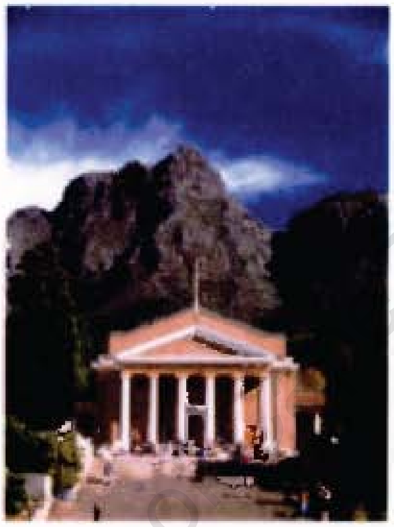
THE DEVELOPMENT AND TESTING OF A FAULT-TOLERANT SERIES RESONANT DISTRIBUTION NETWORK



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August 2004

Thesis prepared in fulfilment of the requirements for the degree of Master of Science in Engineering

Acknowledgements

- Professor Gaunt for his continuous guidance, patience and support
- Chris Wozniak for patiently assisting me with the practical aspects of the thesis
- Ben Sebitosi for giving invaluable insight into the theory of voltage regulation
- Dave Johnson for assisting me and for providing the heating loads
- Tony Britten and Kohlie Kohlmeyer for funding and supporting the research
- Clinton Slabbert and Professor Malangret for designing and building the load end compensator
- Mbulelo Jojozi for "paving the way" in research on the behaviour of power arcs
- My parents, Barbara and Graham Cross, for inspiring me to make the best of myself
- My husband, Michael Goemans, for seeing me through the tough times and believing in me

This thesis is dedicated to my late grandfather, David Cross, who showed all of us what it means to be a good engineer and an even better man.

Declaration

I, Nicola Cross, hereby declare that the work presented in this thesis is my own original work and all work obtained from other sources has been properly referenced.

I also declare that the work presented in this thesis has not previously been submitted to any university for the purpose of obtaining a degree.

N. Cross

Signature:____________________ Date :_________________________

Terms of Reference

Professor C. T. Gaunt of the University of Cape Town initiated and supervised the research undertaken for the completion of this thesis. He requested that a novel, patentable, fault-tolerant technology be tested in a medium voltage laboratory to determine its efficacy and viability.

The specific requirements were to:

- Develop the theory governing a fault-tolerant, series resonant network
- Design and implement an appropriate test protocol
- Test the effect of the technology on power arcs caused by transient earth faults
- Test the success of the technology under various load conditions
- Determine the stability of the proposed system
- Record and interpret the results of the tests performed on the network
- Draw relevant conclusions
- Produce a dissertation based on the theoretical research and the tests carried out in the medium voltage laboratory.

Synopsis

Faults on distribution lines are frequently caused by transient events such as lightning and storms. A direct lightning strike to a line causes a flashover, which may result in a power arc, leading to breaker intervention for protection purposes. This, in turn, increases the customer's exposure to voltage variations and interruptions, resulting in poor quality of supply. The proposed fault-tolerant technology aims to negate the sustainability of power arcs, thereby preventing the need for interruption of supply, which will improve power quality. An arc will self-extinguish if the magnitude of the fault current flowing through it is too small to support the large voltage gradient required to ionise a gap of a specific length. The technology proposes to limit the short-circuit current by means of a large series reactance in the phase conductor of the source transformer. This large reactance causes a significant volt drop in the supply circuit, resulting in an unacceptably low voltage across the circuit's load. It is a "series resonant" concept because this decreased load voltage is regulated by means of an active capacitive load-end compensator.

The active capacitive compensator is connected in parallel across the load and injects reactive power into the circuit which replaces the reactive power required by the supply reactance, and supplied by the source. Because less total current is therefore flowing through the supply impedance, the volt drop across it is not as large and the load voltage is maintained at a level equal to that of the open circuit supply voltage.

The theoretical response of the power arcs to the added reactance in the supply circuit was tested in a medium voltage laboratory. The proposed testing circuit simulates a medium voltage distribution line using a 32kVA ±240/19000V step-up transformer. A large supply impedance is created by means of reactors that are added to the supply circuit. Arcs are initiated on the MV line and measurements of arc duration and arc current magnitude determine the effects of the added impedance on the arcs. The voltage is stepped down by means of a 16kVA 19000/240V transformer. A load is connected to the LV side of the step-down transformer, and the effect of the high source impedance on the load voltage is determined. The compensator is then connected in parallel with the load and its efficacy is determined by means of comparing the compensated load voltage with the source voltage. The effect of loads of varying magnitude and power factor on the power arcs and compensator is then determined by connecting resistive, complex and motor loads. The stability of the system is also tested by means of connecting an unloaded, inductive motor load.

The tests show the proposed technology to be successful in its attempts to reduce the magnitude and duration of transient short-circuit currents. In steady-state conditions, the compensator is able to maintain the load voltage at the required value so that no apparent volt-drop in the

network is evident. In fault conditions, the magnitude of the load voltage decreases while the power arc is burning but increases rapidly, returning to its desired value within a few seconds. The compensator is able to respond to changes in load. If a load of larger magnitude, or lagging power factor is connected, the compensator switches in more capacitors so that the large volt drop in the supply circuit is negated.

Acronyms and Abbreviations

AC	alternating current
ARC	auto re-closer
d	distance
DC	direct current
DSP	Digital Signal Processing
E	electric field strength
IDMT	Inverse Definite Minimum Time
IEEE	Institute of Electrical and Electronic Engineers
MAV	minimum arc voltage
NERC	North American Electric Reliability Council
Ng	ground flash density
NRS	National Regulatory Service
P	real power
pf	power factor
pu	per unit
Q	reactive power
RAV	recovery arc voltage
rms	root mean square
SWER	Single Wire Earth Return
Δ	change in
ω	radian frequency

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Chapter One

Introduction

This thesis presents the development and testing of a fault-tolerant series resonant distribution network. The system was proposed by C. T. Gaunt of the University of Cape Town. The objective of the scheme is the improvement of quality of supply because it aims to reduce the number of interruptions on overhead distribution lines. Faults on distribution lines are frequently caused by non-controllable, transient events such as lightning, storm winds and pollution flashover.

When lightning strikes an overhead distribution line, it causes a significant overvoltage on that line. This overvoltage may lead to flashover to ground which may, in turn, result in a power arc. If the arc burns for long enough, the feeder's protection will see an earth fault on the system and will respond by tripping the feeder breaker. This will cause a brief interruption for the customers supplied by that distribution line (until the ARC has re-closed the breaker). These transient interruptions are preventable if the duration of current flow in the power arc is sufficiently short that the feeder protection does not respond.

The duration of arc-burning can be reduced significantly if the short-circuit current flowing through the earth fault has insufficient magnitude to sustain the power flow through a gap of adequate length. A limited arc current will be unable to support the voltage required to ionise the air in the arc gap and the arc will self-extinguish rapidly. Earth faults that appear on a feeder or distribution line are registered by the earth fault relay on the protection system. The earth fault relay sends a message to the feeder breaker which causes it to trip. The earth fault relay functions according to an Inverse Definite Minimum Time (IDMT) curve. This curve essentially functions according to a current magnitude-time function in which a smaller fault magnitude will cause the feeder breaker to trip in a longer time. Thus, if the proposed technology can limit the earth fault current sufficiently, the trip time of the breaker will be longer than the burning time of the earth fault arc.[9]

The most effective means of limiting a fault-current is by adding a large impedance in the series path of current flow. This increased impedance will, however, increase the volt drop in the supply circuit, providing an unacceptably low load voltage at the on the LV system. This problem can be solved by the inclusion of a load-end compensator which will regulate the load voltage in order to maintain it at a required magnitude. The technology that is proposed by this thesis is novel and viable because the load-end compensator is active; in other words it is able to respond immediately to changes in load magnitude or power factor.

This chapter will introduce the topic in further detail by examining the background to the study. It will state the objectives of the research and the questions that must be answered in order to prove or disprove the central hypothesis of the thesis. The chapter will also present the scope and limitations of the research conducted for this thesis, and will describe the plan of development for the rest of the thesis.

1.1 Background to the problem

The compensator's contribution to the proposed technology is based on the principle of resonance. This principle states that at a certain frequency, the capacitive and inductive reactances "cancel each other out" and this leaves only the resistive part of the total impedance to limit the current in the circuit.

The concept of resonance in feeders is well-known. It is applied in Petersen coil earthing of system neutrals to reduce disruption of supply by single-phase-to-earth faults [36]. The neutral earthing reactor is selected to produce resonance with the feeder conductor capacitance. This reduces the fault currents to very small values. Harmonics and unbalance between the phases of three-phase systems do, however, modify the performance of Petersen coil earthing [36].

The concept has also been exploited in the "Captap" design which seeks to tap power from the shield wires of HV lines. This concept is achieved through the insulation of shield wires from the line towers of lines operating at 132-400kV, for distances of tens of kilometres. The shield wire is then connected to earth through a capacitance, creating a high impedance capacitor divider. The voltage regulation of this "source" is achieved by connecting an inductance into the circuit to compensate for the capacitance. This circuit is sensitive to variations in power factor, such as during motor starting [42].

These previously-researched technologies have advantages and disadvantages. The aim of the research conducted for this thesis is the development of an effective, financially-viable technology that will improve quality of supply of electricity. The benefits will be most evident on rural networks, where customers often suffer the lowest quality of supply.

The technology that is described in this thesis can basically be summed up as follows:

- ✓ A reactance is placed in series in the supply circuit of a distribution network.
- ✓ The purpose of the reactance is to limit any short-circuit currents flowing in the network due to transient faults on the MV overhead lines.
- ✓ This is done so that power arcs caused by faults are rapidly self-extinguished

- ✓ This will reduce the number of interruptions of supply on that distribution network, resulting in improved quality of supply.
- ✓ The now-large supply reactance will be compensated for by means of load-end compensators that are rated at customer supply voltage.
- ✓ The compensator will be active (as opposed to passive and static) so that it can react to changes in load current and power factor.

1.2 Hypothesis and objectives of the thesis

The central hypothesis on which the research presented in this thesis is based, is: "A resonant-based distribution network with a large supply reactance and active capacitive load-end compensator is tolerant to transient faults, and will improve the quality of supply of electricity by reducing the number of interruptions on that distribution system."

In order to prove or disprove this hypothesis, a number of research questions must be answered. This will then lead to the development of the research objectives.

The first objective is to understand fully the concepts laid out in the hypothesis. Some questions concerning these concepts are:

- What is a distribution network?
- What is a fault?
- What is fault tolerance?
- Why should a network be fault tolerant?
- What is resonance?
- What is significant about series resonance?
- How does series resonance result in fault tolerance?

These theoretical questions can be answered by means of a literature survey.

In order to prove or disprove the hypothesis, research and tests must be conducted in a laboratory. These tests aim to answer the following questions:

- Does the technology cause rapid arc extinction when transient faults occur on an MV distribution line?
- Does the compensator meet its requirements, in terms of compensating for the extra line impedance, responding to changes in load, and maintaining a relatively constant voltage across the load before, during and after a line fault, without instability?

In order to answer these research questions, the laboratory set-up and tests must achieve the following objectives:

- Simulate an MV line
- Create arcs on the MV line
- Create a large supply impedance
- Test the effects of the impedance on the arcs in a variety of conditions
- Ensure that the compensator maintains a constant and desirable load voltage
- Test the efficacy of the compensator in a variety of conditions
- Measure the duration and magnitude of the arc current
- Measure the load voltage
- Switch in a variety of loads to test their effects on the arc duration and compensator's efficacy.
- Determine the stability of the system

1.3 Research scope and limitations

The research was conducted in a medium voltage laboratory. The MV line was created using a step-up SWER transformer and the maximum obtainable voltage was 19.1kV. One load-end compensator was available for the tests. It was rated at 32kVA at 460V and 8kVA at 230V. The loads were connected to the LV side of a 16kVA SWER transformer and were supplied at 230V. The load-end compensator was connected in parallel with the load. The compensator was designed and built by Clinton Slabbert and Professor Malangret of the University of Cape Town.

The tests aim to measure the duration of the power arcs initiated across the arc gap, and the magnitude of the load voltage. These values were measured and observed. The tests were conducted on a single-phase system, which means that it can be assumed that nothing is known of the technology's behaviour on three-phase systems (although assumptions, based on the results obtained from these tests, can be made).

The "various conditions" in which the technology was tested was the changing of the proposed circuit's load. These loads were limited to:

- A resistive load
- A complex load with a lagging power factor of 0.87
- A singe-phase unloaded induction motor

The testing system included only one load supplied from a single step-down distribution transformer. Further tests will confirm the behaviour of the technology when more step-down transformers and loads are connected to the system.

The "various conditions" did not include changes in the environment of the laboratory or of an adjoining distribution / transmission system. The tests were conducted in the ideal conditions of a laboratory where there is no wind, moderate heat and light, and little humidity. The results obtained from the tests cannot be assumed to reflect the behaviour of the technology in the field.

1.4 The structure of the thesis

Chapter two presents the literature survey. This chapter will explain the basic concepts governing the proposed technology, and will examine relevant research already conducted on these concepts.

Chapter three discusses the complex resonance and voltage regulation theory on which the proposed technology is based. It explains why the proposed concept is able to achieve its goals of fault current limiting, and load voltage regulation.

Chapter four develops the laboratory protocol and demonstrates how the laboratory set-up enables the required tests to be conducted. These required tests will attempt to answer the central research question posed in section 1.2.

Chapter five presents in detail the tests conducted in the MV laboratory, and their results.

Chapter six puts forward a comprehensive discussion of the results that were presented in chapter five.

Chapter seven draws conclusions and makes recommendations based on the findings presented in chapter five.

Chapter Two: Literature Survey

This thesis will present an analysis and the laboratory testing of a load end compensator for a series resonant fault tolerant network. Although these tests and their results are the main focus of this work, a number of other topics need to be discussed and understood in order to understand the context of the investigation. In chapter one, a number of questions relevant to the thesis' research were posed. They are:

- What is a distribution network?
- What is a fault?
- What is fault tolerance?
- Why should a network be fault tolerant?
- What is resonance?
- What is significant about series resonance?
- How does series resonance result in fault tolerance?

In this chapter, these questions will be answered. This will give the reader a greater understanding of the relevance and general purpose of the research conducted in order to prove or disprove the stated hypothesis.

2.1 The definition of a distribution network

The system of electricity supply is divided into three main categories: generation, transmission and distribution. Essentially, these categories are defined in terms of the voltage levels with which they are concerned. Distribution networks are generally defined at low voltage levels of 88kV and below and include "reticulation" systems which are responsible for reticulating power to customers at 11kV and 400V. While generation is concerned with the creation of electrical energy, transmission is responsible for the transmission of large quantities of power over great distances and distribution is essentially responsible for the delivery of that power to customers. Distribution networks, then, are the connection between step-down substations (considered to be a supply at a particular voltage) and loads. The customer, in the form of domestic, commercial and industrial loads, is the driving force behind all electricity creation and supply.

2.2 The definition and causes of transient faults

This section will answer the question: "What is a fault?" There are three types of faults in a power system: permanent, persistent and transient faults. Because this thesis is concerned with the prevention of (or the minimisation of the effects of) transient faults, these will be examined in detail.

A "transient fault" is 'quick' and temporary, or momentary. In other words, although a fault occurs, thereby establishing a need for circuit breaker action, the cause of this fault (or short circuit) is temporary and does not have any long-term damaging effects on the distribution network. Most faults on overhead lines are transient.[10]

Faults, or short circuits, typically occur when equipment insulation fails, due to

- system overvoltages - which in turn are caused by events such as lightning and switching,
- contamination of insulation
- other mechanical causes.

Faults are also caused by events such as fires, storm winds and small objects which may cause a temporary path to ground.

Power frequency overvoltages are temporary overvoltages that are caused by events such as the shedding of a large load. This will lead to voltage increases on the system as the resistive and reactive volt drops disappear. The equipment on a power system should be able to cope with these power frequency overvoltages. In table 2.1 the typical magnitudes and durations of various overvoltages are given.[10]

	Magnitude (p.u.)	**Duration**
Temporary (50Hz)	1.5	50s
Switching overvoltage	4.0	10ms
Lightning overvoltage	6.5	100μs

Table 2.1: Typical magnitudes and durations of overvoltages

A large overvoltage, such as that caused by lightning, will cause a flashover from the affected line to ground or to another phase conductor. The result would be an arcing fault between 1 phase and ground or between 2 or more phases with or without ground. This arcing fault (following flashover) causes a short circuit on the network. This short circuit will cause an extremely large short-circuit current which will cause protection to operate and remove the faulted line from the system. This action will cause the arc to disappear. Any small object causing a temporary path to ground (e.g. a small branch that has fallen from a tree) will also cause a transient short circuit. The object will either drop to the ground or evaporate due to the high current during the fault. This would leave only an arc which, once again, will disappear as soon as protection intervenes.[10]

In order to understand what causes a fault (and therefore how it could possibly be prevented), it is important to study the physical characteristics of that fault. The main insulating material for overhead outdoor power systems is air at ambient pressure and temperature. The gases of which air consists, namely nitrogen and oxygen, are excellent insulators in "normal conditions". However, under certain conditions, notably a high electric field, the gases can become ionised and therefore conducting. Electrical discharges develop in high field regions, leading to sparks (low current discharges) or power arcs (high energy discharges).[11] In an overhead network, an electric field will always exist between any live phase and ground, and between any two live phases. The space between the live phase and ground is filled with gas atoms or molecules with free space between them. There are always some free electrons in this space, caused by cosmic radiation. If the existing electric field becomes strong enough, this initial free electron will experience a large acceleration in the field away from the negatively charged part towards the positively charged part. This accelerating electron may attain a high speed if the acceleration is great enough. If this speed is high enough, the moving electron may collide with a molecule of gas, transferring its kinetic energy to the molecule. If this energy exceeds the ionisation energy of that particular molecule, one or more electrons will leave their orbits causing the molecule to become a positive ion. This is 'ionisation'.

The free electrons are, in turn, accelerated towards the positive electrode and may cause further collisions. The number of electrons that are 'freed' increases exponentially. This discharge of electrons is called an 'avalanche'. The fast moving, low-mass electrons are at the tip of the 'avalanche', moving towards the positive electrode. This process continues, aided by other similar processes (such as photo ionisation and cathode bombardment by the resulting positive ions) until the gas in the space between the 'electrodes' becomes so ionised that its conductivity allows a discharge current to flow, and a flashover occurs.[11] Simply put, a flashover is the flow of current through ionised air. This flashover can be caused by a large overvoltage on an overhead distribution line because this large voltage causes the electric field between the line and ground to become very large. The equation that describes an electric field is

$$E = \frac{V}{d}$$

where E is the electric field strength, V is the voltage across the gap, and d is the distance of that gap.

In normal conditions, the electric field is low because the distance between a live overhead line and ground is large enough relative to its rated voltage. If this voltage increases dramatically, then E becomes such that ionisation of the air occurs, causing a breakdown of the gap, which in turn causes a flashover to occur. Empirical values show that the flashover voltage (ie the minimum voltage that will lead to a flashover) for a uniform 1cm gap is about 30kV.

As soon as a flashover has occurred, the resulting feature is an "arc". An arc has a very high current density (typically $10^4 - 10^6$ A/cm^2) and extensive thermal effects. An important property of the arc is the "negative resistance" characteristic. In other words, the arc voltage decreases with an increase in arc current.[11]

Looking again at transient faults, it can be seen that because the cause of the fault is temporary, the overall resulting fault will also be temporary. The arc itself may or may not be temporary, depending on the characteristics of the arc and the system in which it is burning. However, in most cases the protection of the system operates so rapidly that it extinguishes the arc. In the case of a transient fault, the supply will be restored by automatic devices, namely the ARC, or auto-recloser. Because the initial cause of the fault is no longer present, the fault will not re-occur and has, effectively, been temporary in nature. The interruption (or voltage dip, depending on the definitions) caused by the temporary fault will thus also be temporary. In summary, if there is a fault on a feeder, the feeder breaker will trip after a small time delay (the duration of which depends on the magnitude of the fault current) and will close again after a "reclosing interval" or "dead time" ranging from less than 1 second to up to several minutes. If the fault is in fact permanent, the protection will again notice large overcurrent after reclosure leading to a second trip.[10]

Although supply will often be automatically restored, these transient faults will cause voltage depressions which will be experienced by all the consumers connected to that distribution point. The severity of the voltage depression will depend on the system fault level, position and type of fault in the network, and the fault impedance and is also a function of the particular protection. These depressions may be considered "dips" or "interruptions" depending on the severity and length of the depression and the definitions of these terms. The term "interruption" is defined specifically as being of certain duration and as causing a specific decrease in the magnitude of the supply voltage. This will be examined further in the section covering quality of supply of electricity. Typical voltage depression durations are from 0.1 to 1.0 seconds but can be longer.[9] Motor drives, computers and other electronic equipment are most susceptible to interference by voltage depressions.

2.2.1 Transient faults caused by lightning

Lightning is one of the most common causes of transient faults and is of particular concern in South Africa where thunderstorms are frequent, and long overhead distribution lines are in abundance. Its characteristics and its effects on power networks will thus now be discussed in great detail.

Lightning is the greatest single cause of overhead transmission and distribution line outages.[9] The electrical phenomena that occur within clouds leading to a lightning strike are complex and not totally understood. Most theories agree that discharges within clouds initiate downward negative ion movement which eventually establishes a channel to earth called a leader. It reaches the earth in about 10ms.[11]

As the leader approaches the earth, positive charge is induced on the earth and a positive leader travels upwards from close-by, high, conducting, and often sharp, objects such as masts and electricity lines. Once the distance between the downward leader and the object reaches a certain value (the striking distance, r), flashover takes place to the nearest object. After the leaders make contact, a travelling wave moves upwards and is accompanied by intense light. The flash lasts for approximately 50µs and has a current of about 20 to 100 kA.[11] 50% of all strokes have a peak current that is greater than 45kA.[9]

The number of ground flashes/km^2/year is known as the ground flash density, Ng. The average ground flash density at about 400 locations in South Africa has been recorded in an 11-year research project started in the 1970s by the CSIR. The ground flash density in South Africa varies widely. Notably, the Southern Cape records less than 1 flash/km^2/annum, while most of the Drakensberg escarpment experiences density values of 8 flashes/km^2/annum and some parts of Mpumulanga have recorded density values of up to 14 flashes/km^2/annum. The ground flash density at any place is extremely variable and depends on the number and severity of thunderstorms from year to year.[13]

Lightning can affect an overhead distribution line either by a direct strike or by an induced voltage. The probability of a line receiving a direct stroke depends on the ground flash density, the line length and height, and also on the unpredictable nature of flash incidence.

Analysis of data collected from 11kV lines in South Africa indicates that equations used to predict the number of direct strikes to a line per year, although otherwise fairly accurate, underestimate the large number of strikes that may be experienced by a distribution line in completely open country.[13] The number of strikes to a line is, however, reduced in proportion to the extent that the line is shielded by nearby tall structures such as buildings, trees etc. In rural South Africa, shielding structures are virtually non-existent and can be ignored.

When lightning strikes a line directly, the voltage on that line rises very quickly because of the characteristic fast rise of the lightning current. If, for example, a typical overhead distribution line has a surge impedance of 400Ω and a lightning current of peak value 50kA is injected into it, an overvoltage of 10 MV peak will theoretically be produced. The voltage will, however never actually reach this value because a flashover to ground (and thereby a discharge of energy) will occur as soon as the voltage has built up to a value that causes breakdown of the air (increased corona, followed by flashover) across the distribution line insulation. In fact, a direct strike to an unshielded distribution line almost always causes flashover to earth of one or more conductors at the pole nearest the strike.[13] When lightning strikes a line, it normally flashes over at the nearest structure when the stroke follows over the insulating string and cross arm and travels down the pole to the ground. This route does not supply a good ground, so the rate of dissipation of energy is quite slow. This leaves a travelling wave of high magnitude which propagates along the line and may flash over a number of successive structures in both directions from the stroke point.[11,14,15]

Due to electromagnetic coupling, the voltages in the healthy phases of the line increase to a level that can be assessed using the conductor coupling factor. These induced voltages are, however, not as high as that for the line that was struck. Nonetheless, the insulators of the healthy phases will be stressed and may be flashed over.[14,15]

Lightning flashes close to overhead lines are also able to induce voltages in it. This is due to electromagnetic coupling.[13] Due to the fact that most lightning strikes are negatively charged, the induced surges or overvoltages, are positive. The number of induced overvoltages that exceed 100kV is about the same as the number of direct strokes to an overhead line. If a line is shielded by tall structures, any induced surges will be of a higher voltage.

Typically, on an unshielded overhead line 8-10 m high, the voltage induced by a nearby lightning strike will sometimes exceed 200 kV and will have a maximum value of about 250 kV.[10] Because the induced voltages have the same wave-shape and very similar magnitudes on all of the phases of the line, one would not expect flashovers between phases; but flashover to ground would be expected at structures which have an insulation strength that is lower than the value of the induced voltage.[13]

The frequency of occurrence and the magnitude of lightning overvoltages can be somewhat controlled by the use of shield wires on bare overhead lines, surge arresters, and grounding with a low ground resistance which will allow for quick dissipation of the current injected into the line by the lightning.

2.3 The characteristics of power arcs

The aim of the technology examined in this thesis is to reduce the effects of faults on distribution systems. The physical manifestation of a fault is the power arc. In order to determine how the arc can be controlled or prevented, it is important to understand its nature. A thorough investigation into the dynamics and characteristics of power arcs has been performed by M. Jojozi. His thesis looked extensively at the behaviour of arcs under various conditions which has led to a more comprehensive understanding of the nature of power arcs in distribution systems. The work was, however, restricted to arcs with high impedance in the supply. This section will attempt to give the reader a fundamental understanding of arcs by summarising his findings.

It should first be established that a flashover that results from a lightning strike to a distribution line will not necessarily lead to power follow current, and therefore a sustained power arc. Although the initial effect of a lightning strike will be the breakdown of the distribution line insulation, leading to a flashover, this may or may not extinguish rapidly. If the flashover extinguishes immediately, it has been self-extinguishing, and some characteristic has prevented it from developing into a full power arc.[16] An arc will extinguish itself when the power frequency current has a momentary magnitude of zero (in other words, when the alternating current experiences a zero-crossing), if the circumstances are correct. "Power follow" implies that the current flowing in the arc channel is at power frequency and is large enough in magnitude to be self-sustaining.

Power follow occurs when the instantaneous power frequency voltage exceeds the 'minimum arc voltage'. The 'minimum arc voltage' is the minimum voltage required to establish a power arc. If a flashover results in a power arc, there will be an 'arc discharge' at the fault point. This arc discharge has a very high current, high temperature and strong light emissions. It is able to cause extensive damage at the fault point and also to electrical power equipment. It is in every way preferable to limit the effects of a power arc by ensuring that it extinguishes rapidly.[17] Arcs are often caused by overvoltages but may also be caused by the separation of contacts.
The static volt-ampere characteristic of an arc has a negative slope and is shown in the figure that follows.

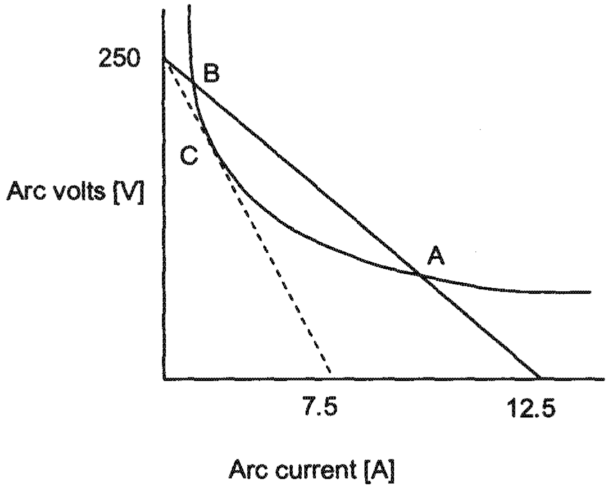


Figure 2.1: The static characteristic of an arc in air [19]

One of the consequences of the volt-amp characteristics is that an arc cannot be maintained in a constant source circuit without the presence of a series resistance. In Figure 2.1 the solid straight line has the following equation:

$$V = 250 - 20I$$

This equation shows the voltage that is available at the terminals of the arc in a circuit that has a 250V source supply and a series resistance of 20Ω. Stable arc conditions can only exist in this particular circuit at points A and B where the arc voltage and the available terminal voltage are equal. Lowering the series resistance would move the stable operating point A to the right which would result in a higher arc current and a lower arc voltage. As the series resistance is increased, the arc current would decrease and the upper limit for the circuit resistance at this source voltage is shown by the dotted line tangent to the arc characteristic at C. As the resistance is increased from 20Ω to 36Ω, the stable operating point A and the operating point B approach each other until they meet at point C. At this stage, the conditions for stability no longer exist. At this point, the arc would extinguish and the arc current would drop to zero. The terminal arc voltage would return to the open circuit voltage value.. [19]

The above describes the basic characteristics of an arc in a DC circuit which gives a simplistic explanation of the fundamental behaviour of arcs in general. The more complex volt-amp characteristic of an AC arc is shown in Figure 2.2.

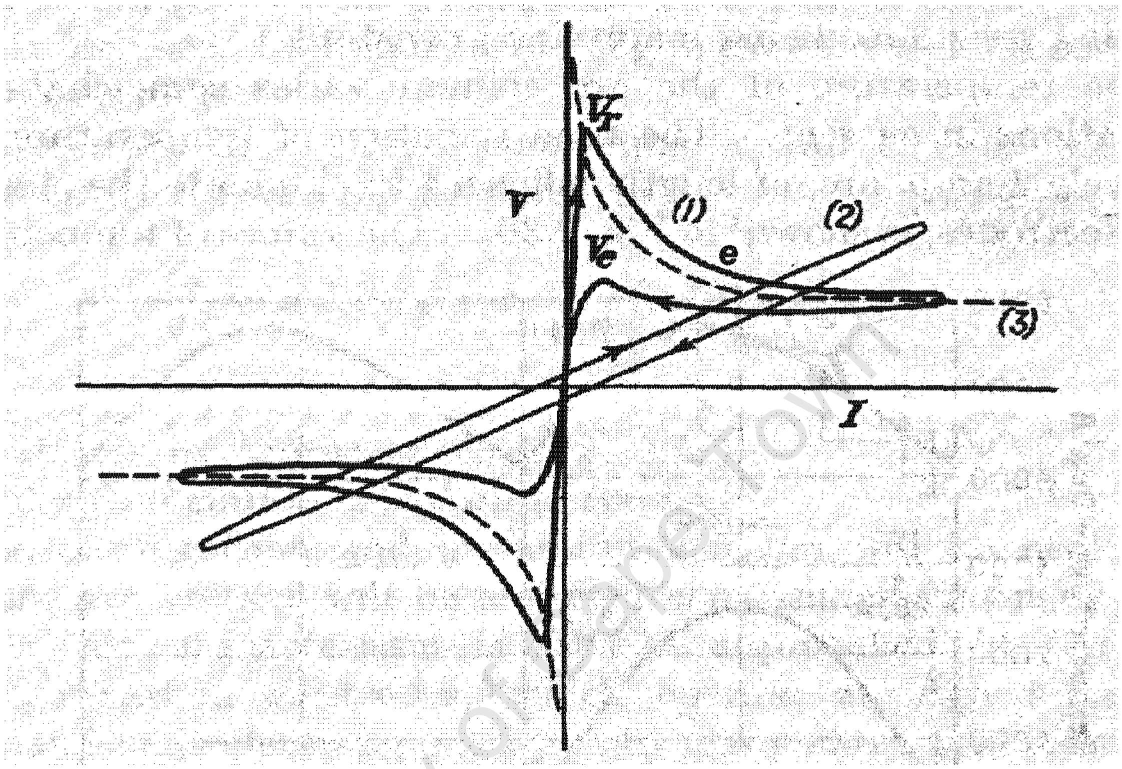


Figure 2.2: An AC arc volt-ampere characteristic showing arcs at (1) low frequency; (2) high frequency; (3) static (dc) [20][21][22]

The voltage across an arc is characterised by a re-ignition voltage V_r, a relatively constant burning voltage e and an extinguishing voltage V_e. If the current flowing in the arc channel is alternating, then it will experience two zero crossings every cycle. At each zero-crossing, the current has an instantaneous magnitude of zero which allows for the de-ionisation of gas in the arc channel and a cooling of the arc 'electrodes' so that a considerable re-ignition voltage may be required to re-ignite the arc. After this period of de-ionisation and cooling, the burning voltage of the arc during the period of increasing current will be greater than the static characteristic value. After the maximum current has been reached, the ionisation of the air in the arc channel is in excess of that required for low currents. Thus, when the arc current is decreasing, the burning voltage is lower than the static characteristic value. Figure 2.3 shows the effect of increasing the arc length on the volt-ampere characteristic, if the applied voltage and circuit resistance remain the same.

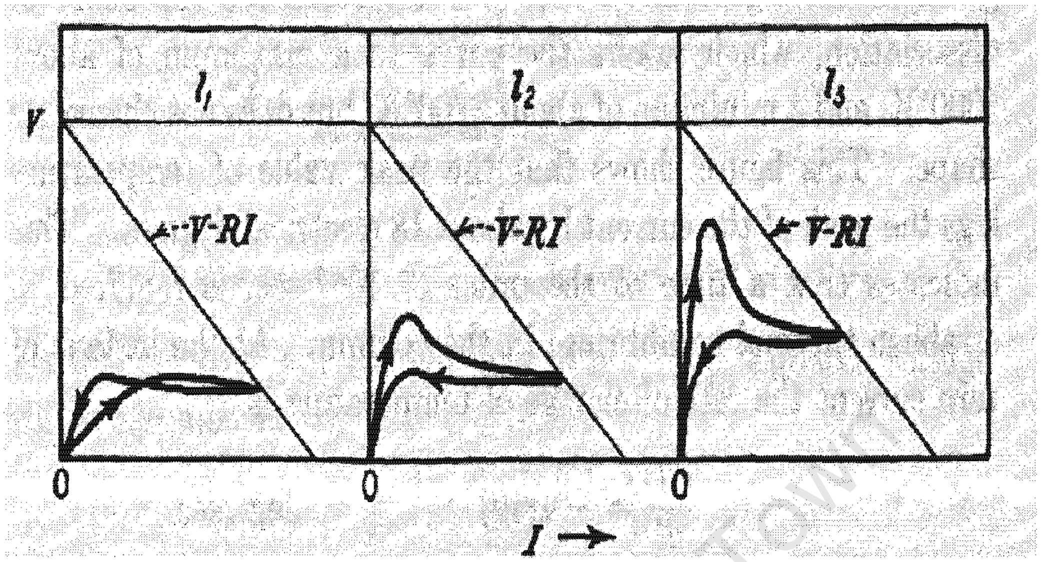


Figure 2.3: the effect of arc length on the volt-ampere characteristic [21] (l_1<l_2<l_3)

The precise modelling of the features of a power arc, and the various equations that describe them, are not in the scope of this thesis. What is of more interest is the behaviour of AC arcs in various conditions; more specifically their extinction and re-ignition properties.

2.3.1 The re-ignition and extinction of power arcs

As explained, the current waveform of an AC power arc will experience a zero crossing at the end of each half cycle and there will be a momentary period during which the arc current is zero. During this period, the arc technically does not exist or has briefly "extinguished" and must be re-ignited. This is because when the arc current is zero, de-ionisation of the gases in the arc column will take place, thereby reducing the conductivity of the column. As the next half cycle begins, the conductivity that existed just before the instant of zero current must be re-established if the arc is to continue "burning". This requires a large voltage (to allow for the re-ionising, or break down, of the air in the arc column), especially if the de-ionisation was rapid. This voltage that is required to re-ignite the arc will be considerably larger than the "steady-state" arc burning voltage and is called the re-ignition voltage. The process of re-ignition is fundamentally a race between the deionisation process in the arc gap and the increasing recovery, or re-ignition, voltage which is determined largely by the external circuit. In the case of short arcs (<1000mm), the behaviour at the "electrodes" of the arc consumes a considerable portion of the total voltage (in other words, a large volt drop is experienced at the electrodes), which is significant in the period of re-ignition.[20]

The arc recovery and arc conducting characteristics play an important part in determining the duration and probability of arc extinction. The extinction of an arc is dependent on the rising time and magnitude of the recovery voltage and the magnitude of the fault current.[20] If an arc does extinguish, it will do so at the zero-crossing of the arc current. After this time, the arc gap recovers considerable strength immediately and will increase further at a relatively slow rate.[20] If, however, a sufficient flashover voltage is not obtained straight after the current zero-crossing, the arc will not re-ignite and will extinguish fully. To allow the recovery voltage to reach a critical magnitude for arc sustainability, the arc (or short-circuit) current must be appropriately large. If the fault current is small, the voltage at the arc terminals will not be able to maintain an ionised channel for the arc.

A number of network and external parameters affect the stability of a power arc and therefore dictate whether or not it will self-extinguish. The exact effects of these parameters in various conditions are not yet fully understood, but research has established a number of findings. The arc will behave diversely due to the influences of the type of gas surrounding the arc and its pressure, temperature and velocity (i.e. wind). The atmosphere will affect not only the electric field of the arc but also the behaviour of the arc column.[17] If all other parameters are constant, a higher source impedance in the distribution network will reduce the magnitude of the fault current and may therefore cause an arc to be unsustainable. If the power frequency current flowing in the arc is not reduced, the arc may well not extinguish. The length of the arc is also of importance. A longer arc path will often cause a flashover to self-extinguish very rapidly, thereby preventing sustained power follow. The material of the arc path is relevant because research shows that a wood path is more likely to lead to arc extinction than an air path.[16]

It is important that the reasons as to why a flashover may or may not lead to a power arc, and as to why that arc may or may not extinguish are fully understood. The nature of arcs in these scenarios allows us to understand *how* the arc burning time can be reduced significantly, which may in turn reduce the need for protection whenever a transient fault occurs on a distribution line. On a typical overhead distribution line, the earth-fault protection relays are set to operate instantaneously at a minimum current magnitude of 40 – 60 A (to prevent operation due to load imbalances). However, in reality, protection schemes take a finite period of time, in the region of 5 – 20 cycles (or 100 – 400ms), to operate.[9] If the burning time of the arc can be reduced to below these values, protection schemes will not need to operate.

Brookes *et al* [24] performed a number of air flashovers in the laboratory and in air, and they found that the probability of power follow was small if the impulse flashover was timed to occur near a power frequency voltage zero. Burgsdorf [25] found that the probability of power follow after flashover was virtually zero if the voltage gradient was less than 7kV/m for air gaps and 10kV/m for paths involving wood. Armstrong *et al* [26] found that the arc quenching phenomena were dependent on the magnitude of the positive short circuit current. Significantly, it was determined that quenching was less likely for larger currents. According to Daverniza [16] the probability of an outage following a flashover of air or porcelain insulation is 0.85. This probability can, however, be smaller for lines which use wood cross-arms and poles. It was also found that if the operating voltage gradient is less than 14kV/m, there is little probability that a power arc will develop following a lightning flashover. These findings were, however, valid only for resistive sources. Little research has been conducted on systems with reactive sources.

It is clear that a lower voltage gradient across the arc path will dramatically reduce the probability that the arc will be stable. The basic factors that influence the arc gap's electric field are the fault current value and the "transport property" in the atmosphere around the arc (e.g. the electrical and thermal conductivity, weather conditions such as rain or wind).[17] According to Daverniza, "the phenomena subsequent to breakdown of insulation is directly influenced by test circuit parameters and the arc extinction capabilities of the insulating media surrounding the arc channel." He provides an equivalent circuit, shown in Figure 2.4, which may represent a generalised voltage source and test circuit.

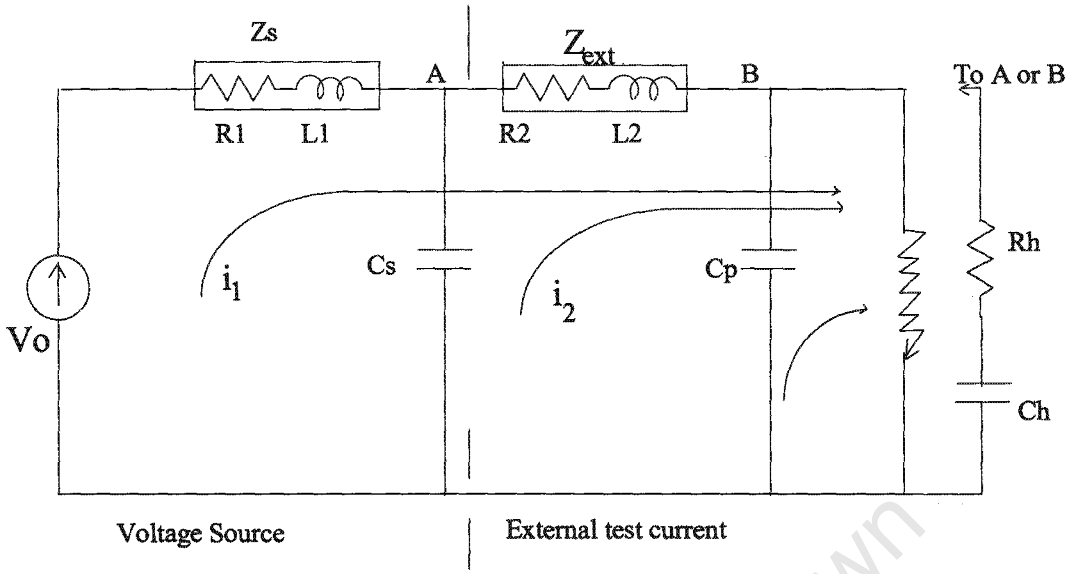


Figure 2.4: Equivalent voltage source and test circuit. *C_s represents stored energy which is available immediately from the test source to the external circuit e.g. the transformer capacitance in an alternating voltage test set, a filter, or a storage capacitance for a surge generator; Z_{ext} is the external test circuit (protective) impedance; C_p is stray or test object capacitance. Rh and Ch form the spark heating circuit.*

The following features would be observed for all types of test voltages:

a) If Z_s and Z_{ext} are large, a breakdown of the air in the gap will result in the discharge of only the test object capacitance, C_p, and will thus not be sustained.
b) If only Z_s is large, the breakdown, which will also be non-sustained, will discharge the energy stored in both C_s and C_p.
c) If Z_s and Z_{ext} are small, breakdown of the gap will result in a sustained arc which will give rise to the flow of current from the source, at least until the first natural current zero.

2.3.2 Arc extinguishing techniques

Arcing faults are very damaging in nature, both to equipment, and to human safety. They enable the flow of short circuit currents in a network, and therefore contribute to a large number of the outages or voltage dips experienced by customers (due to breaker action). It is thus imperative that arcs are extinguished as rapidly as possible. A number of techniques have been developed to fulfil that need. A few of these techniques are discussed briefly:

- **Compensated neutral grounding** makes use of an inductive compensation coil in parallel with a capacitive reactance which represents the phase to earth capacitances of the system. If the two reactances are 'tuned', the earth fault current will have only a resistive component. This residual current will now depend only on the resistances of the suppression coil and network lines, together with the leakage resistances of the system. This reduced fault current will be unable to sustain an arcing fault.[28] This concept can be further applied in the *Petersen coil* which will be discussed in detail later in this chapter.
- **High resistance grounding** will reduce the short circuit current of earth faults in distribution systems with little capacitive charging current (less than 10A).[29]
- **A Magnetically Controlled Reactor (MCR)** is a "device in which DC pulsing through a part of the power winding or through a special control winding changes the duration to period ratio of the magnetic core saturation, thereby changing the inductance and inductive susceptance of the MCR as a whole." [30][31] The principle of their operation is based on the "generation and control of the direct component of the magnetic flux in the MCR's two winding cores" and on the "profound saturation of the two cores under rated conditions, when the saturation magnetism generated by the direct component of the magnetic flux is achieved over about half or more of the grid frequency period."
- **A darverter (arc-quenching device)** exploits the ability of wood to extinguish a large proportion of lightning flashovers, thereby preventing the development of power arcs. The darverter makes optimum use of the wood's insulating and arc-quenching properties by the effective line design and correct co-ordination of pole-tops.[16][31]
- **Diverter gaps** were proposed in the 1940s by Rorden as a means of preventing power follow arcs. The function of the gap is to "divert lightning strokes that hit the conductor so that they will be directed down the pole without flashing over the insulators or cross-arm". This achieved with the use of an arcing horn connected to a steel wire running along a wood brace to the pole, terminating just below the point of support of the brace on the pole. At the base of the H-frame type structure on which the equipment sits, an 8 metre ground rod is driven in at each pole, the function of which is to dissipate the energy of the lightning strike rapidly.[15]
- **Arrestors** are used to protect distribution lines from direct lightning strikes. They are installed at frequent intervals along the line and are spaced to limit the pole-

top voltage at the unprotected structures to "a value less than the phase-to-phase insulation level of the line, thus preventing flashover".[31] Arresters are applied to all the phases on the same structure and are connected to a common ground so that a stroke of lightning that hits the line close to an arrester will be "drained from the line". [26][31]

2.3.3. The main experimental findings of M. Jojozi regarding the stability of short arcs

Tests were performed in a medium voltage laboratory which aimed to investigate the:

- Effect of arc length, voltage and voltage gradient on arc stability
- Volt-time and current-time characteristics of the material in question
- Volt-current characteristics
- Effect of arc paths in air and along a wood surface
- Effect of changing the supply circuit impedance
- Arc resistance

These tests were performed at voltages ranging from 10kV to 40kV and using air gaps and wood lengths ranging from 100mm to 1000mm. Because there was no surge generator, arcs were initiated using a fine thread of Eureka, a copper-nickel alloy with high electrical resistance and low temperature co-efficient. Numerous arcs were initiated in a variety of conditions. The main results and conclusions of interest will follow in brief.

- If an arc is unstable, it will go through the following phases:
    1. arc initiation
    2. full arcing (which includes the processes of ionisation, arcing and de-ionisation)
    3. arc extinction
- Stable arcs experience the following phases:
    1. Pre-arcing. This is the period during which the arc voltage is building up to allow full ionisation of the arc gap
    2. Initial arcing. This includes the burning and evaporation of the fuse wire, coupled with the initiation of the arc
    3. Full arcing. This is illustrated in the V-I characteristic shown in Figure 2.5.

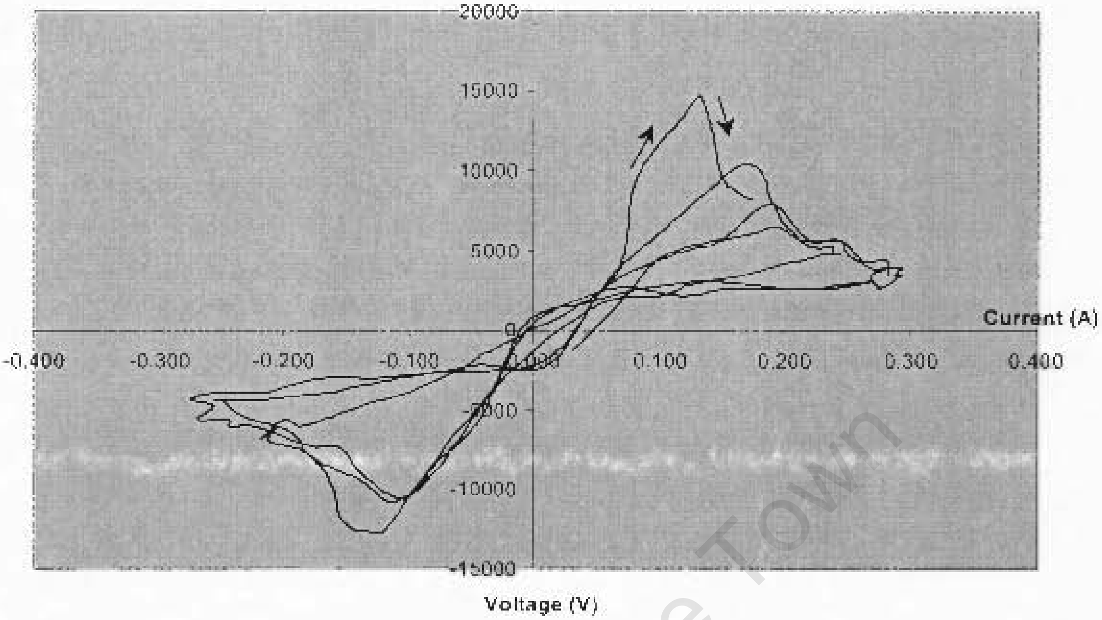


Figure 2.5 V-I characteristic of full arcing phase [31].

4. Near extinction. This phase occurs as the arc attempts to self-extinguish as the air in the gap de-ionises but the minimum arc voltage (MAV) still exceeds recovery voltage. Thus, arcing continues.
5. Continued arcing. Once the arc has recovered, it is "stable" and will continue burning until interrupted manually.

Figures 2.6 and 2.7 show the voltage and current traces of a stable and an unstable arc. The traces depicting a stable arc clearly illustrate the attempts of the arc to self-extinguish before recovery and continued arcing (the gap voltage rises slightly before dropping in magnitude).

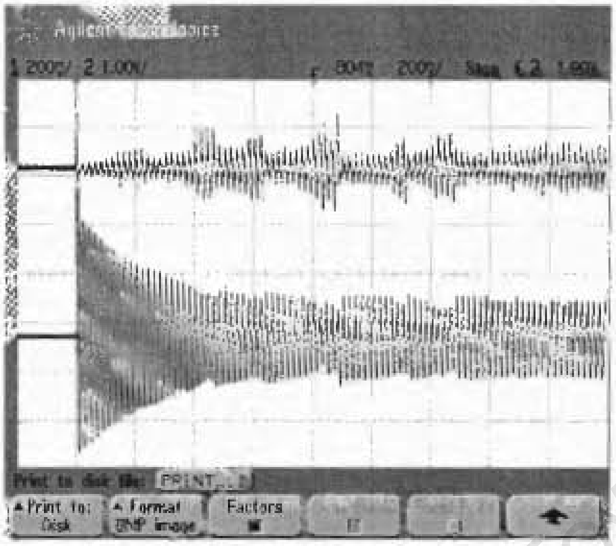


Figure 2.6 A stable arc: the traces of voltage vs time and current vs time for an arc through air at 40kV, gap length of 300mm [31].

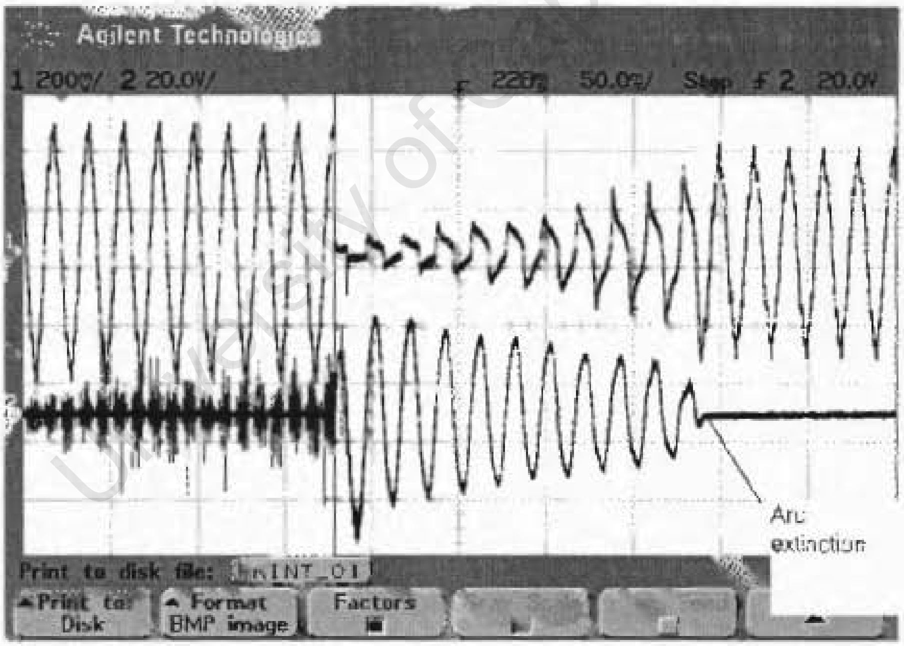


Figure 2.7 An unstable arc: traces of voltage vs time and current vs time for an arc through air at 20kV, gap length of 200mm [31].

Figure 2.8 shows the graphing of a number of lines which represent arc current vs arc length in air and along a wood path, at various voltages. These lines were obtained by repeating tests and measuring the maximum current for each gap length and type of arc path. As the supply voltage increases, the resulting arc current increases provided the supply circuit impedance remains constant. At a specific voltage, a larger arc gap requires a current of greater magnitude to initiate an arc. Thus an arc burning across a long gap (e.g. 500mm) will be characterised by a higher current, or it would not be burning at all. This figure shows arc current to be directly proportional to arc length.

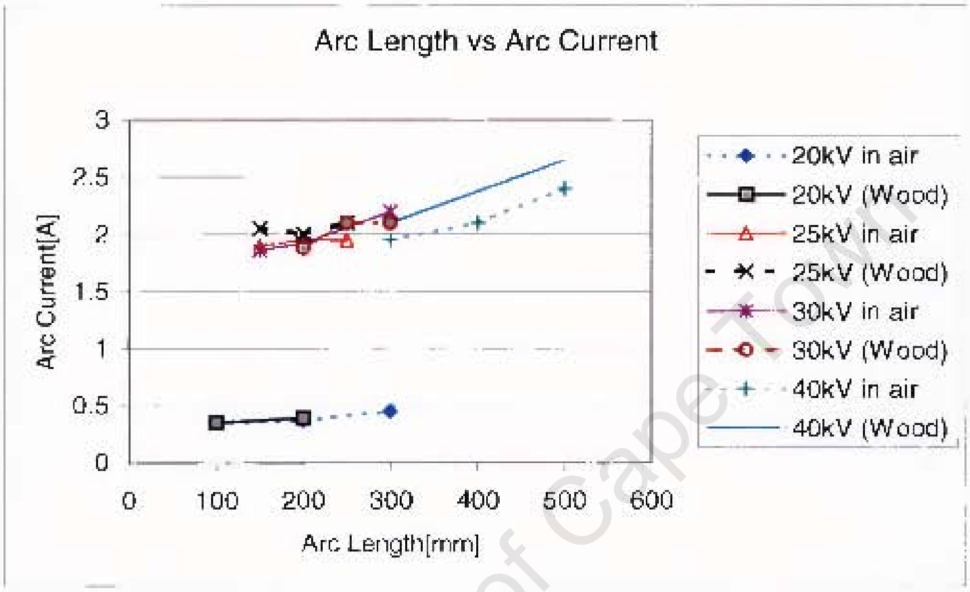


Figure 2.8 Arc current vs arc length in air and along a wood path

Figure 2.9 presents a summary of the stability of arcs of various lengths at different voltages across a path of air/wood by showing the probability of arc extinction vs length in air / wood.

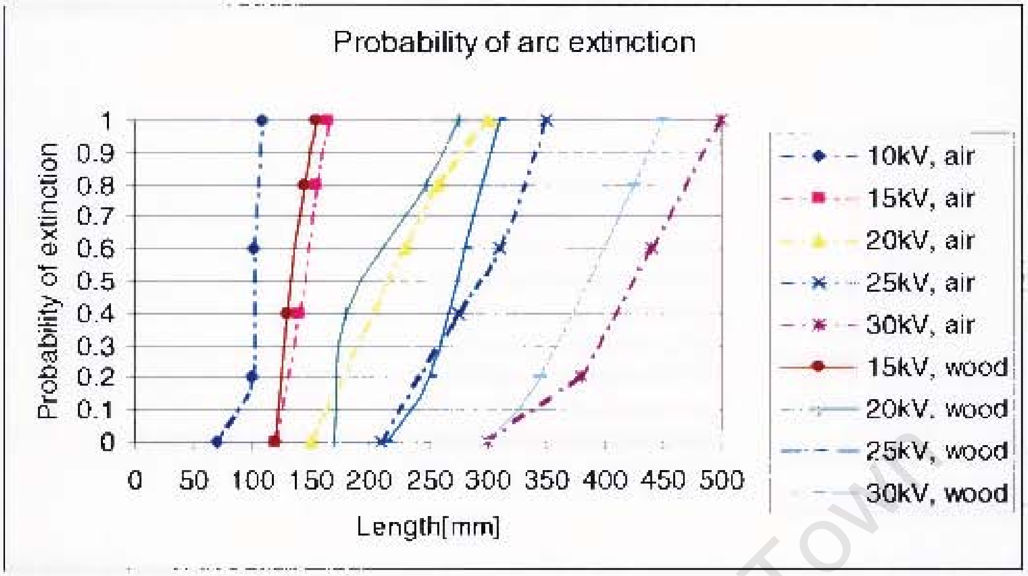


Figure 2.9 Probability of arc extinction vs. length in air and wood

Of particular interest is the line depicting the probability of arc extinction vs arc length at 20kV through air. According to these results, if the arc through air is initiated at a voltage of 20kV, an arc gap of 300mm will cause the arc to be self-extinguishing in 100% of cases. Although Jojozi does not actually demonstrate a direct link between the stability of short arcs and the magnitude of the supply network impedance, the following observations are made:

- At a particular voltage, a longer arc gap leads to a greater probability of arc extinction.
- For a particular gap length, as the supply voltage increases, so the short circuit current magnitude increases, thereby reducing the instability of arcs.
- If, at a particular voltage, that short-circuit current were reduced, the likelihood of arc stability would be reduced.
- At a particular voltage, a longer arc gap and a limited circuit current would together reduce the likelihood of arc stability extensively.
- Thus if an appropriate gap length and current-reducing component (impedance) were provided, arc instability could be guaranteed.
- The average arc initiated at 20kV across a 30cm gap burned for approximately 350ms.

2.4 Quality of supply of electricity

Transient faults and their causes have been examined in detail in previous sections. The next questions which should be asked are: "Why are these faults undesirable, and why should research be conducted in order to reduce their effects on a network?" These questions can be answered by considering concept of quality of supply of electricity.

Historically, the definition of "quality of supply" has been vague and relatively evasive. While the concept clearly refers to the customer's perception of the quality of their electricity supply, it is often difficult to quantify and adequately define 'quality'. For some customers and providers, 'quality' may refer to the number and duration of outages experienced each year. For others, it is desirable that the voltage and frequency of their supply remain within defined limits. In other words, 'quality' is not only to be understood as the physical quality of the electricity delivered but also as the experienced degree of agreement between the expectations of a product and the product delivered.[1] If service dependability is poor, everything else a utility does will be viewed as poor by customers.

It is, at present, widely accepted that a reliability index should be based on a probabilistic approach and should include three fundamental attributes [2]:

- Frequency of events
- Duration of events
- Severity of events

According to Eskom standards[44], an outage or event is defined by its duration being longer than 2 minutes. Any voltage dip of duration less than 2 minutes and more than 3 seconds is defined as an interruption. It is therefore likely that transient faults will not lead to outages, only to interruptions.

Generally, the following power quality parameters are defined (in EN 50160):[1]

- Voltage fluctuations: Cyclic variations of the voltage envelope, or a series of random voltage changes less than 10% of the supply voltage
- Supply voltage dips: Sudden reductions of the voltage with a magnitude between 10% and 100% followed by voltage recovery after a short period of a duration of 10ms to 1 minute
- Supply interruptions, which can be
    2. Prearranged (which, if longer than 2 minutes in duration, are outages or events)
    3. Accidental, short: less than 2 minute duration
    4. Accidental, long: more than 2 minute duration (an outage, or event)
- Temporary overvoltage: Characterised as being an power frequency overvoltage of relatively long duration, and which is undamped or weakly damped
- Transient overvoltage: A short duration oscillatory or non-oscillatory overvoltage usually highly damped and with a duration of a few milliseconds or less

These attributes can be summarised by the following table which defines several types of voltage dips or interruptions based on their duration and severity and has been taken directly from the NRS 048-2 guidelines. It is clear from this table that differentiating between a "dip" and an "interruption" is not always an obvious task. However, the table also shows that some "dips" (such as those defined as "Y") are preferable to others (such as those defined as "T"). The shorter and less severe the dip or interruption, the better the quality of supply will be.

1	2	3	4	5
Range of dip depth V (expressed as a %)	**Range of residual voltage** U (expressed as a %)	**Duration** t		
		20 < t ≤ 150 ms	150 < t ≤ 600 ms	0.6 < t ≤ 3 s
10 < V ≤ 15	90 > U ≥ 85	Y	Y	Y
15 < V ≤ 20	85 > U ≥ 80	Y	Y	Z1
20 < V ≤ 30	80 > U ≥ 70	Y	S	Z1
30 < V ≤ 40	70 > U ≥ 60	X1	S	Z2
40 < V ≤ 60	60 > U ≥ 40	X2	S	Z2
60 < V ≤ 100	40 > U ≥ 0	T	T	Z2

.Table 2.2 Characterisation of depth and duration of voltage dips

The IEEE Std 1159-1995 provides further definitions which distinguish specifically between momentary, sustained and temporary interruptions.[10] A "momentary interruption" is defined as being between 0.5 cycles and 3 seconds. A sustained interruption is longer than 3 seconds and a temporary interruption is between 3 seconds and 1 minute. All of the interruption definitions are summarised in Table 2.3 for clarity.

Most faults on overhead lines are transient: they require operation of protection, but do not cause permanent damage to the system. The moment a circuit breaker opens due to a short circuit current, the faulted feeder and the load fed from it are removed from the system. The effect of this is that the voltage drops to zero very fast. When the voltage is zero (even during a short interruption), there is no supply of power at all to equipment. The overall consequences of a transient fault (an interruption followed by the auto-reclosing of a breaker) will last for only a few seconds or less, but the overall effects can last much longer. Some effects include the slowing of motors, momentary dimming of lights, disruption of production processes, the loss of computer memory contents, and even the evacuation of buildings due to fire alarms going off.[10]

Term	**Definition**	**Source**
Voltage dip	Sudden reduction of voltage with a magnitude of between 10% and 100% followed by voltage recovery	EN 50160
Outage	Reduction in voltage of magnitude 100% for a duration greater then 2 minutes	Eskom Standard DISASACT3
Interruption	Reduction in voltage of magnitude 100% for a duration of between 3s and 2 min	Eskom Standard DISASACT3
Momentary interruption	Interruption lasting between 0.5 cycles and 3s	IEEE Std 1159-1995
Sustained interruption	Interruption lasting longer than 3 seconds	IEEE Std 1159-1995
Temporary interruption	Interruption lasting between 3s and 1 minute	IEEE Std 1159-1995
Transient interruption	An interruption caused by a transient or non-permanent event. This type of fault may result in an "interruption" or an "outage" depending on its cause	Eskom Standard DISASACT3

Table 2.3 Summary of definitions of voltage behaviour

When defining quality of supply, the term 'reliability' may also be used as a 'quality indicator'. The North American Electric Reliability Council (NERC), the main custodian of reliability in North America, defines reliability as "the degree to which the performance of the elements of the system results in power being delivered to consumers within accepted standards and in the amounts desired".

The following reliability levels have also been defined [4]:

- Reliability up to 99.9%: This corresponds to one day of outage in every three years (or about 8 hours of power interruption per year). This total outage may consist of both "outages" and "interruptions" over a period of time. This has been the accepted reliability level of transmission and distribution systems for more than a century.
- Reliability up to 99.9999%: This level of reliability is associated with high technology and manufacturing processes that are very sensitive to power interruptions. When industry was built largely around incandescent bulbs and electric motors, a reliability level of 99.9% was more than adequate. But microprocessor-based controls, computer networks, financial networks, flight control centres and other modern industries demand a higher level of reliability. It amounts to no more than a minute of allowable outage (or interruptions) a year.

Higher levels of reliability are particularly necessary in the electronic and automated manufacturing industries where the electricity-consuming equipment is much more susceptible to power-quality problems and poor reliability than older equipment, such as conventional lighting and motors [45]. According to Eto *et al*, "the changing structure of the U.S. economy, coupled with the proliferation of electronic equipment in all sectors, has increased the economy's vulnerability to electricity-reliability and power-quality problems. Estimates of the annual costs of this vulnerability range consistently in the $10s of billions" [45].

