**DEVELOPMENT OF MONITORING SYSTEMS FOR AGED DISTRIBUTION TRANSFORMERS WITH SMART METERING**

**by**

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## DECLARATION

I, Terence Robert Ventura, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

21/11/2025

**Signed** **Date**

## ABSTRACT

Distribution transformers play an integral role in the electricity network infrastructure, and measuring their health and performance is crucial for electricity supply stability. Advances in smart metering technology enable different stakeholders to measure the relevant properties of distribution transformers in a non-intrusive manner and with a high degree of accuracy. Although distribution transformers have developed progressively, the standard traditional oil types are still predominantly in service in most countries and have a typical life of at least 20 to 30 years when operated within their specifications. This study, therefore, has a global interest as well as a uniquely local South African relevance. South Africans have experienced firsthand how a strained electricity network with excessive demand can abruptly impact their quality of life and livelihood, with a total number of loadshedding hours of 2400 and 6947 recorded in 2022 and 2023 respectively. This research is therefore relevant and addresses an actual and relevant problem.

Due to their function in the power grid and operating levels compared to power transformers, distribution transformers specifically require monitoring, as they are considered higher-risk equipment, being more prone to failure. The dissertation aimed to address the research problem by exploring existing literature available on the topic from reputable technology companies as well as research papers, to critically compare how effectively these measures addressed the ever-changing landscape of the electricity power grid. The literature review started with the wider body of knowledge available and then aimed to narrow it down to address the problem identified. Theoretical principles, case studies, and comparative analysis formed part of this review. The research methodology applied centred around key distribution transformer measurements that included demand, quality of supply, and harmonic distortion. The distribution transformer monitoring was tested in a laboratory where voltage and current injection equipment were utilised to simulate network conditions. GSM communication technology and an Itron ACE SL7000 smart electricity meter were utilised for the laboratory testing.

One key finding of the research conducted was the realisation of the richness of existing smart metering available at the distribution transformer level and how this can be utilised for monitoring. The efficacy of solutions with various degrees of additional hardware and software was compared. The solutions compared consisted of commercially available solutions, empirical research found in the literature, and laboratory testing performed for this dissertation.

The topic that was researched is therefore a truly relevant problem of the electricity distribution network and was intended to provide municipalities and other stakeholders with the assurance that monitoring distribution transformers can be implemented easily where base smart metering infrastructure is in place to prevent complete transformer failure. There is also an energy efficiency aspect as the equipment can be monitored to check performance against its expected specification, whether it is being exceeded or under-utilised. A view of the energy efficiency factor can contribute to energy efficiency audit data that form part of the global United Nations Sustainable Development Goals.

**Keywords:** distribution transformers; electricity power grid; smart metering; South Africa

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Lastly, I want to acknowledge my family for their unwavering love and encouragement. Specifically, thank my wife, Crystal, for her endless patience, love and support. This dissertation would not have been possible without her.

# DEDICATION

I dedicate this dissertation to my loving mother who passed away at the time of editing. I am grateful for seeing how proud she was when I paged through the draft with her and my dad. This graduation will not be as special without her cheering me on from the audience.

I am deeply thankful and grateful to God for His grace and mercy, which allowed me to complete this dissertation, against the greatest odds at times, and for the strength to help me keep at it and persevere.

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# GLOSSARY

| Term | Definition |
|---|---|
| A/D | Analog to digital |
| AMI | Advanced metering infrastructure |
| AMR | Automated Meter Reading |
| CPUT | Cape Peninsula University of Technology |
| $CO_2$ | Carbon dioxide |
| COSEM | Companion Object Specification Model |
| CT | Current transformer |
| DAS | Data acquisition system |
| DLMS | Device language message specification |
| DT | Distribution transformer |
| DTM | Distribution transformer monitoring |
| DTMS | Distribution transformer monitoring solution |
| DTS | Distribution transformer sensing |
| ER | Empirical research |
| $F_{AA}$ | Accelerated aging factor |
| $F_{EQA}$ | Equivalent aging factor |
| GHG | Greenhouse Gas |
| GPRS | General Packet Radio Service |
| GSM | Global System for Mobile Communications |
| iDMS | Integrated Distribution Management System |
| IEA | International Energy Agency |
| IEEE C57.91-2011 | Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators |
| IEC 62056-21 | Electricity metering - Data exchange for meter reading, tariff and load control - Part 21: Direct local data exchange |
| IEC 61000-4-30 | Testing and measurement techniques - Power quality measurement methods |
| I/O | Input / Output |
| IoT | Internet of Things |
| LPU | Large power users |
| LoRa | Long range |
| LoRa WAN | Long Range Wide Area Network |
| MDC | Meter Data Collector |

| Term | Definition |
|---|---|
| MDMS | Meter Data Management System |
| NB-IoT | Narrow band – Internet of Things |
| NOx | Nitrogen oxides |
| NWL | Network Waitaki Limited |
| OBIS | Object Identification System |
| ONAF | Oil Natural Air Forced |
| KNAF | Oil Natural Air Forced – less flammable |
| ONAN | Oil Natural Air Natural |
| KNAN | Oil Natural Air Natural – less flammable |
| QoS | Quality of Supply |
| RTU | Remote terminal unit |
| RMS | Root mean square |
| SMS | Short Message Service |
| SANS | South African National Standard |
| SDG | Sustainable Development Goals |
| Sigfox | Low-Power Wide-Area (LPWA) networking protocol |
| $SO_2$ | Sulphur dioxide |
| THM | Transformer health monitoring |
| THD | Total harmonic distortion |
| UN | United Nations |
| VRE | Variable renewable integration |
| WHO | World Health Organization |
| 4G/LTE | Long term evolution: a wireless data transmission technology that is part of the fourth generation of mobile networks |

# CHAPTER ONE

## INTRODUCTION

## 1.1 Introduction

A famous quote lends itself to the need for research and how important it is to continue thinking differently about something that might seem obvious to most.

> Research is to see what everybody else has seen, and to think what nobody else has thought. – Albert Szent-Gyorgyi (AZ Quotes, 2025)

On this note, this dissertation aims to provide a different approach to the advances of smart metering for monitoring distribution transformers (DTs). DTs play a critical role in the electricity grid and because of this, methodologies to monitor their performance are necessary to assess their health and life expectancy. The study of these transformers has a local and international appeal as electricity grids around the world are under severe strain due to various factors impacting the grid. DT's performance and possible unexpected failures have a significant impact on the energy consumer's livelihood as well as directly impacting the economic growth of a country. In their study Adams et al., (2020) focused on the transmission and distribution energy losses for South Africa over an extensive period between 1971 to 2014. The methodology implemented in this study focused on the deviation of power generated and what is consumed, factoring in both technical and non-technical losses. Their study showed that an average loss of 8.5% was observed for South Africa for this period. However, in the decade since 2014, South Africa has experienced significant challenges impacting the electricity grid that have resulted in increased and persistent load shedding. This was ongoing at the time of this study, as mentioned by the South African Government News Agency, (2024) and therefore on its own is a major contributor to the worsening performance of the electricity grid. The need for DT monitoring for international reach that includes developed and developing countries is discussed extensively in chapter 2.

The electricity grid is divided into three main sectors, namely generation, transmission and distribution. The electricity supply chain by Eskom consists of three main parts as categorised in Figure 1.1. This is relevant to South Africa, as Eskom is the main power utility that has been responsible for the electricity production for the past 100 years (Eskom, 2023). For a better understanding of where DTs fit into the picture, the electricity grid must be viewed as a whole to visualise how these parts interconnect. It starts at the generation stage where power is generated from either fossil fuel, nuclear or hydro sources. This is followed by the transmission stage, typically operating at 400/275 kV, where power is transported by overhead power lines supported by pylons across the transmission and distribution stages, where it reaches consumers at various distribution levels such as 132/33 kV, 11/22kV and 380/220 V.

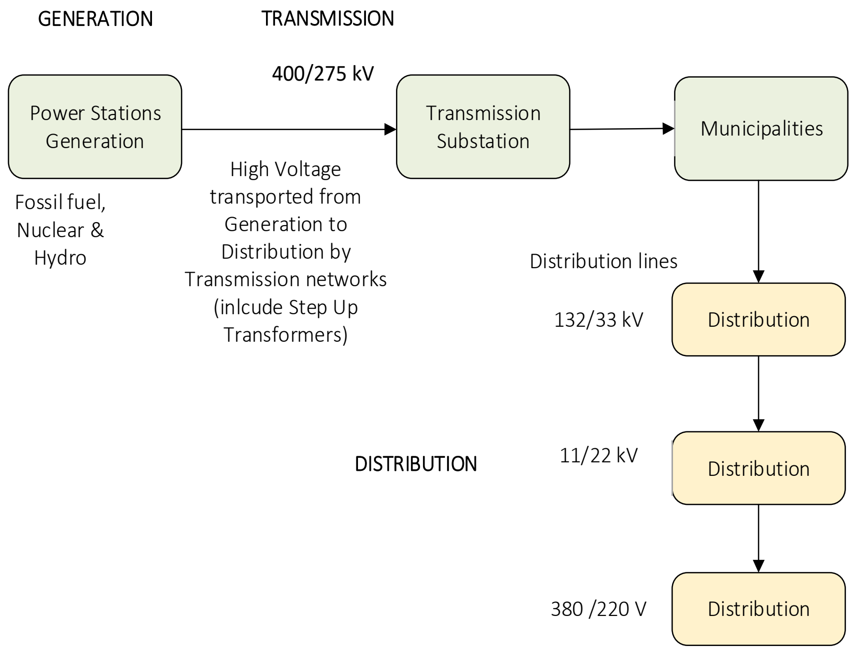


**Figure 1.1: Eskom electricity supply chain** (Eskom, 2023)

As DTs are located in the distribution stage, it is obvious that factors impacting generation or transmission will have a direct impact on them, as shown in Figure 1.2.

