hazards, the new power supply must include;

- Overcurrent protection.
- Emergency stops and/or dead man switches.
- Overvoltage protection.
- Remote voltage control.

3.2 Measurement Equipment

When considering the measurement instruments and associated equipment, one of the most important aspects to consider is accuracy. One of the project aims was to improve testing capabilities, therefore obtaining accuracy and precision of at least the same level as that given by the existing equipment. According to the Tettex Type 2805 user manual, the instrument has the following accuracy on the instrument ranges typically used during Silcar's tests:

Dissipation Factor: ±1% rdg ± 0.0002. Max resolution = 0.0001.
Capacitance: ± 0.1% rdg ± 1pF. Max resolution 0.1pF.

The above values was to be used as minimum standard when considering the accuracy and precision of the new instruments.

Another consideration for the instruments is the ease of use. The Tettex Type 2805 requires manual balancing, potentially leaving room for human error. The research has revealed that there are several instruments commercially available that have automatic balancing and electronic storage of results. A device with this capability would be desirable.

Chapter 4 – Conceptual Designs

4.1 Introduction

One of the objectives of this project was to propose two different options for a DLA test apparatus and pursue the development of one of these designs. Based on the research presented in chapter two a set of design requirements were developed as explained in chapter three. These design requirements are the basis of the design proposals. The apparatus design will be split into two parts, power supply and measurement equipment. Two proposals for each will be presented in this chapter.

4.2 Power Supply Proposals

The basic requirement for the power supply will be to supply a variable AC voltage up to 24kV to a capacitive load of up to 400,000pF. The power will be supplied through a maximum outlet rating of 415V at 63Amps. Safety devices to protect against overcurrent, overvoltage and emergency shutdown must be included.

4.2.1 Power Supply Proposal A

The concept behind this proposal was based greatly on the existing power supply used by Silcar. All of the same primary equipment will be utilised from the existing supply, with improvements being made to protection and control. This option aimed to be a more economical solution in the short term, as all of the primary equipment was already owned.

This setup was a simple variac and transformer arrangement with compensation for the capacitive load being achieved with the use of a variable inductor on the LV side of the circuit. This is same setup as suggested by Kind & Freser (2001). One of the issues with this setup is the weight of the primary equipment. In order to help combat this issue, it was proposed that all protection and control equipment be of a modular design that is adaptable to any variac and transformer combination. This would enable the use of the lowest possible rated primary equipment for the task, without creating protection equipment for each variac/transformer combination. Appendix B contains a list of available preimary equipment that can be used. A simplified schematic of the power supply design is shown in figure 4.1.

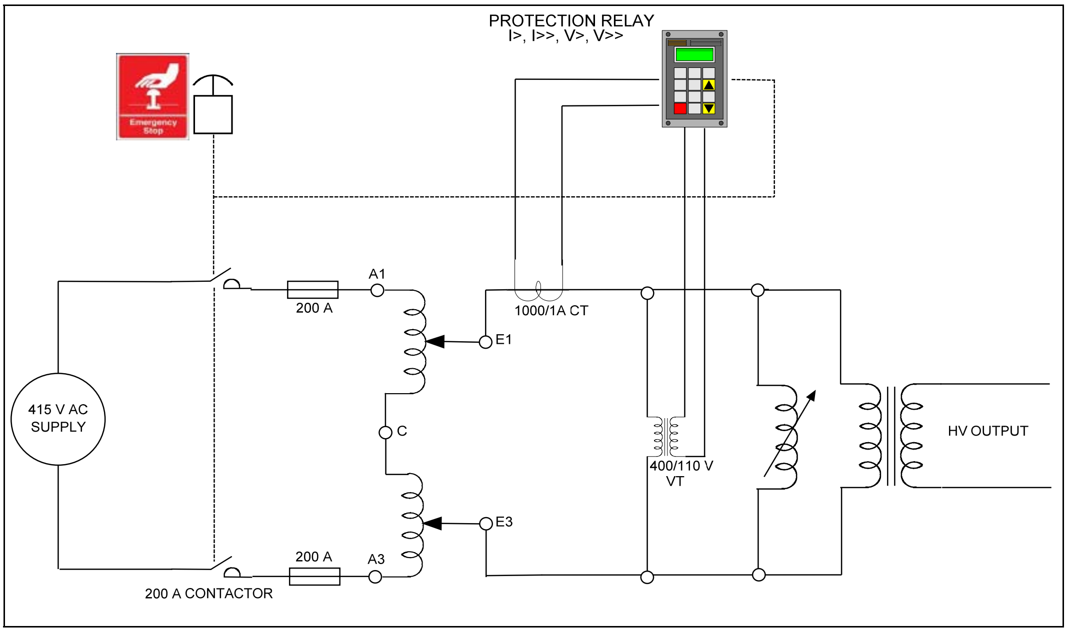


Figure 4.1: Simplified schematic of Power Supply Proposal A

As can be seen in figure 4.1, the main circuit isolation would be by way of a 200Amp contactor. This contactor provides the means of rapidly switching off the power supply. It is expected the maximum load should not exceed 100Amps, therefore the 200Amp contactor would be able to handle the load and break any fault current, with fuses used as back-up protection. The contactor was to be mounted in a transportable case with sockets fitted for interfacing with the power outlet, variac and protection devices. Silcar already owned several 200Amp contactors, that were available for use.

The contactor was to be controlled remotely via two emergency stop push buttons. The emergency stops provide the means to switch off rapidly in the event of an emergency. One stop would be in the vicinity of the operator and other with an observer.

A numerical protection relay would also operate the contactor, providing the overcurrent and overvoltage protection required. A current transformer (CT) already owned by Silcar would provide the current measurement for the relay. A 400/110V VT would need to be purchased to reduce the voltage for input into the relay. Using a numerical relay allows for easy programming so the settings can easily be changed to suit the desired protection levels. The relay would also be mounted in a transportable case with sockets and leads for interface with the CT, VT and contactor control circuit. The relay to be used is a Siemens 7SJ803. This is a compact relay and the Silcar Technical Services Staff are familiar with the programming software. The relay also provides thermal overload protection, which could be used to further protect the power supply equipment. The approximate cost of this relay is $6,000.

It was anticipated that for majority of tests performed either the 25kVA, 400V/20,000V transformer with the 100Amp variac or the 212kVA, 440V/48,700V transformer with the 200Amp variac would be utilised. For this reason remote control of both variacs must be obtained. Both variacs have the motorised drives, but were not currently being utilised. Implementing the remote control would involve a small amount of wiring and the purchasing of some inexpensive switches. This would fulfil the requirement of remote voltage control.

The estimated cost for purchasing all the required materials and labour for the manufacture of this power supply design is detailed in Table 4.1. As can be seen the total cost is significantly less than Proposal B. This was due to all the primary equipment already being owned which is the major cost in a HV power supply.

ITEM DESCRIPTION	ESTIMATED COST
Materials	
Case for contactor	$200.00
50Amp Male Socket for contactor box	$150.00
50Amp Female Socket for contactor box	$100.00
Control relay for contactor	$100.00
240V socket & switch for contactor control supply	$20.00
2 x Emergency Stops	$200.00
Sockets and leads for interface to E/S and protection relay	$100.00
Case for Protection Relay	$200.00
Protection Relay	$6,000.00
240V socket & switch for relay supply	$20.00
Sockets and leads for interface to CT, VT and contactor box	$100.00
400V/110V VT	$150.00
2 x switch and wiring for variac control	$100.00
Labour	
Tradesman 40 hours	$2,800.00
Technician 40 hours	$3,400.00
TOTAL ESTIMATE	$13,440.00

Table 4.1: Cost estimate for Power Supply Proposal A

4.2.2 Power Supply Proposal B

The proposal for this power supply was based on the configuration described by Kind & Freser (2001). This concept was aimed at producing a relatively light weigh power supply that would have advantages for transport. The idea is to reduce the load by way of a variable inductor on the HV side of the supply transformer. The inductor counteract the capacitive load and therefore the rating of the supply transformer and variac can be significantly reduced. This is also the same principle used by the Doble M4100 which has an optional HV reactor. A simplified circuit diagram of the concept is shown in figure 4.2.

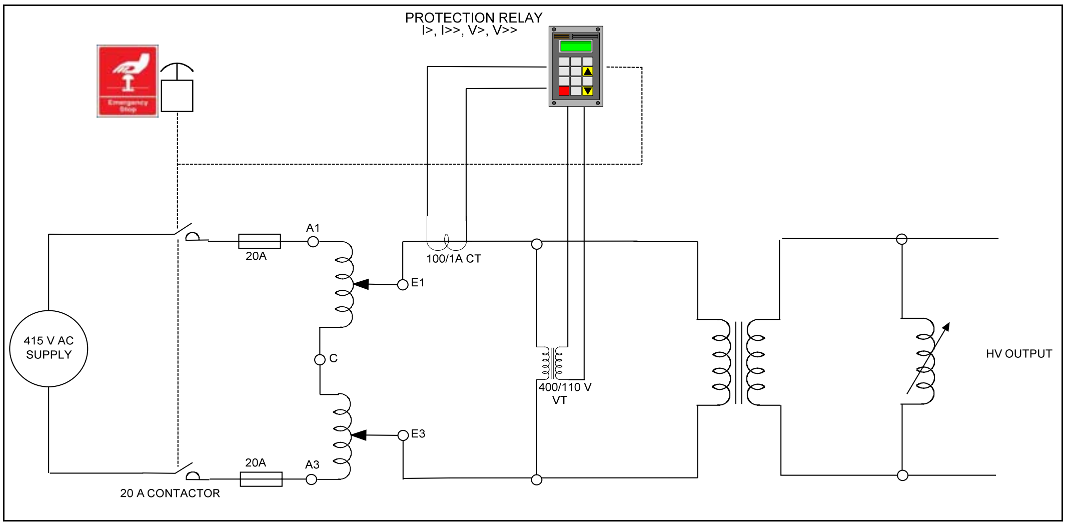


Figure 4.2: Simplified schematic of Power Supply Proposal B

Silcar does not own a variable inductor rated at 24kV, therefore one would have to be manufactured or purchased. This was expected to be the major cost in this power supply proposal, as all other major components were already available. A variable inductor of this nature did not appear to be readily available and must be custom made to order.

In order to estimate the required inductance range of the variable inductor, the capacitive load must be known. As the inductor would operate in parallel with the capacitive load, the inductive reactance of the inductor must match the capacitive reactance of the load to balance the circuit. This is a simplified circuit model and does not consider other influences such as transformer impedance and load resistance. If the estimated capacitance of load is from 100,000pF to 400,000pF, the capacitive reactance range can be calculated using formulas from Robbins and Miller (2001).

$$C = 100{,}000pF, \quad Xc = \frac{1}{2\pi fC} = 31831\Omega$$

$$C = 400{,}000pF, \quad Xc = \frac{1}{2\pi fC} = 7958\Omega$$

Using the above values, an inductance value can be calculated to match the capacitive reactance.

$$Xl = Xc = 2\pi fL = 31830\Omega,\ L = \frac{Xl}{2\pi f} = 101H$$
$$Xl = Xc = 2\pi fL = 7958\Omega,\ L = \frac{Xl}{2\pi f} = 25H$$

The above calculations provided a rough estimate that an inductor would be required that ranged from 25H to 100H. As the most of the current to the load will be supplied from the inductor, it must be able to supply the maximum full load current. Referring to Table 3.1, the max current is approximately 3Amps.