It is clear that many commercial and even residential customers are demanding "more reliable" power supply with fewer interruptions per year. In most cases, the meeting of this need provides "quality".

Generally, there is a large growth in the use of electronic loads that are sensitive to low power reliability. At the same time there is large growth in the use of power electronic devices which produce power quality disturbances. Business and industry normal operations are becoming increasingly dependent on the consistent and predictable performance of their electric and electronic equipment.[4] But there are other factors that are increasing the focus on power quality:

- Decentralised (or distributed) electricity-generating equipment such as wind-turbines generate voltage transients and fluctuation; electronic motor control units raise the general harmonics level; the growing number of computers in offices and private homes adds to the dependence on a continuous supply of high quality electricity.
- The changing structure of the electricity-providing industry (ie a movement towards a competitive market) may also contribute to the interest in power quality. In this case, the emphasis would be on the necessity of objectives, general definitions and standards for quality levels.

Electrical and electronic equipment, in particular, are designed to operate from a "clean and constant" source of supply of AC voltage. Large deviations from the nominal value or continual voltage fluctuations cause overheating, halts in production, machining defects, loss of data memory and programs, failures etc. Electricity providers cannot always prevent the degradation of electrical energy along distribution lines, as they are subject to load variation and interference. For this reason, voltage stabilisation and protection against electrical faults are needed. Voltage regulation is a vital characteristic of a power system in order to limit voltage deviations.[8]

It is in an electricity provider's best interests to reduce the number of interruptions experienced by customers, and to keep output voltages regulated. These are the two main quality characteristics that are focused on in this thesis. The technology proposed in this work aims to improve power quality by increasing the fault tolerance of distribution networks.

2.5 The principle of resonance and its application in compensation techniques

This section will start with a review of some basic power system theory and will go on to expand this theory by applying it to various compensation techniques.

2.5.1 The fundamental concept of power factor correction

This section aims to introduce the concept of power factor correction. The theory behind this concept is fundamental in the understanding of reactive compensation in general.

Let's assume that a load with a lagging power factor is absorbing P_L watts of real power and Q_L vars of reactive power. If one wanted to decrease the number of vars absorbed by the load, thereby reducing total complex power and increasing the source power factor, one would connect a capacitor in parallel with the load. The capacitor will absorb *negative* reactive power and will reduce the magnitude of the reactive power required from the source (because it is delivering reactive power and reactive current to the system). Thus, the capacitor is supplying some reactive power to the load in place of the source. This will decrease the reactive power supplied by the source and increase the source power factor. This will ultimately result in a decrease in total *source* current which will in turn result in lower line losses and lower line-voltage drops. The improved power factor will aid in the efficiency and voltage regulation of the circuit. This can be summarised in Figures 2.10 and 2.11.

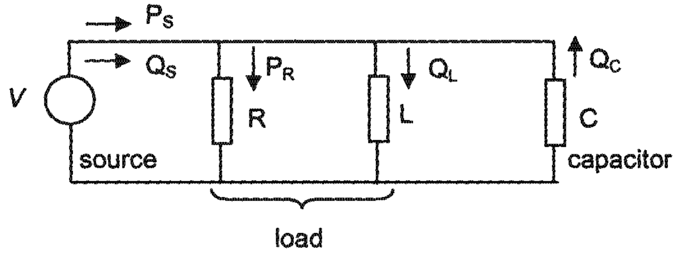


Figure 2.10 Circuit showing power flow in power factor correction

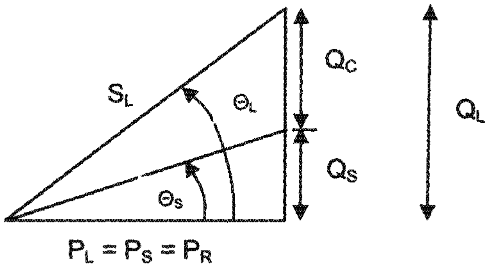


Figure 2.11 Power triangle showing capacitive power factor correction

This concept can also be viewed by means of the calculation of sending and received voltages in terms of power and reactive power. This will now be examined so that a more comprehensive understanding of reactive power flow and its effect on source power factor can be gained.

Although the determination of voltages and currents in a power network can be achieved by means of complex notation, usually in power systems, power (*P*) and reactive power (*Q*) are specified, and the resistance of lines is often negligible compared with the reactance. [32] For example, if $R = 0.1X$, the error in neglecting R is 0.49%. Figure 2.12 shows a simple network and its phasor diagram is shown in Figure 2.13.

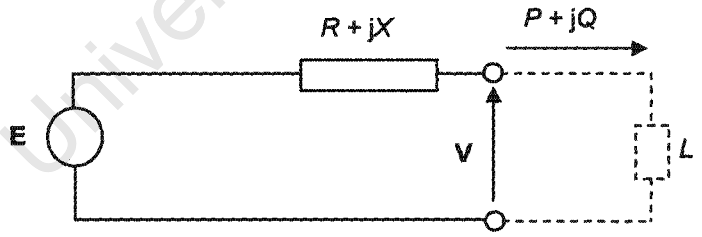


Figure 2.12 Simple transmission link [32]

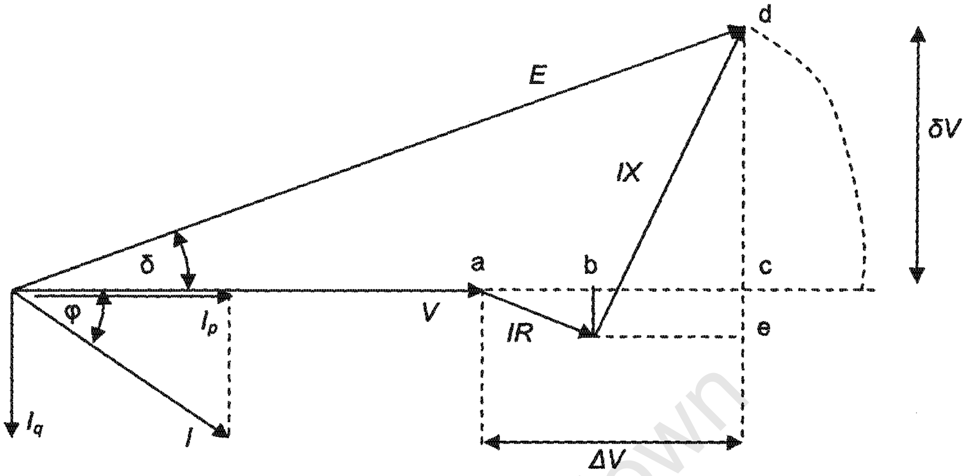


Figure 2.13 Phasor diagram for the transmission of power through a series impedance [32]

From the phasor diagram: $E^2 = (V + \Delta V)^2 + \delta V^2$

$= (V + RI\cos\varphi + XI\sin\varphi)^2 + (XI\cos\varphi - RI\sin\varphi)^2$

therefore $E^2 = (V + [RP]/V + [XQ]/V)^2 + ([XP]/V - [RQ]/V)^2$

Hence $\Delta V = (RP + XQ)/V$

And $\delta V = (XP - RQ)/V$

If $\delta V << V + \Delta V$

$E^2 = (V + [RP + XQ]/V)^2$

and $E - V = (RP + XQ)/V = \Delta V$ [32]

Therefore, the arithmetic difference between the voltages is approximately given by

$$\frac{RP + XQ}{V}$$

If R = 0,

$$E - V = \frac{XQ}{V}$$

In other words, for networks where X>>R, i.e. most power circuits, ΔV is determined by Q. If a scalar voltage difference exists across a largely reactive link, the reactive power flows towards the node of lower voltage. In summary, if in a network, there is a deficiency of reactive power at a point, it will have to be supplied from the connecting lines, and the voltage at that point falls. On the other hand, if there is a surplus of reactive power generated (e.g. by a capacitor bank), then the voltage will rise. [32]

2.5.2 Resonance theory

In this section, the question: "What is resonance?" is answered. The concept of resonance is central to the thesis which aims to test the fault-tolerance of a series resonant network.

Essentially, resonance theory is another manifestation of reactive power flow, and capacitor voltage regulation. In the previous section, it was shown that a capacitor connected in parallel to a load with a lagging power factor could "inject" reactive current into the circuit, thereby reducing line losses and raising the voltage across the load.[33]

In a *series* resonant circuit, a resistor, inductor and capacitor are connected in series. At low frequencies, the capacitive reactance is larger than the inductive reactance. There will thus be a larger volt drop across the capacitor. This large capacitive reactance will allow only a small current to flow in the circuit and it will lead the applied voltage by almost 90°. At high frequencies, the opposite will be true. In this case, the large inductive reactance will also limit the current in the circuit, but it will lag the applied voltage by almost 90°. Between these two extremes, a frequency exists at which the capacitive and inductive reactances are exactly equal. This will occur when

$$j\omega L = 1/j\omega C \text{ or}$$

$$\omega L = 1/\omega C$$

Solving for the frequency in the above relationship yields

$$\omega = 1/\sqrt{(LC)} \text{ or}$$

$$f = (1/2\pi\sqrt{(LC)}) \quad [30]$$

This is known as the resonant frequency. At this frequency, the capacitive and inductive reactances "cancel each other out" and this leaves only the resistive part of the total impedance to limit the current in the circuit. In this case,

$$\mathbf{I}_{RESONANT} = \mathbf{V}_{APPLIED}/\mathbf{R} \ [33]$$

This could also be described in the following way: at power frequency, any volt drop experienced across the inductive reactance can be "undone" by adding a capacitor in series with the inductor which has a reactance that, at power frequency, is equal to that of the inductor. The reactance of the capacitor is seen by the circuit as being in the "opposite" direction to the inductive reactance. Ina series circuit, the voltage across the inductor would be:

$$\mathbf{V}_L = j\omega L\mathbf{I}$$

And the voltage across the capacitor would be:

$$\mathbf{V}_C = (1/j\omega C)\mathbf{I}$$
$$= -j(1/\omega C)\mathbf{I}$$

If $\omega L = 1/\omega C$, then $\mathbf{V}_L = -\mathbf{V}_C$ and thus there is zero resultant volt drop across the reactive components of the circuit because the voltage phasors are 180° out of phase.[33]

2.5.3 A review of load voltage compensation

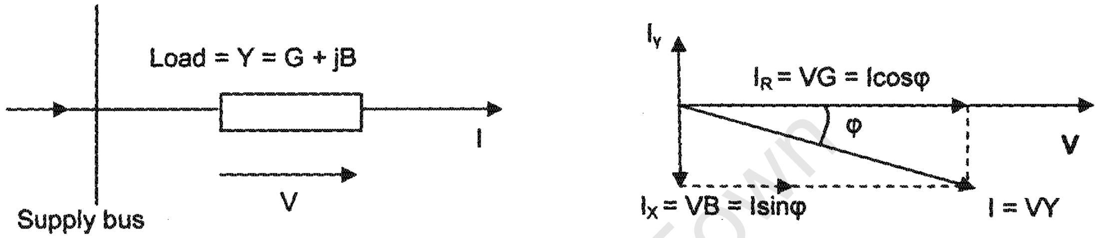
The aim of the technology in this thesis is to increase the fault tolerance of a distribution network by applying the concept of "resonance" to a load-end compensator. The main objective of the load-end compensator is to reduce the system's reactive power requirement. While it is worth noting that load current and load power factor cannot be altered, the *source* or system currents (power requirements) and power factor can be changed with the use of a load compensator.

Load compensation is the management of reactive power to improve the quality of supply in ac power systems.[34] In load compensation, the compensating equipment is usually installed near to the load and its main objectives are power factor correction and improvement of voltage regulation. Load balancing is a further benefit of load compensation but is not relevant to this thesis.

As explained previously, power factor correction is the practice of generating reactive power as close as possible to the load which requires it. Most industrial loads have lagging power factors (in other words they absorb reactive power) and the total load current is therefore larger than is required to supply only the real power component.[34] Only real power is ultimately useful and the excess load current is a waste to the customer, who has to pay the costs for its transmission, and the utility, whose generators and distribution networks cannot be used at full efficiency.[34]

Voltage regulation is a critical issue in the presence of loads which vary their demand for reactive power. The variation in demand for reactive power causes variation in the voltage at the supply point. This can interfere with the efficient operation of all plants connected to that point. The utility is thus usually bound by statute to maintain supply voltages within defined limits. The most practical and economic way to improve voltage regulation is to "size the power system according to the maximum demand for real power and to manage the reactive power by means of compensators."[34]

An ideal compensator is one that will correct the source power factor to unity. In practice, this is not possible and there are a variety of factors that must be weighed up against each other (especially cost) in developing the "optimum" compensator for a specific context.[34] This section will attempt to explain the relationship between the power source, the load and the compensator by looking again at reactive current and power factor in single-phase.



(a) (b)

Figure 2.14 Complex single-phase load and its current and voltage phasors [34]

Figure 2.14a is a Thevenin model. It shows a single-phase load with admittance, Y, which is comprised of a conductance G and a susceptance B. This load is supplied with a voltage, V and this results in I, the load current. [34]
Therefore,
$I = V(G + jB) = VG + jVB = I_R + I_X$

Figure 2.14b is the phasor representation of 2.14a. The voltage, V, is the reference. The current, I, is lagging the voltage. In other words, this load has an inductive susceptance and a resistive conductance. The load current has been decomposed into two parts. I_R is the active current (which is due to the conductance) and is in phase with the supply voltage. I_X is the reactive current (which is due to the susceptance) and is in quadrature with the supply voltage. The angle between the supply voltage and load current is φ. If S is the total apparent power supplied by the voltage source, then
$S = VI^* = V^2G - jV^2B = P + jQ$ [31]
Here, P is the real power (or physically useful) component of S and is Q is the reactive power component. And the power factor is the ratio of P to S (or cosφ).

As mentioned before, the concept of power factor correction is to find a substitute for the reactive power that is being supplied by the voltage source. The source will then only have to supply the useful real power, P. This is the task of the compensator. [34] If the reactive part of the load is jB, then compensation is done by connecting, in parallel with the load, a pure susceptance of an equal but opposite value, -jB. [34] The current supplied by the system to the combined installation of load and compensator is now:

$$\mathbf{I}_S = \mathbf{I} + \mathbf{I}_Y$$
$$= \mathbf{V}(G + jB) - \mathbf{V}(jB) = \mathbf{V}G = I_R$$

I_R is in phase with the supply voltage, making the *system* power factor unity. The supply current $\mathbf{I}_S$ now has the smallest value capable of supplying the full active power of the load.[34]

Before a compensator can be developed, existing compensators and their theoretical bases should be examined in an attempt to determine their advantages, disadvantages and efficacy. In a power system, a number of compensation methods are used in an attempt to reduce source reactive power contribution, thereby improving efficiency and increasing voltage control. Various components in a power system have the ability to generate and absorb reactive power. Obviously, inductors absorb reactive power and capacitors generate reactive power. Synchronous generators can be used to generate or absorb reactive power. Their ability to supply reactive power is determined by the short circuit ratio. [32] Lines, when fully loaded, absorb reactive power (higher loads result in larger currents leading to greater volt drops across the series line reactance). With a current I amps for a line with X Ω of reactance per phase, the vars absorbed are I^2X per phase. On long lines that are lightly loaded (low load current results in small reactive volt drops), the shunt capacitances may become predominant and the lines may become reactive power generators. Transformers always absorb reactive power. Cables generate reactive power due to their high capacitance. Loads are generally reactive power absorbers. If a load has a power factor of 0.95, this implies a reactive power demand of 0.33 kVAr per kW of power.[32]

Voltage control can also be achieved by using automatic voltage regulators. When there are changes in load, this will result in automatic adjustment of the terminal voltage by an automatic change in excitation of a synchronous generator, by tap-changing transformers or by the injection of reactive power into the system. By changing the transformation ratio on a transformer, the voltage in the secondary circuit is varied and voltage control is obtained. This is a common method of voltage control in distribution systems. However, this thesis will focus on the final method of voltage control mentioned: that of reactive power injection.

It is evident from the equation discussed earlier:

$$\Delta V = \frac{RP + XQ}{V}$$

that the volt drop in a network is largely determined by the reactive power. [32] The resulting line currents are larger, leading to increased I^2R losses. In general, three methods of reactive power injection are available, involving the use of

- static shunt capacitors
- static series capacitors

Shunt capacitors can be used to deliver reactive power and increase transmission voltages during heavy loading conditions. This leads to lagging power factor circuits. When the system is lightly loaded, resulting in a leading power factor circuit, shunt reactors may be used to absorb reactive power and reduce overvoltages. In both cases, the effect is to supply the requisite reactive power to maintain the values of the voltage. Capacitors are connected either directly to a busbar or to the tertiary winding of a main transformer and are the disposed along the route to minimise voltage drops and losses.[32] Unfortunately, as the voltage falls, the vars produced by a shunt capacitor also falls. This means that their effectiveness wanes when they are most needed.

Series capacitors are sometimes used on long lines to increase their loadability. [6] Capacitor banks are installed in series with each phase conductor at selected points along the line. They have the effect of reducing the overall series impedance of the line. This in turn reduces the line voltage drops, giving rise to a steadier load voltage magnitude. A major disadvantage of series compensation is the high overvoltage produced when a short-circuit fault current flows through the capacitor.[32] Thus, automatic protection devices must be installed to bypass high currents and to reinsert the capacitor banks after fault clearing. [9] Series compensation could also cause sub-synchronous resonance which is a phenomenon that occurs when the series capacitors excite low-frequency oscillations. These oscillations may damage turbine-generator shafts.[6] With series capacitors, the reduction in line current is small. Thus if thermal considerations limit the current, shunt compensation should be used. If, however, voltage drop is the limiting factor, series capacitors are effective. They are also very effective if the total line reactance is high and they may improve stability.[32]

2.5.4 A review of distribution network methods which make use of the resonance concept

This section will look in detail at methods that are used in distribution networks which make use of the concept of resonance. The two methods that will be presented are:

- the Petersen coil
- Capacitor tapping (Captap)

Petersen coil

The Petersen coil is essentially an earthing method. One of the main and vital purposes of an earthing system is the reduction of earth fault currents which occur when there is a phase-to-earth fault on a distribution network. In Petersen coil-earthed networks, arcs are self-extinguishing. This improves reliability of supply as there are fewer interruptions on the system. Petersen coil earthing reduces the magnitude of short fault currents.[36]

A Petersen coil is sometimes called an arc-suppression coil, or a ground fault neutraliser.[36] Figure 2.15 shows the connection of a Petersen coil.

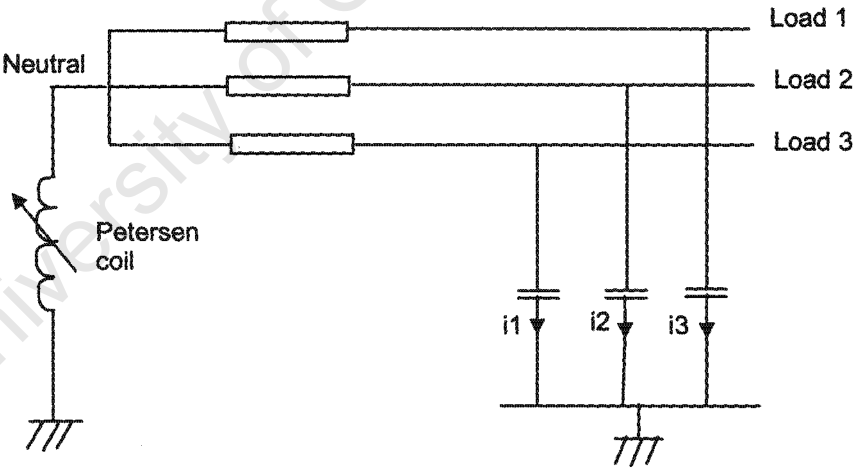


Figure 2.15 Three phase system with Petersen coil earthing

The Petersen coil resembles a single-phase transformer. It is connected between the neutrals of a transformer and earth.[36] When "normal" conditions prevail, there is no voltage across the Petersen coil. However, when an earth fault occurs at any point in the system, the phase neutral voltage of the system is applied across the coil. The reactance of the Petersen coil is causes a lagging current to flow through the coil (or neutraliser) and transformer to the fault and hence the ground. At the same time, the capacitive currents will be flowing from the healthy lines to ground. The reactance of the coil is chosen such that the lagging current from the reactor and the leading current from the line capacitors are virtually 180° out of phase (this is applying the concept of resonance). The actual current flowing to the ground will therefore be the difference between the two "opposing" currents.[40]

By properly tuning the reactor, the difference between the two currents can be equated to zero. This results in a fault current of zero magnitude. If the fault current is reduced, any arc that has resulted from the earth fault will not be sustained. During the arcing stage, a parallel resonant circuit is established.[41]

If the earth fault is transient (which is most often the case), once the fault has been suppressed, the system continues to function as normal without an interruption of supply. If the fault is of a more permanent nature, the system may continue to operate with one phase earthed at the fault. The voltage between the other phases and earth will, however, increase from phase voltage to the line voltage of the system. In this case, a fault current would continue to flow and the system protection would operate to disconnect the faulty line from the supply. Petersen coils are often included in systems that have overhead lines which are subject to transient faults due to lightning, birds, falling tree branches and so on.[35]

The Petersen coil has many advantages, and new compensation technologies should strive to offer similar benefits, some of which are presented below.[36, 41]

- Earth faults are reduced
- Arcs are self-extinguished
- There are no power supply interruptions on Petersen coil earthed systems
- The voltage increase after arc extinction is slow, thus reducing the risk of arc re-ignition
- Power quality is continuous with Petersen coil earthing as there are fewer interruptions to the system due to self-extinguishing arcs
- Negligible fault to ground currents

The Petersen coil has several disadvantages. These will not be discussed in detail, but it should be noted that these disadvantages have prevented the Petersen coil from being used extensively in distribution networks. Existing compensation techniques do not fully meet the needs of the electrical system and this has created an opportunity for further research to be conducted in an attempt develop a usable and viable compensation technique.

A few of the Petersen coil's disadvantages follow [36, 41]:

- The reliability and sensitivity of relays are reduced in protection systems
- Petersen coil tuning is a problem in expanding networks
- Difficulty in locating faults due to the fact that earth fault currents are reduced to very low values
- With respect to lightning, ungrounded neutral service arrestors are applied at sacrifice in cost and efficiency (i.e. the two lines are at full L-L voltages when a fault occurs)
- Feeders cannot be interconnected unless the interconnected system is resonant grounded or isolating transformers are used.
- Central co-ordination in neutraliser settings in interconnected systems is required in order to determine the proper neutraliser tap.
- Taps on neutralisers must be changed when major system switching is performed, and difficulties may arise in interconnected systems.
- There may be a high total cost unless the arc-suppressing characteristic is relied on to eliminate duplicate circuits.

Power tapping (Captap)

In countries which have large but sparsely-populated regions, such as South Africa, many small rural communities do not have access to mains electricity. This is partly due to the associated high costs. This is a difficult scenario and is particularly frustrating for those people living close to high voltage transmission lines. The Research Institute of Hydro Quebec (IREQ) in Canada developed a system that could tap small amounts of power from high voltage transmission lines. These systems use the lightning shield wires which, when insulated from the towers, have a capacitively induced voltage on them. This capacitively-induced energy is then converted into usable electricity by means of reactive compensation.[39] In 1994, L. Stubbs [42] investigated this concept and studied its application in South Africa. This section summarises the findings reported in the resulting dissertation.

In order to achieve a suitable power supply from the insulated shield wire, a regulating system must be developed that delivers a standard output voltage that is relatively constant with varying load magnitudes and phase angles.

L. Stubbs proposed a control in the form of series reactive compensation. "This technique uses a fixed inductive coil (reactor) in series with the shield wire source. The value of the inductive impedance is chosen to be equal in magnitude to the source capacitive impedance at power frequency. This gives an output voltage which is independent of load magnitude or power factor at steady state power frequency. This method of voltage regulation relies on the ability to accurately determine the source parameters, as the reactor has a fixed value and has to be specified up front." [42] Figure 2.16 summarises the concept.

The advantages of this passive compensation technique are:

- No need for electronic control of output voltage
- Few components and thus higher reliability
- Low cost

The disadvantages of this technique are:

- There is a need for accurate values for the equivalent source parameters
- The reactor needs to be designed specifically for each system
- There can be no control of the system output voltage fluctuations due to transmission line conductor geometry variations

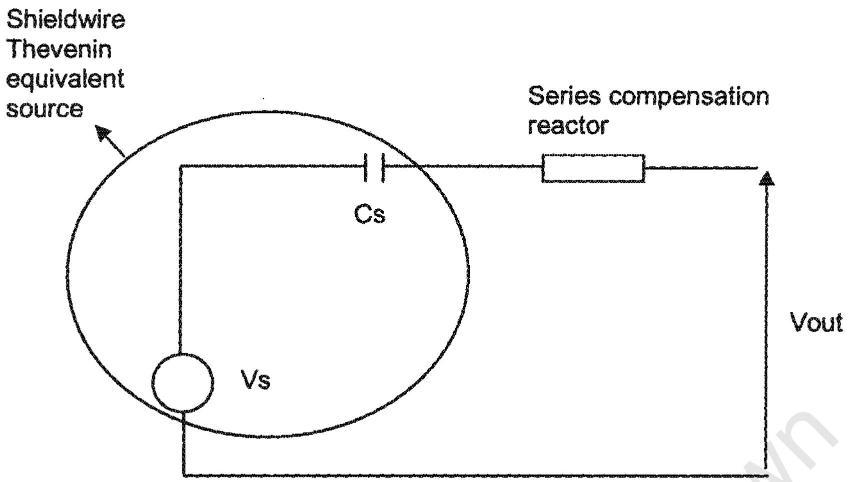


Figure 2.16 Proposed series compensated source

In order to investigate the technique, a prototype power tap-off system was developed using a 9.6km insulated section of one shield wire of the Kendal Minerva 400kV line. A 420kV source was applied to one end of the transmission line under steady state conditions.

The results of tests performed on the prototype showed a voltage regulation of 1.3% when the system was loaded to 17kVA which is satisfactory. When the system was loaded with a non-linear load, the output voltage was distorted almost to a square wave shape because the non-linear load generates a large percentage of the harmonic currents, and the source has a high impedance at frequencies other than series resonant frequency. [42]

This general technique has also been used in capacitive coupling substations. The substation hooks up directly to all three conductors of 115kV to 245kV transmission lines, through a capacitor bank. It provides a three-phase power output of up to 2MVA at voltages ranging from 11kV to 35kV. The substation is easy to install and maintain and is a low cost, environmentally-friendly power supply. It may also provide compensation on heavily loaded transmission lines where it is installed (because it is a capacitor bank). The system includes components which work as a damping circuit to eliminate the risk of sustained ferroresonance (which can occur when a capacitor divider is placed in series with an inductor). The system has, however, been experiencing the effects of sub-synchronous resonance when it is loaded with non-linear, transient loads such as unloaded inductive motors. [43]

Although the above results are specific to the "captap" technology, they present the possibility of instability in resonant systems which are loaded with non-linear or motor loads. In the testing of the technology presented in this thesis, these loads were specifically tested in order to determine its stability in various conditions. This will be examined in more detail in chapter five.

Chapter Three: The theoretical development of a "series resonant" fault-tolerant network

As explained in Chapter two, a "series compensator" is a reactive component that is placed in series with an "opposing" reactive component. In this way, their reactive impedances "cancel each other out" and the effect of the initial reactive component becomes negligible. This concept is often made use of on long lines which experience significant volt drops due to the line inductance. By placing series capacitors in that line, the magnitude of the problematic inductance is minimised and volt drops are decreased. This chapter discusses the complex resonance and voltage regulation theory on which the proposed technology is based. These concepts are based on mathematical principles and equations. The development of this theory paves the way for the manifestation of this theory in a practical laboratory environment.

3.1 An introduction to the aims of the voltage regulation in the proposed technology

The compensative concept discussed in this thesis is described as "series resonant" because its essential function is to compensate for added reactance in the supply line, which limits any short-circuit currents flowing in the network due to transient faults on the MV overhead lines. This extra inductance naturally causes an unacceptable volt drop which must be negated in some way. The load-end compensator must be able to react to changes in load power factor and magnitude. A higher-rated load will draw a larger current which will lead to an increased volt drop across the added supply inductance (and across the inherently-present line impedances). A load with a lower power factor will induce the need for load compensation (or power factor correction) in the form of reactive current injection close to the load itself. Thus, the compensator is a load-compensator and is, in fact, placed in parallel with the load. Thus, its main function is that of reactive power (or current) injection. This reactive power will compensate both for the load (with a non-unity power factor) and the added series inductance in the supply.

The ultimate aim of the compensator is voltage regulation. In other words, its function is to maintain a defined voltage across the load even though the series inductance causes a large volt drop, and the load has a variable magnitude and power factor. As explained, a load with a larger magnitude (higher rating) will draw a larger current, causing volt drops on the line to increase. A load with a lower power factor (but constant power rating) will draw a greater total current because it will have a greater *apparent* power need. The current drawn will increase because its *reactive* component will rise in magnitude, which increases the magnitude of the resultant current. This implies that a larger component of the current that the load draws is "unuseful" and, indeed, wasteful. The reactive component of the total current supplied by the source can be replaced by the reactive current injected by the compensator at the load. This decreases the resultant (or total) current drawn by the load from the source. This means that a current of smaller magnitude will flow through the supply circuit, and the supply impedance (including the added reactance). This, once again, reduces the volt drop experienced by the system. Thus, the compensator will inject the amount of reactive current required to maintain a constant load voltage magnitude. If the load has a large magnitude and low power factor, the compensator will need to inject more reactive power into the system, and vice versa.

This implies that the compensator should be able to respond almost instantaneously to changes in the load. In other words, the compensator needs to be active, not static. In essence, it constantly monitors the voltage across the load. If the voltage (or load) remains constant, at the defined magnitude, then the compensator remains static. If the voltage magnitude goes below a set value, the compensator must inject more reactive current (or power) into the system. The compensator essentially consists of a number of capacitors in parallel which supply the reactive power, power electronics (thyristors) which switch the capacitors in and out as more or less reactive power is required, and a DSP (Digital Signal Processing) board which acts as the control system and monitors the value of the load voltage magnitude. Thus, the thyristors will "switch more capacitors in" when more reactive power is needed. It will continue to switch capacitors in until the DSP board determines that the magnitude of the load voltage is within acceptable (or pre-defined) limits, at which stage the thyristors will stop switching in capacitors.

Turning attention to the series inductance, its function, as explained, is to reduce the magnitude of short circuit currents due to transient faults. If the inductive impedance is large enough, the short-circuit current can be reduced significantly so that its magnitude is less than that required to sustain a power arc caused by the fault. Thus, flashovers resulting from transient faults such as lightning will always be rapidly self-extinguishing, possibly negating the need for protection operation. This depends on the settings of the protection relay responding to the fault. Earth fault relays function according to an IDMT curve which means that the smaller the fault current magnitude, the longer the feeder breaker will take to trip.[9] A fault current magnitude of only two times the full load current of the system will have a relay response time of well over 1 second (the exact response time depends on the design of the specific relay).[9] Thus, if the inductance can both significantly limit the magnitude of the transient fault current, and reduce the duration of the arc burning time, the earth fault relay will not respond at all, and its corresponding breaker will not trip. Assuming the fault is transient, the system will then continue to operate as normal, with the customer experiencing a "mild" and extremely short voltage dip when the arc is briefly burning. If the fault is in fact of a more permanent nature, the arc will continue to re-ignite after it has extinguished at each current zero. In this case, it will be known that the fault is permanent and the feeder breaker will open to prevent any damage to the system.

One of the significant characteristics of the proposed technology is the magnitude of the fixed series inductance. When an earth fault occurs in a system, the short-circuit current that flows through the fault can be up to 10 times greater in magnitude than the expected load current that the network is designed to carry [9]. For purposes of the laboratory and the investigation presented in this thesis, it was decided to include an inductance with a magnitude that resulted in a "fault current" of approximately two times the magnitude of that under rated conditions. If, for example, the supply transformer is rated at 10A on the low voltage side, then the expected current during fault conditions (with the added inductance) should be 20A. The value of the inductor is calculated to fulfil this expectation. The current in fault conditions should be larger than it is in steady-state conditions so that monitoring of the line currents will still give an indication of a fault having had occurred. It should be realised that this "larger" current will flow for only a short period of time, namely while the arc is burning.

Figure 3.1 gives a single-phase line diagram of the proposed circuit.

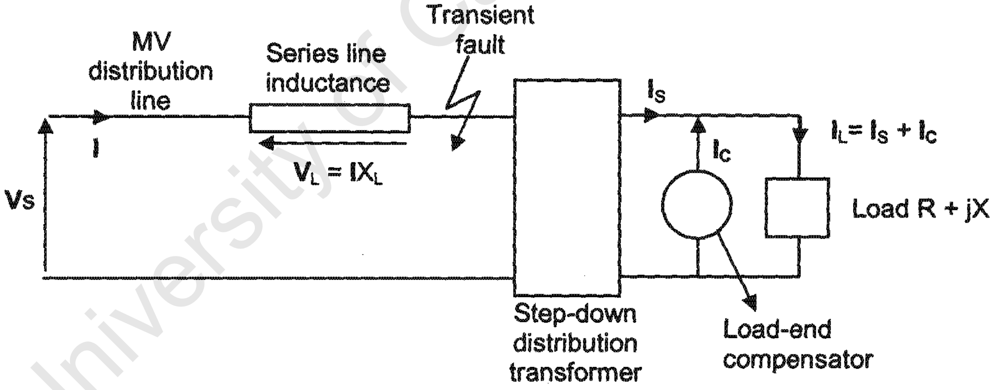


Figure 3.1 A line diagram of the proposed circuit

The diagram shows the added inductance (X_L) in the source supply circuit. Transient faults that occur on the MV part of the distribution line will be extinguished rapidly. There will be a significant volt drop across the reactor. In fault conditions, I should be $2I_L$. In the circuit, I_L, the current required by the load, is complex because the load has a lagging power factor. The complex current is made up of a real part which is drawn by the active power demands of the load, and an imaginary part which is drawn by the reactive component of the load's demand. If the compensator is ideal, then all of the load's reactive power will be supplied by the compensator, and the voltage across the load will be fully regulated because the compensator will compensate for the voltage drop experienced across the supply reactance. The concept of reactive current injection is relatively straight-forward. The voltage regulation that takes place in the circuit is slightly more complicated. The next section looks in detail at the theory behind it.

3.2 Voltage regulation: general concepts, and its application to the circuit.

Although this has been discussed briefly in chapter two, a full explanation of the concept of voltage regulation and its application in the proposed circuit will now be presented. Voltage regulation can be defined as the proportional change in supply voltage magnitude associated with a defined change in load current (e.g. from no load to full load). It is caused by the voltage drop in the supply impedance carrying the load current.[34] Consider a supply system, represented in Figure 3.2 by a single-phase Thevenin equivalent circuit. Figure 3.3 shows the phasor diagram for the supply system when it is uncompensated.[34]

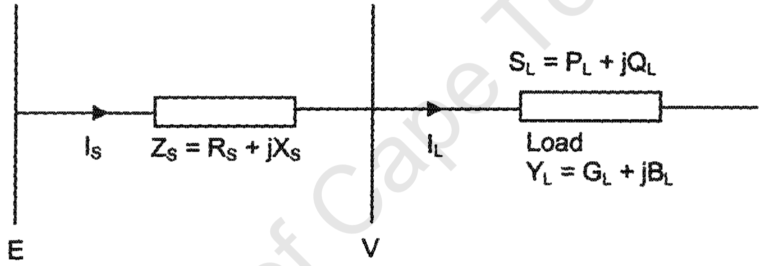


Figure 3.2 Single-phase Thevenin equivalent circuit of a supply system [34]

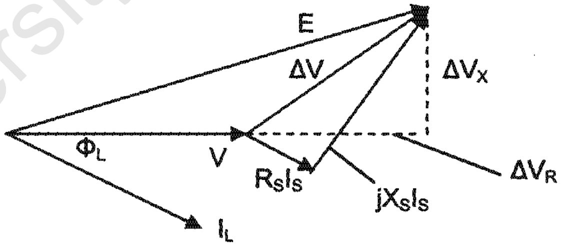


Figure 3.3 Phasor representation of the supply system [34]

The supply voltage change caused by the load current $\mathbf{I}_L$ is shown in Figure 3.3 as $\Delta\mathbf{V}$ and can be expressed as follows:

$$\Delta \mathbf{V} = \mathbf{E} - \mathbf{V} = \mathbf{Z}_S \mathbf{I}_L$$

The voltage change has a component ΔV_R in phase with **V** and a component ΔV_X in quadrature with **V**. Both the magnitude and phase of **V**, relative to the supply voltage **E**, are functions of the phase and magnitude of the load current. In other words, the voltage change depends on both the real and reactive power of the load. [34]

By adding a compensator in parallel with the load, it is possible to make |**E**| = |**V**|. This is equivalent to maintaining the load voltage magnitude constant, at the value *E*, even with load connected. This is shown in Figure 3.4 for a purely reactive compensator.

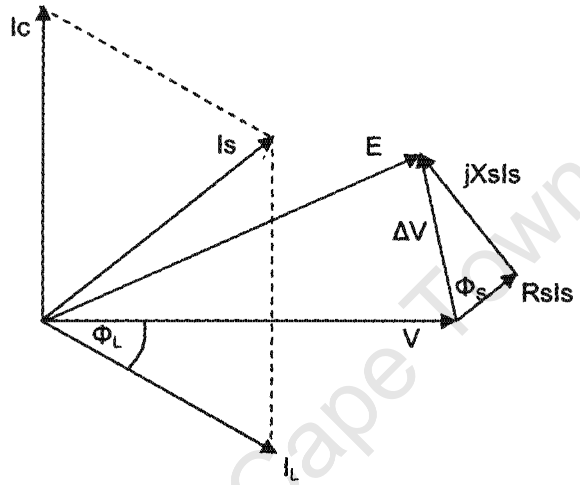


Figure 3.4 Phasor diagram for the compensated system (compensated for constant voltage) [34]

The reactive power drawn by the load (Q_L) is replaced by the sum $Q_S = Q_L + Q_C$ where Q_C is the reactive power provided by the compensator. Q_C is "adjusted" in such a way as to rotate the phasor **ΔV** until |**E**| = |**V**|. Figure 3.4 shows that the lagging current phasor drawn by the load is "vector-added" to the purely reactive current injected into the system by the compensator ($\mathbf{I}_C$). The resultant phasor, $\mathbf{I}_S$, is the actual system current, and its phase is such that the supply and load voltage are equal in magnitude. The magnitude of the reactive current phasor can be adjusted if the load current has a different magnitude and phase, so that the aim of voltage regulation is always met.

The required value of Q_C is found by solving the following equation for Q_S with |**E**| = *V*; then $Q_C = Q_S - Q_L$. The equation is obtained through various algebraic manipulations.[34]

$$|E|^2 = \left[V + \frac{R_S P_L + X_S Q_S}{V}\right]^2 + \left[\frac{X_S P_L - R_S Q_S}{V}\right]^2$$

The most significant concept is that there is always a solution for Q_S whatever the value of P_L. In other words, no matter what the real power requirements of the load may be, it is always possible to determine the value of the reactive compensation needed to maintain a constant load voltage (which is also equal in magnitude to the supply voltage). We can therefore draw the following important conclusion: "A purely reactive compensator can eliminate supply-voltage variations caused by changes in both the real and reactive power of the load." [34] And if the reactive power of that compensator can be controlled smoothly, over a sufficient range, and at an adequate rate, it can perform as an ideal voltage regulator.[34] It is, however, vital to note that only the magnitude of the load voltage is controlled. Its phase varies continuously with the load current.

3.3 The voltage regulation of the proposed fault-tolerant network

This section will apply the voltage regulation concepts explained in the previous section to the specific circuit proposed in this thesis.

3.3.1 The simplification of the proposed network for analysis

As shown in Figure 3.1, the proposed concept is "defined" over two different voltages: the medium voltage of the distribution line and the low voltage of the load reticulation. If, however, we remove the transformer by "bringing the primary-side voltage and impedances over to the secondary side", the circuit, at its most basic level, is shown in Figure 3.5. Essentially, the circuit consists of a supply voltage, a series impedance with a large X/R ratio and a capacitor in parallel with a load. For simplification, assume that the series impedance is a pure inductance and that the load is purely resistive.

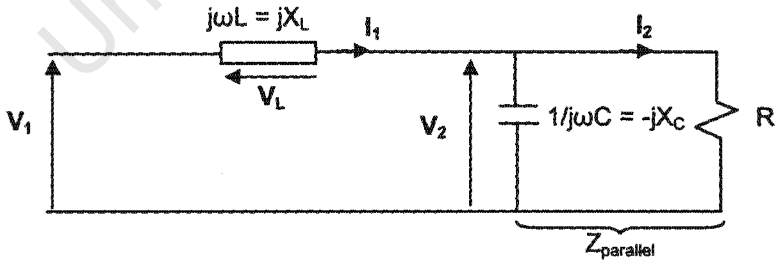


Figure 3.5 A simplified circuit showing the proposed technology

3.3.2 Simulations of voltage regulation in the proposed circuit

The reactive-compensation voltage regulation of this simplified circuit (and the voltage regulation concept in general) is demonstrated using Matlab's Simulink package. The resulting circuits and waveforms are shown in the next few figures. The structure of the simulated circuit is the same as that of the circuit in Figure 3.5 and the specific values of the components are not relevant to the demonstration of a concept but were selected to be sensible in the context of the theoretical development thus far.

The Simulink simulations were carried out using a complex series impedance (i.e. the impedance consists of a resistance and inductance) and purely resistive load. The supply voltage in the simulations was set at 230V which was also the desired magnitude of the load voltage.

Figure 3.6 shows a simulated circuit without the load-end compensator. It shows that the volt drop across the series impedance is significant and that the resulting magnitude of the load voltage is unacceptably low.

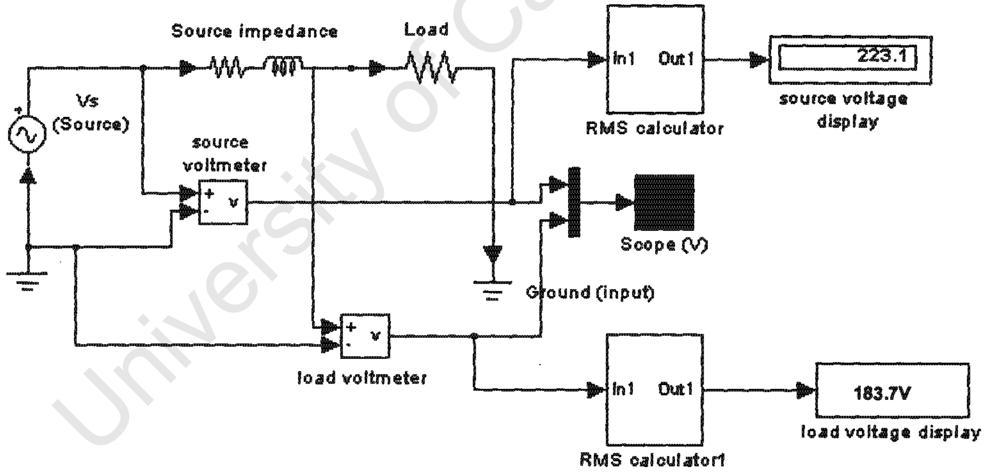


Figure 3.6 The uncompensated circuit as simulated in Simulink

Figure 3.7 below shows the same simulation but with the load-end compensator included in the circuit. This demonstrates that by adding a capacitor in parallel with the resistive load, it is possible to "raise" the load voltage up to 230V (magnitude). The actual output voltage in the simulation is 232.3V. This is because the standard capacitors available in the laboratory for testing had a capacitance of 50μF and the values used in the simulations were thus multiples of 50. This limited the absolute accuracy of the regulator.

Although this was a restriction in the testing for this thesis, it is not necessary to use standard components if a wider range of capacitors of variable values is available.

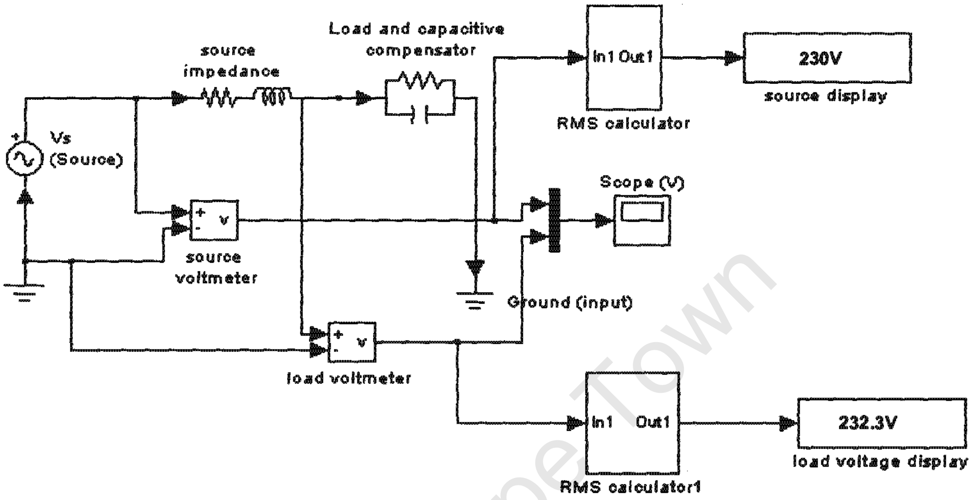


Figure 3.7 The compensated circuit as simulated in Simulink

3.3.3 An explanation of voltage regulation as applied in the proposed circuit

The results of the simulations shown in Figures 3.6 and 3.7 indicate that the load voltage is being regulated by the load-end compensator. In other words, they show that the concept of voltage regulation is being applied in the proposed circuit. The specific effect of the compensator as a regulator in the proposed circuit will now be explained in further detail. Consider the circuit in Figure 3.8 which represents the simplified uncompensated network.

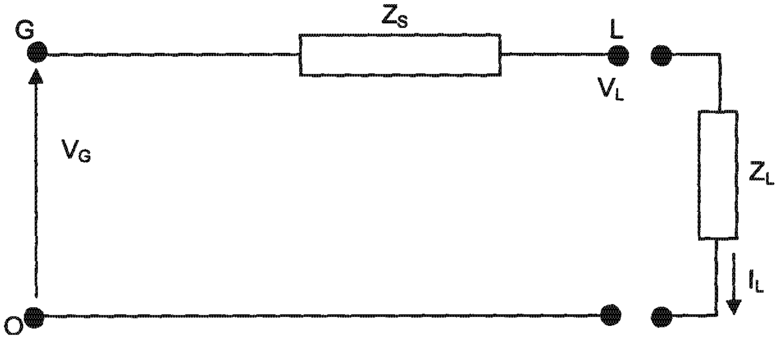


Figure 3.8 A simplified circuit representing the uncompensated network

In the circuit diagram, $\mathbf{V_G}$ is the generator voltage, $\mathbf{Z_S}$ is the line impedance and $\mathbf{Z_L}$ is the load impedance. When no load is connected, $\mathbf{V_G} = \mathbf{V_L}$. When a load is connected, it draws a current $\mathbf{I_L}$. This results in a line voltage drop $\mathbf{V_S} = \mathbf{I_L Z_S}$. Therefore, $\mathbf{V_L} = \mathbf{V_G} - \mathbf{I_L Z_S}$ or $\underline{OG} = \underline{OL} + \underline{LG}$. This vector (phasor) relationship is shown in Figure 3.9.

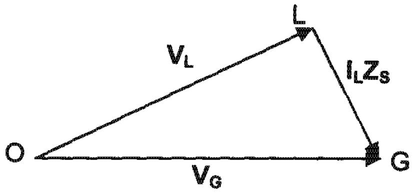


Figure 3.9 The phasor representation of the circuit in Figure 3.8

The magnitude and phase of $\mathbf{Z_S}$ are always constant. Therefore, if $\mathbf{Z_L}$ is a linear, constant magnitude, complex load, it will draw a current, $\mathbf{I_L}$, of constant magnitude, and the volt drop across $\mathbf{Z_S}$ will then also always be constant *in magnitude*. However, the phase angle of the load may very and result in a corresponding phase angle change in the line volt drop (due to a change in the phase of $\mathbf{I_L}$ drawn by the load).

If it is, for the sake of example, assumed that $\mathbf{S_L}$ = 8kVA (in other words, the rating of the load is always 8kVA), then the power drawn by the load can range, theoretically, from -8kVAr (in the case of a purely capacitive load), through 8kW (in the case of a purely resistive load), to 8kVAr (in the case of a purely inductive load). It could have any phase angle "in between" these extremes, but the magnitude of the apparent power drawn will remain constant. This implies that the current drawn by the load can also vary in phase in a similar manner. This will result in a corresponding change in the line voltage drop.

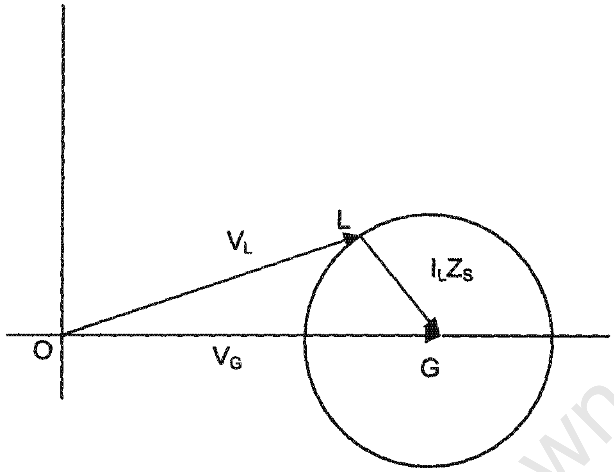


Figure 3.10 A phasor diagram showing the possible line volt drops for the circuit

In Figure 3.10, the circle represents the locus of all possible values of line volt drops for the full complex load range. (Note the magnitude is the same, only the phase angle changes). As the volt drop follows its locus around the circle, it will "take on" a particular value that will result in V_L equalling V_G (in magnitude). The circle thus also represents the locus of V_L.

If the requirement is to maintain the following relationship: $|V_G| = |V_L|$ (but note that $\mathbf{V_G} \neq \mathbf{V_L}$, otherwise no current would flow from the source to the load), then the allowable locus of $\mathbf{V_L}$ is shown in Figure 3.11 on the following page.

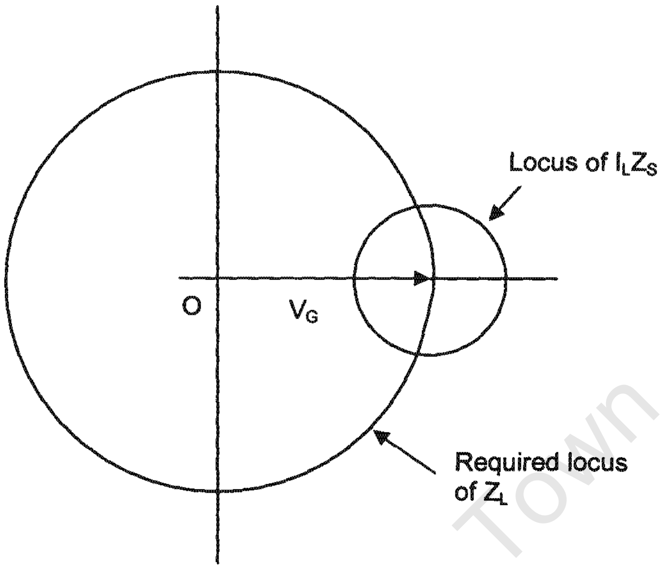


Figure 3.11 The required locus of Z_L on a phasor diagram

This defined locus limits the permissible position of the phasor of the load voltage by forcing it to have a specific magnitude. If the phasor of the load voltage does not lie on the locus, it is possible to force it to do so by "adding another volt drop" to the circuit. The following example illustrates this concept. Suppose the load current is such that the line drop is as shown in Figure 3.12 on the following page.

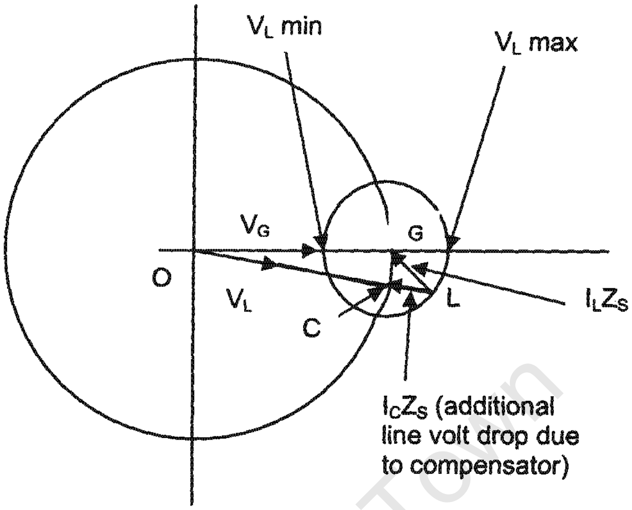


Figure 3.12 Phasor diagram showing the effect of the compensator on the circuit.

When an additional compensating component is connected across the load, it will "draw more current" (with the correct phase angle) and cause a "further" (in an opposing direction) volt drop, $\mathbf{V}_C = \mathbf{I}_C\mathbf{Z}_S$. This will result in a total line drop of $\mathbf{V}_S = \mathbf{Z}_S(\mathbf{I}_C + \mathbf{I}_L)$. This is also illustrated in Figure 3.12.

It can be seen form Figure 3.12 that the current "drawn" or "injected" by the compensator has the effect of altering the magnitude of the load voltage such that it becomes equal to that of the supply voltage. In this example, the compensator current caused the load voltage magnitude to decrease so that it lies on its required locus.

3.4 The Basic Equations governing the proposed fault-tolerant network

The following question may now be raised: "If the load resistance and inductor magnitude are known, is it possible to theoretically determine the value of the capacitor magnitude required to fulfil the purpose of the proposed technology?" If this value can be calculated theoretically, this will lead to the manifestation of this theory in a practical circuit which can be tested in the laboratory. The practical tests can then be used to determine the validity of the theoretical development, and of the success of the technology itself. The equations that follow attempt to answer the proposed question and can be used as a springboard for a more detailed development of the proposed circuit.

The simplified circuit in Figure 3.5 (which is shown again as Figure 3.13) can be modelled with the equations that follow:

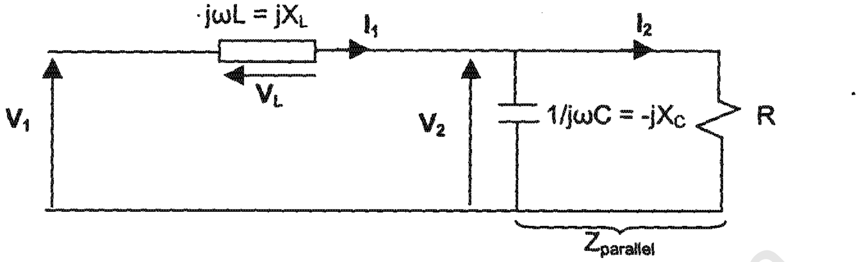


Figure 3.13 A simplified circuit showing the proposed technology.

$$Z_{parallel} = \frac{jRX_c}{jX_c - R}$$

$$Z_{total} = \frac{X_L X_C + jRX_L - jRX_C}{R - jX_C}$$

$$I_1 = \frac{\overrightarrow{V_1}}{Z_{total}} = \frac{\overrightarrow{V_1}(R - jX_C)}{X_L X_C + jRX_L - jRX_C}$$

$$V_L = jX_L I_1 = \frac{jX_L \overrightarrow{V_1}(R - jX_C)}{X_L X_C + jRX_L - jRX_C}$$

$$V_2 = V_1 - V_L$$

$$V_2 = \frac{-jV_1 RX_C}{X_L X_C + jRX_L - jRX_c} \qquad \text{------------------} \qquad 3.1$$

by substitution and algebraic manipulation

Assuming that $V_1 = A\angle\Phi = a + jb$

And that $V_2 = B\angle 0 = c$

Then $A = B$ is the "forced condition".

If a magnitude value of V_2 is pre-defined, then a number of further equations can be solved. Setting the required *magnitude* of V_2 to 230V, gives:

$$A = B = 230$$

$$\sqrt{(a^2 + b^2)} = 230$$

Note that the phase angle of the load voltage has been "set" to 0. It is essential to find the *difference* in phase between the supply and output voltage, thus one can set one of the phases arbitrarily. Thus V_2 consists of a magnitude only, namely 230V (i.e $c = 230$).

Substitute $V_1 = a + jb$ into equation 3.1, gives:

$$V_2 = \frac{-j(a+jb)RX_C}{X_L X_C + jRX_L - jRX_C} = 230 + j0$$

$$V_2 = \frac{-jaRX_C + bRX_C}{X_L X_C + jRX_L - jRX_C} = 230 + j0$$

Algebraic manipulation is then used to transform the above expression into a "c + jd" form (in other words, the real and imaginary components are separated out). This gives the following:

$$V_2 = \frac{aR^2 X_C{}^2 - aR^2 X_C X_L + bRX_L X_C{}^2 + j(bR^2 X_C{}^2 - bR^2 X_C X_L - aRX_L X_C{}^2)}{X_L{}^2 X_C{}^2 + R^2 X_L{}^2 - 2R^2 X_L X_C + R^2 X_C{}^2}$$

The real component can then be equated to 230 and the imaginary component can be equated to 0. This gives three final simultaneous equations, which can be solved only once the values of R and L are known. These are the values of the load resistance and the inductive impedance, which is calculated to reduce the short-circuit current to twice the rated load current. The equations can be used to solve for the capacitive impedance which is needed to fulfil the conditions they set out, and the phase angle of the supply voltage, V_1. The equations are:

1. $\sqrt{(a^2 + b^2)} = 230$
2. $\dfrac{aR^2 X_C{}^2 - aR^2 X_C X_L + bRX_L X_C{}^2}{X_L{}^2 X_C{}^2 + R^2 X_L{}^2 - 2R^2 X_L X_C + R^2 X_C{}^2} = 230$
3. $\dfrac{bR^2 X_C{}^2 - bR^2 X_C X_L - aRX_L X_C{}^2}{X_L{}^2 X_C{}^2 + R^2 X_L{}^2 - 2R^2 X_L X_C + R^2 X_C{}^2} = 0$

One can use these equations to solve for a, b, and X_C. The equations can also be manipulated to include a complex (known) load and a series impedance consisting of both a resistive and an inductive part.

In summary, the theory of voltage regulation and its particular application to the proposed circuit can be better understood by examining the simple equations that govern that circuit. The method of solving simultaneous equations that is proposed in this section is, however, complex and time consuming. Chapter Four examines a more practical means of calculating the required capacitance.

Chapter Four: The development of the laboratory protocol

The laboratory tests of the proposed series resonant fault-tolerant network had the aim of answering two fundamental questions regarding the system:

- Does the technology cause rapid arc extinction when transient faults occur on the MV distribution line?
- Does the compensator meet its requirements, in terms of compensating for the extra line impedance, responding to changes in load, and maintaining a relatively constant voltage across the load before, during and after a line fault without instability?

It is these objectives that determined the laboratory set-up which needed to create an appropriate means for testing them, and the nature of the tests that would be performed. Essentially, in order to performs relevant tests, the laboratory set-up must be able to:

- Simulate an MV line
- Create arcs on the MV line
- Create a large supply impedance
- Test the effects of the impedance on the arcs in a variety of conditions
- Determine how successfully the compensator maintains a constant load voltage
- Test the efficacy of the compensator in a variety of conditions
- Measure the duration and magnitude of the arc current
- Measure the uncompensated and compensated load voltage
- Switch in a variety of loads to test their effects on the arc duration and compensator's efficacy.

The last point is particularly important in determining the success of the proposed technology. Under a variety of conditions, the behaviour of both the arc and the compensator must be examined. The magnitude and power factor of a load determines the current drawn by that load, and therefore the volt drop across the supply impedance. By altering the characteristics of the load, the effects on the system can be observed and measured. Essentially, the laboratory set-up must make it possible to perform all required tests, and those tests must attempt to answer the following questions:

- What is the behaviour of the arc when there is added reactance in the supply circuit compared with that when little impedance is present?
- What are the magnitude and duration of the arc current under no-load conditions?
- What is the behaviour of the arc under rated-load conditions?

- What is the behaviour of the arc when the load magnitude increases or decreases?
- What is the behaviour when the load's power factor changes?
- What is the effect of the added supply inductance on the load voltage?
- What is the effect of the compensator on the arc and load voltage under rated conditions?
- What is the effect of changing the load magnitude and power factor on the compensator and arc?
- What is the effect of a motor load on the efficacy of the compensator and the stability of the system?

This chapter describes in detail the development of the laboratory protocol and the laboratory set-up itself, which must create appropriate conditions for performing tests in order to answer the questions above. The actual tests and their results are described in chapter five.

4.1 The initial laboratory set-up

Two of the main objectives of the laboratory set-up were to

- simulate a Medium Voltage distribution line so that faults could be initiated on it,
- create a "large" series inductance in the supply circuit (although the value of the actual value of this inductance was not initially known)

In deciding on the various constraints impacting the laboratory set-up, it was noted that the type of system to which the proposed technology would often be applied is a single-phase network found in rural areas where loads are sparse and overhead lines are very exposed to transient faults caused by lightning.

Then, in order to meet the above objectives and develop an appropriate laboratory set-up, the following decisions were made:

- The proposed concept was tested in a Medium Voltage laboratory.
- The tests were carried out using SWER (Single Wire Earth Return) transformers; in other words, the concept was tested in a single-phase system.

The resulting initial laboratory set-up was as shown in the schematic circuit in Figure 4.1.

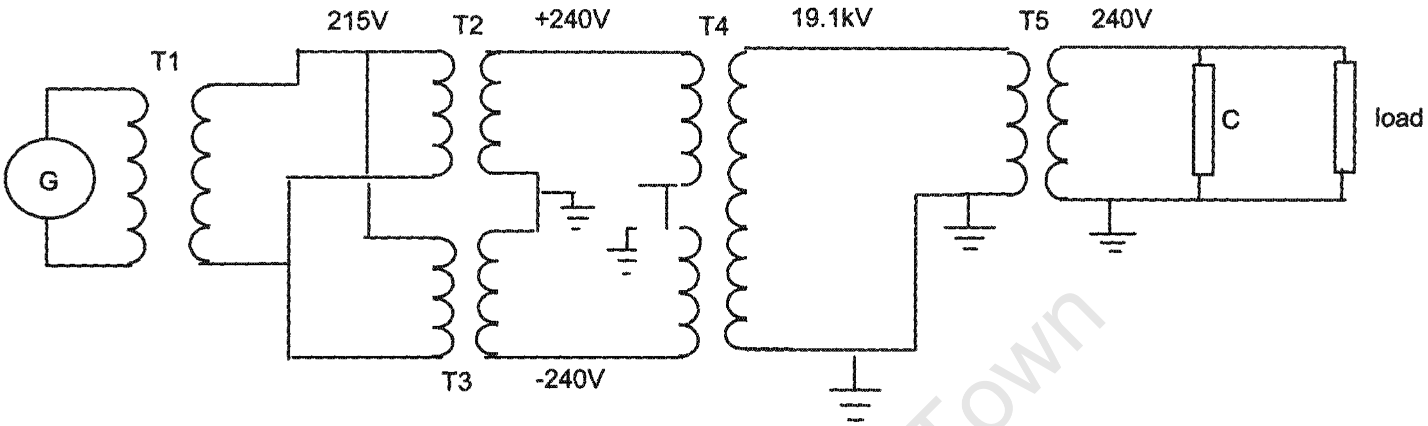


Figure 4.1 The initial laboratory set-up

Each component, and its function, in the proposed circuit will now be described in detail.