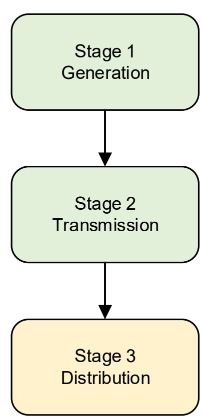


**Figure 1.2: DTM ripple effect**

Therefore, by monitoring DTs it is possible to not only monitor their health, but with the data obtained also to monitor the health of the surrounding grid components that include generation and transmission. DT performances are impacted by many factors causing poor performance and potentially their breakdowns. To understand the dynamics of the South African grid, it is important to consider the power generation mix as a start. Eskom's supply capacity (nominal) amounts to

47 619 MW (Eskom, 2023) as shown in Table 1.1, which shows that at least 8 power station types are utilised.

**Table 1.1: Eskom Power Generation Mix** (Eskom, 2023)

| Power Stations | Capacity MW |
|---|---|
| Coal-fired stations | 39930 |
| Nuclear station | 1854 |
| Peaking stations | 5835.4 |
| Hydro stations | 600 |
| Pumped-storage stations | 2724 |
| Open cycle gas turbines | 2409 |
| Wind energy | 100 |
| Other hydroelectric stations | 2.4 |
| **Eskom Generation Total** | **47619.4** |

Eskom's power generation is geographically spread across South Africa as shown in Figure 1.3 consisting of thermal, nuclear, hydroelectric, wind and gas.

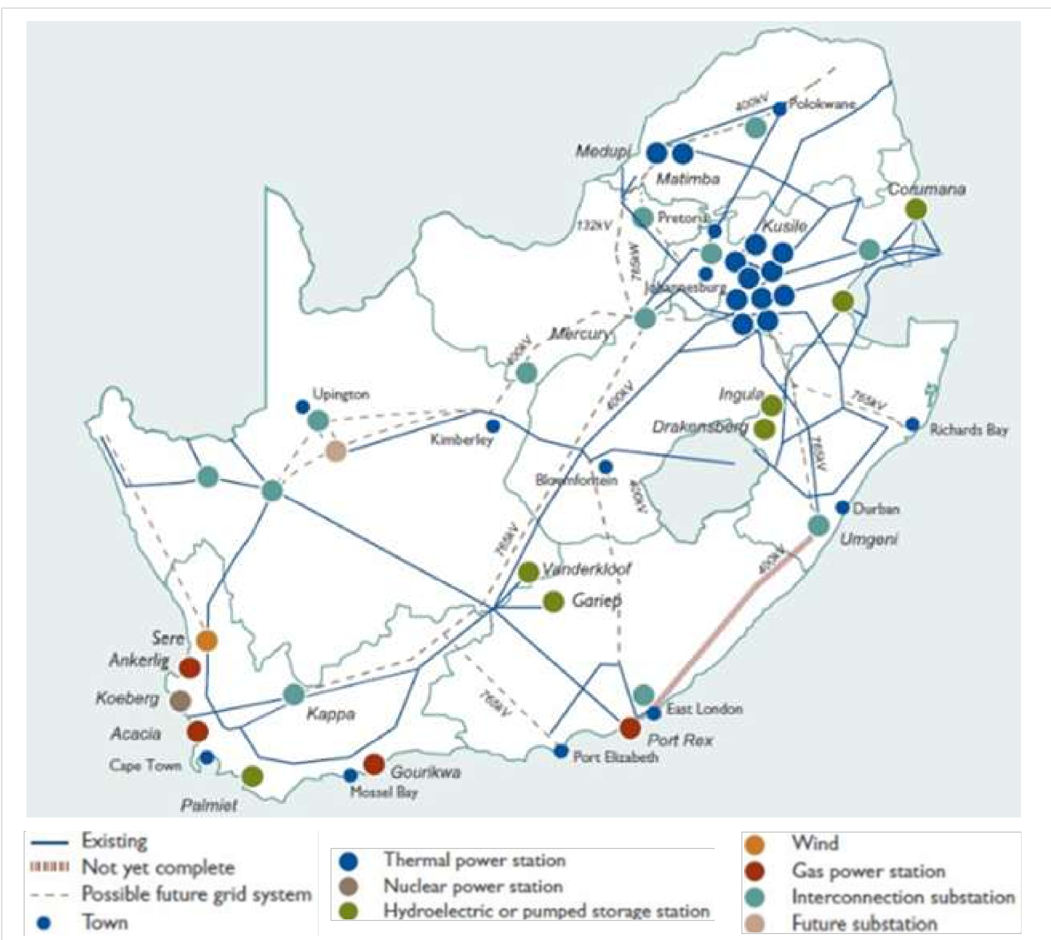


**Figure 1.3: Map of Eskom power generation** (Eskom, 2023)

South Africa has 257 municipalities (Cogta, 2022) that service their regions from the diverse power generation mix. DTs are therefore subjected to this power mix as well as the increase of non-linear loads and distributed energy sources (da Silva et al., 2020) that highlight the complexity of the electricity power grid and impact on the DT performance.

## 1.2 Background to the research problem

As various factors impacting the electricity grid have a direct impact on the behaviour of DTs, some of these will be discussed next. They include load shedding, renewable energy, climate control mandates and economic growth.

### 1.2.1 Load shedding impact on the electricity grid

Load shedding is the mechanism put in place to limit the demand on the electricity power grid to maintain system stability, as explained by the Western Cape (Department of Economic Development and Tourism (2019). Generally, the power system in South Africa has been strained as mentioned by du Venage (2020), who noted that the larger mining industries in South Africa have experienced operational stoppages due to rolling blackouts. This was anticipated by the power utility Eskom in late November 2019, which warned of strain on the electrical power grid and consequently implemented stage 6 load-shedding in December 2019.

The severity level of load shedding applied is determined by the power that needs to be shed to achieve system stability, and is determined by the energy availability factor. In the case of South Africa, Eskom manages the load shedding categories and determines when a certain load shedding limit applies nationally (Eskom, 2020a). The load shedding categories are listed in Figure 1.4, where each stage is linked to 1000 MW increments.

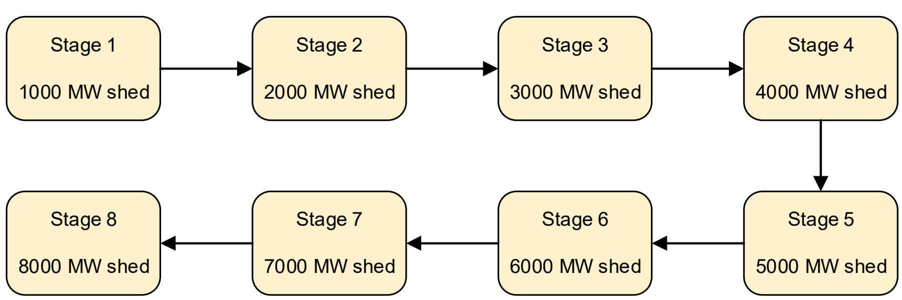


**Figure 1.4: Load shedding categories** (Eskom, 2020a)

Although the purpose of load shedding is to maintain stability of the electricity grid, the frequent switching of equipment on an already aged infrastructure has a detrimental effect on DTs. Coupled with lack of maintenance and monitoring, aged distribution transformers are highly challenged to meet the demand of continuous and quality electricity supply. This is supported by one of the outcomes of an Eskom report (Eskom, 2022) highlighting that generation performance showed a reduction in the energy availability factor.

### 1.2.2 Growth of renewable energy impact on the electricity grid

Another internal factor impacting the grid is the penetration of renewable energy with its unique challenges and considerations. Renewable energy has become the main driver to address global warming, with many countries working towards their commitments in reducing their carbon footprint. Vietnam is considered for the next discussion as the country has reached full capacity at the transmission line level (IUCN, 2022). It has not addressed compatibility of the grid for the saturation of renewable energy. This would be a typical requirement for most countries implementing renewable energy. Vietnam has successfully deployed solar and wind energy projects to support its electricity demand. Solar energy on its own contributes to 25% of the installed capacity, with locations as seen in Figure 1.5 showing the choropleth maps for wind and solar.