Obtaining accurate estimates for the cost of such a device was difficult. Rough estimates from supplier suggested such a device would cost in excess of $100,000. Estimation on the weight of such a device was also difficult without pursuing a full design. A rough value of 200kG was given from one possible supplier.

It was proposed the 5kVA 400V/25000V Test Transformer be used, with the voltage control coming from the 28Amp Variac. The Variac is not motorised and would have required some modification to meet the design requirement of remote voltage control. Assuming a weight of 200kG for an inductor, the total weight of this set up would be less than 400kG. This is significantly less weight than the setup in Proposal A.

Protection and control for the power supply would be based on the same concepts as outlined in Proposal A. The rating of the main contactor would be less, as the load on the LV side will be significantly less. An estimate of the costs is outlined in Table 4.2.

ITEM DESCRIPTION	ESTIMATED COST
Materials	
HV Variable Inductor	$100,000
Case for contactor	$200.00
32Amp Male Socket for contactor box	$150.00
32Amp Female Socket for contactor box	$100.00
Control relay for contactor	$100.00
240V socket & switch for contactor control supply	$20.00
2 x Emergency Stops	$200.00
Sockets and leads for interface to E/S and protection relay	$100.00
Case for Protection Relay	$200.00
Protection Relay	$6,000.00
240V socket & switch for relay supply	$20.00
Sockets and leads for interface to CT, VT and contactor box	$100.00
400V/110V VT	$150.00
variac control motor and gears	$500.00
Labour	
Tradesman 40 hours	$2,800.00
Technician 40 hours	$3,400.00
TOTAL ESTIMATE	$114,040.00

Table 4.2: Cost estimate for Power Supply Proposal B

4.2.3 Power Supply Proposal Comparisons

The most obvious difference between Proposal A and B is the significantly higher cost of proposal B. However, the major downside of Proposal A over Proposal B is the significant weight disadvantage. It was estimated that power supply A would weigh up to 3,500kg more than Proposal A when using the 212kVA transformer or 1,500kg more when using the 25kVA transformer. This amounts to an increase transport cost of approximately $500 for local jobs and $1500 for the average interstate job. With an average of four interstate and six local jobs per year requiring this equipment, this amounts to a difference of $8,000 per year in transport costs.

Proposal A has the advantage of being a proven method with Silcar. As all the primary equipment has been successfully utilised within Silcar in the past, there was guarantee the equipment would satisfy the task.

4.3 Measurement Equipment Proposals

The two measurement equipment proposals will be outlined below.

4.3.1 Measurement Equipment Proposal A

This first proposal was economically attractive and still met all the design requirements set out in chapter three. The main measurement instrument in this proposal is the Doble M4100 Insulation Analyser with the M4120 External Reference Module. The M4120 External Reference Module enables the M4100 to be used purely as the measurement instrument with the HV supplied externally. The other requirement is that an external reference capacitor be used.

As Silcar already owns two M4100 units and two 30kV 100pF reference capacitors, the only major cost is the purchase of the M4120 module. The cost of the M4120 is approximately $3,000.

The tests are conducted using the same software used for normal DLA testing with the M4100. This has the advantage of staff familiarity and thus requires less training. All measurements are automatically taken, including automatic deductions for lead losses. This automated measurement reduces the possibility of human error.

According to Doble, the accuracy of the M4100 instrument using the M4120 module is the same as when it is used in its regular mode of operation. The Doble M4100 Technical Specification datasheets quotes a DLA accuracy of ±0.5% and typically ±0.0004. The Tettex 2805 claims an accuracy of ±1% for DLA readings, so this is within the design requirements. The Tettex 2805 does claim to have a better accuracy for capacitance of ±0.1%, whilst Doble only claim the M4100 is accurate to ±0.5%. This was technically outside the design requirements of equally or improving accuracy, however due to the DLA being more accurate with the M4100, this small level of uncertainty in the capacitance reading would be acceptable.

Using the M4100 with the M4120 module requires the use of a reference capacitor. The M4120 Application Notes (see Appendix C) state the reference current must be between 100µA and 15mA. Given Silcar owns a 100pF reference capacitor, the minimum and maximum test voltages can be calculated using formulas suggested by Robbins & Miller (2004):

$$Min\,Reference\,Current = 100\mu A$$
$$Max\,Reference\,Current = 15mA$$
$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50Hz \times 100pF} = 3.183 \times 10^7\,\Omega$$
$$Min\,Test\,Voltage = Min_{Iref} \times X_c = 3.183kV$$
$$Max\,Test\,Voltage = Max_{Iref} \times X_c = 477.46kV$$

As the reference capacitor has rated voltage of 30kV, the voltage range is 3.18kV - 30kV. The purchase of a 1000pF capacitor would reduce the minimum and maximum voltage by a factor of 10, to 318V – 47.7kV. At this stage it was proposed to try the 100pF capacitor first. The connections between the M4120 and the reference capacitor was intended to made via a clip lead provided with the M4120 module, however the reference capacitor socket was not compatible with this type of connection. A modified lead or connection box would be needed to make connection.

This proposal has significant financial advantages, though it does also have some negatives that must be considered. One being that it requires the use of a M4100 unit. The M4100 unit is quite bulky compared to a bridge setup due to the inbuilt power supply. Although this extra weight is not enough to significantly affect transport costs. This design proposal will also increase the amount of use of the M4100 unit and may cause issues with availability of test sets. Due to the measurement technique utilised by the instrument the power supply used to power the M4100 must be exactly the same frequency as the test supply. It is not foreseeable that this would be a problem, as both supplies are always taken from the power grid.

4.3.2 Measurement Equipment Proposal B

This proposal considered the purchase of a Tettex 2820 bridge. This is an electronic bridge that is software driven. Like proposal A, the bridge fulfils all the design requirements set out in chapter three. As of June 2009, the approximate cost of a Tettex 2820 was $77,000. This represents a significant price increase over Proposal A.

According to Tettex, the bridge provides a DLA accuracy of ±0.5% and a capacitance accuracy of ±0.05%, which is equal to or better than the existing Tettex 2805 bridge and the Doble M4100.

The bridge also requires the use of an external reference capacitor. The 100pF capacitor owned by Silcar would be suitable for this application. The bridge has a reference current range of 20µA to 300mA. From this we can calculate the voltage range for 100pF capacitor.

$$Min\ Reference\ Current = 20\mu A$$
$$Max\ Reference\ Current = 300mA$$
$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50Hz \times 100pF} = 3.183 \times 10^7\ \Omega$$
$$Min\ Test\ Voltage = Min_{Iref} \times X_c = 634V$$
$$Max\ Test\ Voltage = Max_{Iref} \times X_c = 1432kV$$

The max voltage reduces to 30kV due to the rating of the capacitor, giving a range of 634V to 30kV. This has an advantage over proposal A in that it can take readings down to a lower voltage and maintain accuracy. Once again a small cost in modifying a lead to interface between the bridge and reference capacitor would be required.

The Tettex 2805 has some other advantages over the M4100 and M4120 combination. The bridge includes a touch screen control panel, eliminating the need for a remote computer for control. Although control via a computer is still possible using an Ethernet connection. Also, because the bridge has no test supply capabilities, it is smaller and lighter than the Doble. Choosing this option would have also increased the testing capacity of Silcar Technical Services, whereas the other option utilises and existing test set.

Chapter 5 – Final Design Implementation

5.1 Introduction

The final design for the new HV DLA Test Apparatus was based on the proposals set out in chapter four. Power supply proposal A was chosen as the preferred optioned, mainly due to most of the equipment required being available to Silcar already. This meant the power supply could be constructed quickly at a relatively low cost. Also the method is proven within Silcar, so there was a guarantee the primary equipment would satisfy the desired task.

Proposal A was chosen for the Measurement Equipment. This option satisfied all of the design requirements and offered significant cost savings over the other proposal. The realisation of these proposals will be presented in the remainder of this chapter.

5.2 Power Supply

The power supply was developed as per Proposal A in chapter four. The protection and control devices were mounted in transportable cases that can be used with any variac / inductor / transformer combination. Appendix B contains a list of the transformers, variacs and inductors that can be used, including some photos. The simplified circuit schematic shown in chapter four, is repeated here as figure 5.1.

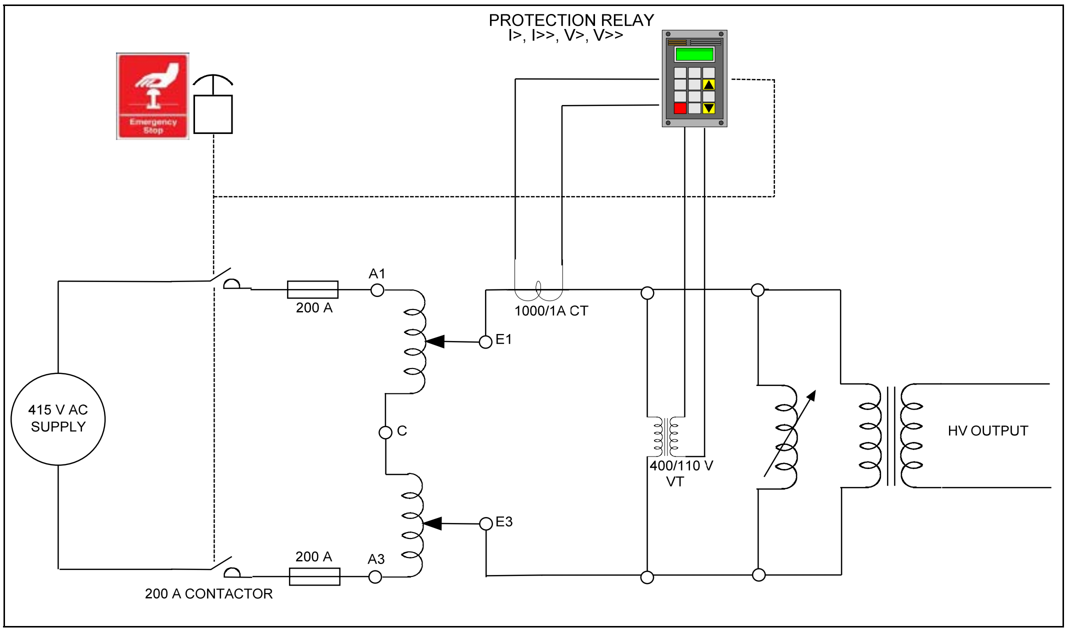


Figure 5.1: Simplified schematic of Power Supply

The contactor is used as the main circuit isolation and is controlled by a relay and a set of safety devices with normally closed switches. This circuit design produced with assistance of Mr Ci DiDios from Silcar. A simplified schematic of the control circuit is shown in figure 5.2.

