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School of Electrical and Information Engineering

Analysis of medium voltage vacuum switchgear through advanced condition monitoring, trending and diagnostic techniques

Dissertation for the Degree of Master of Science in
Electrical Engineering

by

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DECLARATION

I declare that this dissertation is my own unaided work. Where material from other sources is used, this is appropriately acknowledged. It is being submitted as a dissertation to the Degree of Master of Science in Electrical Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

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Electrical utilities are tasked with managing large numbers of assets that have long useful lives and are fairly expensive to replace. With emphasis on medium voltage vacuum circuit breakers, a key challenge is determining when circuit breakers are close to their end-of-life and what the appropriate action at that point in time should be. Condition-based maintenance, intended to “do only what is required, when it is required,” has been reported as the most effective maintenance strategy for circuit breakers. This dissertation provides an overview, together with laboratory measurements, on non-intrusive technologies and analytics that could reduce maintenance costs, unplanned outages, catastrophic failures and even enhance the reliability and lifetime of circuit breakers by means of a real-time condition monitoring and effective failure prevention maintenance approach. The key areas of research are the condition assessment of the mechanical mechanism based on coil current signature diagnosis, degradation detection of the main interrupting contacts through thermal monitoring and interrupter vacuum integrity assessment based on magnetron atmospheric condition (MAC) testing. The information from test results allows both immediate onsite analysis and trending of key parameters which enables informed asset management decisions to be taken.

Acknowledgements

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Further, I would like to gratefully thank my supervisors whose support and inspiration enabled me to achieve the goal of completing this research project. The following people played a significant role:

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- Mr. Nico Smit for sharing his industrial knowledge throughout the research.

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Nomenclature

ABB	ASEA Brown Boveri
A/D	Analog to Digital
ANSI	American National Standards Institute
CB	Circuit Breaker
CBM	Condition Based Maintenance
CIGRE	International Council on Large Electric Systems
DRM	Dynamic Resistance Measurement
EE	Electrical Endurance
FMECA	Failure Mode Effects and Criticality Analysis
HV	High Voltage
IDT	Inter Digital Transducer
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electro-technical Commission
kV	Kilovolt
MV	Medium Voltage
OEM	Original Equipment Manufacturer
O&M	Operations and Maintenance
PD	Partial Discharge
RCM	Reliability Centered Maintenance
RFID	Radio Frequency Identification
RTD	Resistance Temperature Detection
RUL	Remaining Useful Life
SAW	Surface Acoustic Wave
SCADA	Supervisory Control and Data Acquisition
SF_6	Sulphur hexafluoride

Chapter 1 Introduction

1.1 Background

1.1.1 Problem statement

The Medium Voltage (MV) electrical Industry sector has undergone little change in the past 30 years when compared to other electrical industry sectors. The importance of circuit breakers to electric utilities cannot be overstressed - circuit breakers play an important role in the delivery of power and the disconnection of faulted circuits.

A growing concern for Eskom is the ageing of its distribution infrastructure where the existing assets are becoming more expensive to maintain. Maintenance is essential in order to deliver the demanded reliability. The main problem with aged equipment is that, without appropriate maintenance, it is much more prone to failure than new equipment.

Investment that has failed to keep up with the increasing demand has led to increased stresses on the existing infrastructure and this is a contributory cause to the acceleration of the ageing. The level of investment required to modernise the existing Eskom MV distribution network is prohibitive and alternatives must be found such that the system performs with the same reliability as in the past.

1.1.2 Rationale

Unplanned outages and increased down-time have a negative effect on the reliability of a power system. The need for improving the performance, reducing the life-cycle costs and most importantly enhancing the security of the distribution network is ever increasing. The reliability and efficiency of MV vacuum switchgear can be enhanced initially in the design and afterward during the operation and maintenance phase.

The reduced probability of suffering from unnecessary outage costs is the main driver for investment in monitoring and diagnostic technologies. As computing and sensing technology costs becomes less expensive, monitoring and diagnostic systems will become more financially attractive.

1.2 Research focus

1.2.1 Research questions

The research questions addressed during this study are as follows:

- What are the most cost-effective options for improving vacuum circuit breaker reliability while extending the life of MV vacuum circuit breakers?
- What are the most common degradation and failure modes associated with MV vacuum circuit breakers?
- What tests and monitoring techniques are currently employed by Eskom to determine MV vacuum circuit breaker condition and what are their limitations?
- How can the degradation and actual life expectancy of vacuum interrupter contacts be determined?
- What are the latest technologies currently available to monitor vacuum circuit breaker degradation on-line and what are their limitations?
- Is there a relationship between the value of the chopping current and contact erosion/degradation?

1.3 Overall research aim and individual research objectives

1.3.1 Purpose of the study

The objective of this research is to investigate advanced circuit breaker monitoring and diagnostics techniques that can provide early detection of abnormalities and thereby mitigate equipment degradation and prevent failures.

1.4 Value of this research

1.4.1 Established reasons

The underlying purpose of monitoring and diagnostic systems is to provide early warning of impending failures and/or reduce problem diagnosis times in order to restore service as quickly as possible. Due to the development of cost-effective and reliable communications, and the decrease in the cost of computing power and sensing technologies, monitoring and diagnostics have become more attractive. This research explores monitoring and diagnostic tools for medium voltage vacuum circuit breakers and justifies the selected technology, system integration, and monitoring analytics from both technical and financial perspectives.

This research's hypothesis is that it is possible to develop economical monitoring and diagnostic schemes for MV vacuum circuit breakers for the utility market.

1.5 Research methodology

As the project's objective is to ultimately develop an advanced vacuum circuit breaker condition monitoring and diagnostic functional prototype, the development follows a straightforward product development flow as follows:

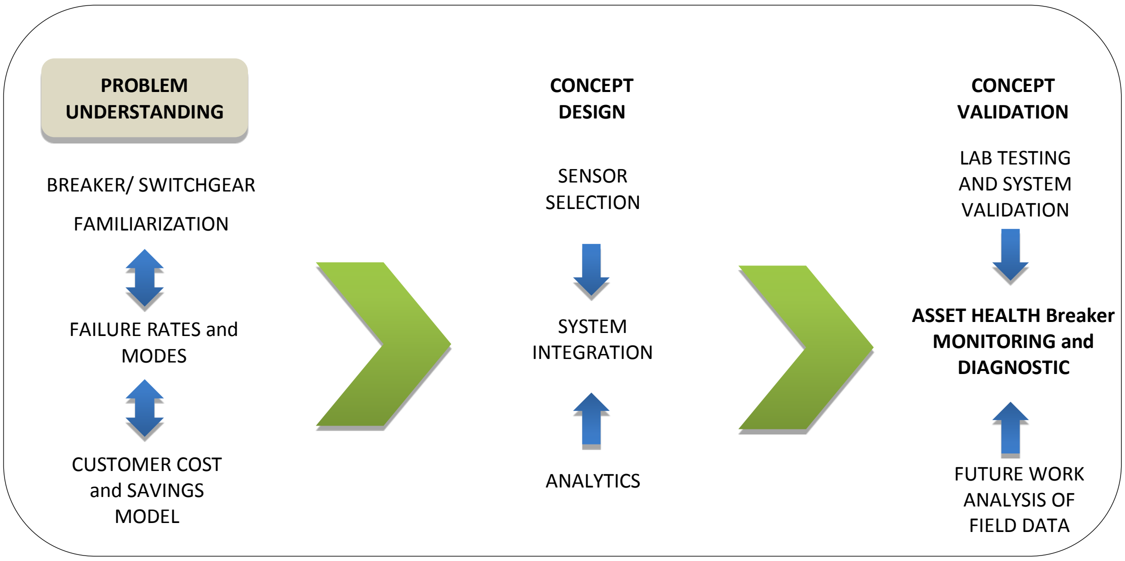

Figure 1-1: Medium voltage vacuum circuit breaker monitoring and diagnostic flowchart

Problem understanding: The first stage focuses on understanding the operation, failure modes and reliability of medium voltage vacuum circuit breakers, as well as considering the financial implications when viewed from the utility's perspective.

Concept design: The objective of this research is to increase equipment reliability and decrease utility costs. This research will therefore assess the merit of different sensing technologies and propose a systematic framework for the most appropriate sensor technologies. The final undertaking for this phase will be the integration of sensors, communications, data aggregation, and analytics.

Concept validation: Extensive laboratory experiments and testing will validate system design before application at one of Eskom's Peaking power plants.

1.6 Dissertation outline

The outline of this dissertation is shown in Figure 1-2.

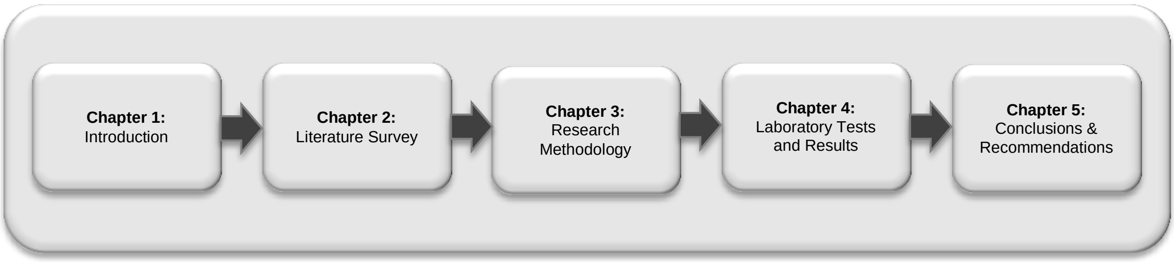

Figure 1-2: Dissertation Outline

Chapter 1 - Introduction

Emphasis is placed on the ageing infrastructure problem faced by Eskom and the opportunities that exist for monitoring and diagnostics. The chapter includes the project's problem statement, rationale, objectives, value of the research and the dissertation outline.

Chapter 2 - Literature survey

This chapter gives an overview on the working principle of vacuum switchgear. It elaborates on the reliability for MV circuit breakers by piecing together information obtained from the German MV distribution system and the IEEE. The absence of information on equipment failure rates justifies the work presented.

This chapter also examines the dominant equipment failure mechanisms. Here too, information is obtained from reports from the German MV distribution system, CIGRE, and the IEEE.

Chapter 3 - Research methodology

This chapter gives an overview on the proposed research methodology and the underlying principles behind magnetic coil profiling and interrupter thermal monitoring analytics, and utilises this framework to justify the selected sensing technologies and overall system integration of the MV circuit breaker monitoring and diagnostic system. The chapter describes the project's research strategy, research focus and design, data collection, limitations, reliability, and validity.

Chapter 4 – Laboratory tests and results

Chapter 4 describes the experimental techniques and then discusses the experimental results. Finally, a comparison is made with other published findings.

Chapter 5 - Conclusions and recommendations

This chapter provides an overview of the research project and brings together the most significant findings and results. Finally, this chapter wraps up with future challenges and research opportunities.

Chapter 2 Literature Survey

2.1 Introduction

The main objective of a circuit breaker is to provide protection from overload or short circuits by interrupting load or fault currents within tens of milliseconds. Fault detection and the tripping of circuit breakers are typically performed by a protection relay. Protection relays are typically located in the switchgear's low voltage compartment and are electrically isolated from the main circuit in order to have sufficient overall system safety and reliability. Nowadays relay systems found in utility and industrial networks also have the ability of receiving remote switching commands. This gives network operators enhanced grid control and coordination ability.

During current interruption by circuit breakers, an electric plasma arc is formed between the two electrodes as the device's contacts begin to separate shown in Figure 2-1. It is therefore critical to have a means in place to quench the arc. This method of quenching the arc is growing in complexity in circuit breakers as the design rating increases (i.e. higher voltage and/or higher current).

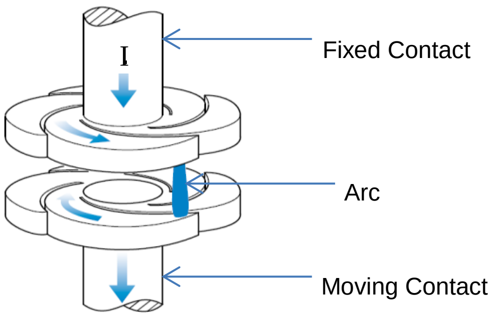

Figure 2-1: Arc formation during separation of contacts [1]

In conjunction with the current and voltage ratings, the arc extinguishing medium is also of great importance for particular circuit breaker ratings. During the twentieth century, circuit breakers rated at 4 kV and above made use of oil as a quenching medium. These oil circuit breakers were prone to fires and were maintenance intensive and alternatives were sought. During the 1940s, compressed air was utilized to extinguish the arc and was an attractive alternative to oil circuit breakers.

By the 1960s, the use of sulphur hexafluoride (SF_6) became widespread due to its low operating cost and it didn't require external compression mechanisms; however there were environmental concerns over the use of this gas. During the mid 1970s, vacuum circuit breakers took over and became the most popular arc extinguishing medium in the MV realm (4 kV – 35 kV).

In vacuum circuit breakers, as the energized contacts part, metal vapor is released and it is this metal vapor that provides the medium for arc formation. The vacuum chamber is designed such that the arc extinguishes when the vaporized metal condenses and solidifies on the electrodes and walls of the interruption chamber [2]. Studies have shown that vacuum interrupter technology offers higher reliability and requires considerably less maintenance than its compressed air and SF_6 counterparts. As a rule of thumb, vacuum circuit breakers should be inspected at least once a year or every 2000 operations, whichever occurs first [3]. This research focuses mostly on vacuum circuit breakers, but the general approach however can be easily applied to SF_6 breakers.

2.2 Background: MV vacuum circuit breaker operation

2.2.1 Vacuum interrupter's construction

Vacuum interrupters are typically used to interrupt medium voltage alternating current (AC) of several thousands of amperes. As the name implies, the interruption process takes place in a vacuum chamber. The vacuum interrupter consists of the following components as shown in Figure 2-2:

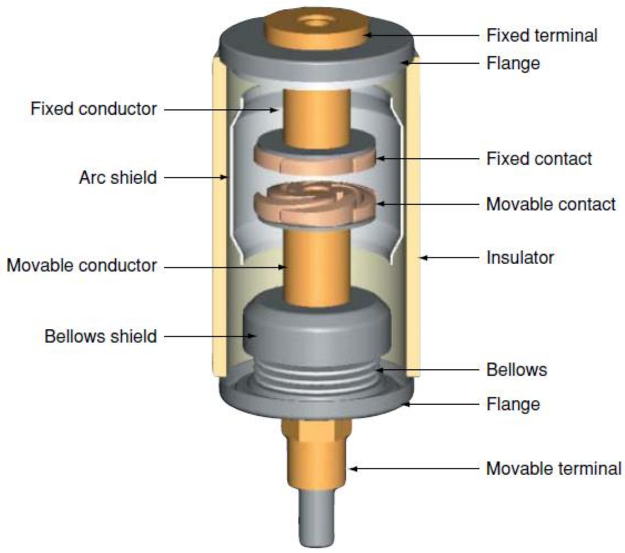

Figure 2-2: Internal view of a typical vacuum interrupter [4]

The bellows allow the movable contact to move while maintaining the vacuum. When the contacts part, some of the contact material is vaporized by the arc. This vaporized and ionized metal serves as the conductive path for the arc. At the first current zero the vaporized metal immediately condenses and solidifies on the shield. The arc is thus extinguished at the first natural current zero and the high dielectric strength of the vacuum ensures that there will be no subsequent breakdown due to the recovery voltage. Depending on the construction of the vacuum circuit breaker, vacuum circuit breakers offer many advantages as compared to other types of circuit interrupters.

The advantages of vacuum switchgear include [4]:

- Relatively long life due to controlled contact erosion.
- Maintenance-free operation provided by enclosure of the contacts within the hermetically sealed housing.
- No atmospheric contamination, which can detrimentally form oxides and corrosion layers on the contacts.
- Relatively few environmental effects as compared to those interrupters where current interruption does not occur in a vacuum and hence where greenhouse or toxic gases can be freely emitted into the environment.
- Very low chopping current, resulting in a minimal induced transient voltage spike during circuit interruption so that surge suppressors are not required.

Because the vacuum circuit breaker has many advantages, demands for higher withstand voltages and larger current breaking capability of the vacuum circuit breaker has become increasingly high.

2.2.2 Vacuum interrupter's working principle

If U_B is the breakdown voltage when a gap of length *d* breaks down, then the breakdown voltage U_B for a given gas with ionization potential U_i is a function of the gas pressure *p,* the distance between the two electrodes, *d,* and the type of gas. This physical principle is known as Paschen's law and was discovered by Louis Karl Heinrich Friedrich Paschen in 1889. This relationship is given in Equation 2.1.

$$U_B = \frac{apd}{\log_e(pd)+b} \tag{2.1}$$

- where *a* and *b* are constants that are derived for the type of gas present (for dry air: *a* = 0.3902 and *b* = 5.399) [5].

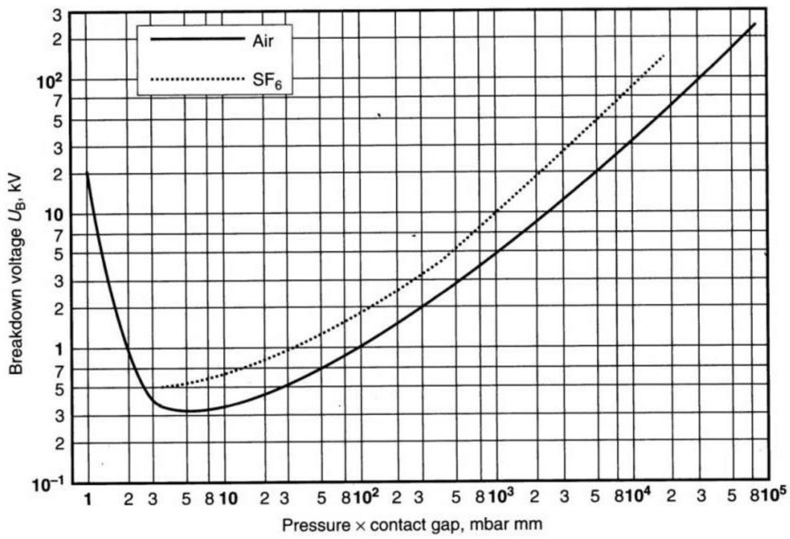

Figure 2-3: Paschen curves for contacts with a uniform electric field [5]

Figure 2-3 shows that the dielectric strength of an airgap with length 1 mm (typical of the separation of the contacts of a vacuum circuit breaker) starts to increase rapidly as the air pressure drops below approximately 10 Pa (10^{-1} millibar or one-ten-thousandth atmospheric pressure). It continues to rise rapidly until the pressure reaches approximately 10^{-1} Pa (10^{-3} millibar or one-millionth atmospheric pressure). The breakdown voltage of an open vacuum interrupter will therefore vary depending on contact design, contact separation and vacuum level [5].

2.2.3 The arc and current interruption

When a circuit breaker is opened, an arc is formed between the contacts. The most difficult part of circuit breaker construction is to design it in such a way that the arc is extinguished as soon as possible. After the contacts have parted mechanically, the current will continue to flow between the contacts through an electric arc, which consists of a core of extremely hot gas (±15000°C). The high arc temperature vaporizes the contacts in an explosive change from solid to vapor. Metal is blasted and splattered from the blast location [6]. The vacuum arc exists in three modes:

- The diffuse vacuum arc (for currents ≤ 6 kA)
- The columnar vacuum arc (for currents ≥ 10 kA)
- The transition arc (for currents ≥ 6 kA and ≤ 10 kA)

The ionized path has a very low resistance and the arc will continue as the contacts are further separated. Conductive vapours help sustain the arc. Figure 2-4 illustrates the development of current and voltage trends during a single phase vacuum interruption Radial Magnetic Field (RMF) contact geometry.

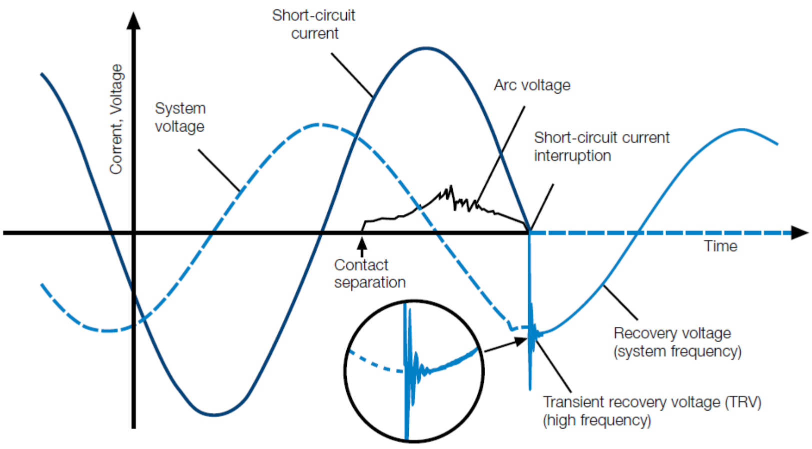

Figure 2-4: Current and voltage waveforms for a Radial Magnetic Field (RMF) contact geometry during short-circuit current interruption [1]

2.2.4 Recovery voltage and dielectric strength

De-ionizing the air will extinguish the arc at least for a short time. At this time voltage is available on the source side of the contacts while the other side is connected to a load or grounded. Thus voltage will build up across the contacts. This is called the recovery voltage and may or may not be sufficient to break down the separation between the contacts. With respect to time, the dielectric strength is increasing as the former path of the arc cools and the contact separation increases. However, the recovery voltage is also increasing.

Successful current interruption depends on the outcome of the race between the increasing dielectric strength and increasing recovery voltage. If the dielectric strength increases faster than the recovery voltage then the arc will not re-ignite. However, if the recovery voltage increases faster than the dielectric strength, the arc will re-ignite and current will continue to flow until the next current zero where a new attempt will be made to clear. This delay to the next current zero causes additional damage to the contacts [5].

2.2.5 Arcing contact materials

Contact materials vary depending on the application of the vacuum interrupter but are typically made from copper tungsten (CuW), chromium copper (CrCu) or alloys utilizing stainless steel. The type of load to be interrupted controls the type of contact design needed.

Softer materials designed in a spiral configuration (left of Figure 2-5) or better known as the Transverse Magnetic Field (TMF) geometry are used in standard MV vacuum circuit breakers and have excellent arc interruption capabilities. The current is spread across the face of the contact by the spiral magnetic field action. Their advantage is a simple physical structure and low power loss at nominal currents. Harder materials are designed in a configuration (right of Figure 2-5) known as the Axial Magnet Field (AMF) geometry and are used at higher voltages and for capacitor switching. They employ designs where the magnetic field is parallel to the current flow increasing the switching capacity of the interrupter [7].