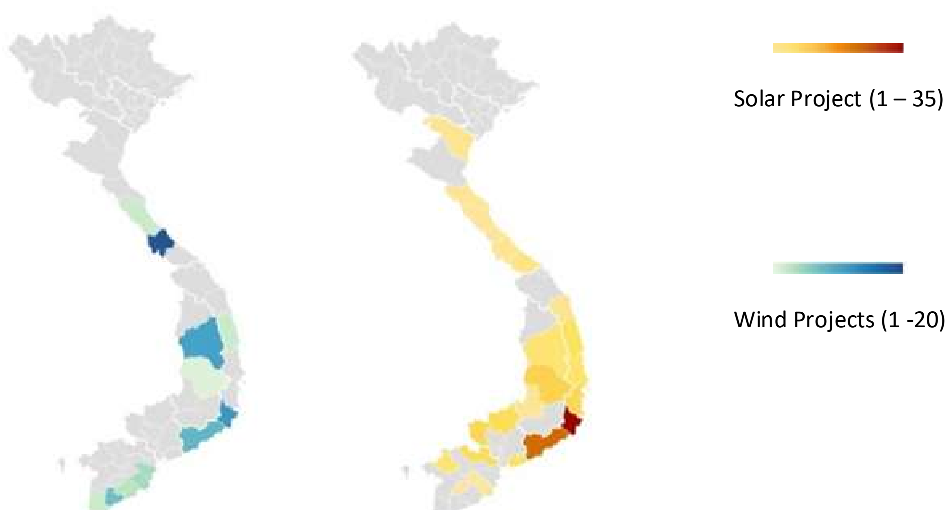


**Figure 1.5: Vietnam wind and solar generation** (IUCN, 2022)

According to the International Energy Agency (IEA) (IEA, 2023) the phases of variable renewable integration (VRE) can be categorised and phases described as in Table 1.2:

**Table 1.2: VRE integration phases** (IEA, 2023)

| Phase | Phase Description | VRE installed capacity |
|---|---|---|
| 1 | There are a few VRE power plants connected to the grid that have an impact at the grid point of connection. The power system operation is not impacted. | $\leq 5\%$ |
| 2 | The power produced from VRE has increased to a noticeable difference. The power system can manage the impact with minor operational management. | $\sim 5\% \geq 10\%$ |
| 3 | VRE has increased sufficiently to cause disruptions in the network and impacts stability. Additional work on the power system or VRE curtailment is required for system stability. | $\sim 10\% \geq 25\%$ |
| 4 | VRE has increased to produce all electricity for certain periods of time. Significant work on the power system is required that includes regulatory and operational changes. | Less flexible grids $\sim \geq 20\%$ Developed grids $\sim \geq 30\%$ |
| 5 or 6 | VRE has increased to the extent where surplus electricity is provided, and the grid has a greater dependency on this supply. This has not been realised in any country at the time of this study. | Grid operation is dependent on installed VRE. |

## 1.3 Climate control mandates

Global warming has received increasing interest and a drive to move away from fossil fuel has been the goal of the UN led initiative. The average temperature of the earth's surface has increased by 1.1 °C since late 1800. More importantly, climate scientists have claimed that the past decade – between 2011 and 2020 – was the warmest decade on record since 1850 (UN, 2023). This has been ascribed purely to human industrial activities resulting in increased greenhouse gases.

According to the UN (UN, 2023) It is evident that greenhouse gas emissions still need to be significantly addressed to reach a sustainable climate. Countries contributing the most to these emissions are a concern as the global climate system is impacted. In the case of South Africa, as the most carbon-intensive producer of electricity, partnerships have been formed with countries such as the United Kingdom, France and Germany to transition to low carbon energy.

## 1.4 Significance of monitoring DTs

Monitoring data on DTs that is easily accessible can provide stakeholders with the necessary information for effective management and maintenance, as well as plan for increased capacity where a greater demand is found. Advances in smart metering have made it easier to implement available technology to perform the monitoring of transformers remotely and non-intrusively. This can be achieved by smart metering equipment with the relevant algorithms to perform measurements of the transformer's performance and ageing rate. Data read and viewed remotely can be further analysed using related smart metering software. Technology providers such as Actom （Actom, 2021） and Itron （Itron, 2021）provide the monitoring software to perform these functions. Researching this problem is therefore of utmost importance for sustainability and quality of electrical supply at a pinnacle time globally and in South Africa. There is sufficient research material available to research this problem that entails monitoring and estimation techniques.

As DTs play in integral role in the electrical network infrastructure, they need improved measures for monitoring their performance in real time to prevent unplanned shutdowns. Advances in smart metering technology makes it possible to measure pertinent characteristics of these transformers non-intrusively with high accuracy and ease. Researching this topic is significant as it addresses the health of the power system and the role of municipalities in managing the challenges of an unreliable power grid. Interrupted supply has an impact on sectors such as manufacturing and business that influence the growth of the economy. It is also relevant to the electrical engineering community in addressing the current technical problems being faced. Technology service providers are constantly looking for solutions to address problems for utilities and municipalities. This research will therefore be significant in shaping their solutions.

One of the sustainable development goals (SDGs) of the UN is to ensure that access to affordable, reliable, sustainable, and clean energy is provided for all (UN, 2022). The topic of this dissertation addresses reliability and sustainability of energy and therefore speaks to a global concern. Monitoring the health of DTs is therefore an important contribution when working towards SDG 7, as seen in Figure 1.6, in particular, the need to address electrification and energy efficiency.


**Figure 1.6: SDG 7: Affordable and clean energy** (IEA et al., 2024)

SDG 7 has a direct impact on other sustainable design goals. The ones more relevant for this dissertation are:

- SDG 3 where good health and well-being define the goal to promote well-being for all ages.
- SDG 6 where clean water and sanitation define the goal for sustainable management.
- SDG 9 where sustainable industry, innovation, and infrastructure define the goal.
- SDG 13 where climate change is combatted.

## 1.5 Research question, aims and objectives

The research question, aims and objectives are discussed next.

### 1.5.1 Research question

What is the current state of distribution transformers globally and in South Africa, and how can advancements in smart metering be leveraged to monitor key parameters for estimating transformer health and aging?

### 1.5.2 Aims of the research

The research aimed to achieve analysis of the current state of distribution transformers globally and in the South African context. Further, it aimed to consider smart metering developments for monitoring important characteristics to estimate DT health and aging factors.

### 1.5.3 Objectives of the research

The research planned to achieve the objectives by researching the material that was available on these topics by using the Cape Peninsula University of Technology's (CPUT's) library sources, and by using technology provider resources, initially with a broader global context search and then specifically focusing on municipalities or utilities that utilise DTs; finally, by researching current smart metering technology that monitored DT characteristics. Metering technology providers specifically have focused on development of equipment using the latest technology for the electricity distribution environment. The advances of these technology providers were of particular interest.

## 1.6 Delineation of the research

Research started within a broader context of the global environment where the problem exists and then was narrowed down to distribution transformers as important components of the electricity power grid. The failure of DTs due to rapid aging and lack of monitoring was then researched in the municipal domain in the South African context.

## 1.7 Expected outcomes, results and contributions of the research

The expected outcome of this research was to find significant evidence of solutions to a relevant problem in the electricity distribution environment.

The expected results were to list similarities and contrasts amongst solutions showing the wide range that is possible.

The contributions made by the research are to inform utilities and municipalities of the range of solutions that are applicable for their requirements; to provide technology service providers with insight to the significance and practicality of their solutions; then lastly, to raise awareness amongst all stakeholders of high greenhouse gas (GHG) emissions due to poorly managed DTs.

## 1.8 Structure outline

The chapters are structured as follow:

**Chapter 1** provides an introduction, background, main objectives, and literature overview of the research problem.

**Chapter 2** commences with the detailed body of literature and theory of technology that applies to the research problem. Comparisons are made with the smart metering technologies available and their different functionality and benefits. This chapter also includes the collection of empirical data, where a collective view of commercial solutions and the empirical research helps to identify the research gap.

**Chapter 3** describes the research methodology design used to reach the objective and aims of this dissertation. The laboratory testing criteria are also defined here that leads into the next chapter.

**Chapter 4** is where the testing of DT performance based on research methodology criteria are performed. Detailed laboratory test points are covered with reporting results.

**Chapter 5** is where data analyses are performed on the test outcomes, empirical research and DTM cases. Comparative analyses are performed to determine efficacy of the different solutions.

**Chapter 6** finally concludes the dissertation and responds to the main objectives set out in chapter 1.

# CHAPTER TWO

## LITERATURE REVIEW

## 2.1 Introduction

This dissertation is a study on the advances of smart metering for monitoring DTs and aims to understand the current state of DTs globally as well as in the South African context. These transformers are of interest as electricity grids around the world are under severe strain due to multiple factors impacting them. The literature review starts with the global need to monitor DTs. The theoretical framework is next, discussing the theory behind DTs and listing the different types and their unique applications. The theory of smart electricity metering follows, including the origins and latest smart metering capability. Advances in DT monitoring technology are listed where different DTM commercial solutions are compared by key selection criteria. The empirical research section reviews literature where solutions have been researched with the objective of drawing conclusions and comparisons between them. The literature review is then summarised in the conclusion chapter.