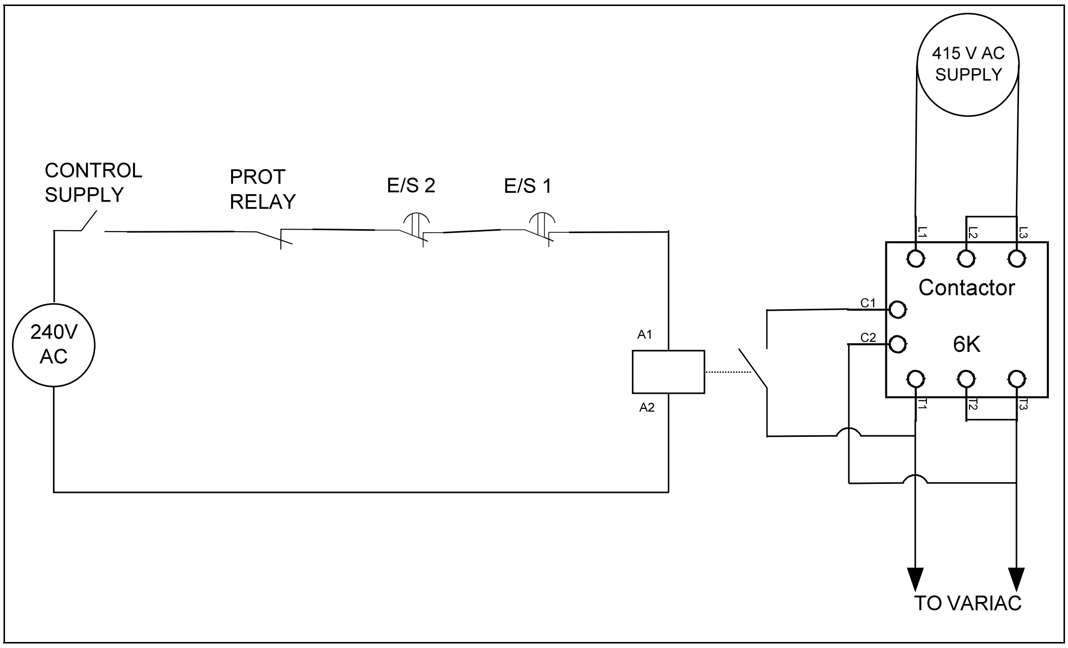


Figure 5.2: Simplified schematic of the contactor control circuit

The 200Amp contactor and control relay were mounted in a metal box with a hinged lid for easy access. This box has been named the "Contactor Box" and can seen in figure 5.3. Three phase power sockets are mounted either side of the Contactor Box for easy interface to the wall outlet and variac.

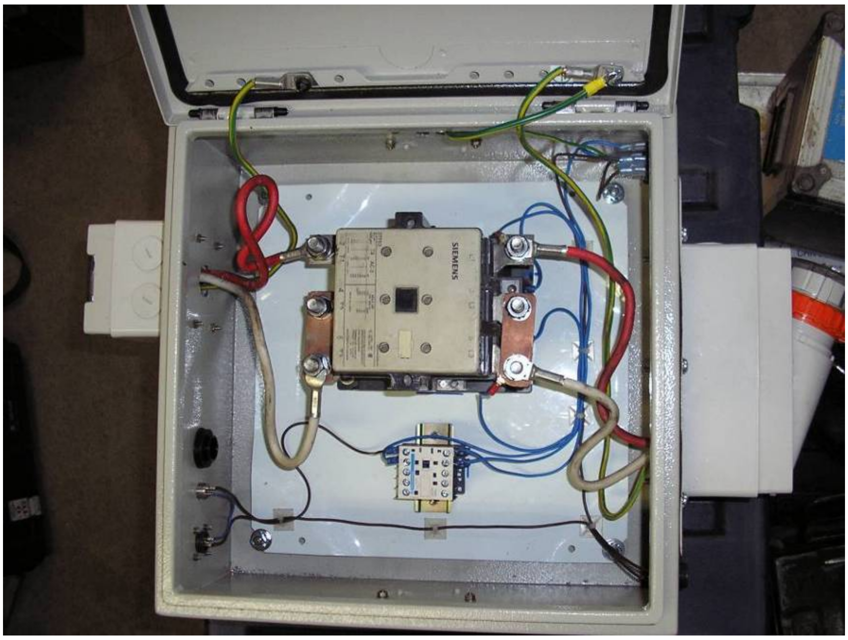


Figure 5.3: Photo of Contactor Box

Emergency stops interface with the contactor box as shown in figure 5.4. Two emergency stops are used, one for the operator and one for a remote observer.

Figure 5.4: Emergency Stop plugged into contactor box.

A Siemens 7SJ803 relay was purchased to provide the overcurrent and overvoltage protection for the power supply. Figure 5.5 shows the relay mounted in the same type of metal box used to house the contactor. The relay box has sockets at the rear to interface with the contactor box, CT, VT and 240V power supply from the wall outlet.

 a)  b)

Figure 5.5: Relay Box. a) Front view b) Side view with lid open

An existing connection box designed by Mr Lalit Varma from Silcar is used to connect the primary high current leads from the variac to the HV transformer and variable inductor. This primary connection box contains digital voltmeters and ammeters and can be used to monitor current in the power supply circuit. Two inductors can be hooked up in parallel if required for very high capacity loads. A photo of the connection box is shown in figure 5.6.

Figure 5.6: Primary Connection Box

5.3 Measurement Equipment

The measurement equipment was developed based on proposal A, with the purchase of Doble M4120 External Reference Module to be used in conjunction with the Doble M4100 Insulation analyser. Very little work was required other than to purchase the module and create connection box to interface the M4120 with the existing 100pF reference capacitor.

The 100pF reference capacitor is SF6 insulated capacitor which is screened. The connection on the capacitor was not directly compatible with the clip type connection supplied with the M4120 module. A connection box was created with a double screened lead used between the box and the capacitor. Figure 5.7 shows the capacitor, connection box and the M4120 module.

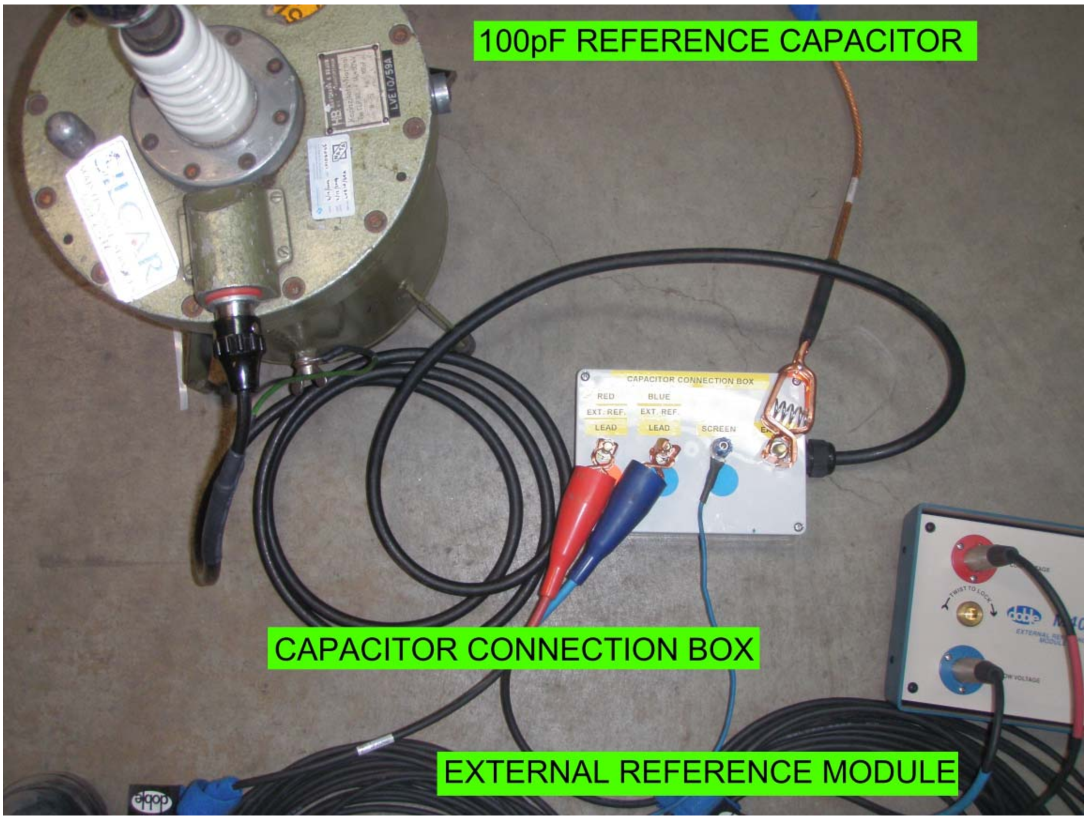


Figure 5.7: Measurement Equipment

The outer screen of the connection box lead is connected to the capacitor tank and the earth stud on the connection box. The inner screen of the lead is connected to the capacitor screen and both the centre blue studs of the connection box. The blue colour represents the guard circuit. The main conductor of the connection box lead is connected to the LV side of the reference capacitor and the red stud on the connection box. The red colour represents the reference measuring circuit. The colour codes on the connection box make for easy connection to the M4120 module.

The connection of the measuring circuit varies slightly depending if the test specimen tank is grounded or insulated. If the tank of the specimen is grounded, losses must be measured through the ground circuit. Doble calls this test a Grounded Specimen Test or GST. If the tank is isolated from the earth, the leakage current can be measured through a dedicated lead that is also isolated from earth. Doble calls this an Ungrounded Specimen Test or UST. Figure 5.8 shows the circuit setup for a GST test using the M4120 module.

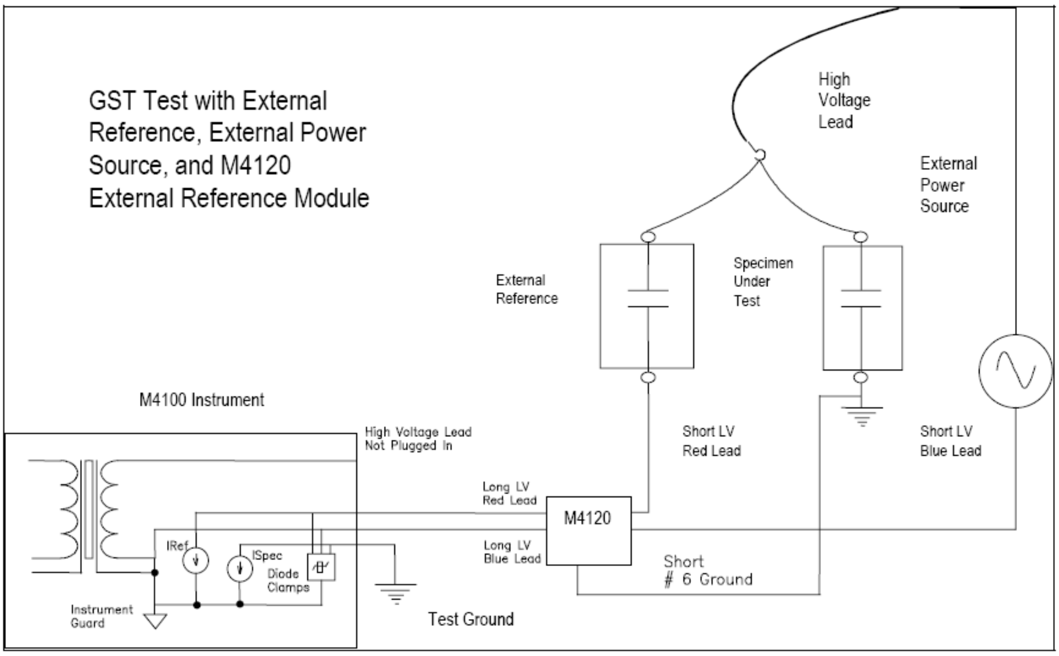


Figure 5.8: GST Test setup (Doble M4120 Application Notes, page 5)

As can be seen in figure 5.8 the specimen under test has a grounded tank, therefore leakages from the specimen insulation must be measured through the ground circuit. The Blue lead in this diagram is grounded through a guard circuit within the M4100 Instrument, allowing unwanted losses to be removed from the measurement. The capacitor connection box shown in figure 5.6 allows for the blue guard circuit to be connected to the HV supply transformer winding and the transformer screen to guard out any losses to earth. If an unscreened HV supply transformer is used, the transformer will be insulated from earth and the tank connected to the blue guard circuit. As the reference capacitor is screened, its screen is also connected to the guard circuit.