- G – This is the generator that supplied the circuit. It is located in the Machines Laboratory. It has a rated voltage of 6.6kV and a rated power of 520kVA. It was decided to supply the test circuit by means of a generator as opposed to mains because the mains supply in UCT is prone to severe harmonics due to the large number of computer loads. The generator provided a clean, constant supply which ensured that any results obtained from tests were reflective of changes in relevant or known conditions, and not of those which were uncontrollable or unknown. The use of the generator also prevented extra loading on the mains supply which may have resulted in voltage dips on the building supply.
- T1 – The generator output is fed directly to this 300kVA, 6600/380V 3-phase transformer. For the purposes of testing, only two of the three phases are used. This transformer steps the voltage down to required level. The supply is then fed to the Medium Voltage Laboratory via a double cable of approximately 70m.
- T2 and T3 – These transformers have two main functions: firstly, they add inductance to the supply circuit, and secondly they are used to deliver, on their secondary sides, the correct input supply for the SWER transformer (T4). These transformers are identical, each being 3-phase, and rated at 48kVA, 380/425V. They are set-up quite unusually in the sense that they are connected in parallel on the primary side, but are then connected "in series" on their secondary sides. The primary sides are obviously fed with the same supply, but two of the opposite output (secondary) phases are connected to each other and then to earth. Thus at any one time, each of the other (non-earthed) secondary

phases supplies a voltage of identical magnitude but opposite in phase (or 180° out of phase). If the one supplies +230V, the other is supplying -230V. The total *series* supply from the transformer is thus 460V. These transformers step the supply voltage up from 215V (which is supplied via the cable from the generator)

- T4 – This is a 32kVA, ±240/19100V SWER transformer. This transformer also contributes to the supply series impedance, but its main function is to step the supply voltage up to a distribution line medium-voltage level. It essentially creates the MV line on which faults will be initiated. Although the HV side of this transformer is rated at 19.1kV, the actual voltage of the MV line during testing was approximately 18.3kV. This is because the compensator is rated at 230V and is programmed to maintain this voltage across the load (the transformer is supplied with +-230V).
- T5 – This is a 16kVA, 19100/240V SWER transformer. It no longer contributes to the supply impedance that leads to arc extinction (because it is located *after* the MV line where faults occur) but does contribute to the overall series impedance that must be compensated for in steady-state. This transformer's main function is to step the supply voltage down to "reticulation" level so that a load can be supplied. Once again, because this transformer is supplied with 18.3kV, its output voltage is 230V, not 240V.
- C – This is the load-end compensator. This specific compensator is designed to maintain the load voltage at 230V in the laboratory and 460V in the field. When it is used in the field at double the voltage, the rating of the compensator is four times larger. The compensator was initially designed to operate at a rating of 32kW at 460V (which is matched to the 32kVA transformer, T4). Because only one 16kVA step-down transformer was used, the load voltage is half of 460, or 230V. The compensator is therefore operated (in the laboratory) at 230V, requiring half its capacitors, and has a rating of 8kW. The compensator's rated power factor was not specified.
- L – This is the load that is supplied by the network. Tests were carried out on the system using no load, rated load of 8kVA (this is now matched to the capabilities of the load-end compensator), and a number of other loads with varying ratings and power factors. These loads will be described in detail later in this chapter.

The following photograph depicts some of the above apparatus:

Figure 4.2 This photograph shows the two 48kVA transformers (T2 and T3) to the left (the two grey box-shaped transformers), the 32kVA SWER transformer (T4) to the back right, and the 16kVA SWER transformer (T5) to the front right.

The main purpose of this proposed network is to limit a short-circuit current in the system by means of a large inductance in the supply circuit. This will ensure that any transient faults on the system are rapidly extinguished. For the proposed system, it was decided that the supply inductance should limit the fault current to two times the rated steady-state current. This current magnitude will be unable to sustain arcing faults but will still be noted as an abnormality on the system. The method used to determine the actual value of this supply impedance will be presented in the next section.

4.2 The equipment and method used to initiate faults on the MV line

In steady-state conditions, the MV line supplies the 16kVA SWER transformer. When a fault is initiated on this MV line, it is necessary to "divert" the current flowing through it so as to prevent its flow to the load. This current needs to be diverted directly to ground in order to create a short-circuit, or earth fault. The MV line thus supplies two separate circuits: one which is supplied in the steady state, and one which is supplied in fault conditions. This is shown in Figure 4.3

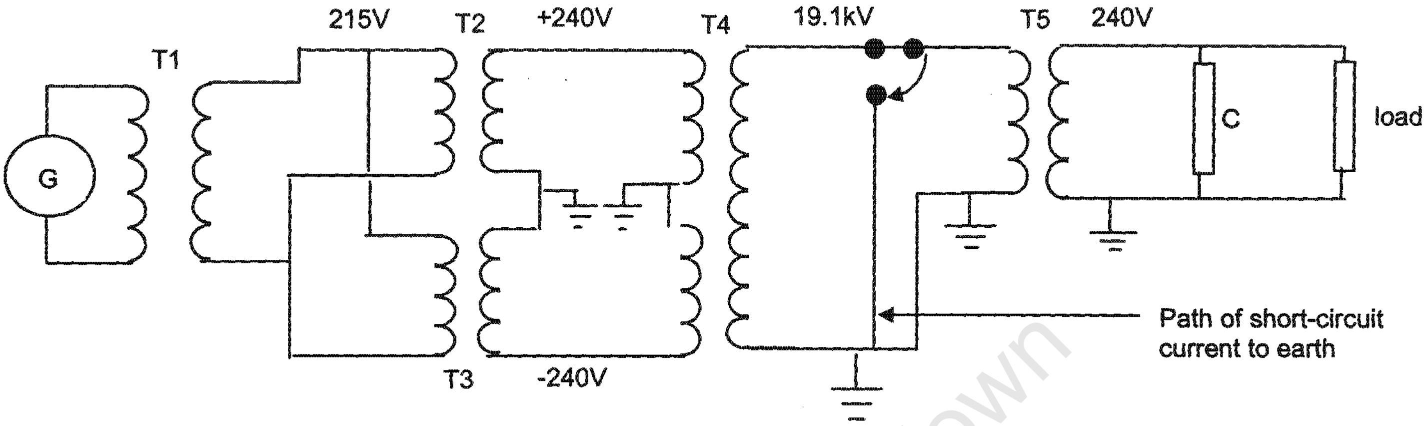


Figure 4.3 Test circuit showing path of fault current to earth

The MV line is connected to a fuse link, which, in steady-state conditions, is "normally open" and is in turn connected to a capacitive divider (used for measurement purposes; it will be discussed in detail later) which features a horizontal electrode. This divider is placed on a table, and a metal plate which is connected to earth is placed a distance beneath the electrode so as to create a gap of specific length. The fuse, which is raised away from the link (to ensure the "normally-open condition") is attached to a rope which is fed to the measuring area *outside* the insulating cage via a primitive pulley system. The rope is secured using a clip. When the clip is released, the rope slides through the pulley, the fuse closes the link, and the voltage appears on the line connected to the capacitive divider and electrode. This initiates an arc across the gap between the electrode and the earth plate. Because a surge generator is not used to initiate the arc, it is initiated with a fine thread of Eureka, a copper-nickel alloy with high electrical resistance and low temperature co-efficient. This wire is attached to the electrode so that it hangs down, its end lying just a few millimetres above the earth plate (neutral electrode). This air in this very small gap ionises rapidly. This initiates the arc, causing the thread (fuse wire) to burn and evaporate, resulting in a full arc between the two electrodes.

The gap lengths across which the arc burned were decided based on the findings by Jojozi (see chapter 2). According to his research, at 20kV, 100% of arcs were self-extinguishing at 30cm. The arc gap was therefore set at 33cm. (The differential is due to the practical limitations of creating the arc gap using pre-cut pieces of wood on which the electrode rested). In order to obtain comprehensive results, tests were also performed with an arc gap of 45cm. This decision was based on the need to increase the range of results, to provide a comparative base for the

results at 33cm, and also to determine the impact that this gap length had on the arc duration. If the increased gap length decreased the arc duration extensively, then a cost-benefit analysis (for implementation in the field) may show that the increased cost of insulation is viable if it guarantees that any arc caused by transient events will not trip feeder breakers.
This set-up is depicted in the following photographs.

Figure 4.4 This photograph shows the fuse link which, for stability purposes, is mounted on the 32kVA SWER transformer. The MV output is connected to the base of the fuse link. The top of the link is connected via cable to the electrode (the cable is shown at the top of the photograph). The fuse has fallen, closing the link, resulting in a fault. The nylon rope used to raise and drop the fuse is seen connected to the fuse.

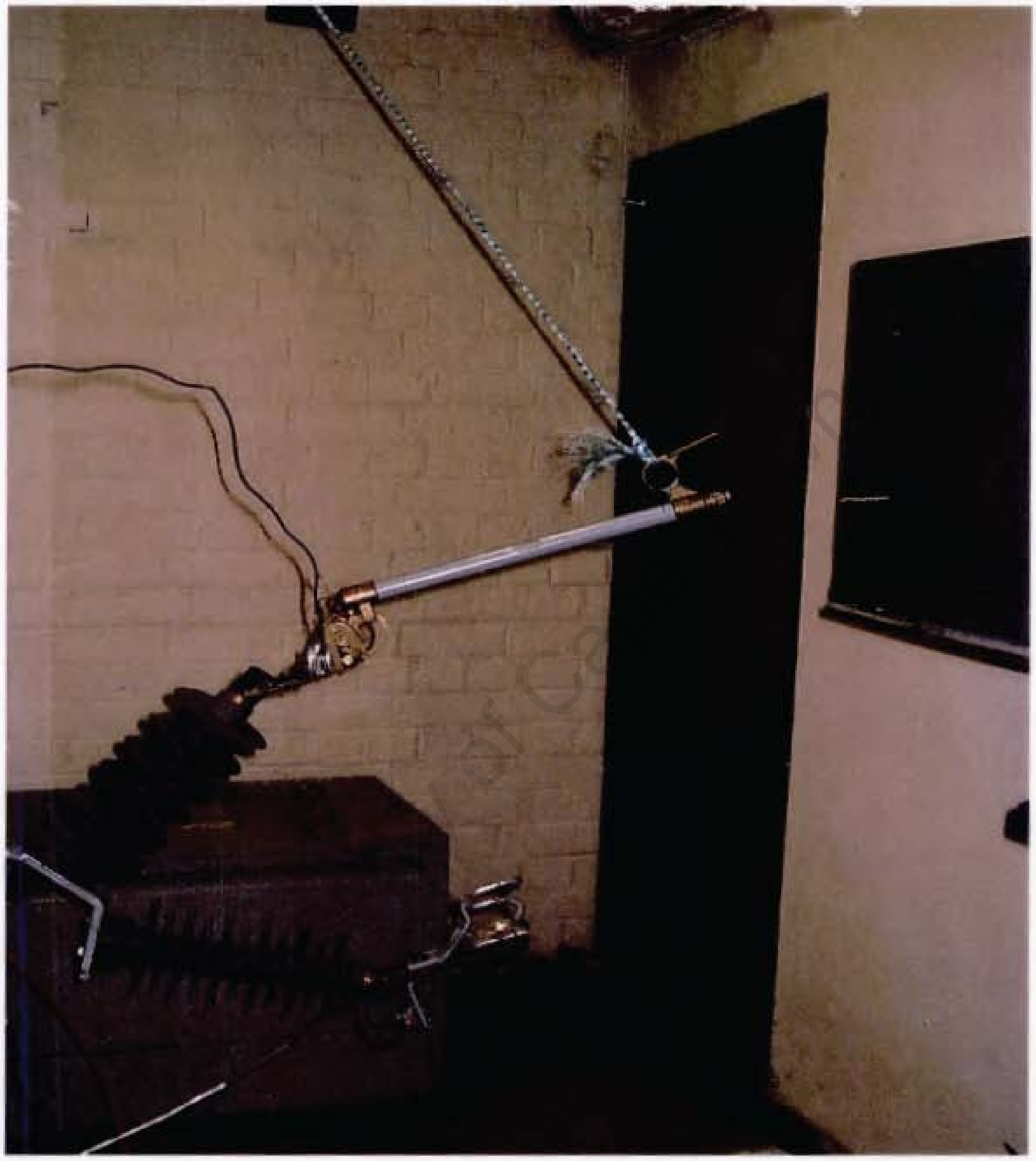


Figure 4.5 This figure shows the fuse link in the normally open position which ensures the steady-state condition of the system.

Figure 4.6 This photograph shows the capacitive divider which features a horizontal electrode. The divider is connected to the fuse link. A distance beneath the electrode is the neutral electrode (metal plate) which is connected to earth.

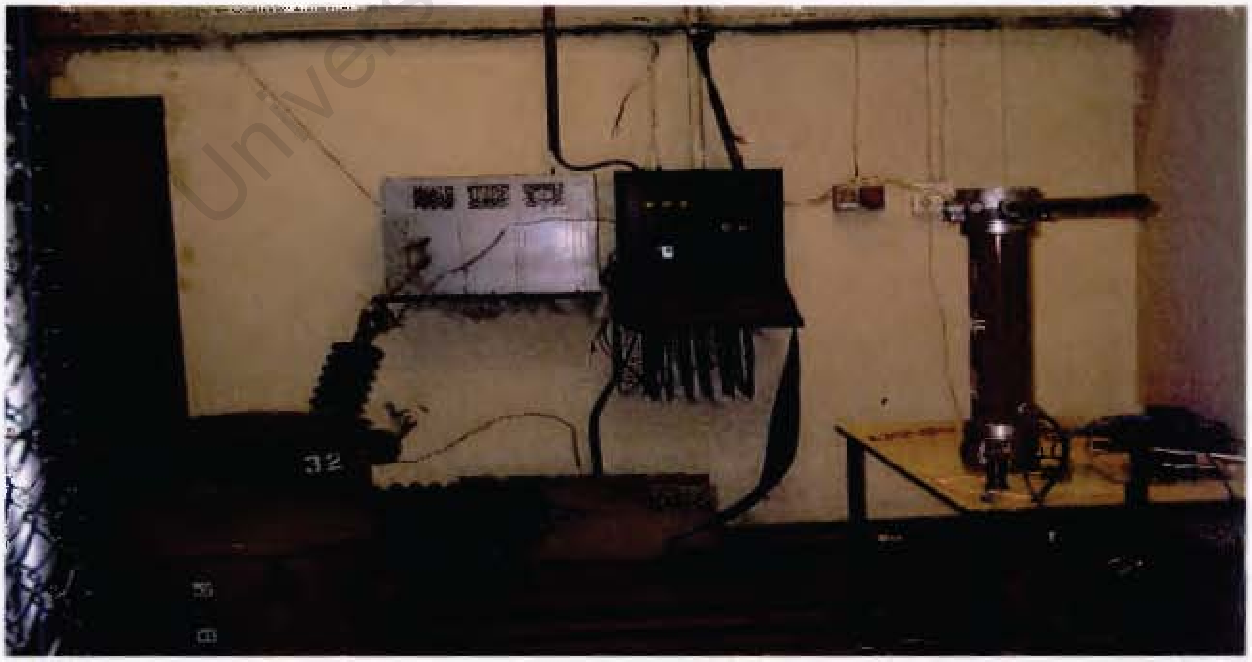


Figure 4.7 The connection between the fuse link and the capacitive divider

4.3 Method used to evaluate the supply impedance of the proposed circuit

The calculations presented in this section are vital for the process of developing the laboratory protocol.

The reasons for, and aims of, the calculations presented in this section are now summarised.

- The proposed circuit aims to reduce the magnitude of short-circuit currents.
- This reduction in current magnitude aims to achieve rapid arc extinction.
- The reduction will be achieved by a large inductance in the supply circuit.

The following facts have been presented in chapter 2 and must also be taken into account when considering the specific aims of this section:

- At 20kV, 100% of arcs across a 30cm gap are unsustainable (Jojozi's results)
- At 20kV, an arc across a 30cm (air) gap will last, on average, for 350ms (Jojozi's results)
- Protection systems take between 100 and 450ms to respond to earth faults
- The shorter the arc duration, the more successful the technology will be (by removing the need for interruptions due to protection intervention)
- In Jojozi's tests, the arcs tests at any voltage (e.g. 20kV) may have actually been initiated at a lower voltage due to the ionisation of the air in the gap before arc voltage built up to expected value
- In the tests conducted for this thesis, the steady-state voltage will build up to the specified value (±20kV) before the arc is initiated which might result in comparably longer durations of arcs initiated across the proposed 33cm gap.

In order to achieve the aims of the proposed technology, the arc current must be limited as much as possible to decrease arc duration; the objective will be to reduce the circuit's short-circuit current to twice that of its rated steady-state current. To achieve this:

- The existing inductance of that supply must be determined.
- It must be determined if inductance must be added / removed in order to reduce short-circuit current magnitudes to the desired value.
- The value of the total inductance will enable calculations to be performed in order to determine the required characteristics of the compensator which must compensate for the large supply reactance.

This section discusses the process followed in determining the value of the supply impedance required to achieve the desired current limiting characteristics of the proposed circuit.

In order to implement this process, the calculations presented in this section need to be as accurate as possible. Due to the large number of transformers present in the proposed circuit, the per-unit calculation method was used to determine the existing inductance. For these calculations, the rating and power factor of the load and the series impedances of all other components must be known. This is because the load rating will determine the rated current in the system. This, in turn will determine the value of the required fault current (2 times the rated value). In these calculations, the load was assumed to be of rated magnitude (8kVA) and, for simplicity, purely resistive, i.e. 8kW. (Note that an 8kW load at 230V will draw a steady-state current of 33.3A; the fault current then needs to be limited to 66.7A). The impedances of the other components in the system were evaluated by means of short- and open-circuit tests that were performed on each piece of equipment. The calculations and their results are now presented briefly.

4.3.1 The results of the open- and short-circuit tests performed on circuit components

The open- and short-circuit tests were performed to evaluate the series and shunt impedances of all components in the proposed test circuit. The series impedance of some of the equipment used had previously been determined, namely that of the generator and the first transformer of the network, located in the Machines Laboratory. Open-circuit and short-circuit tests were carried out on the other components in the circuit. For the purposes of this research, only the series impedances of the transformers have been considered. The transformer shunt impedances (obtained in the open-circuit tests) have been considered negligible. The cable's impedance was determined using a cable manual. All of these results are now presented.

Generator:	%Z = 194;	Zpu = j862
T1 (300kVA 6600/380V):	%Z = 4	Zpu = j13.33
Cable:	PVC insulated SWA, length = 140m; Z = 0.122 + j0.173Ω (impedance referred to LV side)	
T2 (48kVA 425/380V):	Z = 0.144 + j0.128Ω (impedance referred to LV side)	
T3 (48kVA 425/380V):	Z = 0.146 + j0.124Ω (impedance referred to LV side)	
T4 (32kVA +-240/19100V):	Z = 0.127 + j0.36Ω (impedance referred to LV side)	
T5 (16kVA 19100/240V):	Z = 512.73 + j843.37Ω (impedance referred to HV side)	

To calculate the total impedance of a circuit that includes several transformers, it is necessary to convert the network to a per-unit system. This in effect, removes the transformer windings from the circuit, leaving only their impedances to have any effect. The per-unit calculations are presented briefly in the section that follows.

4.3.2 The per-unit calculations performed on the network

The per-unit method has been used in the development of the laboratory protocol for two reasons:

- These calculations will determine the actual value of the series impedance in the supply circuit.
- The calculated value of the supply impedance will enable a decision to be made as to whether further reactance needs to be added to the supply circuit in order to reduce the short-circuit current to twice that of the rated load current.

These calculations are fairly complex and lengthy but are essential for the purpose of the laboratory set-up for testing, and they also ensure that one of the fundamental hypotheses is tested. This can be summarised with the following question: "Will a reduction in the magnitude of the short-circuit current – by the addition of inductors in the supply circuit – result in rapid arc extinction?" The essential points and results are presented here. Refer to Appendix B for the details.

The load was regarded as being purely resistive for the calculations and was designed (and manufactured) with a rating of 8kW at 220V. This implies that the ohmic resistance of the load is 6Ω (this was considered constant, although the heating of the load did cause the resistance to increase during testing). A base of S = 100MVA was used for all the per-unit conversions. Then the following equation is used to convert Z(actual) to Z(pu):

$$Z_{pu} = Z_{actual} \times \frac{100}{E^2}$$

where $E^2 = V_{LL}$ in kV

Once the various voltage "zones" were established, the impedance values in that zone were multiplied by a constant which was obtained by dividing 100 by the square of that voltage to obtain the equivalent per-unit value.

This data is used to obtain the simplified per-unit system shown in Figure 4.8:

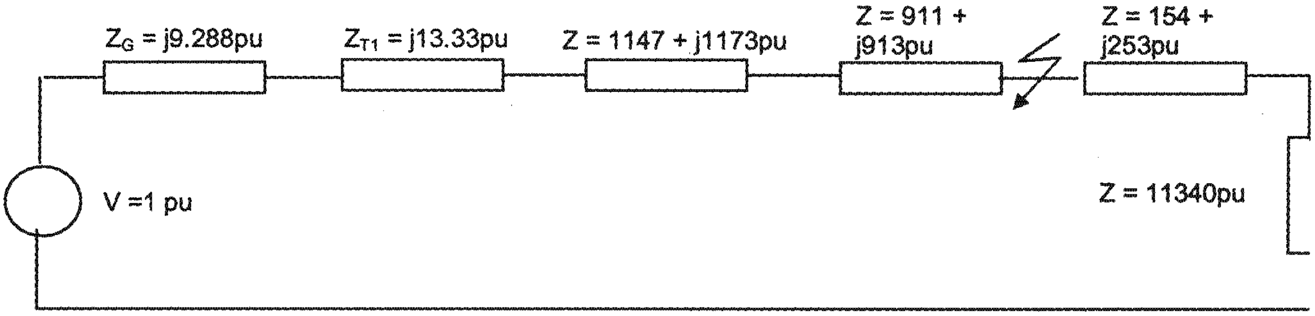


Figure 4.8 Simplified per-unit system

Thus, the per-unit impedance up to the MV line is:

$Z = 2058 + j2109 = 2947\angle 45.7°$

The aim is to ensure that this impedance is sufficient in magnitude so as to limit the short-circuit current magnitude to twice that of the steady-state current. If one considers the load "zone", the base voltage is 230V and the base current (when the base apparent power is 100MVA) is 416666.67A. For a 6Ω load, the steady-state current is 38.3A. Thus the desired short-circuit current is 76.7A.

If $I = 76.7A$

And $I_{base} = 434782.6A$

Then $I_{pu} = 0.000176pu$ is the desired per-unit current throughout the per-unit system.

The desired per-unit impedance which limits the short-circuit current is:

$Zpu = 5668.6pu$

At present, (as shown previously), the impedance has a per-unit magnitude of 2947. This impedance needs to be increased in magnitude (to limit the fault current) by the addition of reactors in the supply circuit. It is now necessary to calculate the value of the required reactance.

If the "final value" of the impedance magnitude is 5669 and the value of the resistance remains the same, then the reactance can be calculated as follows:

$$R = 2058\,pu$$
$$Z = 5669\,pu$$
$$\therefore X = \sqrt{(5669^2 - 2058^2)} = 5282\,pu$$

The current value of X is 2109pu. Therefore, the required reactance to be added has a value of 3173pu. It was decided to place the reactors in the 205V "zone" of the supplying circuit. The most accessible point in their connection as shown in Figure 4.9.

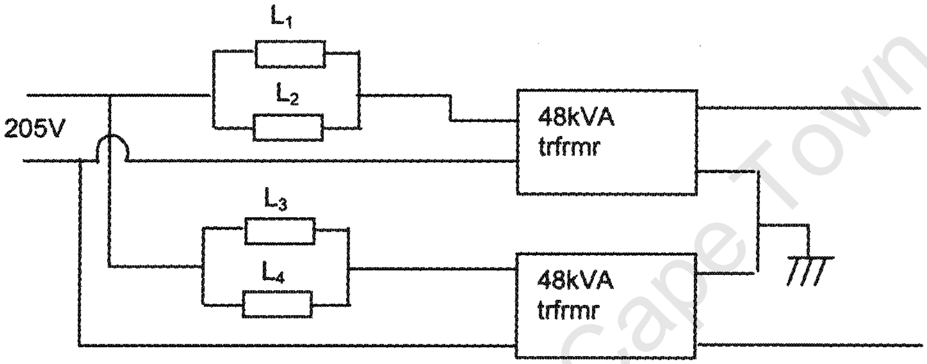


Figure 4.9 A representation of the set-up of the reactors and two 48kVA transformers

Then, for each parallel-connected branch,
L = 8.5mH

For testing, four reactors are used in parallel (two reactors in parallel with each other in each parallel branch of the LV connection of the two 48kVA transformers). Each reactor is rated at 20mH @ 15A. Thus in each parallel branch, the total reactance is 10mH @ 30A (this reactive value is acceptably close to the required 8.5mH). The photograph that follows shows the reactors.

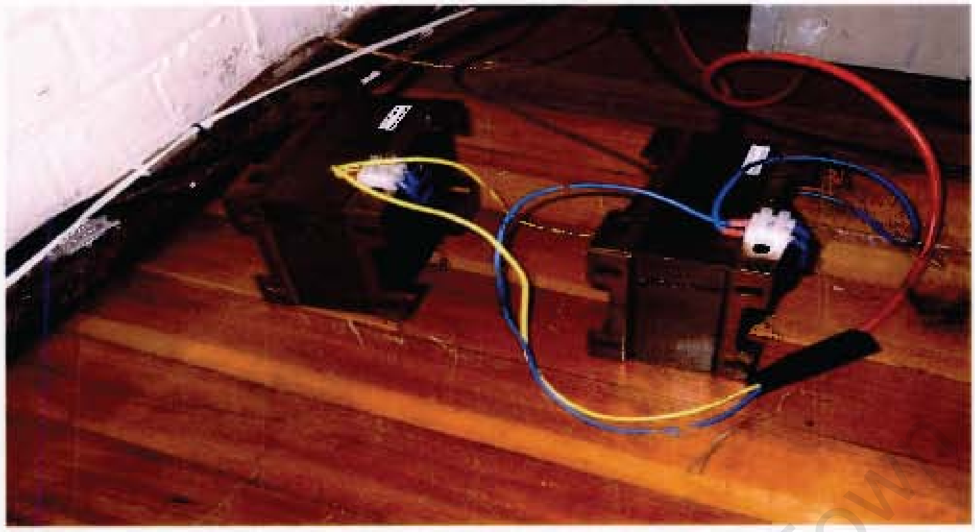


Figure 4.10 This photograph shows two of the added reactors that are connected in parallel with each other, and in series with one of the 48kVA transformers.

It is now necessary to reconsider the per-unit system with the reactors included. The impedance provided by the reactors in each branch is 3.14Ω. This implies a total added impedance of 1.57Ω. The equivalent per-unit value is:

$X_{p.u.}$ = 3736pu

This gives a total per-unit reactance up to the MV line (which is the impedance that will oppose the short-circuit current in the case of a fault) of 5846 pu.

Then:

$R = 2058\,pu$

$X = 5846\,pu$

$\therefore Z = 2058 + j5846\,pu = 6198\angle 70.6\,pu$

The added reactance results in the following *total* system impedance (which includes the 16kVA step-down transformer after the MV line) as follows:

$R = 2058\,pu + 154\,pu = 2212\,pu$

$X = 5846\,pu + 253\,pu = 6099\,pu$

$\therefore Z = 2212 + j6099\,pu = 6488\angle 70$

The circuit can now be represented by the following figure:

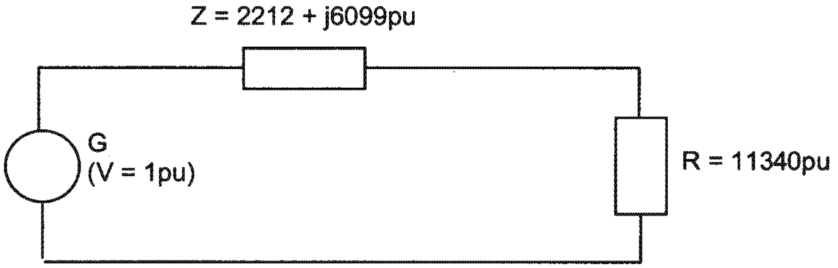


Figure 4.11 The simplified per-unit system

For the purposes of calculations and simulations, it was decided to convert this per-unit network to the equivalent system at 230V. In this system, the voltage source has a supply value of 230V, the series impedance has a value of $Z = 1.17 + j3.2\Omega = 3.4\angle 70$ and the load has a resistance of 6Ω.

There are advantages to using the per-unit concept to calculate the series impedance of the proposed system. However, a disadvantage to using this method is that it is purely theoretical and any number of external or unforeseen effects has not been taken into account. All the equipment in the system is *real* and may have defects. For these reasons, it was decided to determine the total series impedance of the network using another method. Two different loads were connected to the circuit output, and the resulting voltage across and current through these loads were measured. The first load was a resistive load (in the form of heating bars) that has a rating of 8kW at 220V. When it was connected, the voltage across it measured 183V and the current through it measured 29.4A. The load was allowed to cool and was then reconnected. The voltage and current measured 186V and 31A respectively. An average of these results was used as the actual value. The second load was also a resistive load that has a rating of 4kW at 220V. The first time it was connected to the circuit, the voltage across it measured 205V and the current through it measured 16A. It was also connected a second time which resulted in a voltage and current of 209V and 17A. These values were used in simultaneous equations to calculate the practical value of the series impedance of the network. The calculations show the impedance to be the following:

$$Z = 0.63 + j3.07\Omega = 3.1\angle 78^\circ$$

This value is applicable at 230V. A practical disadvantage of this method is the fact that the inductance of the added reactors is non-linear. Therefore, as the load (and thereby the current) varies, the reactance will also vary.

The calculated and measured impedance values are slightly different. However, the similarity of the results confirms the approximate value of the series impedance. Because the second, more practical, method took into account any inaccuracies or unexpected behaviour of the components, its resulting value will be used in future calculations.

In summary, this section has contributed the following information and results:

- The reactance contributed to the series supply circuit by the generator, line and transformers was not sufficient to reduce fault currents flowing through it to twice the steady-state current (when the load is 8kW)
- The magnitude of the required reactance to be added to the circuit in order to achieve that objective was calculated
- The theoretical total inductance of the supply circuit was calculated. This value will be used to determine the magnitude of the parallel capacitance required to compensate for the large supply impedance.

4.4 The role of the compensator in determining the laboratory protocol

In previous sections, topics such as arc creation and the large supply inductance have been discussed. The topic of this section is the compensator and the effect it has on the laboratory protocol. Essentially, testing the efficacy of the compensator is simple: connect it in parallel with the load and observe its effects on the load voltage. In these tests, the vital questions to be asked are: “Does the active compensator maintain the load voltage at 230V when a variety of loads are connected?” and “Does the compensator have any effect on the arcs that are created on the MV line?”

4.4.1 Calculating the value of the compensator’s capacitance

Before the compensator and its role in the circuit are examined, the *required* capacitance of that compensator must be calculated. As will be further shown in this section, the required value of the capacitance will change as the magnitude and power factor of the connected load change. As mentioned at the beginning of this chapter, one of the main objectives of the laboratory tests is to test the ability of the compensator to respond to changes in load and to maintain a constant load voltage in a variety of conditions. The calculations used to determine the required value of the capacitance in the circuit must take into account load magnitude and angle, and must also be able to respond to changes in these values.

The calculations presented in this section are, in fact, "static" in the sense that they can be applied only when a specific load is connected and must be re-done when there is a change in load. The actual compensator is active because it is able to switch the correct number of capacitors in as soon as the load (and steady-state current) change. However, the theoretical calculations will give a broader understanding of the role of the capacitance in the proposed circuit. Note that these calculations have initially been performed using the "base" load of 8kW.

In chapter three, the equations which govern the simplified proposed circuit were examined in order to determine the magnitude of the capacitance required to compensate for a highly inductive supply. This method of calculation is complex and laborious. It was found to be more beneficial, once the circuit was understood, to use Microsoft Excel to model the circuit and find an appropriate capacitor value. The spreadsheet and its associated equations can be found in Appendix A. The aim of the spreadsheet is to determine an appropriate value for the parallel capacitor largely by trial and error. Once the equations have been formulated and the various values of V_1, L and R have been chosen and calculated, by changing the value of the parallel-connected capacitive impedance, the magnitude of the load voltage can also be altered. The capacitive impedance can be manipulated by the user until the value of load voltage magnitude is the same as that of the supply voltage. If a purely inductive series impedance and purely resistive load (of 8kW) are still assumed, the following can be obtained from the simple spreadsheet.

Firstly, the spreadsheet assumes that the supply voltage has zero phase angle. The magnitude of the supply voltage has been "set" at 230V, which is then also the "desired" value for the magnitude of the load voltage. The resistive load is assumed to have a rating of 8kW at 220V, which gives a resistance of 6Ω. (Obviously this value is not constant and will increase slightly as the load heats up. It will be assumed constant for the scope and purposes of this thesis). The rated load current magnitude is therefore I = 230/6 = 38.3A. Twice the rated current is therefore I_{SC} = 2*38.3 = 76.7A. This fault current would flow through the inductor only, to ground. The *required* value of the inductive impedance is thus: X_L = 230/76.7 = 3Ω. (Note that this required theoretical impedance is close in magnitude to the "actual" value of 3.4Ω that was calculated in the previous section) This gives a series impedance of $Z = 3\angle 0 = j3\Omega$ and a reactance of $L = 9.5mH$.

In brief, this particular calculation is applicable if:

- The open-circuit voltage is 230V
- The series impedance is purely inductive and has a magnitude of 3Ω
- The load is purely resistive and has a resistance of 6Ω.

Then, if X_C is manipulated to be 22Ω (i.e. $Z_C = -j22 = 22\angle -90\Omega$), making C = 144.7μF,

$$Z_{parallel} = 5.8\angle -15\Omega$$
$$Z_{TOTAL} = 5.6\angle 1.5\Omega$$
$$I_1 = 39.8\angle -14.8A$$
$$V_{INDUCTOR} = 119.4\angle 75.2V$$
$$V_{LOAD} = 230.5\angle -30V$$

where $Z_{parallel}$ is the impedance of the load in parallel with the capacitor
Z_{TOTAL} is the total impedance of the circuit which is $Z_{parallel}$ added to the impedance of the series reactor
I_1 is the current in the main series circuit
$V_{INDUCTOR}$ is the voltage across the series reactor
V_{LOAD} is the voltage across the load

Thus, with the capacitor having a specific value (when a load of particular magnitude and power factor is connected), the magnitude of the supply and load voltage are the same.

According to the spreadsheet, if the series impedance is equal to the "actual" circuit value of 0.63 + j3.07Ω, and the load remains a 6Ω resistive load, then a capacitance of 300μF in parallel with the load will result in a load voltage of 226V, and a capacitance of 350μF will result in a load voltage of 234V. The spreadsheet can be used to calculate the value of capacitance required to obtain a load voltage of desired value.

Until now, only a resistive load has been considered. The spreadsheet can, however, also be used to show the effect of a complex load on the output voltage of the system. If the load has an *impedance* magnitude of 6Ω, then the *angle* of the load can be altered from -90° (in the case of a purely capacitive load) through 0° (in the case of a resistive load) to +90° (in the case of a purely inductive load). The magnitude of the uncompensated load voltage corresponding to various load angles is shown in Figure 4.12.

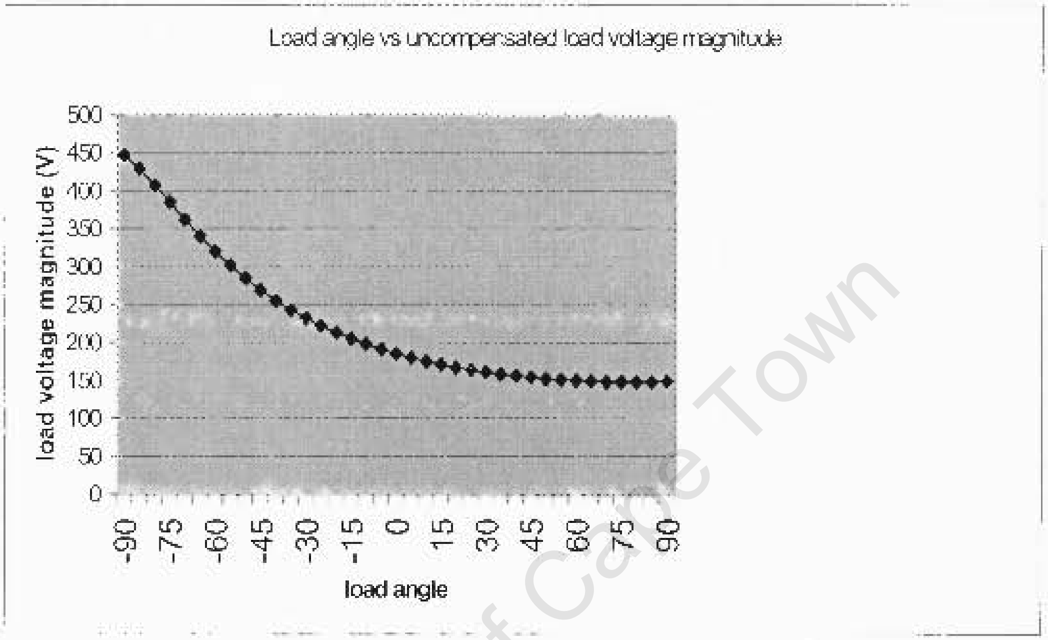


Figure 4.12 The uncompensated load voltage corresponding to various load angles

It is clear, from the graph, that an inductive load (in other words, a load with a lagging power factor) results in a lower uncompensated load voltage than a resistive or capacitive load. This implies that when a complex load with a lagging power factor is supplied by the proposed circuit, the compensator will need to switch in more capacitors in order to compensate for the greater voltage drop. The spreadsheet can be used to calculate how much more or less capacitance is required for any load that is connected to the circuit. The theoretical results presented in this section provide an understanding of what is expected of the compensator, and what characteristics the compensator will need in order to meet these expectations.

4.4.2 A detailed description of the practical compensator

The compensator is essentially an active capacitor. It therefore consists of two fundamental parts: the power electronics which ensures that it is "active", and the capacitors which are switched in and out depending on the load. The compensator features fifteen 50μF capacitors which are connected in parallel. The resolution of the compensation is thus 50μ, implying that the compensator will switch in the number of capacitors that will take the load voltage to a value as close to 230V as possible, but it will not be 100% accurate in its regulation. The power electronics which monitors the magnitude of the load voltage consists mainly of thyristors and a DSP board. The compensator is connected in parallel with the load and is programmed to maintain a load voltage of 230V.

When the compensator is used in the field at double the voltage, the rating of the compensator is four times larger. The compensator was initially designed to operate at a rating of 32kW at 460V (which is matched to the 32kVA transformer, T4). Because only one 16kVA step-down transformer was used, the load voltage is half of 460, or 230V. The compensator is therefore operated (in the laboratory) at 230V, requiring half its capacitors, and has a rating of 8kW.

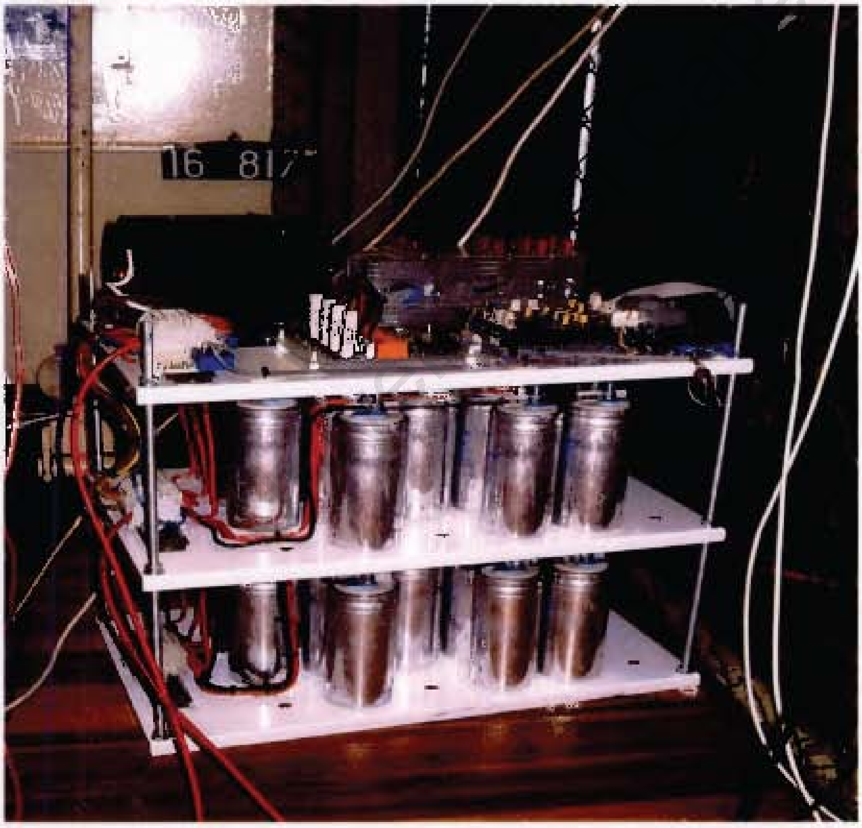


Figure 4.13 This photograph shows the compensator. The 50μF capacitors can be seen on the bottom two levels, while the power electronics can be seen on the top of the compensator.

As explained at the start of the chapter, one of the aims of the laboratory tests was to determine the performance of the compensator with a variety of loads connected to the system. As previously explained, when a complex load with a lagging power factor is connected, the compensator has "more to compensate for" and it was imperative to ascertain that the compensator could still be effective in this, and other conditions.

4.5 A description of the tests performed

In previous sections, the proposed laboratory set-up has been examined in detail. Each component has been discussed and an attempt has been made to meet the objectives of the laboratory set-up, namely the:

- Simulation an MV line
- Creation of arcs on the MV line
- Creation of a large supply impedance
- Ensurance that the compensator which will maintain a constant load voltage

Tests now need to be developed which will determine the behaviour of the arc on the MV line and the compensator under various conditions. The most significant changing condition will be the magnitude and power factor of the connected load. Thus, the following aspects of the testing protocol need to be addressed:

- Test the effects of the impedance on the arcs in a variety of conditions
- Test the efficacy of the compensator in a variety of conditions
- Measure the duration and magnitude of the arc current
- Measure the load voltage
- Switch in a variety of loads to test their effects on the arc duration and compensator's efficacy.

These objectives are essentially achieved by altering the circuit conditions (namely, the load), igniting an arc on the MV line, and measuring the response of the arc and compensator. This section will summarise the tests that need to be performed in order to test the thesis' hypothesis, and describe the tools and methods used for the measurements of components' responses. The results of the tests (interpreted from the measurements) will be described in detail in chapter five.

4.5.1 A summary of the laboratory tests

Initially, arcs were initiated on the MV line with no load connected. These tests were carried out to ascertain the current-limiting effect of the supply inductance before the extra reactance was added to the circuit. One of the disadvantages of these tests is the following. When the contactor in the MV lab is closed, the supply is fed to the step-up transformers which results in an immediate voltage build-up across the arc gap. Although the MV line voltage is set at 18.3kV, the air in the arc gap may break down at a lower voltage as it is building up. This implies that with these tests it is not possible to guarantee the initiation of an arc "at 18.3kV", or any other specific voltage. Nonetheless, these tests aim to confirm the arc-extinguishing properties of the supply circuit and provide benchmark results with which to compare those from tests conducted with the added supply reactance.

Tests were then performed with the added reactance and a connected load. The first load to be connected was the rated 8kW resistive load. The connected load contributed positively to the tests in two ways. Firstly it created the circuit property of "load voltage" which, as a vital criterion of the proposed technology, should remain virtually constant. Secondly it allowed a steady-state condition to be achieved which enabled the MV line voltage to build up to full voltage before the fault was initiated (using the rope control, pulley system, and fuse link).

The base or rated load is rated at 8kW at 220V and was in the form of eight 1kW heating bars connected in parallel. The load also featured a fan for cooling purposes. The structure of the load resulted in high flexibility because the bars could be connected and disconnected at any time, and this, in effect, provided eight different resistive loads ranging from 1kW up to 8kW (in steps of 1kW). This was could be used as an 8kW resistive load, a 4kW resistive load, and provided the resistive part of the complex load that was tested. It should be remembered that the load was rated at 220V and that at 230V, the ratings are slightly higher. The "8kW" load actually draws about 8.8kW at 230V, while the "4kW" load draws approximately 4.4kW.

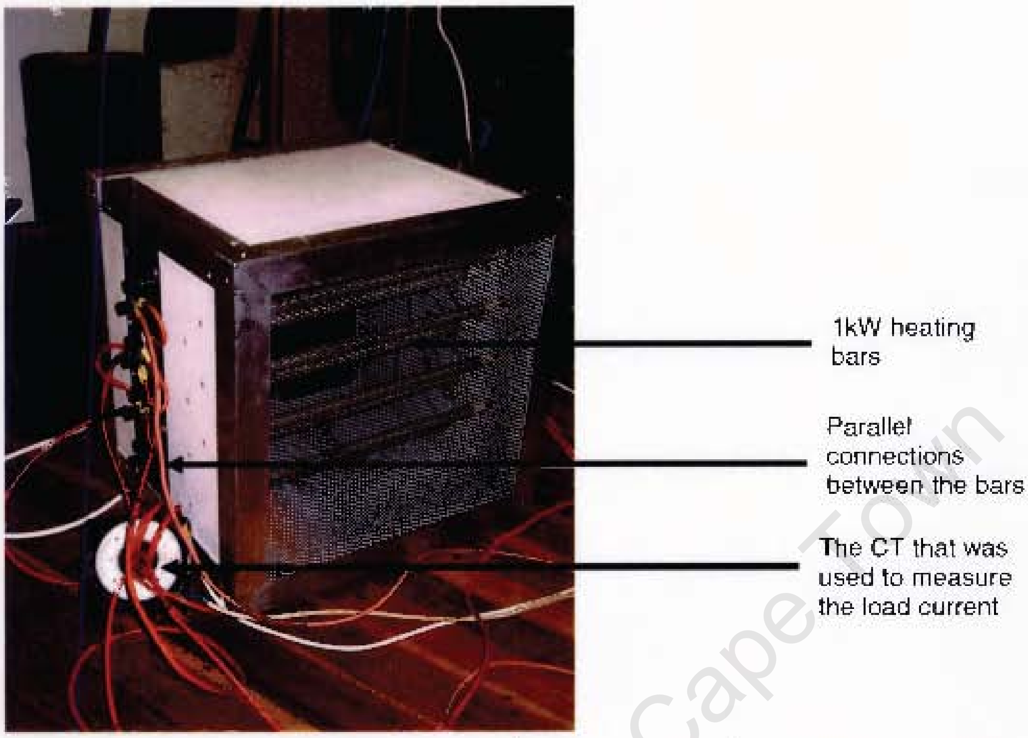
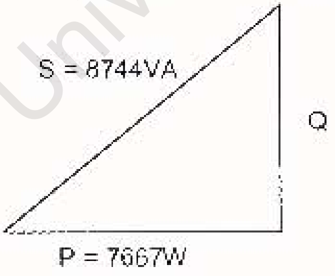


Figure 4.14 8kW resistive load

In order to determine the efficacy of the compensator, arcs were initiated without the compensator connected in the circuit, and then with it connected. This allowed a comparison to be made between the two scenarios. It would also demonstrate the full extent of the load voltage recovery due to compensation. Before the actual compensator was connected, tests were performed using a "passive compensator" in the form of capacitors which were switched in manually. The purpose of these tests was to confirm the theoretical calculations that were carried out to determine the number of capacitors required to raise the load voltage to 230V. Previously, mention was made of the Excel spreadsheet that was used for these calculations. According to the spreadsheet, seven or eight capacitors are required when an 8kW load is connected to the system.

The requirements of the compensator will alter as the load alters. Tests must therefore be performed with a variety of loads being supplied by the proposed circuit. The tests would determine the flexibility, robustness and efficacy of the compensator, and ultimately, its ability to perform as expected. They would also confirm the continued arc-extinguishing property of the system in a variety of conditions. As the magnitude of power drawn by the load increases (with the load power factor remaining constant), so the current flow to the load increases. This increased current will cause a greater volt drop across the series inductance, placing greater demands on the compensator. Similarly, as the current drawn by the load decreases, so the number of capacitors switched in by the compensator will decrease. Alternatively, as the power factor of the load decreases, the compensator will have to compensate further for the lagging nature of the system, and will have to switch in more capacitors. These scenarios were tested by the connection of a 4kW load (created by disconnecting four of the heating bars in the rated 8kW resistive load, leaving only four bars still connected in parallel),a 16kW load (created by connecting two 8kW heating loads in parallel) and a complex load with a lagging power factor. All of these tests were conducted without and then with the compensator connected in the system.

The complex load would also be rated at 8kVA (to match the rating of the load-end compensator at 230V) and was developed from the 8kW resistive load. Because the resistive load was rated at 220V and would be used as a part of the complex load, the actual apparent power to be drawn by the 8kVA complex load was set at 8.744kVA. Initially, a single heating bar was disconnected to create a resistive load of 7kW (at 220V). This implies that the resistance of that load was 6.9Ω. At 230V, this resistive load draws 7.67kW of power. This resistive load would then be connected in parallel to an inductive load to create a complex load with a lagging power factor. Because the real power of the resistive load and the reactive power of the inductive load are added together to achieve the "set" apparent power of 8.744kVA, the power triangle can be used to calculated the required reactive power.



From the power triangle, it can be shown that 4.2kVAr of reactive power is required. Now, the following parameters can be obtained:

$$Q = 4.2kVAr$$
$$V = 230V$$
$$\therefore I = 18A$$
$$\therefore X = 12.6\Omega$$
$$\therefore L = 40mH$$
$$pf = 0.87$$

To achieve this, four inductors were used. Two were placed in series with each other (to increase the value of the inductance) and were then placed in parallel with the other two inductors (which were also in series with each other) to ensure a sufficient current rating. The four inductors were not identical but were close enough in structure and nature to be used effectively as a group. This set of inductors was then placed in parallel with the resistive load on which only seven heating bars were connected. The set-up can be represented in the following figure:

Figure 4.15 The set-up of the complex load; p.f. = 0.87

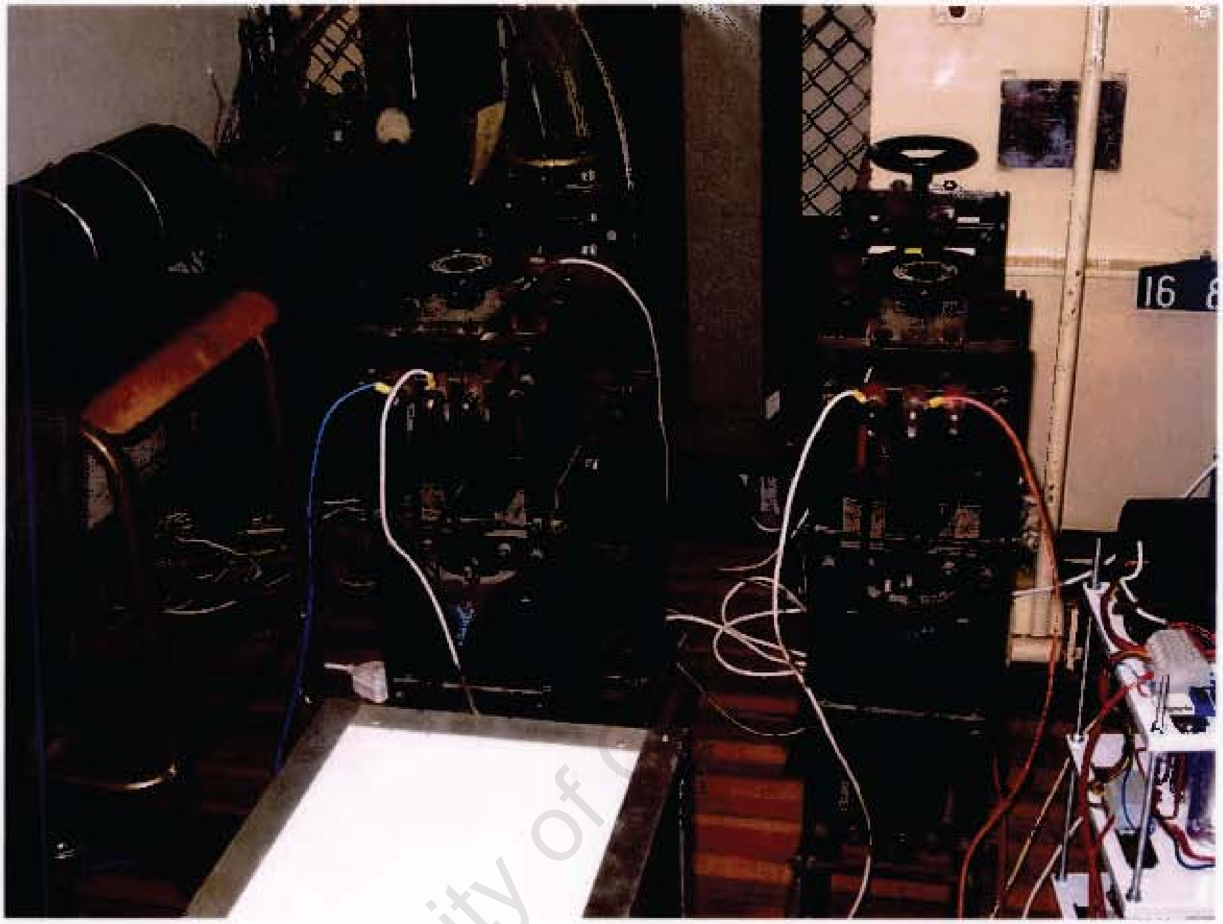


Figure 4.16 The four inductors used in the complex load

Tests were also conducted with a 16kW resistive load. This load consisted of two of the 8kW resistive load connected in parallel. The aim of this test was to determine the behaviour of the compensator when a highly over-rated load is connected to the system. The question to be answered by this test is: "Will the compensator be able to cope with the volt drop caused by a current magnitude rated at twice its own rating?" In other words, this test aimed to determine the limits of the compensator.

Finally, tests were performed with a motor load. It was specifically desirable to test the system with an unloaded motor connected as a load. In this situation, two scenarios were of interest: the behaviour of the system and compensator when the motor was switched in, and then the behaviour of the compensator and the motor in the usual fault condition. The main purpose of these tests was to confirm the absence of ferroresonance in the system. The motor was also tested in parallel with a complex load.

This placed further demands on the compensator which now had to compensate for the supply inductance (which had a greater effect because the higher-rated total load was drawing more current than the motor alone), the inductive nature of the unloaded motor, and the reactive part of the complex load.

The motor that was used in tests is a single-phase inductive unloaded General Electric Compressor Pump with a rating of 750W. In one set of tests, the load consisted of only the motor. In another set of tests, the load comprised the motor in parallel with the complex load that was discussed above (except that the resistive part of the load had only six heating bars connected to create a resistive load with a rating of 6kW at 220V. This was done so that when the motor was added in parallel to the complex load, the total apparent power drawn by the load would remain close to 8kVA).

Figure 4.17 The single-phase unloaded motor that was used during testing.

4.5.2 The equipment and methods used to take measurements

The three parameters that are of particular interest are the arc current, arc voltage and the voltage across the load.

The arc current flows between the two electrodes, and this current is measured using a current LEM with a ratio of 1000:1. The output voltage is measured across a 1kΩ resistor which results in a 1:1 ratio (i.e. 1V = 1A). This output is measured using a 100mHz Agilent oscilloscope.

A capacitive divider is used for the measurement of the arc voltage. The output voltage can be described by the following equation:

$$V_{out} = \frac{C_1}{C_1 + C_2} V_{in}$$

where
$$C_1 = 100\rho F$$
$$C_2 = 13.6\eta F$$

This divider reduces the magnitude of the arc voltage by a factor of 138. This reduced voltage is then fed to a High Voltage Differential Probe P5200 with a ratio of 1:1175, and then the oscilloscope. Effectively, this means that the magnitudes of all arc voltage traces on the oscilloscope should be multiplied by 1175 and then by 138 i.e. by 1.62×10^5.

The load voltage was measured using the same voltage probe. In other words, the cable from the capacitive divider is disconnected and a cable connected across the load is fed to the probe. In this set-up, either the arc voltage or the load voltage can be measured. When the load voltage is measured, because the capacitive divider is bypassed, the magnitude of the voltage trace on the oscilloscope need only be multiplied by 1175.

The equipment described above is shown in the following photographs.

Figure 4.18 This photograph shows the current LEM, the voltage Differential Probe, and the power supply which powers both of them.

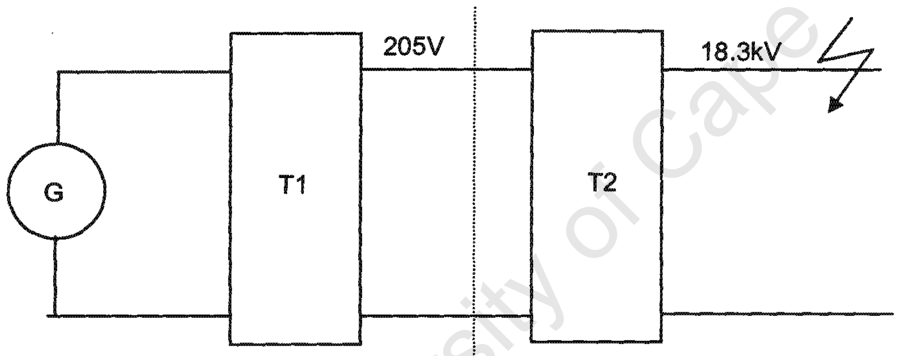
Figure 4.19 The Agilent 100MHz oscilloscope

Chapter Five: The laboratory tests and results

This chapter will describe in detail all of the laboratory tests that were carried out for the purposes of determining the efficacy of the added inductance in extinguishing power arcs, and the compensator in regulating the load voltage. The results will be discussed in Chapter Six.

5.1 Arc tests on the no-load system

The following circuit diagram depicts the lab set-up for the no-load tests. Note that the tests were performed on the system which features neither a load nor the 16kVA SWER step-down transformer. The arc gap was set at 33cm.



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer

Figure 5.1 The laboratory set-up for the no-load arc tests

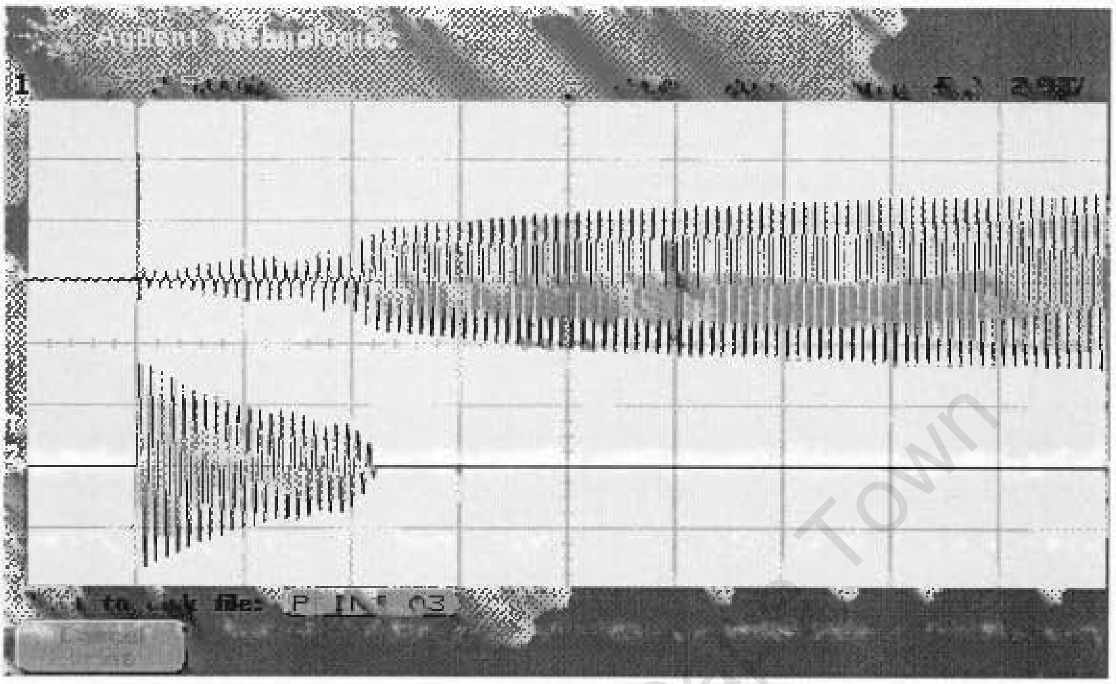


Figure 5.2 The traces of a no-load arc test. The top trace is the arc voltage while the bottom trace is the arc current.

The above oscilloscope traces are typical results of the no-load arc tests. In this figure the voltage scale is 100mV/division, the current scale is 5A/division (as explained in Chapter Four, 1V = 1A) and the time scale is 200ms/division. It should be remembered that the voltage magnitudes need to be multiplied by 138 and then by 1175 (in other words, by 162 150). As an example, at the very end of the voltage trace, the voltage trace has a magnitude of 0.14V. When multiplied by 162 150, this gives a peak voltage of 22.7kV, which in turn, gives an rms voltage of 16kV. The traces are triggered on current – in other words, the oscilloscope starts to display both waveforms only when an input from connection 2 is detected. Note that these traces were recorded before the reactors were added to the circuit. In the next figure, the time scale has decreased and the two traces have been placed on top of one another.

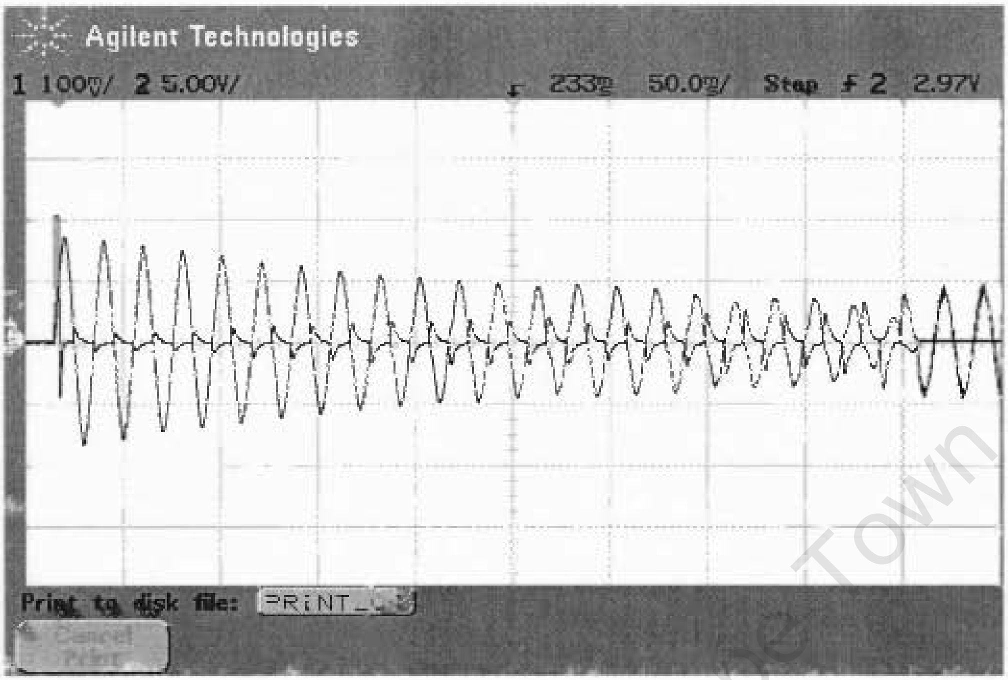


Figure 5.3 The results of a no-load arc test. The current magnitude is decreasing, while the voltage magnitude is increasing.

This particular arc burnt for approximately 450ms. Eight tests of this nature were performed to gain enough data to draw probabilistic conclusions about the results. The arcs in all the tests were self-extinguishing. The longest arc duration was 700ms. The results of these tests are presented in Appendix D.