Figure 2-5: Transverse Magnetic Field (TMF) electrode geometry (soft material) and Axial Magnetic Field (AMF) electrode geometry (hard material) [8]

2.2.6 Arc erosion of contacts

For the designer of circuit-switching devices, one of the most significant consequences of arcing is the effect that the arc has on the erosion of the contact material. Contact erosion occurs with stationary arcs when both the cathode and the anode under the arc roots are heated to the boiling point of the contact material. In fact, even when the arc is forced to move swiftly across a contact surface, the arc roots still melt the contact surface directly under them. The amount of erosion per operation of the contacts depends upon numerous parameters such as

1. Current being interrupted;
2. Arcing time;
3. Contact material;
4. Contact size and shape;
5. Contact opening velocity;
6. Contact bounce on make;
7. Open contact gap;

8. Arc motion on the contacts; and
9. Design of the arc chamber
   (a) Gas flow
   (b) Insulating material

The phenomenon of contact erosion is further complicated by mechanical stresses seen by the contact as a result of contact impact on closing [7].

2.2.7 Main contact end of life estimation based on the arc integral

In order to predict impending failures it is vital to have insight into the condition of the system. By using advanced algorithms, and also by taking into account failure statistics, the failure probability can be calculated and the fault occurrence can be predicted. Based on monitoring the integral of the arcing current one can have insight into the state of the main interrupting contacts of the vacuum interrupter without having to open it.

Common practice is to follow the OEM’s recommendation for the inspection or replacement of the vacuum interrupters after a set number of operations has been reached and/or depending on the operating conditions in which the circuit breaker has been operated (short-circuits interruptions).

This monitoring technique calculates the arc integral (integral of the square of the arc current multiplied by the arcing time) based on the main circuit current that has been interrupted during each opening operation as well as the duration of arcing as shown in Figure 2-6. This value is never the same and is a function of the current interrupted. Therefore, it is essential to monitor the sum of the arc integrals, and when the sum reaches a set value (see Figure 2-7 for an alternative way of expressing lifetime – interruption current versus number of operations) it indicates that the vacuum interrupter has reached the end of its life [6].

The sum of arc integrals can be expressed as [9]:

$$I = \sum_{p=0}^{n} \int_{t_1}^{t_2} i^2 t dt \qquad (2.2)$$

where:
i - main circuit current [A]
t_1 – instant when contacts separate [ms]
t_2 – instant when the arc extinguishes [ms]
n - number of operations

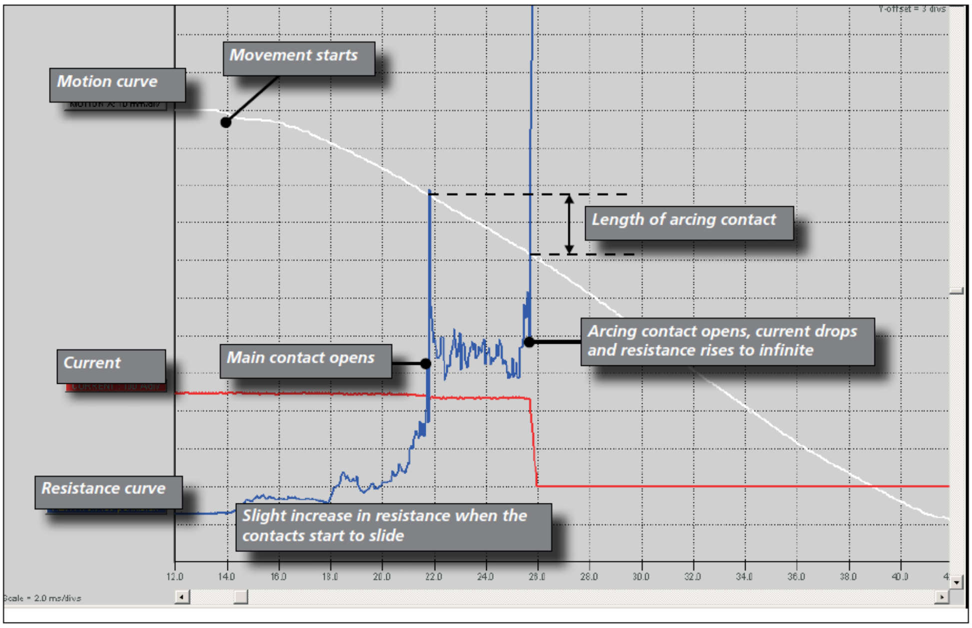

Figure 2-6: Contact travel curve, arc current, arc resistance and the arcing duration (the x-axis has units of time) [10]

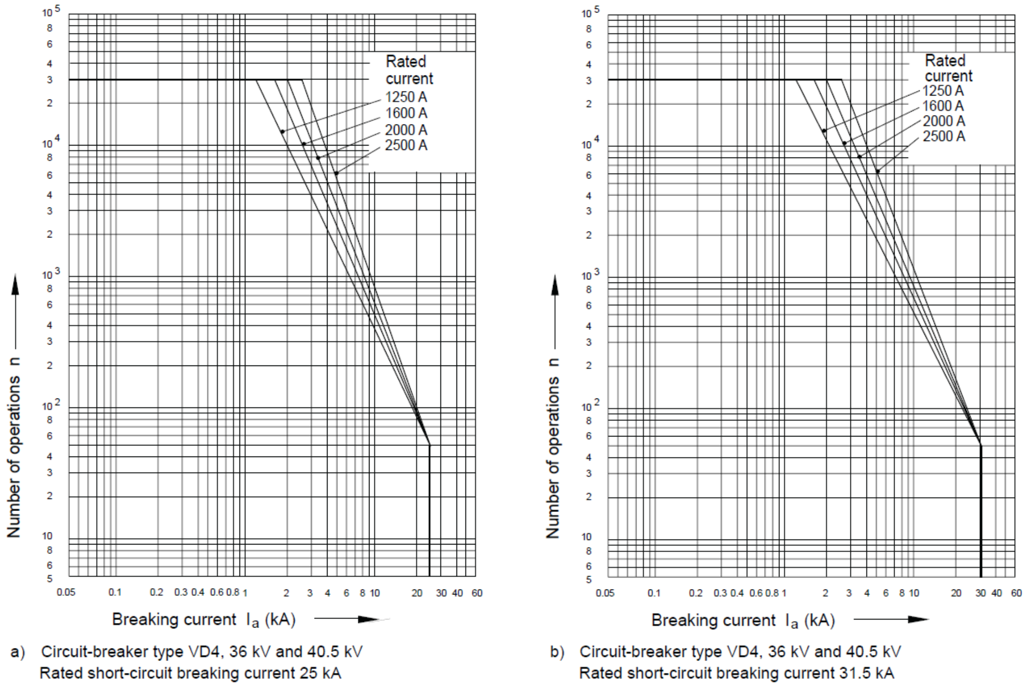

Figure 2-7: Circuit breaker contact life characteristic curve [10]

The main disadvantage of this technique, however, is that history information about the total amount of current interrupted as well as the number of operations for service aged circuit breakers is absent. Therefore, this technique would only be suitable for new circuit breakers that can be monitored during their lifetime.

2.2.8 Current chopping phenomena of vacuum circuit breakers

When interrupting current in inductive circuits (unloaded transformer or motor during start-up) using a vacuum switching device (contactors, circuit breakers, switches), it is likely that the current can be interrupted before it reaches its natural current zero.

When this happens, the arc plasma channel between the contacts no longer permits the passage of the current and the current drops to zero in a very short time. This phenomenon is termed “current chopping”. If the value of chopping current is high enough the magnetic field energy in the disconnected circuit resonates with the capacitance of the circuit and can result in high overvoltages that may lead to damage to the insulation of transformers and motors [12].

The following equation defines the resulting overvoltage (see Figure 2-8):

$$u_{\max} = \sqrt{\frac{L}{C}} \cdot i_{chop} \qquad (2.2)$$

Figure 2-8 illustrates the waveforms of the arc voltages and chopping currents during inductive load switching.

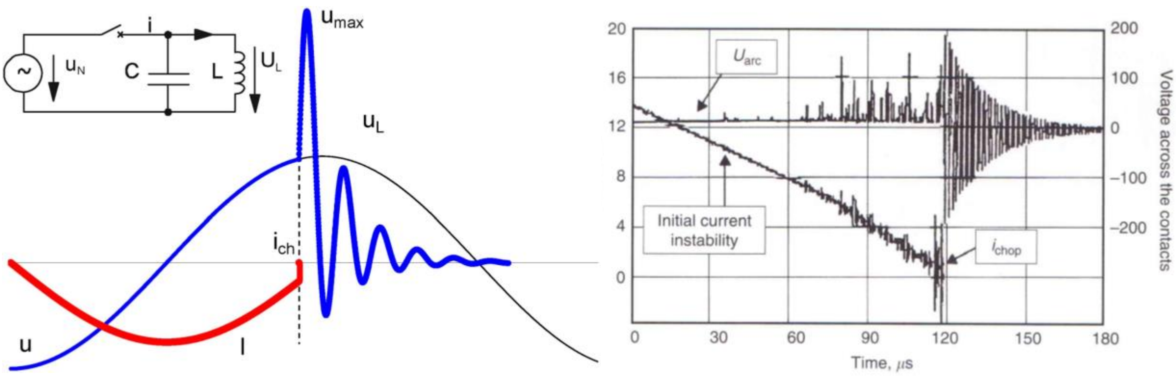

Figure 2-8: Current chopping during inductive switching [5][12]

With circuit-breakers using gas for arc quenching, the design of the arc quenching unit determines the chopping current. In contrast to this, the chopping current of vacuum circuit breakers only depends on the contact material. Table 2-1 tabulates the chopping current of some pure metals.

Table 2-1: Chopping current for some pure metals and alloys used for the contacts[5][13]

Metal	Average chopping current (A)	Maximum chopping current (A)
Ag	3.5	6.5
Cu	15	25
Cr	7	16
Ni	7.5	14
W	16	350
CuCr	4	8
AgWC	0.5	1.1

For all practical purposes, the maximum value of the chopping current for modern, vacuum interrupters using the optimum contact alloys (such as CuCr) is low enough that the phenomenon no longer poses a problem in the electrical circuits they are designed to switch and/or protect.

2.3 MV vacuum circuit breaker routine and type tests

2.3.1 Dielectric Tests

Power systems occasionally experience temporary power frequency over-voltages which arise during load disconnection, incorrect tap changer operation, insufficient shunt compensation and resonance. The dielectric tests are performed to verify the rated insulation strength of the switchgear to ensure that when a breaker is placed into service, it is capable of withstanding over-voltages occurring due to the aforementioned reasons and due to lightning and switching operations. [14].

2.3.2 Vacuum Integrity Test / High Potential Test

Since the inside of the vacuum interrupter cannot be visually examined, the only practical and widely used practice to check the vacuum integrity is by means of a dielectric test across the open contacts. This is recognized in a variety of standards, including ANSI/IEEE standard C37.09-1999 [15].

The purpose of vacuum integrity testing is to demonstrate that the pressure in the vacuum interrupter is still below the maximum level required to perform the switching and insulating functions. Measuring the pressure inside a vacuum interrupter is a very difficult task and these measurements can only be performed on a vacuum interrupter on its own, not when installed in a circuit breaker.

On a new 15 kV circuit breaker, the open contacts must be able to withstand 36 kV ac. For a circuit breaker that has been in service, the open contacts must be able to withstand 75% of the above value, or 27 kV ac. The 75% level for field dielectric tests is established in ANSI/IEEE C37.010 [16], clause 5.5.1, and provides a margin for normal deterioration, minor contamination, and the like.

2.3.3 One minute Power Frequency Voltage Withstand

This test is carried out to verify the capability of the equipment to withstand the power frequency test voltage for one minute. Suppliers shall prescribe the test procedures, including gap settings and test voltages, for conducting power-frequency withstand voltage tests on vacuum interrupters or switchgear utilizing vacuum interrupters [14].

2.3.4 Lightning Impulse Voltage Withstand Test

In contrast, the test to demonstrate the ability to withstand the rated lightning impulse (1.2/50 µs) withstand voltage is a statistical test. That is, 1 or 2 breakdowns are permitted in a group of a certain number of tests. This test is tolerant of the occasional breakdown at the rated impulse voltage. In fact, according to the testing standards, a component satisfies the lightning impulse requirement when it withstands the rated impulse voltage about 90% of the time (this constitutes the Basic Insulation Level (BIL) test). The test overvoltage does not ensure that all possible overvoltages will be withstood, but the requirements do provide that the equipment will withstand the most typical overvoltages that can occur in service [14].

2.3.5 Switching Impulse Voltage Test (Optional)

This test is performed to confirm whether switchgear is able to withstand over-voltages due to switching surges. Switching surges are produced when breaking inductive/capacitive loads. Switching surges are of longer duration, lower rate of rise and are represented by a standard switching impulse (250/2500 µs) wave shape.

2.3.6 Temperature Rise Test

This temperature rise test determines the highest continuous current that the switchgear can carry without exceeding the maximum permitted temperature at any point. The current rating is dependent upon the maximum ambient temperature.

2.3.7 Short Time Current Withstand Test

This test verifies the capability of a circuit breaker to carry the specified power frequency short-circuit current for a rated duration of 1 second or up to 3 seconds.

2.3.8 Short-circuit Current Duty Test

This test proves that the circuit breaker will reliably interrupt the complete range of fault currents up to its maximum short-circuit current rating.

2.3.9 Impulse Voltage Testing of Vacuum Interrupters

When a vacuum interrupter is newly installed in a mechanism, it is usual to perform a number of no-load operations to test the mechanism's operation. This switching without current can have a temporary effect on the Basic Insulation Level (BIL) high voltage withstand ability of the new vacuum interrupters. Under no load there can be a wide variation in the breakdown voltage of the contact gap. The breakdown voltage can be much less than the conditioned value.

Smith [17] describes a testing procedure that can be followed during laboratory tests that both assures the reconditioning of the new contacts as well as enabling the true BIL of the new vacuum circuit breaker to be determined. In fact, it is even possible for the BIL to be much higher. One reason for this is that the contact surfaces will be work hardened as they make contact. The work hardening of the contact surfaces will help to increase their voltage withstand capability.

2.4 MV vacuum circuit breaker reliability and failure modes

2.4.1 Reliability

When establishing the financial viability of any monitoring and diagnostic approach, reliability figures are a vital component. Whenever a circuit breaker fails, it means that switching did not occur within the time frame required to prevent damaging interconnected assets (e.g., transformers and/or generators) and the circuit breaker itself. Studies have indicated that MV circuit breaker records that could be used to do a proper analysis of circuit breaker reliability are imperfect, incomplete and outdated [18].

The IEEE has completed nationwide surveys and data collection in order to gain knowledge on equipment reliability and failure modes. Although the results obtained were incomplete, the report was published as IEEE Std. 493-2007 [18] which has become a standard resource across the industry.

The most recent reliability figures for MV circuit breakers published in IEEE Std. 493-2007 indicate an annual failure rate of 3.3%. This high rate is somewhat in line with other published guidelines, which place circuit breaker failure rates roughly between 0.1% and 3.0% [19].

2.4.2 Failure modes

With continued strengthening of the national power system, the system fault levels at older installations can in some cases exceed the fault rating of the switchgear. The switchgear then becomes overstressed during fault conditions and the risk of failure is increased. As in the previous section, failure rates described how often equipment fails. Failure modes, however, describe how an individual component, assembly or system associated with the MV switchgear can result in maloperation.

As with MV circuit breaker failure rates, comprehensive failure mode records are also scarce, incomplete and outdated. In spite of this inadequacy, industry is aware that gradual mechanical and/or electrical degradation of components is the leading contributors to failure. It is uncertain, however, as to what the root causes of deterioration are.

2.5 Parameters of the study

2.5.1 Parameter and sensor technology evaluation

During the development of this project, multiple monitoring parameters and sensing technologies were researched. Table 2-2 summarizes the merit of all monitoring parameters and sensing technologies considered during the development phase of the project. A simple technology score provides a degree of overall merit [19][20].

Table 2-2: Parameter monitoring and sensor evaluation

Viability (0 represents potentially viable, 1 represents viable, and -1 represents not viable)										
Monitoring Parameters	Cost	Dev. Time	Access to Data	Reliability	Life expectancy	Maturity	Fault detection accuracy	Overall failure reduction	Technology Score	Existing solution
Trip/Close Coil current profiling	**0**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**6**	**No**
Interrupter Temperature (SAW)	**0**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**6**	**No**
Humidity	1	1	0	1	0	1	0	0	4	Yes
Trip/Close coil continuity	0	0	0	1	1	1	1	-1	3	Yes
Position proximity sensors	1	0	0	1	1	1	-1	-1	2	No
Primary/secondary fault current (interrupter wear)	-1	-1	1	1	0	1	1	-1	1	Yes
Interrupter pressure sensors	-1	-1	1	1	0	1	1	0	2	No
Position travel sensors	-1	-1	1	0	0	1	1	1	2	No
Interrupter resistance	-1	-1	1	1	1	-1	1	-1	0	No
Primary/secondary fault current (timing/trending)	0	-1	-1	1	1	-1	-1	0	-2	No
Vibration	1	-1	-1	1	1	-1	-1	0	-1	No
Partial discharge (Ozone)	1	0	-1	-1	-1	-1	0	-1	-4	No
Partial discharge (Electrical)	-1	-1	-1	-1	1	-1	0	-1	-5	Yes

From Table 2-2 it is clear that mechanical and thermal monitoring might potentially be the most effective means of assessing circuit breaker health.

2.5.2 IEEE suggestion for the monitoring of circuit breakers

The IEEE, along with the work of CIGRE, published a report [21] in which it highlighted the most common failure modes for equipment rated 1 kV or higher. The objective of the report was for it to serve as a guideline when designing or selecting equipment monitoring schemes. The report gives a thorough understanding of failure modes and provides the key supporting structures and ideas that need to be considered. The major part of the report [21] documents 60 expected failure modes usually observed in circuit breakers. The report recommends the best monitoring technologies and/or practices for the specific failure mode, and labels the inception of each failure mode as gradual, sporadic, or a combination.

Bearing in mind that a main design objective for MV monitoring and diagnosis is to capture the most gradual failures with the least number of sensors, this grouping of failures is very useful when evaluating the merit of different sensor technologies. Of the 60 failure modes documented, 54 apply to vacuum interrupters. Of these, 21 are gradual, 16 can be either gradual or sporadic and the remaining 17 are sporadic and do not have a practical means of detection. Table 2-3 presents the parameters that have the most impact from a monitoring perspective, as well as percentage of failure modes they can detect.

Table 2-3: Failure mode detection for MV vacuum circuit breakers [21]

Detection method	21 out of 54 are gradual failures	16 out of 54 are both gradual and sporadic failures	17 out of 54 are sporadic failures
Mechanical Operation Profiling	8 out of 21 (38%)	5 out of 16 (31%)	Do not have a practical means of detection.
Temperature Trending	5 out of 21 (24%)	2 out of 16 (13%)	
Primary Current Interruption (Relay)	1 out of 21 (5%)	1 out of 16 (6%)	
System Current and Voltage (Relay)	1 out of 21 (5%)	1 out of 16 (6%)	
Total→	15 out of 21 (71%) failures can be detected by monitoring parameters 1 to 4	9 out of 16 (56%) failures can be detected by monitoring parameters 1 to 4	

- Mechanical Operation Profiling – captures the information relating to the mechanical operation of the device (i.e., speed, timing, etc.). The principle behind mechanical monitoring is to detect discrepancies in behaviour that precede failure.
- Temperature Trending – its function is to identify changes in the electrical resistance of the load carrying components of the equipment. Resistance will increase as a result of deterioration and consequently the equipment will experience higher temperatures.
- Existing Information – Current and voltage readings available in conventional relay systems can tell if fault currents and/or high load currents were present in the equipment's history. The number of switching operations recorded by an operations counter can also indicate if the equipment is experiencing some form of accelerated ageing.

2.6 Existing time-based maintenance strategies

Although reliability information is incomplete and outdated, industry reports find mechanical and thermal stresses as the biggest contributors towards failure. The use of existing test equipment and maintenance practices in most industries serves as a confirmation of this.

2.6.1 Circuit breaker time travel analyses

With emphasis on the operating mechanism of circuit breakers, one useful parameter to effectively diagnose the health of the mechanism is the trip/close coil current signature. The coil current is easily accessible and measurable, which can be assessed online or offline [22]. The time-travel analysis is done to determine the time the breaker contact takes to move from the closed to the open position. This analysis is a means of proving that a circuit breaker's opening mechanism is in good physical condition. The test equipment used to do the analysis comprises a time-travel analyzer that is capable of capturing the actuator's coil current signature (open and close coils), and provides timing information across all three breaker phases for both TRIP and CLOSE switching operations.

Figure 2-9 shows a commonly used time-travel analyzer along with the test unit's interrupter timing trends (red, yellow, blue trends) and the circuit breaker's actuation coil current pulse (brown trend). This coil current pulse, a 40-200-millisecond breaker-specific signal that can reach 50-150 Amperes, provides a measure of the total energy required to operate the circuit breaker.

The signal also gives an indication of overall circuit breaker health and provides technicians valuable troubleshooting information while performing maintenance and restoration work. A drawback of these systems is that coil current profiling can only be done offline during time based maintenance activities

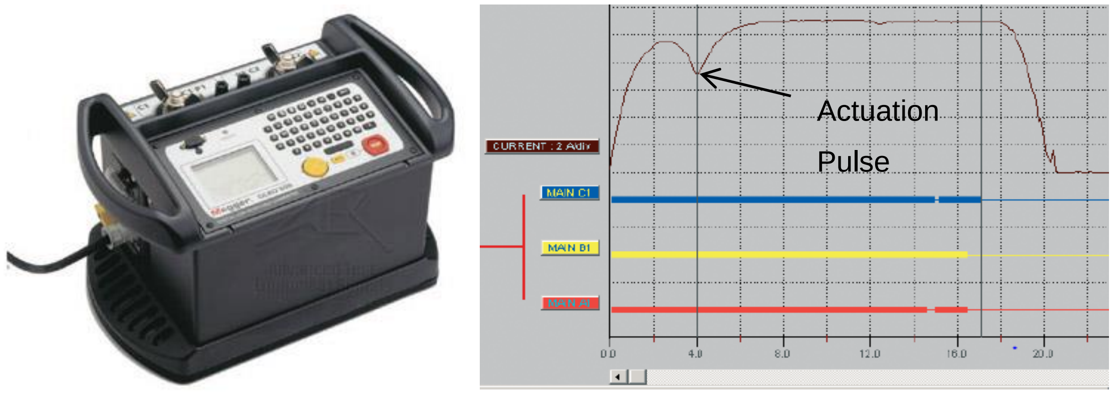

Figure 2-9: Time-travel analyzer with actuation coil current signature [23]

One objective of this research is to monitor the trip/close operation of medium voltage vacuum circuit breakers online and to provide an intelligent failure detection algorithm based on the results of exploring the characteristics of trip/close coil current signatures of healthy and defective circuit breaker mechanisms. The failure modes within the mechanical mechanism of the circuit breaker that should be investigated are the variation in auxiliary supply voltage, increase in coil resistance, excessive friction of the release mechanism and faulty auxiliary contacts.