For UST tests, the problem of guarding out unwanted losses to earth is not an issue. Figure 5.9 taken from the Doble M4120 Application Notes shows the test setup for the M4120 External Reference Module in UST mode.

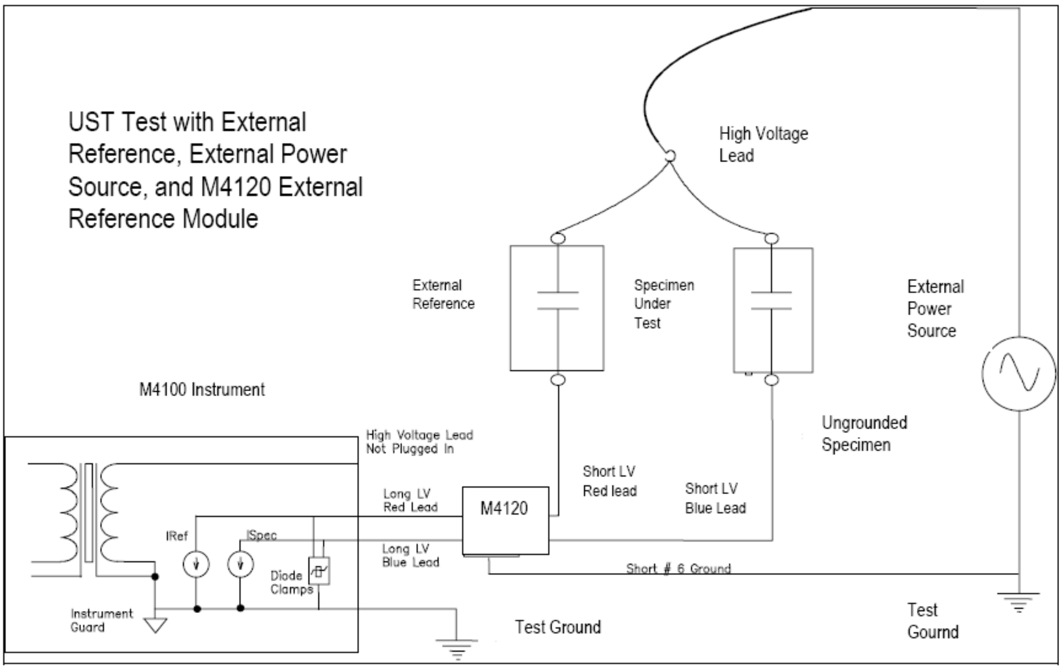


Figure 5.9: UST Test setup (Doble M4120 Application Notes, page 4)

It will be very unlikely that the M4120 module will ever be used in UST mode. If it is required the capacitor connection box can still used. The only difference will be that the blue lead from the M4120 will be connected directly to the test specimen flange as shown in figure 5.9. The blue stud on the capacitor connection box will be grounded, thus earthing the capacitor screen.

Chapter 6 – Experimental Testing Analysis

6.1 Introduction

Prior to the DLA test apparatus being placed into service for field testing a series of experimental tests were conducted to ensure safety, accuracy and reliability. The results and critical analysis of the experimental tests are presented in this chapter.

6.2 Power Supply Protection & Control Tests

The power supply consists of several safety devices that had to be proven through testing. The power supply also includes current and voltage monitoring devices that required calibrating. The tests were conducted using the 100Amp variac and 25kVA 20000/415V tests transformer. No test specimen was required for these tests.

The main isolation point for the power supply is the 200Amp contactor located in the contactor box. The contactor should only be closed if all safety devices are reset. Each device was individually checked and the results are displayed in Table 6.1.

SAFETY DEVICE AND CONDITION	EXPECTED CONTACTOR POSITION	ACTUAL CONTACTOR POSITION
All devices in a RESET and 415V & 240V ON	CLOSED	CLOSED
Emergency Stop 1 OPERATED	OPEN	OPEN
Emergency Stop 2 OPERATED	OPEN	OPEN
Protection Relay OPERATED	OPEN	OPEN
240V control supply switch OFF	OPEN	OPEN
240V control supply OFF	OPEN	OPEN
415V power supply OFF	OPEN	OPEN

Table 6.1: Safety Interlock test results

The current transformer (CT) used for input into the protection relay was checked for accuracy. A short circuit was applied to the high voltage side of the test transformer and the variac was wound slowly up. Readings on the relay display were taken at 50A, 100A and 150A. All results were compared to the ammeter in the connection box and were within ±1%. The CT and relay were deemed to be operating within an acceptable accuracy for the task and no further testing was required.

Following the CT calibration checks, some trip checks using the overcurrent function of the protection relay were conducted at various load levels. Initially the relay was set to trip instantaneously at 100Amps. With the short circuit on the HV side still applied the current was rapidly ramped up and the relay operated the contactor at 100Amps. A successful test was also repeated at 200Amps. The oscillographic fault record produced by the protection relay, also known as a Comtrade File, indicated the contactor was opened within 40msec of the fault being detected. This short clearance time will ensure the power supply and test specimen is well protected in the event of a fault condition.

The voltage measuring equipment was calibrated against a HV voltmeter used on the HV side of the circuit as well as a digital multimeter on the LV side. A voltage transformer (VT) with a ratio of 400V/110V is used to input into the protection relay for voltage measurement. Since the ratio of the test transformer is 20,000V/400V, a ratio of 20,000V/110V was programmed into the relay. Initial tests at various voltages indicated a large discrepancy between the high voltage meter and the protection relay. Further investigation revealed the error was in the VT, which had a ratio of 400V/128V not 400V/110V. The relay setting was adjusted to 20,000/128V and subsequent tests at 5kV, 10kV, 15kV & 20kV indicated a match between the relay and the HV voltmeter. Trip checks were completed using the overvoltage function of the protection relay.

6.3 Insulated specimen tests

There are two basic types of DLA tests; insulated specimen and grounded specimen. Doble refers to these tests as UST and GST respectively. A UST test is used when the casing of the tests specimen is completely isolated from earth, where as a GST test is used when the casing is solidly earthed. As the primary use of this apparatus will be for in-service generators the GST tests will almost certainly always be used. However it is possible that a UST test may be required, such as during a stator rewind on individual stator bars that could be isolated from earth. Therefore one set of UST experimental tests were performed. Refer to Chapter 5.3 for an explanation of the GST and UST test setup.

6.3.1 UST Tests on a 100kVA Transformer

The intended methodology was to conduct the tests using three different test apparatus and compare the results. Unfortunately the Tettex Type 2805 was missing a screened connecting lead used for UST tests and had to be replaced with a temporary unscreened lead. Therefore results for Tettex should be dealt with some scepticism. Tests were also conducted using the Doble M4100 unit and the new Doble M4120 External module.

The test specimen used for these tests was a 100kVA 3 phase transformer. In order to conduct the testing in UST mode, the transformer was placed on an insulating rubber mat and wooden crate. The LV was shorted to the tank and test supply was applied to the HV winding. Due to the 12kV voltage limit of the M4100, all tests were limited to 12kV so comparisons could be made. Test results are listed Table 6.2 and shown in graphical form in figures 6.1 and 6.2.

Test Voltage (kV)	Doble M4120 Ext Ref		Doble M4100		Tettex Type 2805	
	DLA	Cap (pF)	DLA	Cap (pF)	DLA	Cap (pF)
5.00	0.00552	5189	0.00566	5192	0.00642	5194
10.00	0.00564	5189	0.00572	5192	0.00649	5194
12.00	0.00571	5189	0.00577	5192	0.00653	5194

Table 6.2: UST DLA and capacitance test results

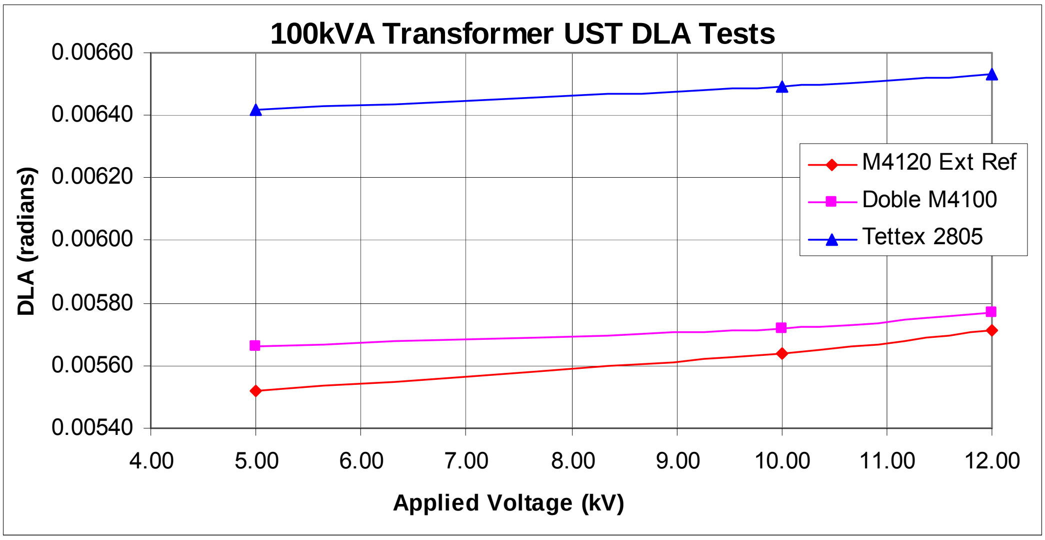


Figure 6.1: UST DLA test result comparisons for 100kVA Transformer.