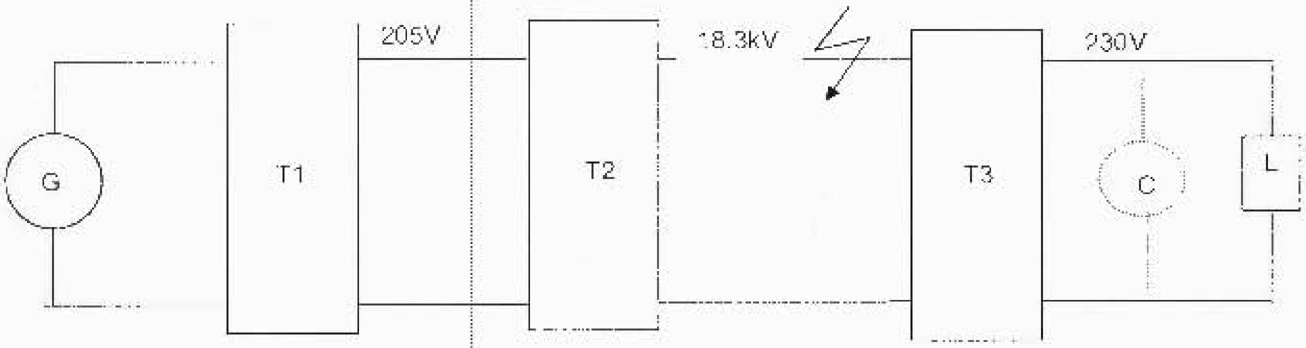
When the no-load tests were complete, the reactors were added to the system. Arc tests were then conducted with a connected load.

5.2 Arc tests on a system with an 8kW load

These tests were conducted

- without the load-end compensator,
- with static compensating capacitors, and
- with the load-end compensator.

The following figure depicts the circuit on which the arc tests were conducted.



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
L – 8kW load
C – load-end compensator (variable active capacitance)

Figure 5.4 The circuit representing the 8kW system on which arc tests were performed

The step-down SWER transformer and 8kW load were connected to the system and arcs were initiated on the MV line. Initially, the compensator was not connected. The arc gap was set to 33cm and then 45cm, as discussed in chapter 4, section 4.2.

The following traces are the results of an arc test carried out when the arc gap was set at 33cm.

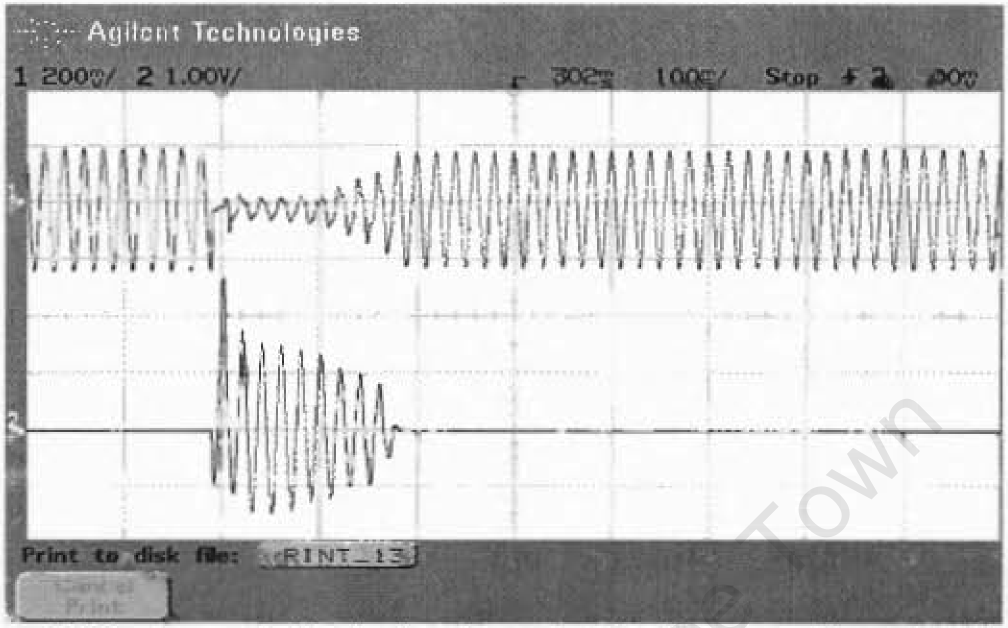


Figure 5.5 Uncompensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kW pure resistive load

The voltage scale in the previous figure is 200mV/division, the current scale is 1A/division and the time scale is 100ms/division. Before the arc is initiated, the load voltage (rms value) is, according to the trace, approximately 180V. This is the result of the volt drop across the large series impedance. When the fuse link closes, the arc is initiated and the resulting earth fault causes the load voltage to collapse for the duration of the arc. When the arc extinguishes, the load voltage is quickly restored to its pre-arcing value which is still well below the expected value of 230V. The arc has a duration of just less than 200ms. The added series inductance has resulted in a rapidly self-extinguishing power arc.

The following traces are the results of an arc test carried out when the arc gap was set at 45cm.

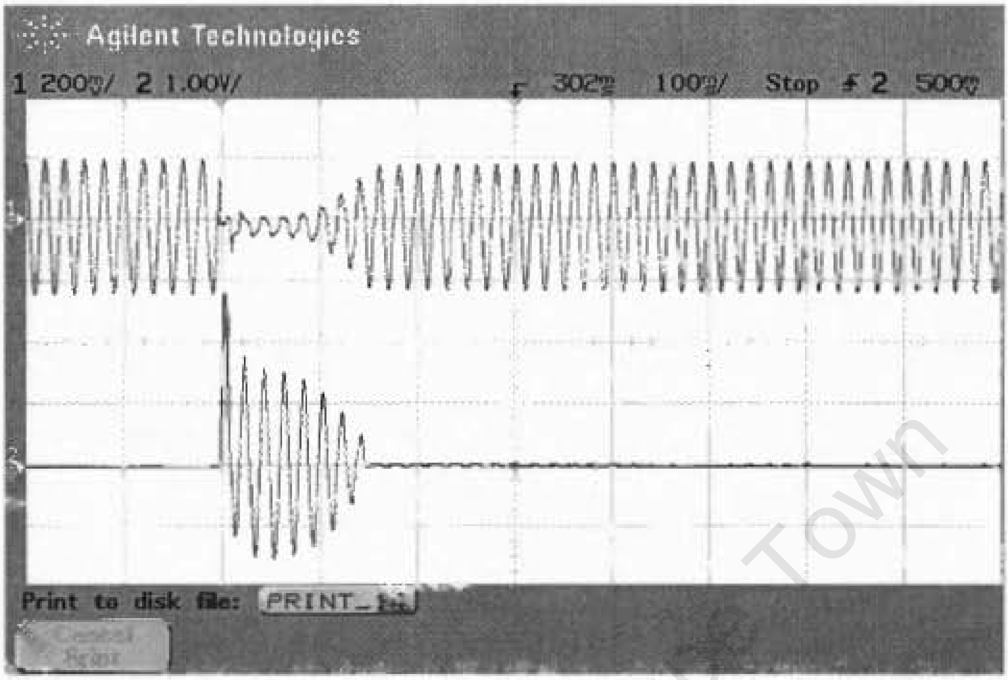


Figure 5.6 Uncompensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 8kW pure resistive load

For the test which delivered the above result, the arc gap was increased from 33cm to 45cm. It is expected that the arc across this gap would be self-extinguishing because the 33cm gap is the "worst-case scenario" in the sense that a shorter gap is more likely to support the burning of a power arc. In this particular test, the arc burnt for approximately 150ms. Ten arc tests were performed and in all of the tests the arcs were rapidly self-extinguishing. These results of these tests can be found in Appendix D.

Tests were then carried out on the system with a "passive compensator". According to the calculations, a capacitance (in a 50µF resolution) of 350µF would be sufficient to raise the load voltage up to a level close to that of the required 230V. Seven 50µF capacitors were connected in parallel and the connected set was then connected in parallel with the 8kW load. When the system was powered, all of the capacitors were effectively "switched-in" immediately. The following trace shows the resulting load voltage.

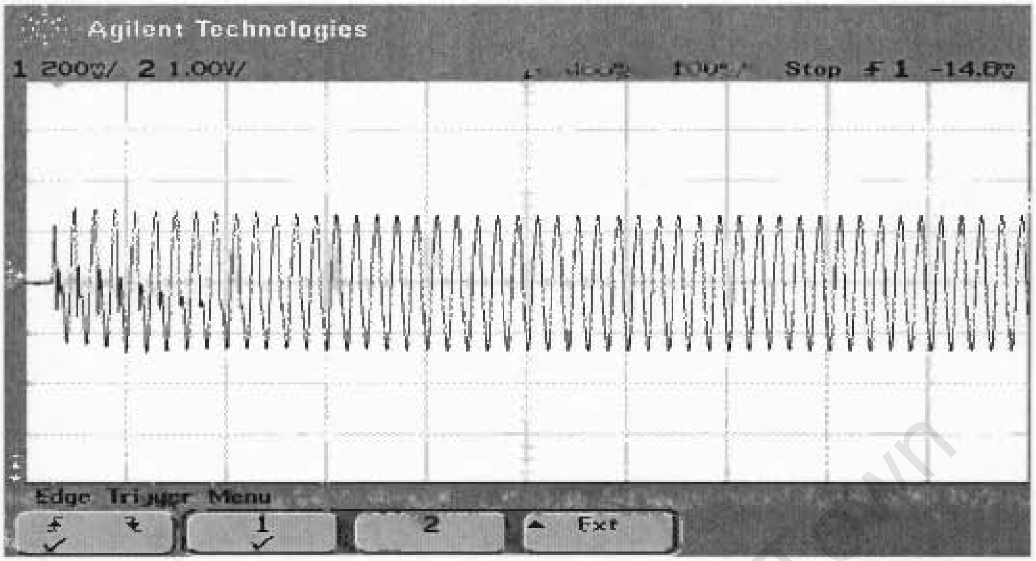


Figure 5.7 The resulting load voltage when a "passive compensator" is placed in parallel with the 8kW load

The above figure shows that the load voltage rises to approximately 232V almost instantaneously. This test confirms the calculations used to predict the value of capacitance required for compensation, which were performed in chapter four, section 4.4.1. An arc was then initiated on this particular system. The resulting traces follow.

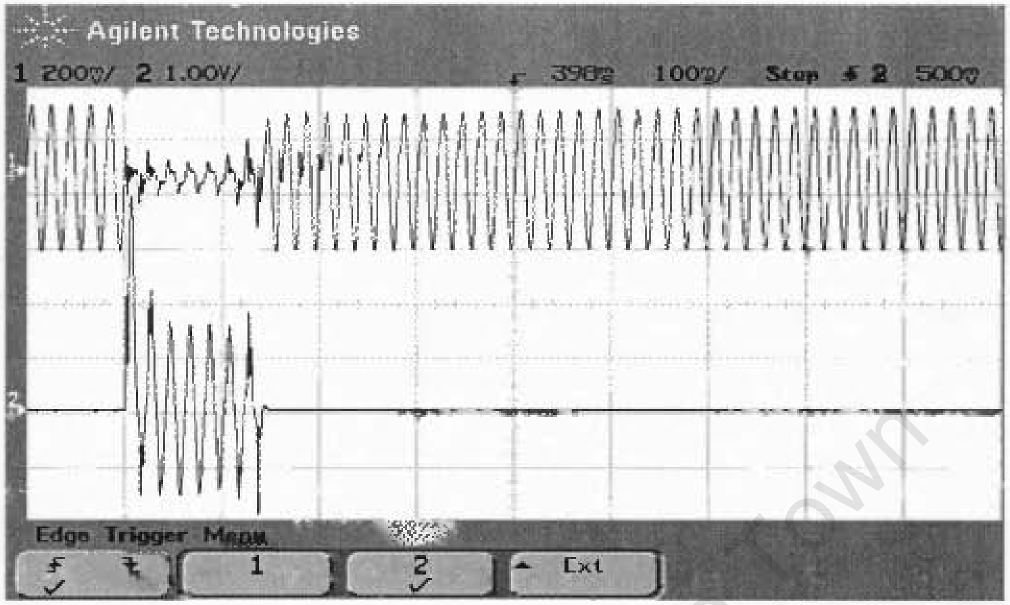


Figure 5.8 "Passively-compensated" load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kW resistive load

When the arc has extinguished, the load voltage once again rises to its required level almost instantaneously. The power arc has a duration of approximately 150ms.

The compensator was then connected to the system in parallel with the 8kW load. When the contactor in the MV laboratory was closed, the steady-state system was powered by the generator. The initial load voltage was approximately 180V. The compensator switched in seven 50μF capacitors until it "observed" that the load voltage was as close to 230V as the limited resolution would allow. The compensator would then stop switching in capacitors and the load voltage would remain at a value that is well within the accepted margin of +-10%. When the load voltage was steady, the arc would be initiated. Once again, tests were performed on the system with an arc gap of 33cm and then with an arc gap of 45cm.

The following traces show the results of two tests performed with an arc gap of 33cm.

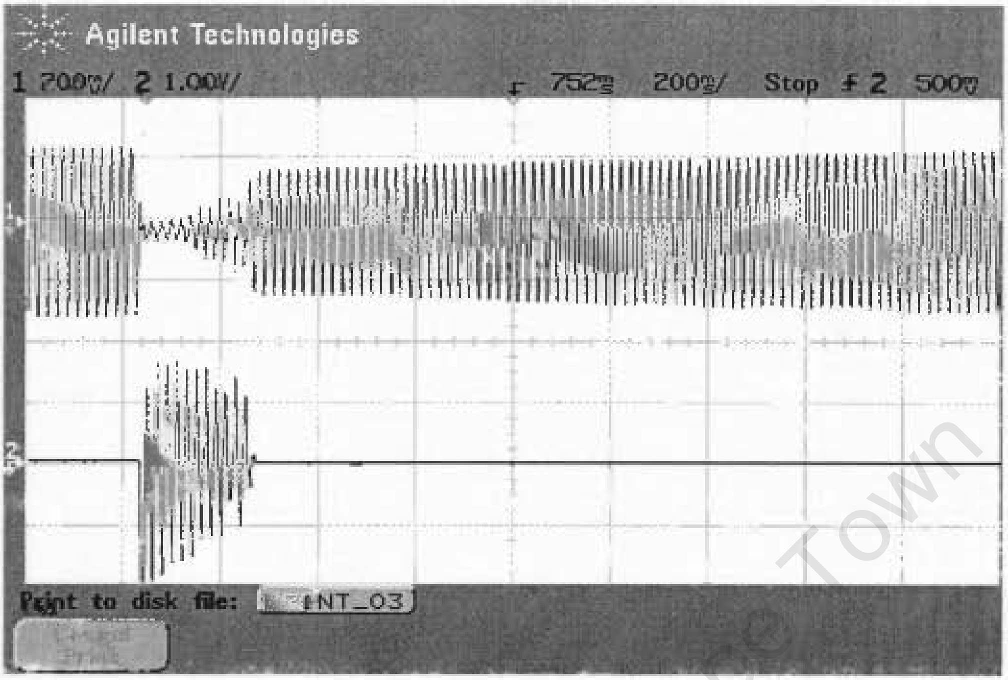


Figure 5.9 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kW pure resistive load

In the above figure, the voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 200ms/division. The arc current flowed for approximately 200ms before it self-extinguished.

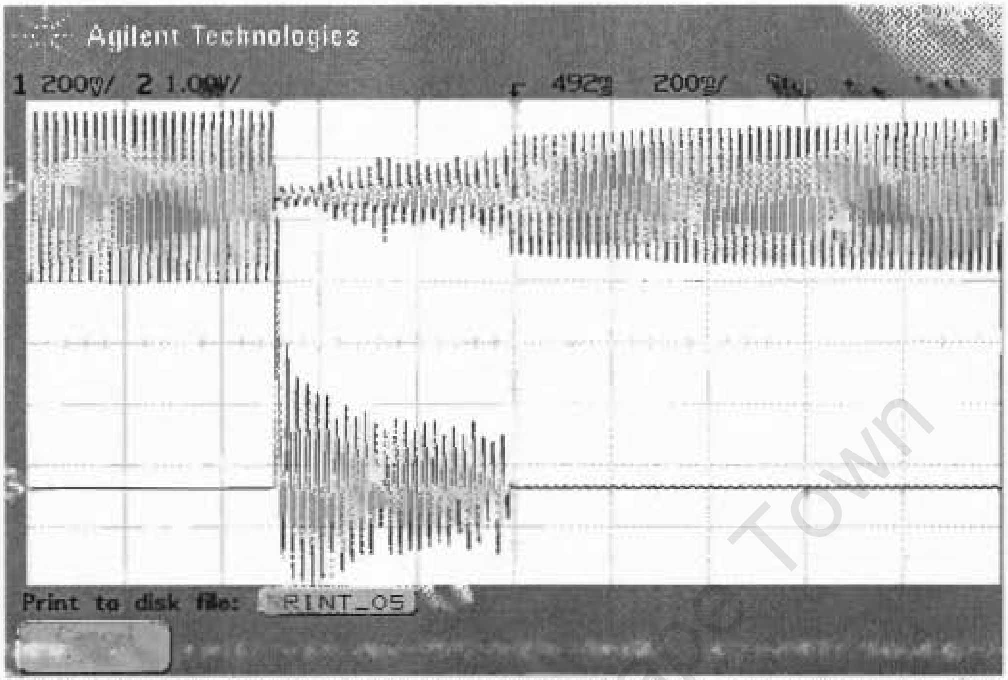


Figure 5.10 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kW pure resistive load

The above result also shows an arc test performed on the system with a 33cm arc gap. The arc initiated in this test burnt for a total of 400ms. When the arc extinguished, the load voltage again built up to approximately 233V as the compensator switched in its capacitors.

The traces that follow show the results of a test performed with an arc gap of 45cm.

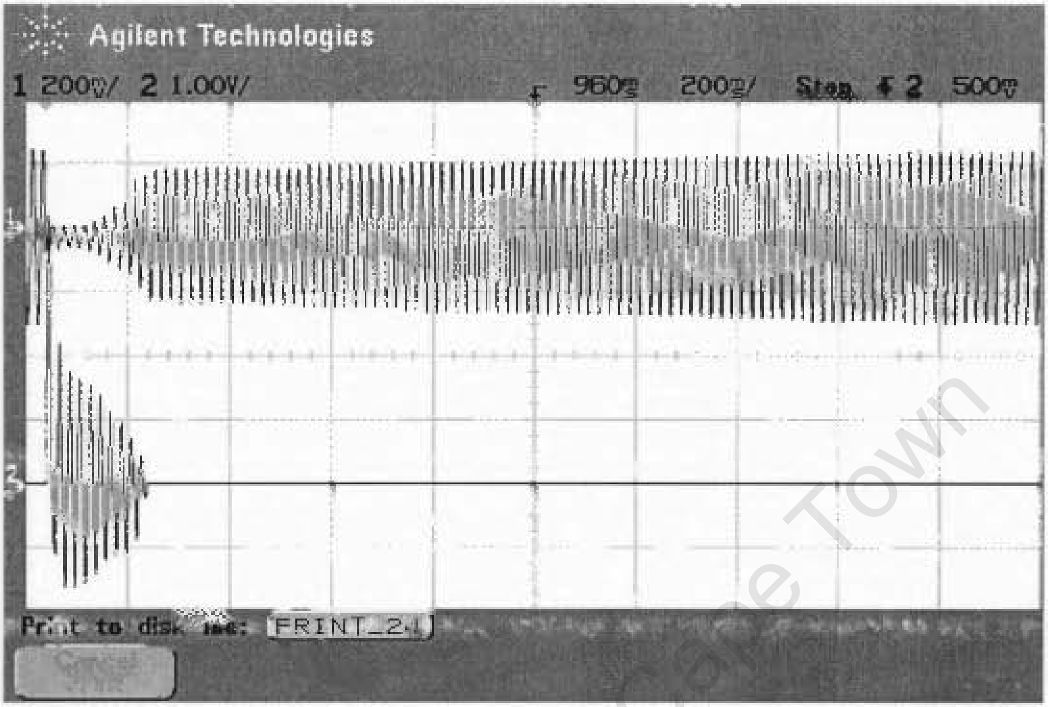
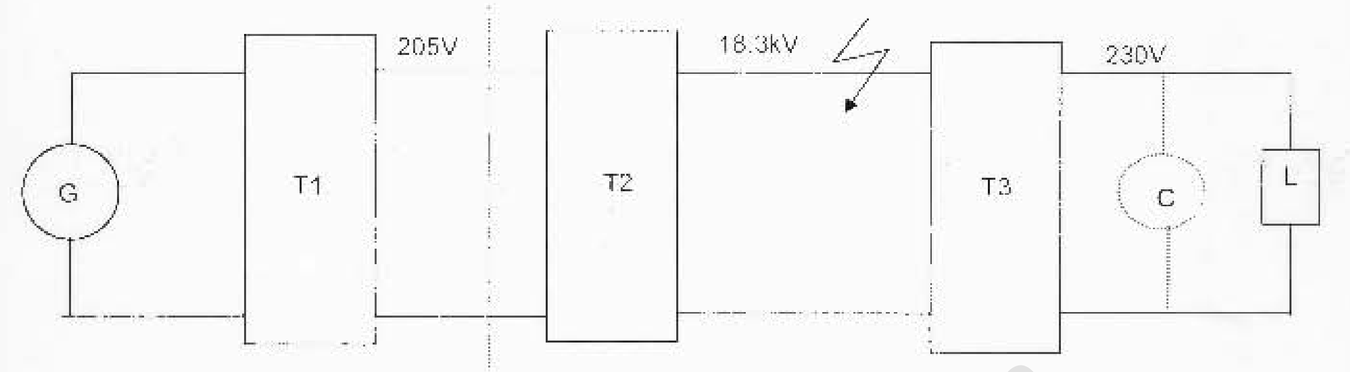


Figure 5.11 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 8kW pure resistive load

In the above figure, the voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 200ms/division. In this particular test, the compensator switched in seven capacitors and the load voltage stabilised at 229V before the arc was initiated. The arc lasted for just over 200ms. The initial spike is once again evident in the arc current. Further results of these tests are presented in Appendix D.

5.3 Arc tests on a system with a 4kW load

Tests were performed on the system with a 4kW pure resistive load connected. The effect of this change would be the halving of the steady-state current drawn by the system. This would, in theory, reduce the demands placed on the compensator due to the reduced volt drop across the series impedance. Tests were performed on the system with an arc gap length of 33cm and then of 45cm and were performed first without and then with the compensator connected. The following figure depicts the circuit on which the tests were performed.



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
L – 4kW load
C – load-end compensator (variable active capacitance)

Figure 5.12 The circuit representing the 4kW system on which arc tests were performed

The following traces show the results of the arc tests performed on the system without the compensator. The first test was performed on the system featuring a 45cm arc gap length while the second test was carried out on the system when a 33cm arc gap had been created.

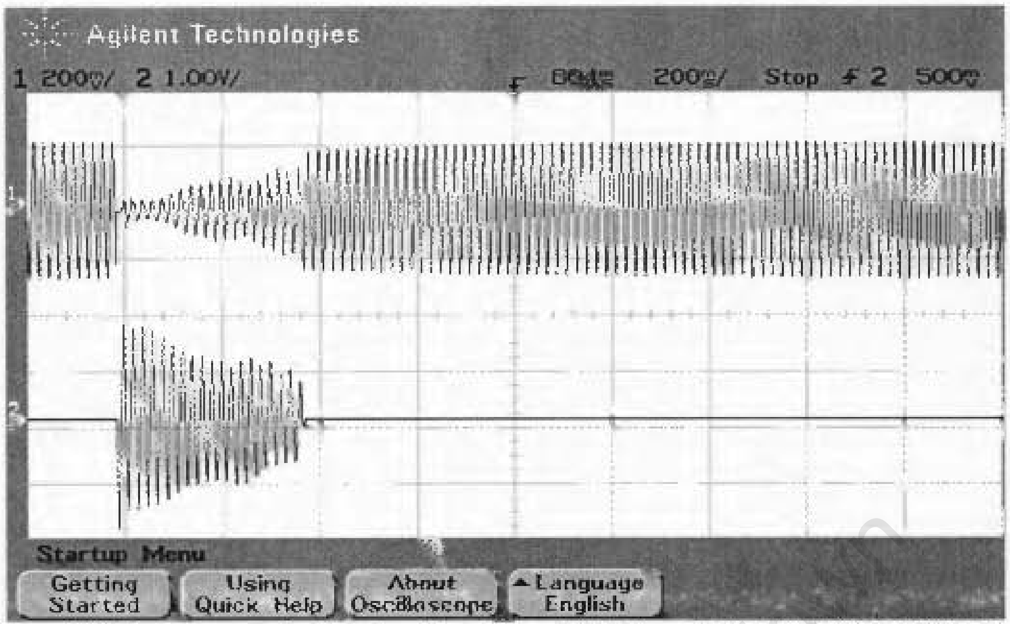


Figure 5.13 Uncompensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 4kW pure resistive load

In the above figure, the voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 200ms/division. Before the arc is initiated, the uncompensated load voltage has a magnitude of approximately 206V. The voltage magnitude is not as low as that of the uncompensated load voltage when the 8kW load was connected. The arc has a duration of just less than 400ms.

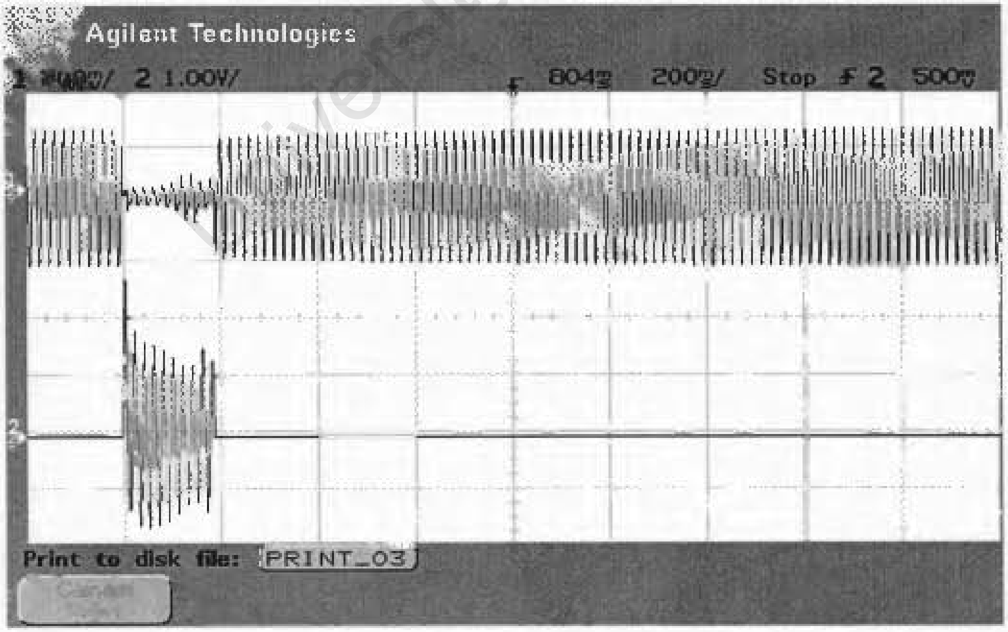


Figure 5.14 Uncompensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 4kW pure resistive load

In the previous figure, the uncompensated load voltage has a magnitude of approximately 200V. The power arc burns for about 200ms before self extinguishing. In all the tests at both 33cm and 45cm, the power arcs were rapidly self extinguishing due to the added series impedance in the supply circuit.

The compensator was then connected in parallel with the 4kW load. The following trace shows the load voltage as it builds up when the load is switched in for the steady-state operation of the system (in other words before the arc is initiated). In this test, the compensator switched in three capacitors and the voltage built up to a steady value of 229V.

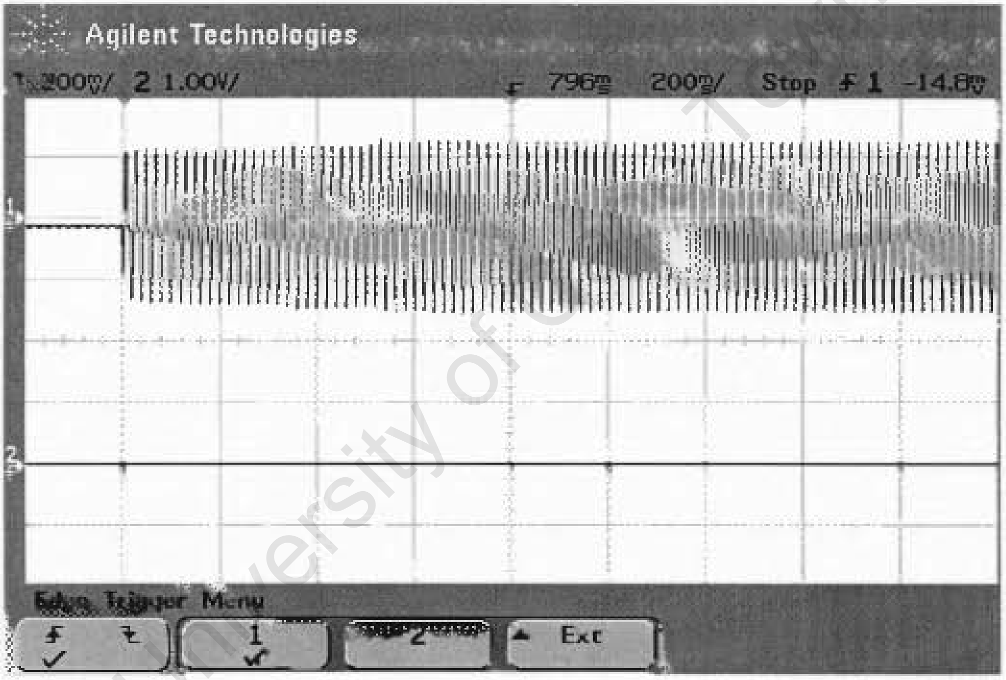


Figure 5.15 The steady-state load voltage when the active compensator is connected in parallel with a 4kW resistive load.

The load voltage does not build up to its required value instantaneously because the compensator is programmed to switch in one capacitor at a time while continuously monitoring the magnitude of the voltage. The build up is, however, fairly rapid because only three capacitors (or 150µF) are switched in.

The following trace shows the results of an arc test conducted on the system with both the 4kW load and compensator connected, and with an arc gap length of 33cm.

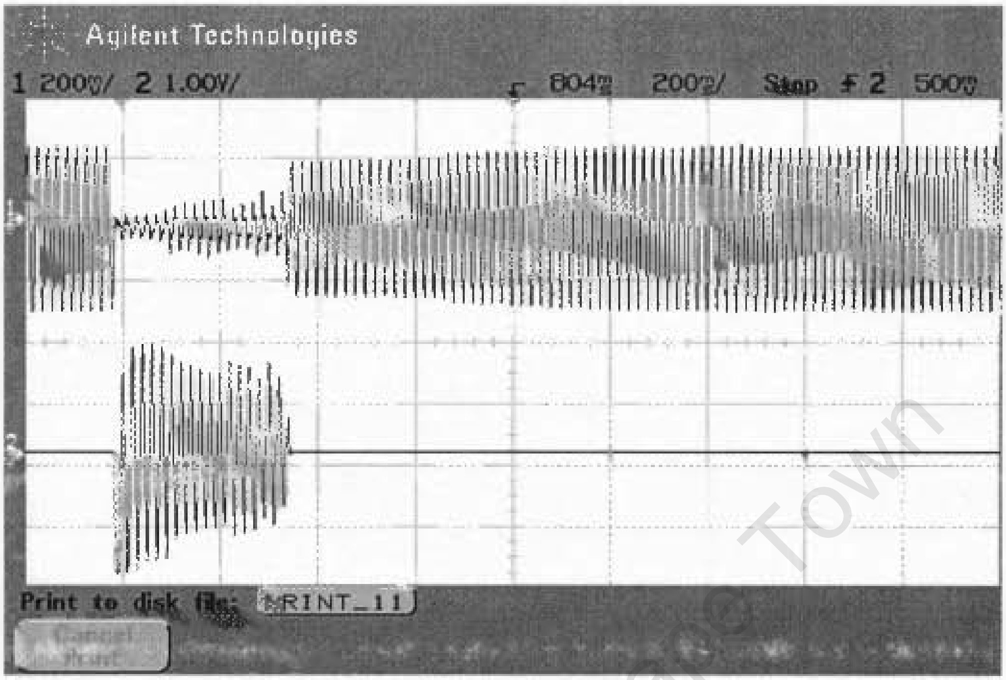
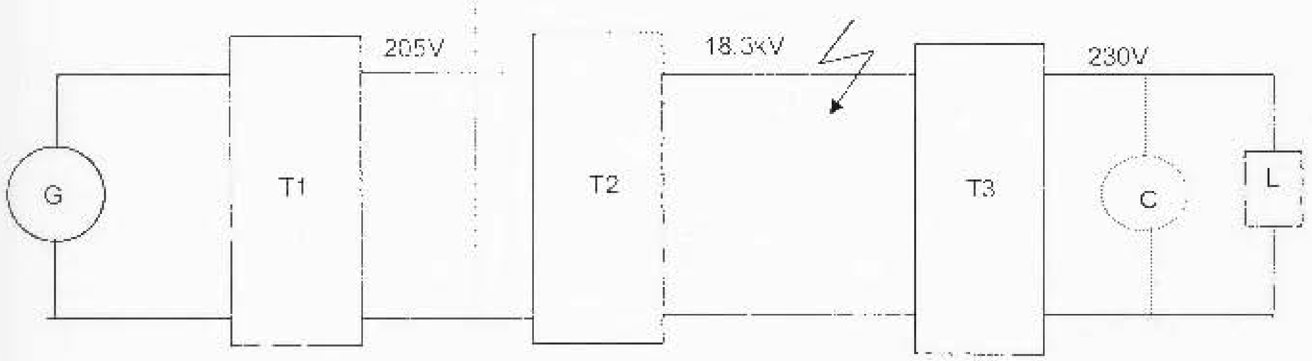


Figure 5.16 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 4kW pure resistive load

In the above figure, the voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 200ms/division. Further results can be found in Appendix D.

5.4 Arc tests on a system with an 8kVA complex load

The technical details of the laboratory set-up for these tests have been described in the previous chapter. In summary, inductors were placed in parallel with a resistive load to create a complex load with a rating of 8.8kVA and a lagging power factor of about 0.87. Once again, these tests were carried out on the proposed system with and then without the compensator connected. For each scenario, the arcs were initiated across a gap of both 33cm and 45cm. A selection of these results will now be presented. The following figure depicts the circuit on which the tests were carried out.



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
L – 8kVA load; p.f. = 0.87
C – load-end compensator (variable active capacitance)

Figure 5.17 The circuit representing the 8kVA system on which arc tests were performed

The following traces are the result of a non-compensated arc test across a 33cm arc gap.

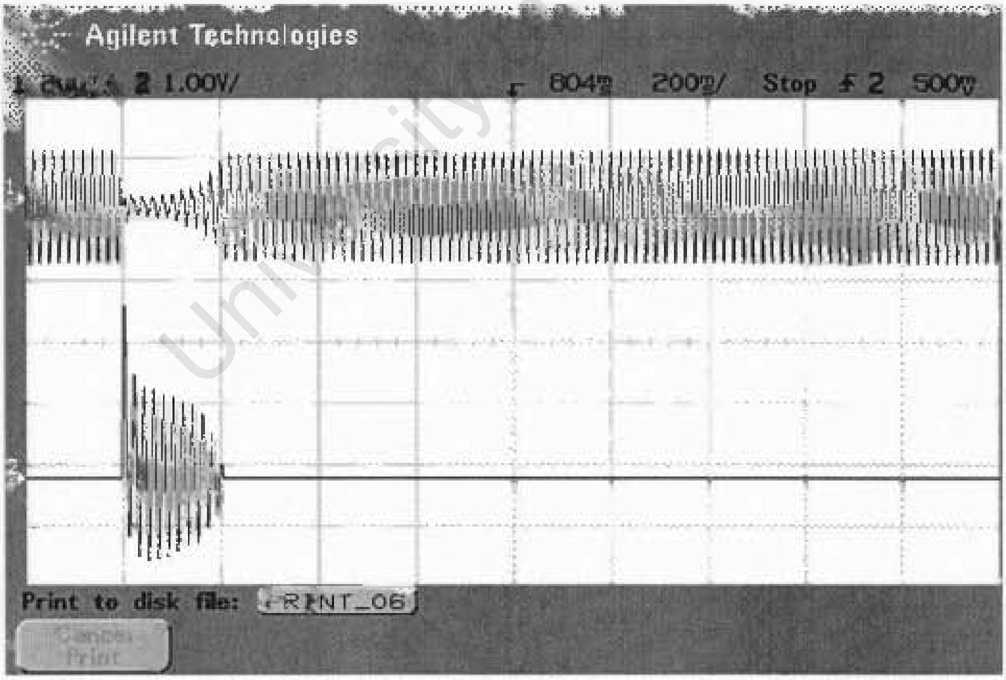


Figure 5.18 Uncompensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kVA complex load pf = 0.87

In the previous figure, the top trace depicts the load voltage and the bottom trace represents the arc current. The voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 200ms/division. In this particular test, the arc burnt for about 200ms demonstrating, once again, the effective arc-extinguishing nature of the system.

The compensator was then connected in parallel with the 8kVA complex load. The following trace shows the load voltage as it builds up when the load is switched in for the steady-state operation of the system (in other words before the arc is initiated). In this test, the compensator switched in thirteen capacitors and the voltage built up to a steady value of 232V. The time scale used in the figure is 500ms/division. This large scale results in a fairly unclear image but allows more of the waveform to be observed, thus enabling the complete load voltage build-up to be viewed. The total time taken for the load voltage to reach its maximum level is approximately 3 seconds.

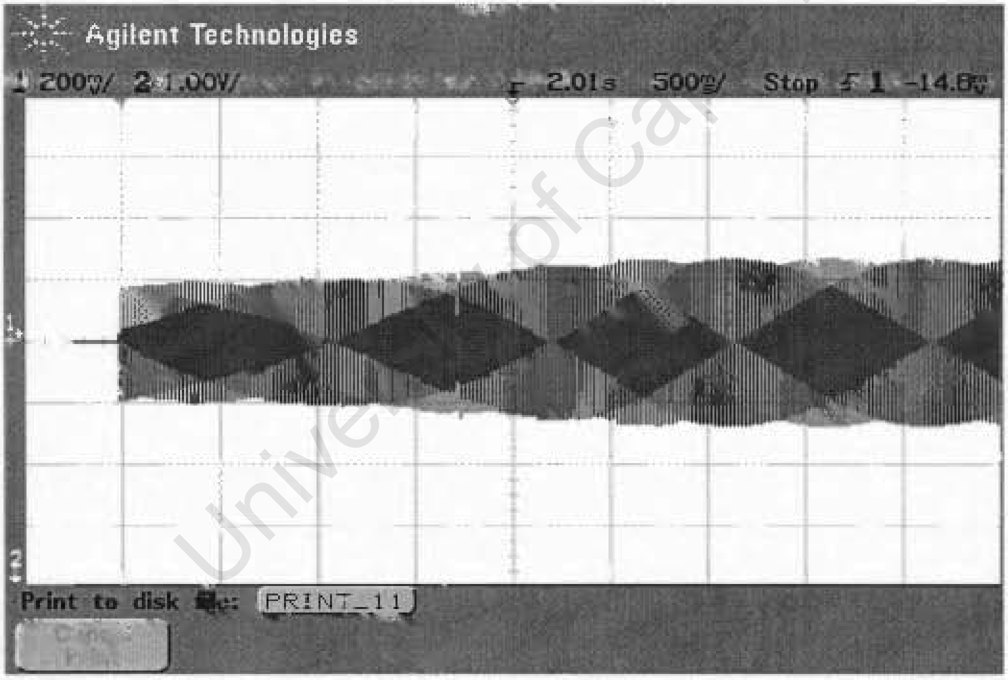


Figure 5.19 The steady-state load voltage when the active compensator is connected in parallel with an 8kVA complex load.

The following traces show the results of an arc test carried out on the system across a 45cm gap with the compensator connected to the system. The first figure shows the results on a time scale of 500ms/division so that the entire scenario can be observed and the second figure shows the same test on a time scale of 200ms/division so that more detail can be observed.

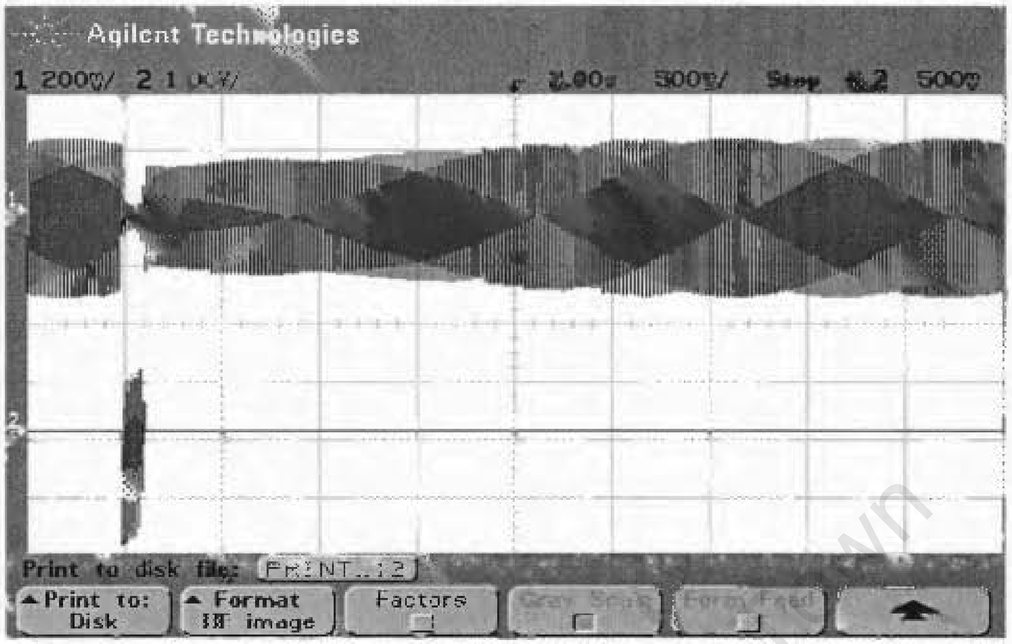


Figure 5.20 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 8kVA complex load pf = 0.87

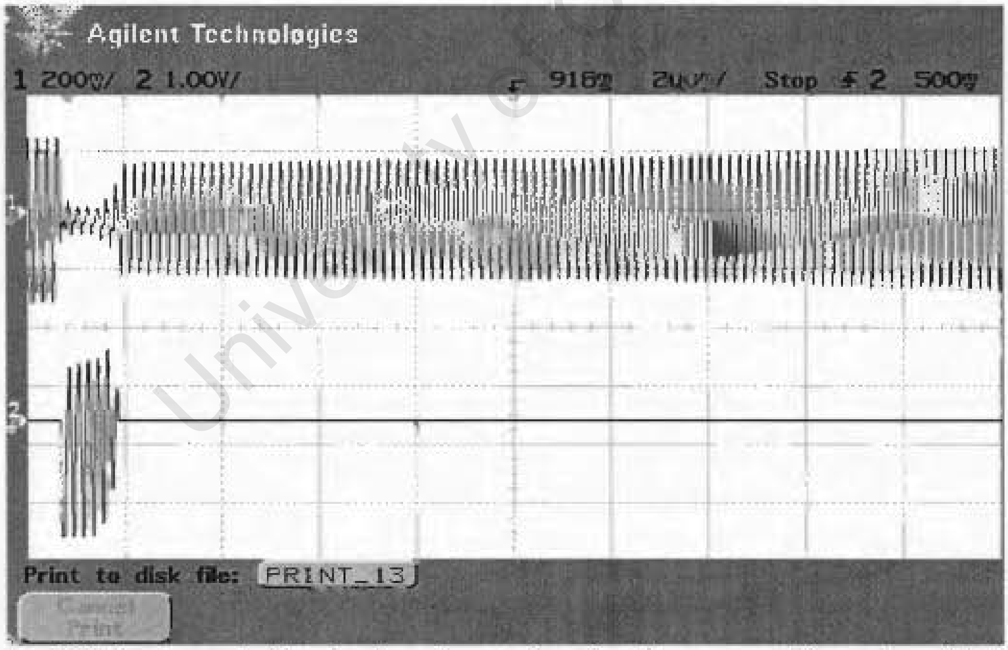


Figure 5.21 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 8kVA complex load pf = 0.87

The above figures show, once again, the transient nature of the arc – it burnt for less than 200ms. Before the arc is initiated, the load voltage has a stable magnitude of approximately 234V after twelve capacitors (or 600μF) have switched in. After the arc has extinguished, the compensator starts to switch in capacitors one at a time until all twelve are once again connected. At this stage, the load voltage once again has a magnitude of 234V. This "switching-in procedure" takes just under 3 seconds. In other words, the more capacitors that the compensator has to switch in (in other words, the lower the uncompensated voltage), the longer it will take for the load voltage to build up to the required value. In this test the load current measured 38A (this was measured using a CT and ammeter in series with the load) which implies a total load rating of 8.892kVA. The real power absorbed by the load was 7.9kW. This implies an actual power factor of 0.88. The power factor did tend to change slightly as the testing period unfolded because the resistance of the resistive part of the complex load would begin to increase in value as the heating bars increased in temperature.

The following traces show the results of an arc test carried out on the system across a 33cm gap with the compensator connected to the system. Only the result with the time scale of 500ms/division is presented. This allows the entire "event" to be observed.

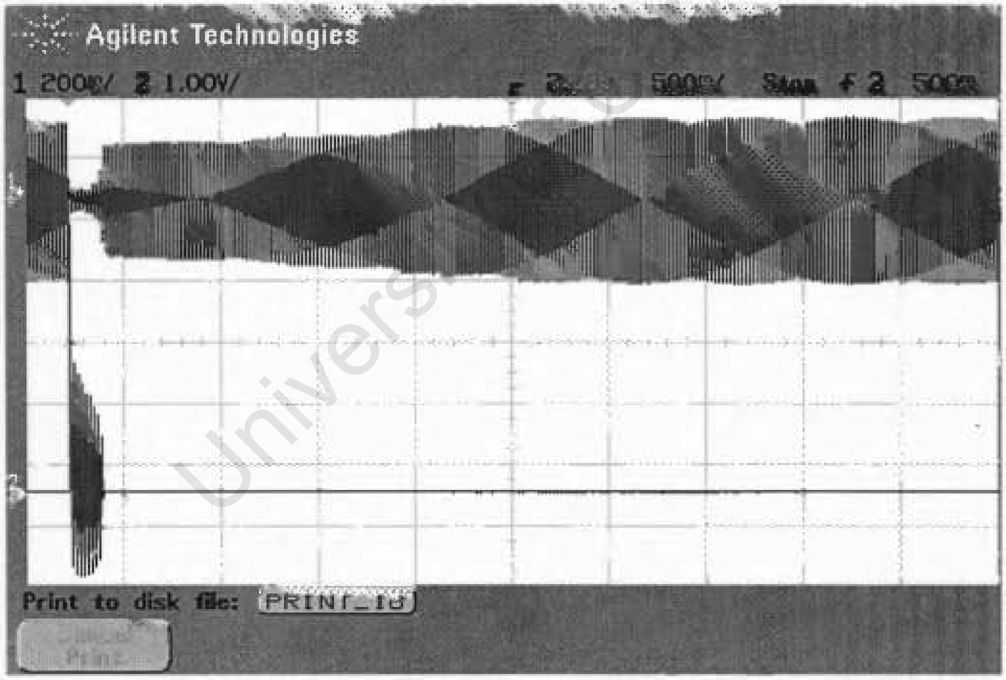


Figure 5.22 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 8kVA complex load pf = 0.87

The above figure depicts a very similar result to the previous test. This result also features a very transient arc. In this test the compensator also switched in twelve capacitors to raise the load voltage up to 234V. In this particular test (conducted after the previous test) the total current absorbed by the load had increased to 40A while the total real power absorbed by the load had increased to 8kW.

The following result shows a particular result of a test performed across a 45cm arc gap.

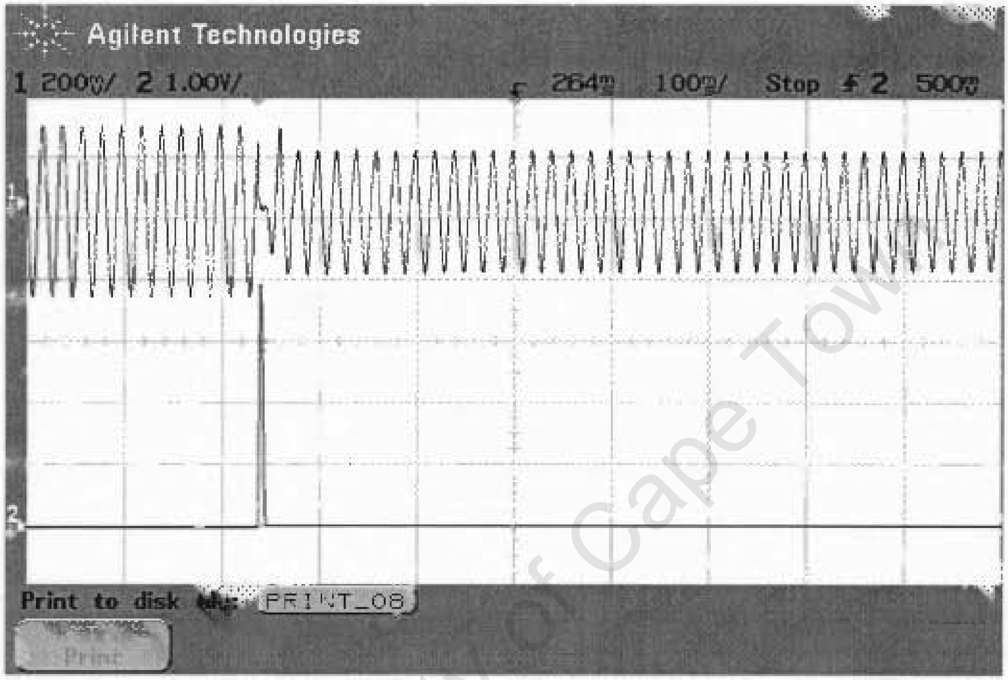
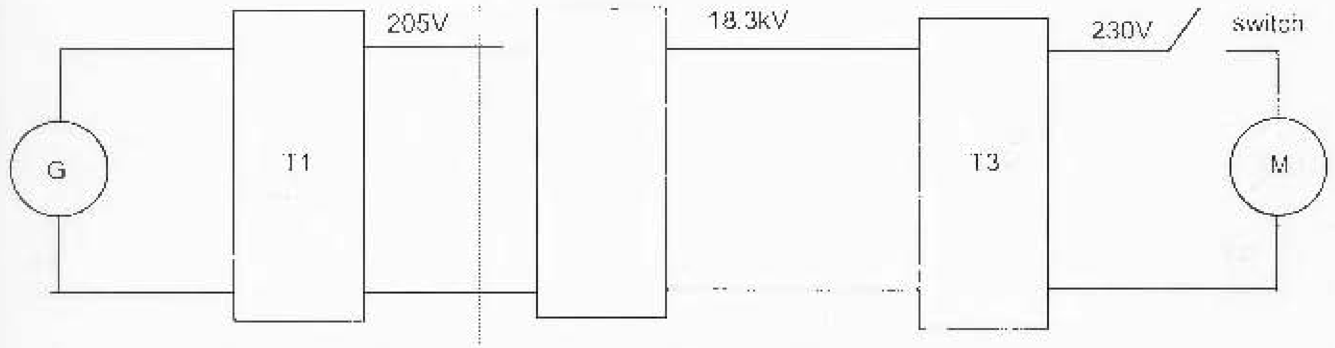


Figure 5.23 Compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 45cm arc; 8kVA complex load pf = 0.87

In this particular test, the arc is extremely transient and extinguishes almost immediately. The load voltage collapses rapidly and then does not recover to its original compensated value of 234V.This unusual, and unexpected behaviour, is discussed in chapter six. Further results can be found in Appendix D.

5.5 Arc tests on a system with a single-phase unloaded motor load

A variety of tests were performed on the system while a single-phase unloaded 750W motor load was connected. These tests aim to determine the behaviour of the motor and the compensator during two distinct transient events: switching and arcing due to a transient fault. Initially, the motor was connected as a load and a switching mechanism was connected in series with it. The system was powered and the motor load was then switched in. This test was performed so that the characteristics of the motor could be determined. The following circuit diagram depicts the set-up for the test.



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
M – Single-phase unloaded 750W motor

Figure 5.24 The laboratory set-up

The following figures show the results of this test.

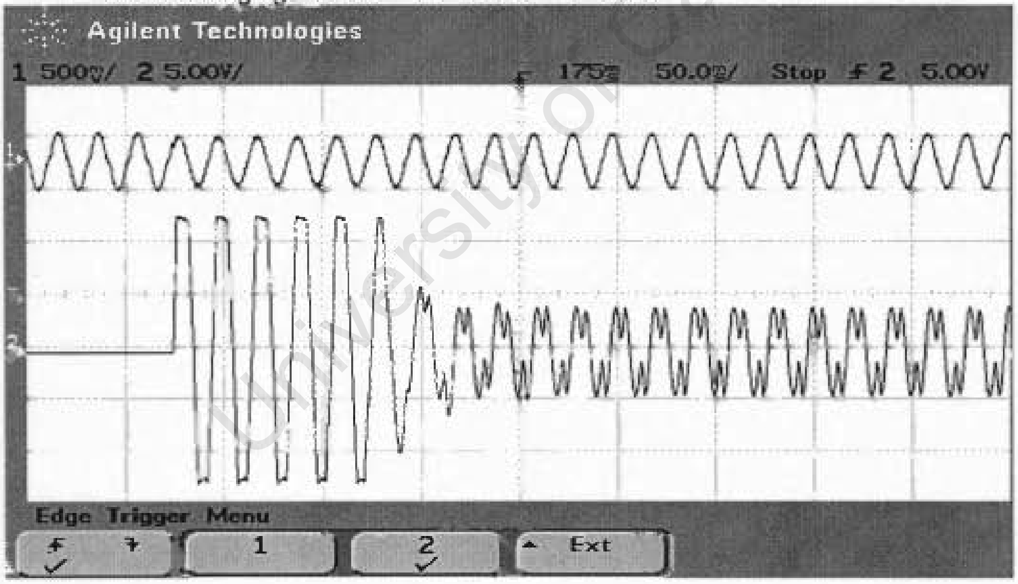
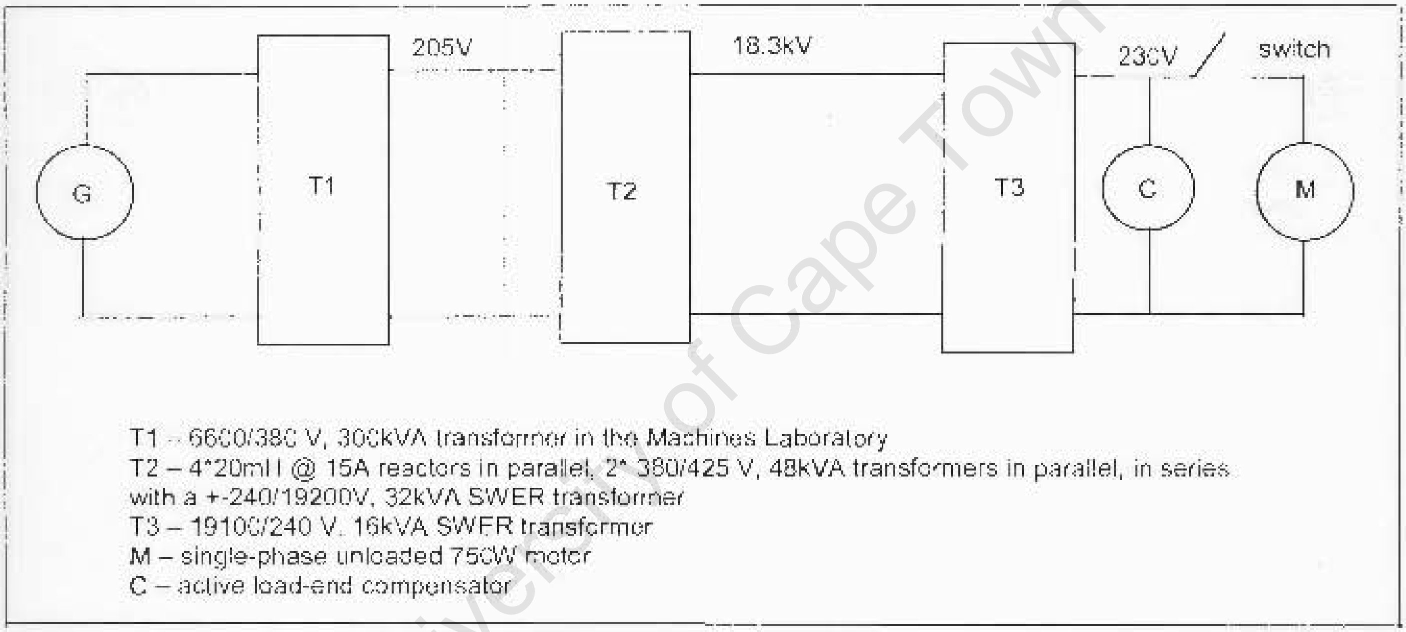


Figure 5.25 The characteristic motor voltage (upper trace) and current (lower trace)

In the previous figure, the top trace represents the motor voltage and the bottom trace represents the motor current. When the motor is switched in, a large start-up current is observed (the tip of the waveform is cut off due to the measuring characteristics of the current LEM). It is then clear that the steady-state motor current has a distorted waveform. This is a characteristic of this particular motor. It may be due to the capacitor which is connected across single-phase motors which tends to "amplify" any harmonics present in the voltage produced by the generator. The load voltage has a magnitude of approximately 210V. The voltage is higher than previous tests because the motor has a rating of only 750W and therefore draws a relatively smaller current, resulting in a smaller volt drop across the series impedance in the supply circuit.

The next test that was carried out was that of switching in the motor when the compensator is already connected (across a "no-load"). When the motor is switched in, the compensator is able to respond effectively to the current that is drawn by the load. It switches in three capacitors and the load voltage stabilises at 233V. The following diagram depicts the set-up for the test



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a +-240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
M – single-phase unloaded 750W motor
C – active load-end compensator

Figure 5.26 The laboratory set-up

The next figure shows the results of switching in the motor when the compensator is already connected. In order to view the full start-up current magnitude, the 1kΩ resistor across the current LEM was replaced with a 500Ω resistor. This results in a current ratio of 1.2 (in other words, all values of current magnitude should be multiplied by 2, instead of 1).

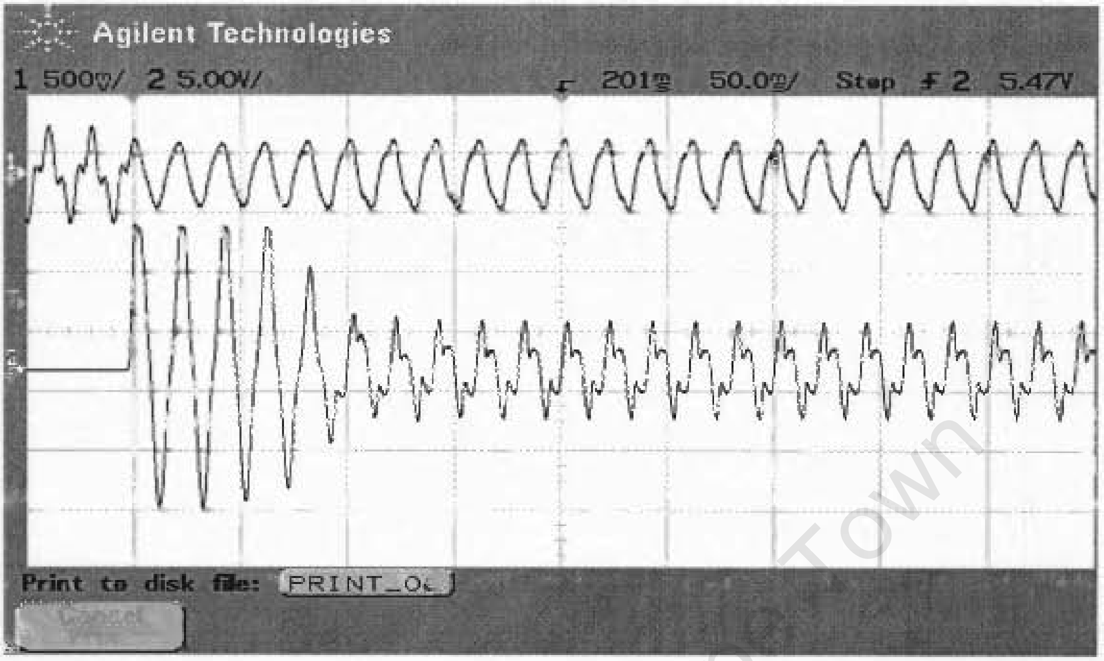
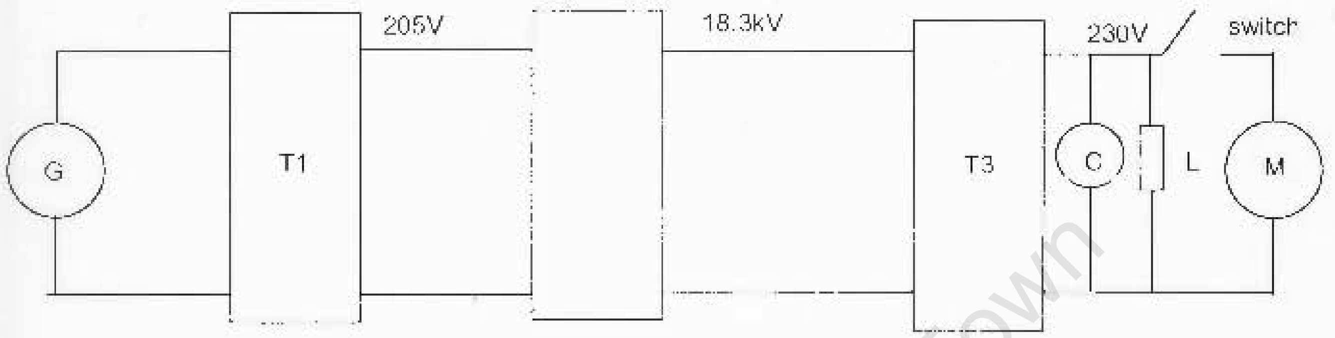


Figure 5.27 The compensated motor voltage (upper trace) and current (lower trace) before and after the motor is switched in.

In the above figure, the voltage scale is 500mV/division, the current scale is 5A/division and the time scale is 50ms/division.

In the next test, the motor was switched in when the compensator and complex load were already connected. The complex load that was used in previous tests was altered by reducing the resistive "part" from 7kW to 6kW (by the disconnection of one heating bar) in order to "make room" for the motor's 750W in power. This ensured that the total apparent power drawn by the load remained approximately 8kVA. The inductive "part" of the complex load remained the same as that for previous tests. The complex load was tested on its own and was found to draw a current of 31.4A (at 233V). This implies that it draws a total apparent power of 7.3kVA. The total real power absorbed by this complex load was found to be 6.7kW. This particular complex load therefore has a power factor of 0.9. The circuit diagram depicting this test is shown in the figure that follows:



T1 – 6600/380 V, 300kVA transformer in the Machines Laboratory
T2 – 4*20mH @ 15A reactors in parallel, 2* 380/425 V, 48kVA transformers in parallel, in series with a 240/19200V, 32kVA SWER transformer
T3 – 19100/240 V, 16kVA SWER transformer
M – Single-phase unloaded 750W motor
C – Active load-end compensator
L – Complex load, pf = 0.9

Figure 5.28 The laboratory set-up

Before the motor is switched in, the compensator is connected across the complex load. The load draws sufficient current for the compensator to respond to and the resulting load waveform is sinusoidal. The compensator switches in 8 capacitors at this stage and the load voltage stabilises at 233V. At this stage, the motor is switched in. The following figure depicts the results of this test.