The impact of each specific failure on the coil current behaviour and operation time of circuit breakers (closing and opening times) needs to be observed to derive the discrepancies in the coil current behaviour during the healthy and faulty conditions. Section 3.3 gives an overview on circuit breaker actuation systems and a methodology of how the aforementioned actuation pulse current behaviour can be used for monitoring and diagnostic applications.

2.6.2 Circuit breaker hot-spot thermal imaging

A key requirement for vacuum interrupters is to pass continuous current in the closed position with a limited temperature rise range [19]. Although vacuum interrupters spend the bulk of their service life in the closed position, they could be subjected to extreme stresses such as short-circuit current interruption.

After short-circuit operations, the resistance across electrical contacts will generally increase due to the melting of the contact surfaces caused by the making and breaking arcs. In electrical equipment, abnormally high temperatures are associated with an increase in the resistance of the conducting path. As infrared technology has become accessible, maintenance crews have adopted thermal imaging as a means of identifying these potentially hazardous hot-spots on the breaker contacts or electrical connections to the breaker.

During circuit breaker maintenance, infrared technology is very convenient when looking at the equipment's external frame, but has its limitations when penetrating through enclosures. Due to the increased popularity and effectiveness of this testing technique, circuit breaker manufacturers now design their enclosures to include infrared scanning windows through which hot-spot visualization of internal components is possible. Figure 2-10 shows an example of a circuit breaker hot spot using a thermal image infrared scanner.

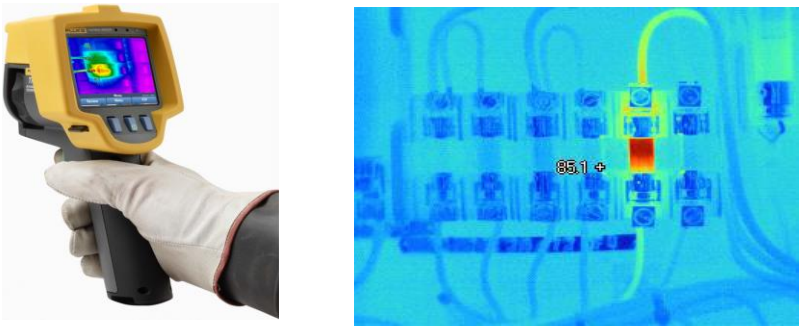

Figure 2-10: Thermal imaging equipment and example of circuit breaker hot-spot [24]

A second objective of this research is to focus on an online monitoring and diagnostic technique to detect the thermal behaviour of the interrupters. Direct measurement of the interrupter's electric contact temperature using continuous temperature monitoring of energized equipment provides real information related to the condition of the electrical contact. The advantage of continuously monitoring the condition of energized equipment online enables operation and maintenance personnel to determine the operational status of equipment, to assess the present condition of equipment, timely detect any abnormalities and initiate maintenance preventing impending possible forced outages [25].

2.6.3 Static contact resistance measurement

As mentioned previously, mechanical stresses on circuit breaker contacts reducing the area of the contact surfaces combined with arcing will increase the resistance across the closed contacts. This condition will generate heat that can reduce the reliability of the circuit breaker. Periodic measurements will show the rate of increase of the contact resistance value. When these values are compared to the data of the manufacturer's specification, a decision can be made to continue operation or replace. The measurements are taken as a dc voltage drop in the measurement circuit. The applied current will be a minimum of 100 A and a maximum of up to rated current. The maximum measured value can be 1.2 times of the value obtained at the temperature rise test. The Auto-Ohm 200 S3 true dc (direct current with controlled rise/fall time which aids in reducing magnetic transients) micro-ohmmeter from Vanguard Instruments can supply a current of up to 200 A [26] to accommodate the preferred standards for the testing of circuit breaker contacts. Measurements range from 10milli-ohms at 200 A to 5 ohms at 1 A to meet all standard high current requirements.

Table 2-4: Auto-Ohm 200 S3 Technical Specifications [26]

Input Power	100-240Vac, 14A, 50/60Hz
Resistance Reading Range	1 micro-ohm to 10 milliohms at 200A (0.1 micro-ohm resolution) 1 micro-ohm to 5 ohms at 1A
Accuracy	1A to 4.99A: 1% ±10 micro-ohms 5A to 9.99A: 1% ±2 micro-ohms 10A to 200A: 1% ±1 micro-ohm
Test Current Range	1 Ampere to 200 Amperes (selectable in 1A steps); Thermally protected dc power supply

Figure 2-11: Vanguard Auto-Ohm 200 S3 true dc micro-ohmmeter

2.6.4 Vacuum integrity assessment: Magnetron Atmospheric Condition (MAC) test

Focusing on the vacuum integrity of vacuum interrupters, the main disadvantage of vacuum interrupters is the possibility of losing vacuum and the absence of a simple method for effectively monitoring the level of vacuum in the interrupter. Although the lifetime of a modern vacuum interrupter is supposed to be more than twenty years, the possibility of abnormal inner pressure rise due to leakage, long term diffusion and other factors [27] cannot be completely excluded. In order to determine whether the inner pressure of a vacuum interrupter is within its safe operational limits, many techniques and test equipment have been developed [25], all of which are functional offline and require the removal of the vacuum interrupters from the circuit breakers.

Consequently, when the interrupters are to be reinstalled, some of the mechanical parameters of the vacuum interrupters must be calibrated, which is labour intensive and should be performed by qualified technicians.

Recently, a pressure diagnostic method known as the leak-rate test has been used by field technicians to detect the vacuum integrity of vacuum interrupters. Leak-rate testing provides results beyond a “pass/fail” result obtained from a high potential test which provides quantifiable data based on the internal pressure and interrupter geometry that allows maintenance personnel to use predictive maintenance procedures and programs that result in higher equipment reliability and improved lifetime compared to reactive maintenance programs [28].

Once the vacuum interrupter is finally assembled, evacuated, and brazed, the final product has a vacuum below 10^{-2} Pa sealed inside it (a ten-millionth atmospheric pressure). The method for measuring the vacuum level is based on the principle of a Penning discharge. Here a high dc voltage is applied between two suitable electrodes in the presence of an Axial Magnetic Field (AMF). Electrons are drawn from the cathode electrode by field emission and then spiral back and forth around the magnetic flux lines. Their travel path to the anode is thus considerably lengthened. When these electrons collide with residual gas atoms/molecules, ionization can occur and a small current flow can be measured. The level of current measured is directly proportional to the residual gas pressure. One way of performing this measurement using a vacuum interrupter is illustrated in Figure 2-12.

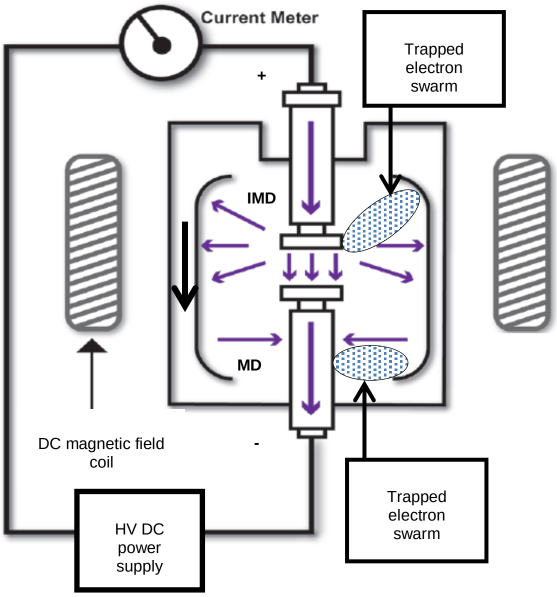

Figure 2-12: Vacuum level test using the Penning discharge principle [5]

The vacuum interrupter is placed inside a magnetic field coil. The contacts are opened and a dc voltage of about 10 kV is applied across them. In this case the trapped electron swarm is captured between the upper contact (in this example the anode) and the floating shield (i.e., an inverted magnetron discharge, IMD) [5]. An electron swarm is also trapped between the floating shield and the lower cathode (i.e., a magnetron discharge, MD). The current measured in the high voltage circuit thus flows from the anode to the shield and then to the cathode.

The actual current/pressure relationship for a particular vacuum interrupter depends on its internal geometry. Thus, before the magnetron method can be routinely used as a manufacturing test device, it has to be calibrated for each vacuum interrupter type. One way of performing this calibration is to add a nozzle to a vacuum interrupter and then attach it to a pressure gauge and to a vacuum system. The magnetron current can then be measured for a given vacuum interrupter as a function of the actual pressure inside the interrupter. A calibration test setup is shown in Figure 2-13.

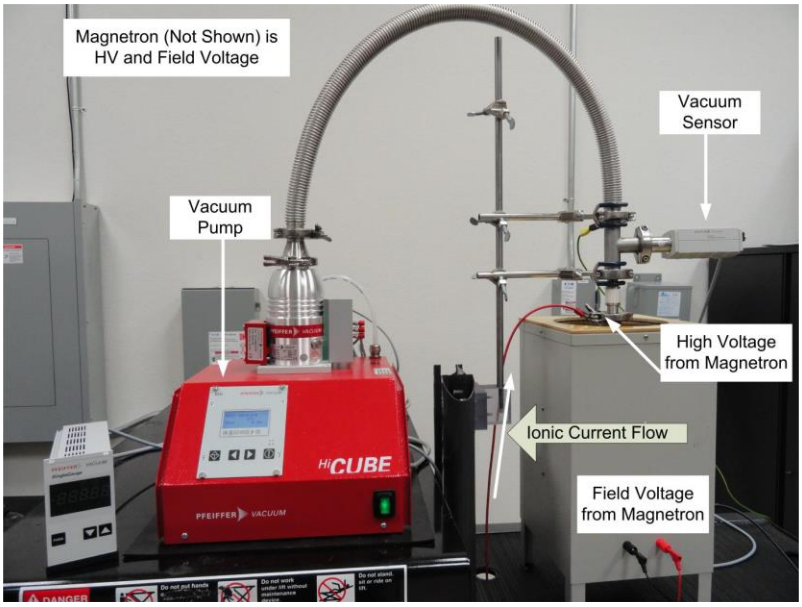

Figure 2-13: Creation of pressure versus current data [28]

Previously both technical and logistical problems have prevented the use of the magnetron in the field. With the new procedures and equipment that are available, the vacuum can now be tested in the field. Case studies have proven that incipient failures can be predicted with this test. Figure 2-14 shows a portable magnetron connected to a vacuum interrupter via a flexible field coil.

Figure 2-14: Vacuum interrupter pressure measurement with portable magnetron [28]

2.7 Condition monitoring and Condition-Based Maintenance

Condition-Based Maintenance (CBM), also known as Predictive Maintenance, is a maintenance strategy utilized by industry to actively manage the condition of assets in order to execute maintenance only when it is necessary and at the most suitable times. CBM intended to “do only what is required, when it is required,” has been reported as the most efficient maintenance strategy for circuit breakers [29]. Since utilities have an interest in downscaling their staff and subcontracting the work, this strategy may cause crucial knowledge and skills to be jeopardized [30]. Consequently, all of these point towards the need for intelligent knowledge base circuit breaker diagnostic algorithms and a smart fault detecting method. CBM can radically cut operating costs and increase the safety of assets requiring maintenance. Corrective/reactive maintenance can be very expensive, and preventive/scheduled maintenance replaces parts before the end of their useful life. As seen from Figure 2-15 below, CBM optimises the trade-off between maintenance costs and performance costs by increasing availability and reliability while eliminating unnecessary maintenance activities.

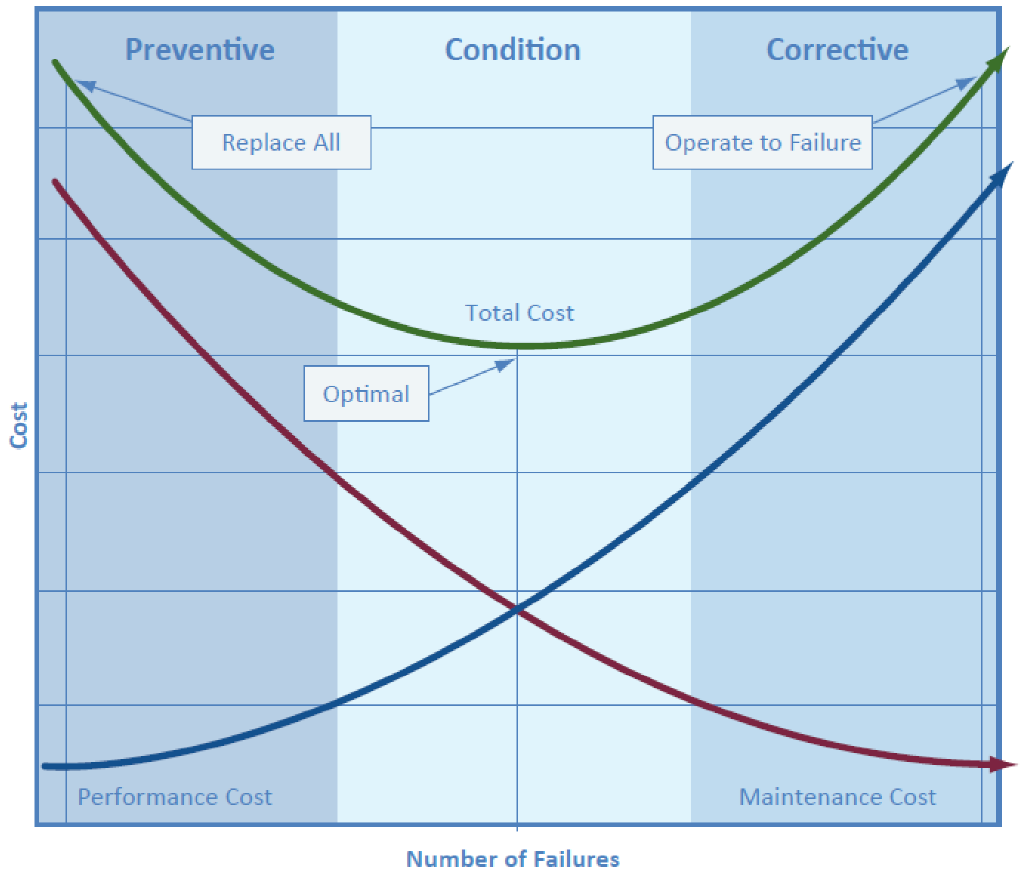

Figure 2-15: Condition-based Maintenance Graph [29]

Table 2-4 below lists the main advantages and disadvantages of three different maintenance strategies [32].

Table 2-5: Comparison between maintenance strategies [32]

Strategy	Advantage	Disadvantage
Corrective maintenance	• Low maintenance costs during operation. • Components will be used for a maximum lifetime.	• High risk in consequential damages resulting in extensive downtime. • Maintenance scheduling is not possible. • Spare part logistics is complicated. • It is likely to have long delivery periods for parts. • High one-time maintenance costs.
Preventive maintenance	• Expected downtime is low. • Maintenance can be scheduled. • Spare part logistics is easy.	• Components will not be used for the maximum lifetime. • Maintenance costs are higher compared to corrective maintenance.
Condition-based maintenance	• Components will be used close to their full lifetime. • Expected downtime is low. • Maintenance activities can be scheduled. • Spare part logistics is easy given that a failure can be detected at an early stage. • Identification of incipient component degradation; • Automated and consistent assessment of component conditions; • Recognition of manufacturing faults; • Reduced maintenance costs.	• Reliable information about the remaining lifetime of the components is required. • Additional condition monitoring hardware and software are required. • The market for condition monitoring systems within power industry is not mature.

2.7.1 Existing condition monitoring technologies

MyRemoteCare and MySiteCare are ABB solutions developed to remotely monitor and diagnose the health of circuit breakers and enable engineers to recommend the right type of maintenance at the most suitable time for each asset by analysing the extracted data. With these monitoring and diagnostic systems, failures can be prevented and accurate planning of maintenance can be done.

MySiteCare implements predictive diagnostic algorithms and provides indications concerning the mechanical, electrical and operating conditions of the circuit-breaker [33]. MySiteCare monitors the following parameters:

- Operation of the mechanical mechanism: opening and closing times, spring charging time, slipping and spring load failure, switching operations, idle time.
- Remaining life prediction and contact wear.
- Monitoring enclosure temperature and auxiliary voltage.

MySiteCare has an easy to read interface that presents faults by means of a traffic light indication: red, yellow and green. This signal indicates the severity of the fault, thus the probability of failure or weakened reliability and health of the monitored equipment.

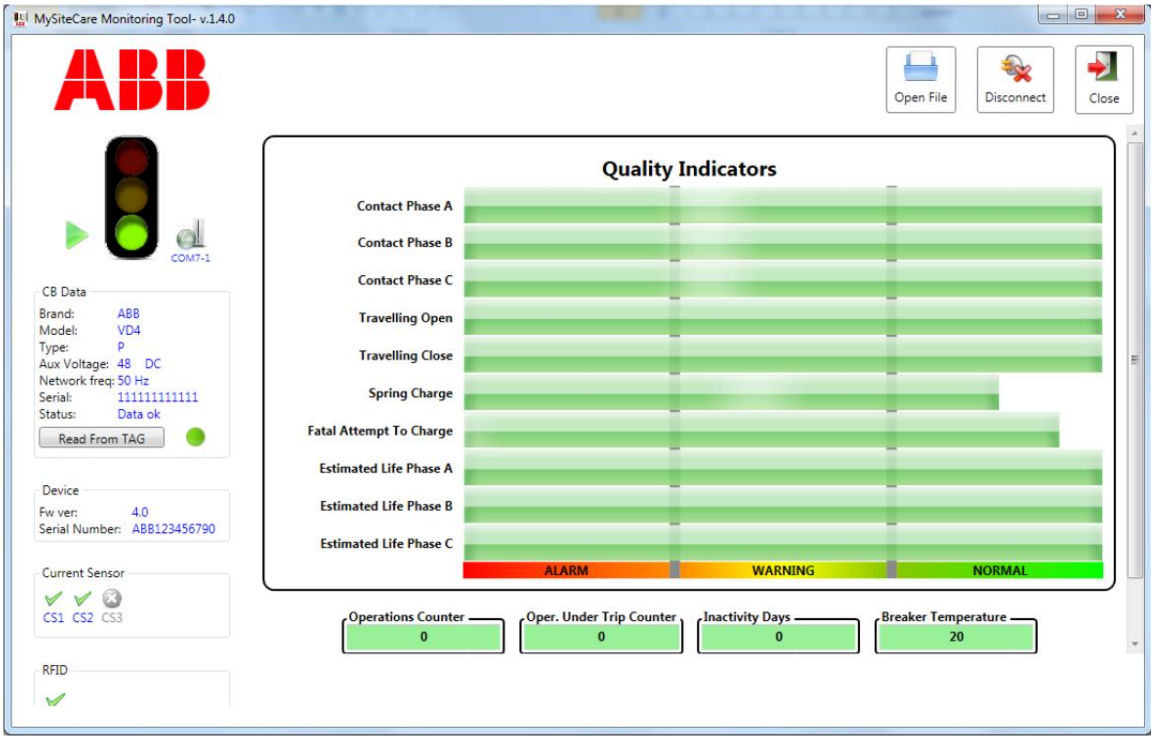

Figure 2-16: MySiteCare Monitoring Interface [33]

One MySiteCare has to be installed on each breaker and the switchgear does not require any changes to the circuit breaker, the protection relay or switchboard.

MySiteCare consist of:

- the central unit with digital inputs,
- the current sensor that measures the trip current, and
- the radio frequency identification (RFID) device.

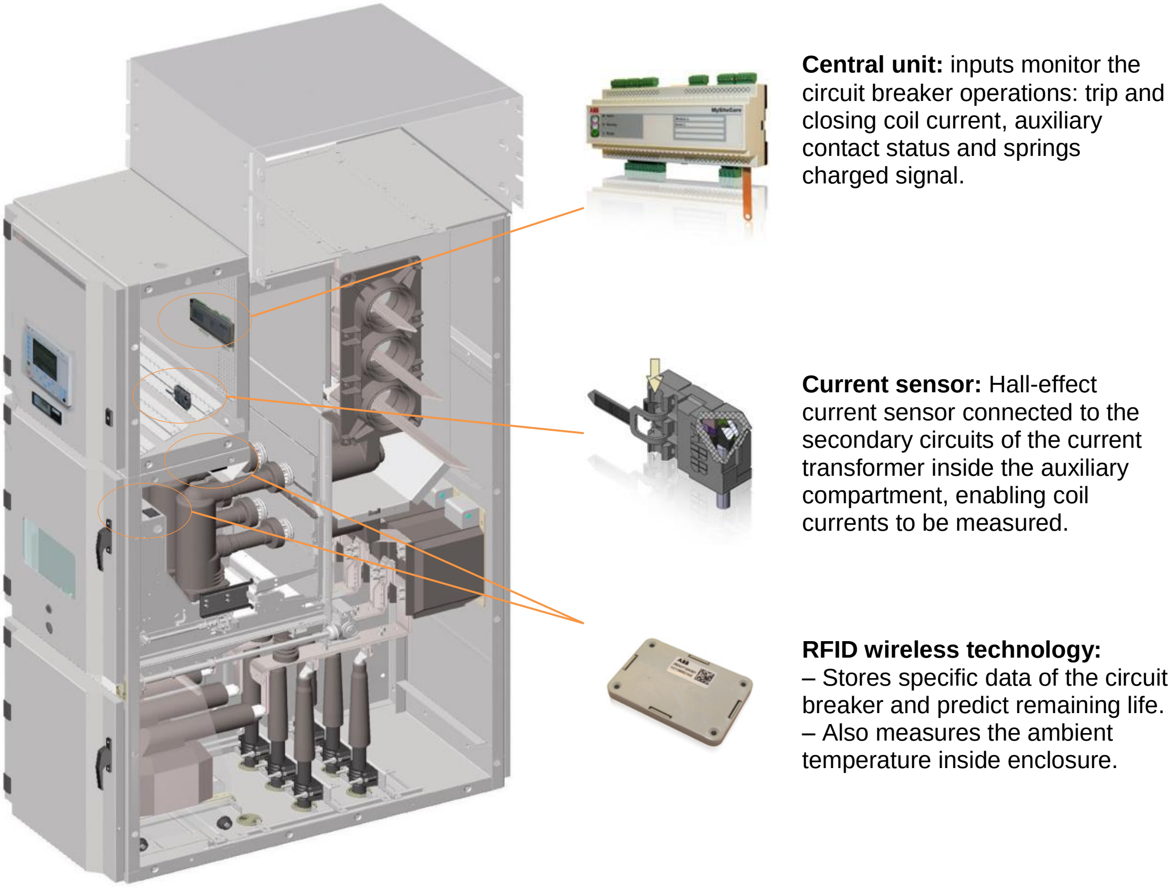

Figure 2-17: MySiteCare Monitoring and Diagnostic System [33]

ABB's MyRemoteCare is a simple service for remote display and analysis of the conditions of the circuit breakers. MyRemoteCare stores diagnostic information about the individual asset and uses it to generate reports and alarms. In addition, it allows historical data to be analysed, which helps to detect abnormality. With this tool, technical support can be provided to maintenance personnel and optimal maintenance planning can be done.