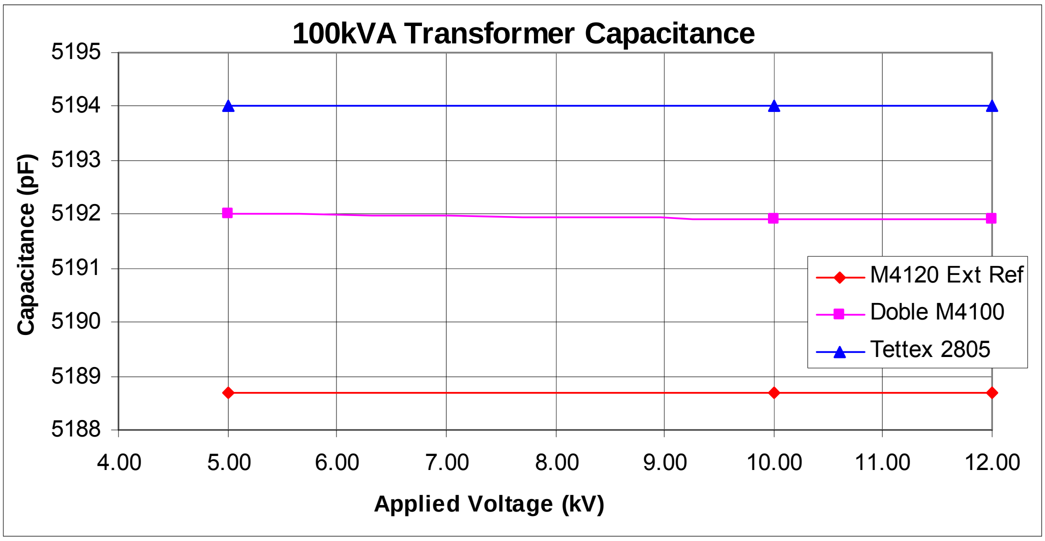


Figure 6.2: UST Capacitance test result comparisons for 100kVA Transformer.

Beginning with the DLA results, it can be seen there are some differences between the results of the three test apparatus. The measurements taken with the Tettex 2805 bridge shows larger DLA readings than the other two methods. Although the largest deviation between the three test sets was around 15%, this is only a difference in DLA of 0.0009 and is a relatively small discrepancy. However, considering the Tettex was used with an unscreened measurement lead, the measurements could be susceptible to external noise and the accuracy not guaranteed. Therefore it would be logical to rely on the M4100 for accurate measurements, as it is a calibrated instrument and was used as per the user manual instructions.

Now comparing the M4100 with the M4120 external reference module, the differences in reading are very small. With a max deviation of 0.00014 or around 2%, the differences are almost negligible. One reason for the small difference could possibly be attributed to the size of the reference capacitor. Because the reference current at 5kV is very small and nearing the minimum current threshold required, it is possible that there could be some external interference affecting the result. As the test voltage increased along with the reference current, the differences between the two test methods reduced and at 12kV the readings were almost identical. Repeating tests with a larger reference capacitor, possibly 1000pF would be required to prove this theory.

Reviewing the capacitance measurements taken by the three tests methods shows there is very little difference, with a max deviation of 5pF or around 0.1%. This falls within the quoted accuracy of the measurement instruments and differences are not significant enough to warrant any further investigation.

Overall the UST tests were satisfactory and sufficient to prove the accuracy of the new test apparatus. If UST tests were required above 12kV, the M4120 external reference module could be used with confidence of obtaining accurate results.

6.4 Grounded Specimen Tests

The test setup for a GST test differs slightly from a UST test. Because the casing of the test specimen is grounded, measurements are made with current returning through the ground circuit. Therefore any losses that occur to ground within the power supply must be guarded out of the measurement circuit.

As the new test apparatus will primarily be used for GST mode tests, more experimental testing was conducted than for UST mode tests. Three different test specimens were tested in total. Firstly a 100kVA transformer was tested in the Silcar test facility, then a 6.6kV 4750hp motor and finally a 20kV 400MVA generator, both at a local power station.

6.4.1 GST Tests on a 100kVA Transformer

The methodology for these GST test on a 100kVA transformer was the same as for the UST test. Three different measurement methods were used and the results compared. The missing screened test lead from the Tettex device is not used for GST tests, therefore all three measurement devices were in full working order. The 25kVA screened test transformer was used for the test supply for the Doble M4120 and Tettex 2805. Using the screened test transformer is preferable for GST tests as it less susceptible to external influences affecting the results. For these test the 100kVA transformer tank and LV windings were grounded and test voltage was supplied to the HV winding. The results can be seen in Table 6.3 or in graphical form in figures 6.3 and 6.4.

Test Voltage (kV)	Doble M4120 Ext Ref		Doble M4100		Tettex Type 2805	
	DLA	Cap (pF)	DLA	Cap (pF)	DLA	Cap (pF)
2.50	0.00838	3491	0.00708	3498	0.00773	3492
5.00	0.00716	3492	0.00711	3497	0.00777	3492
7.50	0.00726	3493	0.00726	3498	0.00792	3493
10.00	0.00775	3495	0.00765	3500	0.00830	3495
12.00	0.00812	3496	0.00823	3503		

Table 6.3: 100kVA Transformer GST DLA and capacitance test results

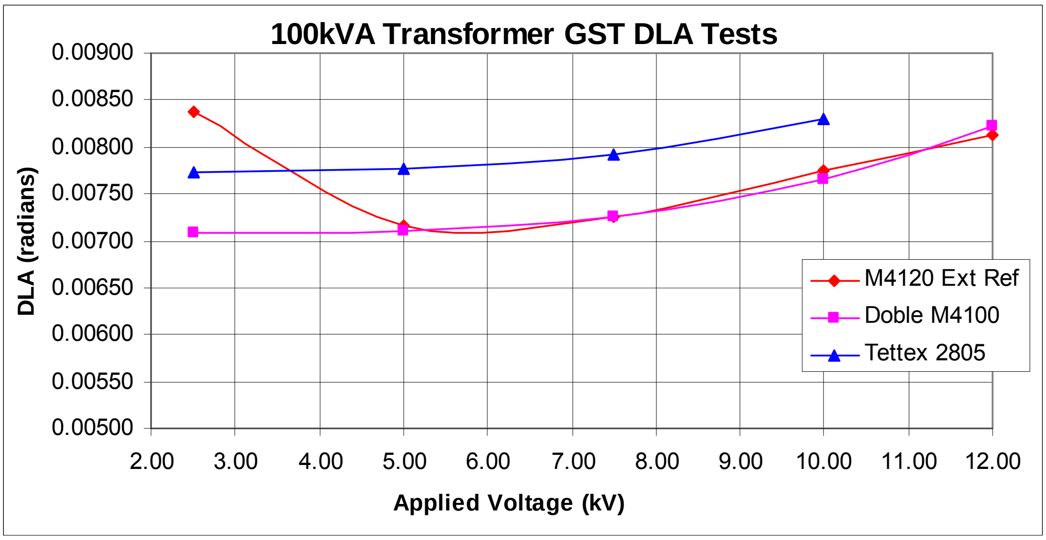


Figure 6.3: GST DLA test result comparisons for 100kVA Transformer .

The first point to note about the DLA results is the missing readings at 12kV for the Tettex 2805. This was due to an unstable null-indicator being used. This instability is believed to be caused from an aging null-indicator instrument.

The second obvious point is the high DLA reading at 2.5kV taken by the M4120. This is believed to be the result of using the instrument below the voltage range. The minimum test voltage required by the M4120 for a 100pF reference capacitor is 3.18kV. Above this test voltage, the M4100 and M4120 gave almost identical results, with very small deviations possibly coming from slight differences in the test voltages. The M4100 automatically sets and measures the test voltage, whilst manual voltage adjustment is required with the M4120. As voltage control is done with an autotransformer on the LV side of the tests circuit, the finest adjustment on the HV side is around 20volts.

Similar to the UST tests on a 100kVA transformer, the Tettex gives higher DLA readings than the Doble. The difference was consistently around 0.0006radians higher at any given voltage. The difference could possibly be attributed to an error in the null-indicator being used. Because the indicator is aging, the trace is no longer as sharp as it once was, making it difficult for accurate balancing of the bridge.

Human error in balancing the bridge is not a factor for the M4100 unit and is therefore more likely to be providing accuracies as quoted by the manufacturer. As the M4120 gave similar results to the M4100, it can be concluded the M4120 will give accurate DLA results for GST tests in a test laboratory environment, provided the voltage is above the 3.18kV threshold.

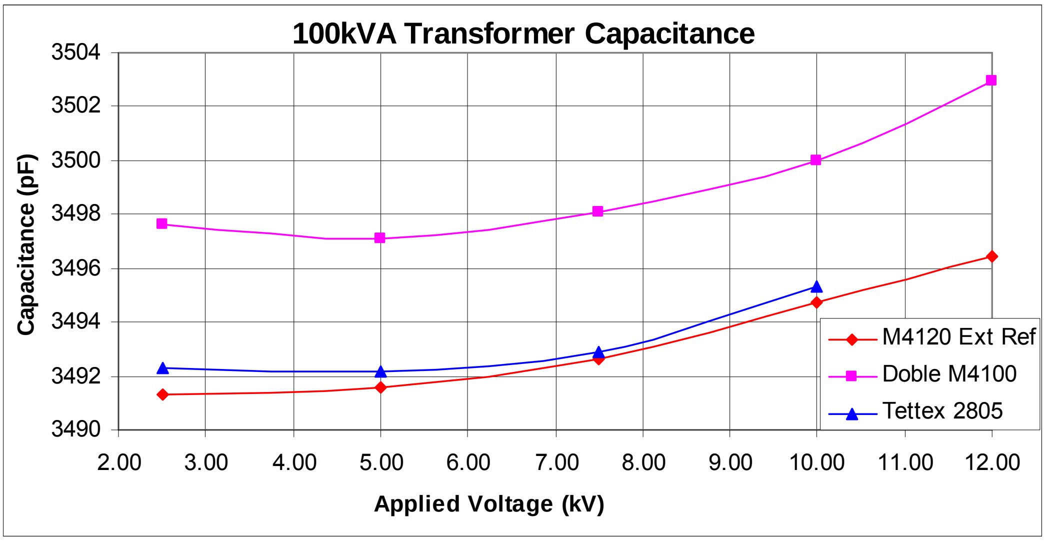


Figure 6.4: GST Capacitance test result comparisons for 100kVA Transformer.

The capacitance results show some slight deviation between the three tests methods. With a max deviation between the three of 0.25%, the capacitance measurements are very similar. Reasons for these differences could be attributed to the same reasons mentioned for the DLA results, however these small differences are of no concern and all methods seem to give accurate results.

6.4.2 GST Tests on a 6.6kV 4750hp Motor

Again the methodology for testing the 6.6kV motor stator was to use the three different devices and compare the results. The motor was tested onsite at a local power station during a plant outage. Due to time restrictions only the white phase winding of the stator was tested with all three devices. The testing was conducted using the 5kVA screened test transformer for the power supply. The motor stator casing was solidly grounded, thus the GST method applies. Results are tabulated in Table 6.4 and in graphical form in figures 6.5 and 6.6.