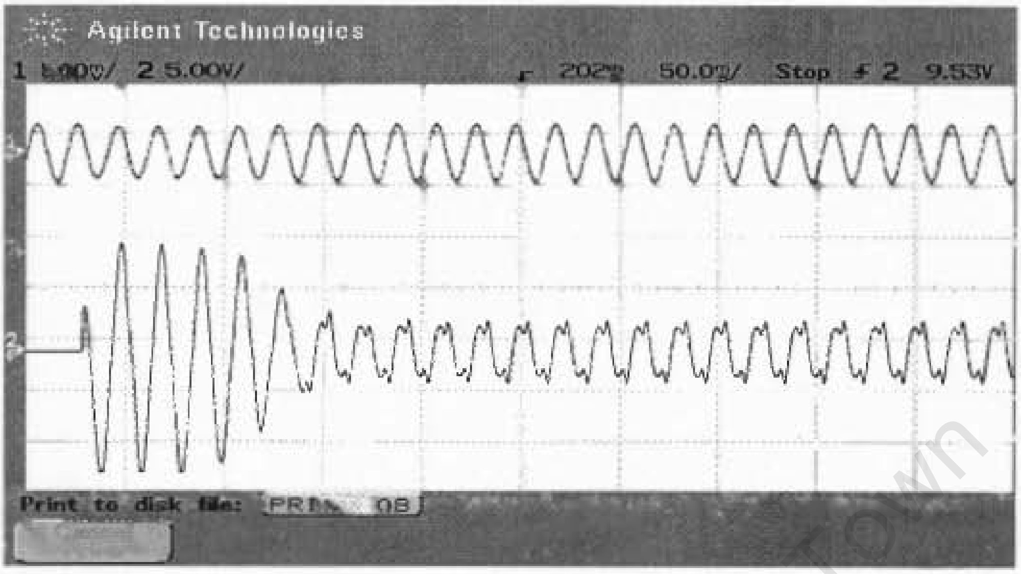


Figure 5.29 The compensated load voltage (upper trace) and motor current (lower trace) before and after the motor is switched in.

The final arc tests carried out on the system aimed to determine the behaviour of the motor and compensator in the event of a transient fault. In the first test, the compensator and motor were connected in parallel across the terminals of the 16kVA SWER transformer and an arc was initiated on the MV distribution line. The arc was initiated across both a 33cm and a 45cm gap. In the second test, the arcs were initiated on the MV line with the compensator, motor and complex load connected to the system. A sample of the results will now be presented but further results can be found in Appendix D. Because the results show the *arc* current (as opposed to the motor current), the 500Ω resistor across the current LEM was replaced with the original 1kΩ resistor. This implies that the current ratio is once again 1:1.

The following figure depicts the results of a 33cm arc test performed on the system with only the compensator and motor connected.

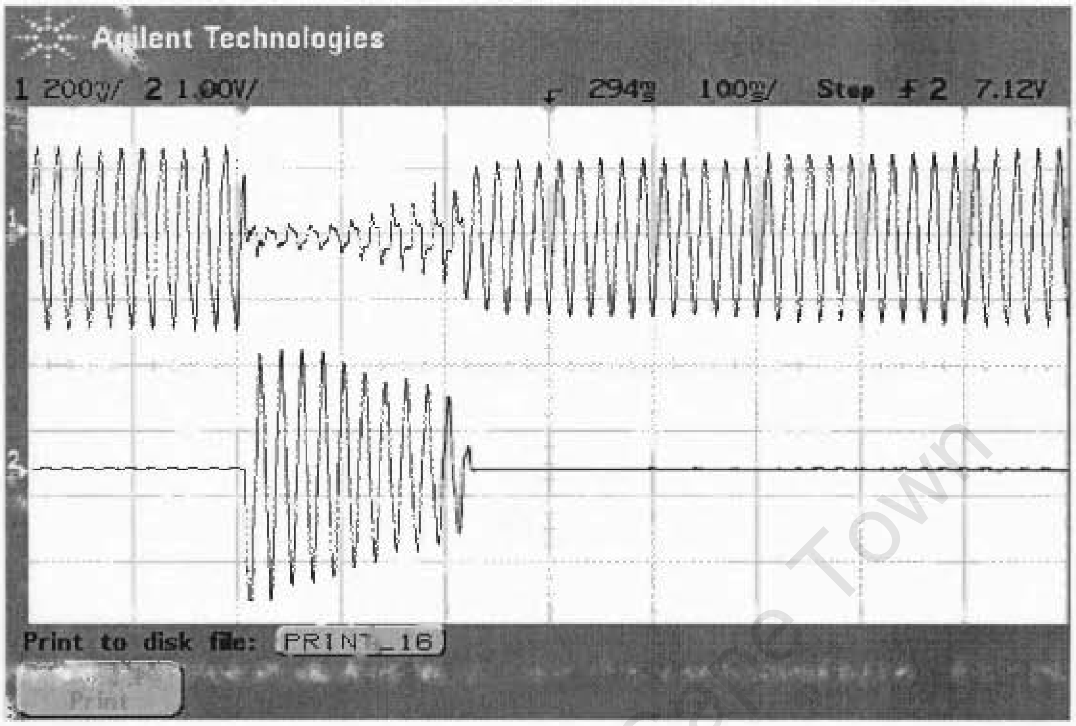


Figure 5.30 The compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 750W single-phase unloaded motor

In the above figure, the voltage scale is 200mV/division, the current scale is 1A/division and the time scale is 100ms/division. The arc was initiated across a 33cm gap. As before, the load voltage dips in magnitude for the duration of the power arc, which is extremely short (approximately 200ms) due to the current-limiting nature of the system. When the arc has self-extinguished, the load voltage recovers to its uncompensated value (in this case approximately 210V) after which the compensator immediately begins switching in capacitors for the purposes of further voltage recovery. The compensator switches in three capacitors (or 150μF) and the load voltage again stabilises at 232V. In this case, the voltage recovery process takes just under 500ms.

The following figures show the results of an arc test carried out on the system (across a 33cm gap) with the compensator, motor and (altered) complex load connected (in other words, as before, the *total* rating of the load was just under 8kVA, with a power factor). The first figure shows the results on a time scale of 500ms/division so that the full voltage-recovery event can be viewed. The second figure shows the same results on a time scale of 100ms/division so that more detail can be observed.

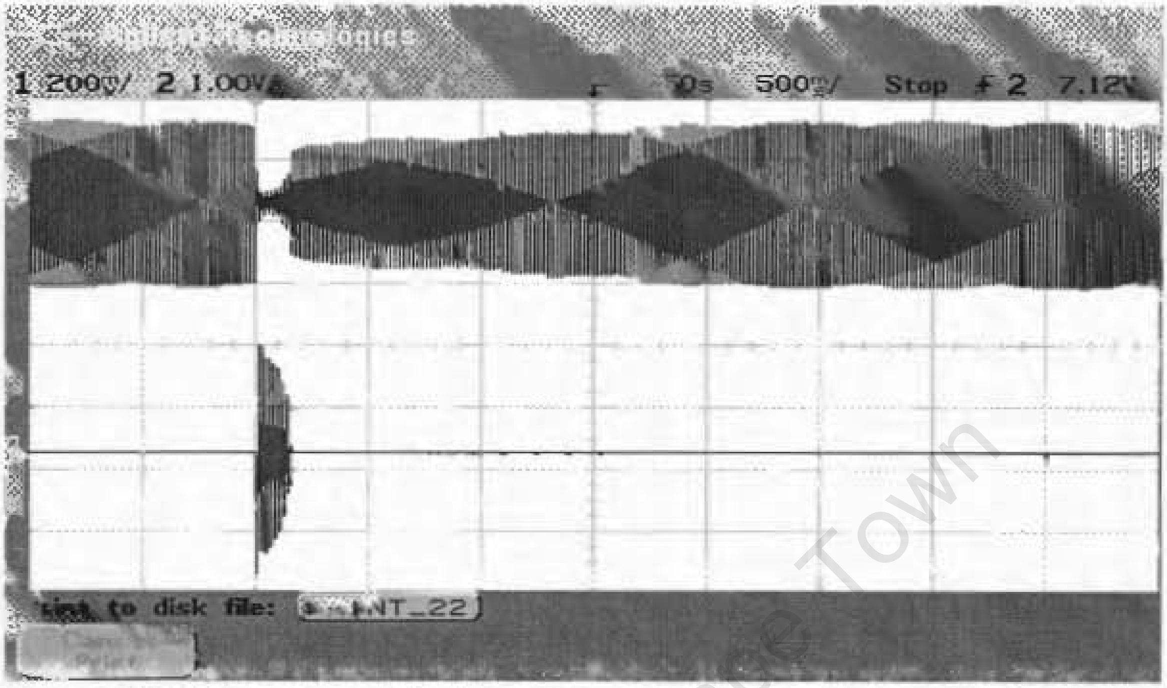


Figure 5.31 The compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 750W single-phase unloaded motor and complex load with pf = 0.9

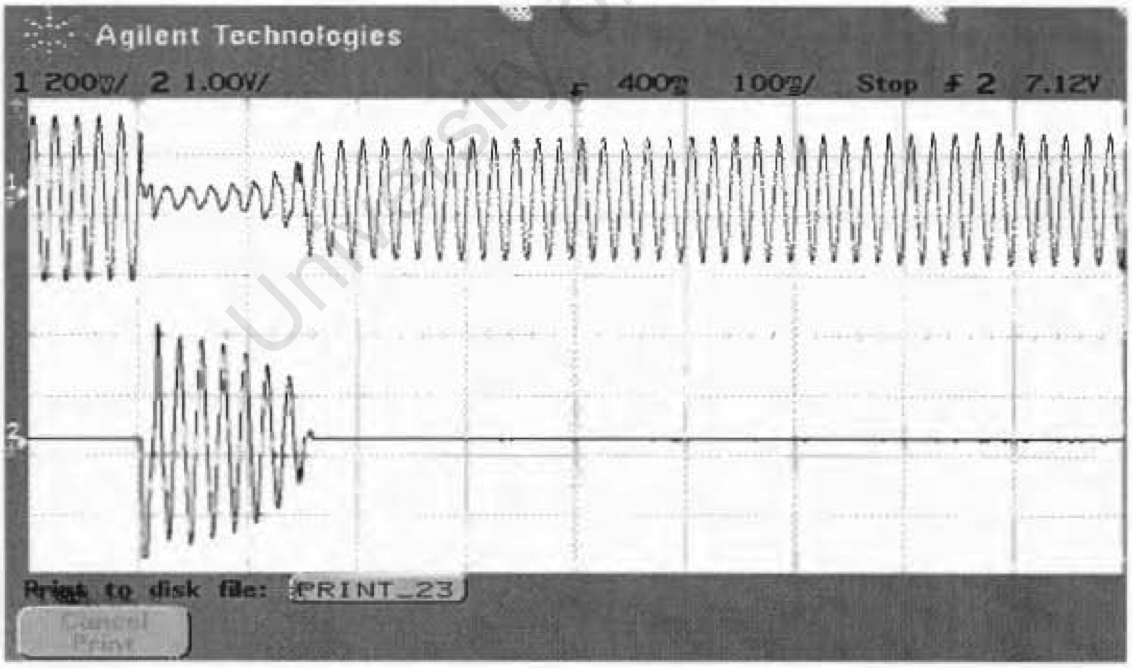


Figure 5.32 The compensated load voltage (upper trace) and arc current (lower trace) before, during and after a 33cm arc; 750W single-phase unloaded motor and complex load with pf = 0.9

In the figures above, the voltage scale is 200mV/division and the current scale is 1A/division. Figure 5.31 has a time scale of 500ms/division to show the entire load voltage recovery, while figure 5.32 has a time scale of 100ms to provide a more comprehensive illustration of the arc. In this particular test, the arc burnt for approximately 150ms. This extremely rapid arc once again demonstrates the efficacy of the system in current limiting and arc extinction. When the arc has extinguished, the load voltage begins its compensator-initiated recovery.

Finally, the effect of a 16kW load on the system was tested. A 16kW resistive load was connected as the circuit load and the compensator (rated at 8kW) was connected in parallel with the load. When the circuit switched on, the uncompensated voltage was 138V. The compensator switches in all 15 capacitors (a total of 750µF) and the load rises to approximately 158V.

Chapter Six: A discussion of the results

A sample of the results obtained from the laboratory tests were presented in Chapter Five. A full set of results can be observed in Appendix D. In this chapter, the results will be discussed so that conclusions can be drawn in Chapter Seven.

6.1 The no-load arc tests

The results of the no-load tests were presented in section 5.1. The results show how the voltage across the arc gap collapses as soon as the arc is initiated and the arc current begins to flow from the positive to the neutral electrode. The arc voltage does not have a sinusoidal waveform, but instead a distorted rectangular waveform. As the arc current decreases in magnitude, so the voltage across the arc gap increases, signalling the imminent extinction of the arc. The limiting of the fault current prevents the continued burning of the arc, and its actual extinction is signalled by the disappearance of the arc current. The voltage across the arc gap then continues its steady increase (with a sinusoidal waveform) until its maximum value is attained (in the laboratory, another arc would not initiate because the trace wire would not have been placed between the electrodes).

Table 6.1 provides a summary of the results obtained from the no-load tests.

Arc gap (cm)	% Self-extinguishing	Arc duration (ms)			Max arc current (A)
		Min	Max	Avg	
33	100	420	700	540	5.8

Table 6.1: Summary of no-load arc tests

These no-load arc tests were performed before the added reactance was placed in the supply circuit. Although 100% of the arcs that were initiated were self-extinguishing, the arc current was larger than twice the steady-state load current. (Note that the current is measured at the MV line, i.e. at 19.1kV.) Because the arc current is close to seven times the full load current, the response time of the feeder breaker (according to a general IDMT curve [9]) will be just under 300ms.The average duration of arc burning is thus longer than desired. If a fault was registered by a protection system for this length of time, the feeder breaker would trip.

6.2 The arc tests with an 8kW resistive load

This section discusses the results obtained from the uncompensated and compensated arc tests with the 8kW resistive load connected.

6.2.1 The uncompensated 8kW arc tests

Before these arcs are initiated, the uncompensated load voltage (rms value) is, on average, approximately 180V. This is the result of the volt drop across the large series impedance. When the fuse link closes, the arc is initiated and the resulting earth fault causes the load voltage to collapse for the duration of the arc. When the arc extinguishes, the load voltage is quickly restored to its pre-arcing value which is still well below the expected value of 230V. The added series inductance has resulted in a rapidly self-extinguishing power arc.

The initial spike that is present in most of the arc current traces is likely to be due to the inductive nature of the circuit. Inductors inherently oppose sudden and large changes in current and try to maintain a constant current through their windings. When the fault is initiated, it immediately causes a larger current to flow through the series R-L supply circuit. This results in a transient response, which causes the current spike that is observed.

Apart from the initial spike, the RMS value of the short-circuit current is, on average, approximately 1.2A. This is the value of the current in the 18.3kV "zone". This implies that the magnitude of the circuit impedance (up to the MV line) in the 18.3kV "zone" is 15 250Ω. According to the measurements described in Chapter Four, the magnitude of the *total* supply impedance in the 230V "zone" is 3.1Ω. When transferred to the 18.3kV "zone", this impedance becomes 19 600Ω. This value is significantly higher than the 15 250Ω that was obtained from the current trace.

This could be due to a number of factors. Firstly, the measured impedance (of 19 600Ω) includes the impedance of the 16kVA SWER step-down transformer (which does not actually contribute to the limiting of the short-circuit current). The per-unit calculations can be used to determine the supply impedance up to the MV line (and according to these calculations, the arc current in the 18.3kV "zone" should be approximately 0.9A which is lower than the actual 1.2A). However, while the per-unit calculations show the *total* supply impedance to have a magnitude of 3.4Ω, the measured supply impedance magnitude is 3.1Ω. This implies that the calculated impedance is higher than the actual impedance and that the expected fault current of 0.9A *should be* lower than the actual current, and is a fairly inaccurate "benchmark" for the comparison of expected and actual current values.

Another possible reason for the difference in "expected impedance" and "actual impedance" is the likely saturation of the four reactors that were added to the supply circuit. In Chapter Four, the non-linearity of these reactors was demonstrated. In the steady state, the contributing impedance of the reactors is as expected. However, when the fault condition is initiated, a large current flows suddenly through the reactors causing them to saturate, thereby reducing the magnitude of their effective reactance. This causes the actual impedance of the system to be lower than expected (measured and calculated).

Table 6.2 provides a summary of the uncompensated arc tests with an 8kW resistive load.

Arc gap (cm)	% self-extinguishing	Arc duration (ms)			Max. arc current (A)	Avg uncompensated load voltage (V)
		Min	Max	Avg		
33	100	130	180	150	1.4	180
45	100	150	520	250	1.4	180

Table 6.2: Summary of uncompensated 8kW arc tests

The table shows that 100% of the arcs initiated in these tests were self-extinguishing. This, in itself, is not particularly noteworthy. However, the duration of arc-burning is significantly shorter than in the previous tests. As well as this, the magnitude of the arc current is also lower. These values indicate that the added series reactance is limiting the arc (or short-circuit) current severely which impedes the sustainability of the arc. For this reason, the arc duration is impressively short. On average (for both arc gap length), the arc duration is less than that required for breaker intervention.

Interestingly, the tests performed with the longer arc gap (45cm) provided the result with the longest arc duration. One would assume a longer arc gap to result in an even shorter arc duration. It appears, though, that in this case, the longer arc gap has not resulted in the expected or predicted behaviour. This is possibly because the sample size is smaller than required to show statistical consistency.

However, this also illustrates the somewhat unpredictable behaviour of power arcs. There are no "guarantees" in these tests. In fact, the longest arc duration is longer than desired. This illustrates the fact that the proposed technology may not be effective in

100% of cases in preventing an interruption, even if the fault current has been sufficiently limited and the insulation length adequately designed (for the particular voltage at which the fault may occur).

Another notable result is the unacceptably low load voltage, which has been discussed briefly. The load voltage has, on average, a value of 180V. This is 22% below the required voltage of 230V, which would, of course, imply extremely poor quality of supply. This low voltage is the result of the large volt drop across the supply impedance. Thus, although these results show the technology (thus far implemented) to be successful in limiting the fault current, they also show the negative effect that this current-limiting characteristic has on the system (specifically the voltage delivered to the customer). The section that follows discusses the results when the compensator is connected in parallel with the load.

6.2.2 The compensated 8kW arc tests

In these tests, the initial uncompensated voltage was also, on average, 180V. When it measured a low voltage, the compensator would switch in capacitors until it load voltage was as close to 230V as the limited resolution would allow. The compensator would then stop switching in capacitors and the load voltage would remain at a value that is well within the accepted margin of +-10%. In these tests, the compensator switched in a total of either seven or eight capacitors (350µF or 400µF). If seven capacitors were switched in, the load voltage stabilised at 229V. If eight capacitors were switched in, the load voltage would stabilise at 234V. This differential may be due to a slightly different initial voltage supply from the generator. It should be noted that the generator was turned on at the start and off at the end of each period of testing. The generator voltage was displayed on an analogue voltmeter and thus, despite best efforts, the actual generator voltage output may have differed slightly from one testing period to another.

While the arc is burning, the load voltage collapses rapidly before increasing steadily in magnitude. When the arc has extinguished, the load voltage once again builds up to a level close to the desired value of 230V as the compensator switches in either seven or eight capacitors.

From the results, it can be seen that each power arc burns for a different length of time (and this applies for all arcs at all voltages and all gap lengths). This is due mainly to the stochastic and unpredictable nature of power arcs. In each test, the conditions are slightly different. The generator voltage may be set to a slightly higher or lower value, the trace wire between the electrodes may hang slightly lower or higher thereby causing the very initial arc gap to be slightly longer or shorter. Each arc is initiated at a different point in the arc voltage waveform, causing each arc voltage to have an initial magnitude that is slightly larger or smaller (this is known as the "point of wave theory"). All of these factors influence the characteristics of the power arc and will result in various arc durations. This does, however, simulate the variety and unpredictability of conditions that would be experienced in the "real world". Lightning may strike an MV distribution line at any time and therefore at any point in the line-voltage waveform.

Table 6.3 shows a summary of the results of the compensated arc tests with an 8kW load.

Arc gap (cm)	% self-extinguishing	Arc duration (ms)			Avg uncompensated voltage (V)	Max current (A)	Avg time to recover load voltage (s)	Avg compensated voltage (V)
		Min	Max	Avg				
33	100	200	490	330	180	1.48	1.67	231
45	100	120	320	207	180	1.45	1.66	292

Table 6.3: Summary of compensated 8kW arc tests

Once again, as shown by the results, 100% of the arcs are self-extinguishing. These results show very clearly the double benefits of the proposed fault-tolerant technology. As with the previous results, the arc durations are generally low, as are the maximum arc currents (at each gap length). Once again, this result is due to the large inductance in the supply circuit. However, the load voltage, which, left uncompensated, is, on average, 180V, rises to approximately 230V when the compensator is connected in parallel with the load. Thus the negative effect of that reactance is negated by the compensator which manages, very effectively, and without fail, to maintain the load voltage at the desired value of 230V.

The other value of interest is the time taken for the load voltage to recover. Once the arc has self-extinguished, the load voltage takes a finite amount of time to rise back to 230V. The compensator is left without power momentarily when the arc is burning, but as soon as the arc extinguishes, it turns back on (with no capacitors switched in), registers the post-arc low load voltage, and switches in capacitors until it reaches an acceptable value. This process takes, on average 1.46 seconds. Thus, although a full interruption may not result from these very short transient faults, a voltage dip will be experienced while the load voltage is reduced by the arc, and recovering afterwards. This type of voltage dip will be acceptable for many households, but will be detrimental to factories and sensitive electronic equipment.

Note again that the arc durations are not 100% consistent and that occasionally, an arc burns for an unexpectedly long time. Once again, this does not appear to be directly related to the arc gap length.

6.3 The arc tests with a 4kW resistive load

This section discusses the results obtained from the uncompensated and compensated arc tests with the 4kW resistive load connected. These tests were conducted to observe the effects of connecting a load to the system which is rated at half the rating of the compensator.

6.3.1 The uncompensated 4kW arc tests

The compensator is rated at 8kVA. The tests conducted with an 8kW load are within the rated limits of the system. The current drawn by the 4kW load is half of that drawn by the 8kW load. The relevant question is: "Will the lightly-loaded system have any significant impact on the technology?"

Before the arc is initiated, the uncompensated load voltage has, on average, a magnitude of approximately 206V. This uncompensated voltage magnitude is not as low as that of the uncompensated load voltage when the 8kW load was connected. This is because the circuit current, and therefore, the volt drop across the supply reactance, is not as large. This system behaviour was predicted.

Table 6.4 presents a summary of the results of the 4kW uncompensated arc tests.

Arc gap (cm)	**% self-extinguishing**	**Arc duration (ms)**			**Max. arc current (A)**	**Avg uncompensated load voltage (V)**
		Min	**Max**	**Avg**		
33	100	200	440	320	1.3	206
45	100	200	400	300	1.3	206

Table 6.4: Summary of uncompensated 4kW arc tests

As expected, the main effect of the under-rated load is the fact that the uncompensated voltage magnitude is not as low. 100% of the arcs are self-extinguishing and the arc durations and arc current magnitudes continue to be low.

6.3.2 The compensated 4kW arc tests

When the compensator is connected in parallel with the 4kW resistive load, it registers that the load voltage is unacceptably low, and switches in enough capacitors to increase that voltage to approximately 230V. In most cases, the compensator switched in 4 capacitors which resulted in a compensated voltage of 232V. In a few cases, the compensator switched in only 3 capacitors which raised the voltage to 228V.

When the arc is initiated, the load voltage dips rapidly and remains unacceptably low for the duration for the duration of the arc. When the arc has extinguished, the compensator switches in three or four capacitors again and the voltage build up to a value close to 230V. In all of the tests (performed with an arc gap of both 33cm and 45cm), the arc was rapidly self-extinguishing.

Table 6.5 presents a summary of the results obtained from the 4kW compensated arc tests.

Arc gap (cm)	**% self-extinguishing**	**Arc duration (ms)**			**Avg uncompensated voltage (V)**	**Max current (A)**	**Avg time to recover load voltage (s)**	**Avg compensated voltage (V)**
		Min	**Max**	**Avg**				
33	100	360	600	500	206	1.4	1.36	231
45	100	180	450	294	206	1.36	1.48	231

Table 6.5: Summary of compensated 4kW arc tests

The most noticeable result here is the fact that the arc durations at 33cm are generally somewhat longer than those at 45cm.

Otherwise, all results are as predicted: 100% of arcs are self-extinguishing, the arc current is acceptably small, and the compensated arc voltage is always close to 230V.

6.4 The arc tests with an 8kVA complex load

This section discusses the results obtained from the uncompensated and compensated arc tests with the 8kVA complex load connected. As explained, this load has a power factor of 0.87. The objective of these tests was to determine the behaviour of the compensator and arcs when a more demanding load was connected. One can expect the uncompensated load voltage to be lower then 280V (the voltage when the 8kW load was connected). One can also expect the compensator to switch in more capacitors in order to compensate for the extra volt drop across the supply impedance.

6.4.1 The uncompensated 8kVA arc tests

With an 8kVA complex load of lagging power factor 0.87 connected to the system, the uncompensated load voltage sits at a level of approximately 156V. The lagging nature of the load contributes to the lower load voltage together with the large supply impedance. Table 6.6 provides a summary of the results obtained from the uncompensated arc tests with the 8kVA load.

Arc gap (cm)	**% self-extinguishing**	**Arc duration (ms)**			**Max. arc current (A)**	**Avg uncompensated load voltage (V)**
		Min	**Max**	**Avg**		
33	100	200	520	360	1.1	156
45	100	170	180	175	1.15	156

Table 6.6: Summary of uncompensated 8kVA arc tests

As with the other uncompensated arc tests, it can be seen that although 100% of the arcs are self-extinguishing, and the arc duration and arc current are small, the load voltage is low. In this case, the load voltage is lower than it has been in previous tests. This test results in the largest volt drop across the supply reactance. The maximum arc current is similar to the values in other tests. This indicates that the *load* does not affect the arc current, which behaves independently of the load side of the circuit. The current magnitude is dependent on the current limiting capabilities of the components in its path.

The arc duration is, once again, longer when the gap is shorter. The pattern of longer arc gap length resulting in shorter arc duration is becoming more consistent as more results are examined.

6.4.2 The compensated 8kVA arc tests

As shown, the uncompensated load voltage is 156V. The compensator, when connected, switches in twelve capacitors which increases the voltage to 234V. The compensator switched in 12 capacitors (or 600μF) in all the 8kVA tests that were conducted.

When the arc has extinguished, the compensator begins switching in capacitors. Because more capacitors need to be switched in, the load voltage recovery time is longer than in previous tests.

Of some significance are the tests which resulted in a transient arc (in other words of extremely short duration) and no further response from the compensator. When the arc is extremely transient in nature, the power supply to the compensator is suddenly removed. The compensator is occasionally unable to cope with this rapid removal of power supply and extinction of the arc and appears to be electro-magnetically incompatible. The power to the compensator is never re-instated and the compensator essentially turns off. It is then unable to switch in any capacitors, and the load voltage remains at its uncompensated value. The extreme transience of the arc is likely to be caused by its initiation at a specific point in the voltage waveform. This type of test (on a complex load) was carried out approximately 40 times and this particular event occurred approximately 10% of the time.

Table 6.7 provides a summary of the compensated arc tests with an 8kVA complex load.

Arc gap (cm)	**% self-extinguishing**	**Arc duration (ms)**			**Avg uncompensated voltage (V)**	**Max current (A)**	**Avg time to recover load voltage (s)**	**Avg compensated voltage (V)**	**% non-recovering**
		Min	**Max**	**Avg**					
33	100	190	500	318	156	1.44	2.7	234	10
45	100	120	290	184	156	1.42	2.48	234	10

Table 6.7: Summary of compensated 8kVA arc tests

In these results, 100% of arcs are self-extinguishing. As the pattern now confirms, the shorter arc gap length results in the longer arc duration. Once again, the maximum arc currents are virtually unchanged from the previous results (but still lower than the open-circuit results, due to the added supply reactance). The load voltage recovery times are almost double those of the 4kW arc tests and about one and a half times those of the

8kW arc tests. This shows clearly the fact that if the compensator needs to switch in more capacitors, it will take longer to do so.

6.5 The start-up tests with an unloaded single-phase induction motor

These tests did not include the initiation of arcs. Their results depict the response of the compensator to switching (another transient event). They also indicate the stability of the compensator during these conditions.

6.5.1 Switching in the motor only

This test illustrates the characteristics of the motor. When the motor is switched in as the load of the system, the load voltage has a magnitude of approximately 210V. The uncompensated load voltage is higher than in previous tests because the motor has a rating of only 750W and therefore draws a relatively smaller current, resulting in a smaller volt drop across the series impedance in the supply circuit.

6.5.2 Switching in the motor with the compensator already connected

This test was conducted to determine the stability of the compensator. It was expected that the compensator and system would be stable when the motor was switched in. An unexpected benefit of the test was an indication of the behaviour of the compensator when a load with a rating well below 8kVA is connected to the system.

Before the motor is switched in, the compensator is connected across the 16kVA transformer on its own and there is no load present to draw a current. This creates an unusual situation for the compensator to respond to because it is unable to monitor the level of reactive current flowing into the load. In an attempt at a response, the compensator vacillates rapidly between switching in two and three capacitors. This behaviour takes the no-load voltage up to 247V. This is unusual, because when there is no load, there is no current being drawn by the system, and therefore no volt drop across the series impedance in the supply circuit. Nonetheless, this is the measured response of the compensator in the "no-load" condition and it results is an extremely distorted voltage waveform.

When the motor is switched in, the compensator switches in 3 capacitors 100% of the time. This consistently results in a load voltage of 233V. As soon as the motor is switched in, a very large load current (the start-up current) is drawn. The compensator "understands" that a load has been connected, is able to monitor the reactive current absorbed by the load and responds by switching in the capacitors required to deliver reactive current. During the motor start up, the load current is very large and the compensator is able to deliver a sinusoidal load voltage. The steady-state motor current has a much smaller magnitude and while the compensator is able to monitor and respond to this current, the resulting load voltage is slightly distorted. Once again, this is due to the fact that the load has a rating that is well below that which is "expected" by the compensator. Although the voltage is slightly distorted, it is acceptable in comparison to that which is the result of the no-load condition. The steady-state motor current is also highly distorted but this is a characteristic of this particular motor (as explained previously). An important observation is that when the unloaded motor is switched in, there is no subsynchronous resonance experienced by the characteristically resonant system (due to the series inductance and shunt capacitance). The system is completely stable throughout this transient switching event. The compensator was stable and responsive 100% of the time.

6.5.3 Switching in the motor with the compensator and complex load already connected

In these tests, the motor is switched in once the compensator has already been connected in parallel with the complex load. Before the motor is switched in, the compensator switches in eight capacitors, ensuring a voltage of 233V across the complex load. This response occurred 100% of the time.

While the motor is drawing its large start-up current, the load voltage drops slightly. This condition lasts for, on average, approximately 150ms. When the motor is drawing a steady-state current, the compensator responds by switching in another capacitor implying that a total of nine capacitors (or 450µF) are required for the compensation of the motor and complex load. The load voltage stabilises at 230V. This response also occurred in 100% of the tests.

Once the motor has been switched in, the load voltage continues to feature a sinusoidal waveform because the connected loads draw a total apparent power that is very close to the value expected by the compensator. In other words, the rating of the motor and complex load together ensures that a large current flows through the system and the compensator. The compensator is able to respond more predictably to this situation than that where the rating of the load is well under that of the compensator itself (in this case 8kVA).

In these tests, the compensator was stable 100% of the time.

6.6 The arc tests with a single-phase, unloaded motor

This section discusses the results of the uncompensated and compensated arc tests with a motor load.

6.6.1 The uncompensated motor-load arc tests

Because the motor is rated at 750W, it draws a very light current. For this reason, the volt drop across the supply reactance was not very significant. The uncompensated load voltage was approximately 210V.

Table 6.8 gives a summary of the uncompensated motor-load arc tests.

Arc gap (cm)	% self-extinguishing	Arc duration (ms)			Max. arc current (A)	Avg uncompensated load voltage (V)
		Min	Max	Avg		
33	100	250	350	300	1.4	210
45	100	200	320	260	1.3	210

Table 6.8: Summary of uncompensated motor-load arc tests

These results continue to give evidence to the fact that arcs initiated across shorter gaps are of shorter duration. In this case, the difference between the average durations at the two lengths is not significant. This indicates, once again, the fact that it would not be possible to conclude with certainty that every arc initiated across a 45cm gap will have a shorter duration than those initiated across a 33cm gap.

6.6.2 The compensated motor-load arc tests

When the compensator was connected in parallel with the motor load, it regulated the steady-state load voltage by switching in 3 capacitors. This maintained a load voltage of 232V. The compensator behaved in this manner in all of the tests conducted in the laboratory.

As with other tests, the arcs were rapidly self-extinguishing due to the low arc currents. When the arcs extinguished, the capacitor, once again, switched in the three capacitors to regulate the load voltage. The load voltage recovery (after arc extinguishing) took, on average, 1s.

Table 6.9 provides a summary of the results obtained from these tests.

Arc gap (cm)	% self-extinguishing	Arc duration (ms)			Avg uncompensated voltage (V)	Max current (A)	Avg time to recover load voltage (s)	Avg compensated voltage (V)
		Min	Max	Avg				
33	100	220	500	360	210	1.35	0.95	232
45	100	200	210	205	210	1.5	1.05	232

Table 6.9: Summary of compensated motor-load arc tests

In 100% of these tests, the arcs were self-extinguishing. In all tests, the load-end compensator ensures that the load voltage recovers rapidly after each transient event and maintains the load voltage at 232V. The compensator and entire system were stable in every arc test. The fact that the load was a non-passive motor did not have any affect on the arc or the compensator, which both behaved as they would with any other load. The only feature of the test to have any notable impact was the low rating of the motor (load).

6.6.3 The compensated motor and complex load arc tests

Before the arc is initiated, the compensator is connected in parallel with the unloaded motor and the complex load. In all of these tests, the compensator switches in nine capacitors and the voltage across the total load stabilises at 230V (the *sinusoidal* nature of the load voltage waveform, due to the higher load rating, can be observed both before and after the arc).

Once the arc has been extinguished, the compensator begins switching in the nine capacitors one by one, while continuously monitoring the magnitude of the load voltage. When the voltage reaches a value of 230V, the compensator stops the switching-in process and the load voltage stabilises. Once again, it can be noted that the transient nature of the event did not induce any subsynchronous resonance even though an unloaded motor is connected as a load to a "resonant" system.

Table 6.10 gives a summary of the results obtained from these tests.

Arc gap (cm)	% self-extinguishing	Arc duration (ms)			Avg uncompensated voltage (V)	Max current (A)	Avg time to recover load voltage (s)	Avg compensated voltage (V)
		Min	Max	Avg				
33	100	180	200	193	171	1.6	2.6	230
45	100	170	240	202	171	1.3	2.4	230

Table 6.10: Summary of compensated motor-load arc tests

Because the load consists of 6kW of resistive load, approximately 1kVAr of inductive load, and 750W of motor load, the total rating of the load is close to 8kVA, but is lagging in nature. This draws a greater current than the 8kW resistive load but less than the 8kVA inductive load (without motor). Thus, the volt drop across the supply impedance results in an uncompensated load voltage of 271V. As mentioned, 9 capacitors were required to regulate this voltage to a level of 230V. The load voltage recovery time is fairly long because of the large number of capacitors to be switched in.

Interestingly, in these tests, the average arc duration across the 33cm gap is slightly shorter than that across the 45cm gap. The results disturb the consistency of the gap length vs. arc duration pattern thus far. At the end of this chapter, an overall view of this pattern will be presented.

6.7 The compensation of the voltage across a 16kW load

In this test, the compensator switched in all of its capacitors in an attempt to increase the voltage to 230V. However, the 16kW load was too over-rated for the system, and the compensator was able to maintain a load voltage of only 159V. In this case, the volt drop across the supply impedance due to the sizeable current drawn by the load, was too large for the capabilities of the compensator as it was rated, designed and manufactured. The compensator was designed to have a rating of 8kVA at 230V. The supplier did not specify the rated power factor of the compensator. The tests conducted for this thesis confirm that although the compensator is able to regulate the voltage across an 8kVA load with a power factor of 0.87, it is unable to regulate the voltage across a 16kVA load with a power factor of 1.

6.8 General analysis of the results

In this section, some of the overall characteristics of the tests conducted for this thesis will be examined. The first feature to be discussed is the effect of arc gap length on arc duration. Table 6.11 provides an overall summary of these results.

Gap length	Min duration (ms)	Max duration (ms)	Average duration (ms)
33	130	600	315
45	120	520	230

Table 6.11: A summary of gap length vs. arc duration

This table indicates that overall, arcs initiated across a 33cm gap have a longer duration than those initiated across a 45cm gap.

Another relationship that is of interest is that between the load and the load voltage recovery time. A load with a high rating or low power factor will result in a greater volt drop across the supply impedance. This, in turn, will result in a lower uncompensated load voltage. The compensator will therefore need to switch in many capacitors, leading to a long voltage recovery time. Table 6.12 illustrates this.

Uncompensated load voltage (V)	No. of caps to be switched in	Time taken for load voltage to recover (s)
156	12	2.6
171	9	2.5
180	7	1.67
206	3	1.4
210	3	1.4

Table 6.12 Relationship between the uncompensated load voltage and the load voltage recovery time.

As indicated, this table illustrates the fact that the lower the uncompensated voltage, the longer the time taken for load voltage recovery. It also shows that the relationship is not linear. The compensator takes, on average, 2.5s to switch in both 9 and 12 capacitors.

Another point of interest is the limits of the load-end capacitor. As has been discussed previously, the compensator has a rating of 8kVA at 230V. The tests do indicate, however, that the compensator's limits are "flexible". When a load of 8kVA with a power factor of 0.87 is connected, the compensator switches in 12 of its 15 capacitors. Although tests were not conducted on a load with a lower power factor, the results create the expectation that at 8kVA a power factor of lower than approximately 0.84 would be beyond the specifications of the compensator. Tests also confirmed that the compensator could regulate the load voltage across an 11kW load, but not a 12kW load. This, then, appears to be the limit of the compensator. This was not analysed extensively because within its *specified* limits, the compensator behaved as was predicted by regulating the voltage at 230V.

Finally, the overall arc durations will be examined. In chapter 3, it was mentioned that a feeder breaker takes over 1 second to respond to an earth fault with a current magnitude of approximately 2 times the full load current. The following data provides a summary of the all the arc durations which resulted from the tests conducted once the extra reactors had been added to the supply circuit.

- Overall, 78% of arcs lasted for less than 400ms.
- Overall, 68% or arcs lasted for less than 300ms.
- Overall, 33% of arcs lasted for less than 200ms
- 45% of arcs across a 45cm gap lasted for less than 200ms.
- 24% of all arcs across a 33cm gap lasted for less than 200ms.

The no-load tests indicate that the arc durations are significantly longer without the inclusion of the added supply reactance. The following statements can be made concerning the no-load tests:

- 87.5% of arcs lasted for less than 700ms
- 62.5% of arcs lasted for less than 600ms
- 37.5% of arcs lasted for less than 500ms
- 0% of arcs lasted for less than 400ms.

Chapter Seven: Conclusions and recommendations

The conclusions and recommendations presented in this chapter are based on the results and the discussion based on them.

7.1 Conclusions

- The system that was set up in the laboratory was an effective testing station. This is because it successfully facilitated the tests that were required to determine the behaviour of the proposed technology. The laboratory set-up:
    - Simulated a MV distribution line and a "reticulation network" with connected load.
    - Allowed faults to be initiated at a voltage that had built up to a specific steady-state value.
    - Created arcs on an MV line
    - Created a large supply impedance
    - Tested the effects of the impedance on the arcs in a variety of conditions
    - Determined how successfully the compensator maintained a constant load voltage
    - Tested the efficacy of the compensator in a variety of conditions
    - Measured the duration and magnitude of the arc current
    - Measured the uncompensated and compensated load voltage
    - Switched in a variety of loads to test their effects on the arc duration and compensator's efficacy.

- The large series impedance in the supply circuit of the system was generally effective in its current-limiting and arc-extinguishing abilities. 100% of all arcs initiated in the tests were self-extinguishing. All the arcs had a duration of under 520ms, (when the extra reactance was added), which means that the supply impedance results in desirably low arc durations (which will prevent feeder breakers from tripping) 100% of the time. This is true because the series impedance also reduces the magnitude of the fault currents to approximately two times the full load current which, in turn, results in a response time from the earth fault relay and feeder breaker of over 1 second (according to the IDMT curves). As shown in chapter six, 78% of all the arcs lasted for less then 400ms which is well below the expected relay response time of over 1 second. In comparison to the results of those tests conducted without the added reactance (the no-load tests conducted for this thesis), both the fault current magnitudes and the arc durations are, on average, low. In the no-load tests, none of the arcs lasted for less than 400ms, and 37.5% of the arcs lasted for less than 500ms. As well as this, the average fault current magnitudes of the no-load tests were seven times the rated load current of the system.

- The technology is effective in improving the quality of supply of the supply to the connected load (or customers). The load sees fewer full voltage interruptions in its supply because the proposed technology prevents the relevant feeder breaker from tripping in response to every transient fault. Because the customers experience fewer full supply interruptions, their effective quality of supply in this regard will be improved. The technology will not, however, prevent the brief voltage dips that will be experienced while the arc is burning. These voltage dips will have a negative impact on the quality of supply in terms of dips and depressions. Because the dips will be brief (approximately 400ms), their effect on the domestic and commercial customers' perception of quality will be limited. However, these brief dips would still have a negative impact on major industrial plants. It thus seems apparent that the proposed technology should only be used in rural or domestic networks (as initially proposed)

- As shown in Chapter Six, the arc duration is dependent on the arc gap length. In other words, in general, a longer arc gap will, on average, result in an arc with a shorter duration.

- The load-end compensator is successful as a load voltage regulator and is able to switch in capacitors quickly to maintain a constant load voltage of 230V. The compensator's success is limited to those scenarios where the current drawn by the load is within the rated limits of the compensator (both in terms of magnitude and phasor angle). The compensator is rated at 8kVA at 230V. When the system's load is within the compensator's *specified* limits, it regulates the voltage to a level well within 10% of 230V in 100% of the tests.

- The compensator behaves predictably in both steady-state and transient (switching-in and fault) conditions. It was predicted that the compensator would successfully regulate the load voltage and would be stable during and after all transient events.

- The compensator does not have an effect on the magnitude of the load voltage during the power arcs because one of the effects of the arc is that the voltage across the compensator is reduced suddenly and significantly, which effectively turns the compensator off. The short circuit caused by the fault results in the rapid and short-lived collapse of the load voltage which cannot be prevented or improved by the compensator.

- The compensator has no effect on the arc duration or the magnitude of the arc current. The arcs burned for similar periods of time (at a certain length) during both the uncompensated and the compensated arc tests. In other words, the arc behaves independently of the compensator. Although it was not expected that the compensator would affect the behaviour of the arcs, tests confirm this assumption.

- The time taken for complete voltage compensation depends on the magnitude and power factor of the load. The voltage across a load with a high apparent power rating or low power factor will be low in magnitude (due to an increased volt drop) and will require more compensation. The compensator will need to switch in more capacitors and because the compensator switches in one capacitor at a time, the more capacitors that need to be switched in, the longer this process will take.

- The compensator has operational limits specified by its design. The compensator is rated at 8kVA. It is therefore expected that any load with an apparent power rating above this (in other words, with a magnitude greater than 8kW if the power factor equals one, or with a power factor below one if the load's magnitude is 8kW) will result in a system that cannot be regulated by the compensator. However, its operational limits are of a wider range than this. Although the compensator's rated power factor was not confirmed, it can be concluded that at 8kVA, a power factor of 0.87 is within the compensator's limits. According to tests, it can also be concluded that when the load's power factor is equal to one, the compensator is unable to regulate the load voltage for a load magnitude of greater than 11kW. If the load's magnitude is greater then this, or if the power factor of the load is below a certain (unspecified) level, the compensator will try to restore the load voltage to 230V by switching in the maximum number of capacitors that it features, but will be unable to raise the voltage sufficiently. The compensator is bound within the limits created by the physical number of capacitors that it features.

- The compensated voltage magnitude is not dependent on the arc gap, the arc duration, or the uncompensated arc voltage. The compensator acts independently of all of these conditions. The compensator only monitors the load voltage and will switch in capacitors until that voltage is within acceptable limits. If the required voltage is set at 230V, this is the voltage that the compensator will work to achieve, regardless of the voltage's starting point, or any event that has occurred (e.g. an arc).

- The compensator appears to be electro-magnetically incompatible in very few cases. This occurs specifically when the load is complex in nature with a lagging power factor.

- There is no subsynchronous resonance evident in the system. The system is stable when an unloaded motor is switched in, even though the system is "resonant" in nature. The conclusion to be drawn is that the system and compensator were never unstable, regardless of the load type or the nature of the transient event.

- The load-end compensator delivers a distorted load voltage waveform when there is no load or a load that is rated below the level expected by the compensator.

7.2 Recommendations

- It is recommended that the following further tests be carried out in the laboratory:
  1. The concept should be tested on a system to which more than one step-down transformer is connected a (two transformers would be a viable and manageable number for a laboratory). Each transformer should, in turn supply more than one load, each one being of a different type (e.g. one resistive and one motor etc). This should be carried out in conjunction with the variation of the number and position of compensators in the system. This should determine whether or not each load needs it own dedicated compensator for its voltage regulation. It will also determine the interactive behaviour of numerous components (including the compensators) in the system.
  2. The concept should be tested on a three-phase system, if required. The technology as developed from the tests featured in this thesis could be successfully applied to SWER systems. The results in this thesis can not, however, be assumed to be a reflection of the behaviour of the technology in a three-phase system. The technology may be beneficial for three-phase overhead systems in rural or peri-urban areas which are regularly struck by lightning. The compensator would have to be developed into a three-phase compensator and may have to extend its functions so as to include load balancing as well as voltage regulation.

  3. The proposed technology would achieve its fault-tolerant characteristics if:
     - The arc duration is reduced to less than 200ms
     - The load voltage recovery time after a transient event is less than 1 second.

     To achieve these objectives (and develop a viable technology), research should be continued in order to improve the current-limiting properties of the supply circuit, and to increase the speed with which the compensator switches in capacitors (which can be researched by power electronic or DSP specialists). Research should include tests in which the series impedance is increased such that the fault current is limited further (possibly to one and a half times the steady-state current magnitude), and the arc gap is increased further (possibly to 50cm and then 55cm). The results of these tests will allow a cost-benefit analysis to be done. A question that could be raised is: "If all arcs burn for less than 200ms when the arc gap is increased to 55cm, will the cost savings resulting from the consequent decrease in power interruptions outweigh the costs of the increased insulator lengths, the compensator and the added supply reactance?"

4. The response of the compensator to a continuously-changing load should be determined. In the "real-world" loads are constantly changing in magnitude and power factor in "real time". The response time of the compensator to the continuous changes would need to be examined. A rapidly changing load will require the compensator to have switching speeds similar to the speed of load change. A quick response time will result in a more constant and steadier load voltage. This could be achieved in the laboratory by connecting several loads in parallel, each one connected to the system via a switch that can be operated from outside the live chamber. The tester can then open and close load switches rapidly to determine the compensator's behaviour. This switching can be interspersed with faults that would be in initiated on the MV line. A system of this nature would determine comprehensively the response of the compensator to a complex and continuously-changing system.
5. Further investigation should take place into the apparent electro-magnetic incompatibility of the compensator when a complex load is connected to the system. The possible causes of this incompatibility should be researched further in order to determine what changes need to be made to the system to prevent this incompatibility from occurring.

- When points 1, 3 and 4 have been researched in the laboratory, a prototype should be developed and tested in the field on a SWER system. Specific decisions should be made regarding the required magnitude, structure and position of the supply inductance that would be added to a real supply system. The compensator's rating should be altered for field performance and it should be re-programmed to ensure that its voltage regulation is more rapid and that its "voltage level" is correct for its application. The field tests would expose the technology to a greater variety of conditions. The impact on the system of wind, humidity and cold weather can be determined. Obviously, the laboratory is an "ideal" environment and the behaviour of the technology in other conditions could be predicted, but will not be known.

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Appendix A: The spreadsheet used to calculate the required compensating capacitance

Note that “a” and “b” indicate the values used in complex figures in the form of a + jb

Source Voltage	**Inductance**	**capacitance**	**load**	**series R**	**load**	**load**	**load**
Volts	ohms	ohms	magnitude	ohms	angle	a	b
230	3.07	1.06E+01	6	0.63	0	6	0

omega	**inductance**	**capacitance**
314.1593	henrys	farads
	0.00977211	3.00E-04

For parallel cap and load:						
Z1Z2			**Z1+Z2**			
Magnitude	63.6619772		Magnitude	12.1893	a	6
Angle	-90		Angle	-60.5124	b	-1.06E+01

Z parallel			
Magnitude	5.222774459	a	4.546229
Angle	-29.487581	b	-2.57083
Z series			
A	0.63	Magnitude	3.133975
B	3.07	Angle	78.40323

Z total (with series resistance)			
a	5.17622884	Magnitude	5.200242
b	0.49916816	Angle	5.508269

Current			
Magnitude	44.2287133	a	44.02448
Angle	-5.5082693	b	-4.24549

Voltage across series impedance			
Magnitude	138.611687	a	40.76907
Angle	72.8949631	b	132.4805

Voltage across the load			
Magnitude	**230.996594**	a	189.2309
Angle	-34.99585	b	-132.48

Appendix B: Detailed per-unit calculations used to determine the series impedance of the proposed circuit (refer to section 4.2)

The per-unit method has been used in the development of the laboratory protocol for two reasons:

- These calculations will determine the actual value of the series impedance in the supply circuit.
- The calculated value of the supply impedance will enable a decision to be made as to whether further reactance needs to be added to the supply circuit in order to reduce the short-circuit current to twice that of the rated load current.

These calculations are fairly complex and lengthy but are essential for the purpose of the laboratory set-up for testing, and they also ensure that one of the fundamental hypotheses is tested. This can be summarised with the following question: "Will a reduction in the magnitude of the short-circuit current – by the addition of inductors in the supply circuit – result in rapid arc extinction?"

The main obstacle in the per-unit conversion was the two 48kVA transformers which are connected in parallel at the source end and in series at the end which supplies the 32kVA SWER transformer. The transformers were each used to step a voltage of 205V up to 230V. It was decided that the easiest method of calculating the per-unit impedances of these particular transformers would be to halve each transformer's actual impedance, placing one half of each in parallel with each other (representing the LV connection) and the other half of each in series with each other (representing the HV connection).

$$\mathbf{(0.5)Z_{T2} = 0.72 + j0.64\Omega}$$
$$\mathbf{(0.5)Z_{T3} = 0.73 + 0.62\Omega}$$

So, the two transformers can now be "separated" into two parts: the LV connection is represented by an impedance of 0.36 + j0.32Ω (obtained by placing 0.72 + j0.64Ω in parallel with 0.73 + j0.62Ω) and the HV connection is represented (on the LV side) by an impedance of 1.45 + j1.26Ω (obtained by placing 0.72 + j0.64Ω in series with 0.73 + j0.62Ω). Transferred to the HV side, this impedance becomes 1.8 + j1.57Ω. The load was regarded as being purely resistive for the calculations and was designed (and manufactured) with a rating of 8kW at 220V. This implies that the ohmic resistance of the load is 6Ω (this was considered constant, although the heating of the load did cause the resistance to increase during testing). A base of S = 100MVA was used for all the per-unit conversions. Then the following equation is used to convert Z(actual) to Z(pu):

$$Z_{pu} = Z_{actual} \times \frac{100}{E^2}$$

where $E^2 = V_{LL}$ in kV

Once the various voltage "zones" were established, the impedance values in that zone were multiplied by a constant which was obtained by dividing 100 by the square of that voltage. For example, in the 205V "zone", the impedance values were multiplied by 100/(0.205^2), or by the constant 2380.

T1 steps the voltage down from 3560V to 205V (which is supplied to the 48kVA transformers via the cable), thus the generator has a voltage output of 3560V which is 1p.u. Figure B1 gives a summary of the voltage "zones" and the impedances.

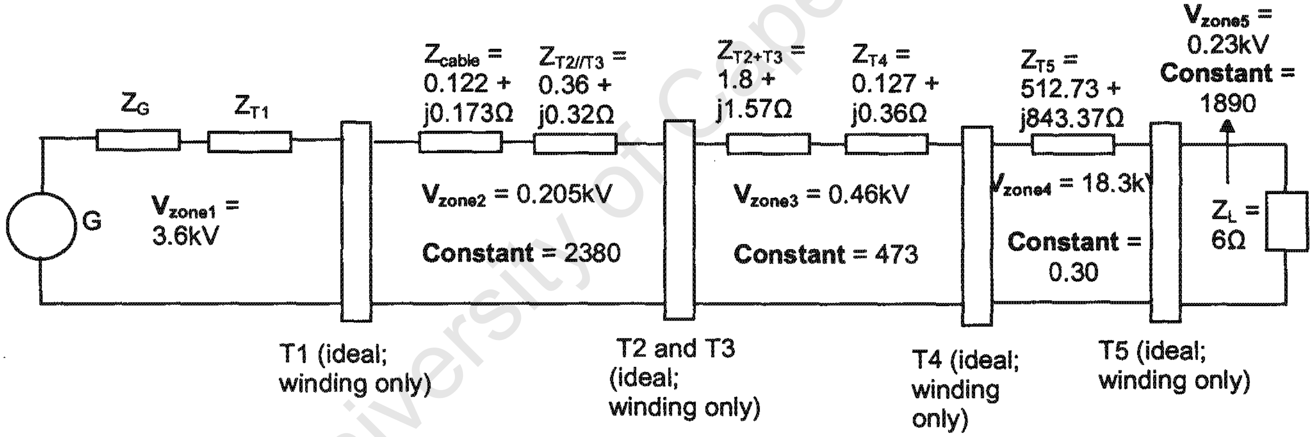

Figure B1 The voltage zones, multiplication constants and impedances used for per-unit calculations

This data is used to obtain the simplified per-unit system shown in Figure B2:

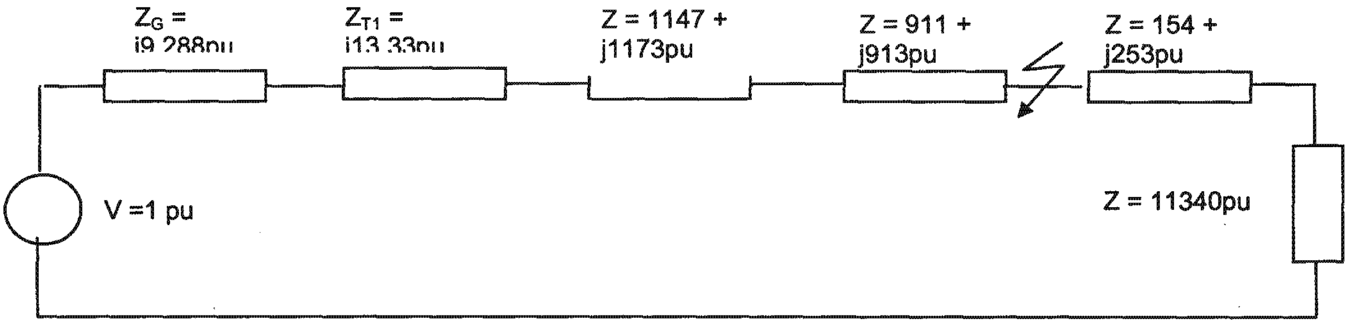

Figure B2 Simplified per-unit system

Thus, the per-unit impedance up to the MV line is:

$$Z = 2058 + j2109 = 2947\angle 45.7°$$

The aim is to ensure that this impedance is sufficient in magnitude so as to limit the short-circuit current magnitude to twice that of the steady-state current. If one considers the load "zone", the base voltage is 230V and the base current (when the base apparent power is 100MVA) is 416666.67A. For a 6Ω load, the steady-state current is 38.3A. Thus the desired short-circuit current is 76.7A.

If $I = 76.7A$

And $I_{base} = 434782.6A$

Then $I_{pu} = 0.000176pu$ throughout the per-unit system.

In the case of a fault on the MV line, only the impedances up to that fault will have a limiting effect on the fault current. Thus, one can consider these impedances to form a simple series circuit (together with the voltage source). If the voltage and current in that circuit are known, one need simply apply ohm's law to obtain the impedance. In this case, the voltage is 1pu and the current is 0.000176pu.

So

$$Zpu = \frac{Vpu}{Ipu}$$

$$Zpu = \frac{1}{0.000176}$$

$$Zpu = 5668.6pu$$

This is the required per-unit magnitude of the total impedance up to the MV line. At present, (as shown previously), the impedance has a per-unit magnitude of 2947. This impedance needs to be increased in magnitude (to limit the fault current) by the addition of reactors in the supply circuit. It is now necessary to calculate the value of the required reactance.

If the "final value" of the impedance magnitude is 5669 and the value of the resistance is remaining the same, then the reactance can be calculated as follows:

$$R = 2058\, pu$$
$$Z = 5669\, pu$$
$$\therefore X = \sqrt{(5669^2 - 2058^2)} = 5282\, pu$$

The current value of X is 2109pu. Therefore, the required reactance to be added has a value of 3173pu. It was decided to place the reactors in the 205V "zone" of the supply circuit. The most accessible point in the circuit was immediately before (or on the LV side of) the two 48kVA transformers. Because these transformers are connected in parallel on their LV side, the reactors, too, would be connected in parallel to each other. In the 205V voltage "zone", the constant that was used to convert actual impedance to per-unit impedance was 2380. This constant can now be used to obtain the actual reactance form the per-unit reactance.

$$X = \frac{3173}{2380} = 1.33\Omega$$

For each parallel-connected branch,

$$Z = 2 \times 1.33 = 2.66\Omega$$
$$Z = \omega L = 2.66$$
$$L = \frac{Z}{\omega} = \frac{2.66}{314} = 8.5mH$$

For testing, four reactors are used in parallel (two reactors in parallel with each other in each parallel branch of the LV connection of the two 48kVA transformers). Each reactor is rated at 20mH @ 15A. Thus in each parallel branch, the total reactance is 10mH @ 30A (this reactive value is acceptably close to the required 8.5mH). It should be remembered, though, that the magnitude of the reactance is dependant on the magnitude of the current. The resistive load that was used for testing has an approximate resistance of 6Ω. At 230V, this load has a rating of:

$$P = \frac{V^2}{R} = \frac{230^2}{6} = 8817W$$

Looking back at the two 48kVA transformers, the LV parallel connections are each drawing a load of approximately 4.4kW. The voltage supplied to each transformer is approximately 205V.

Therefore, the current flowing into each transformer is approximately 21A. This current will also flow through the reactors that are connected in series with each transformer (but parallel to each other). The following figure shows a simplified representation of the connection:

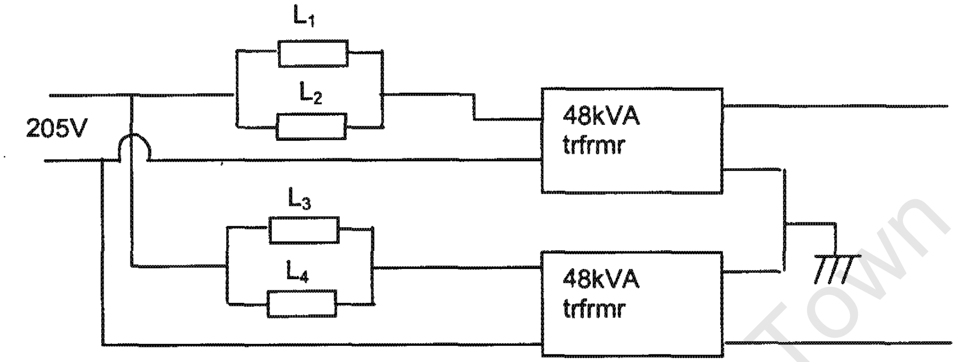

Figure B3 A representation of the set-up of the reactors and two 48kVA transformers

Each pair of parallel-connected reactors is rated at 10mH @ 30A. However, as shown, when the load is rated at approximately 8.8kVA, only 21A will flow through the reactors. The reactors were tested to determine their dependence on the magnitude of the current. These tests show the reactors to be non-linear in nature in the sense that as the current through them increases, the magnitude of their impedance values decreases. (Refer to the test details in Appendix C). However, at 21A, the impedance of each parallel pair of reactors is 10.2mH, which is acceptable.

It is now necessary to reconsider the per-unit system with the reactors included. This will assist in providing a complete and succinct representation of the entire complex system. As mentioned, while the required inductance in each parallel branch is 8.5mH, the actual inductance is 10mH (or 20mH per reactor). Therefore, the impedance provide by the reactors in each branch is 3.14Ω. This implies a total added impedance of 1.57Ω. Once again, the constant used in the 205V "zone" is 2380. This can be used to convert the actual value of the reactance to a per-unit equivalent.

$$X = 1.57\Omega$$
$$X_{pu} = 1.57 \times 2380 = 3736 pu$$

The total resistance of the system remains constant; in other words R = 2058pu. The added reactance is 3736pu which can be added to the original reactance of the system (2109pu). This results in a total per-unit reactance (up to the MV line) of 5846pu.

$$R = 2058pu$$
$$X = 5846pu$$
$$\therefore Z = 2058 + j5846pu = 6198\angle 70.6pu$$

The magnitude of the resulting impedance is 6198pu as opposed to the required value of 5669pu. In the case of a fault, this impedance would limit the fault current, and the expected per-unit magnitude of this current would be:

$$Ipu = \frac{Vpu}{Zpu}$$
$$Ipu = \frac{1}{6198} = 0.000161pu$$

This value is slightly lower than the "required" fault current magnitude of 0.000176pu. The fault-current magnitude can be converted to the actual expected value in any of the voltage "zones". For example, in the 18.3kV "zone", the expected value of the short-circuit current is 0.9A.

The impedance of the final 16kVA transformer in the system (located *after* the MV line) can now be added to the impedance up to the MV line to obtain the total supply impedance of the network.

$$R = 2058pu + 154pu = 2212pu$$
$$X = 5846pu + 253pu = 6099pu$$
$$\therefore Z = 2212 + j6099pu = 6488\angle 70$$

The circuit can now be represented by the following figure:

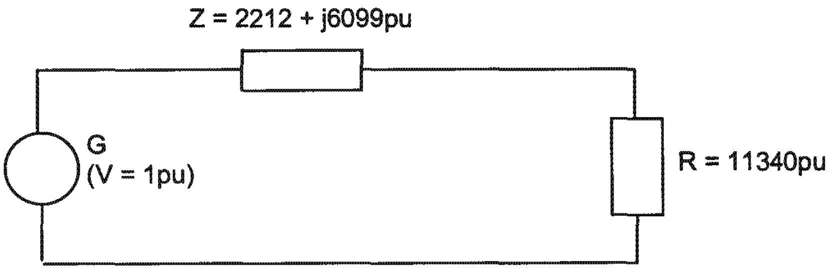

Figure B4 The simplified per-unit system

For the purposes of calculations and simulations, it was decided to convert this per-unit network to the equivalent system at 230V. In this system, the voltage source has a supply value of 230V, the series impedance has a value of $Z = 1.17 + j3.2\Omega = 3.4\angle 70$ and the load has a resistance of 6Ω.