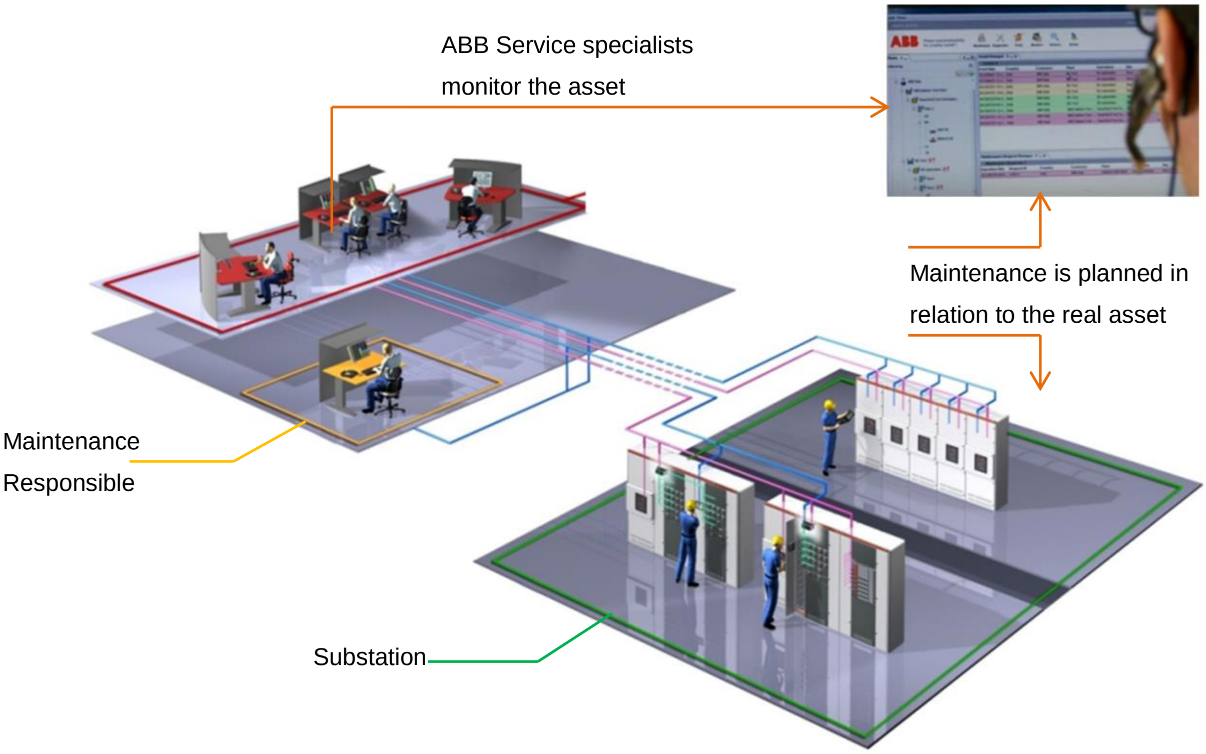

Figure 2-18: MyRemoteCare Monitoring Interface [33]

2.8 Literature Survey Conclusion

The MV vacuum circuit breaker yearly failure rates published in the latest international standards are in the 0.1-3% range [19]. The failure rates are highly influenced by environmental conditions, equipment loading, and maintenance activities. As ageing begins to emerge, equipment failure rates will increase notably unless maintenance operations transition from time based practices towards condition based practices. Although detailed reliability information is absent, industry experience has shown that mechanical and thermal monitoring are the first and second most effective means of assessing circuit breaker health.

To design a monitoring and diagnostic system that would be capable of detecting all failure modes would be too ambitious and expensive. However, it is realistic to assume that 50-70% of failures should be detectable with monitoring and diagnostic systems that utilize mechanical and thermal trending capabilities, as well as the additional existing parameters such as the voltage and current measurements. This statement, however, can be validated by detailed reliability information and extensive field testing.

Chapter 3 Research Methodology

3.1 Introduction

Rather than increasing the frequency of time-based maintenance intervals to mitigate the ageing infrastructure problem, an online switchgear monitoring and diagnostic system offers the possibility of implementing condition based maintenance schemes as a means of extending the life of existing equipment. The research's hypothesis is that it is possible to develop a cost-effective monitoring and diagnostic scheme for MV vacuum switchgear which should be capable of predicting impending failures and to detect equipment aging and deterioration. The focus of this research will be on circuit breaker temperature and mechanical operation monitoring and diagnostics.

3.2 Thermal monitoring of vacuum interrupter contacts

From a real-time monitoring standpoint, thermal imaging technologies are limited by cost, are restricted to certain fields and require complex image algorithms that limit their flexibility as a monitoring and diagnostic system for electrical equipment. For this reason, alternatives need to be investigated. With reference to MV circuit breakers, the main source for hot-spots originates from the interrupter's contact surface, which over time will deteriorate and will result in increased electrical resistance and temperature [34].

If these parameters are not monitored for a long period of time and deterioration reaches a critical state, arcing across the contact surface - a high temperature phenomenon – will most probably occur. With this understanding, industry saw the need for developing reliable and rugged long-life sensors capable of withstanding the harsh conditions that exists in the area directly outside the vacuum interrupter's contact enclosure indicated by the red zones in Figure 3-1.

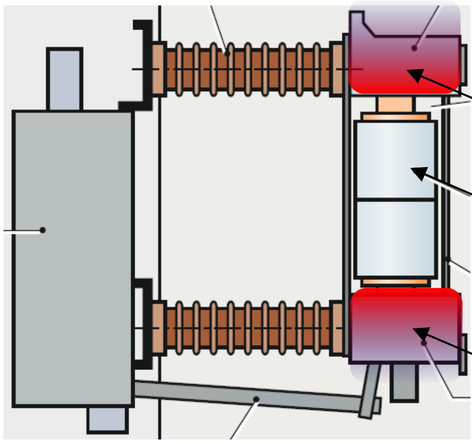

Figure 3-1: Preferred temperature monitoring areas in MV circuit breakers [35]

3.2.1 Thermal monitoring and analytics

Thermal protection for circuit breakers has been implemented in the HV range since the mid 1990s [36] and the fundamental physics is well understood and documented. It is only recently, as technology has advanced, that it is worthwhile to implement such monitoring systems in the MV range. Monitoring can range from basic alarms that initiate upon reaching a pre-set temperature threshold typically set at limits established by ANSI or IEEE standards, to the more complex real-time modelling of the interrupter's temperature relationship with current and heat transfer physics.

In most cases, an alarm implies that equipment is undergoing overtemperature stresses and is therefore more prone to failure, as equipment should hardly ever experience such high temperatures. On the other hand, real-time monitoring of the interrupter begins with a physical model of the heat energy balance: heat energy generated in the interrupter due to its contact resistance must add up to the heat convected to the interrupter's surroundings and the system's absorbed heat – as reflected in the equipment's temperature (3.1) [37].

$$RI^2dt = K\theta dt + mCd\theta \tag{3.1}$$

R = Interrupter resistance [Ω]

I = Interrupter current [A]

K = Characteristic constant of heat exchange [W/°C]

$\theta = T_i - T_e$ [°C]

T_i = Interrupter internal temperature [°C]

T_e = Interrupter external temperature [°C]

m = Interrupter heat capacity [W/kg]

t = Time [s]

Further manipulation of (3.1) is possible when an interrupter is in steady state with known temperatures and load current [37].

$$\theta = \frac{RI_1^2}{K}\left\{\left(\frac{I_2}{I_1}\right)^2 - \left[\left(\frac{I_2}{I_1}\right)^2 - 1\right]e^{-t/\tau}\right\} \tag{3.2}$$

I_1 = Interrupter current initial state [A]

I_2 = Interrupter current end state [A]

Figure 3-2 shows a typical heat rise behaviour expressed in terms of a thermal time constant τ as a function of $H = \theta_2/\theta_1$ as described by (3.2). From a trending perspective, as the equipment degrades and τ decreases, shifts in thermal response times and temperature levels are detectable.

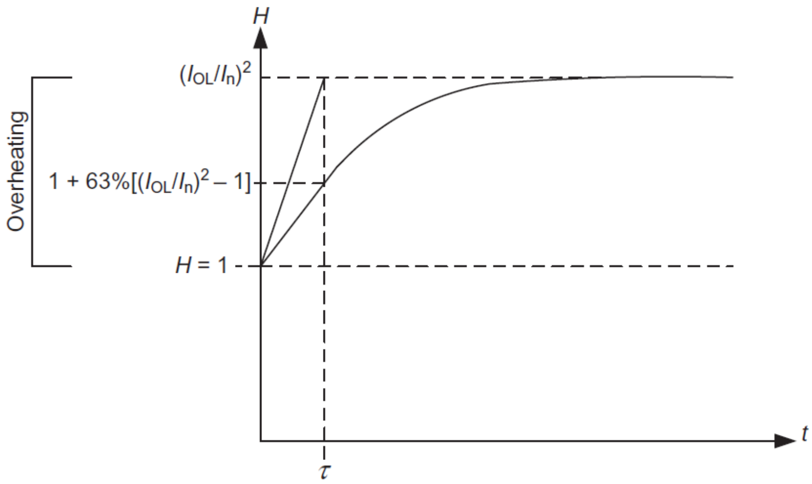

Figure 3-2: Interrupter heat rise characteristic [37]

Figure 3-3 shows the effect of current and interrupter condition on observed equipment temperature. Notice how temperature behaves linearly in the equipment's normal operating region. At elevated loads there is a visible upward inflection point. Thermal monitoring and diagnostic schemes are designed to sense this type of condition.

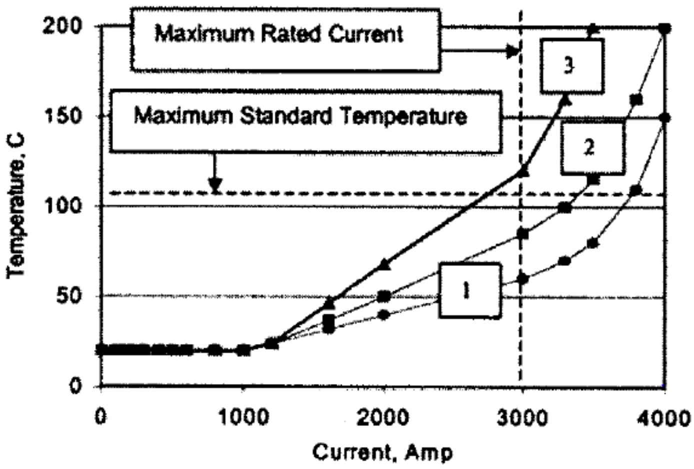

Figure 3-3: Interrupter steady state thermal behaviour: normal (1), worn (2), faulty (3) [34]

Real-time temperature prediction applications to monitor MV circuit breaker behaviour are based on a mathematical solution such as (3.2). In conjunction with the online temperature measurements, the load current must also be monitored when temperatures are measured in order to conduct a proper analysis. When abnormalities in readings occur, corrective action is initiated via preventive maintenance alarms.

3.2.2 Temperature sensor selection

Temperature sensing technologies commonly utilized in industries are thermistors, resistance temperature detectors (RTDs), thermocouples and quartz thermometers. The disadvantage of using these technologies on MV circuit breakers is that such sensors require a power source or battery packs and that the transmission of information captured by them would be difficult to realise since unwanted cabling would be required.

Present-day wireless and passive sensor technologies have significantly advanced and would be ideal for MV equipment and other applications in the electrical industry. Surface Acoustic Wave (SAW) based technology adapted for electrical equipment temperature monitoring is capable of sensing a broad range of temperatures (-40 to 220 °C). The SAW sensor system consists of a transceiver and the sensor itself. The operating principle, as illustrated in Figure 3-4, is as follows [38]:

The transceiver emits an electromagnetic wave that is received by the sensing element's antennae. The signal is then conducted to an Inter-digital Transducer (IDT) that will convert the energy of the signal into a SAW that will propagate and bounce off the sensor's reflectors back to the IDT.

The temperature of the device affects the wave propagation speed across the sensing element. Back at the IDT, the SAW is converted back into an electromagnetic signal that is sensed by the transceiver. The transceiver will then compute the time distance and translate this into a temperature reading.

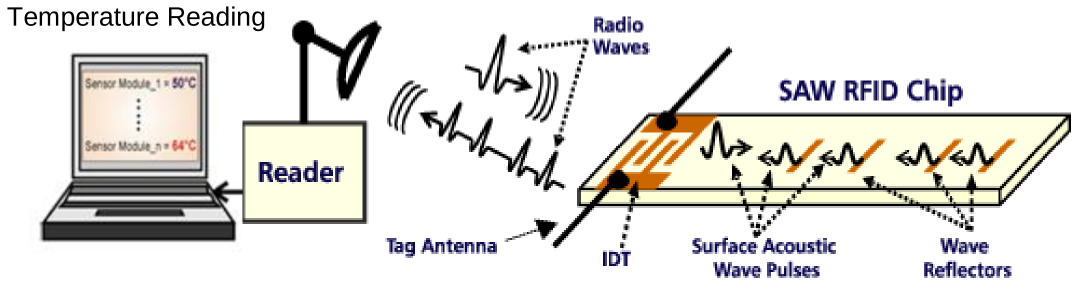

Figure 3-4: SAW wireless temperature sensing system [39]

IntelliSAW's wireless temperature sensing system for MV switchgear utilizes Surface Acoustic Wave (SAW) sensor technology that does not require an external power supply or batteries, simplifying installation and commissioning without contributing to arcing and flashover concerns.

These wireless temperature and humidity monitoring solutions use standard industrial Ethernet and RS485 data protocols such as Modbus to provide instantaneous monitoring and control to remote control rooms. IntelliSAW's wireless temperature sensing system is designed for harsh industrial and utility applications.

Figure 3-5 shows the IntelliSAW IS485 system that was used in this research for contact temperature measurement.

Figure 3-5: IntelliSAW IS485 temperature sensing system [40]

The IntelliSAW IS485 temperature monitoring system can accommodate twelve passive sensors per antenna - each with an independent frequency. This system can be extended to 48 sensors as it has four antenna connections. Challenges such as sensor drop-out, complex set-up procedures, sensor calibration sensitivity, and non-compliance to high-voltage applications are all overcomed by the IntelliSAW system. Figure 3-6 illustrates a typical IntelliSAW wireless temperature monitoring system installation for a fleet of six circuit breakers in an electric power switchgear substation.

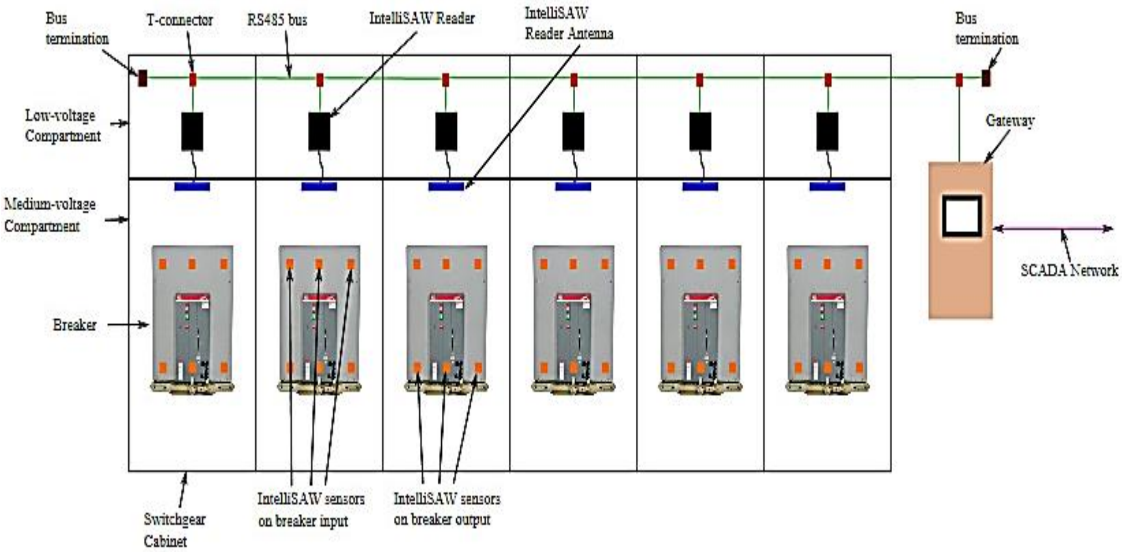

Figure 3-6:Typical IntelliSAW wireless temperature monitoring system installation in switchgear [41]

3.3 Mechanical operation monitoring of MV circuit breakers

As previously mentioned in Section 2.6.1, a circuit breaker time-travel analyser is used by industry to capture mechanical operation profiles. This analyser however, is used in time-based maintenance programs and requires that technicians install high frequency current sensors on the circuit breaker's actuator trip/close coils, install and calibrate displacement transducers on all three interrupters and connect the analyser to the circuit breaker's electronic control card. The information obtained from this instrument is precise and valuable from a maintenance and fault finding standpoint, as experienced technicians are able to diagnose and isolate impending issues based purely on specific circuit breaker components in motion at the time an abnormality is identified. From an MV circuit breaker monitoring and diagnostic standpoint though, this level of accuracy is not required as the objective of real-time monitoring is rather to provide early warning of approaching equipment problems. This is ideal for monitoring and diagnostic solutions which utilise fewer sensors in order to save costs.

3.3.1 Circuit breaker mechanical operation monitoring

The main reason why monitoring of the actuator coil current signature is so effective for circuit breakers is that the coil current's behaviour is directly impacted by the actuator system. Within the MV domain, circuit breakers are either spring or magnetically actuated.

By capturing and analysing the circuit breaker's actuation coil current signatures from open and close operations, it is possible to initiate preventive maintenance alarms based on the outcome of the analysis. In contrast with circuit breaker time-travel analysers, which require the combination of multiple sensed parameters, monitoring of the actuator coil current signature reduces the number of sensors to one or two high frequency current sensors that are connected to the circuit breaker's control circuitry [42][43][44][45]. Figure 3-7 and Figure 3-8 show the operation basics behind spring actuated circuit breakers and how they relate to the characteristic currents observed by the open –trip coil. Indices a-f, shown in the figures and described below, describe the sequence of events a typical spring actuated circuit breaker goes through during an OPEN switching operation:

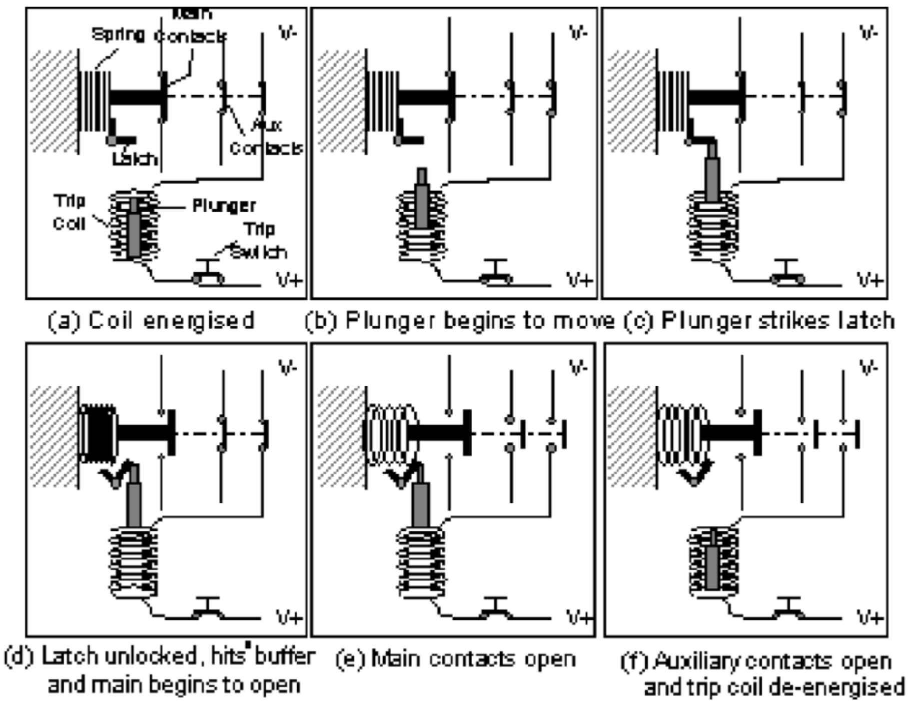

Figure 3-7: Spring actuator trip operation sequence [44]

a) **Coil energized** – The circuit breaker's trip coil is energized. The power source is either a capacitor bank or a storage battery.

b) **Plunger movement –** As the current in the trip coil increases, there will come a point after which the actuator's plunger will begin to move (magnetic – mechanical energy transfer).

c) **Plunger latch strike** – The plunger will strike the latch mechanism holding back the circuit breaker's OPEN spring mechanism.

d) **Latch unlock** – Towards the end of the plunger's travel, the latching mechanism will completely unlock and release the OPEN spring mechanism – the circuit breaker main contacts begin to separate.

e) **Main contacts open** – Once the OPEN mechanism springs are fully extended the interrupter main contacts will be completely OPEN.

f) **Trip coil de-energized** – Once the main contacts are open, auxiliary contacts supplying energy to the trip coil will also open and de-energize the actuation system.

Spring based circuit breakers have the disadvantage that when monitoring coil current, some insight pertaining to the mechanical operation of the apparatus is lost once the plunger has released the latch-buffer system.

Despite this, the approach provides valuable timing information that can be used in conjunction with existing primary and/or auxiliary interrupter contact position signals in order to produce a more effective real-time monitoring system. Figure 3-8 illustrates the shape of a typical circuit breaker coil current characteristic with spring actuator mechanism.