Test Voltage (kV)	Doble M4120 Ext Ref		Doble M4100		Tettex Type 2805	
	DLA	**Cap (pF)**	**DLA**	**Cap (pF)**	**DLA**	**Cap (pF)**
1.32	0.01203	70509	0.01154	70410	0.01243	70530
2.64	0.01232	70569	0.01185	70490	0.01287	70590
3.30	0.01316	70646	0.01272	70580	0.01379	70680
3.81	0.01449	70787	0.01376	70690	0.01498	70800
3.96	0.01491	70832	0.01409	70730	0.01523	70840
4.62	0.01615	71042	0.01564	70910	0.01680	71080
5.28	0.01822	71285	0.01728	71120	0.01902	71250
5.94	0.02003	71504	0.01910	71340	0.02101	71490
6.60	0.02240	71782	0.02118	71590	0.02306	71700

Table 6.4: 6.6kV Motor Stator GST DLA and capacitance test results – white phase winding.

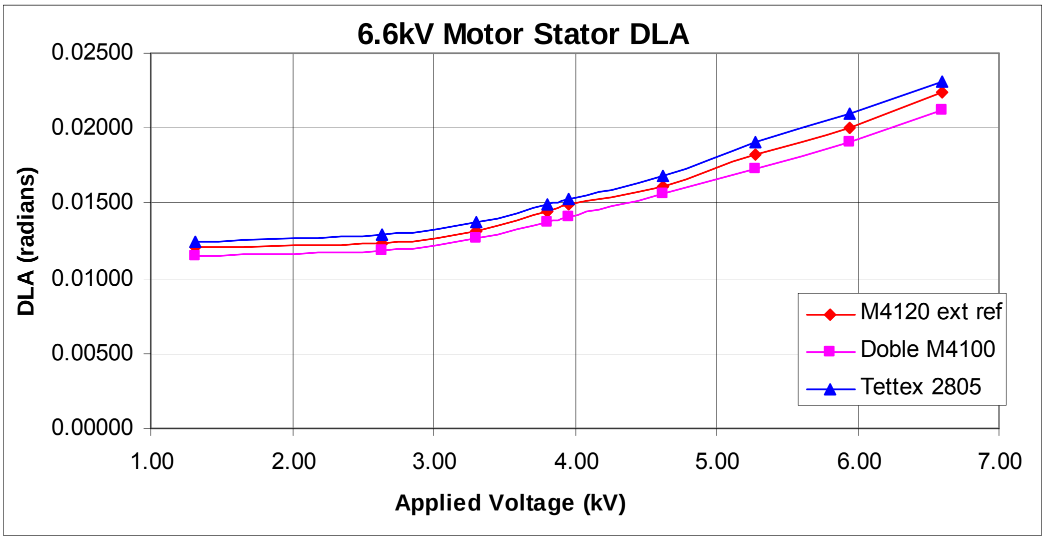


Figure 6.5: GST DLA test result comparisons for a 6.6kV Motor Stator – white phase winding.

Analysing the DLA results for the three tests methods reveals some significant deviation. The largest difference occurs between the M4100 and the Tettex 2805, with a consistent margin of approximately 10% at all voltages. According to Doble, GST tests can be susceptible to external influence and use some techniques to help mitigate these influences. One technique used by the M4100 is to conduct the tests at 45Hz and 55Hz to avoid 50Hz interference. The M4120 and Tettex 2805 do not have this altered frequency capability. These tests were conducted in an industrial environment and external influences could be influencing the results.

The method recommended by Doble for the reduction of external influences for the M4120 unit, is a reverse polarity test. This requires repeating all tests twice, once with normal polarity and again with the input polarity on the supply transformer reversed. The Doble then combines these results to calculate a corrected DLA and capacitance. Tettex also suggest the same tests, however the results must be combined manually. The reverse polarity test was not completed on this motor, due to time restrictions and unfamiliarity with the test procedure at the time. Due to the differences between the three tests sets, it would be logical to conduct reverse polarity tests in the future, when testing in an electrically noisy environment.

It is also worth noting that the Doble M4120 seemingly gave reasonably accurate readings at test voltages below the 3.8kV threshold.

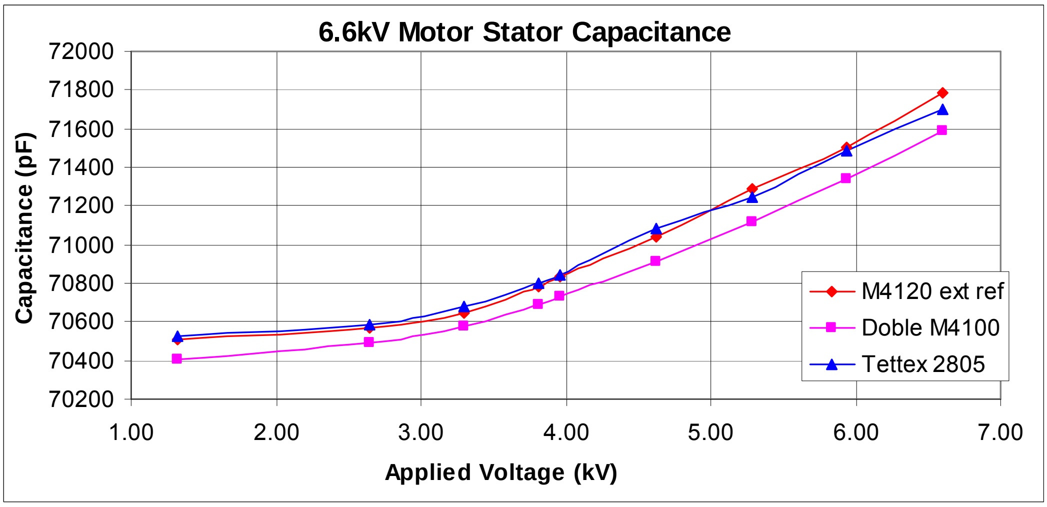


Figure 6.6: GST Capacitance test result comparisons for a 6.6kV Motor Stator – white phase winding.

The capacitance results for the motor also show some differences between the three methods. The M4120 and Tettex 2805 gave similar readings, whilst the M4100 had consistently lower measurements. This could again be attributed to the reverse polarity correction tests not being performed. That being said the largest deviation between all the results is about 0.2%, which is only a small margin.

6.4.3 GST Tests on a 20kV 450MVA Generator Stator

For this set of experimental tests, the indented methodology was to compare the M4120 with the Tettex 2805. A test voltage of up to 20kV was required for the test, therefore the M4100 was not used, as it has a maximum test voltage of 12kV. The 48kV 212kVA test transformer was used for the test supply.

On the day of testing the null-indicator used with the Tettex 2805 failed and no accurate measurements could be obtained. This only left the M4120 device and measurements were compared with tests conducted in 2006 using the Tettex 2805. This was not an ideal comparison due to the large time difference between tests, however the results were promising. Only the results for the red phase winding will be reported and discussed in this report, as the other two phases showed similar results. Results are tabulated in Table 6.5 and in graphical form in figures 6.7 and 6.8.

Test Voltage (kV)	Doble M4120 Ext Ref – 2009 Test results		Tettex Type 2805-2006 Test results	
	DLA	Cap (pF)	DLA	Cap (pF)
2	0.01227	402540	0.01300	402820
4	0.01313	402680	0.01310	403300
6	0.01372	403050	0.01350	403660
8	0.01450	403510	0.01400	403960
10	0.01530	403930	0.01470	404450
12	0.01614	404490	0.01570	405010
14	0.01668	404970	0.01580	404960
16	0.01716	405510	0.01640	405500
18	0.01744	405960	0.01690	406140
20	0.01772	406280	0.01740	406610

Table 6.5: 20kV 400MVA Generator Stator GST DLA and capacitance test results – red phase winding.

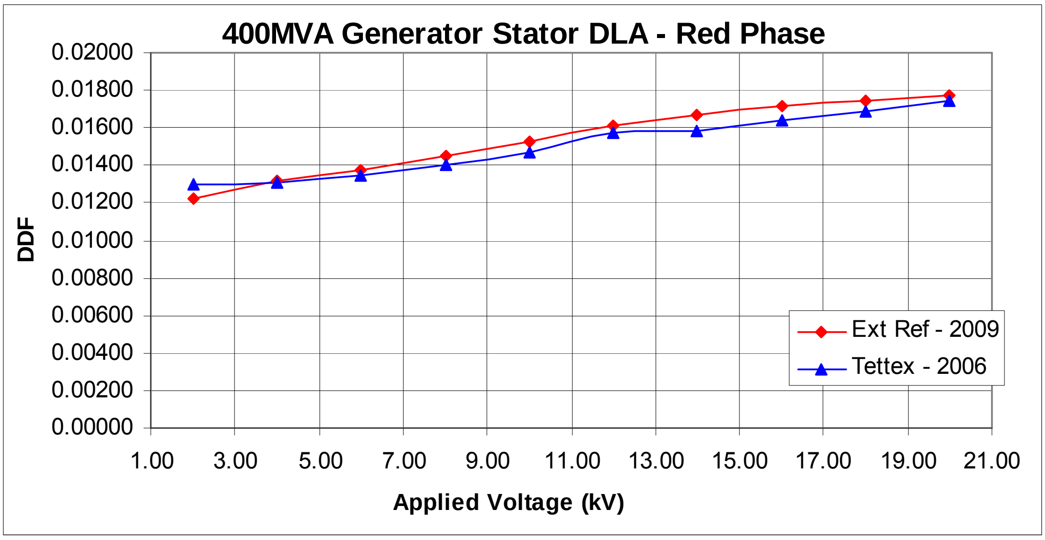


Figure 6.7: GST DLA test result comparisons for a 20kV 400MVA Generator Stator – red phase winding.

Making definitive comparisons between the two DLA results is difficult due to the time difference between tests. The insulation properties of the stator could have changed over the three year period and also temperature differences on the days of testing could have slightly affected the results. Nonetheless, it is the same stator and it is expected that the values should be similar unless severe deterioration had occurred. In this case the DLA readings at all test voltages are similar in both 2006 and 2009.

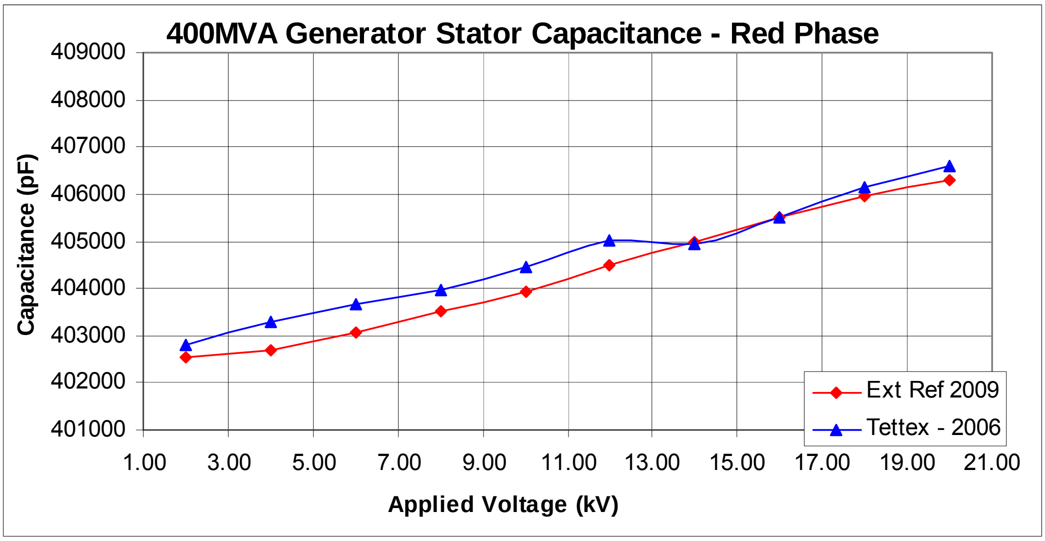


Figure 6.8: GST capacitance test result comparisons for a 20kV 400MVA Generator Stator – red phase winding.