There are advantages to using the per-unit concept to calculate the series impedance of the proposed system. However, a disadvantage to using this method is that it is purely theoretical and any number of external or unforeseen effects has not been taken into account. All the equipment in the system is *real* and may have defects. For these reasons, it was decided to determine the total series impedance of the network using another method. Firstly, the open circuit (no load) voltage was measured and found to be 225V. Then, two different loads were connected to the circuit output, and the resulting voltage across and current through these loads were measured. The first load was a resistive load (in the form of heating bars) that has a rating of 8kW at 220V. When it was connected, the voltage across it measured 183V and the current through it measured 29.4A. The load was allowed to cool and was then reconnected. The voltage and current measured 186V and 31A respectively. The second load was also a resistive load that has a rating of 4kW at 220V. The first time it was connected to the circuit, the voltage across it measured 205V and the current through it measured 16A. It was also connected a second time which resulted in a voltage and current of 209V and 17A. These values were used in simultaneous equations to calculate the practical value of the series impedance of the network. The calculations show the impedance to be the following:

$$Z = 0.63 + j3.07\Omega = 3.1\angle 78°$$

This value is applicable at 230V. A practical disadvantage of this method is the fact that the inductance of the added reactors is non-linear. Therefore, as the load (and thereby the current) varies, the reactance will also vary.

Appendix C: The results of the tests performed to determine the dependence of the impedance of the added reactors on the current they draw

To obtain the required supply impedance in the proposed circuit, four reactors are added in parallel (two reactors in parallel with each other in each parallel branch of the LV connection of the two 48kVA transformers). Each reactor is rated at 20mH @ 15A. Thus in each parallel branch, the total reactance is 10mH @ 30A (this reactive value is acceptably close to the required 8.5mH). It should be remembered, though, that the magnitude of the reactance is dependant on the magnitude of the current. The resistive load that was used for testing has an approximate resistance of 6Ω. At 230V, this load has a rating of:

$$P = \frac{V^2}{R} = \frac{230^2}{6} = 8817W$$

Looking back at the two 48kVA transformers, the LV parallel connections are each drawing a load of approximately 4.4kW. The voltage supplied to each transformer is approximately 205V. Therefore, the current flowing into each transformer is approximately 21A. This current will also flow through the reactors that are connected in series with each transformer (but parallel to each other). The following figure shows a simplified representation of the connection:

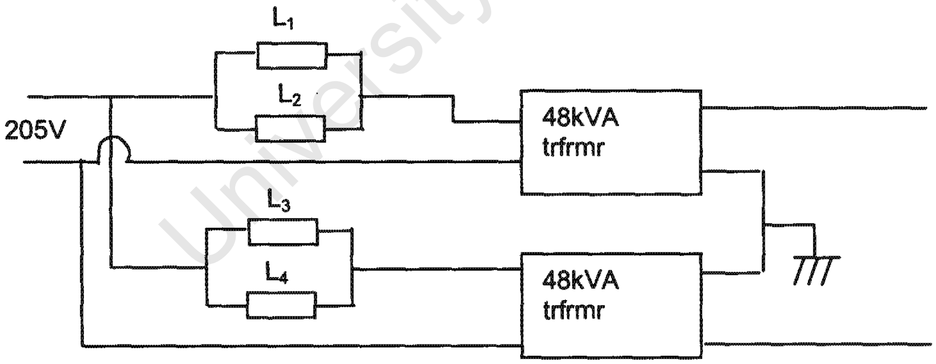

Figure C1 A representation of the set-up of the reactors and two 48kVA transformers

Each pair of parallel-connected reactors is rated at 10mH @ 30A. However, as shown, when the load is rated at approximately 8.8kVA, only 21A will flow through the reactors. The reactors were tested to determine their dependence on the magnitude of the current. These tests show the reactors to be non-linear in nature in the sense that as the current through them increases, the magnitude of their impedance values decreases. The following table shows the average results of the tests performed on the reactors. The table shows the values obtained when a voltage source is applied to a single reactor and the voltage is increased from 10V to 140V. The voltage and current values were recorded; the impedance and inductor values were calculated using these.

V (V)	I (A)	Z (Ω)	L (mH)
10	0.99	10.1	32
20	2.6	7.7	25
30	4.2	7.1	22.6
40	5.96	6.7	21.3
50	7.7	6.5	20.7
60	9.4	6.4	20.4
70	11.11	6.3	20
80	12.93	6.2	19.7
90	14.9	6	19.1
100	16.5	6.1	19.4
110	18.3	6	19.1
120	20.2	5.9	18.8
130	22.2	5.8	18.5
140	25.2	5.5	17.5

Table C1 Results of tests performed on the reactors; each is rated at 10mH @ 15A

The results show that there is a fairly linear range between approximately 6A and 20A. The inductance can be regarded as 20mH for these values of current. Therefore, when 21A is flowing through each parallel pair, 10A will flow through each reactor (the reactors are assumed to be identical in nature). At this value of current, the reactor provides the 'expected' inductance.

Appendix D: Results of all tests conducted in the laboratory

D1 - No-load tests arc tests, 33cm gap (added reactors not connected)

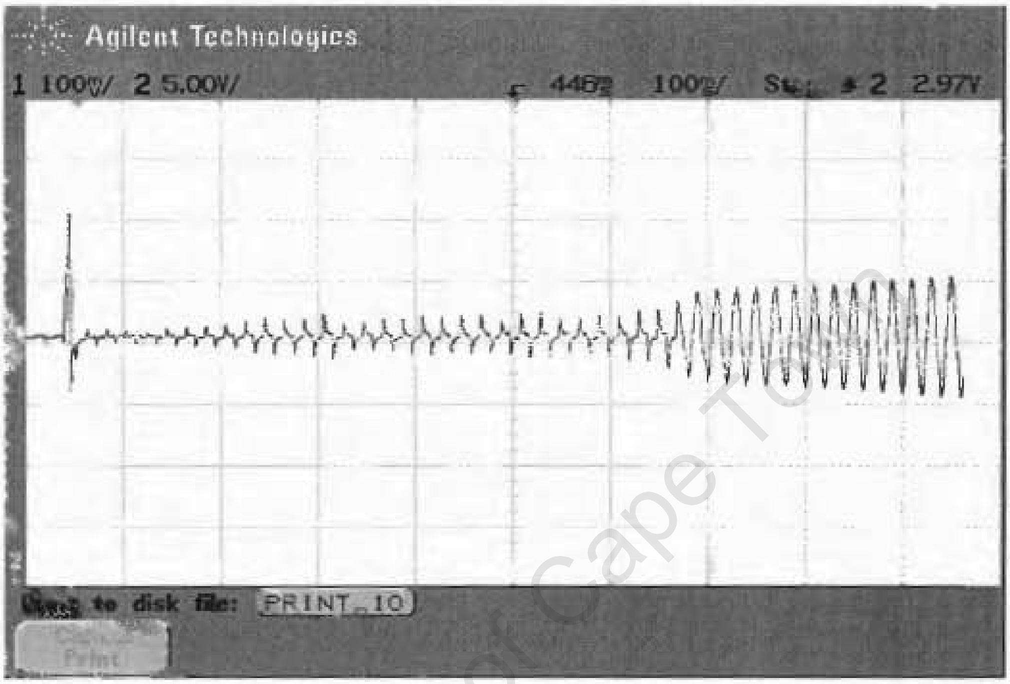

Fig 1: Arc voltage trace of test 1

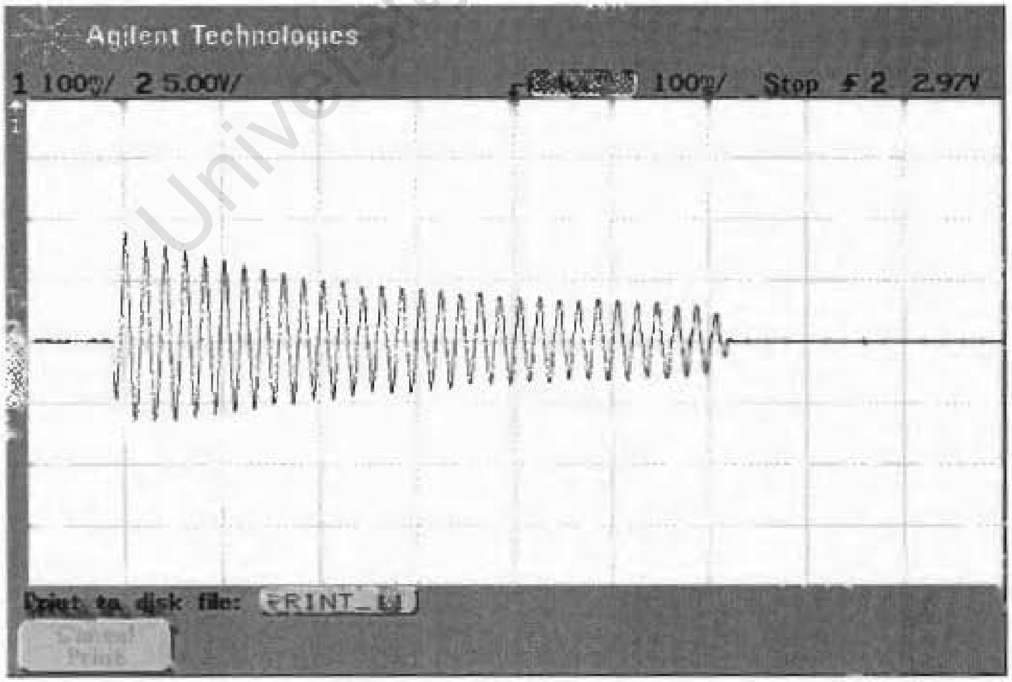

Fig 2: Arc current trace of test 1

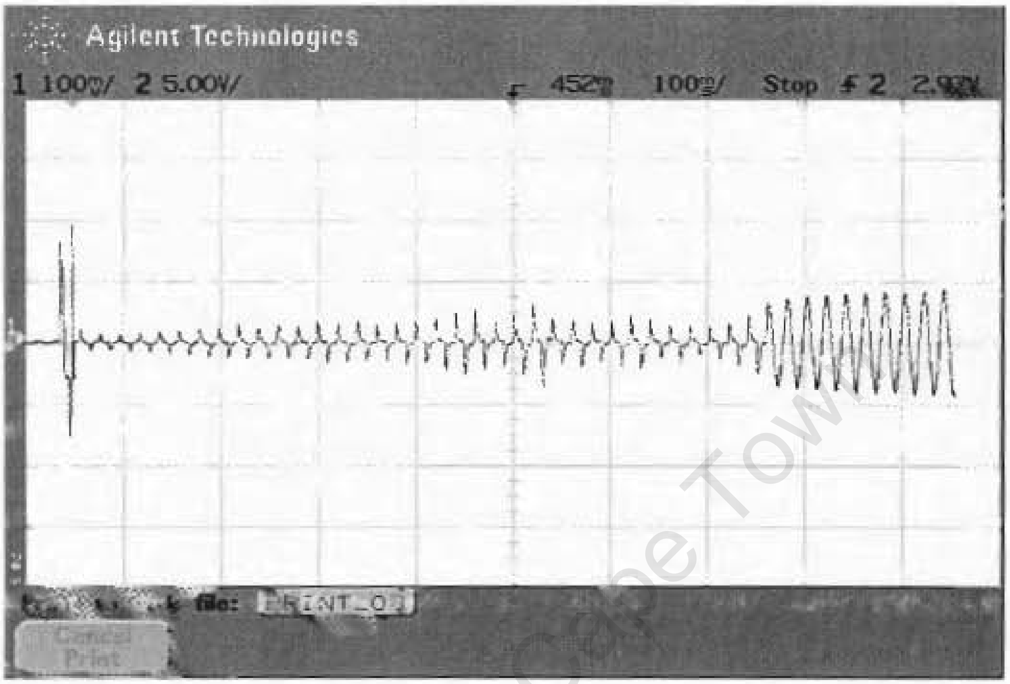

Fig 3: Arc voltage trace of test 2

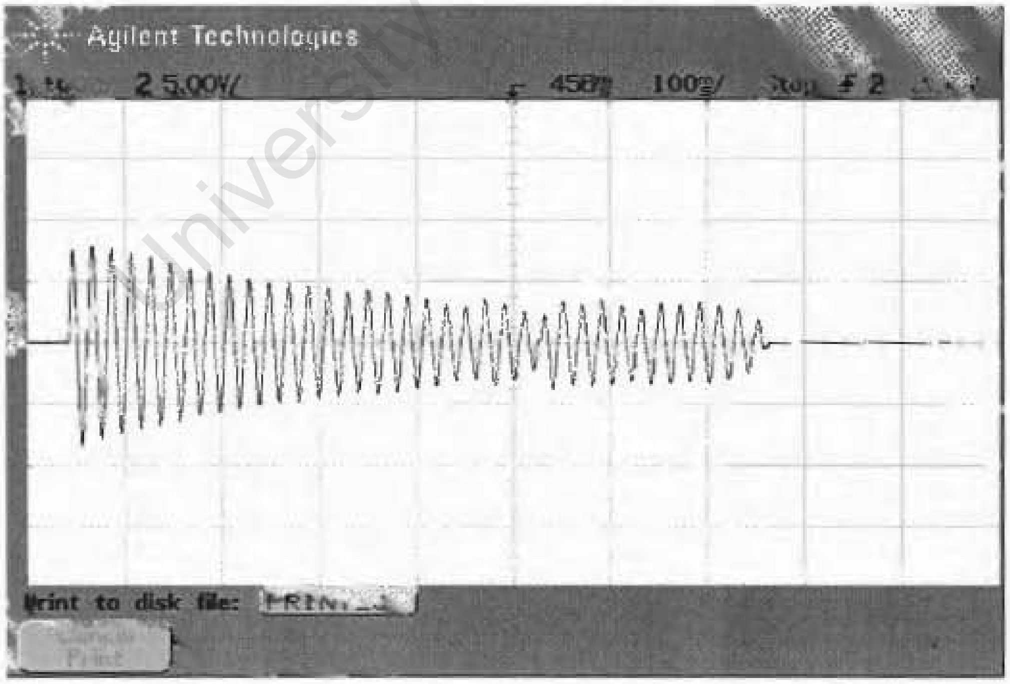

Fig 4: Arc current trace of test 2

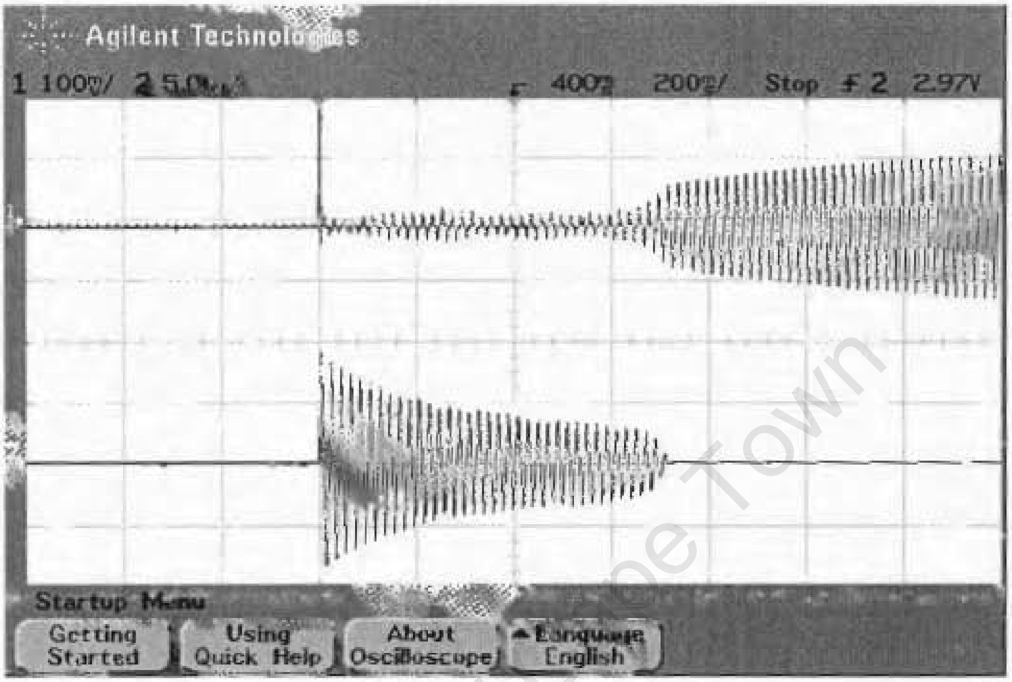

Fig 5:Arc voltage (upper trace) and arc current (lower trace) of test 3

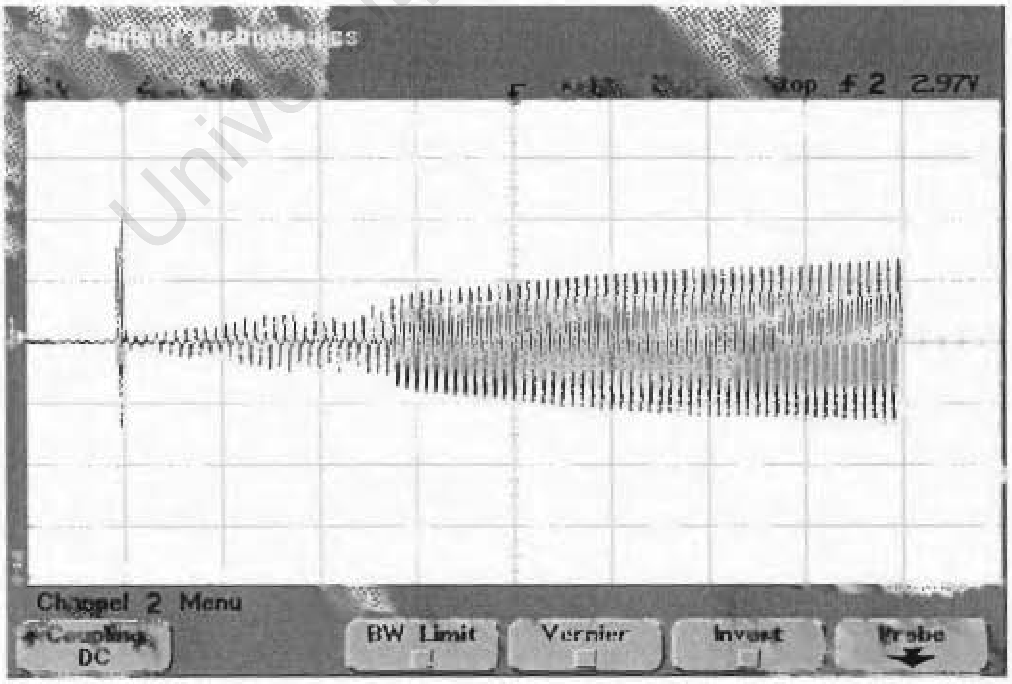

Fig 6: Arc voltage of test 4

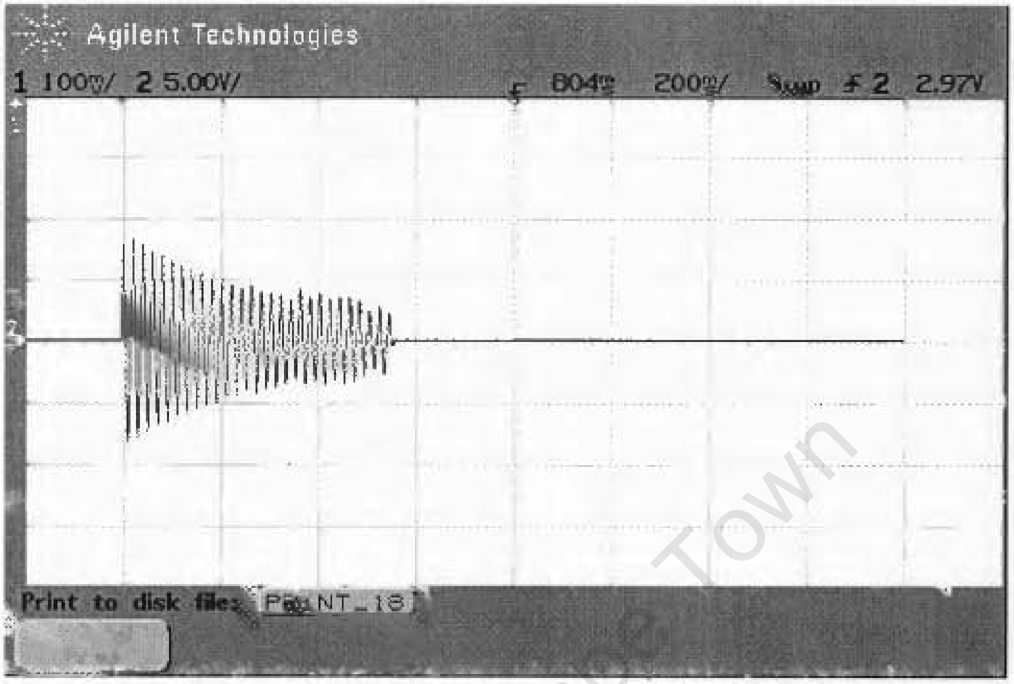

Fig 7: Arc current of test 4

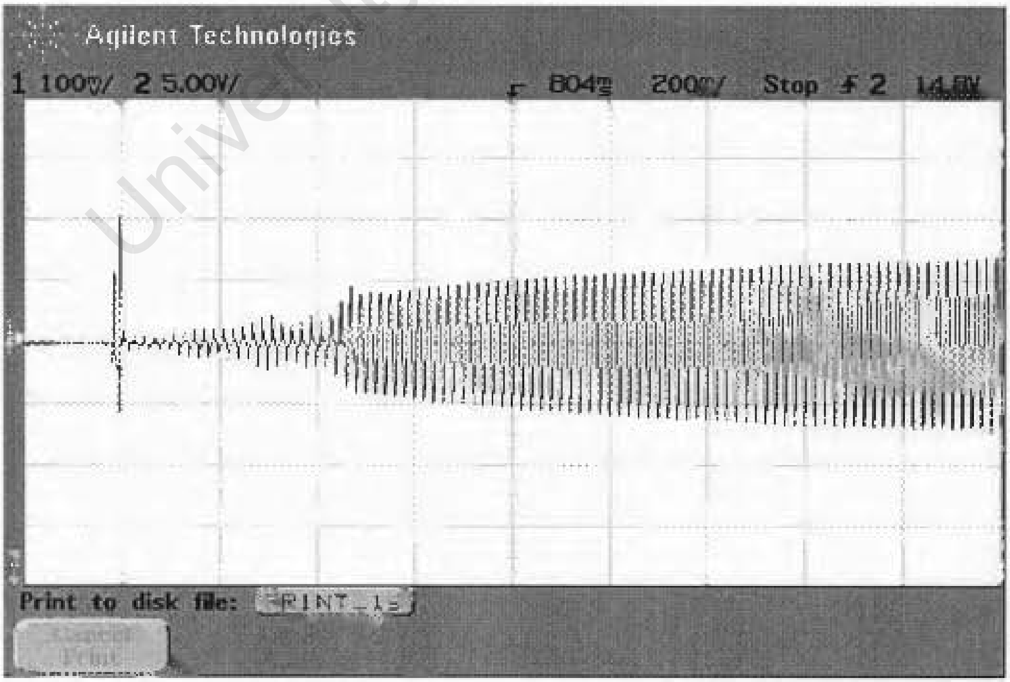

Fig 8: Arc voltage of test 5

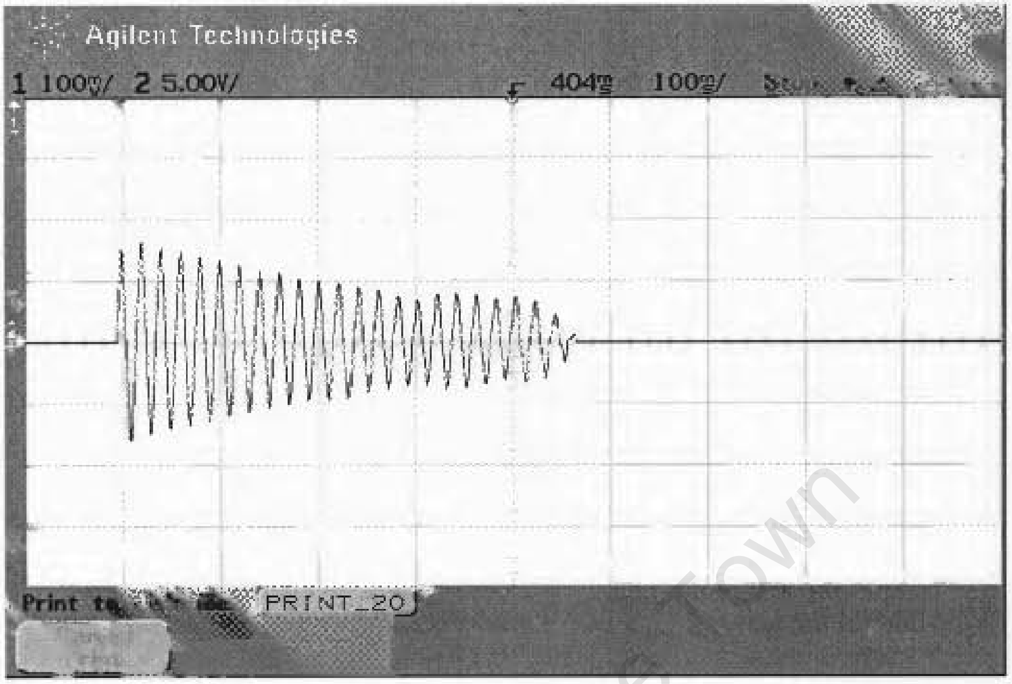

Fig 9: Arc current of test 5

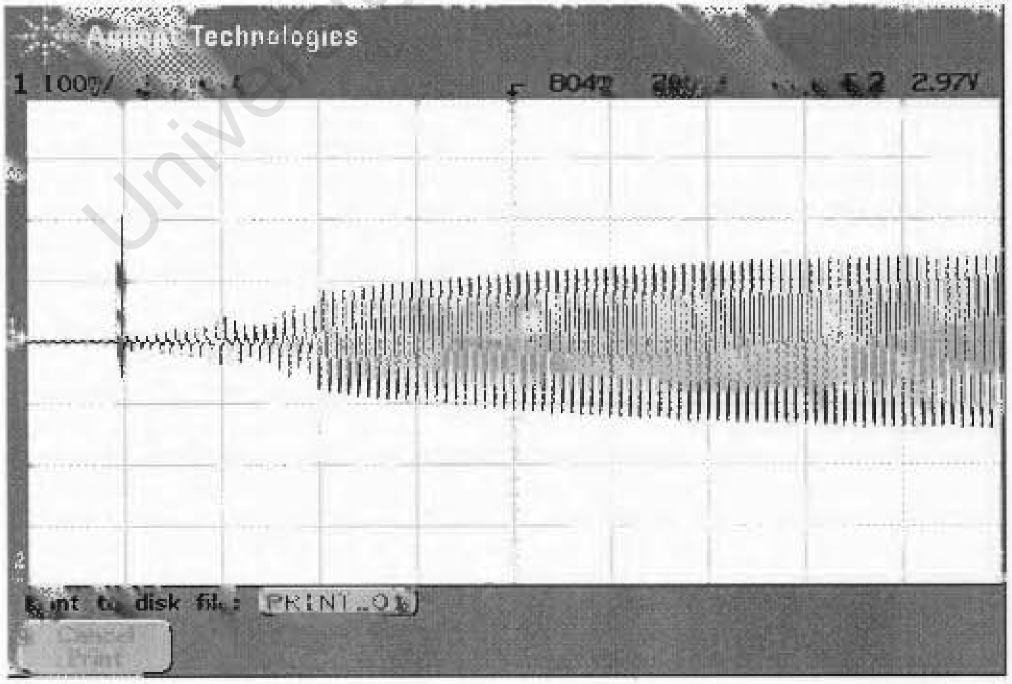

Fig 10: Arc voltage of test 6

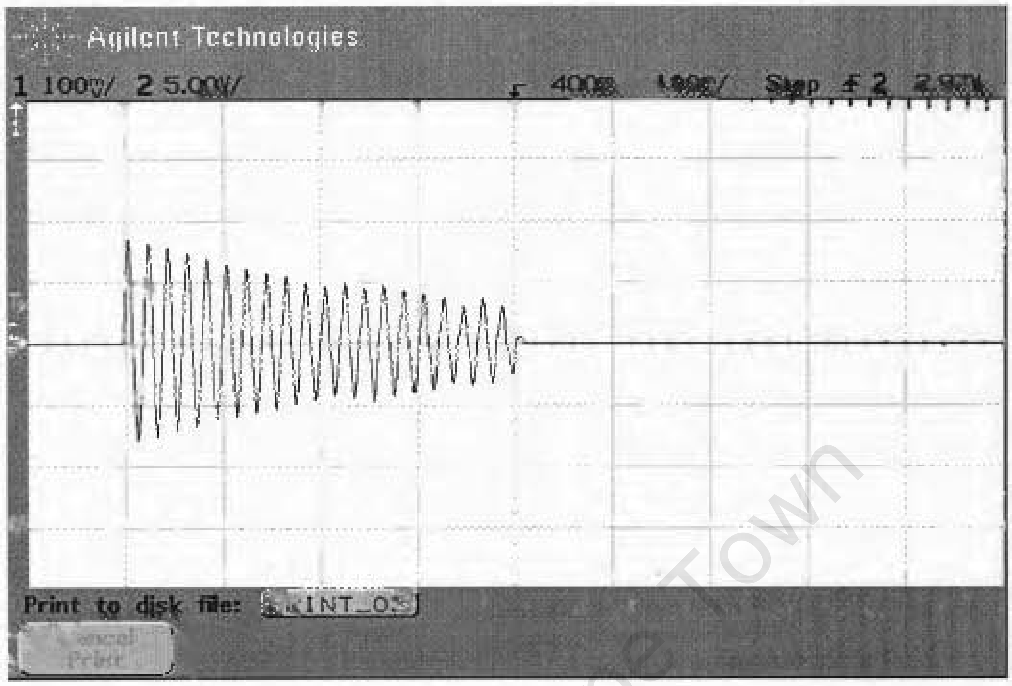

Fig 11: Arc current of test 6

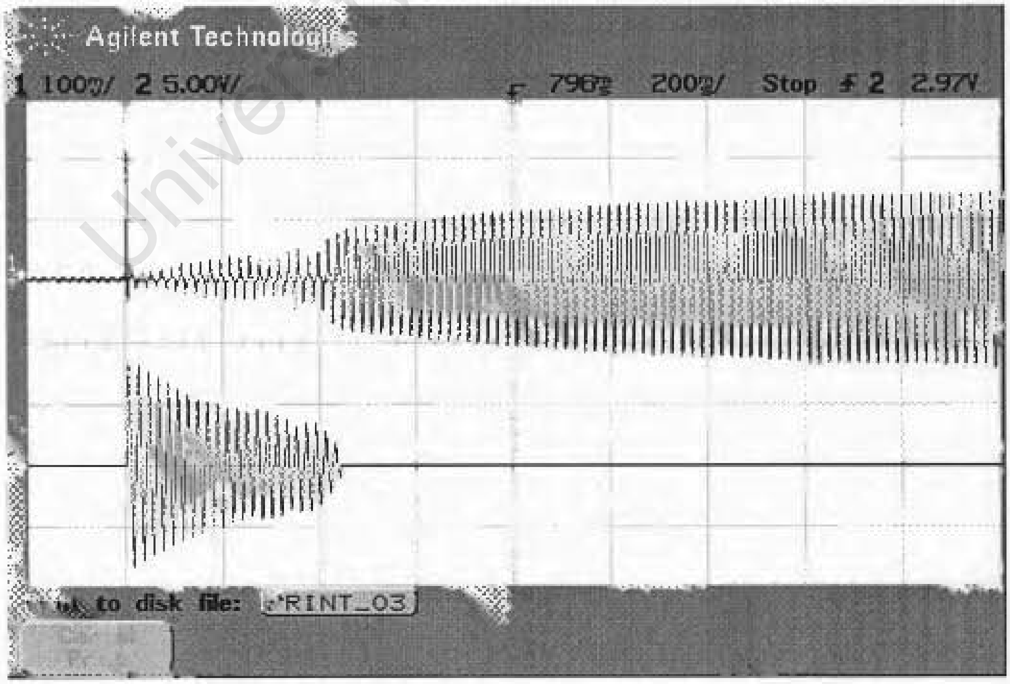

Fig 12: Arc voltage (upper trace) and arc current (lower trace) of test 7

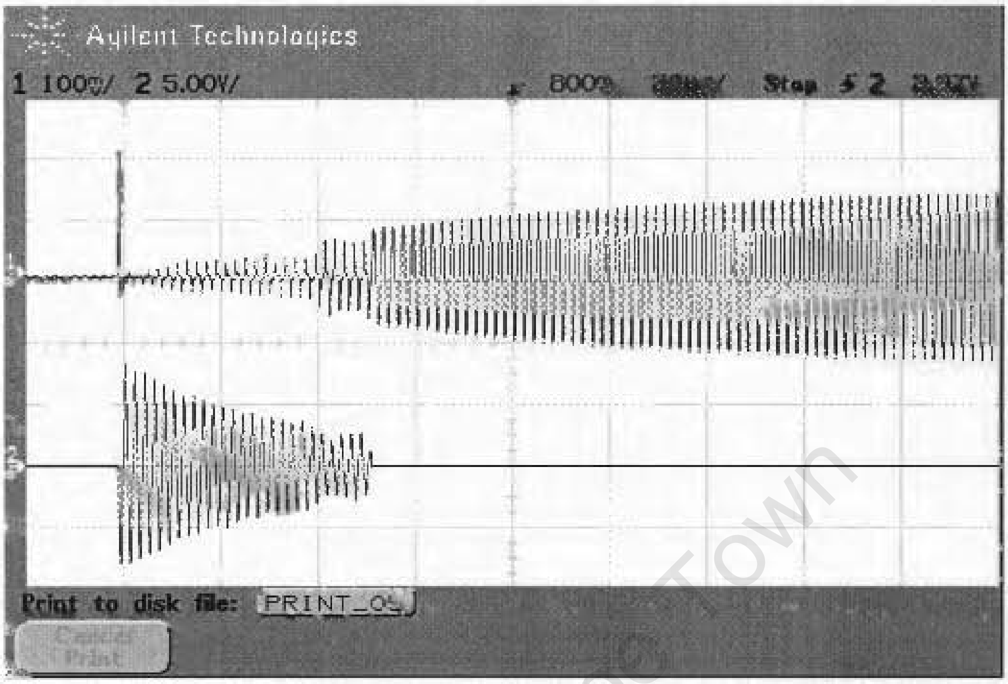

Fig 13: Arc voltage (upper trace) and arc current (lower trace) of test 8

D2: Arc tests with 8kW load, uncompensated (added reactors were connected), tests 1 – 5: arc gap of 33cm, tests 6 – 10: arc gap 45cm

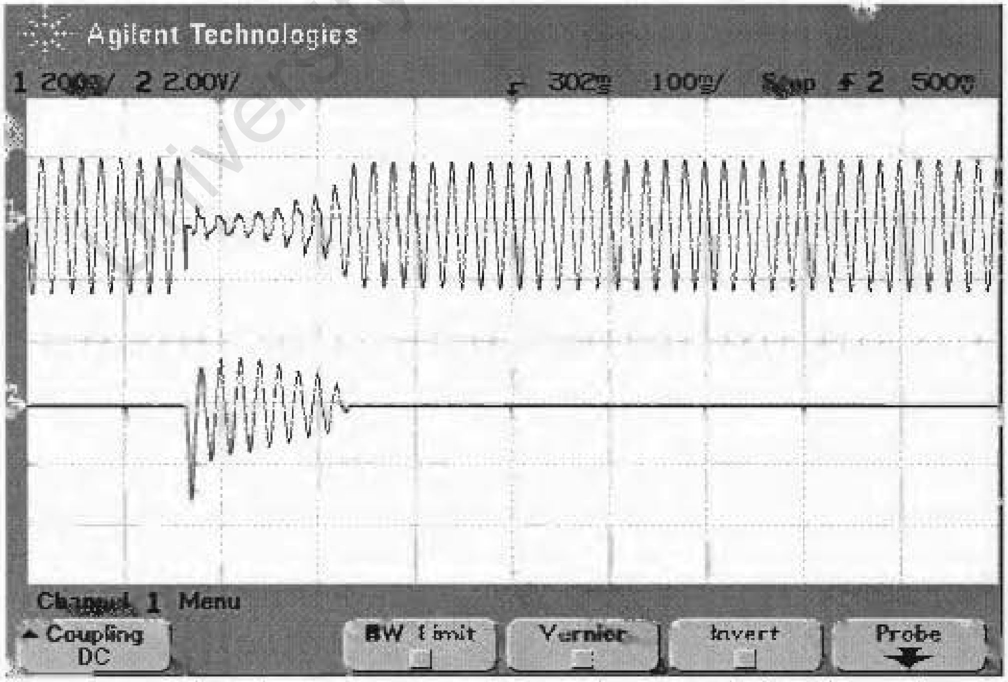

Fig 14: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

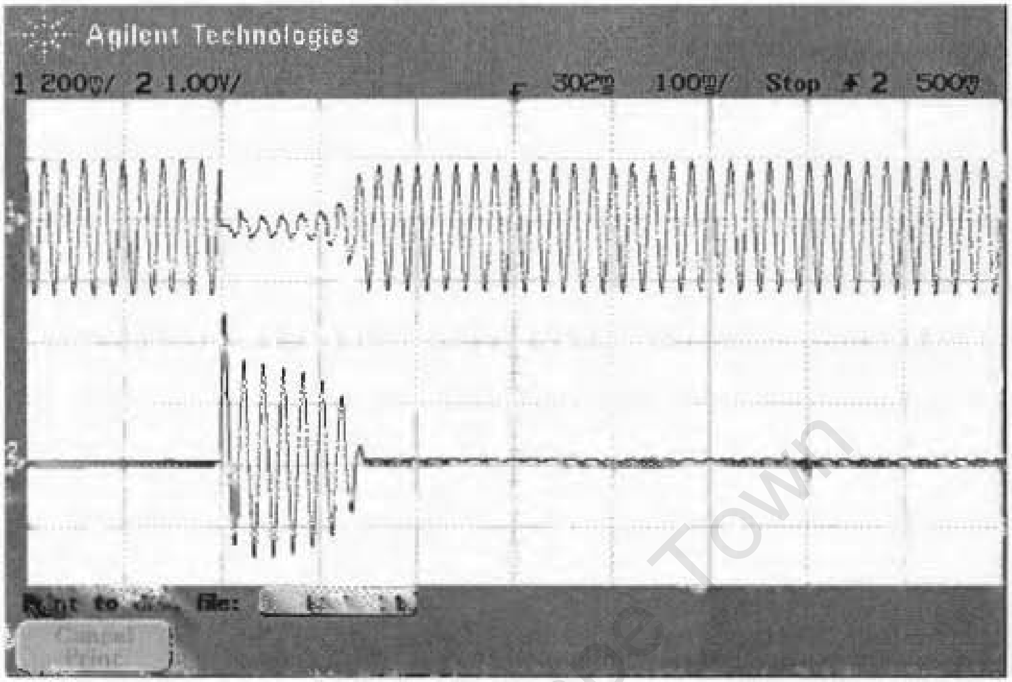

Fig 15: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

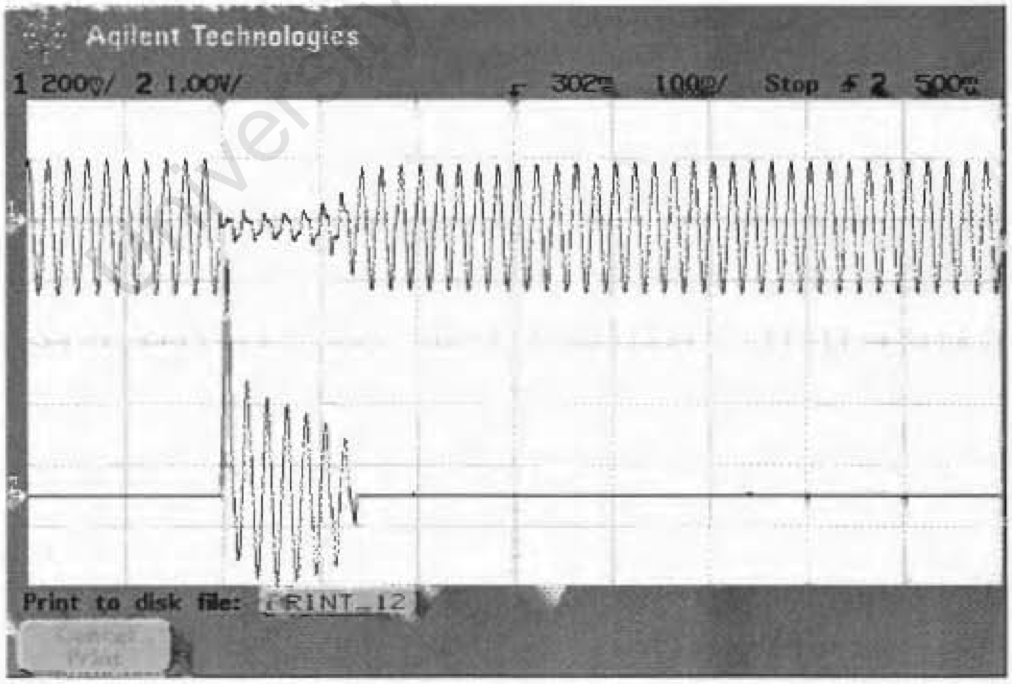

Fig 16: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 33cm

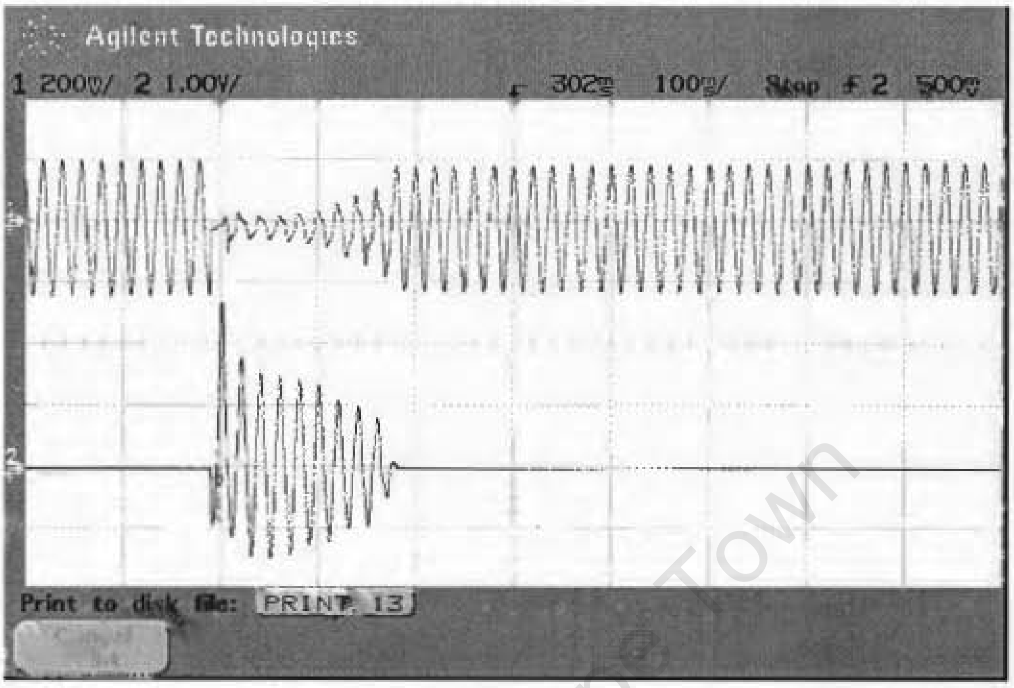

Fig 17: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 33cm

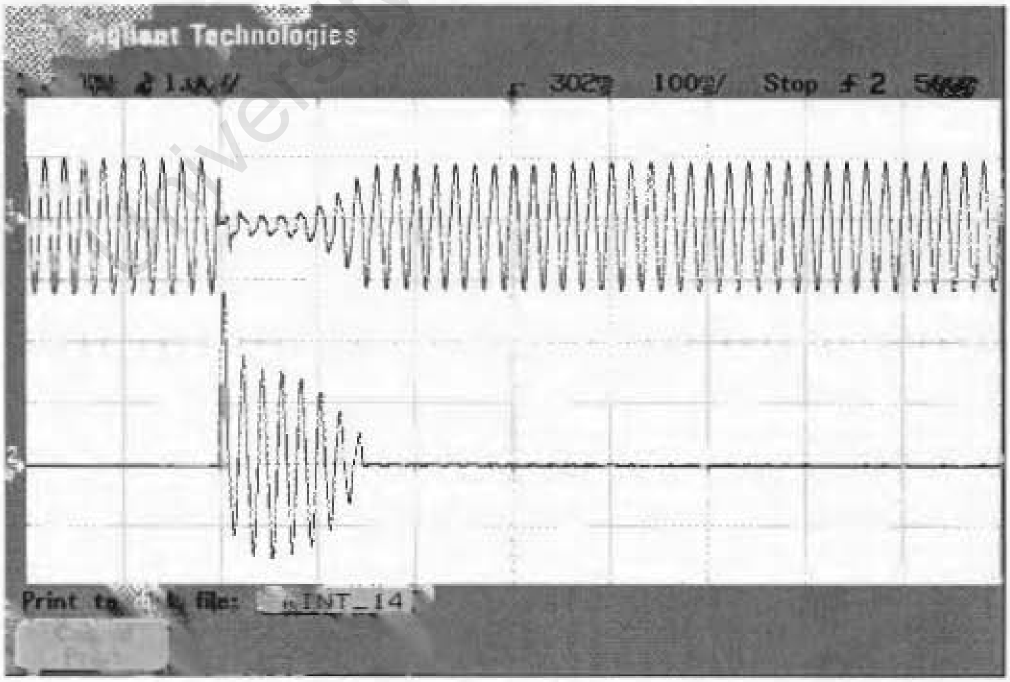

Fig 18: Load voltage (upper trace) and arc current (lower trace) of test 5; gap of 33cm

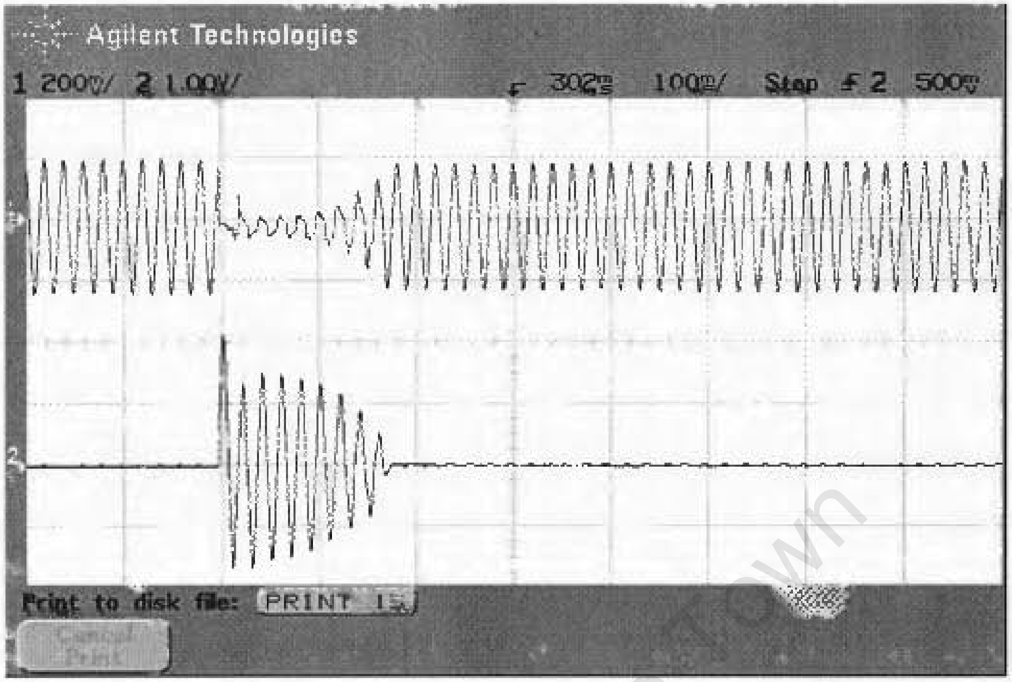

Fig 19: Load voltage (upper trace) and arc current (lower trace) of test 6; gap of 45cm

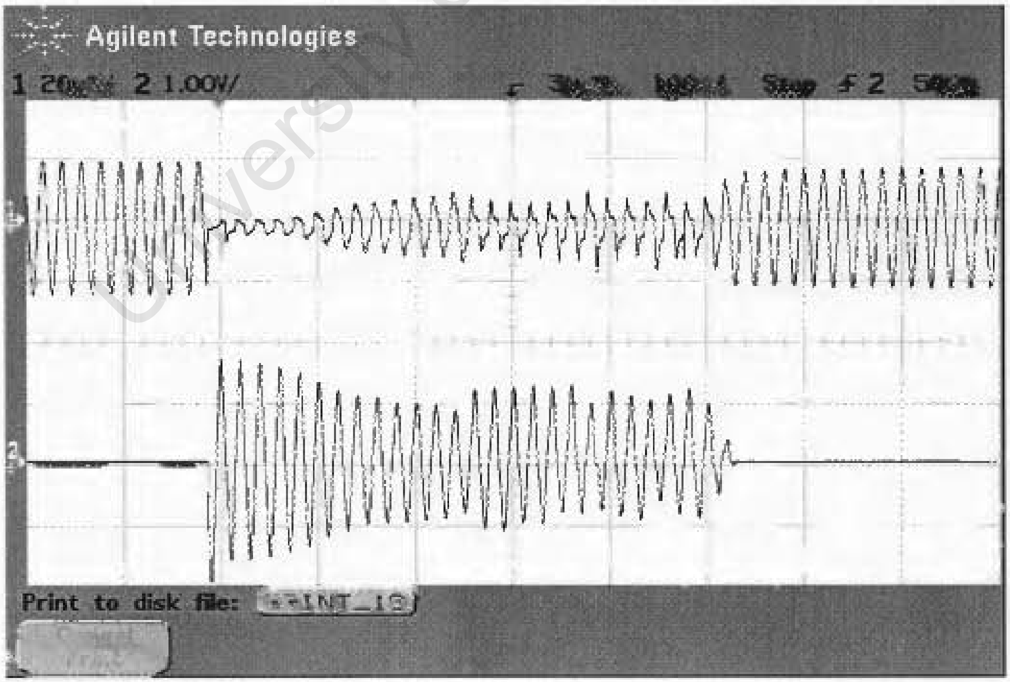

Fig 20: Load voltage (upper trace) and arc current (lower trace) of test 7; gap of 45cm

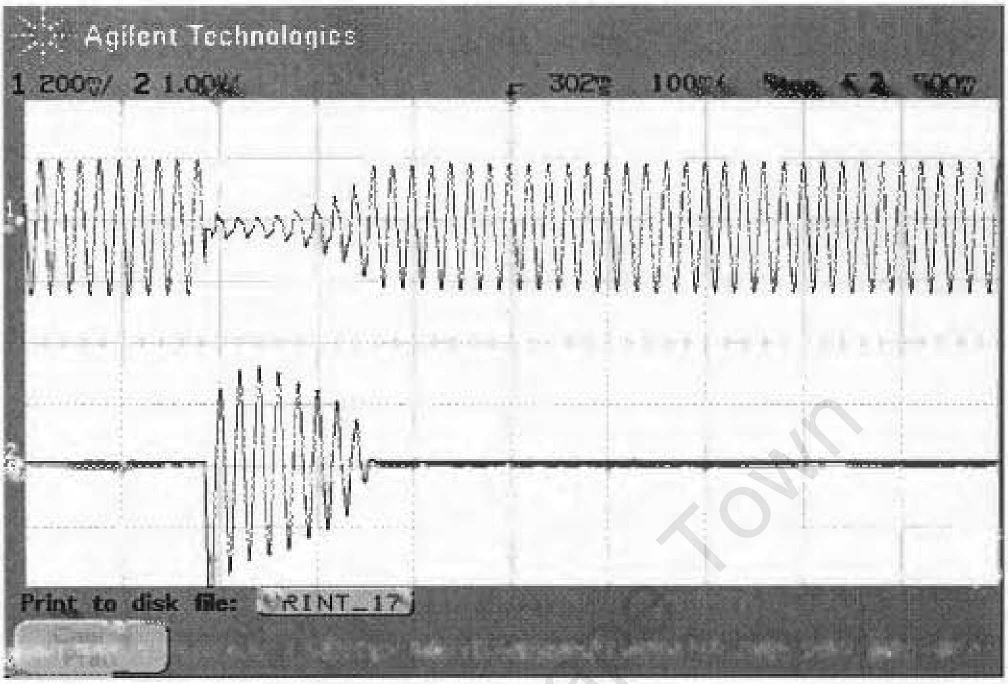

Fig 21: Load voltage (upper trace) and arc current (lower trace) of test 8; gap of 45cm

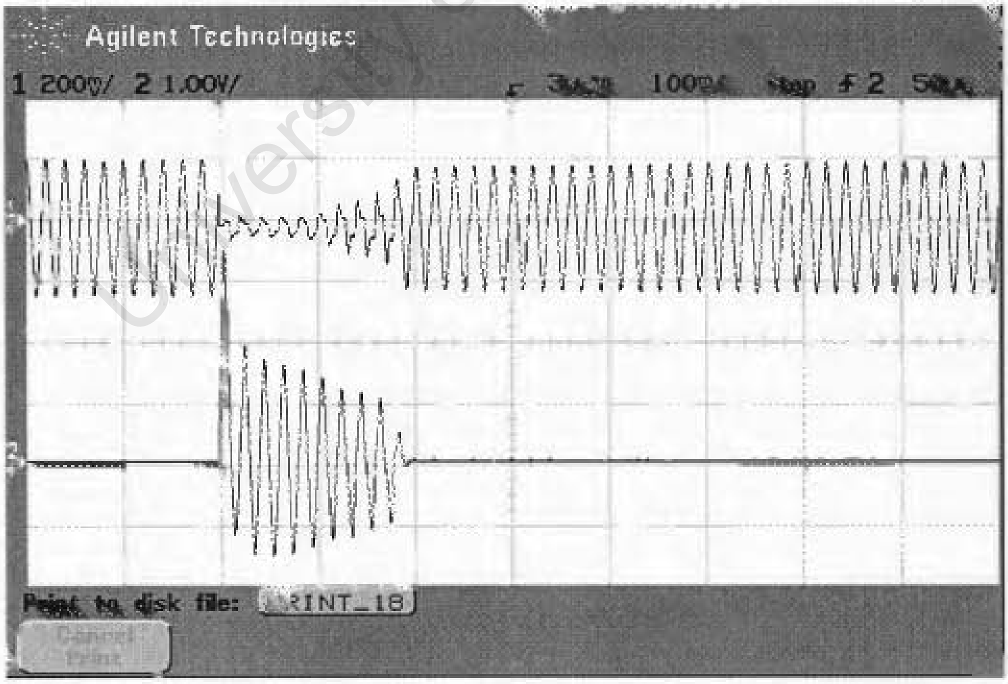

Fig 22: Load voltage (upper trace) and arc current (lower trace) of test 9; gap of 45cm

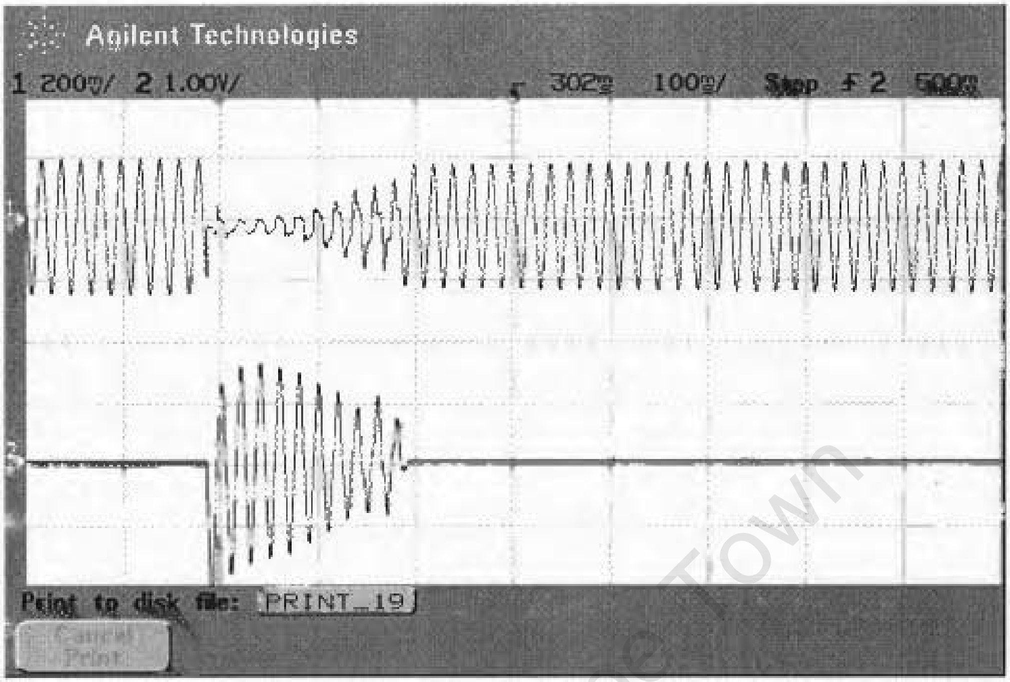

Fig 23: Load voltage (upper trace) and arc current (lower trace) of test 10; gap of 45cm

D3: Arc tests with 8kW load, compensated, tests 1 – 5: arc gap of 33cm; tests 6 – 9: arc gap of 45cm

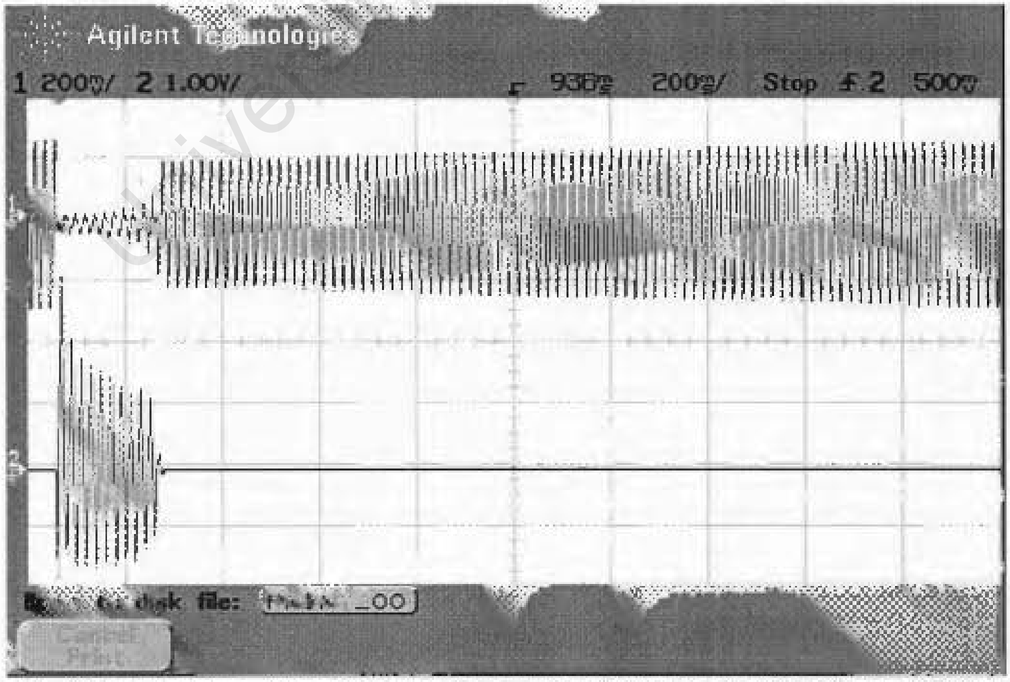

Fig 24: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

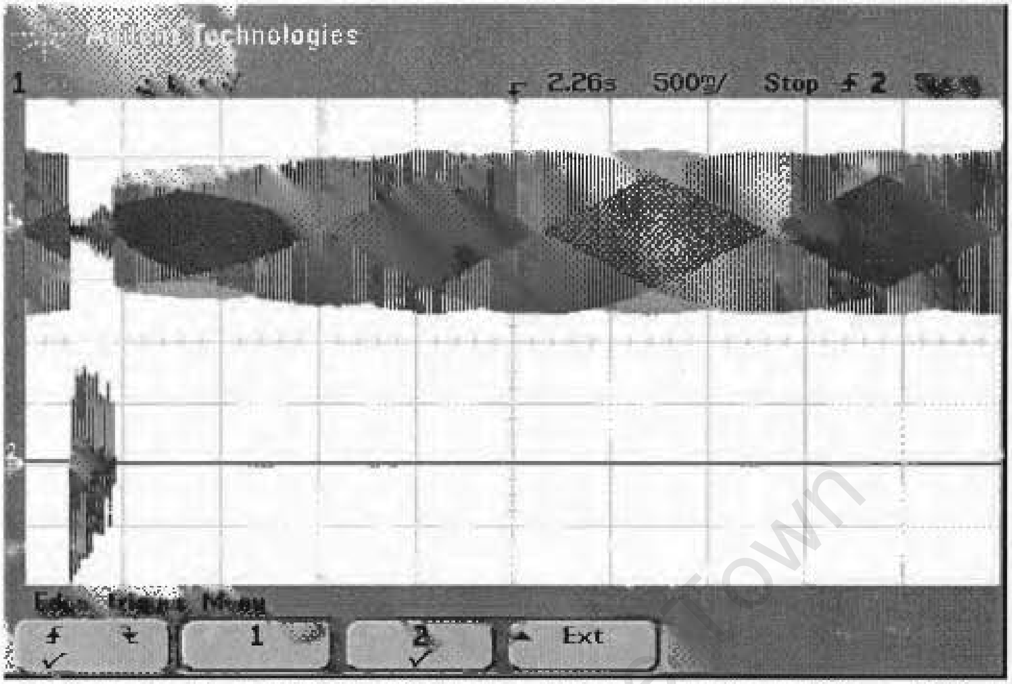

Fig 25: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

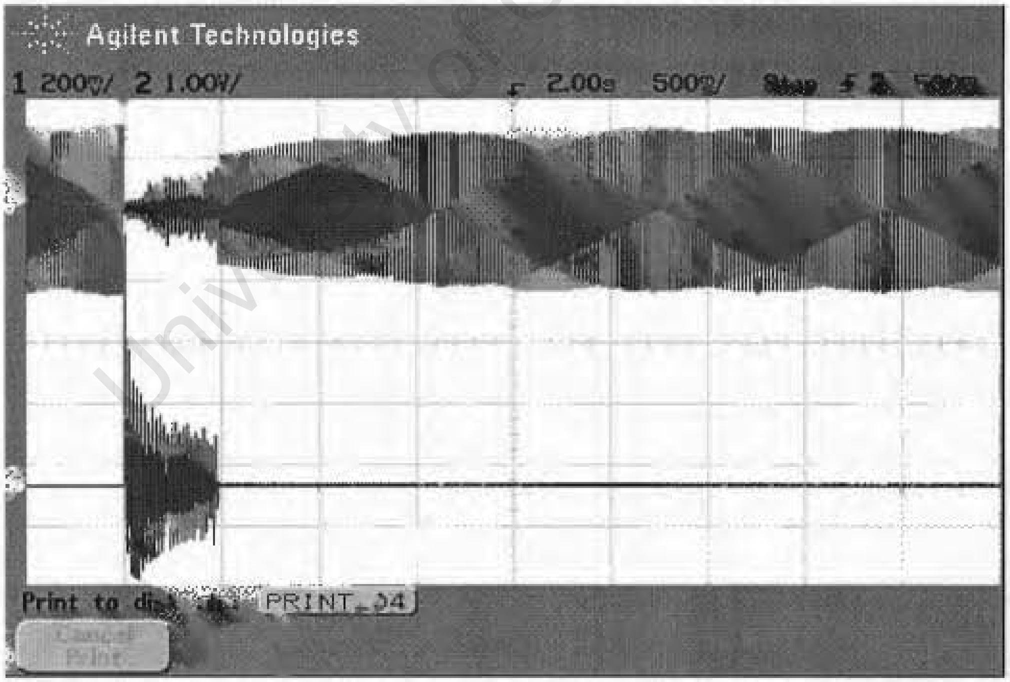

Fig 26: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 33cm

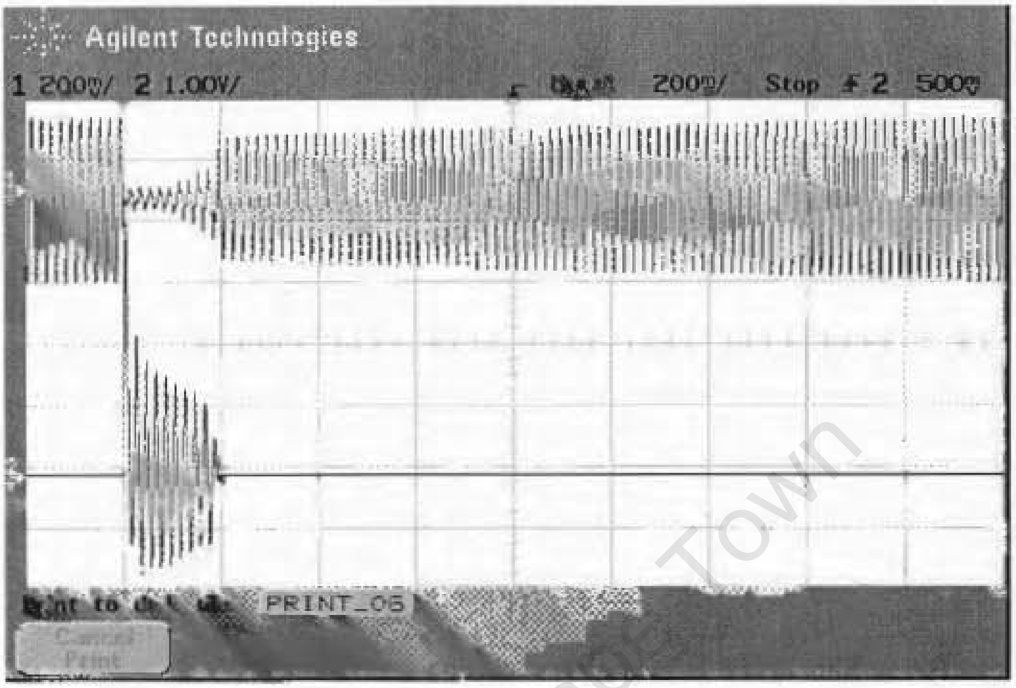

Fig 27. Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 33cm

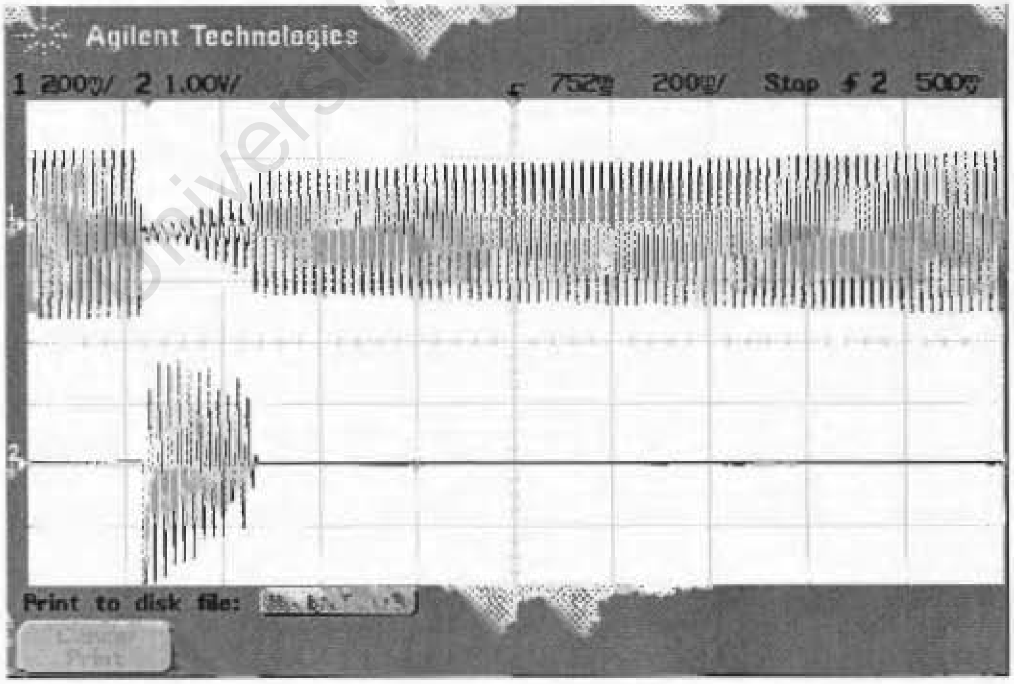

Fig 28: Load voltage (upper trace) and arc current (lower trace) of test 5; gap of 33cm