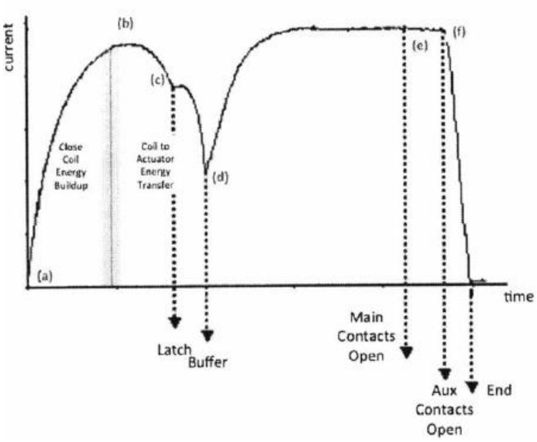

Figure 3-8: Spring actuator pulse relationship to mechanical trip operation [44]

From a design perspective, the ability to monitor both spring and mechanical actuation systems satisfies the design objective of creating a monitoring and diagnostic system capable of monitoring a wide variety of vacuum interrupter MV circuit breakers. The pulse characteristics are directly influenced by the physical resistance of all movable parts and therefore, the coil current characteristics can be used as a means of identifying deviations in the mechanical operation of a magnetically actuated circuit breaker. From a monitoring and diagnostic scheme's perspective, the ability to monitor both spring and mechanical actuation systems on a wide range of vacuum interrupter MV circuit breakers is advantageous.

3.3.2 Mechanical operation monitoring and analytics

From an analytical viewpoint, when considering magnetic coil current signatures as a means to conclude on circuit breaker health, the biggest challenge that industry and academia encountered is to make sense of the incomplete information that exists for MV circuit breakers in the field. The fleets of different makes and models of MV circuit breakers, the shortage of installed sensors, and the fact that the majority of circuit breakers are only operated once or twice a year, clarify the above-mentioned lack of information. Some methods that have been investigated by academia are Bayesian methods [46], pattern recognition algorithms and data mining techniques [47] in order to extract meaningful insight of the data and to infer on equipment health.

The right hand side of Figure 3-9 illustrates the relative and cumulative frequency distributions for all characteristic signatures monitored for a fleet of the same make-model circuit breakers. The information extracted from these plots can be utilized as feedback for more effective maintenance planning.

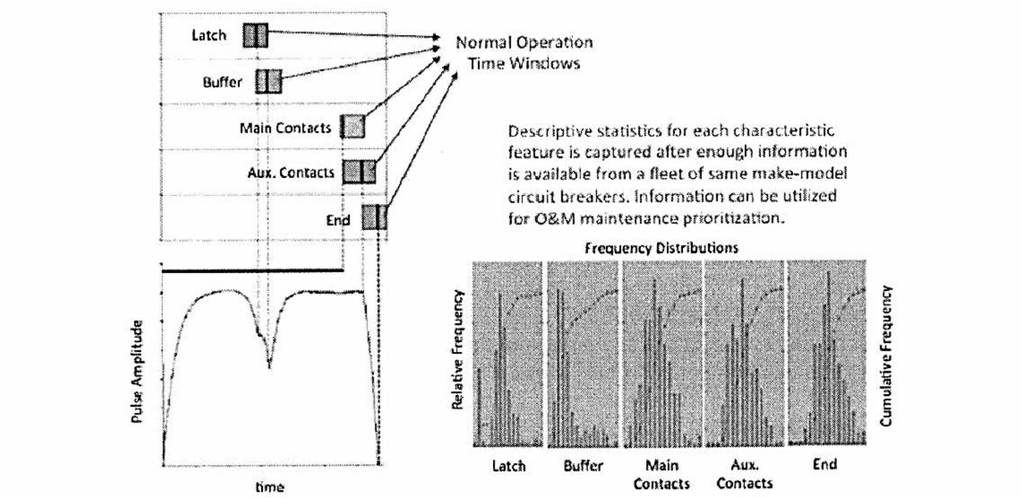

Figure 3-9: Spring actuator circuit breaker coil monitoring analytics - TRIP pulse [44]

Despite the fact that field data currently does not exist, TRIP/CLOSE actuation coil current signatures are immediately obtainable upon deployment of the monitoring and diagnostic scheme.

3.3.3 Mechanical operation sensor selection

In order to capture the current flowing through the actuator's coil, a sensor capable of rapid response times is crucial in order to observe the pulse's defining characteristics during a trip or close operation. Sampling at a frequency of 80 kHz proves to be adequate to perform equipment diagnostics and analytics. When sampling at 80 kHz on a 150 ms pulse, the timing resolution error will be approximately ±1.5%. Besides the sampling capability requirements, the sensor's packaging needs to be such that installation of the sensor is possible in confined spaces. The design should also be such that installation of the sensor can be done without having to disconnect any of the wiring in the area where actuator coils and controller cards are normally installed.

The sensor technology that fulfils the above criteria the best is a Hall-effect current-to-voltage transducer that responds to magnetic fields. These sensors are widely used in industrial and automotive applications and have proven to be successful in detecting circuit breaker actuator pulse characteristics [48].

The only concern however, is that when this type of sensor is installed, the magnetic fields in the vicinity of the sensor could possibly cause sensing distortions that could lead to false actuator coil current readings.

To mitigate this problem, the development of an integrated circuit Hall-effect transducer (Figure 3-10) should possibly reduce the aforementioned distortions.

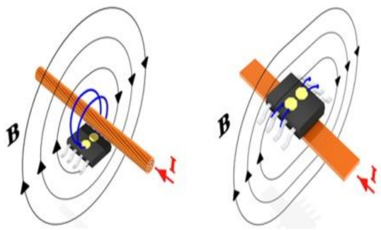

Figure 3-10: Hall-Effect transducer and current induced magnetic field [49]

3.3.4 Proposed MV monitoring and diagnostic integrated system overview

The proposed integrated MV circuit breaker monitoring and diagnostic system in Figure 3-11 consists of sensors physically connected to a communication module capable of real-time processing, data storage and analysis. The temperature monitoring system, as described in section 3.2, includes the SAW sensors, transceiver antennae, and a reader-decoder.

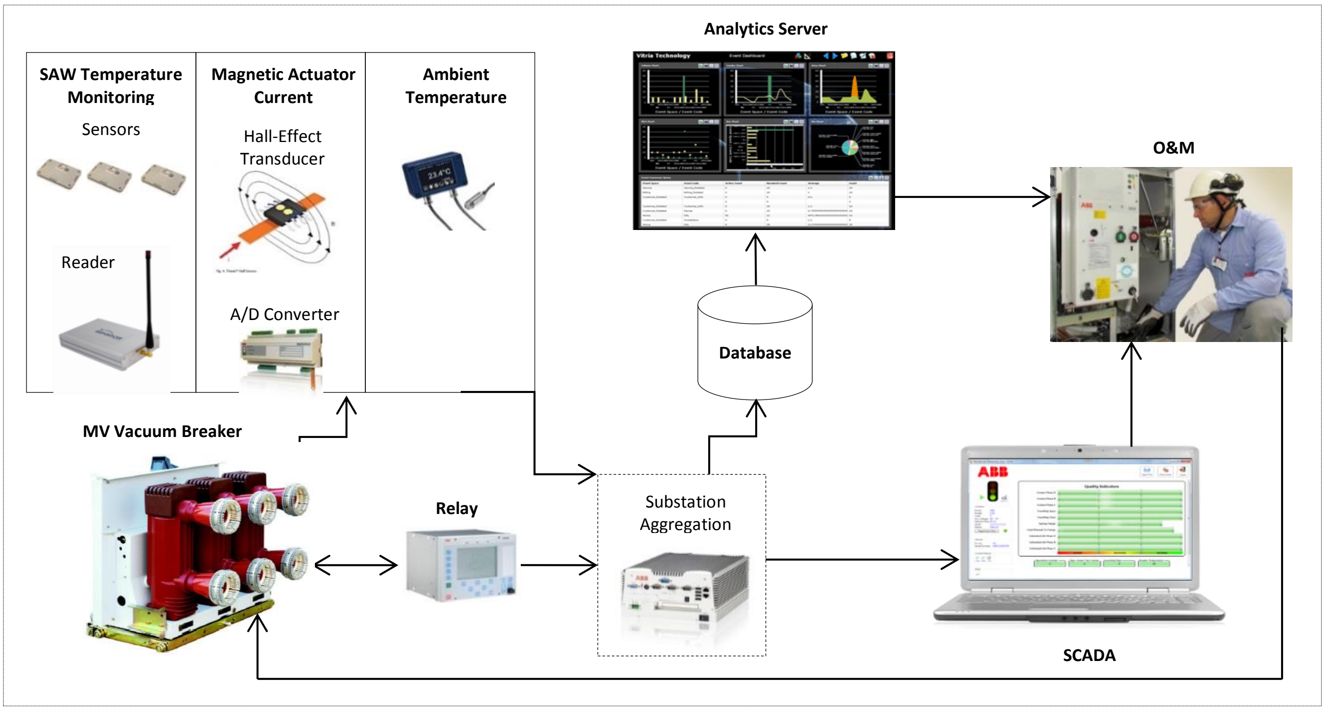

Figure 3-11: Proposed MV circuit breaker monitoring and diagnostic system

The mechanical operation monitoring system, as discussed in Section 3.3, is composed of two Hall-effect sensors linked to an A/D converter module which can handle multiple circuit breakers.

Additionally, the ambient temperature inside the MV circuit breaker cubicle is sensed and utilized by both the thermal and mechanical operation monitoring and diagnostic analytics. Finally, circuit breaker observed currents and voltages are also utilized as these parameters provide valuable fault and equipment overloading information. From a costing point of view, the proposed system's limited number of sensors and flexibility to connect to multiple breakers, should keep the per-breaker price within the estimated range of R20 000 to R30 000, targeted at the beginning of the project. With reference to the described reliability and failure rates information presented in Chapter 2, this monitoring and diagnostic system could pay for itself within a very short period.

3.3.5 Practical Utility application: Eskom's Drakensberg pumped storage scheme pony motor switching

The switching of the four pony motors at Eskom's Drakensberg pumped storage scheme is performed at the 11 kV level by individual vacuum circuit breakers. The power plant is equipped with four 280 MVA synchronous machines. Figure 3-12 depicts a single line diagram of one of the units at the power plant.

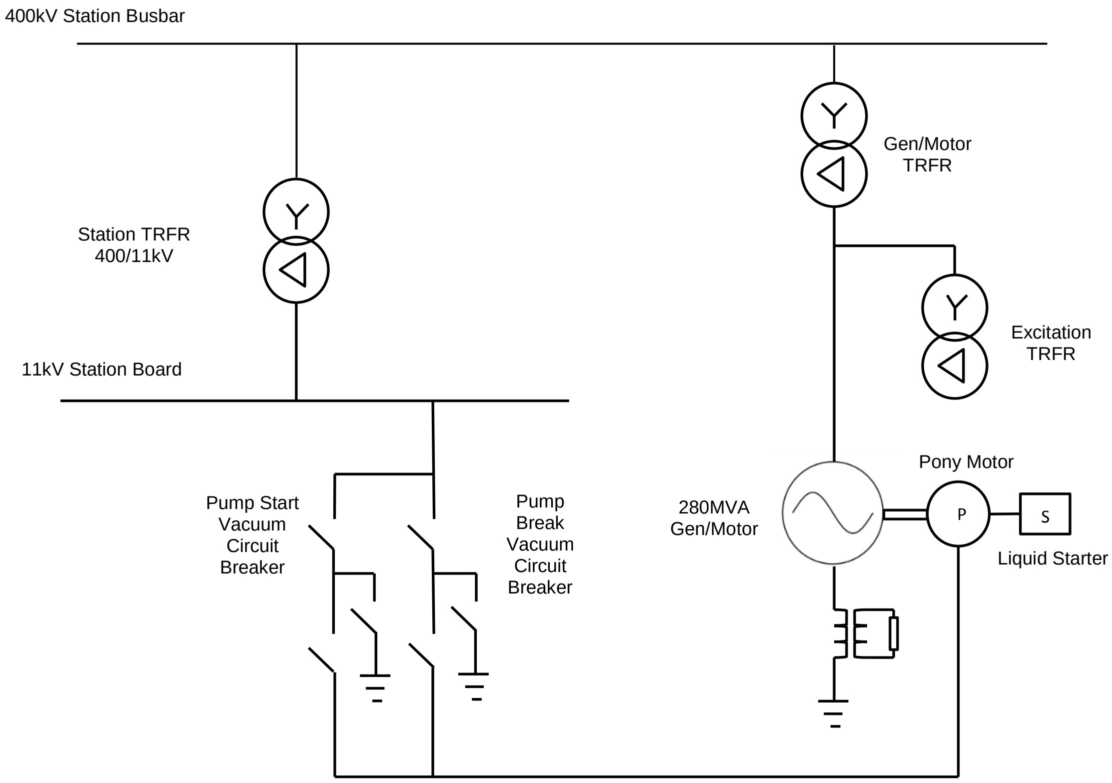

Figure 3-12: Single line diagram of the Drakensberg pumped storage unit [50]

The plant is used to generate during periods of high demand and pump during periods of low demand, i.e. overnight and at weekends. The pony motors are used to get the synchronous machines up to their synchronous speed. The circuit breakers experience high stresses due to the high number of mechanical operations and high making and breaking currents. The relative high number of operations might result in frequent outages due to circuit breaker mechanical failures and thermal overload.

An intensified maintenance programme could result in an improvement of availability, but can cause an in-proportionate increase of the operating and maintenance costs. Therefore, condition monitoring and diagnostic tools could serve as a valuable proposition to this power plant as these tools will help predict impending failures and provide early warning for equipment degradation.

3.4 Limitations and potential problems

Despite the limitation of outdated failure rates and failure mode datasets, industry is aware that gradual mechanical and/or electrical degradation of components are the leading contributors to failure.

With regard to thermal behavior, the proposed wireless temperature monitoring system can be used throughout a facility without any limitation to the type of equipment to be monitored. This monitoring system can be utilized as a universal tool to manage and control various assets and could become a key component in asset management.

From a mechanical standpoint, the development of circuit breaker coil current signature analytics for circuit breaker fleet analysis is still an immature area of research that will require sufficient field data that is currently non-existent. Despite this limitation, maintenance personnel could still benefit from this technique as the use of actuation coil currents has the advantage that the current pulse's signature contains information that is immediately actionable upon deployment of the monitoring and diagnostic system.

With the existing pressure monitoring techniques for vacuum interrupters, both emission current (high voltage withstand test) and positive ion current (magnetron pressure test) depend upon the internal layout and material of the vacuum interrupter components like centre shield, end shields, arc control contact diameter, contacts gap material etc. Both test methods can only be applied by taking the interrupter out of service and are therefore, not suitable for on-line monitoring.

Although, in the past, both technical and logistical problems have prevented the use of the magnetron in the field, new age magnetron test equipment makes it possible to determine the pressure in the field. The limitation, however, is that these new magnetron testers cannot be applied universally for all the models and makes of vacuum interrupters and require calibration for each interrupter type used.

Chopping current as a diagnostic tool was investigated to see if the condition of the main contacts has an effect on the magnitude of the chopping current. An attempt was made to measure the value of the chopping current but the following problems and limitations were encountered during the experiment:

- The measured chopping current values were unexpectedly large due to the low voltage output of the high current transformer used in the tests.
- From a repeatability point of view, the value of the chopping current varied significantly at the same peak current level and therefore it will be difficult to compare a service aged interrupter with a new interrupter.

This investigation of chopping current used as a diagnostic tool for determining contact health is therefore deemed to be <u>not viable</u> as the resources to carry out this experiment are limited. It will however be an interesting topic for future research. The laboratory results are presented in the next Chapter.

3.5 Research methodology summary

The final monitoring and diagnostic system employs a Hall-effect current sensor to observe the magnetic actuator's timing characteristics and a wireless SAW temperature monitoring system to follow the interrupter's thermal behaviour. The justification for the selected technologies is both technical and financial, and supports the fact that each component employed is fit for purpose in the risk adverse utility sector.

The proposed monitoring and diagnostic system uses technologies that are off the shelve items and analytics with parameters the industry is familiar with: current monitoring and thermal trending. With regard to thermal monitoring, the heat transfer physics is straightforward enough that effective tracking of abnormal thermal changes, and estimation of long-term equipment degradation, are only a matter of developing software, capturing data and calibrating the analytic algorithms over time.

Further, from a technological point of view, the availability of cost effective wireless-passive temperature sensors makes thermal monitoring a safe and viable proposition. The fundamentals of mechanical operation monitoring are also well recognized, but development of effective analytics is difficult given the absence of field data, as well as the challenge of using the approach for different types of circuit breakers.

Nevertheless, extensive implementation of such a monitoring scheme would provide enough information in a very short time to identify impending failures. In other words, the information captured from the field will become more effective over time (learning period), and with the aid of analytic algorithms utilities will be able to reduce maintenance operation costs while maintaining a high degree of service reliability.

Chapter 4 Laboratory Tests and Results

4.1 Introduction

Circuit breaker monitoring and diagnostic systems were tested using ACTOM 11 kV MV switchgear in the University's High Voltage laboratory. These monitoring systems incorporate thermal monitoring and mechanical monitoring. ACTOM internal resources aided in the design of an efficient test sequence. The tests aimed to demonstrate the viability of the monitoring and diagnostic systems.

The large amount of data obtained from the 11 kV vacuum circuit breaker provided by ACTOM clearly showed that mechanism degradation as well as interrupter contact degradation can be trended.

This chapter describes the steps taken to characterize the 11 kV circuit breaker thermal behaviour along with the trip and close actuation pulse current waveforms, the experimental sequence and the results obtained.

4.2 Measurement of the temperature adjacent to the breaker contacts in order to quantify contact degradation

Contact degradation (erosion) causes a rise in contact resistance and hence an increase in the temperature rise when the closed circuit breaker contacts carry current. Because the contacts are inside the interrupter and hence inaccessible, temperature measurements can be performed only at the interrupter terminals. However higher temperatures measured at this position will suggest higher temperatures at the contact position and hence contact degradation (erosion).

4.2.1 Continuous monitoring of conductor temperature

Temperature rise is a function of current and hence two temperature rises can only be compared if the currents were the same for both measurements. By monitoring the temperature rise of a new or refurbished unit, a reference value for future analysis at that particular current is generated. Evidence of contact degradation can be made by comparing the reference temperature rise with the temperature rise measured for the field-aged circuit breaker (for the same breaker current). The IntelliSAW IS485 wireless Surface Acoustic Wave (SAW) temperature monitoring system shown in Figure 4-1 was used for the temperature rise measurements.

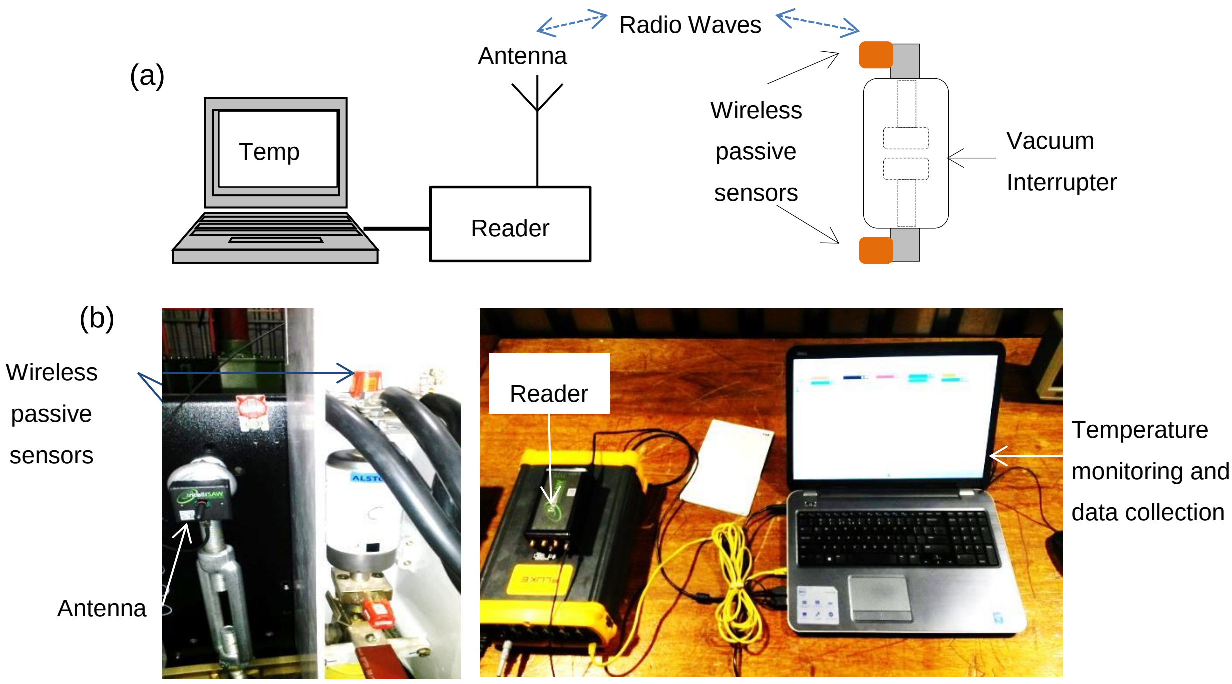

Figure 4-1: (a) Temperature monitoring system block diagram (b) IntelliSAW IS485 temperature monitoring laboratory setup

4.2.2 Condition assessment

Contact temperature in steady state is dependent on the balance between the heat generated by the combination of the contact resistance and the square of the current flow and the heat dissipated by conduction and convection to the interrupter's surroundings. The heat dissipation components are designed to limit the interrupter temperature rise to a safe value when conducting rated current.

The resistance of the contact has a tendency to rise over a period of time due to the aging which is caused by multiple factors such as electrical, mechanical and environmental stresses. At some critical point in the aging process of the contact, the higher resistance will generate excessive amounts of heat and raise the temperatures. Consequently, the temperature of an aged contact will be considerably higher at the same current level. If it is assumed that the heat dissipation mechanisms have not changed during the observation period, the temperature rise over time at the point of measurement will essentially be dependent on the variation of the contact resistance.

Therefore, changes in the temperature rise at the point of measurement at the same current level over the period of time could be utilized as a diagnostic tool to evaluate contact degradation. V207 vacuum interrupters from ACTOM (shown in Figure 4-2 (a)) were used during these thermal experiments. They had a rated voltage of 11 kV and a rated current of 800 A. The contact resistance for new vacuum interrupter contacts is specified as 22 μΩ.