## 2.2 Global need for monitoring of DTs

The need for monitoring of DTs is a global concern and of interest to developed and developing countries. In this section, references are made to countries that fit these categories using the UN country classification (UN, 2024). The research performed by Msane et al. (2024) provides an insightful and thorough view of the need for monitoring of transformers. They have identified an interesting breakdown of countries where the total contribution of publications was considered. The distribution of research contributions in the field of smart metering for electrical transformer status monitoring is shown in Table 2.1, and the percentage is rated out of a total of 25 countries. India accounts for 55% of the publications, China for 8,3% and Pakistan for 3.3%. The rest of the countries account for 1% each.

**Table 2.1: Research distribution country** (Msane et al., 2024)

| | Country of research | Percentage |
|---|---|---|
| 1 | India | 55% |
| 2 | China | 8.3% |
| 3 | Pakistan | 3.3% |
| 4 | Angola, Bangladesh, Europe, Ethiopia, Ghana, Rwanda, Spain, United States of America (For indication, 8 of 22 are listed). | 1% |

### 2.2.1 Monitoring in developed countries

Finland and Spain are among the developed countries that have deployed monitoring systems for power and distribution transformers. In their case, they deployed the use of the ABB electrical service and Danish Oktogrid's solution called TRAFCOM, which is an asset manager system that performs real-time monitoring measurements that includes temperature of transformers, humidity, and surface temperature (ChannelLife UK, 2024).

### 2.2.2 Monitoring in developing countries

Transformer oil testing services were performed by the company SGS in Angola that performed oil testing to identify issues concerning temperature health (SGS, 2024). In the case of Ethiopia, Tariku & Bekele (2020) highlighted the need for transformer monitoring as 89 transformers burnt down the East Addis Ababa region. The causes of failure were identified with solutions provided to the utility.

### 2.2.3 Country of focus (South Africa)

The country of focus for this study is South Africa, where network conditions are described in the introduction of chapter 1. Actom Energy (de Nysschen & Jain, 2020) has identified various reasons for transformer failures, applicable to municipalities in South Africa, that included system issues, faults, damage and external factors. To visualise the need for DT monitoring in developed and developing countries, Figure 2.1 shows a top-down filter to the focus country.

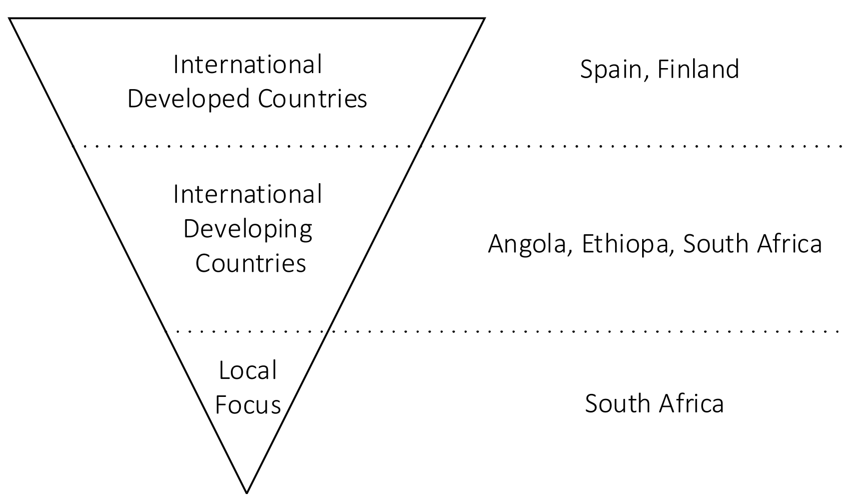


**Figure 2.1: Need for monitoring DT**

## 2.3 Theoretical framework of DTs

A theoretical framework for DTs is covered next where the theory and transformer types are discussed.

### 2.3.1 Electrical transformer theory

Electrical transformer operation is based on electromagnetic theory as defined by Lenz's law that was further develop by Maxwell. Power is transferred by means of electromagnetic induction. An alternating voltage source is applied at the primary winding, resulting in an alternating flux produced that is necessary for the transfer to the secondary winding. To induce a voltage, alternating current is necessary for a changing magnetic field (Eskom, 2010). As can be seen in Figure 2.2, there are two type of circuits that are in operation: namely the electrical and magnetic circuits. The electrical circuit consists of the current I1 flowing through the primary winding of the transformer, when applying an alternating voltage E1 on the primary winding.

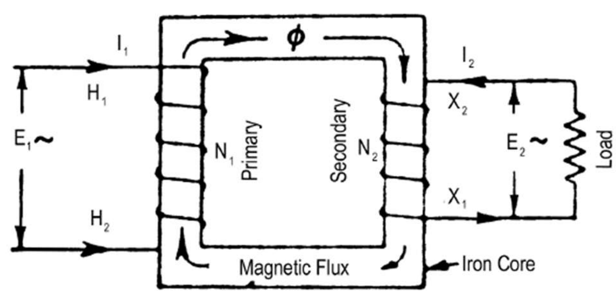


**Figure 2.2: Basic Transformer Function** (Eskom, 2010)

This will in turn produce an alternating magnetic field with magnetic flux $\boldsymbol{\theta}$ that will flow through the transformer core and energise the secondary winding, resulting in a voltage across the coils. The relationship of the voltage between the primary and secondary winding is dependent on the ratio of the number of turns (N).

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} \text{ or } \frac{E_1}{E_2} = \frac{N_1}{N_2}$$ **Equation 2.1**

The fundamental relationship is the ratio of the primary and secondary voltage when considering the ratio between the primary and secondary winding turns.
Considering that power is the product of voltage and current, the primary and secondary power will be equal, as addressed in the following formula:

$$P_1 = P_2$$
$$E_1 I_1 = E_2 I_2$$
$$\therefore \frac{N_1}{N_2} = \frac{I_1}{I_2}$$

**Equation 2.2**

### 2.3.2 Distribution transformer types

DT technologies can be grouped in two main categories, namely liquid-filled and dry types. In addition to this, advances in digital DTs will also be considered. Comparing a few leading distribution transformer manufacturers such as General Electric, Daelim, Hitachi Energy, and SGB-SMIT, the distribution transformer categories will be discussed as follows:

- Liquid-filled DTs: pole- and pad-mounted single- and three-phase.
- Dry-type DTs: epoxy-resin dry type, vacuum cast coil (VCC), open wound transformers.
- Advances in DTs: Hitachi Energy CompactCool™ and ester-filled transformers.

#### 2.3.2.1 Liquid-filled DTs

Liquid-filled DTs typically utilise mineral insulating oil. There are, however, more expensive minerals that can be utilised such as silicon oils and esters (Daelim Belefic, 2023). The technology has been around for approximately 50 years and is low cost and is easy to maintain. As transformers by design are inefficient, the losses that occur will be converted into heat. The cooling mechanism is therefore critical to alleviate the heat and prevent the transformer from failing. Alfanar (2023) describes the following types of cooling oils:

- Liquid with flash point < 300 ℃ uses Oil Natural Air Natural (ONAN)
  This method uses convection to move the heated oil from the bottom to the top of the tank, where the ambient temperature takes the heat away.

- Liquid with flash point < 300 ℃ uses Oil Natural Air Forced (ONAF)
  This method also uses convection to move the heated oil from the bottom to the top of the tank. However, external cooling fans are required to take the heat away.

- Liquid with flash point > 300 ℃ uses Oil Natural Air Natural – Less flammable (KNAN)
  This method uses less flammable non-mineral oil for natural air convection.

- Liquid with flash point > 300 ℃ uses Oil Natural Air Forced – Less flammable (KNAF)
  This method uses less flammable non-mineral oil for forced air convection. External cooling fans are required to take away the heat.

The natural air forced transformers can be operated at above normal rating of ~ 25%. Different types and applications of DTs are discussed next.

#### 2.3.2.2 Pole-mounted single- and three-phase DTs

Pole-mounted single-phase and three-phase DTs, as seen in Figure 2.3, are applicable for overhead line distribution and are typically rated at primary voltages up to 36 kV with a demand rating of 315 kVA. They are used for small load applications such as switchgear control power, lighting for billboards, traffic & street lighting, and pump stations (Hitachi, 2022).

**Figure 2.3: Pole-mounted liquid type DTs** (Hitachi, 2022)

#### 2.3.2.3 Pad-mounted single- and three-phase DTs

Pad mounted three-phase transformers, as seen in Figure 2.4, are DTs that are applicable for underground distribution and are rated at primary voltages up to 36 kV with a demand rating of 250 kVA for single-phase and 3000 kVA for three-phase DTs. They can be used to service urban and rural residential and commercial demands, industrial loads, as well as wind and solar farm demands (Hitachi, 2022).

**Figure 2.4: Pad-mounted liquid DT** (Hitachi, 2022)

#### 2.3.2.4 Dry-type DTs

Dry-type DTs utilise air to dissipate heat as opposed to liquid-filled DTs that use oil (Daelim Belefic, 2023). They operate at lower power with poor moisture resistance, while oil-immersed transformers operate at higher power and are more resistant to moisture. Due to the solid form build of dry-type transformers, they inherently do no provide the conditions for fire and oil spillage. They can be easily recycled as the majority of insulating components are not conditioned to wear and tear (Hitachi, 2022).