Again due to the time difference, meaningful comparisons between the capacitance results are limited. It should be noted that a "lead loss" test was not conducted in 2006 with the Tettex 2805. This test is conducted with the lead not connected to the test specimen and a set of measurements taken. The capacitance value is deducted from the readings obtained. The lead loss obtained in the 2009 test was approximately 400pF. If a lead loss of 400pF was assumed for the 2006 tests, the differences between the two would be less.

Chapter 7 - Conclusions

7.1 Achievement of Project Objectives

Research was conducted into the theory and purpose of DLA testing as well as techniques used for DLA testing. The knowledge gained from this research enabled the successful development of DLA test apparatus.

The DLA tests apparatus was developed using new and existing equipment from within Silcar's Inventory for both the power supply and measuring equipment components, satisfying one of the key objectives of the project.

The experimental testing provided evidence that the apparatus could perform the required task and produce accurate measurements. The control and protection devices implemented on the power supply have improved the safety of HV DLA testing for Silcar personnel and their clients.

7.2 Future Work

The outcomes of this project have satisfied the original objectives, however there is a potential for future work on the subject. The experimental testing revealed some minor deviation of results between the test methods. Further experimental tests and comparisons would be required to explain these deviations. Further investigation into the effects of external influences on test results would also add value to the topic.

Although not a key objective, one of the intentions was to have two working DLA test apparatus capable of testing up to 24kV. Due to the improvements in safety of the new power supply and the advantages of the new automated measuring equipment, it is not likely that the existing system would be used in its current form. Sufficient primary equipment exists to have two test apparatus, therefore the protection and control equipment could easily be duplicated and another M4120 external module purchased.

REFERENCES

Doble Engineering Company, *M4100 Insulation Analyser*, Doble Engineering Company, USA, viewed 2nd May 2009, <http://www.doble.com/products/m4000_features.html>

Doble Engineering Company, *M4100 Technial Specifications*, Doble Engineering Company, USA, viewed 22nd August 009, <http://www.doble.com/litlib/files.html/download/63>

Doble Engineering Company, *M4120 Application Notes*, Doble Engineering Company, USA, viewed 4th June 2009, <http://www.doble.com/support/download_m4000.html>

Farahani, M, Borsi, H, Gockenbach, E & Kaufhold, M 2005, 'Partial discharge and dissipation factor behavior of model insulating systems for high voltage rotating machines under different stresses', *IEEE Electrical Insulation Magazine*, Volume 21, Issue 5, Sept-Oct, pp. 5-19.

Institute of Electrical and Electronic Engineers 1995, *Guide for diagnostic field testing of electric power apparatus - part 1: oil filled power transformers, regulators, and reactors,* IEEE std 62-1995, Institute of Electrical and Electronic Engineers, New York.

Institute of Electrical and Electronic Engineers 2000, *Recommended Practic for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation,* IEEE std 286-2000, Institute of Electrical and Electronic Engineers, New York.

James, RE & Su, Q 2008, *Condition Assessment of High Voltage Insulation in Power System Equipment,* The Institute of Engineering and Technology, London.

Kind, D & Freser. K 2001, *High Voltage Test Techniques*, 2nd edition, Newnes, Oxford.

Kind, D 1978, *An Introduction To High-Voltage Experimental Techniques*, Vieweg, Germany.

Naidu, MS & Kamaraju, V 1995, *High Voltage Engineering,* 2nd edition, McGraw Hill, New York.

Muhr, M, Knollseisen, G, Schwarz, R, Sumereder, C, 2006, 'Comparison of methods for the dissipation factor measurement', *51st Internationales Wissenschaftliches Kolloquium,* Technische Universität Ilmenau, Sept 11 – 15 2006.

Rojas A 2006, ‘Power Factor Testing in Transformer Condition Assessment -Is There a Better Way?’, *Proceedings of the Transmission and Distribution Conference and Exposition: Latin America,* IEEE/PES, Aug 15-18, pp 1-4.

Robbins, A & Miller, C 2004, *Circuit Analysis with Devices: Theory and Practice,* Delmar Learning, Ney York.

Schwab, AS 1972, *High Voltage Measurement Techniques,* The Massachusetts Institute of Technology, Massachusetts.

Standards Australia 2008, *Insulated bushings for alternating voltages above 1000V* , AS 60137-2008, Standards Australia, Sydney, viewed 08 May 2009, <http://www.saiglobal.com.ezproxy.lib.monash.edu.au/online/autologin.asp>.

Standards Australia 2008, *Power Transformers Part 3 - Insulation levels, dielectric tests and external clearances in air*, AS 60076.3-2008, Standards Australia, Sydney, viewed 08 May 2009, <http://www.saiglobal.com.ezproxy.lib.monash.edu.au/online/autologin.asp>.

Steed, J 2001, ‘Life management of electrical plant’, in Ryan, HM (eds), *High Voltage Engineering & Testing,* 2nd edition, The Institute of Engineering and Technology, London.

Tettex AG Instruments 1976, Product manual for ‘Type 2805 – Portable Measuring Bridge for Capacitance and Dissipation Factor’, Tettex AG, Zurich.

Tettex Instruments, *2820 Automated C, L & tan d/ cos j measuring bridge*, Haefely Test AG, Switzerland, viewed 2nd May 2009, < http://www.haefely.com/pdf/LL_2820.pdf>

Tettex Instruments, *2877 Automatic C, L & tan d/ cos j precision measuring bridge*, Haefely Test AG, Switzerland, viewed 2nd May 2009, < http://www.haefely.com/pdf/LL_2877.pdf>

Tettex Instruments, *MIDAS Mobile Insulation Diagnosis & Analysing System*, Haefely Test AG, Switzerland, viewed 2nd May 2009, <http://www.haefely.com/pdf/LL_MIDAS288x.pdf>

Virsberg, LG, 1966, *The H.V. testing of electrical large machines, particularly at 0.1Hz,* ASEA 8323 E, Switzerland.

APPENDIX A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	**SHANE BACKMAN**
TOPIC:	DEVELOPMENT OF HIGH VOLTAGE DLA (DIELECTRIC LOSS ANGLE) TEST APPARATUS.
SUPERVISOR:	TONY AHFOCK
ENROLMENT:	ENG4111 – S1, EXT, 2009 ENG4112 – S2, EXT, 2009
PROJECT AIM:	To develop a high voltage DLA test apparatus from new and existing equipment in order to expand SILCAR HV&ES Technical & Engineering Services testing capacity. The test apparatus should be capable of producing voltages up to at least 20kV.
SPONSORSHIP:	Silcar Pty Ltd. – HV&ES division

PROGRAMME: **Issue A, 27th February 2009**

1. Research background information relating to the theory of DLA testing and purpose of conducting DLA testing on High Voltage Equipment, such as generators and transformers.

2. Research current techniques and apparatus used in industry to perform DLA testing on high voltage equipment.

3. Itemise Silcar HV&ES existing equipment and determine whether any of it can be used in constructing the new test apparatus.

4. Develop at least two conceptual designs to present to Silcar HV&ES management.

5. Upon approval of a design, purchase and/or manufacture any required equipment and construct apparatus.

6. Conduct testing of new test apparatus to ensure the apparatus is fit for purpose.

AGREED:

______________________(student) ________________________ (supervisor)

Date: _____/_____/ 2009 Date: _____/_____/ 2009

Examiner / Co-examiner: ____

APPENDIX B

List of Primary Equipment

Description	Image
25kVA 200-400/20kV Screened Test Tranaformer ID: SILGIP-2-663 Weight: 570kG	
212kVA 440V/48.7kV Test Transformer ID SILGIP-2-770 Weight: 2,420kG	
5kVA 200-400/25,000kV Screened Test Transformer ID SILGIP-2-774 Weight: 95kG	

Table B.1: List of primary equipment, page 1 of 3

Description	Image
25kVA 250-500/22kV Test Transformer ID: SILGIP-2-765 Weight: 250kG	
100Amp 415V Variac Motorised Control ID: SILGIP-2-736 Weight: 633kG	
200Amp 440V Variac Motorised Control ID: SILGIP-2-737 Weight: 878kG	

Table B.2: List of primary equipment, page 2 of 3

Description	Image
28Amp 415V Variac Manual Control ID: SILGIP-2-764 Weight: 70kG	
100Amp 415V Vertical Variable Inductor Range: 0.3mH – 57mH ID: SILGIP-2-772 Weight: 800kG	
100Amp 415V Horizontal Variable Inductor Range: 0.3mH – 58mH ID: SILGIP-2-773 Weight: 750kG	
Doble M4100 Insulation Analyser Max voltage output: 12kV ID: SILGIP-2-798 Weight: 50kG	

Table B.3: List of primary equipment, page 3 of 3

APPENDIX C

Doble M4120 Application Notes

M4000 PRODUCT LINE

APPLICATION NOTE: M4120:01

Subject: Using the M4100 with an External Reference and Power Supply.

Scope: Define a procedure for performing a power/dissipation factor test for voltages greater than 12 kV combining the M4100 and the M4120 External Reference Module.

INTRODUCTION

The M4100 has an internal power supply and reference element for testing potentials up to 12 kV. For test potentials greater than 12 kV, the M4100 serves solely as the measurement instrument and operates in conjunction with an external reference and power supplies:

- The external reference, typically a capacitor (such as the Hipotronics 3300 series or Haefely NK series), provides the means for M4100 measurement of the test voltage. The M4100 monitors the voltage, displays the test potential and uses the voltage as the reference in calculating the real and reactive components of the measured current. See the *Test Parameter* section for the calculation to determine the appropriate capacitor size.
- The external power supply, usually a step-up transformer, provides the test potential. Hipotronics manufactures high voltage AC transformers for test applications.

For potentials greater than 30 kV RMS, the M4120 provides surge protection. See *Surge Protection for Tests Above 30 kV*.
Two important issues to properly complete testing are:

- *Interference Cancellation*
- *Eliminating Test Lead Loss*

Interference Cancellation

In the External Reference mode, the M4100 operates under electrostatic interference conditions. The line synchronization reversal technique rejects this interference by shifting the applied voltage 180^0. This technique requires that two successive tests be run, reversing the polarity applied to the external power supply between tests, and then averaging the results. The M4000 software multiple test option can run tests at different voltages, repeat the tests with the polarity reversed and then automatically combine the appropriate results.

Eliminating Test Lead Loss

The M4100 high voltage lead is double-shielded and can guard away lead losses from its measuring circuit. This high voltage lead should not be exposed to electrical stresses in excess of 15 kV. If an alternative high voltage lead is used to supply the test potential, it should be configured so that the lead losses are guarded away. The guard circuit is designed to handle current up to 5 A. If the losses associated with this lead cannot be guarded, additional tests should be performed to compensate for the lead losses.