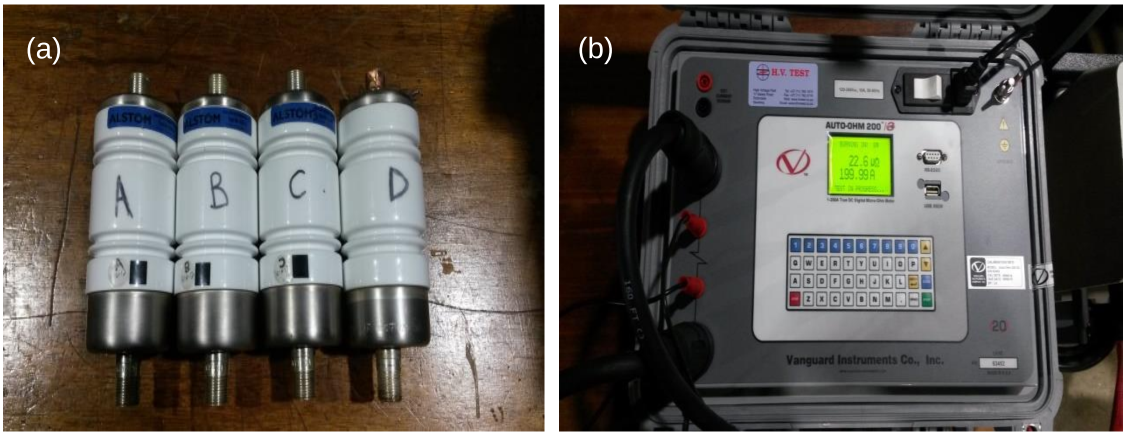

Figure 4-2: (a) ACTOM V207 vacuum interrupters (b) Vanguard 200 Micro-ohm meter

The test setup is shown in Figure 4-3. Three vacuum interrupters each with a different contact resistance (different levels of contact degradation) were tested for the same range of 50 Hz rms currents. The resistances measured and results are shown in Figure 4-4.

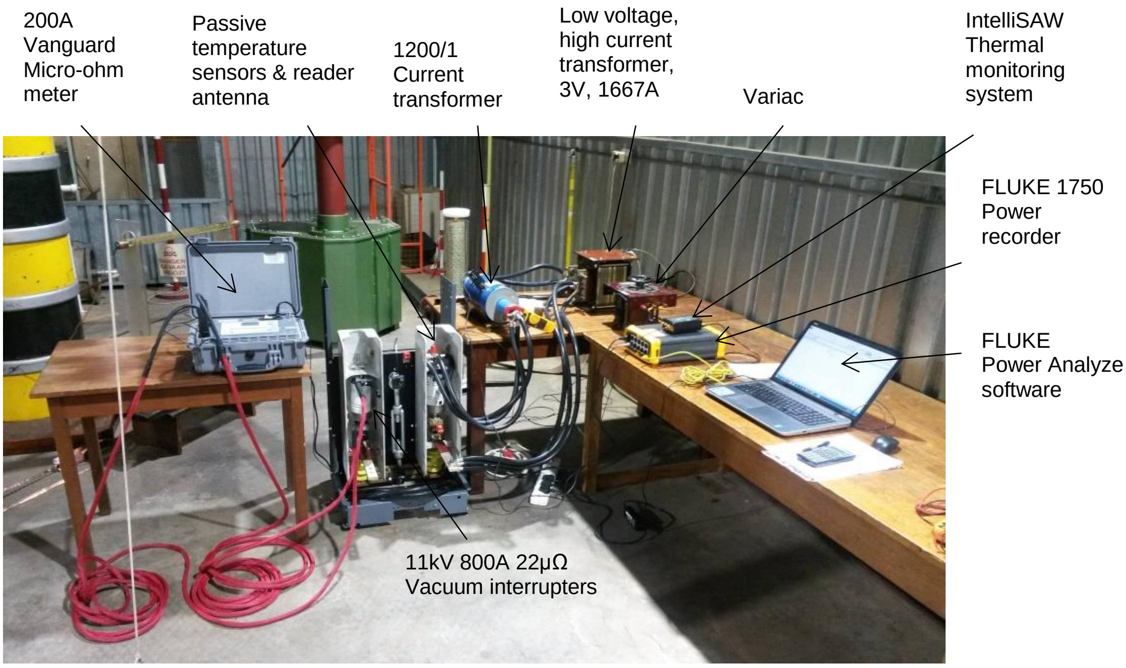

Figure 4-3: Experimental setup of main interrupting contact thermal monitoring

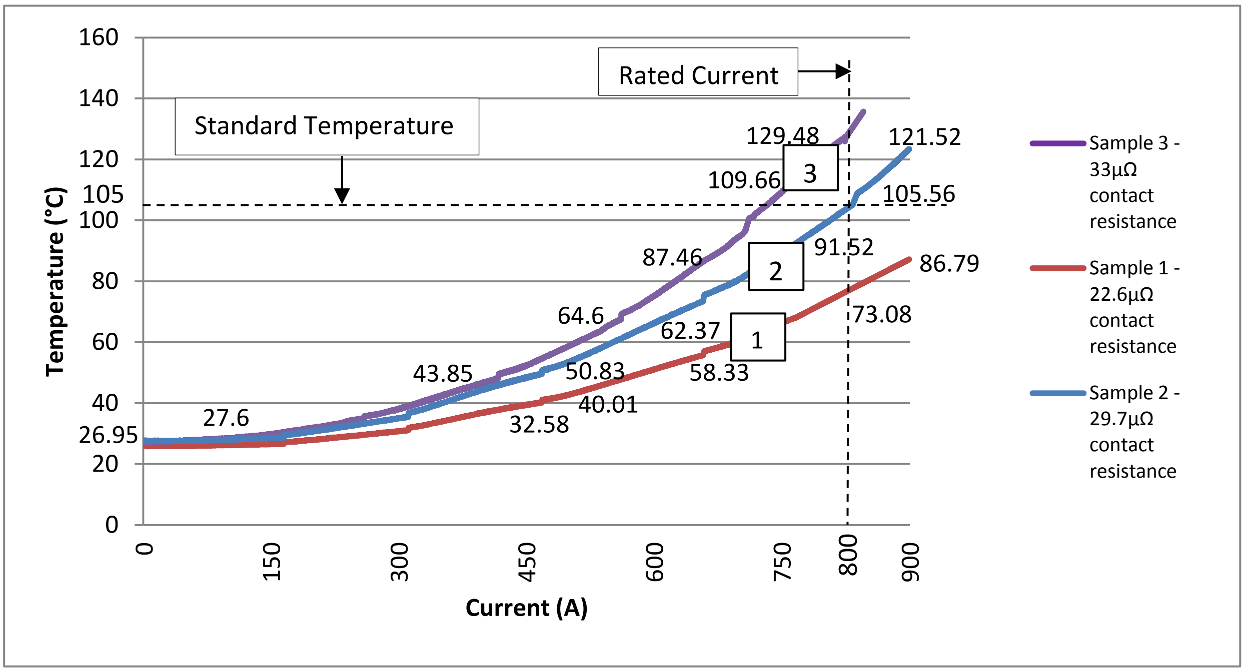

Figure 4-4: Contact resistances of interrupters with different levels of contact degradation (the resistances shown are measured with the Vanguard 200 Micro-ohm meter which measures at the standard 200 A)

Curve 1(red curve) in Figure 4-4 presents the thermal behavior of contacts in a healthy condition. Curve 2 (blue curve) shows the thermal behavior of service aged contacts, which generate a higher temperature at the same current level. These contacts are deteriorating, but are still safe to operate since the temperature at the rated current is still within the temperature limits according to IEC 62271-1. Curve 3 (purple curve) illustrates the thermal behavior of heavily degraded contacts and thus would be considered unacceptable as the temperature exceeds the allowable maximum temperature rise at rated current. From an operating and maintenance point of view, the interrupter unit can continue in service, but at a derated current rating. If these contacts continue to carry currents near their rated value, there will be an elevated risk of thermal runaway. To prevent thermal runaway, timely scheduled condition-based maintenance would result in the interrupters being replaced to avoid future failures.

4.2.3 Maintenance scheduling and asset management

Monitoring and diagnostics of contact temperature helps to predict and prevent any excessive overheating of the contacts in a timely manner which allows for more effective maintenance planning to be done. The envisaged outcome by asset managers should be reduced maintenance costs and activities.

4.3 Monitoring of the actuator coil current waveform to detect mechanical mechanism degradation

4.3.1 Relationship between the actuator coil current waveform and the circuit breaker mechanism performance

The trip and close coils consist of a wound stationary solenoid around a moving iron armature forming an electromagnetic actuator. The moment the control circuit receives a trip or close signal, the opening or closing of the main interrupter contacts commences. When a voltage is applied to the coil, a coil current flows. The magnetic field produced by the current in the solenoid causes the armature to move toward the circuit breaker latch mechanism and initiates the movement of the spring operated mechanism. The stored energy from the charged spring is utilized to open or close the main interrupting contacts within milliseconds; while, at the same instant, the coil current reaches its maximum value. Finally, the auxiliary contacts open after a very short delay and disconnect the voltage supply to the coil and, as a result, the coil current is interrupted as seen in Figure 4-7. As discussed in the previous chapter, Alegro ACS715 Hall-effect current-to-voltage transducers (as shown in Figure 4-5) were used to record the coil current waveforms from the trip and close operations.

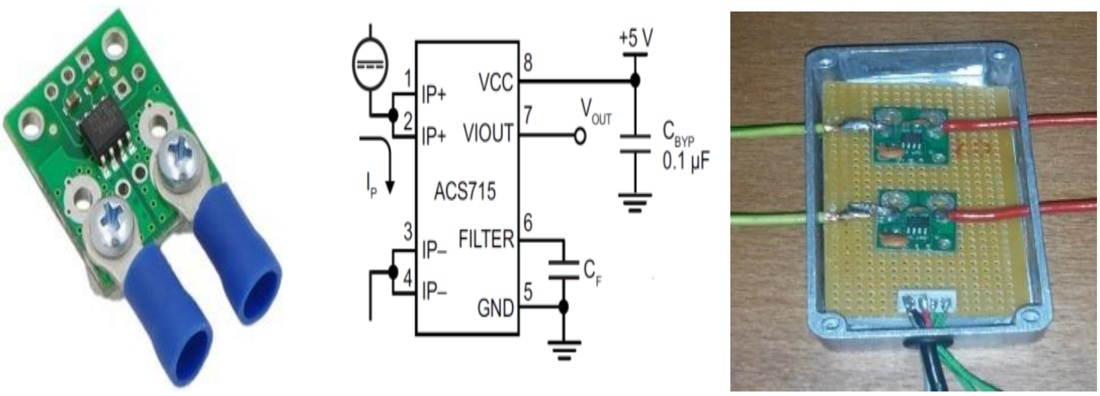

Figure 4-5: ACS715 Hall-effect transducer used to record the coil current waveforms [51]

The mechanical mechanism of the ACTOM SBV4 11 kV circuit breaker consisted of a spring-drive mechanism, as well as a trip and a close coil (rated 10 A) as shown in Figure 4-6.

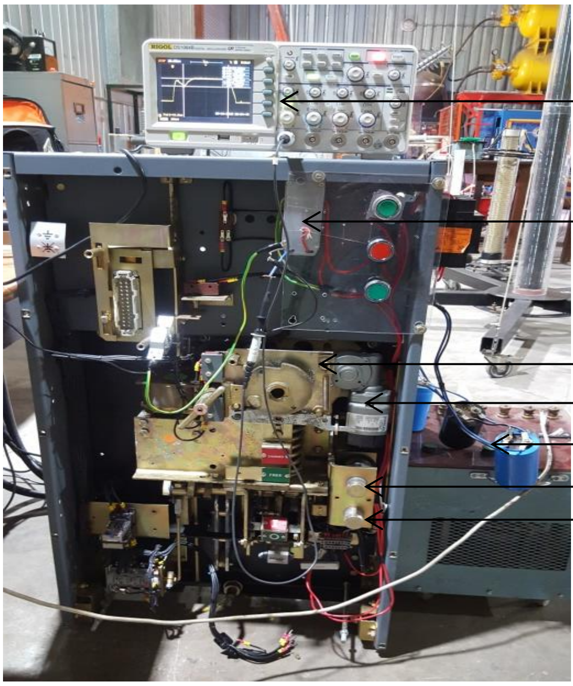

Figure 4-6: Experimental setup of mechanical mechanism monitoring

4.3.2 Circuit breaker trip/close actuator coil current waveform parameters

In order to assess the condition of the circuit breaker mechanical mechanism through its actuator coil current waveform, six parameters reflecting the circuit breaker mechanism abnormalities are shown on a typical measured coil current waveform in Figure 4-7.

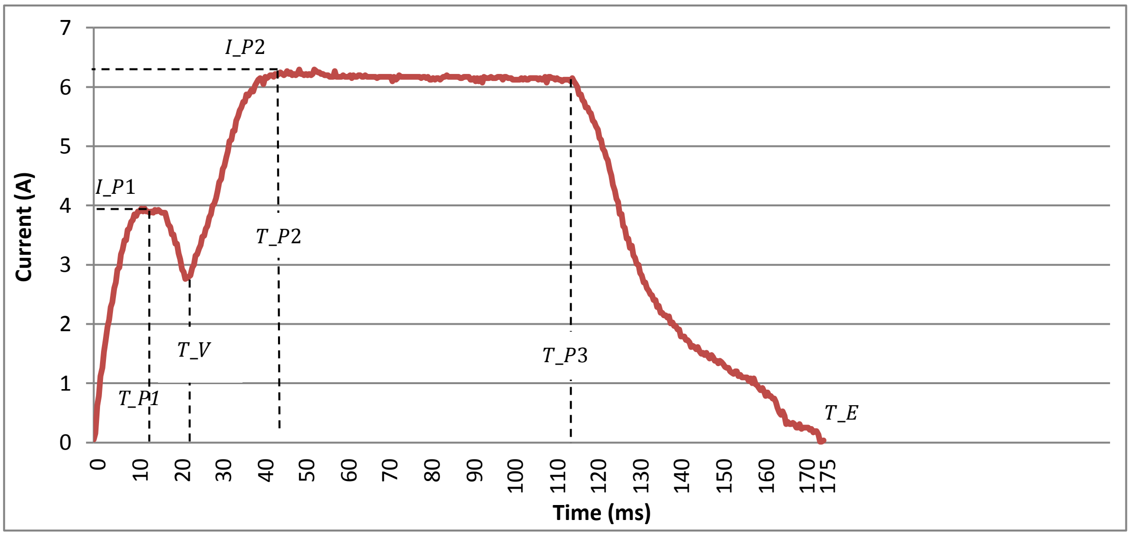

Figure 4-7: Actuator coil current waveform parameters on a recorded waveform of a healthy mechanism

The following nomenclatures are introduced in Fig. 4-7.

- I_{P1} - first peak current;
- T_{P1} – time to first peak current;
- I_{P2} - second peak current;
- T_{P2} - time to second peak current;
- T_V – Circuit breaker latching time; the drop in current is due to the motion of the coil armature generating a back electromotive force;
- T_E - total time of coil current flow.

In order to analyze the effect of different defects in the circuit breaker mechanism on the circuit breaker trip/close actuator coil current waveform, a reference actuator coil current waveform of a healthy circuit breaker mechanism is required. A large number of measurements must be performed to determine the statistical behavior of the parameters of the reference actuator coil current waveform. For the experiments discussed in the following sections, the actuator coil current waveforms of 50 close and open operations were recorded and the mean values of the waveform parameters were calculated for the SBV4 circuit breaker. The results are summarized in the following sections.

4.3.3 Problems detectable by monitoring the trip or close actuator coil current waveforms

Failures in the circuit breaker mechanical mechanism have an impact on the actuator coil current waveforms and allow the detection of these defects. To investigate the relationships between the coil current waveform parameters and these defects, the trip and close coil resistance is increased by connecting external resistance as pointed out by the arrow in Figure 4-8.

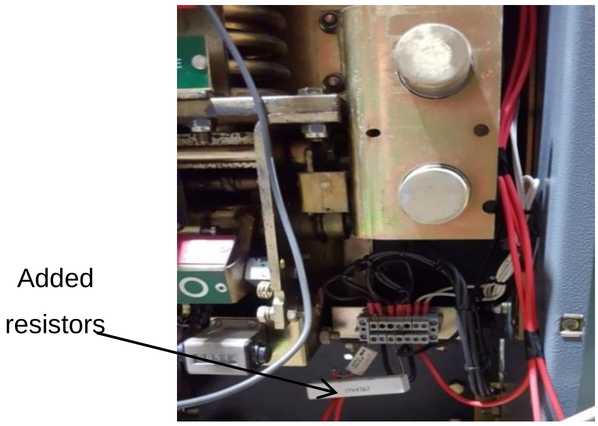

Figure 4-8: Resistance added to the trip and close coils

The abnormality in the coils, mainly caused by short circuits, has a great impact on the features, because the resistance and inductance of the coils are changed and, therefore, all features are influenced. The impact of changes in the resistance of the close coil on the close coil current waveform is shown in Figure 4-9.

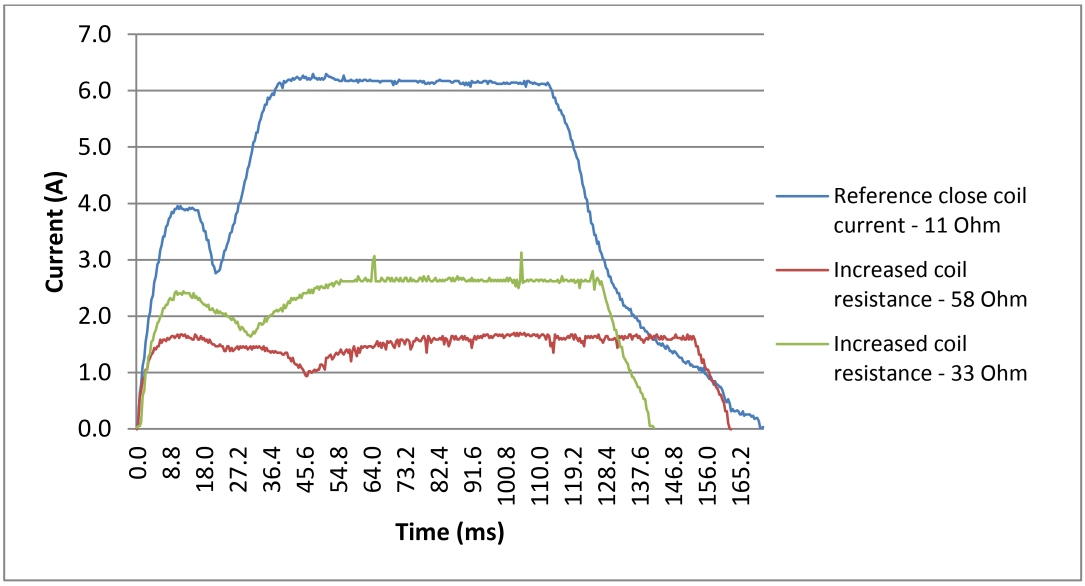

Figure 4-9: Impact of the increase of the resistance of the close coil on the close coil current waveform

As seen in Figure 4-9, the most affected parameters are the peak currents, time to first peak current, and latching time. It appears that variation in coil resistance can change the circuit breakers operation time significantly. From this investigation, it can be assumed that the most suitable coil current parameters for the detection of faulty coils are T_{P1}, I_{P1}, I_{P2}, and T_V since these are greatly affected by the variation in coil resistance.

4.3.4 Failures in trip or close coil supply voltage

The supply voltage for operating the trip of close coils is provided by a substation battery. If the substation battery is not fully charged, the voltage applied to the trip or close coils could deviate from the rated voltage. As a result, the circuit breaker will not perform as expected. In order to evaluate the effect of voltage on the actuator coil current waveforms, three different voltage values were applied to the trip and close coils as follows:

i. 89% of rated voltage (under voltage);
ii. 100% of rated voltage;
iii. 109% of rated voltage (overvoltage).

For the circuit breaker investigated here, the rated supply voltage of the coils was 110 VDC. Figure 4-10 shows the effect of voltage deviations on an 11 kV circuit breaker closing coil current waveform.

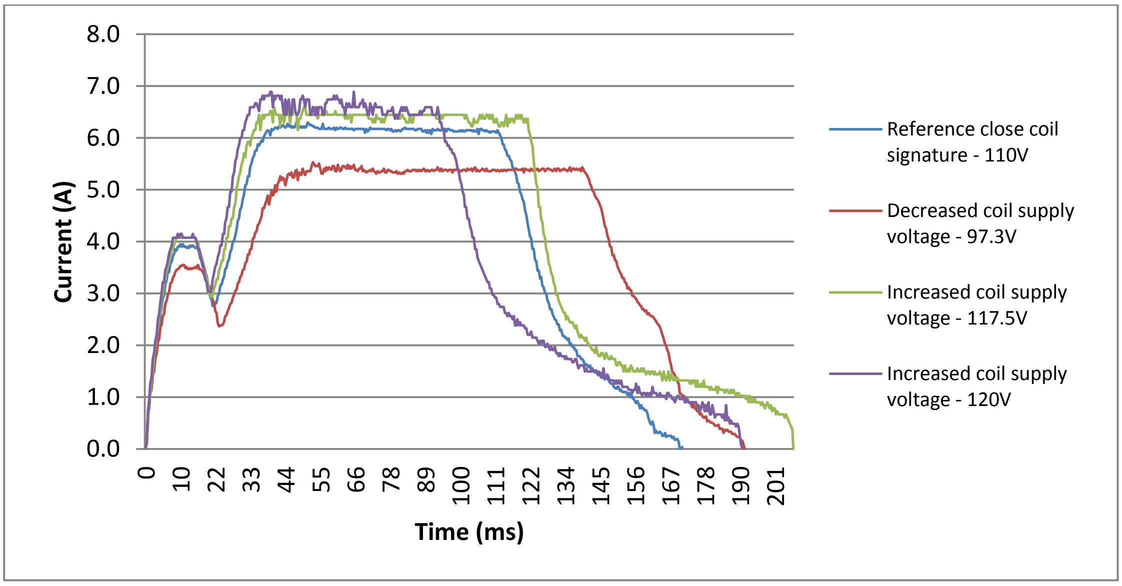

Figure 4-10: Effect of coil supply voltage variations on close coil current waveform

In Figure 4-10 an increased voltage shifts the coil current waveform upwards and to the left. In contrast, a decreased voltage shifts the coil current waveform downwards and to the right. As can be seen, the operating time of the breaker is significantly influenced by deviations in the coil supply voltage. The reason behind these differences in features can be attributed to the fact that voltage deviations have a direct impact on the electro-motive force applied on the armature, which is directly proportional to the square of the coil current. The latch movement commences if the resultant force is higher than the sum of all frictional and gravity forces. This emphasizes the impact that voltage variations have on the mechanical movement of the actuator. Similar impacts are observed on the measured trip coil current of the 11 kV circuit breaker.

4.3.5 Failures in latch operation

Normally, circuit breakers remain in a closed position for long periods of time until a command signal is send to interrupt the load current or the fault current. Consequently, the latch operation can malfunction due to the absence of lubrication or mechanical deterioration. The latch sluggishness can affect both the operation time as well as the actuator coil current waveform significantly. This subsection discusses how coil current waveform profiling can assist in the detection of failures in the latch operation.