#### 2.3.2.5 Epoxy-resin dry types

Three-phase epoxy-resin dry type transformers, as seen in Figure 2.5, are applicable for heavy load centres for the commercial and industrial sectors, such as factories and shipyards. Their primary rated voltages, 10 kV, 25 kV, and 35 kV can cover a wide demand range of 50 to 2500 kVA. Their features include being compact and lightweight, damp proof, flame resistant, and having high overload ability (Daelim Belefic, 2023).


**Figure 2.5: Dry type transformer 10 kV** (Daelim Belefic, 2023)

#### 2.3.2.6 Vacuum cast coil (VCC) transformers

VCC dry type transformers, as seen in Figure 2.6, are applicable for use in very humid (higher than 95%), or heavily polluted environments. These can be installed close to the point of consumption as they are very safe to operate and carry no risk of catching fire. They provide a high resistance to short circuits and support high capacity of overload conditions. Their primary rated voltages vary from up to 24 kV and 72.5 kV with a wide demand range of up 63 MVA (Hitachi, 2022).

**Figure 2.6: Vacuum cast coil DT** (Hitachi, 2022)

#### 2.3.2.7 Open wound transformers

Open wound transformers, as seen in Figure 2.7, are grouped in two categories: vacuum pressure encapsulated (VPE) and vacuum pressure impregnated (VPI). With VPEs, the use of multiple sealant processes provides enhanced protection for maritime applications exposed to moisture, salt air and dust. With VPIs, the transformers use vacuum pressure with a polyester varnish. This provides transformers with excellent resistance to short circuits, no fire risks, as well as no liquid spills. Their primary rated voltages are low voltages up 24 kV, and high voltages up to 36 kV, with a wide demand range of up 30 MVA (Hitachi, 2022).

**Figure 2.7: Open wound transformer (VPE)** (Hitachi, 2022)

#### 2.3.2.8 Advances in DTs

At this stage it is worthwhile mentioning a few advances in DTs when comparing the traditional liquid and dry type transformers, and also to assess whether technology has advanced in addressing transformer performance monitoring. Hitachi Energy CompactCool™ is considered for dry type and ester-filled for liquid type transformers.

#### 2.3.2.9 Hitachi Energy CompactCool™ technology

Hitachi utilises an advanced cooling mechanism whereby a liquid coolant is pumped through the inside of the coils. This action extracts losses from the windings and supplies an external heat exchange unit as seen in Figure 2.8. The losses are now converted to heat energy distributed to an external ambience. Hitachi CompactCool™ devices are applicable for locations where a smaller footprint, safety and low maintenance are required (Hitachi, 2022).

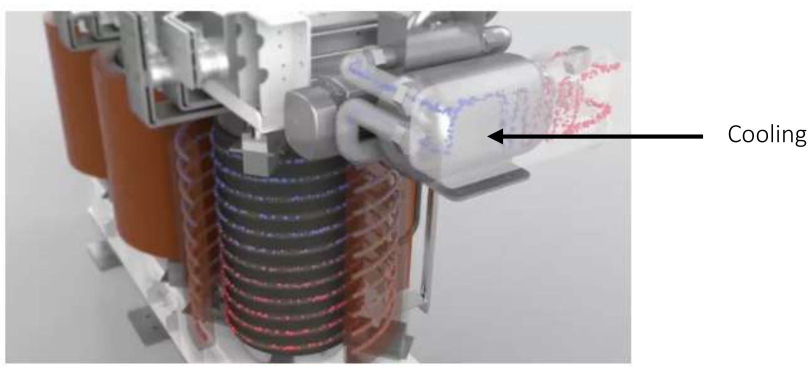


**Figure 2.8: CompactCool (TM)** (Hitachi, 2022)

#### 2.3.2.10 Ester-filled distribution transformers

In their research, Das and Patel (2022) studied the sustainability and efficiency of DTs by using sustainable ester fluids. They concluded that the same level of network reliability is achievable by replacing the traditional fluids with ester. Ester is considered more costly than mineral oils which normally deters the purchase of this more expensive option. However, it is the more sustainable option for transformer lifespan. This also has the advantage of reducing $CO_2$ emissions tremendously and contributes towards a sustainable and greener power grid.

### 2.4 Theorical framework of smart metering

Automated meter reading (AMR) has proven to be crucial for energy measurements globally, and the infrastructure utilised enables other readings, such as DT data, to be measured by the same mechanism. For DT monitoring, it is therefore important to understand the functioning and components of an AMR system. The South African National Standard (SANS) 473 (SABS, 2017) defines an AMR standard when transitioning from local meter reading to an automated process, which is read by an interoperable meter reading system. This standard has been defined for use in South Africa and adopted for large power users (LPU).

#### 2.4.1 AMR and AMI systems theory

The AMR system flow illustrated in Figure 2.9 is described next according to SANS 473 (SABS, 2017). The electronic AMR meter records and registers energy consumption, ensuring that metering data is possible to be downloaded for the data acquisition system (DAS). All AMR meters support optical port compliance to IEC 62056-21 as well as modular industry ports such as RS232, RS485 or TCP/IP for remote reading. Metering software should be able to read registers and configure parameters in the meter. The remote master station, also known as the data acquisition system (DAS), should be able to read data from various AMR meters installed in the field and accommodate different remote devices using compatible communication interfaces. The function of the AMR system is also to represent billing information and store the data for a pre-determined time.

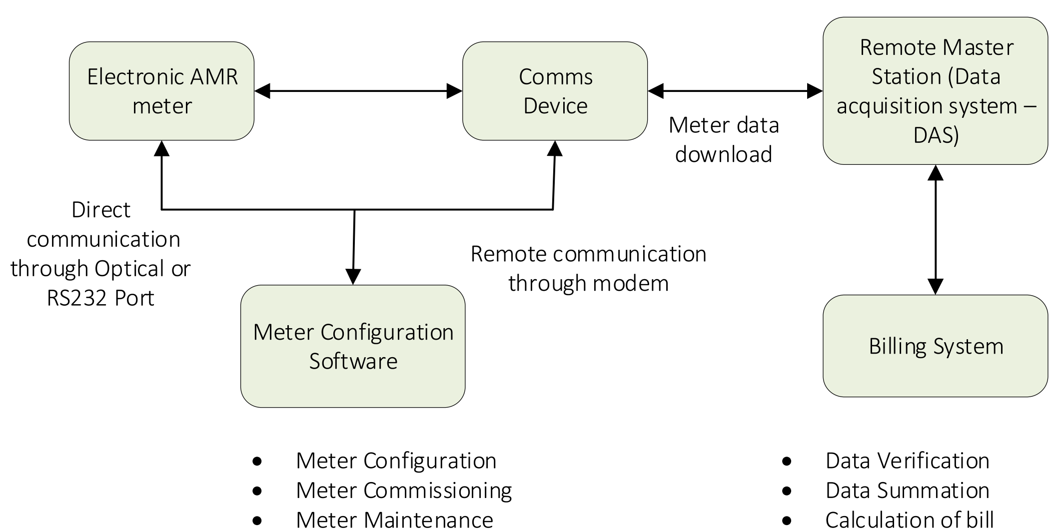


**Figure 2.9: AMR system flow (SABS, 2017)**

AMR systems have since improved and started to include Advanced Metering Infrastructure (AMI) functionality based on the Eskom NRS 049 standard (Eskom, 2016), that includes multiple services additional to the standard billing requirement. In fact, in most cases AMR and AMI terminology is used interchangeably. A view of how these technologies compare is listed in Table 2.2 where the following processes are compared.

Communication is one way, meaning it can only be established from the system end; or two-way, where communication can be established from both system and device end. Data collection refers to the interval period whether monthly data registers or interval data registers. 'Business processed' refers to the type of services available and 'consumer participation' describes whether customer interactions are required.

**Table 2.2: AMR and AMI Comparison** (Kaur, 2021)

| **Process** | **AMR** | **AMI** |
|---|---|---|
| Communication | One-way | Two-way |
| Data collection | Monthly data and Interval data | Interval Data |
| Business processed | • Billing<br>• Consumer information system | • Billing<br>• Consumer information system<br>• Outage management<br>• Emergency demand response |
| Consumer participation | None | • In home display<br>• Demand response |

A typical AMI system could therefore be constructed as Figure 2.10 based on the Itron DTM solution (Itron, 2017). Starting with the electricity meter that measures the transformer performance, it then communicates this by the communication network that is fully flexible with the latest technology to the Meter Data Collector (MDC) and the Meter Data Management System (MDMS) reports on DT behaviour.