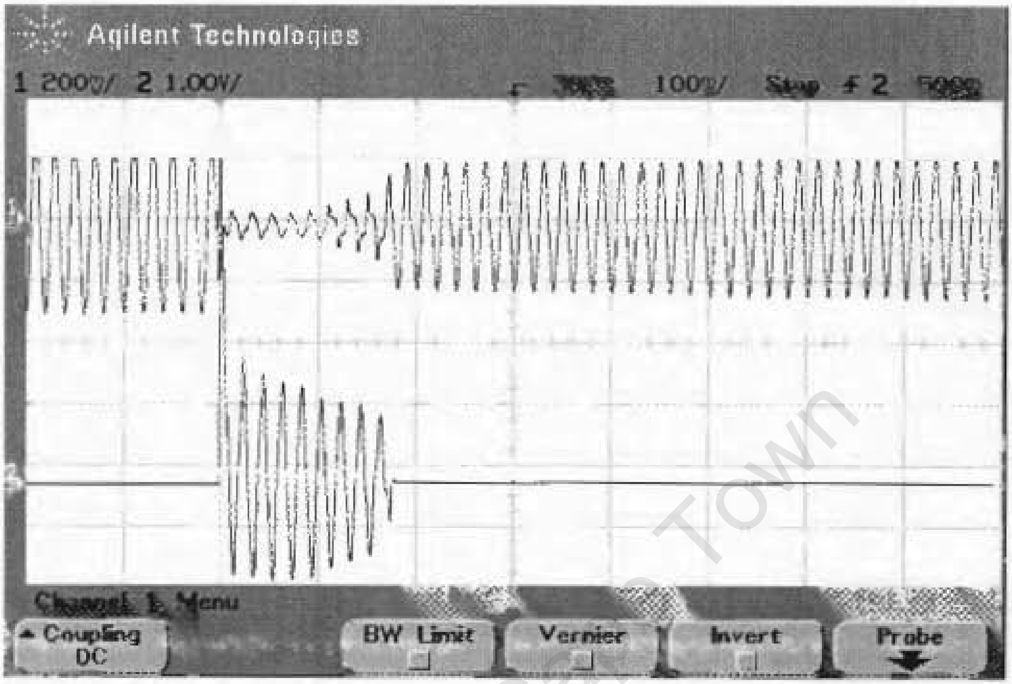

Fig 29: Load voltage (upper trace) and arc current (lower trace) of test 6; gap of 45cm

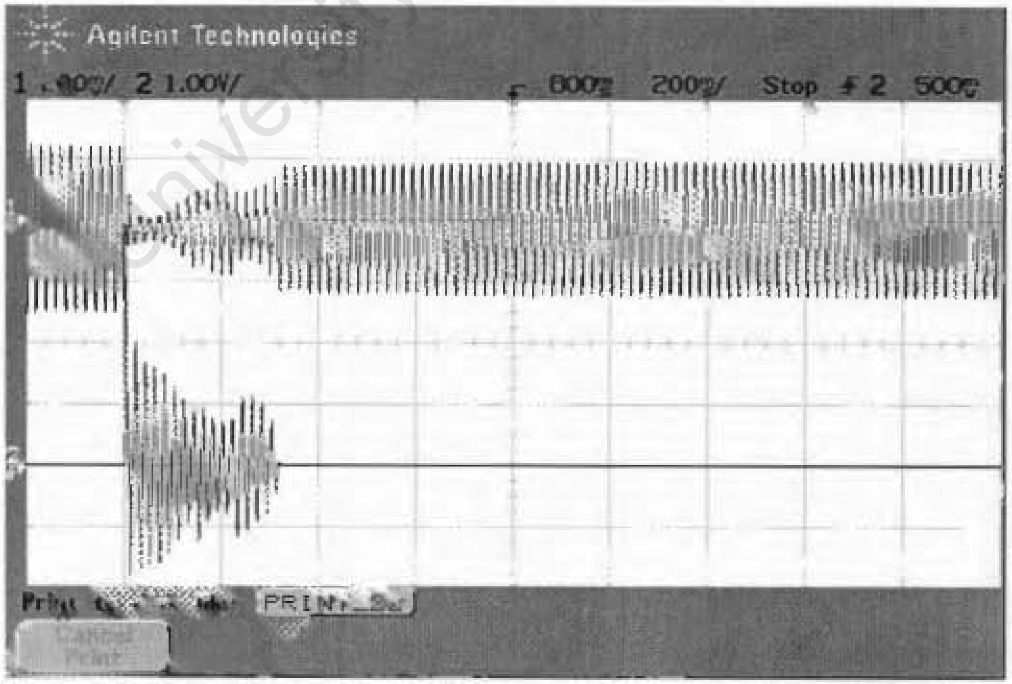

Fig 30: Load voltage (upper trace) and arc current (lower trace) of test 7; gap of 45cm

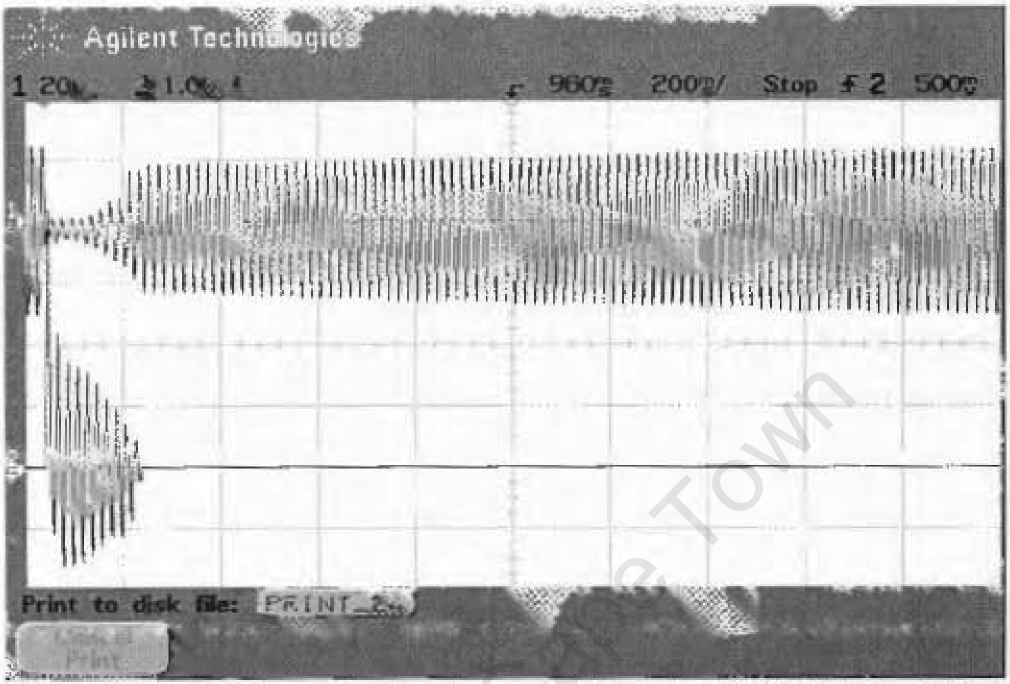

Fig 31: Load voltage (upper trace) and arc current (lower trace) of test 8; gap of 45cm

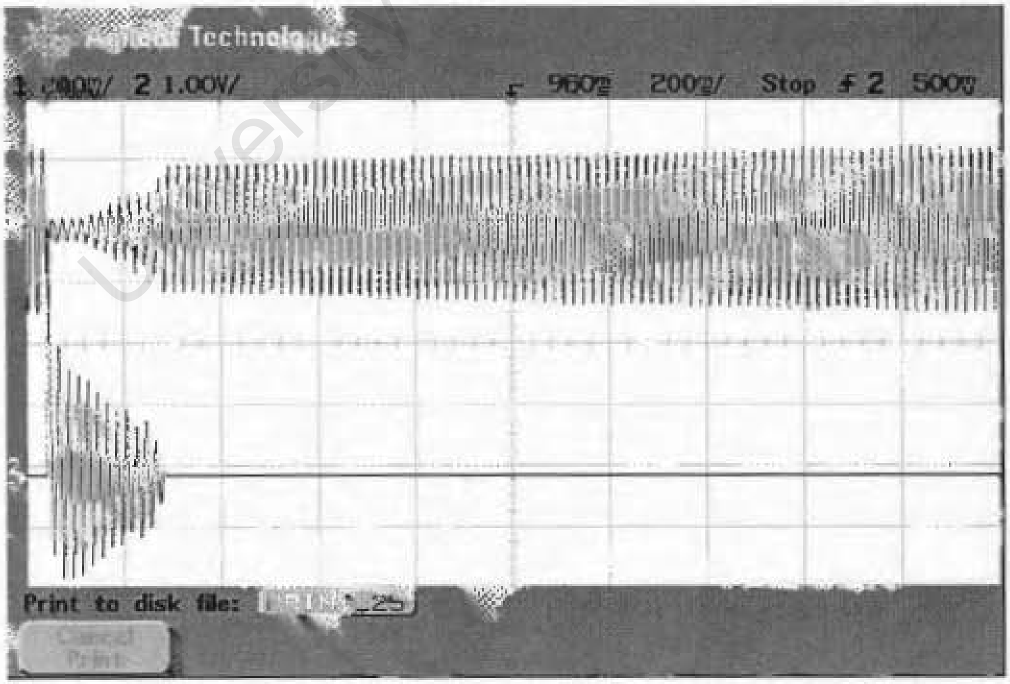

Fig 32: Load voltage (upper trace) and arc current (lower trace) of test 9; gap of 45cm

D4: Arc tests with 4kW load, uncompensated, added reactors connected in; tests 1 & 2: arc gap of 33cm; tests 3 & 4: arc gap of 45cm

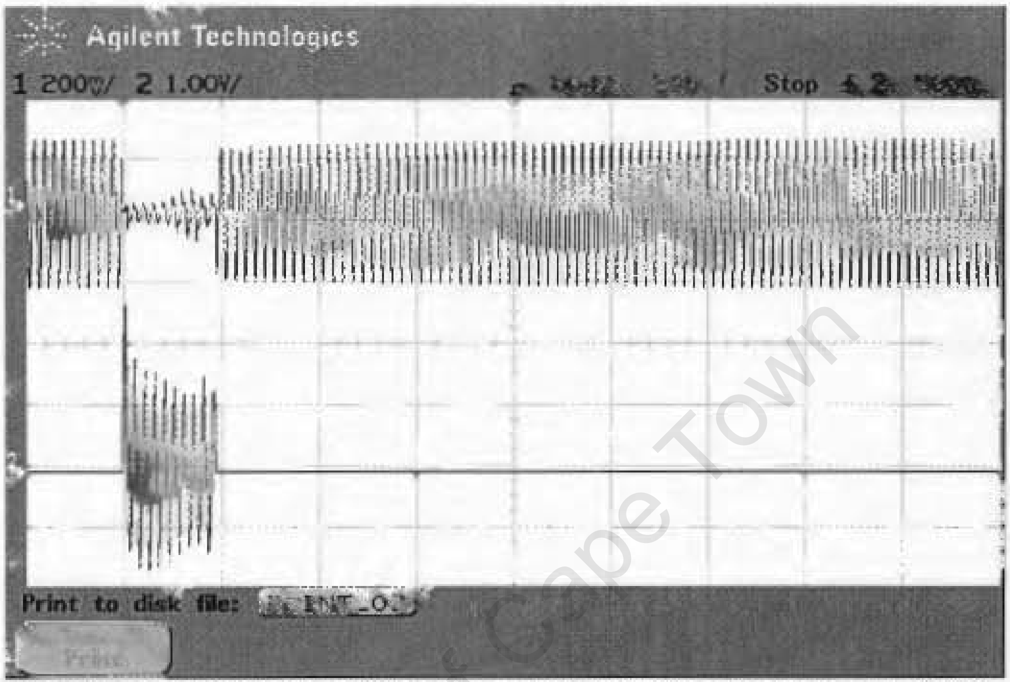

Fig 33: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

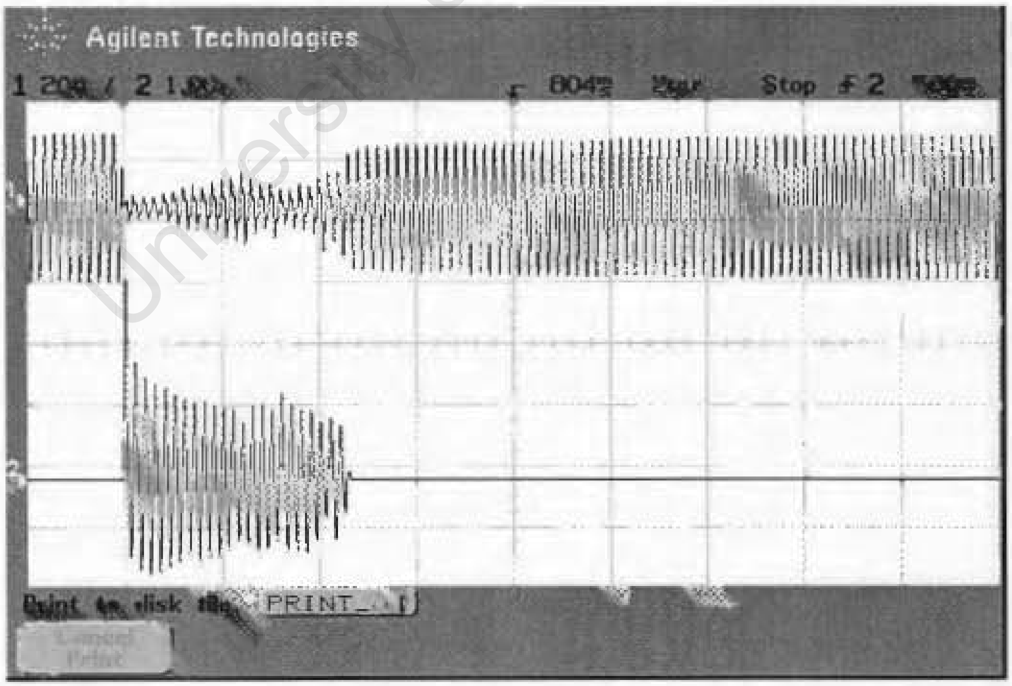

Fig 34: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

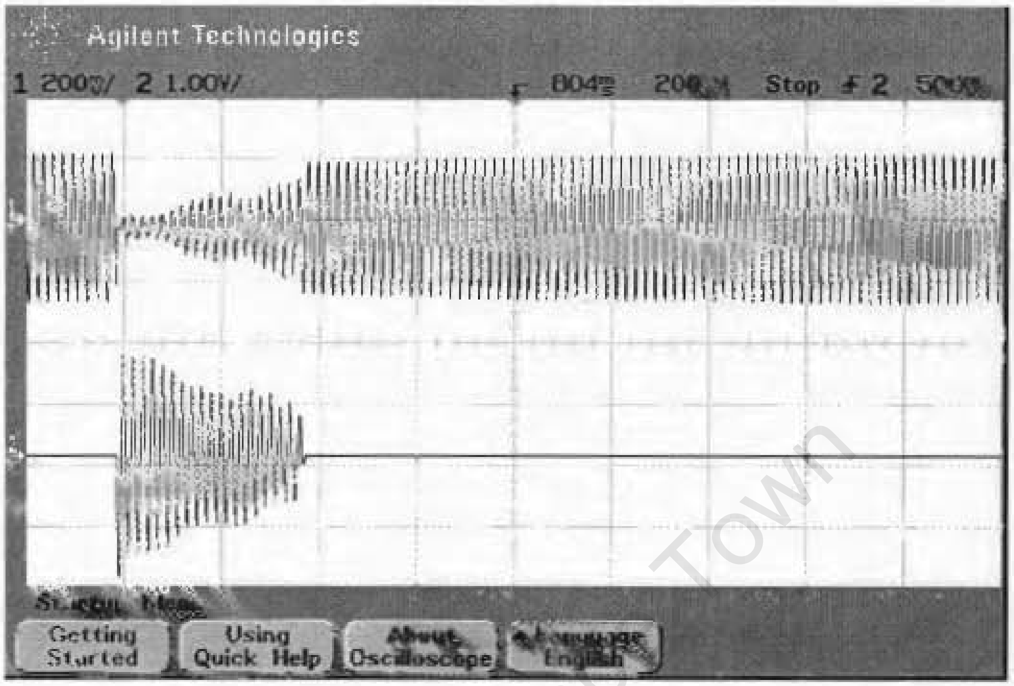

Fig 35: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 45cm

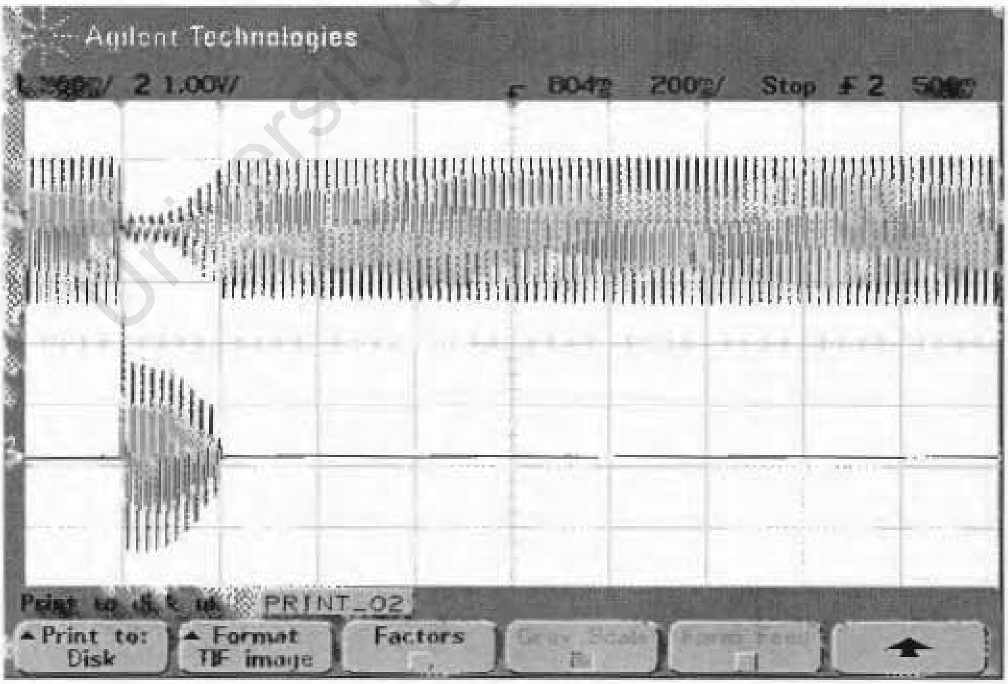

Fig 36: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 45cm

D5: Arc tests with 4kW load, compensated, tests 1 - 4: arc gap of 33cm; tests 5 - 9: arc gap of 45cm

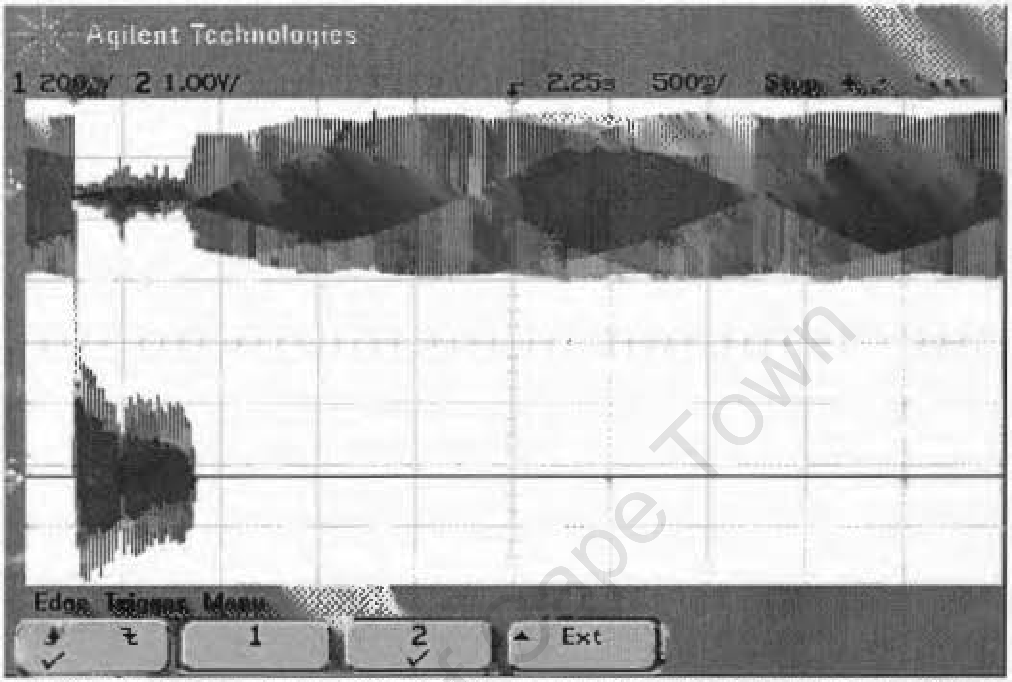

Fig 37: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

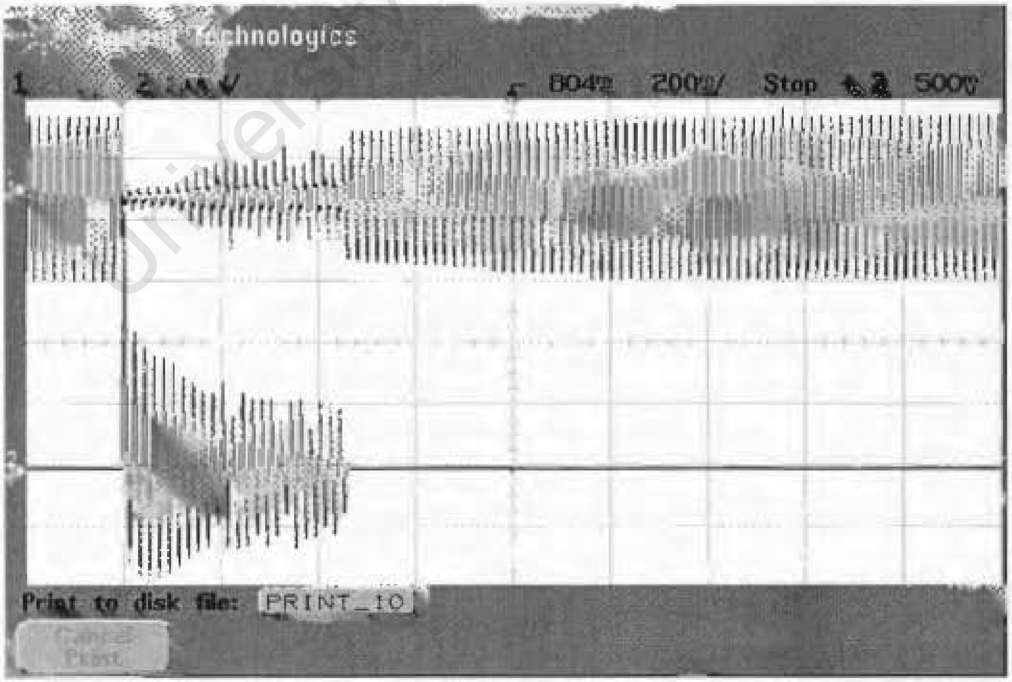

Fig 38: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

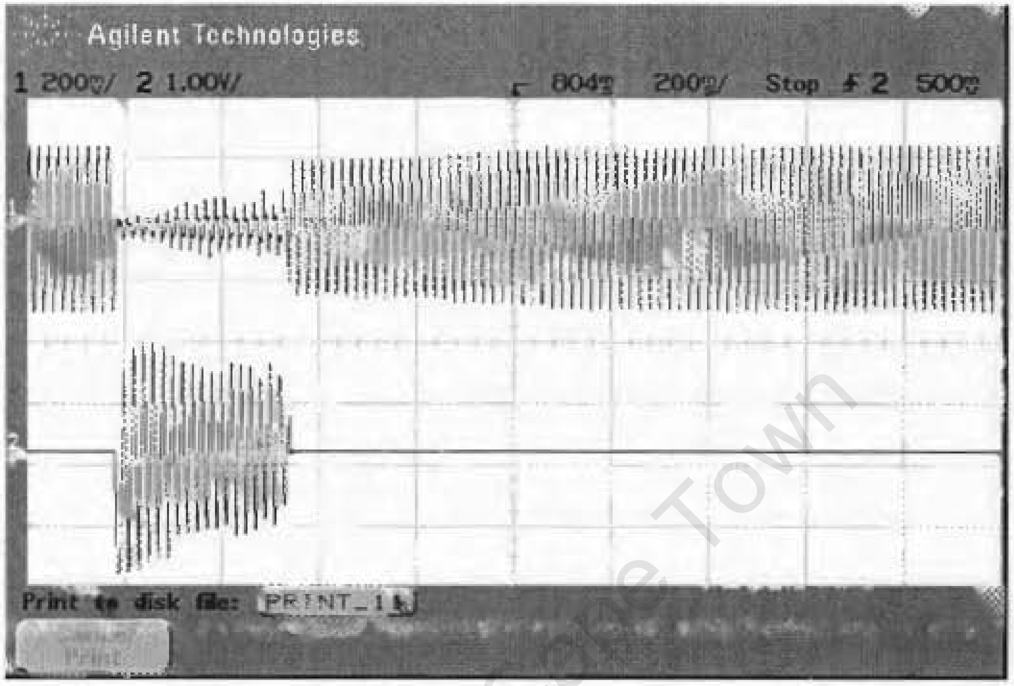

Fig 39: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 33cm

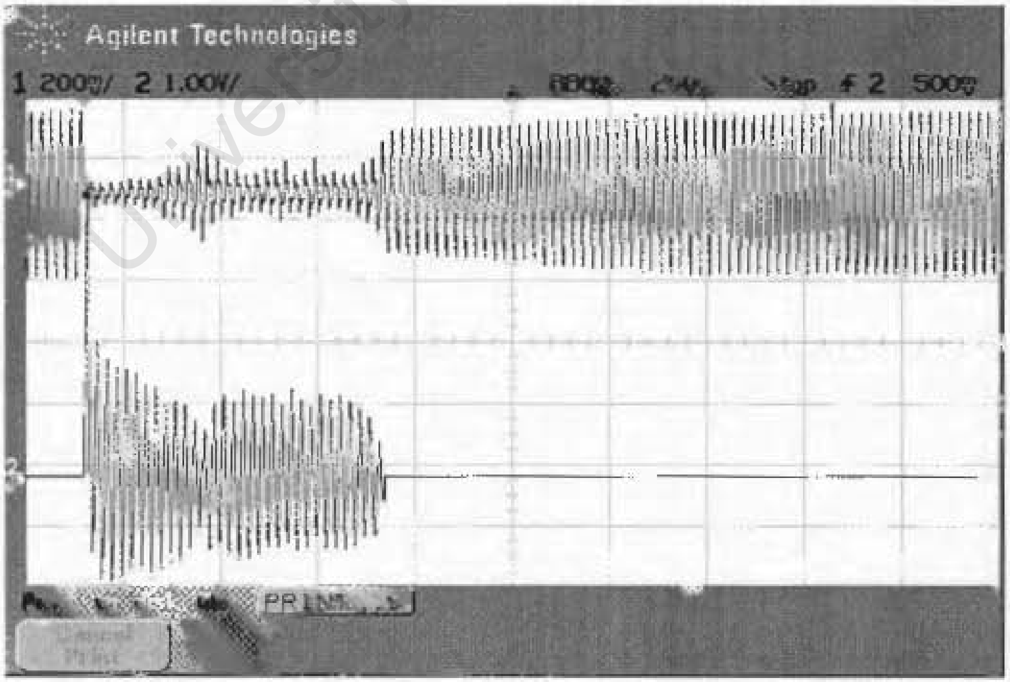

Fig 40: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 33cm

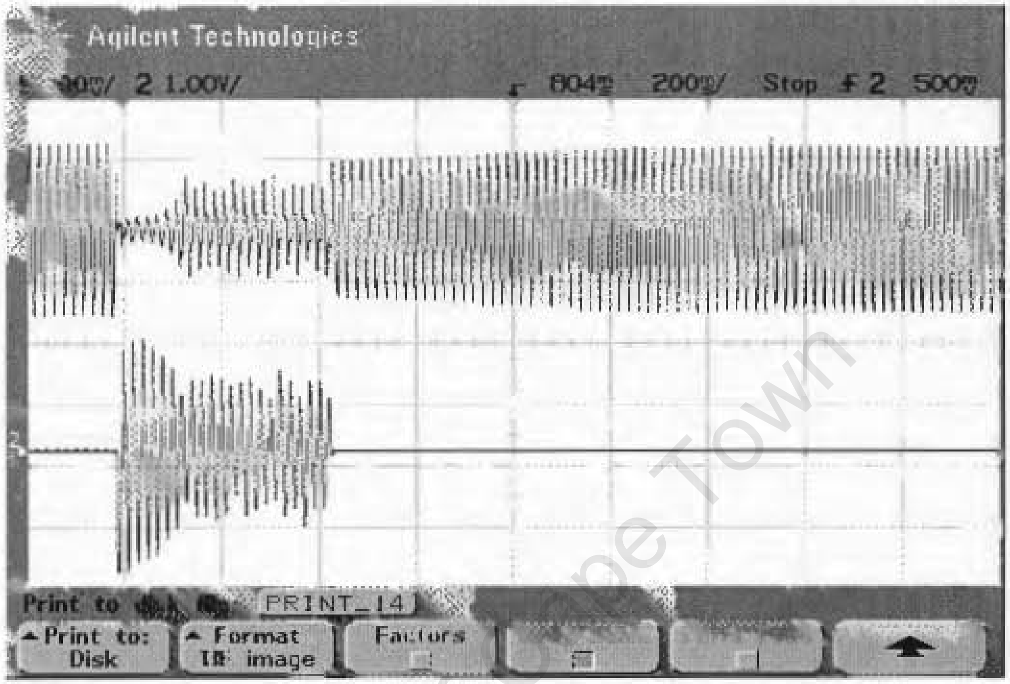

Fig 41: Load voltage (upper trace) and arc current (lower trace) of test 5; gap of 45cm

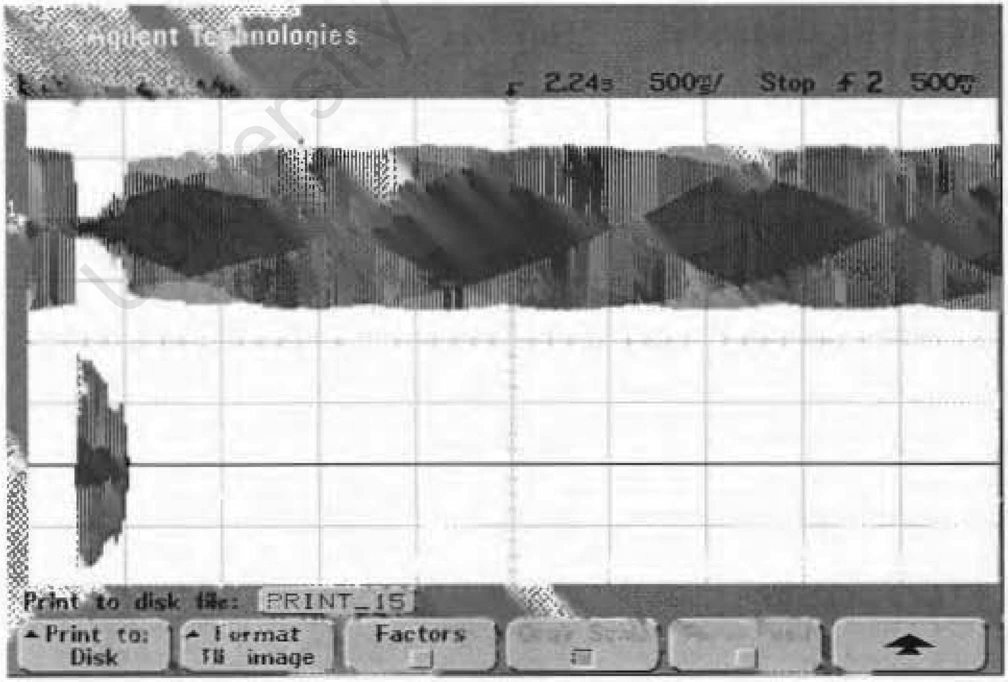

Fig 42: Load voltage (upper trace) and arc current (lower trace) of test 6; gap of 45cm

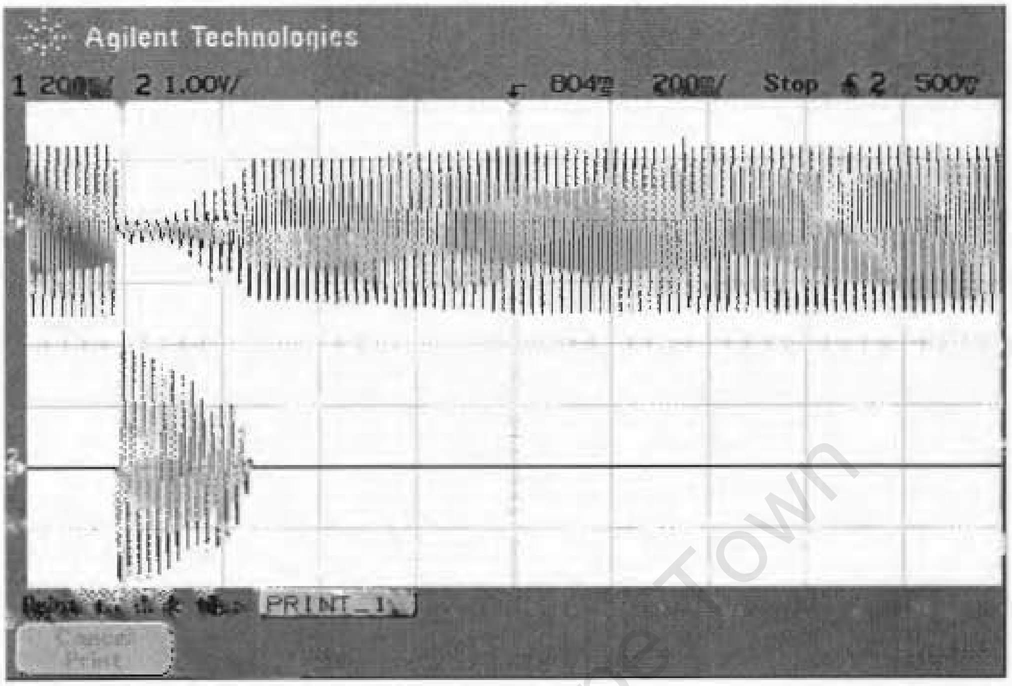

Fig 43: Load voltage (upper trace) and arc current (lower trace) of test 7; gap of 45cm

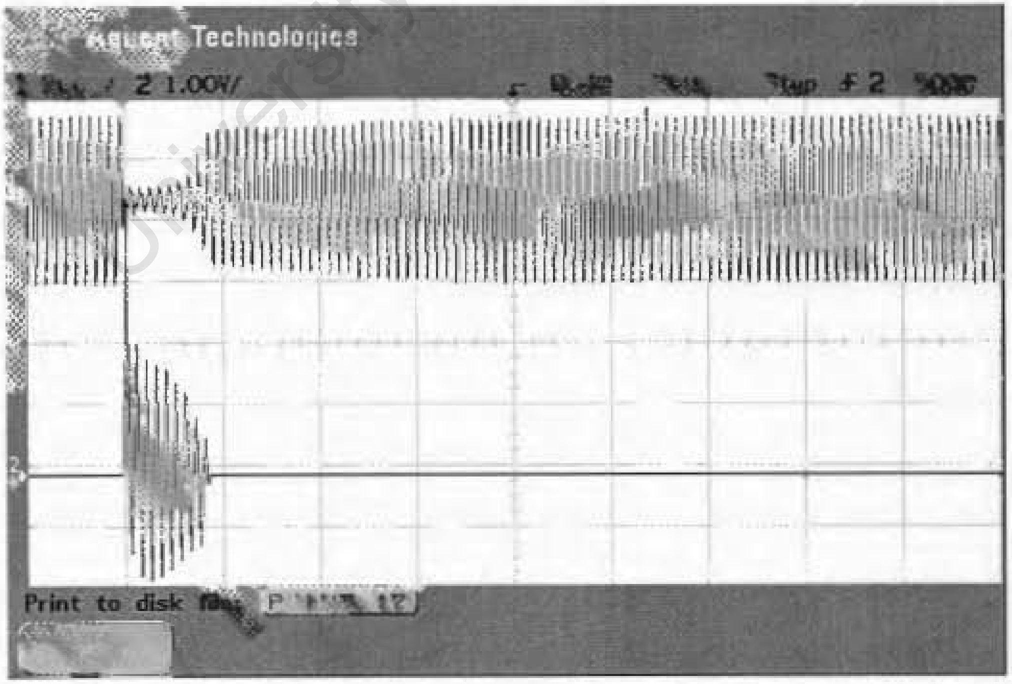

Fig 44: Load voltage (upper trace) and arc current (lower trace) of test 8; gap of 45cm

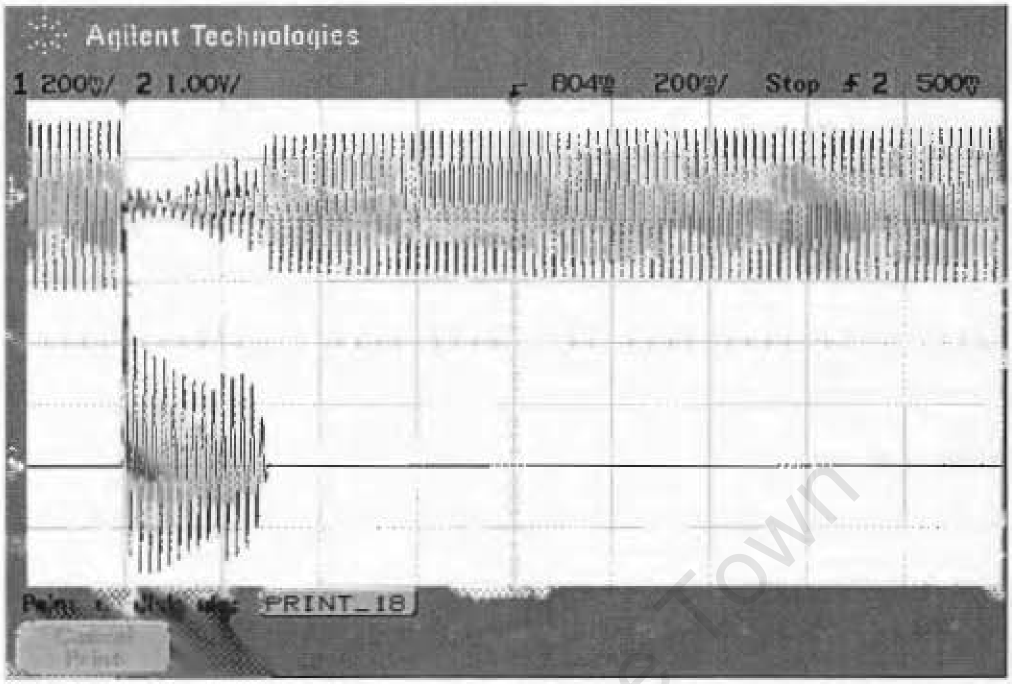

Fig 45: Load voltage (upper trace) and arc current (lower trace) of test 8; gap of 45cm

D6: Arc tests with 8kVA load, pf = 0.87, uncompensated; tests 1 - 2: arc gap of 33cm; tests 3 - 4: arc gap of 45cm

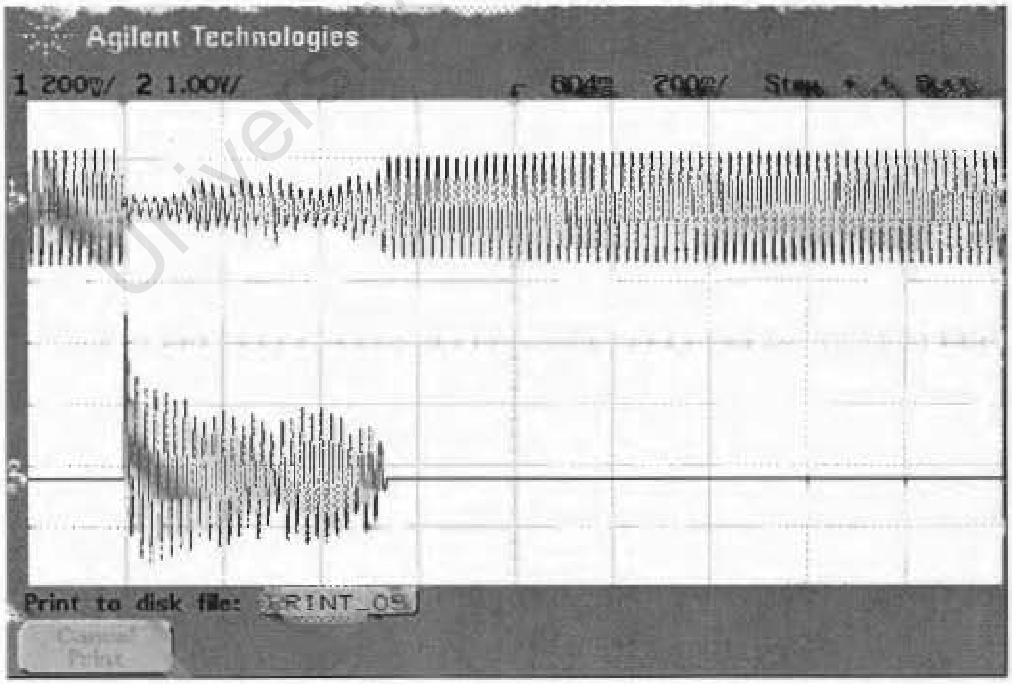

Fig 46: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

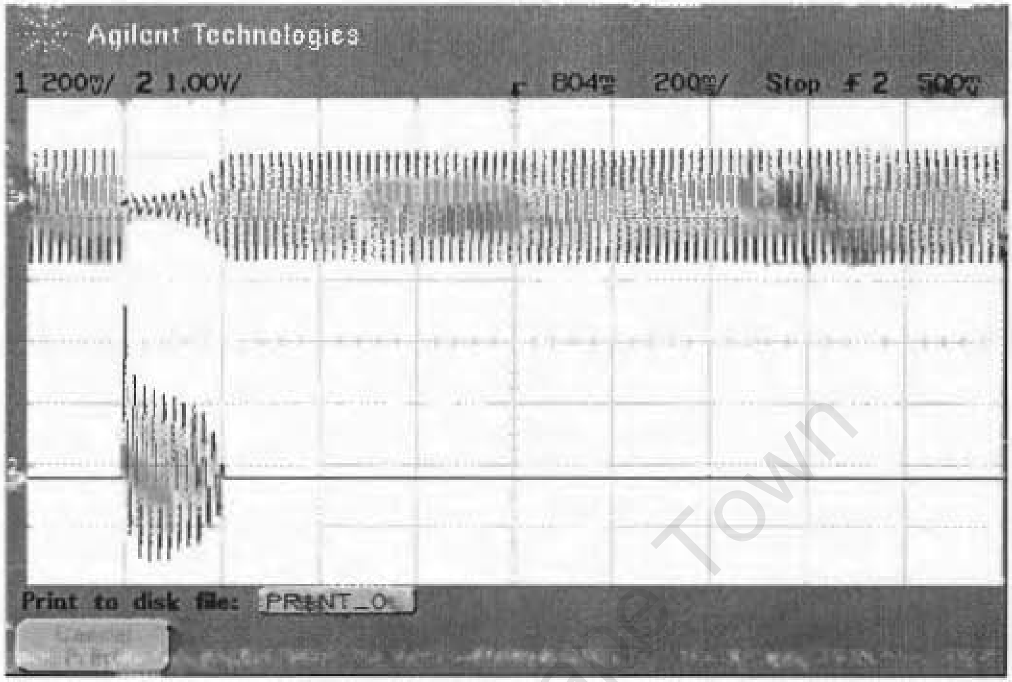

Fig 47: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

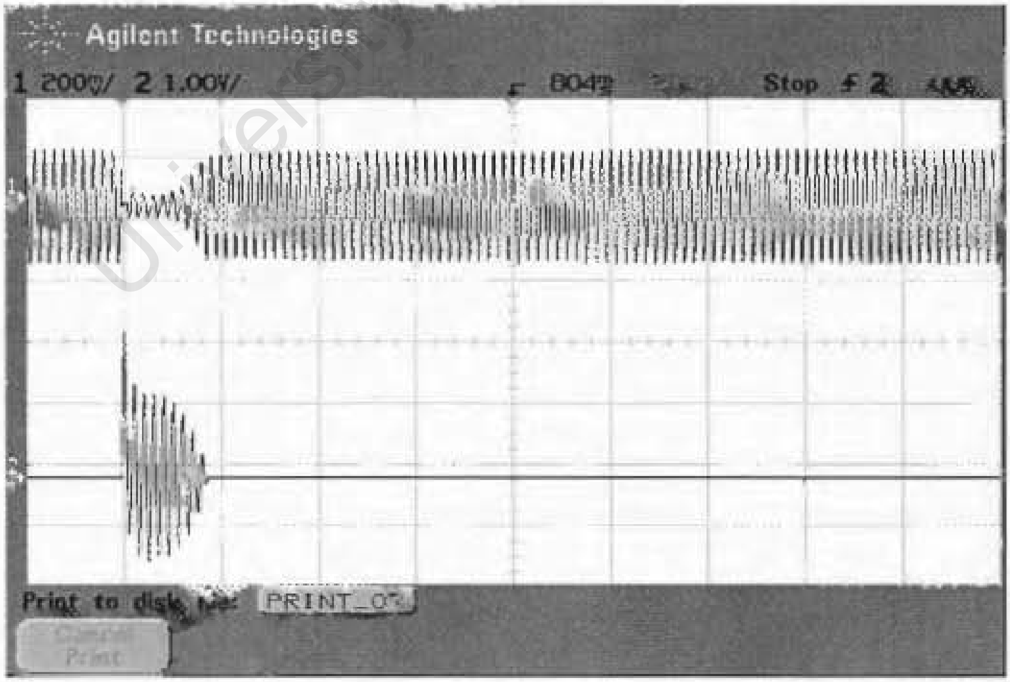

Fig 48: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 45cm

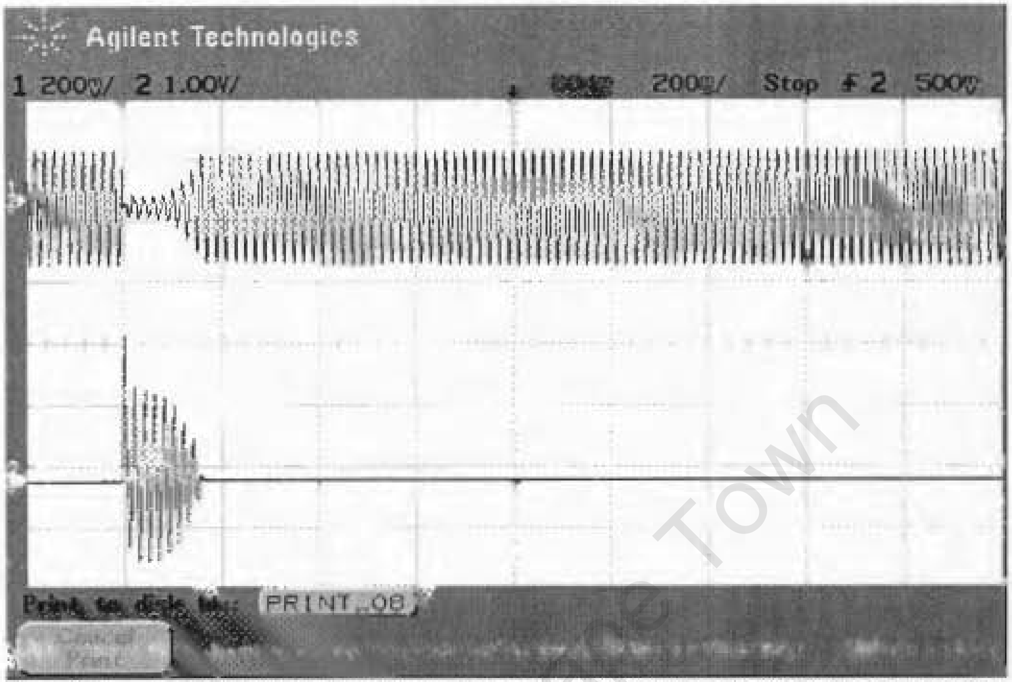

Fig 49: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 45cm

D7: Arc tests with 8kVA load, pf = 0.87, compensated; tests 1 - 5: arc gap of 33cm; tests 6 - 10: arc gap of 45cm; test 11 – 12: transient arc current spike

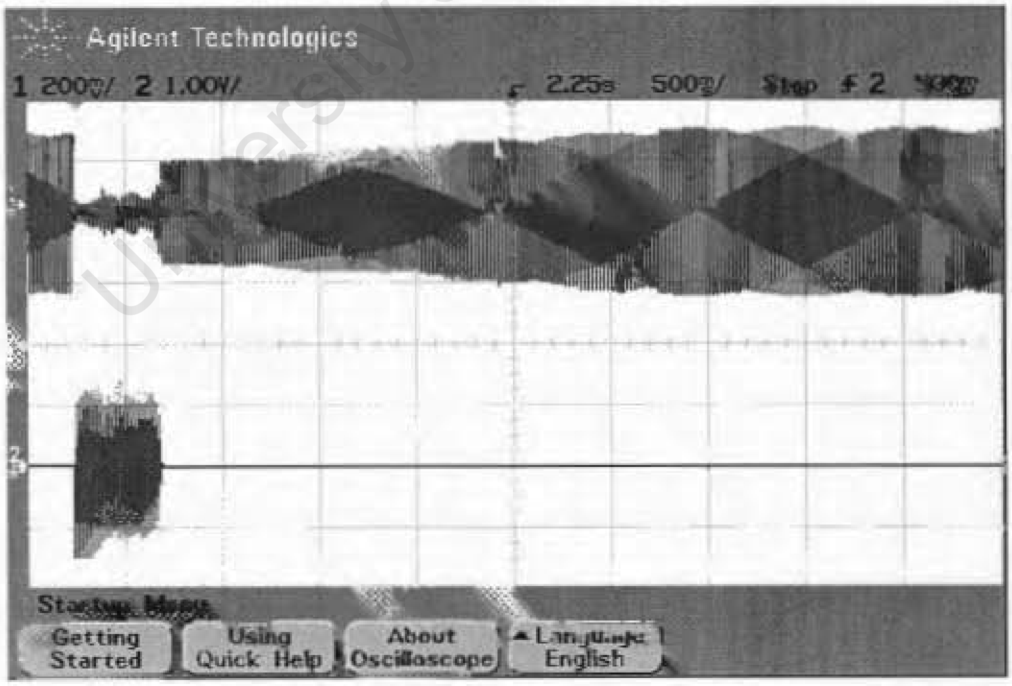

Fig 50: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

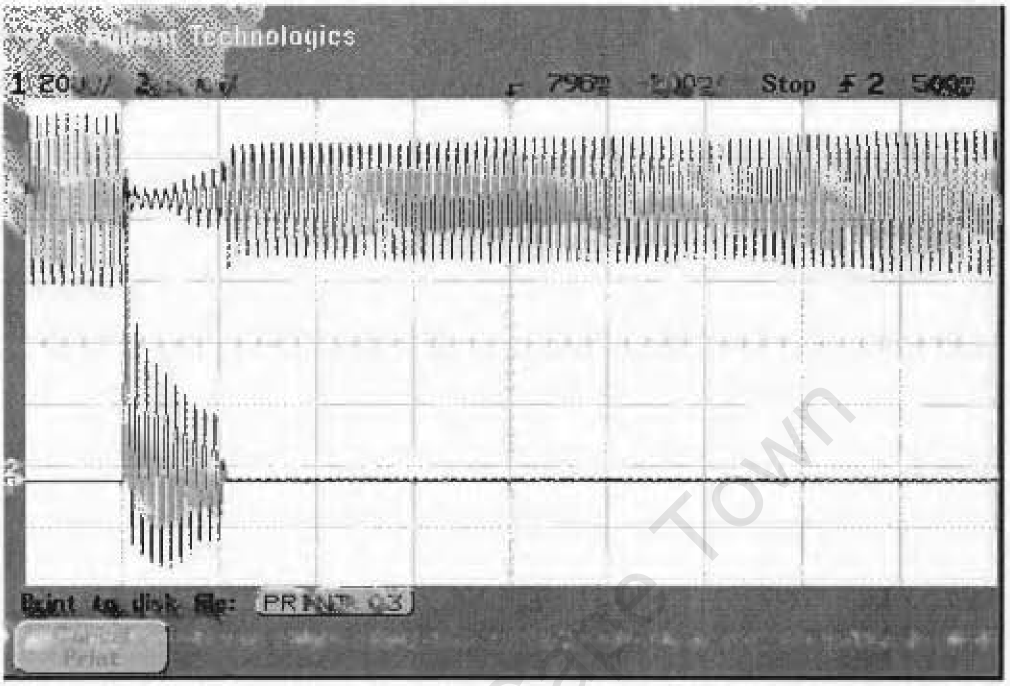

Fig 51: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

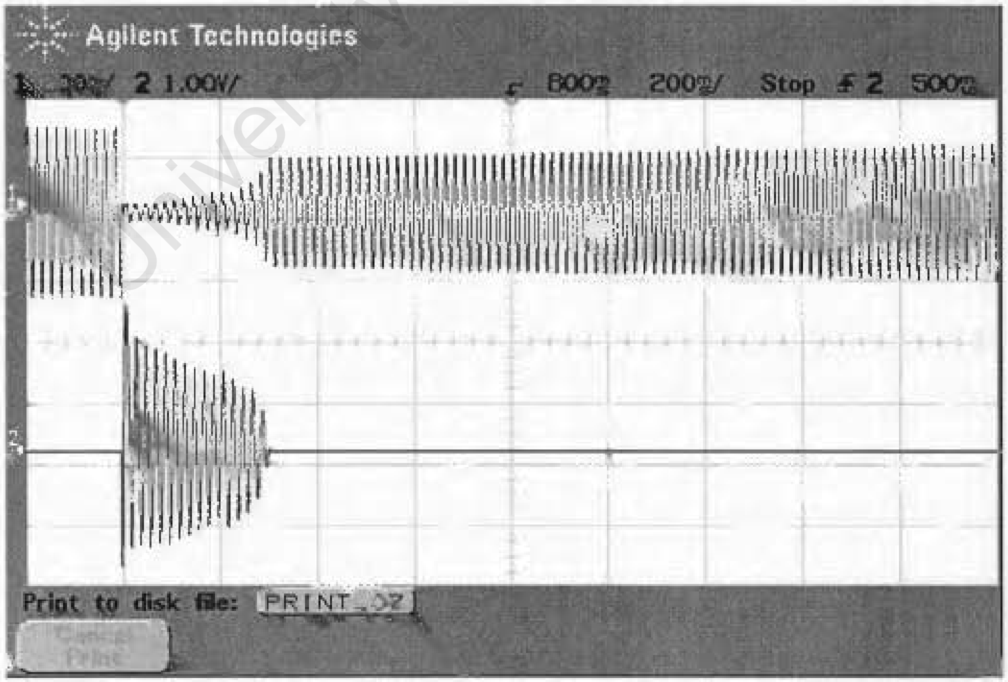

Fig 52: Load voltage (upper trace) and arc current (lower trace) of test 3: gap of 33cm

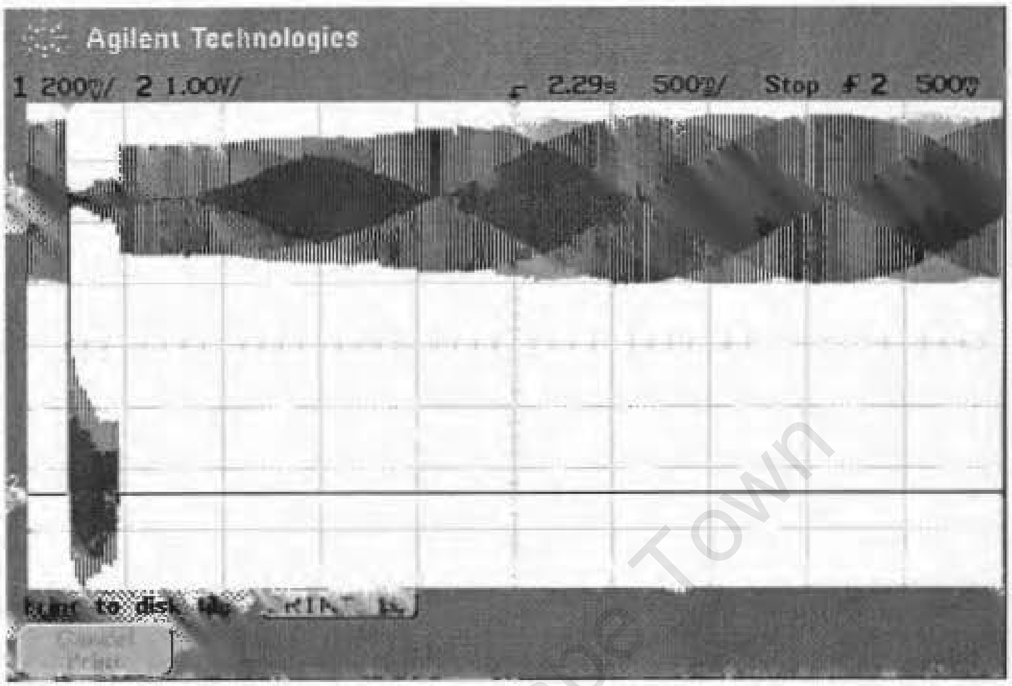

Fig 53: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 33cm

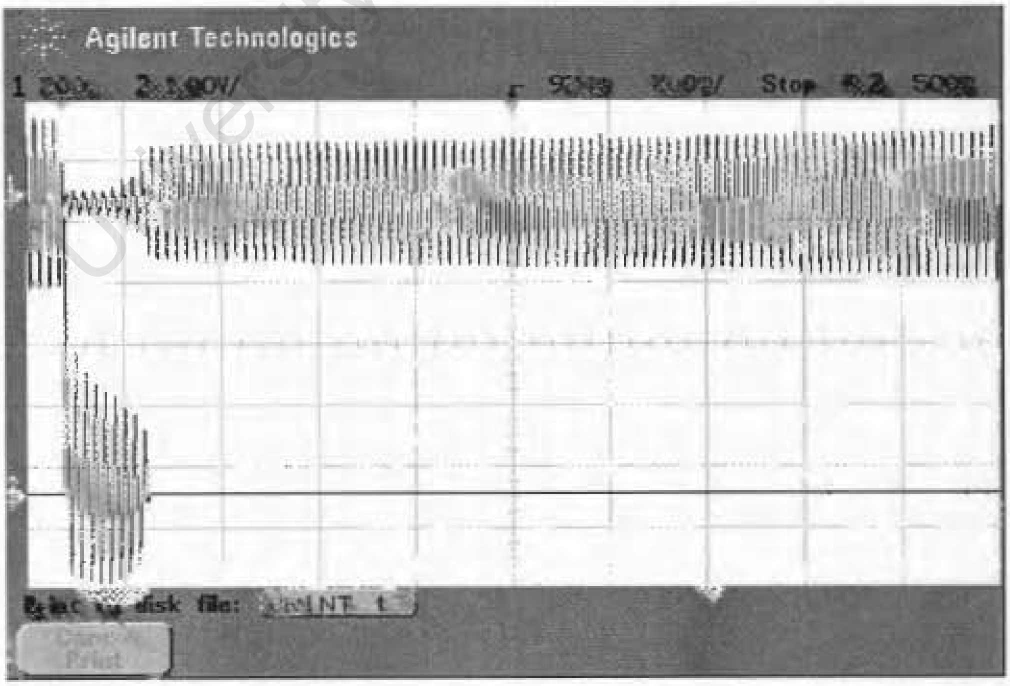

Fig 54: Load voltage (upper trace) and arc current (lower trace) of test 5; gap of 33cm