In order to investigate the effect of increased mechanical resistance in the 11 kV circuit breaker mechanism, the mechanical movement is intentionally constrained by adding elastic bands as shown in Figure 4-11.

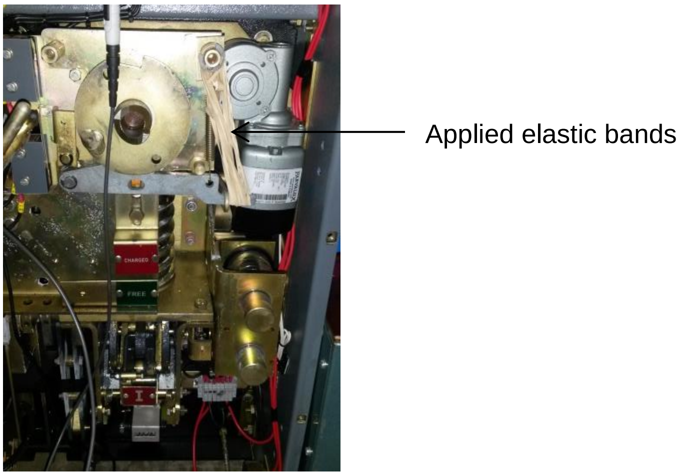

Figure 4-11: Latch movement intentionally constrained by adding elastic bands

Figure 4-12 demonstrates the impact of this simulated defect on the trip coil current waveform of the 11 kV circuit breaker.

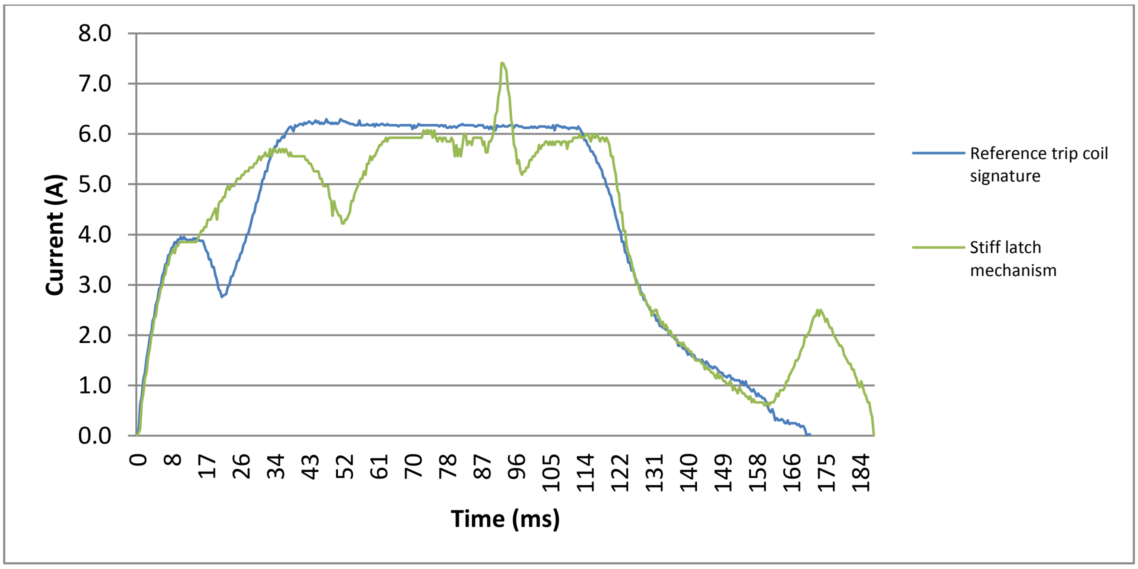

Figure 4-12: Effect of latch movement constraint on the trip coil current waveform

As seen in Figure 4-12, a stiff latch operation leads to an increase in circuit breaker opening time by approximately 20 ms. In the case of soft latch sluggishness, due to the reduced latch sensitivity, the latch takes longer to trigger the other mechanical parts.

This failure mode can be detected through the most affected features, namely T_V, T_{P1} and T_{P2}, which can be seen in Figure 4-12.

In order to compare the previous measured waveforms, Figure 4-13 presents the impact of malfunctions in the coil resistance, coil voltage supply and latch mechanical constraint on the close coil current waveform of an 11 kV circuit breaker.

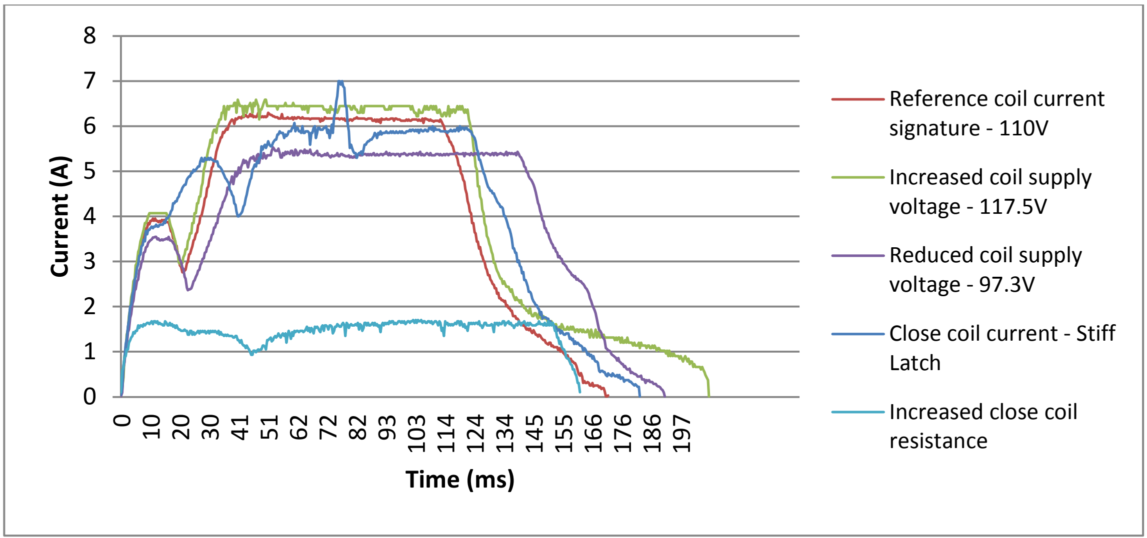

Figure 4-13: Effect of various malfunctions on the close coil current waveform

4.3.6 Failure detection algorithm

This section presents a failure detection algorithm using the trip or close coil current waveforms based on the results of the investigations in the previous sections. The algorithm is illustrated in Figure 4-14. The following steps encompass the fault detection principles and diagnosis method:

1) Data capturing and calculating feature values

After circuit breaker operation is completed, the coil current waveform is captured in order to determine the discrepancies between the defined parameters (refer to Figure 4-7).

2) Determination of discrepancy of features and sorting

By comparing the calculated parameter values in Step 1 with the reference values, the discrepancy percentage of the parameters is calculated. Subsequently, these parameters are sorted from the most affected to the least affected.

3) Identification of failures and their causes

The mode of failure and their causes are identified in this step.

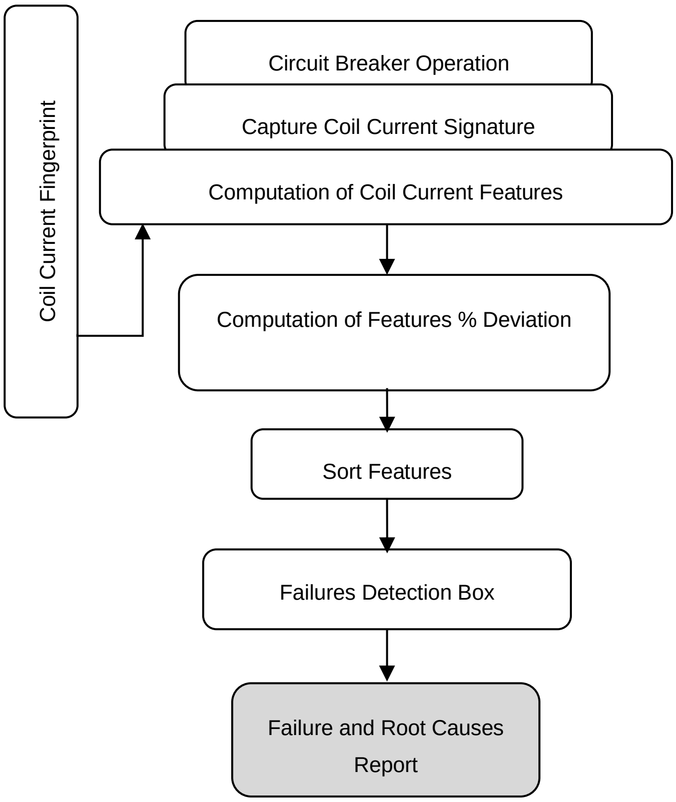

Figure 4-14: Outline of the proposed failure detection algorithm

In addition, a comprehensive overview of the main causes of failures, as well as the most affected parameters of the coil current waveform is shown in Table 4-1.

Table 4-1: Circuit breaker failures and causes from a coil current waveform perspective

Failure cause	Causes description	Affected parameters
Voltage supply	Voltage level increasing Voltage level decreasing	T_E I_{P1} I_{P2} T_V T_{P1}
Latch	Soft latch Stiff latch	T_E T_{P2} T_E T_V T_{P1}
Coil	Resistance decreasing Resistance increasing	T_E I_{P1} I_{P2} T_V T_{P1}
Mechanism and auxiliary contacts	Auxiliary bounce, faulty operation	T_E T_{P2} T_E I_{P2}

4.4 Empirical findings and analysis of current chopping

As discussed in Chapter 2, current chopping is the premature suppression of the arc current before the natural (50 Hz) current zero due to the instability of the low current arc in a vacuum interrupter. The main disadvantage of current chopping is that when it occurs, energy stored in the effective load inductance is transferred to the available load-side capacitance to generate large overvoltages leading to possible failure of downstream insulation. The possibility of using the value of the chopping current as a diagnostic tool was investigated as shown in Figure 4-15 to investigate whether the condition of the main interrupting contacts had an effect on the magnitude of the chopping current.

Figure 4-15: Measuring the chopping current of vacuum interrupters rated at 1250A

An attempt was made to measure the value of the chopping current. Figures 4-16 and 4-17 illustrate the outcome of the measured waveforms.

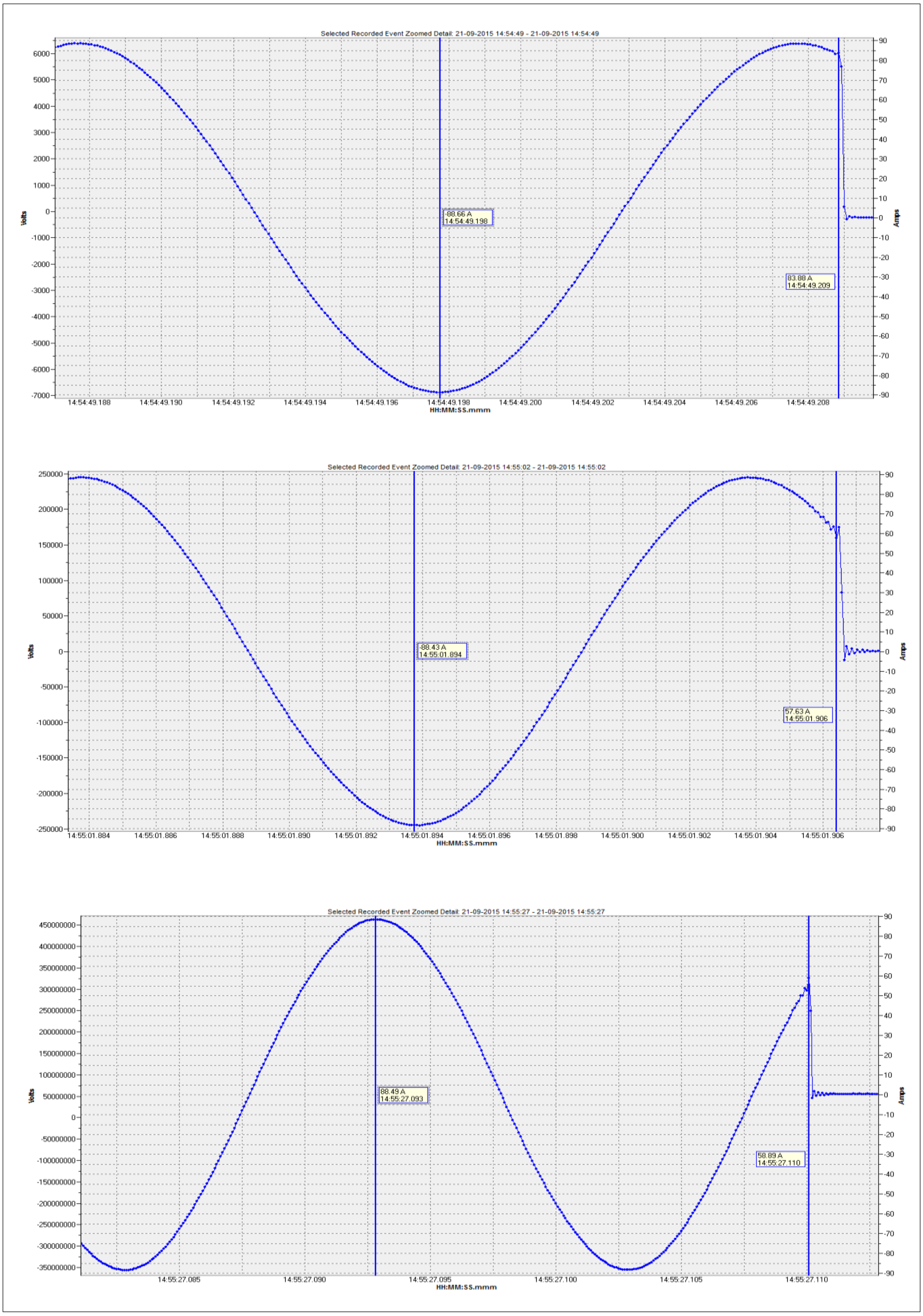

Figure 4-16: Chopping current waveforms at 89A load current

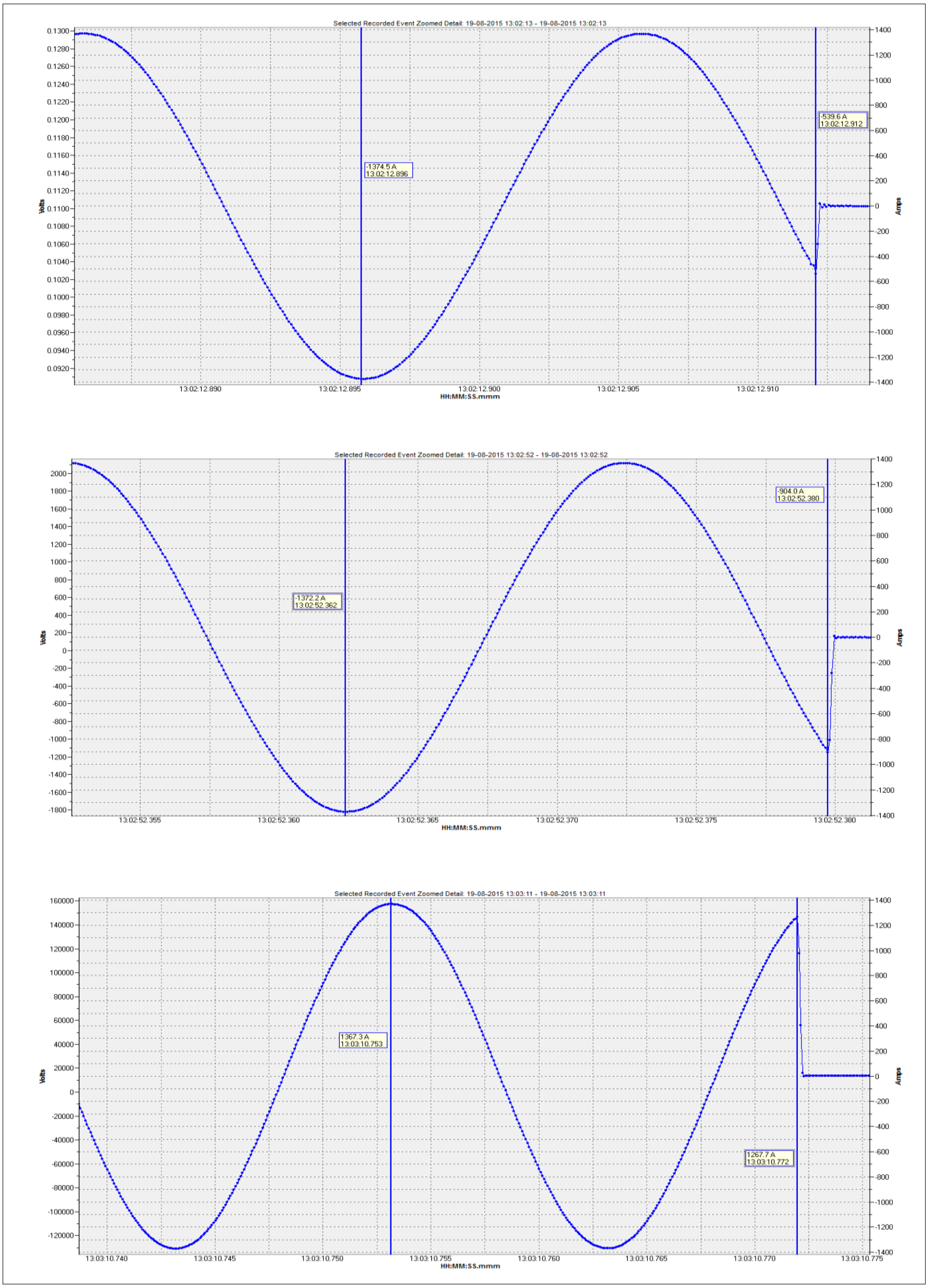

Figure 4-17: Chopping current waveforms at 1367A load current

From Figures 4-16 and 4-17 it is clear that the measured chopping current values are very high. As explained in section 2.2.8, if the value of chopping current is high enough, this rapid change in current interacting with the circuit's surge impedance can result in high overvoltages which may cause the insulation of motors and transformers to fail.

From a repeatability point of view, the value of the chopping current varied significantly at the same peak current level and therefore it will be difficult to compare a service aged interrupter with a new interrupter.

This investigation of chopping current as a diagnostic tool for determining contact health is deemed to be not viable for the test equipment used in this project. It will however be an interesting topic for future research.

4.5 Summary

The results are encouraging from an analysis point of view for the following reasons:

- For interrupter contacts with higher resistance, the temperature rise is greater; thereby allowing the detection of contact degradation (erosion).
- All failure modes within the circuit breaker mechanism have an impact on the operating time of the circuit breaker.

Although the results obtained are not universal to all circuit breakers, the results do fall in line with expectations based on the limited data collected and analysed for the particular 11 kV vacuum circuit breaker tested.

Due to test restrictions and limitations, the experiment was limited to a single 11 kV vacuum circuit breaker and as a consequence, accurate breaker-breaker (of the same family) variation is unknown. As field information and datasets become available and updated, evaluating the root cause of variability and its potential impact on fleet analytics will be possible.

Chapter 5 Conclusions and Recommendations

5.1 Background information

This research project investigated the issues associated with the monitoring and diagnostics of medium voltage vacuum circuit breakers from both a technical and a financial perspective in order to formulate recommendations on which approach to adopt. During the initial research project phase, it was important to investigate vacuum circuit breaker failure rates, failure modes and the impact on the utility when the circuit breaker fails. The main findings from this literature survey were:

- Medium voltage vacuum circuit breakers have an annual failure rate of 0.1-3%.
- The leading failure modes for MV vacuum circuit breakers are mechanical and contact degradation.
- MV vacuum circuit breaker fleets are beginning to show higher failure rates due to increasing age.

5.2 Monitoring and diagnostic system design and integration

Analysis of existing maintenance practices, existing sensing technology and recent circuit breaker analytics, motivated the selection of interrupter temperature and mechanical actuator coil current profiling as the means to diagnose vacuum circuit breaker degradation.

It is expected that monitoring and diagnostic systems that address these parameters will significantly reduce the failure rates and pay for themselves in a very short period when employed in a typical utility environment. The advantage of the proposed integrated system is that it is capable of monitoring multiple medium voltage vacuum circuit breakers simultaneously.

The proposed system, currently deployed in a pilot experimental setup consisting of an 11 kV vacuum circuit breaker with a spring drive mechanism, provides contact resistance and mechanical operation monitoring and trending capability particularly important in the high opening and closing duty environment of a pony motor circuit breaker utilized at one of Eskom’s pumped storage schemes. Extensive laboratory testing also allowed the determination of the relationship between the temperature rise and the interrupter contact condition.

5.3 Research objectives: Summary of findings and conclusions

5.3.1 Research objective 1: Thermal monitoring of the main interrupting contacts

The main cause of circuit breaker hot-spots is the deterioration over time of the interrupter's contact surface, which results in an increased contact resistance and hence increased temperature of adjacent conductors. The generated heat is a function of the square of the interrupter current and the contact resistance. The contact resistance has a tendency to rise over time due to the contact deterioration. Therefore monitoring of conductor temperature at the same current level over the period of time could serve as the qualitative tool for the evaluation of contact deterioration.

5.3.2 Research objective 2: Mechanical operation monitoring

The circuit breaker actuator coil's current is directly influenced by the mechanical resistance presented by all of the moving parts of the actuator system and therefore the actuator coil current as function of time can be used as a means of identifying degradation in the mechanical mechanism of a circuit breaker.

5.3.3 Research objective 3: Current chopping behavior of aged contacts

The value of the chopping current was investigated to see if the condition of the main contacts has an effect on the magnitude of the chopping current. An attempt was made to measure the value of the chopping current but the following problems were encountered during the experiment:

- The measured chopping current was unexpectedly large due to the low voltage output of the high current transformer used in the experiment.
- From a repeatability point of view, the value of the chopping current varied significantly for the same peak current level and therefore it will be difficult to draw conclusions from the values measured for a service aged interrupter and the values measured for a new interrupter.

This viability of using the chopping current value as a diagnostic tool for determining contact health could be an interesting topic for future research.