- If a UST (ungrounded specimen test) is performed, high voltage lead losses do not affect the results.
- If a GST (grounded specimen test) is performed, a second set of tests to measure the high voltage lead losses (normal and reversal if electrostatic suppression is required) are performed with test leads disconnected from the apparatus under test. If a resonating inductor is used to compensate for the capacitive load of the test specimen, removing the test specimen may require removal or adjustment of the inductive load. The External Reference software automatically subtracts these losses from the results obtained on the apparatus. *These additional tests are only required in the GST Guard test mode*.

TEST PARAMETERS

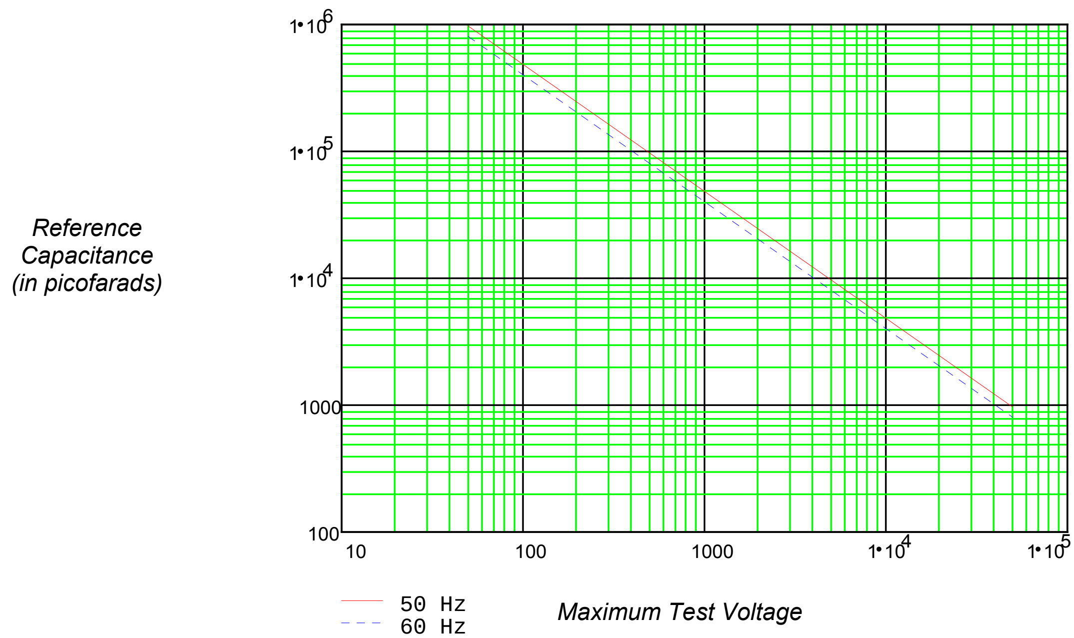
The test parameters are:

- Maximum Reference Current = 15 mA RMS (21.2 pk)
- Minimum Reference Current = 100 uA RMS

The following parameters are used to both validate that the test configuration meets these requirements and to determine the reference capacitor maximum value:

V_{max} = maximum test potential
C_{ref} = value of reference capacitor
I_{ref} = reference current

Maximum Test Voltage
The graph below shows maximum test voltage on the y-axis versus Reference Capacitance, in picofarads, on the x-axis for both 50 and 60Hz test frequencies.



The maximum allowable test voltage is limited by the rating of the External Reference Capacitor, or by the voltage capability of the available external source, provided the criteria for maximum allowable reference current is not exceeded.

Test Voltage Range
The accuracy of the M4100 in the External Reference mode is within the published specifications for all test voltages from 10% to the full Entered Maximum Test voltage. For example, given a Maximum Test Voltage of 30 kV, the measurement accuracy is guaranteed to be within published specifications down to 3 kV.

SETUP

The M4100 power amplifier and safety switches are disabled while a test is running; therefore, all safety procedures, which are used in good high voltage testing practice, must be rigorously observed.

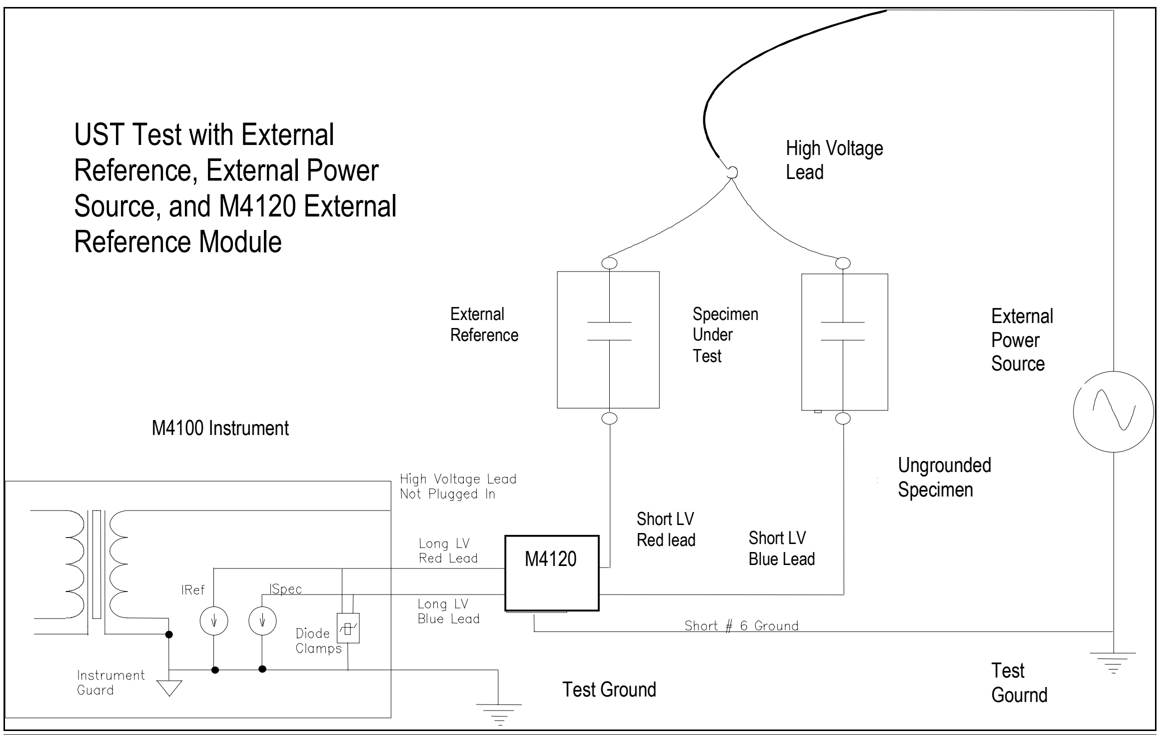
Reference I.E.E.E Standard 510-1983 Recommended Practices for Safety in High Voltage and High Power Testing.

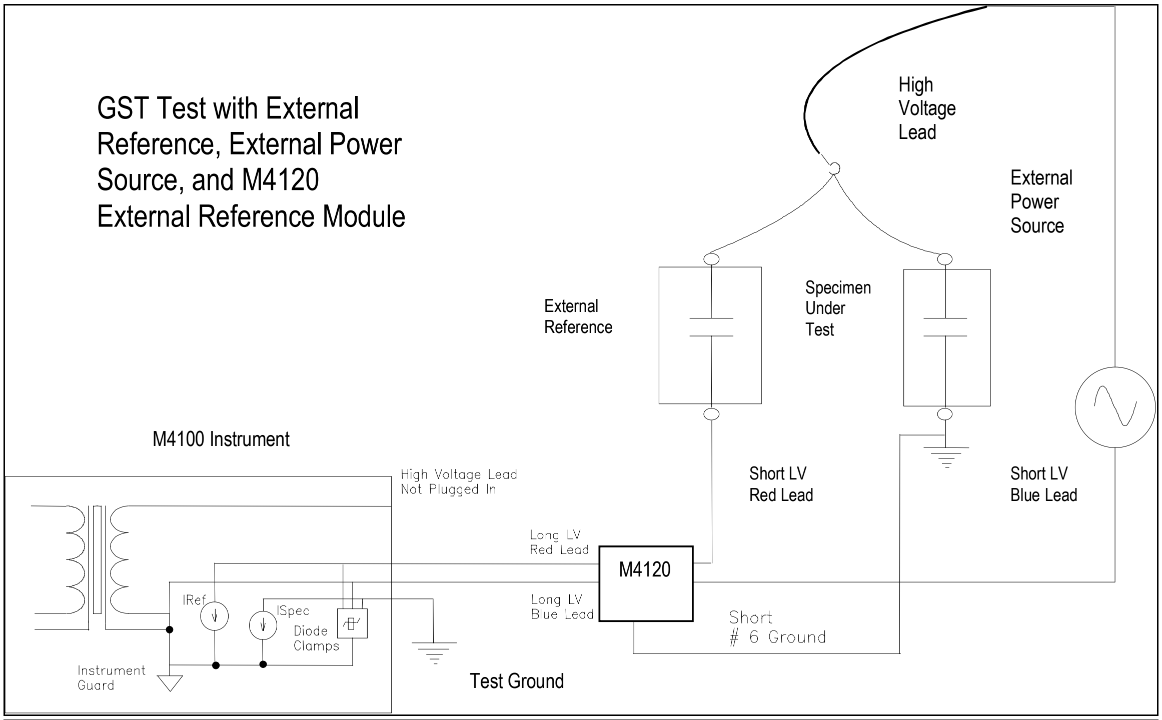
To set up the test:

1. Input the **Capacitance** and **Power Factor** of the external reference and the **Maximum Test Voltage** into the software.
   The software does a preliminary calculation to set up voltage scaling and to insure that the maximum reference current limit is not exceeded.
2. Power the M4100 from the same AC source as the power source used to energize the test circuit.
   The M4100 must operate in the Line Synchronized mode, requiring the M4100 to synchronize to the input source.
3. Connect both low voltage leads to the M4100.
   In most instances, the high voltage lead is not be used.

4. Start the M4000 External Reference option from the main screen.
   The instrument turns on its data acquisition network, while the test specimen and external reference are energized to the designated test voltage by the external power source.
   Once the External Reference software is selected, the M4100:
   - Automatically disconnects the low side of the internal high voltage reference resistor.
   - Routes the current from the red lead (which is connected to the low voltage side output terminal of the reference capacitor) into the reference measurement channel. The red low voltage lead serves as the reference path and current from the specimen branch is measured by the blue low voltage lead.

Test Setup with M4120 External Reference Module





M4120 SURGE PROTECTION FOR M4100 TESTS ABOVE 30 KV

The M4100 is equipped with heavy duty clamps to protect its input against large transient surges. At higher voltages, as is the case in the external reference mode, this input protection may prove inadequate in handling a Specimen or Reference Capacitor arc over to ground. Since most high quality Reference Capacitors are equipped with small spark gaps between the low side output terminal (UST tap) and the grounded shell at the bottom, the M4120 ensures maximum protection to the M4100 and the Reference Capacitor.