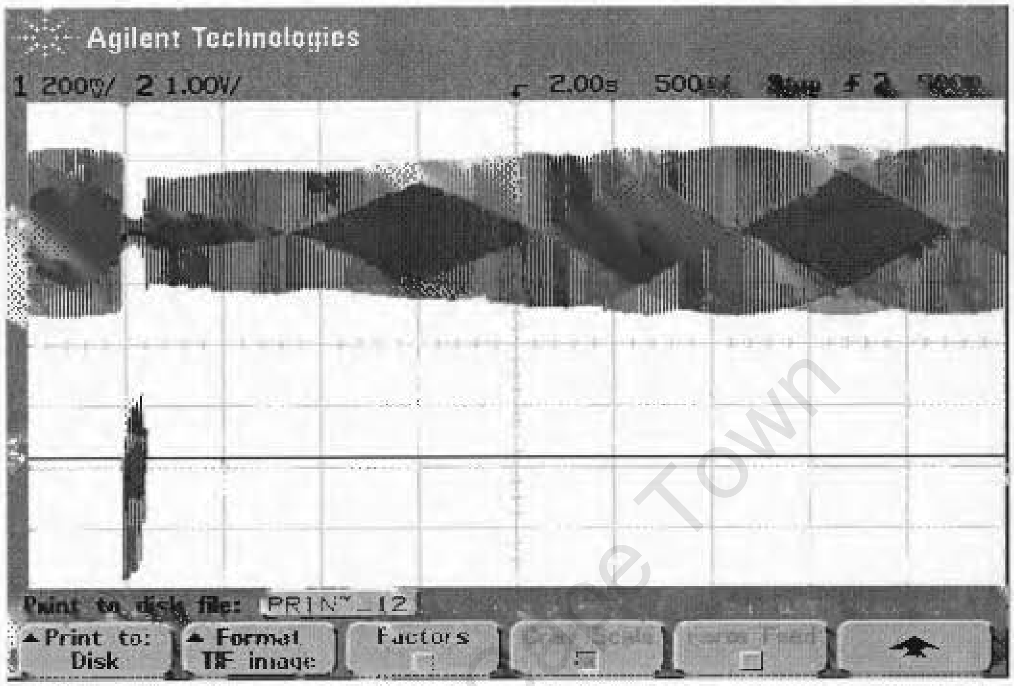

Fig 55: Load voltage (upper trace) and arc current (lower trace) of test 6; gap of 45cm

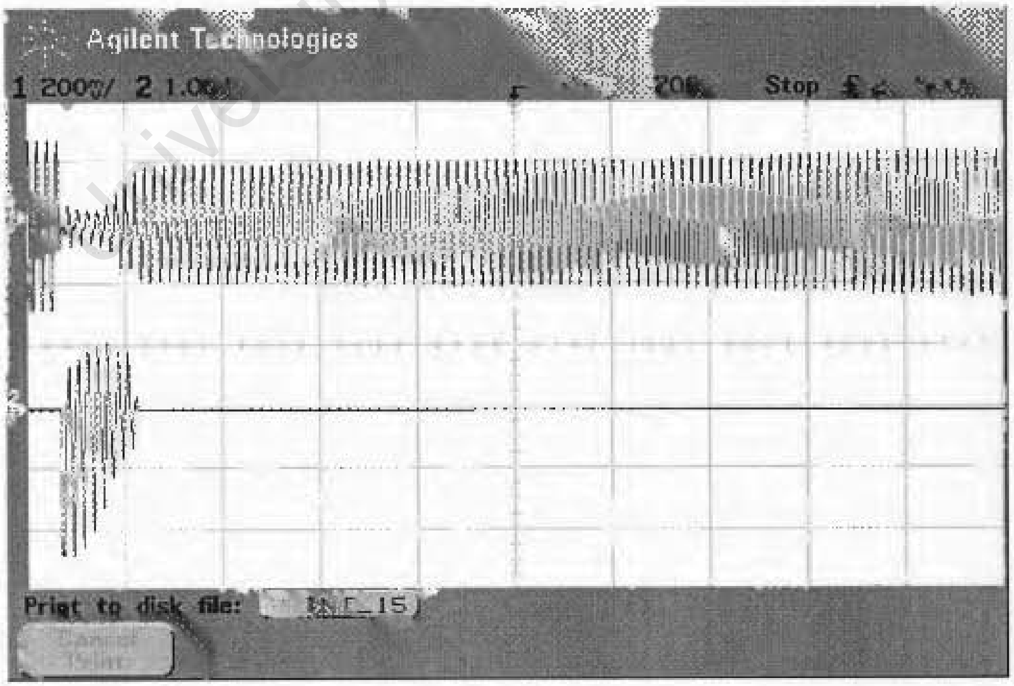

Fig 56. Load voltage (upper trace) and arc current (lower trace) of test 7; gap of 45cm

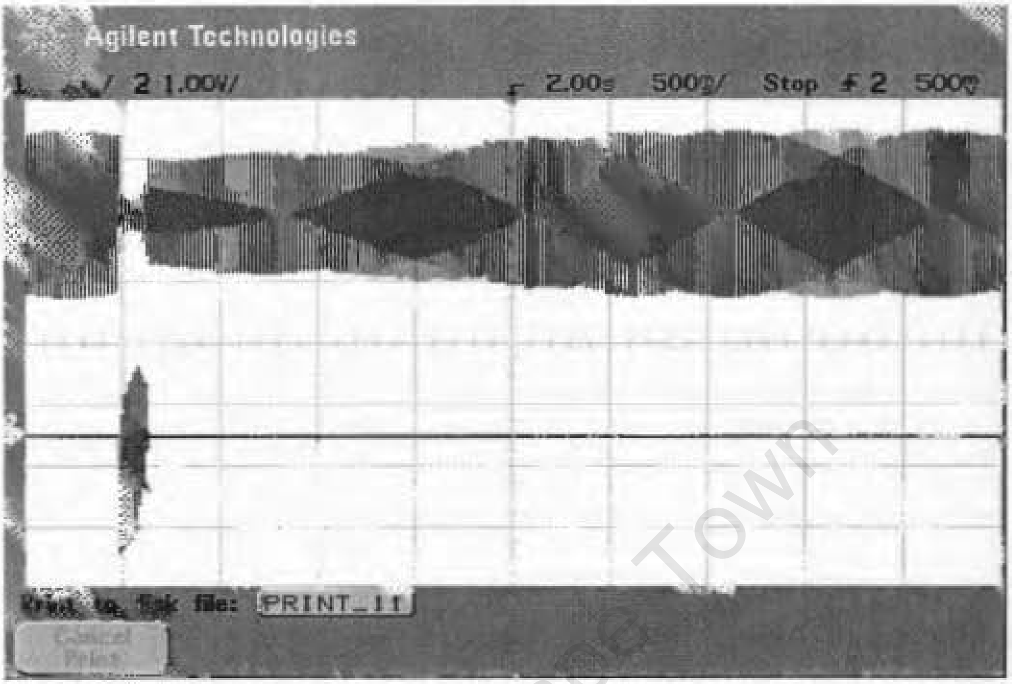

Fig 57: Load voltage (upper trace) and arc current (lower trace) of test 8, gap of 45cm

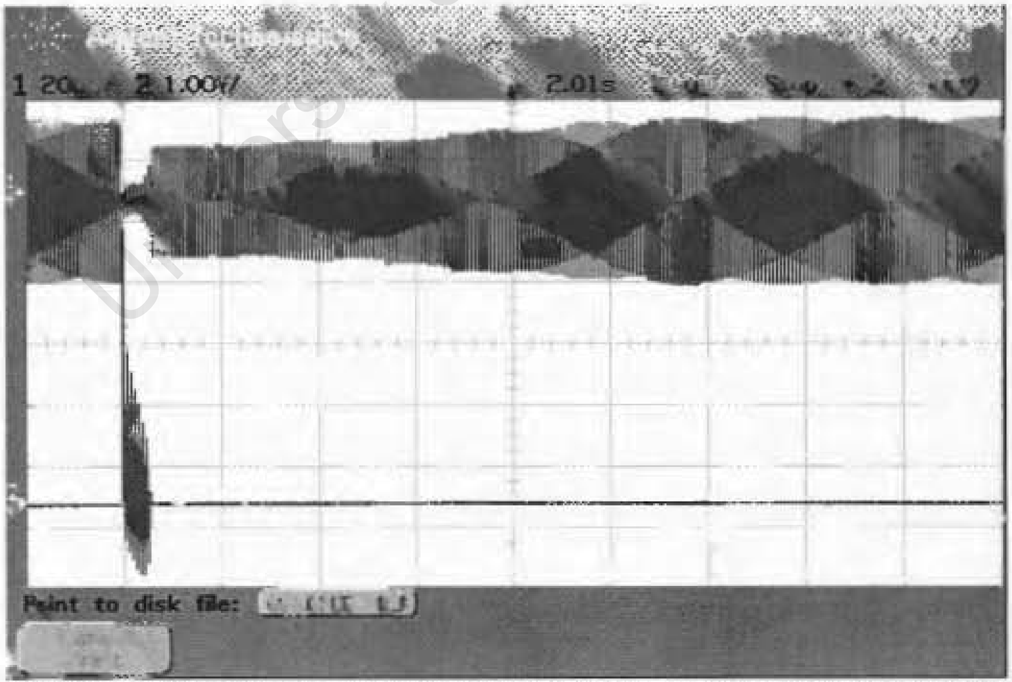

Fig 58: Load voltage (upper trace) and arc current (lower trace) of test 9; gap of 45cm

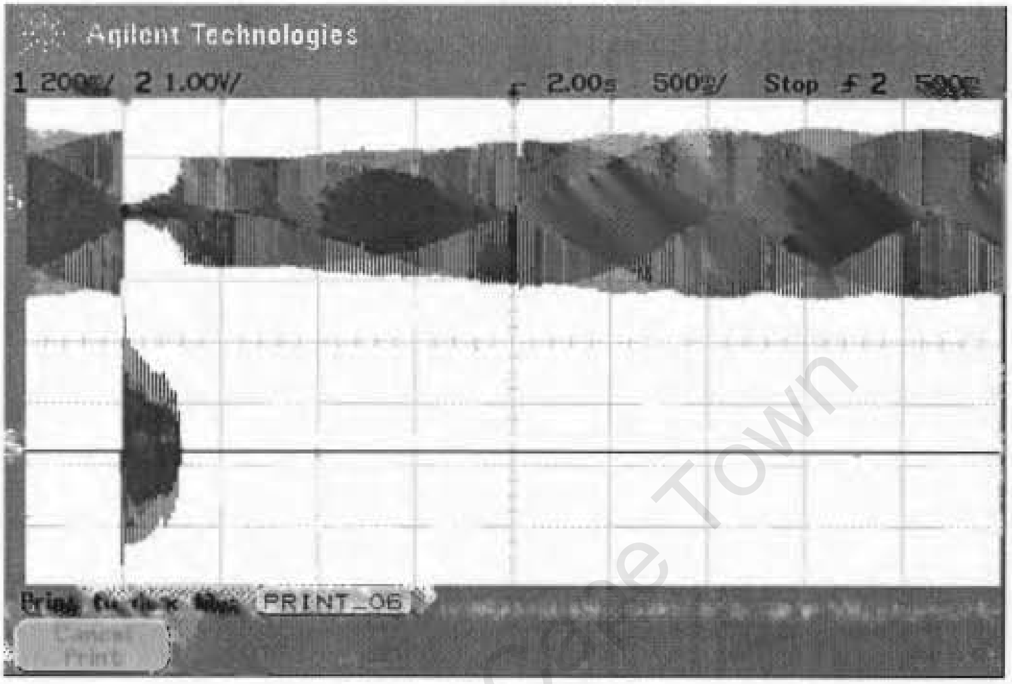

Fig 59: Load voltage (upper trace) and arc current (lower trace) of test 10: gap of 45cm

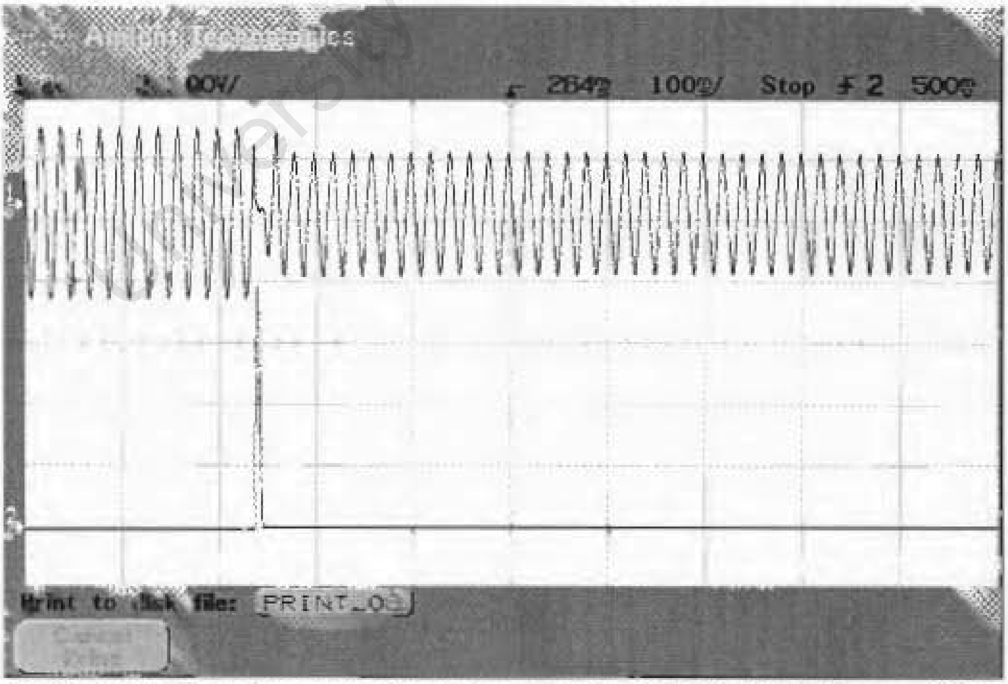

Fig 60: Load voltage (upper trace) and arc current (lower trace) of test 11: gap of 45cm

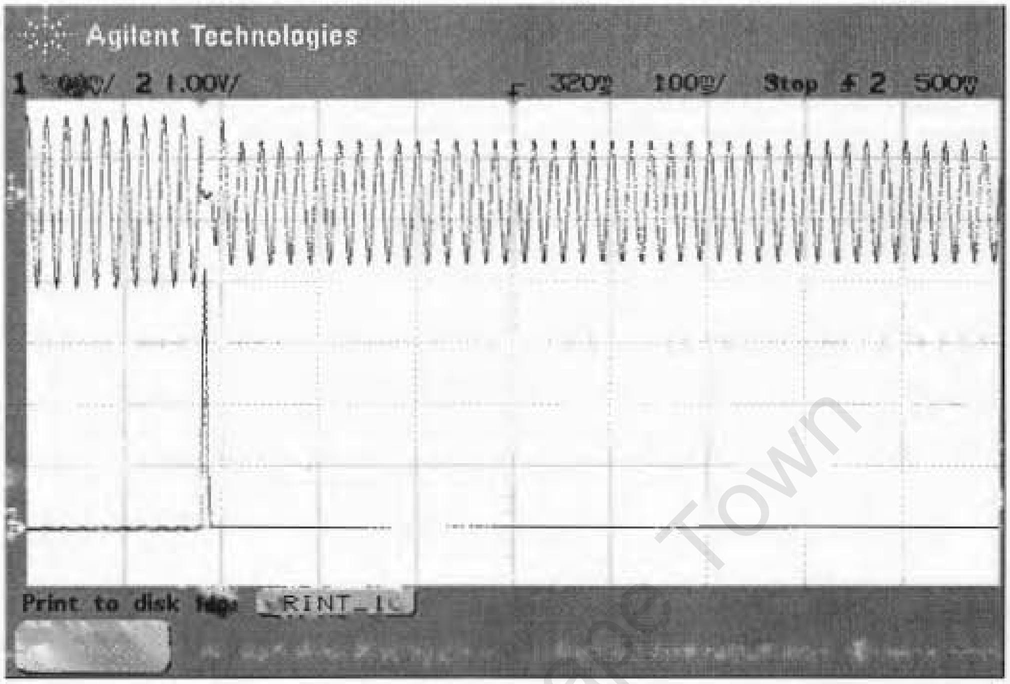

Fig 61: Load voltage (upper trace) and arc current (lower trace) of test 12; gap of 45cm

D8: Single-phase unloaded induction motor-start up voltage and current

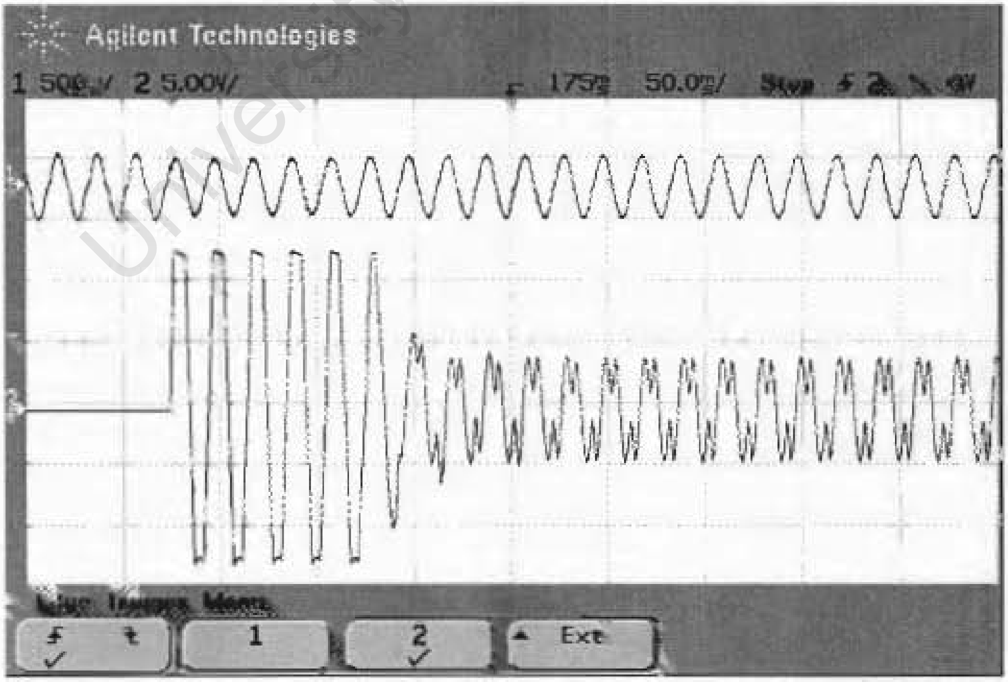

Fig 62: Motor voltage (upper trace) and motor current (lower trace) of test 1

D9: Single-phase unloaded induction motor start-up voltage and current; compensator switched in before motor is started up

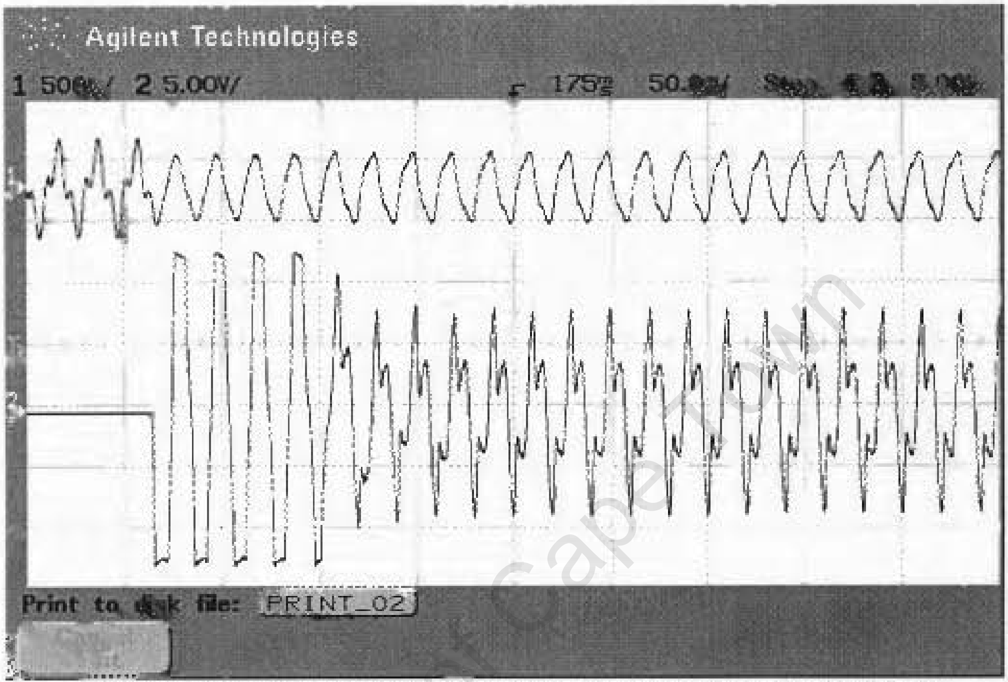

Fig 63: Motor voltage (upper trace) and motor current (lower trace) of test 1

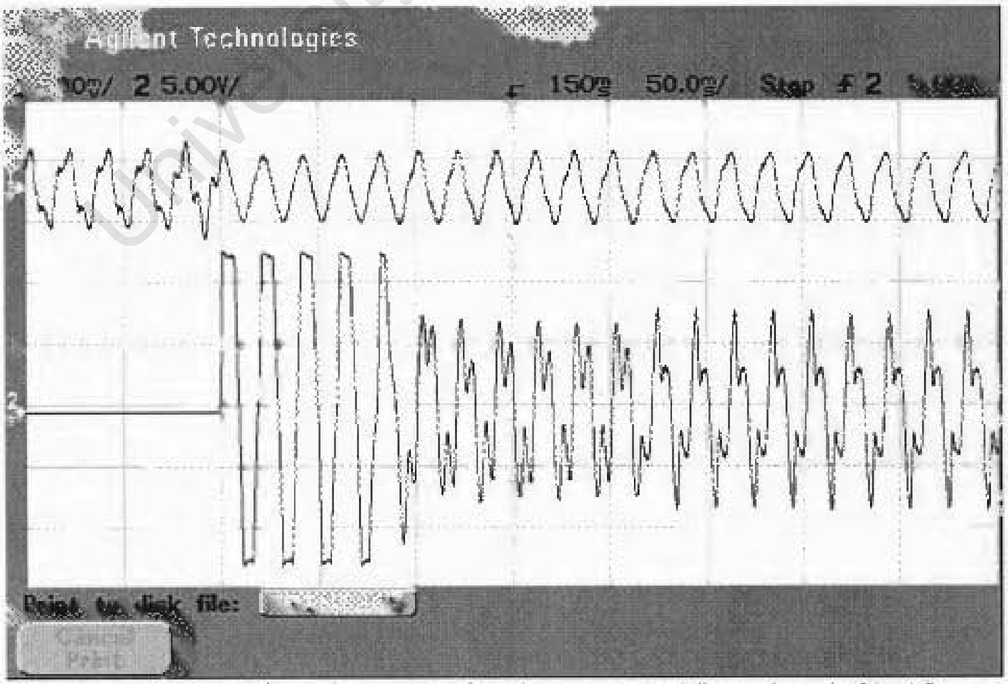

Fig 64: Motor voltage (upper trace) and motor current (lower trace) of test 2

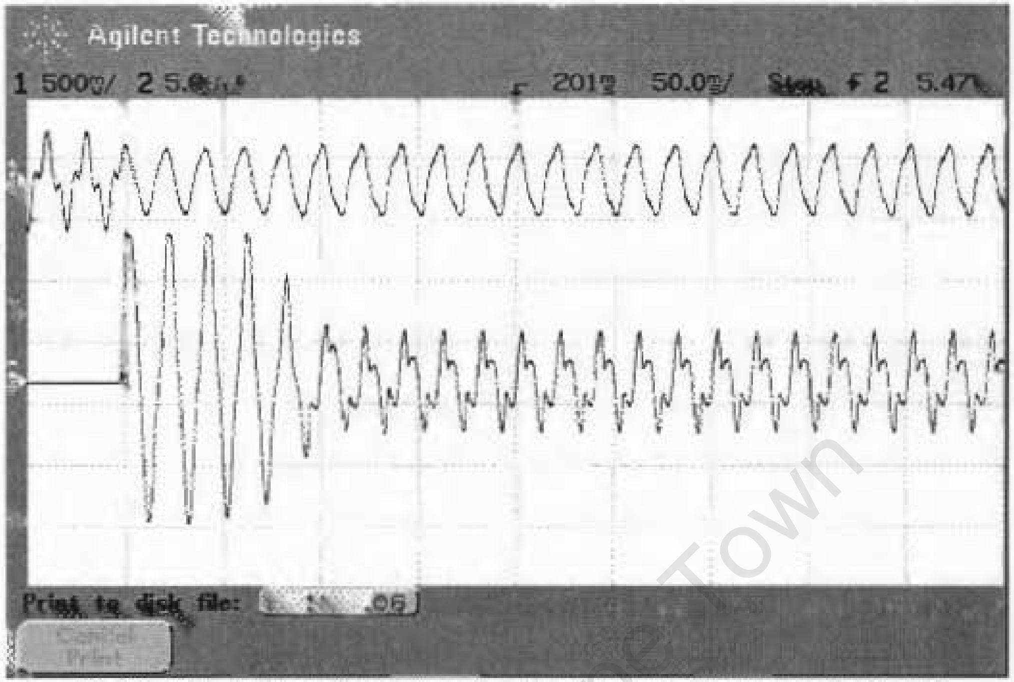

Fig 65: Motor voltage (upper trace) and motor current (lower trace) of test 3

D10: Single-phase unloaded induction motor-start up voltage and current; compensator and complex load switched in before motor is started up

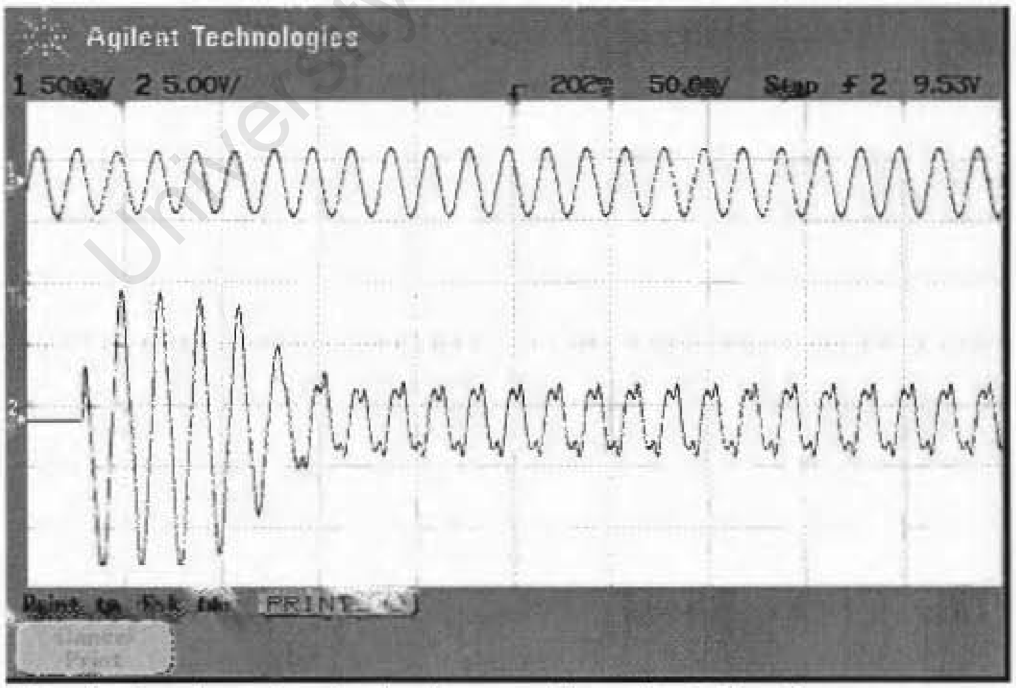

Fig 66: Load voltage (upper trace) and motor current (lower trace) of test 1

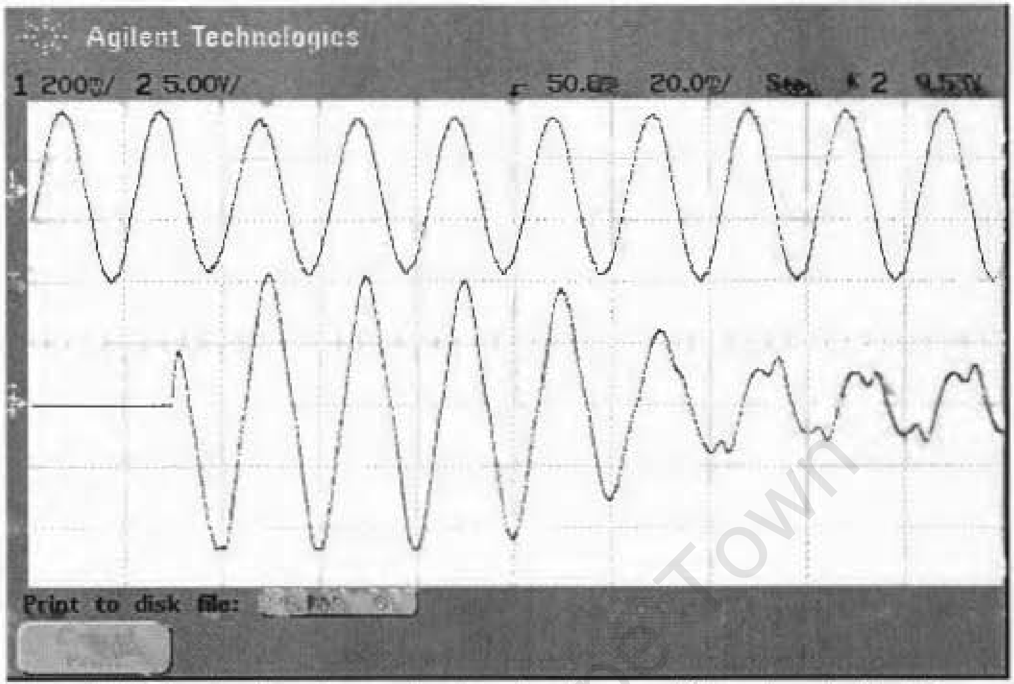

Fig 67: Load voltage (upper trace) and motor current (lower trace) of test 2

D11: Arc tests with unloaded motor load, uncompensated; test 1: arc gap of 33cm; tests 2 - 3: arc gap of 45cm

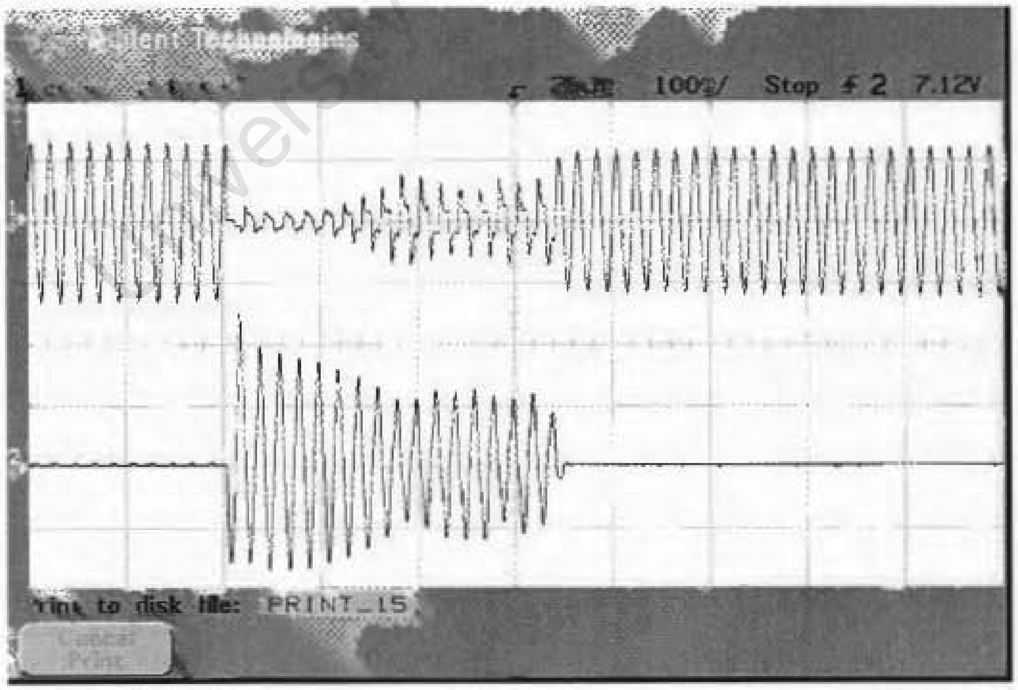

Fig 68: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

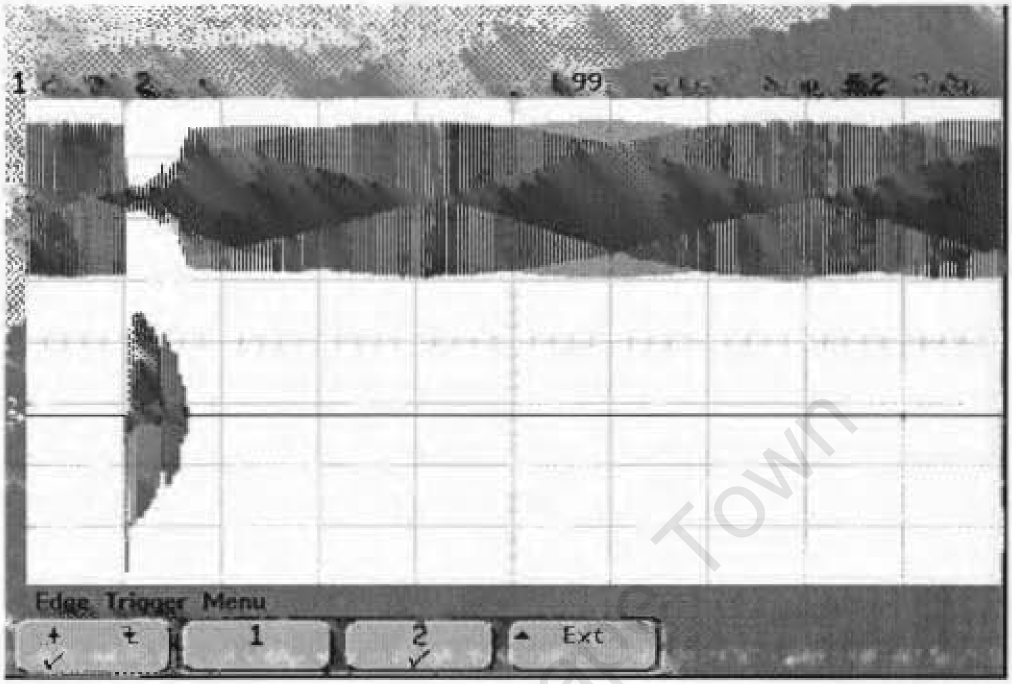

Fig 69: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 45cm

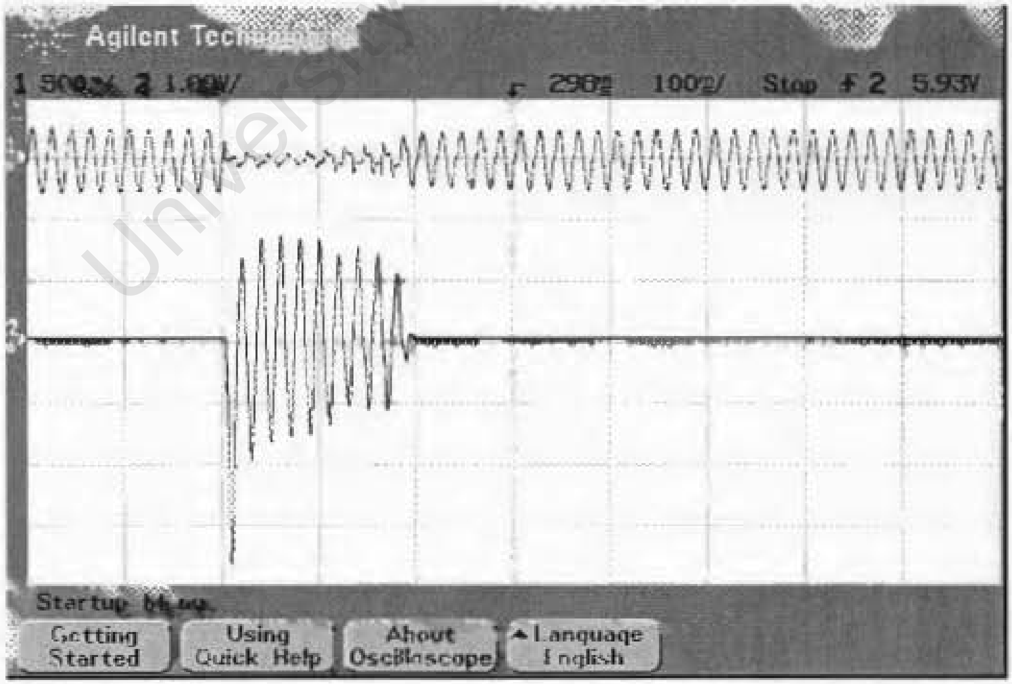

Fig 70: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 45cm

D12: Arc tests with unloaded motor load, compensated; tests 1 - 2: arc gap of 33cm; tests 3 - 4: arc gap of 45cm

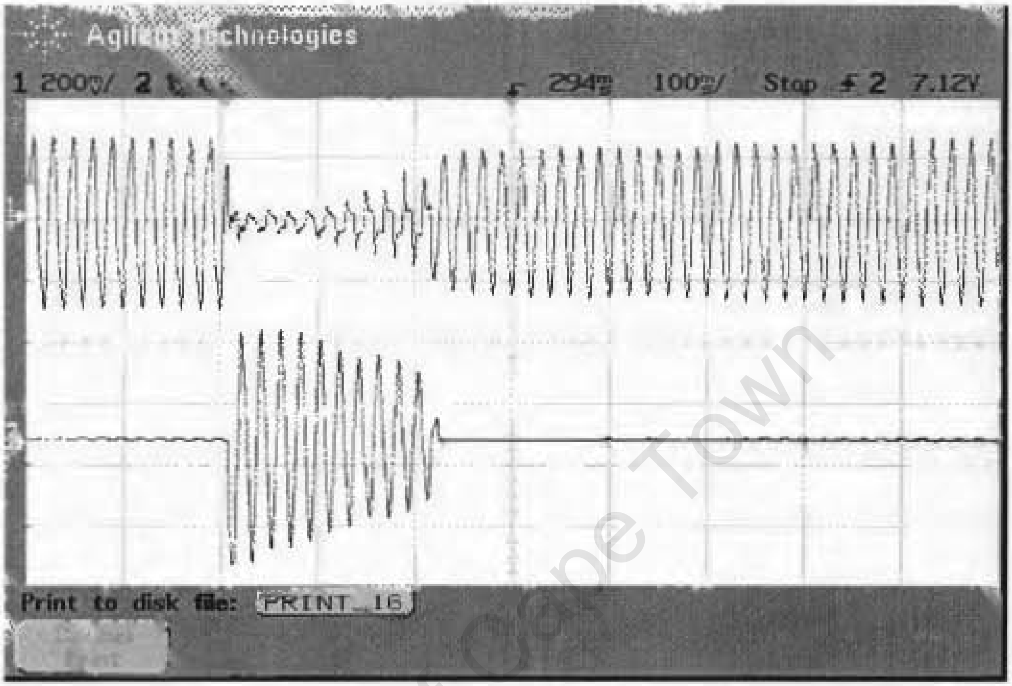

Fig 71: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

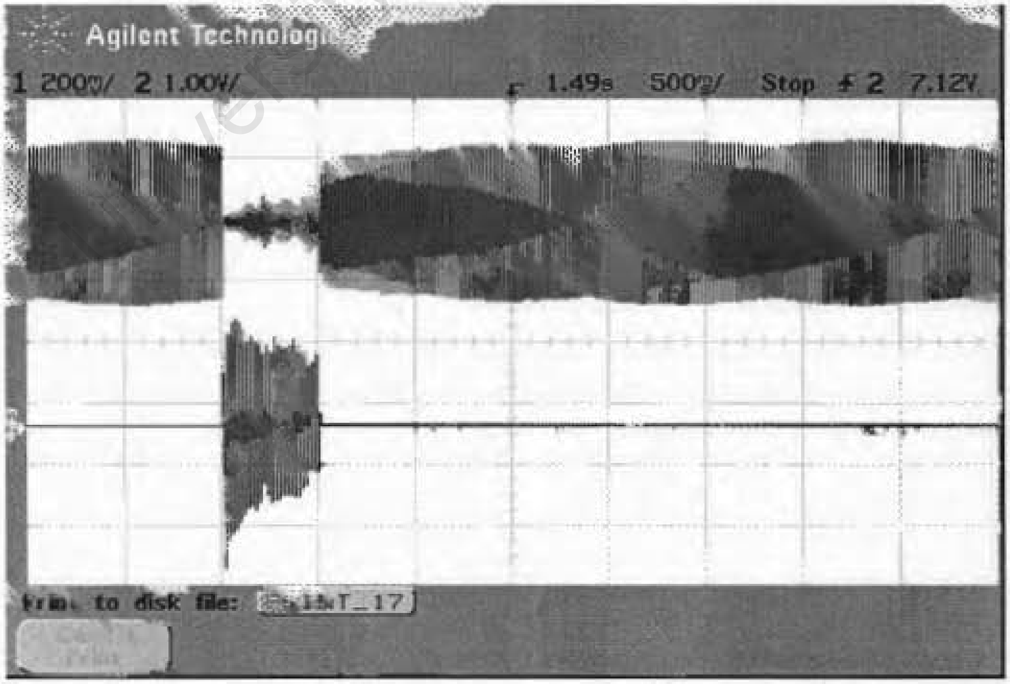

Fig 72: Load voltage (upper trace) and arc current (lower trace) of test 2; gap of 33cm

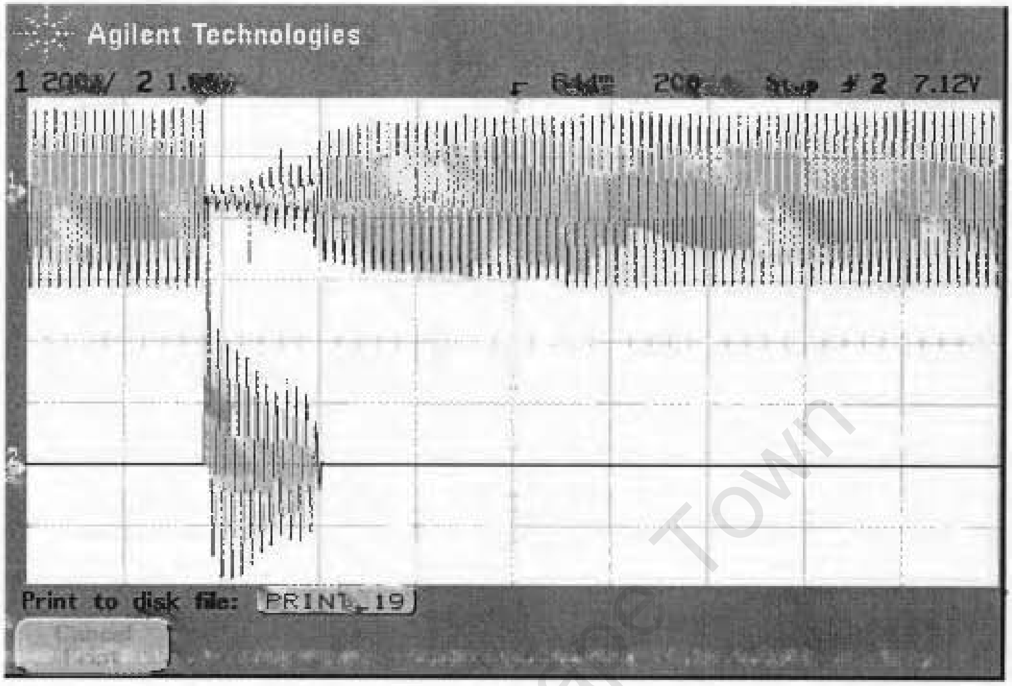

Fig 73: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 45cm

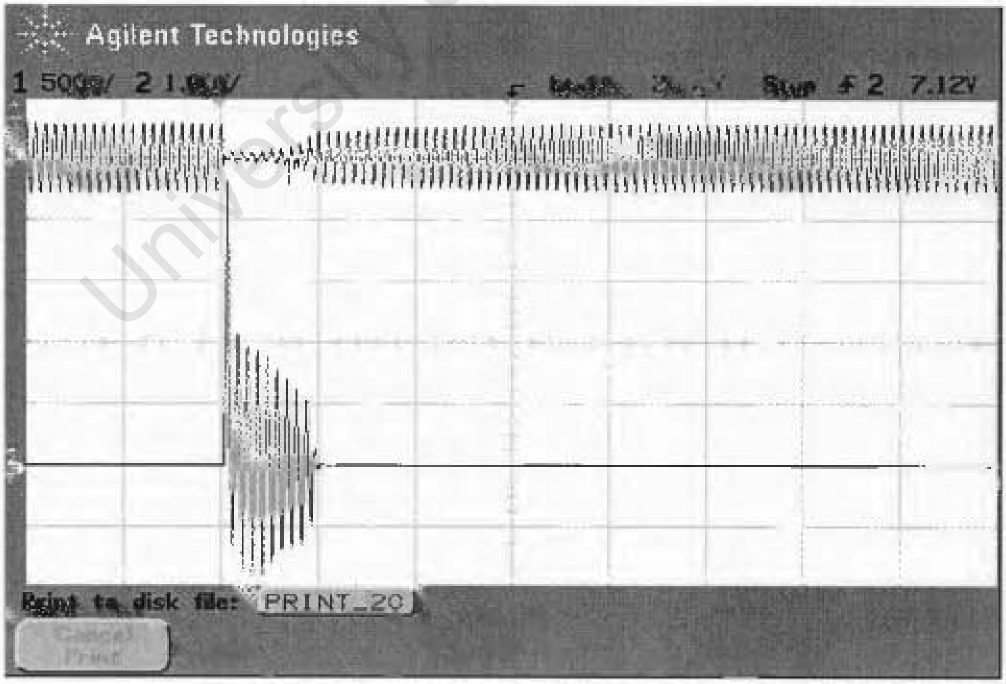

Fig 74: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 45cm

D13: Arc tests with unloaded motor load and inductive load, compensated; tests 1 - 3: arc gap of 33cm; tests 4 - 7: arc gap of 45cm

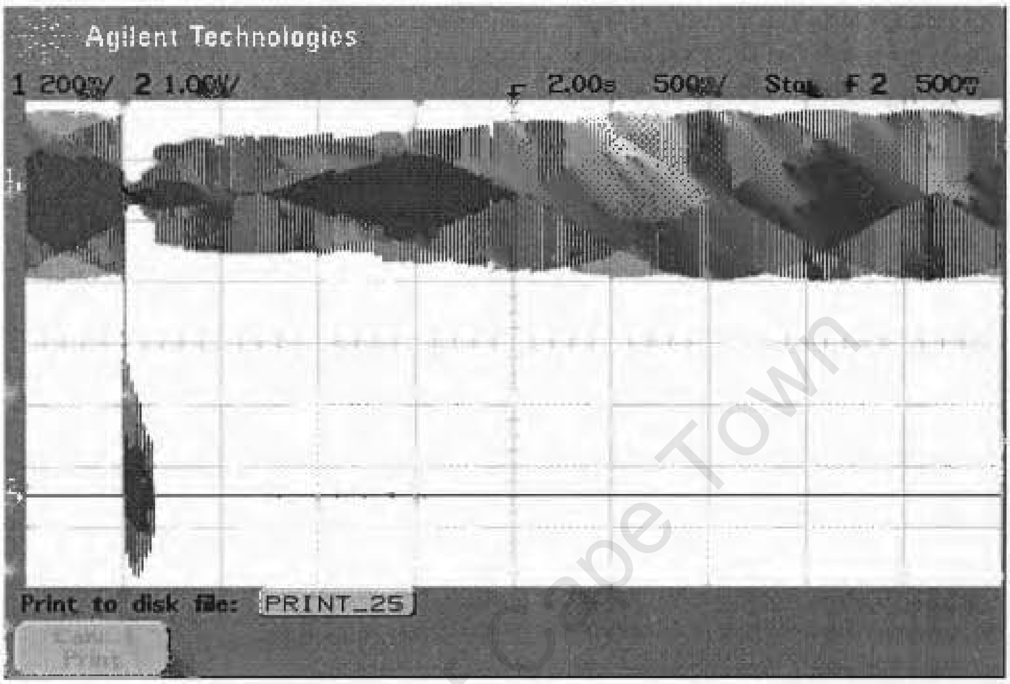

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Fig 75: Load voltage (upper trace) and arc current (lower trace) of test 1; gap of 33cm

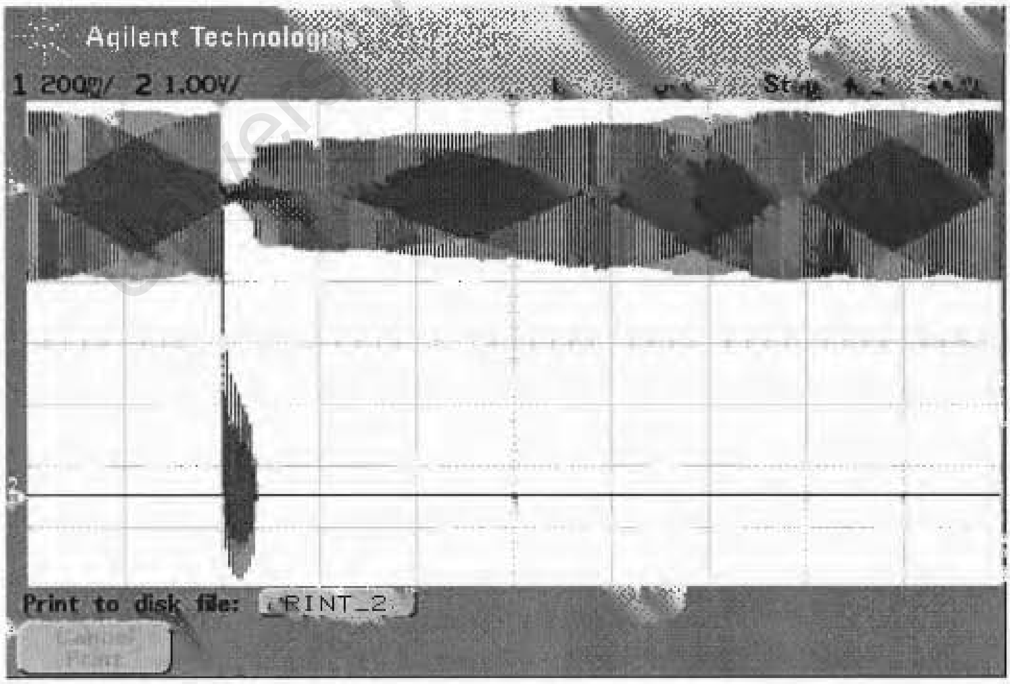

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Fig 76: Load voltage (upper trace) and arc current (lower trace) of test 2: gap of 33cm

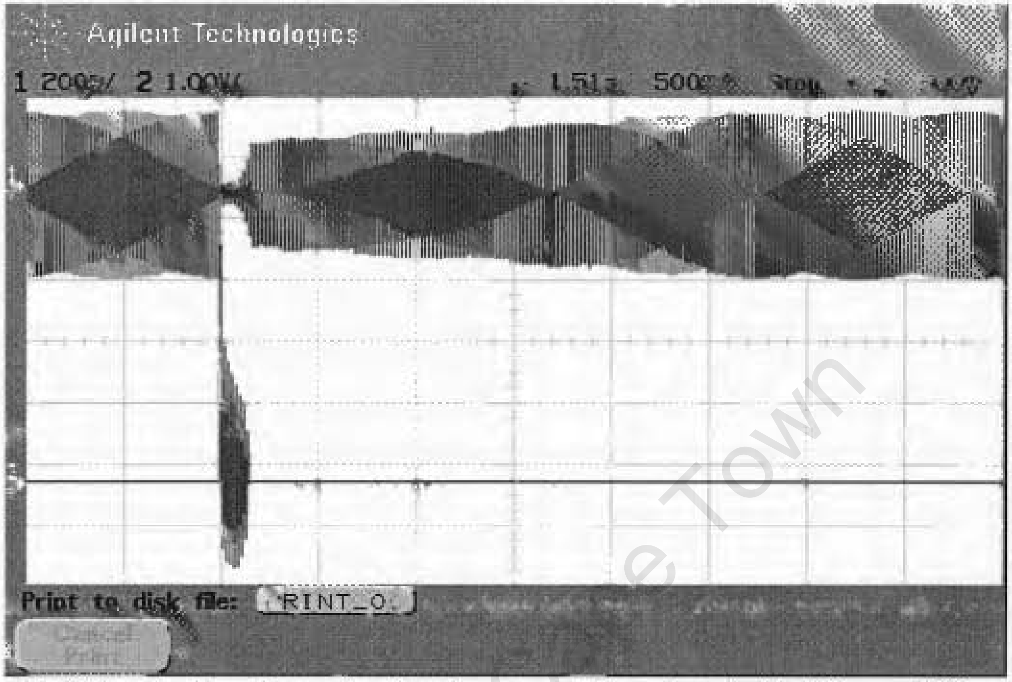

Fig 77: Load voltage (upper trace) and arc current (lower trace) of test 3; gap of 33cm

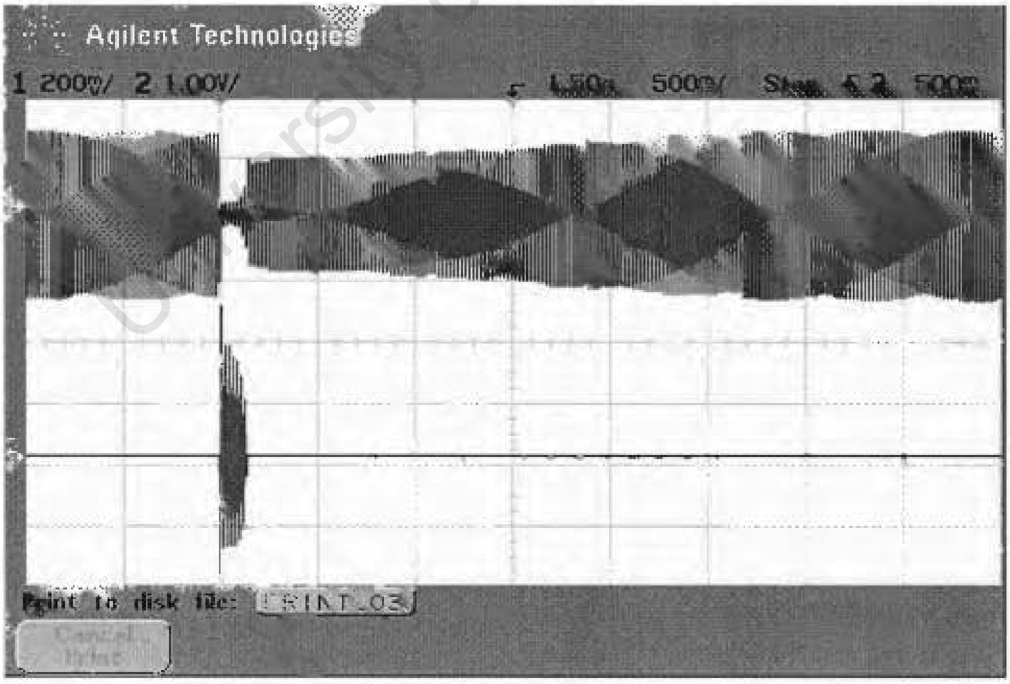

Fig 78: Load voltage (upper trace) and arc current (lower trace) of test 4; gap of 45cm

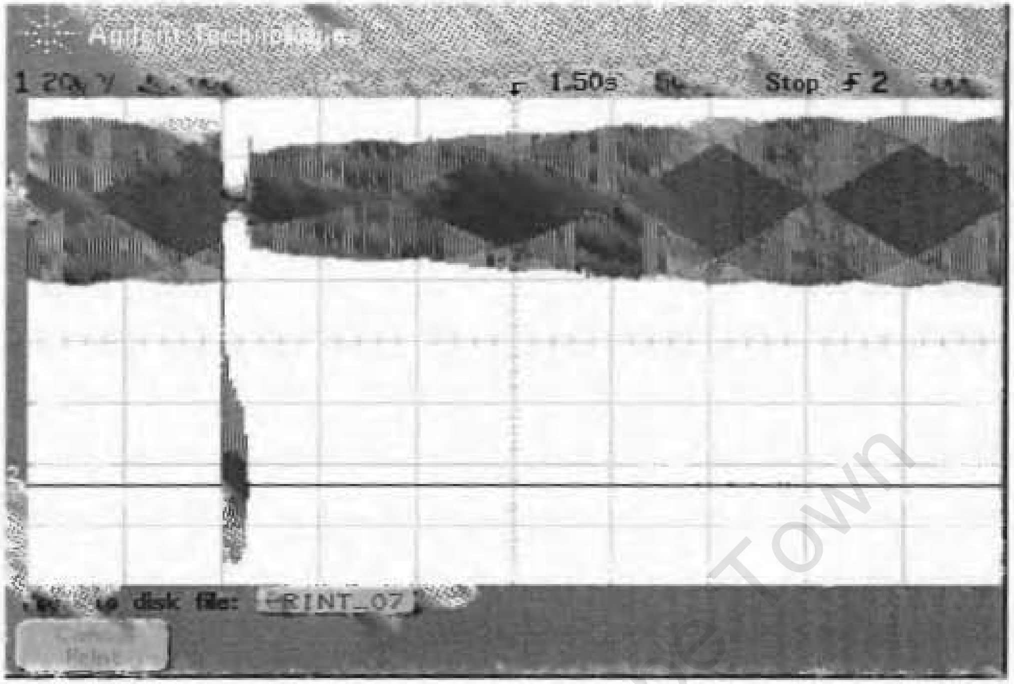

Fig 79: Load voltage (upper trace) and arc current (lower trace) of test 5; gap of 45cm

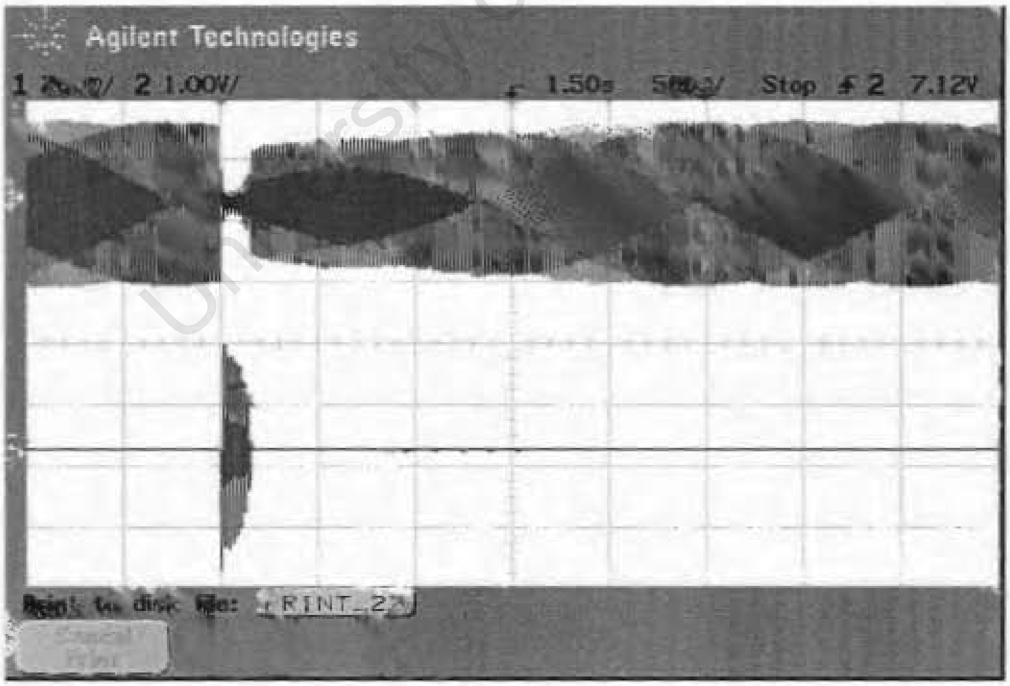

Fig 80: Load voltage (upper trace) and arc current (lower trace) of test 6; gap of 45cm

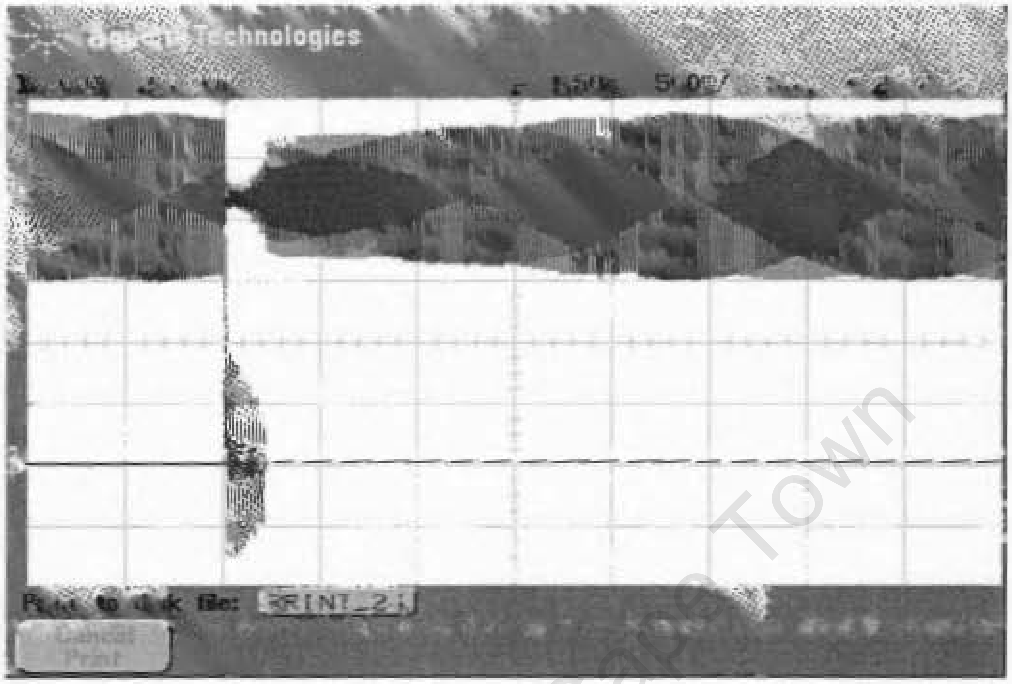

Fig 81: Load voltage (upper trace) and arc current (lower trace) of test 7; gap of 45cm