5.4 Research questions addressed

- **What are the most cost-effective options for improving vacuum circuit breaker reliability while extending the life of MV vacuum circuit breakers?**
  From this research it is clear that thermal and mechanical monitoring are the most effective means of assessing circuit breaker health and thereby extending its life. The justification for the selected technologies is both technical and financial.
- **What are the most common degradation and failure modes associated with MV vacuum circuit breakers?**
  Although reliability information is outdated and incomplete, previous studies indicate that mechanical and thermal stresses as the major contributors towards failure. Existing test equipment and maintenance practices also serves as a reaffirmation of this.
- **What tests and monitoring techniques are currently employed by Eskom to determine MV vacuum circuit breaker condition and what are their limitations?**
  The following tests and monitoring techniques are currently employed by Eskom [52]:
  a. Circuit breaker time-travel analysis – has the limitations that it can only be deployed during time-based maintenance programs, requires trained personnel and requires sophisticated sensors to be installed that needs to be calibrated frequently.
  b. Circuit breaker hot spot testing – has its limitation when monitoring the busbar temperatures behind enclosures and doors from the outside.
  c. High voltage withstand test – has the limitations that it can only be deployed during time-based maintenance programs, it is a pass/fail test which only tells you if the pressure is acceptable or not (i.e. it does not indicate the remaining life of the interrupter) and if the test result is a fail, the interrupter is already unsafe and could have caused catastrophic failure.
  d. Main interrupter contact resistance testing - has the limitation that it can only be deployed during time-based maintenance programs.
  e. On-line partial discharge monitoring.

- **How can the degradation and actual life expectancy of vacuum interrupter contacts be determined?**

  The degradation can be estimated by means of the sum of the arc integral method as discussed in section 2.2.7. An alternative method is to monitor the temperature rise versus current online to detect any abnormality and hence degradation. When an abnormal temperature rise is detected, the degradation can be verified offline by means of a contact resistance test.

- **What are the latest technologies currently available to monitor vacuum circuit breaker degradation on-line and what are their limitations?**

  Nowadays, there are numerous technologies available to monitor critical parameters on switchgear. With regards to mechanical operation of circuit breakers, the degradation on the mechanism of the circuit breaker can easily be detected by means of installing hall-effect current-to-voltage transducers on the trip and close coil circuits in order to monitor and diagnose the coil current profiles. This technique is still an immature area of research that will require sufficient field data that is currently non-existent.

  In terms of vacuum integrity, magnetron pressure testing discussed in section 2.6.4 is used to monitor the vacuum of interrupters. The drawbacks of this test are its dependency upon the internal layout and material of the vacuum interrupter components like shield dimensions, contact diameter and gap, etc. The magnetron test cannot be applied universally for all the models and makes of vacuum interrupters and requires calibration for each and every interrupter types to be used. Lastly, this technique can only be applied offline with the interrupter out of service.

  As temperature is a very critical parameter to monitor and thermal stresses are one of the major contributors to electrical failures. Wireless surface acoustic wave temperature monitoring systems are used to monitor the temperature of strategic points within switchgear. The only limitation is that it can temporarily loose signal between the reader antenna and sensors.

- **Is there a relationship between the value of the chopping current and contact erosion/degradation?**

  The relationship between the chopping current and contact degradation of vacuum interrupters were investigated but limited resources were available and accurate results could not be obtained. This research question however could be an interesting research topic for future.

5.5 Key findings

The most important finding from this work was that monitoring and diagnostic systems for MV vacuum circuit breakers are both viable and affordable.

Other important findings:

- Monitoring and diagnostic systems have the capability of contributing to MV vacuum circuit breaker reliability determination.
- Analysis of the monitoring data will allow utilities to reduce their maintenance operation costs while maintaining a high degree of reliability and availability.

5.6 Future challenges and research opportunities

The MV sector has undergone little change when compared to other technology sectors and is behind in terms of the development of highly integrated systems. The arrival of Smart Grid initiatives will drive the industry towards more sophisticated approaches to monitoring MV equipment. Although the concepts of the Smart Grid are still being developed, extensive research in this area and a better understanding of the changes required will be of great benefit to the utility of the future.

The advantages and opportunities of developing integrated monitoring and diagnostic systems are large, especially systems that can share multiple products and share common platforms. The research opportunities in this area that are an extension of the work in this thesis include:

- Investigating online methods of monitoring the level of vacuum within vacuum interrupters;
- Investigating the impact on service reliability, daily utility operations, and costs that integrated monitoring and diagnostic systems could have;
- Developing the analytic capability that will improve utility operations and enhance maintenance decisions;
- Proposing a policy for highly integrated systems and practices across the utility industry.

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Appendix A – Drakensberg Pumped Storage Measurements

In areas where water resources are limited, pumped storage schemes are used as an alternative to conventional hydroelectric power stations to provide the power needed during peak loads. A pumped storage scheme consists of lower and upper reservoirs with a power generating/pumping plant between the two. During off-peak periods, when the demand for electricity is lower, the water in the lower reservoir is pumped to the upper reservoir in order to store the energy. During peak periods, the water from the upper reservoir is released downwards by gravity through a turbine in order to generate electricity. Due to the frequent switching nature of pumped storage schemes, electrical switchgear experiences high electrical and mechanical stresses which cause the degradation and failure rates to be high. During this research measurements and recordings was obtained at Eskom's Drakensberg pumped storage scheme. The idea behind the recordings was to understand what stress levels the 11kV vacuum circuit breakers (see Fig. A-1) experience during switching operations.

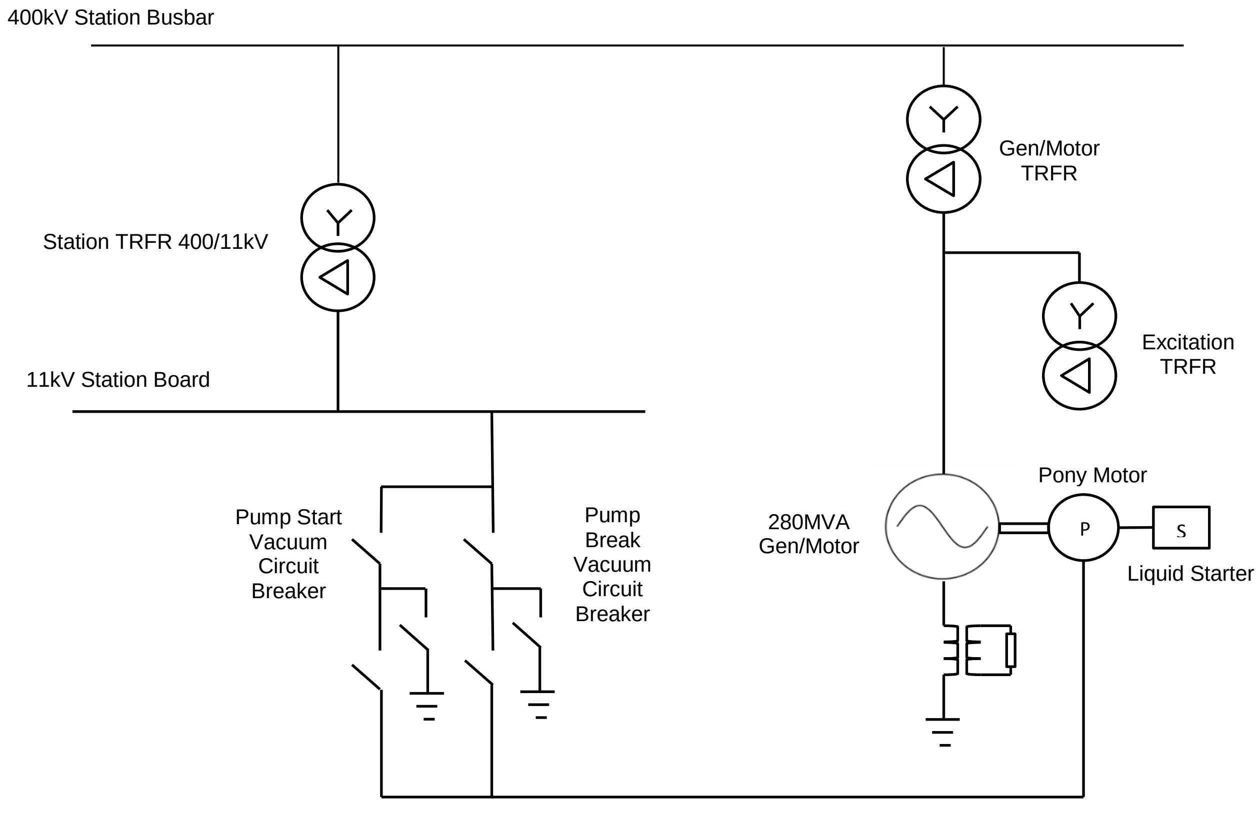

Figure A-1: Unit 1 - MV single line diagram

Three events were recorded. The pony motor voltage and current switching waveforms are shown in Figure A-2 to Figure A-7.

Event 1: Unit 1 Pony Motor – Generator Brake

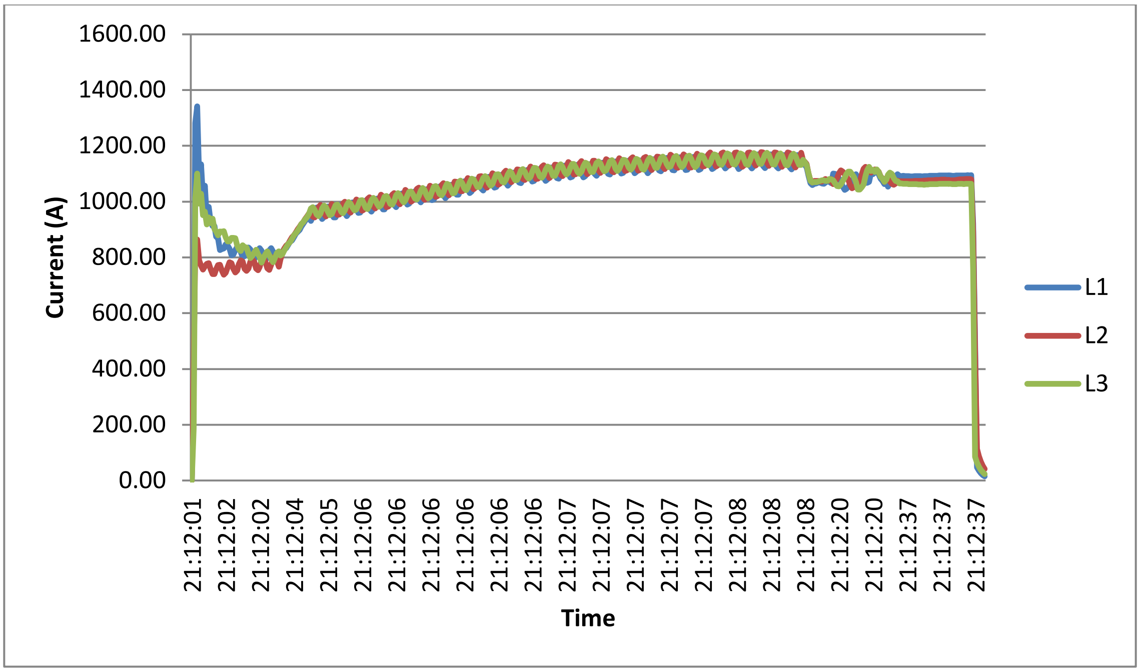

Figure A-2: Generator brake current waveforms

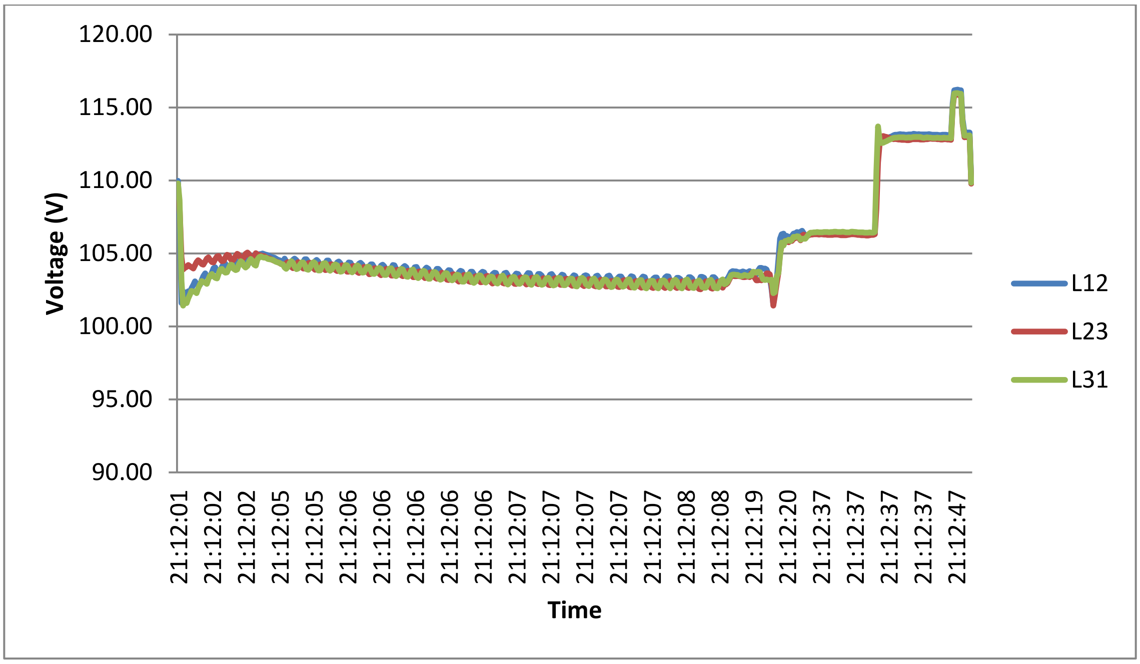

Figure A-3: Generator brake voltage waveforms

Event 2: Unit 1 Pony Motor – Pump Start

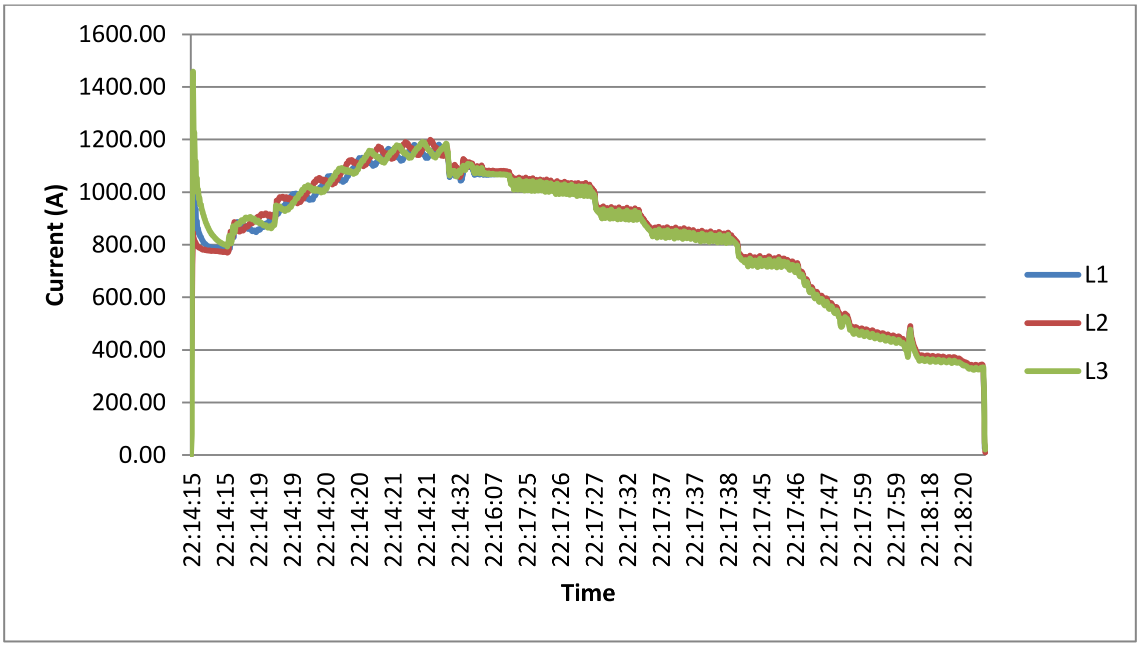

Figure A-4: Pump start current waveforms

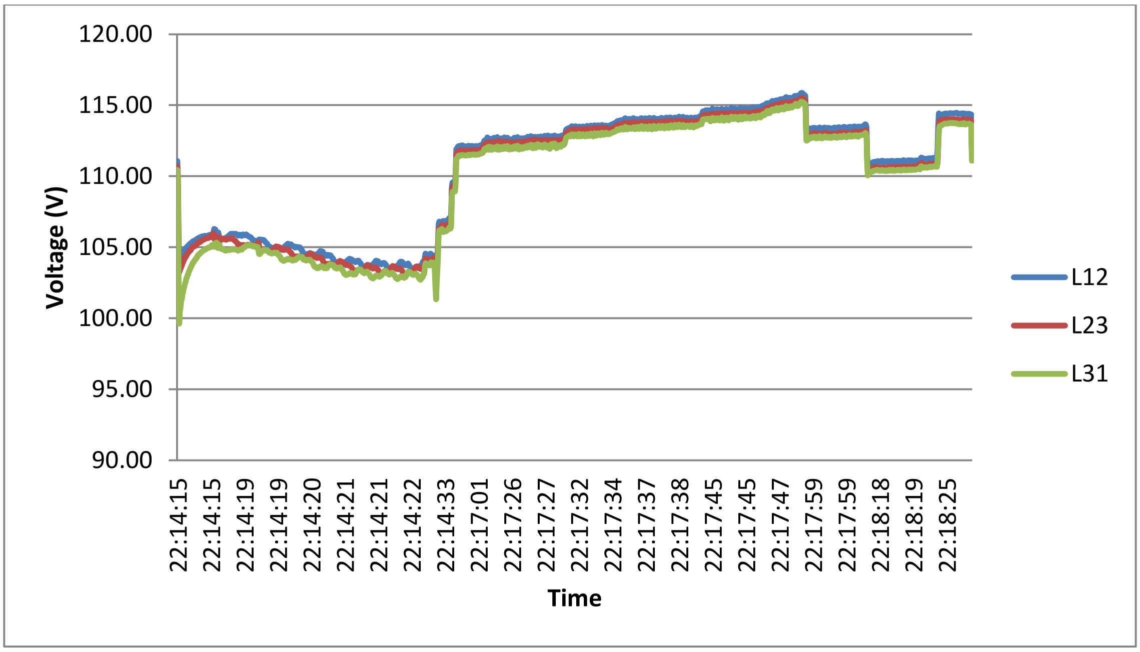

Figure A-5: Pump start voltage waveforms

Event 3: Unit 1 Pony Motor – Pump Brake

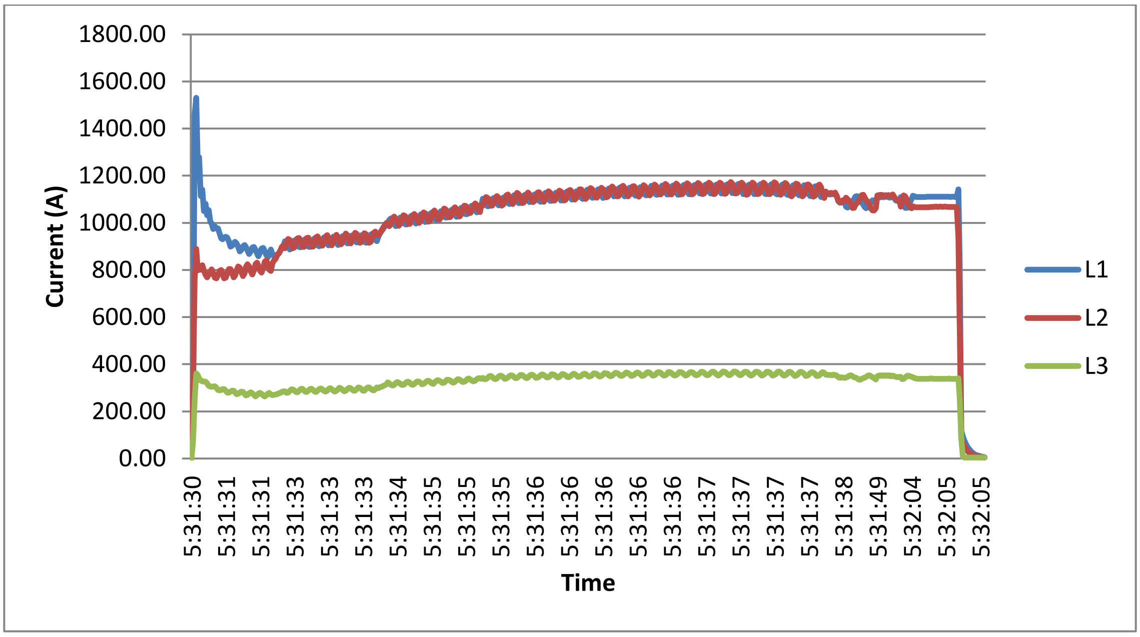

Figure A-6: Pump brake current waveforms

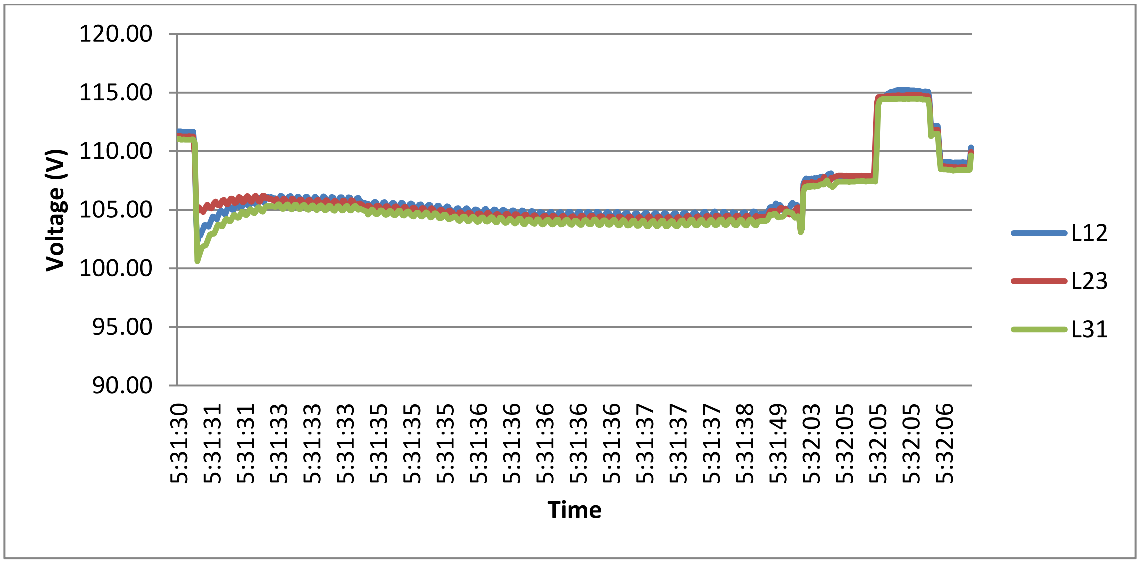

Figure A-7: Pump brake voltage waveforms