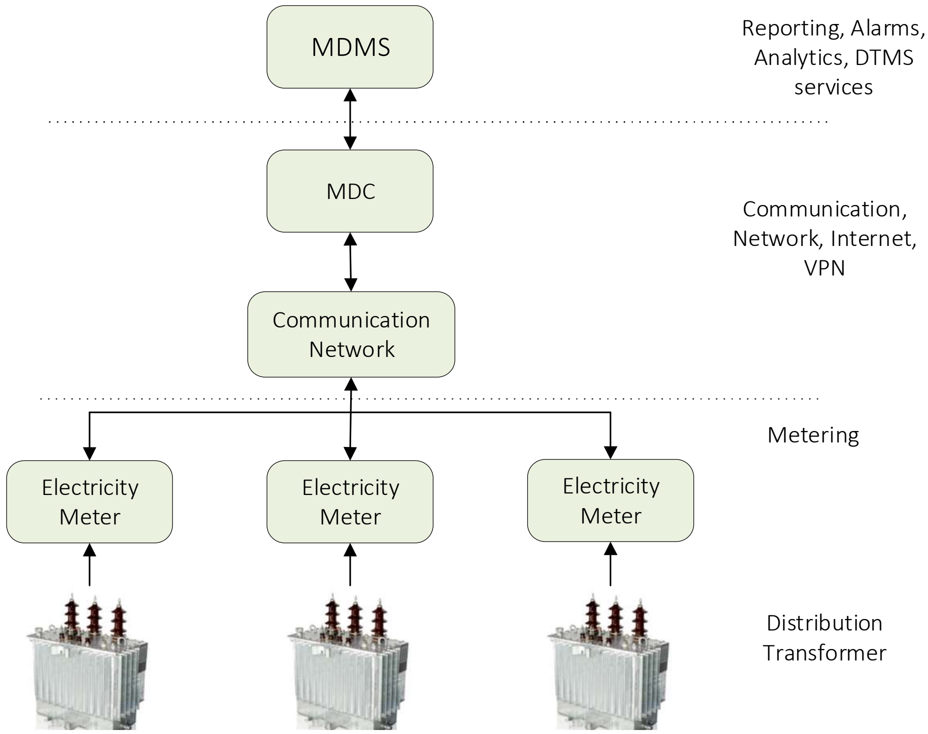


**Figure 2.10: Typical AMR system flow**

### 2.4.2 MDC communication technologies

It was noted above that the communication network is fully flexible and equipped with the latest technology. A few of these technologies are now listed and are based on one of South Africa's leading telecommunications service providers, Vodacom's available services.

For the Low Power Wide Area (LPWA) category: Narrow band – Internet of Things (NB-IoT), SigFox, and Long Range (LoRa) are amongst the top technologies. These address key functionality of strong coverage over larger areas, greater power efficiency, massive scale rollout application, and low bandwidth (Vodacom, 2017).

In terms of the rest of the IoT services, 5G, LTE, 3G, Edge and GPRS are available on the cellular front (Vodacom, 2024).

### 2.4.3 AMR and AMI system benefits

In their paper Makwarela & Mamanyuha (2022) described how leveraging AMI data can facilitate operational efficiency of a distribution network. They emphasised that by building a smarter grid using smart metering, a telecommunication network with advanced analytics, it is possible to capture demand in real time, which enhances command centre analytics and in turn makes it possible to respond accordingly to asset lifecycle management.

They listed a few use cases that could be realised when deploying a full AMI system:

- Real-time demand responses for residential customers.
- Being alerted to outages faster and being able to respond faster.
- Improving productivity and safety by automating tasks.
- Safety risks being mitigated as tasks are automated.
- Possibility of performing dynamic demand side management using certain algorithms.
- Being able to implement asset lifecycle management proactively.

### 2.4.4 Transformer monitoring progression

Monitoring of transformers can therefore only be as effective as the technology that is available at the time. In order to visualise a progression of transformer monitoring, the following categories in Figure 2.11 have been identified. In category 1, transformers are monitored by electricity meters that perform basic electricity metering functions with primary objectives for billing and limited functionality to monitor transformers. The readings are also performed locally, which means that the data is not available in real time (Eskom, 2016). In category 2, as the electricity meters advance to smart metering, further functionality becomes available including AMR. Though remote readings are possible, it is still not possible to perform full transformer monitoring that includes transformer aging calculations (Eskom, 2016). In category 3, full transformer monitoring becomes possible as transformer hot spot measurements can now be included into the monitoring algorithm. These readings can be measured as a standard input at the smart meter and the hot spot reading is available at the MDMS (Itron, 2018). In category 4, transformers are integrated with smart metering capability with sensors that can dynamically manage the transformer loading and monitor the performance. These are read remotely by the system for reporting. 'Digital distribution transformer' is another term used for transformers with such functionality (Hitachi, 2022).

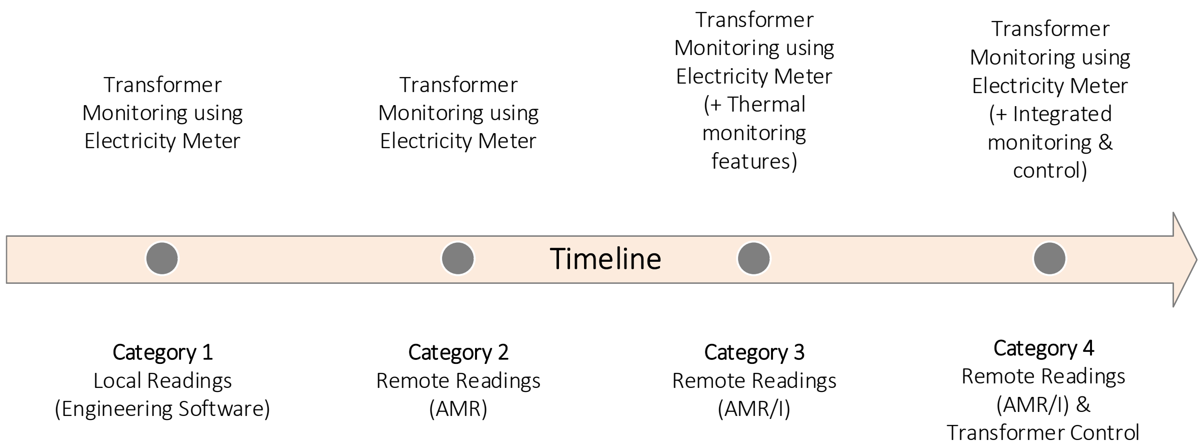


**Figure 2.11: Transformer monitoring progression**

### 2.4.5 Electricity meter communication protocol

As most electricity meters comply with the Device Language Message Specification (DLMS) protocol, it is important to understand how this protocol is implemented throughout the smart metering system. The DLMS User Association (DLMS User Association, 2019) illustrated the architecture and protocol between the meter, Companion Object Specification Model (COSEM) server, and smart metering system, COSEM server, as shown in Figure 2.13.

The physical layer contains the actual hardware such as modems, that connects to the transnit (communication) network for communication to the outside world. The data link follows and interfaces the data to the application layer from where it can be accessed. Lastly the client layer accesses the data by an application used by the client.

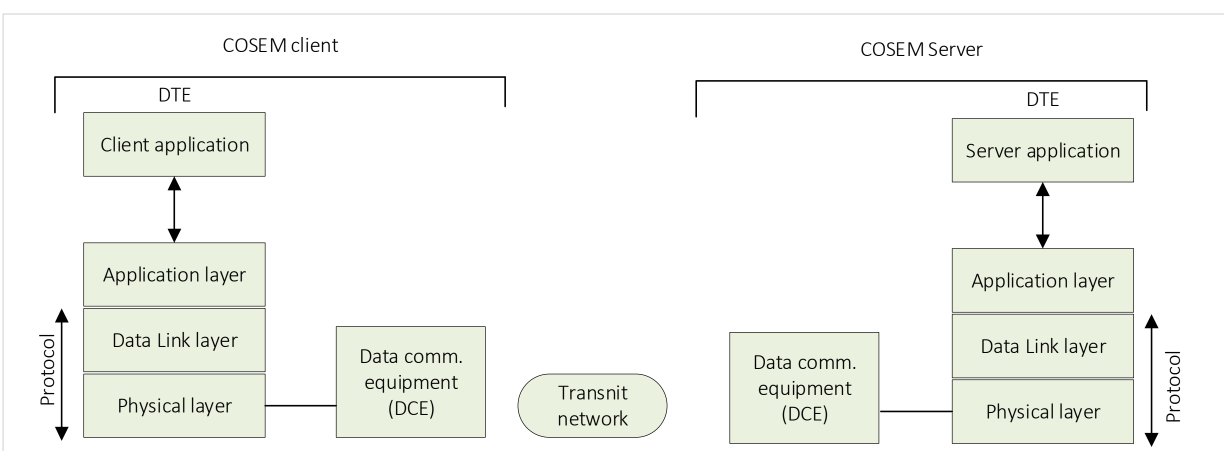


**Figure 2.12: COSEM Client and Server – protocol layers** (DLMS User Association, 2019)

In the case of electricity meters, the DLMS/COSEM protocol specifies all registers as DLMS/COSEM objects with Object Identification System (OBIS) codes. The active energy and apparent energy are typical registers that are utilised by electricity meters, with their OBIS code listed below:

- Active energy – OBIS code 1.1.1.8.0.255
- Apparent energy – OBIS code 1.1.9.8.0.255

### 2.5 Comparison of advances in DTM solutions

To further obtain an understanding of how DTM solutions are implemented, a few cases will be studied to review the characteristics of different solutions. Advances in smart metering will be explored with the criteria below in mind, shown in Table 2.3, as these were found to be most applicable for DTM solutions.

**Table 2.3: DTM solution criteria**

| No | DTM solution criteria | Criteria detail |
|---|---|---|
| 1. | Distribution Transformer Monitoring Solution (DTMS) services | What are the DTMS services? Do they include services such as analytics, alarms and reporting? |
| 2. | Transformer measurements | What transformer measurements can be achieved? Do they include QoS, harmonics, phase unbalances, energy and demand readings? |
| 3. | Aging factor calculation | Is it possible to calculate the aging factor or life expectancy of the transformer? |
| 4. | Communication technology | Is the communication method reliable with real time reading capability? |
| 5. | Complexity of applying solution | How easily can the solution be applied and what are the prerequisites? |
| 6. | Digitally-enabled transformer | Does the solution require a transformer with digital controls? |

#### 2.5.1 DTM case 1 – Hitachi TXpert™ asset management solution

The Hitachi Energy TXpert™ solution is an asset management system that is based on digital monitoring and diagnostics connectivity (Hitachi Energy, 2023). Their aim is to allow utilities and industrial services to maximise performance and efficiency of transformers as assets. They service transformers throughout the entire life cycle for a large range of manufacturer and transformer types. The solution enables power transformers from Hitachi Energy and transformers of other manufacturers to be retrofitted.

The solution consists of the following components:

The TXpert™ Hub monitoring system is powered by CoreTec and holds all the data that is sensed. It is here that the digitalisation takes place, regardless of if it is liquid-filled, dry, new, or retrofitted, and is not manufacturer-specific. It is where data is collected, interdependencies are correlated, and patterns are realised. The hub also offers cybersecurity at its core. TXpert™ Ready sensors consist of sensors and monitoring devices that are physically installed in the transformer to enable digital monitoring of health and performance. One of the diagnostics services involving sensors is the inspection of dielectric fluid. TXpert™ Services relate to the level of digitisation of the transformer that the asset owner decides on to have visibility and control of the transformer. TXpert™ Lumada APM is the component that combines all the data in a common platform where plots and trends are visualised, and transformer performance and aging are assessed.

The Hitachi Digital TXpert ™ Ecosystem is shown in Figure 2.13.

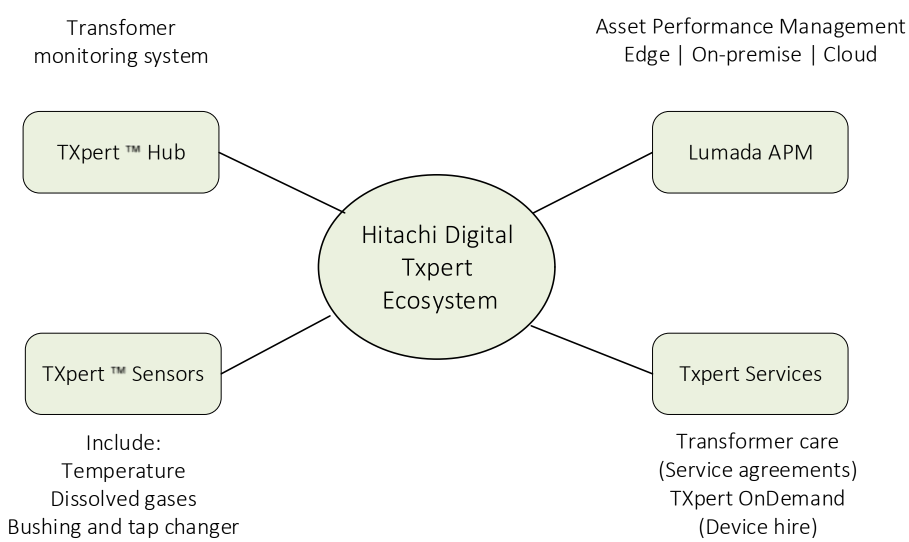


**Figure 2.13: Hitachi Digital TXpert ™ Ecosystem** (Hitachi Energy, 2023)

### 2.5.2 DTM case 2 – Itron DTM metering solution

The reach of the distribution transformer monitoring (DTM) solution is reviewed in the white paper (Itron, 2018) by Network Waitaki Limited (NWL). The focus of NWL was to improve their quality of service to their stakeholders by improving the awareness of issues on their distribution network and the root causes of these. Two important elements to consider these goals were the knowledge improvement of the long-term life cycle, and then also improve the real-time awareness of network operations. The DTM solution (Itron, 2017) is described next.

The hardware components consist of the DTM electricity meter and communication device to the network.

- The DTM SL7000 electricity meter is installed on the low voltage side of the transformer, using Rogowski coils to measure the full current range.
- The communication device is an ACE Sparklet 2G, 3G and ethernet module device.

The software components consist of the collection management engine, Itron Analytics and Itron Total Outcomes Services.

- The collection management engine collects, stores and manages the data that is measured.
- Itron Analytics then finds the data to be presented as well as highlighting key customer information for the client.
- The Itron Total Outcome Services include an additional level of intelligence to include transformer health information. These include:
    - Transformers identified with high risk of failure
    - Transformers identified with accelerated aging
    - Transformers identified with exposure to overheating
    - Voltage issues detected that exceed the configured thresholds
    - Phase unbalances that exceeded configured thresholds

The Itron DTM solution is illustrated in Figure 2.14.

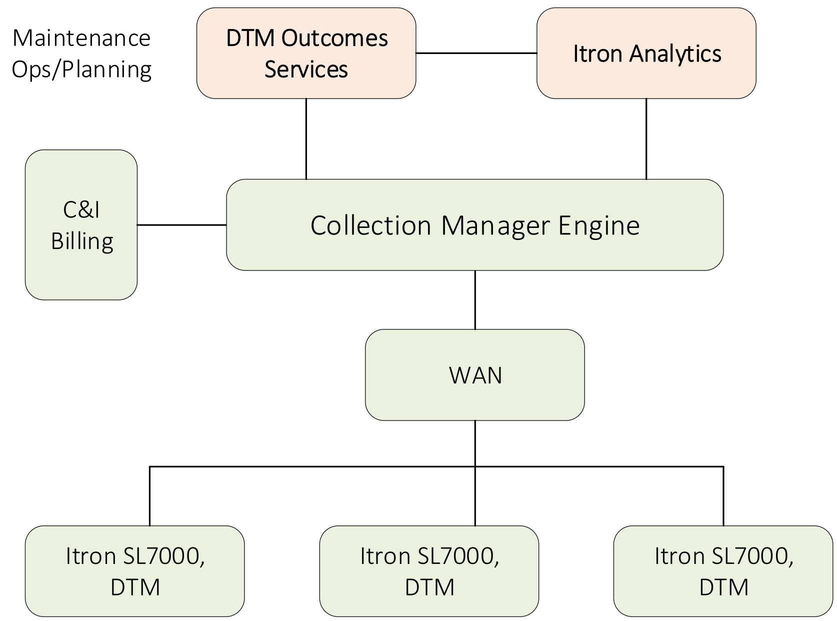


**Figure 2.14: Itron Total Outcomes DTM Architecture** (Itron, 2017)

### 2.5.3 DTM case 3 – Hexing iDMS fully integrated solution

Hexing's Integrated Distribution Management System (iDMS) solution is a fully integrated distribution management system that allows utilities to monitor, control, and manage distribution networks. The system tracks faults and outages to manage the restoration processes in order to stabilise the network (Hexing, 2023). As a backbone of the smart grid platform, multiple functions can be plugged into this platform with services such as substation and feeder monitoring, system tracking faults and outages, and managing the restoration processes to stabilise the network, as noted above. Hexing also supports a range of electricity meters at the DT level, such as the HXF300 meter (Hexing, 2024)

The Hexing electricity meters have the functionality to register measurements that facilitate the monitoring of DTs. These include the following:

- Metrology – active and reactive energy measurement
- Load profile – recording channels that measure power factor, temperature and frequency
- Power quality – voltage cuts, sags, swells, total harmonic distortion (THD) on voltages and currents.

### 2.5.4 DTM case 4 – Meter software local reading solution

This case was included to highlight the option of using engineering software that is provided by the meter manufacturer. The software can accurately read measurements from these meters that can be used to assess the status of transformers. According to (Eskom, (2016), the minimum data required from AMR devices includes energy and demand registers and integration period values, as well as quality of supply (QoS) values where this is supported. The engineering software for commonly used meters in South Africa such as Elster, Landis+Gyr, Itron and Hexing with software is listed in Table 2.4. All such software is installed on Microsoft operating systems and can communicate with the meters remotely or locally.

**Table 2.4: Meter engineering software**

| No | Manufacturer | Meter Engineering Software |
|---|---|---|
| 1. | Elster | SMARTset (Elster, 2015) |
| 2. | Landis+Gyr | .MAP110 (Landis+Gyr, 2024) |
| 3. | Itron | ACE Pilot (Itron, 2020) |
| 4. | Hexing | HexView 4 (Hexing, 2024) |

A visual view of meters and the respective meter engineering software is shown in Appendix A.

### 2.5.5 DTM cases summary

The DTMS cases discussed in the previous section are summarised here and cross-referenced to the transformer monitoring progression of Figure 2.11 using the criteria in Table 2.5. The solutions were intentionally selected to explore all categories.

**Table 2.5: DTM cases summary**

| No | DTMS | DTM criteria (See Table 2.3) | | | | | | Transformer Monitoring Progression (See Figure 2.11) |
|---|---|---|---|---|---|---|---|---|
| | | DTMS services | Transformer Measurements | Aging factor | Communication Technology | Installation Complexity | Digital Capability of Transformers | |
| 1. | Hitachi TXpert™ | ✓ | ✓ | ✓ | ✓ | High | ✓ | Category 4 |
| 2. | Itron | ✓ | ✓ | ✓ | ✓ | Low | ☒ | Category 3 |
| 3. | iDMS | ✓ | ✓ | ☒ | ✓ | Low | ☒ | Category 2 |
| 4. | Engineering software | ☒ | ✓ | ☒ | ✓ | Low | ☒ | Category 1 |

The different cases of section 2.5 show mixed results against the DTM criteria measured, and in the particular category they fit in according to Figure 2.11.

## 2.6 Comparison of empirical research in monitoring DTs

A collection of empirical data was obtained by researching journals that were available from the CPUT library and similar reputable resources. The main criteria to identify suitable papers were that they needed to indicate the sample size, methodology applied and have actual data to correlate (Centennial College, 2024).The criteria for comparisons are listed in the following questions, as listed in section Table 2.3. The following papers were selected as they best describe similar research undertaken to address the research problem. The aim was to position this dissertation in the current body of research, as these research papers have unique methodologies and approaches.

### 2.6.1 ER case 1 – Overloading analysis using temperature measurement model

Muthukaruppan et al. (2022) analysed the overloading of DTs using existing smart metering data and the temperature estimation model based on the IEEE C57.91-2011 standard. Their aim was to estimate the winding hot-spot temperature and the aging of transformer insulation life to predict transformer overloading.

**Sample size**

The scope of the analysis was 10 DTs over a period of 24 hours to one year. AMI data were used from a utility in North Carolina with 8757 customers with 1415 DTs ranging from 10 kVA to 1500 kVA.

**Methodology deployed**

The methodology deployed leverages on the AMI data available, with a clustering method used for the meters that were part of a partially deployed system. Temperature data was utilised from a weather station in North Carolina.

The IEEE standard C57.91-2011 is a temperature model applicable to mineral oil-immersed transformers that explains how transformer temperature is impacted by transformer loading and ambient temperature. The standard is further used by calculating the accelerated aging factor $F_{AA,}$ where Φ is the winding hot spot temperature in °C for the nth period, as seen in Equation 2.3.

$$FF_{AA,n} = \exp\left[\frac{15000}{383} - \frac{15000}{\emptyset_{H,n} + 273}\right]$$

**Equation 2.3**

The daily equivalent aging factor $F_{EQA}$ indicates the effective aging time within a time period N. When the transformer ages by one day for a natural day, it indicates normal operation.

$$F_{EQA} = \frac{\sum_{n=1}^{N} FF_{AA,n}}{N}$$

**Equation 2.4**

Another important formula to consider for the estimation of transformer overloading is calculating the overloaded energy using Equation 2.5.

$$OL_{energy} = \frac{\sum_{t=0}^{T} FF_{AA,n} - 1}{\Delta t}$$ **Equation 2.5**

**Results**

There are two main results from this study that address ranking the transformer aging. These are ranking per their overloaded energy and equivalent aging factor. By using these two sets of results, it is possible to overlap and highlight transformers that are deteriorating at a faster rate than normal. Figure 2.15 shows the ranking of overloaded energy and Figure 2.16 the yearly equivalent age of the first five overloaded transformers.

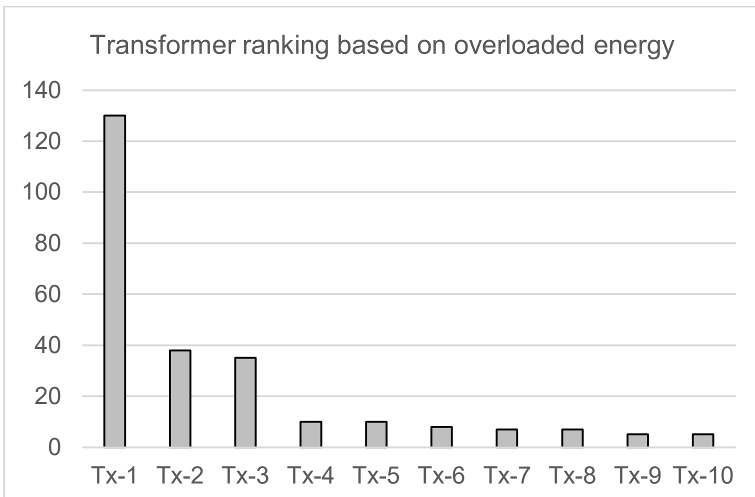


**Figure 2.15: Ranking per overloaded energy** (Muthukaruppan et al.,2022)

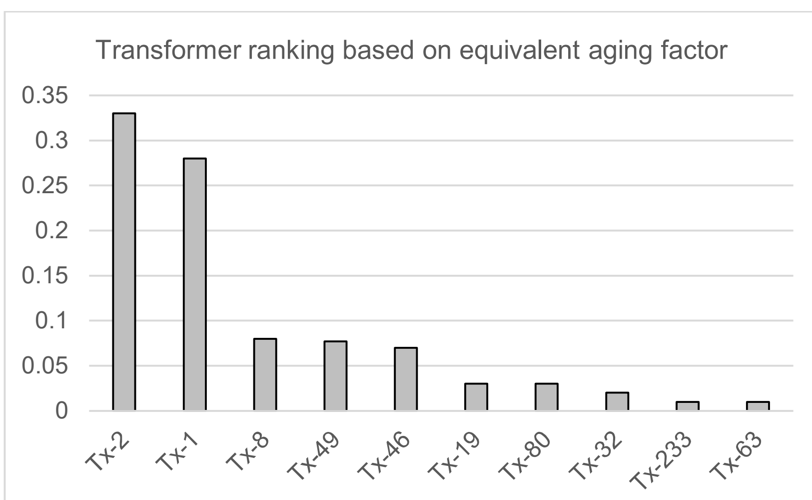


**Figure 2.16: Ranking per equivalent aging factor** (Muthukaruppan et al.,2022)

The authors found that by superimposing the yearly equivalent aging over the first five overloaded transformers, it was possible to identify transformers that needed to be prioritised over others. In Figure 2.17 it is evident that transformer Tx-2 was overloaded in 2018 and 2020 approximately 1.5 times, thus its operating level and needs had to be addressed first. However, transformer Tx-1 experienced significant overloading in 2018 that has since been brought down to normal operation. This means that it did not have to be prioritised for attention.

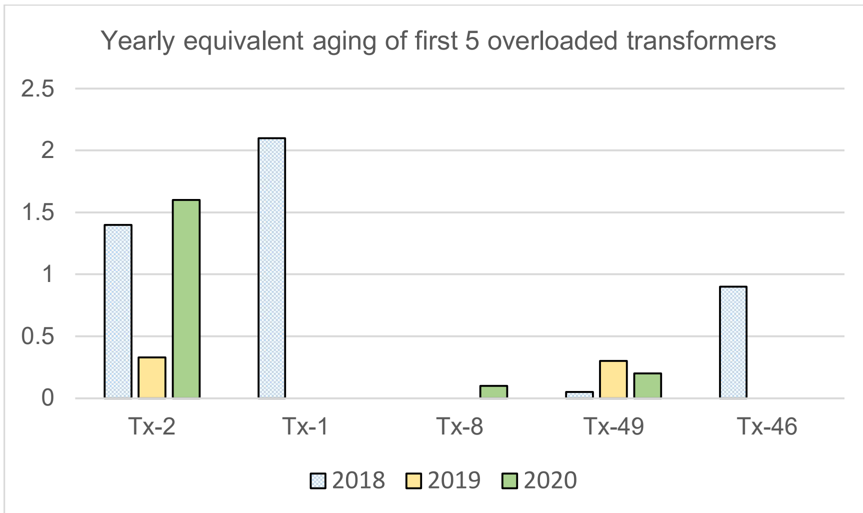


**Figure 2.17: Yearly equivalent aging of first 5 overloaded transformers** (Muthukaruppan et al.,2022)

### 2.6.2 ER case 2 – DT health monitoring using smart meter data

Ashok et al. (2020) presented a paper to monitor DT health using smart meter data to detect high voltage insulation degradation.

#### Sample size

The scope of the analysis was to monitor 590 transformers by baselining their performance for a period of 3 months and evidence of degradation analysed after this period.

#### Methodology deployed

The methodology deployed used an algorithm that built on the assumption that the primary network topology of the feeder was available and that there was negligible degradation for the initial baselining period during the time when smart data recorded voltage and power measurements.

The voltages on the secondary neighbouring transformers can be related using the following method in Equation 2.6 where $V^{pri}$ and $V^{sec}$ are the primary and secondary voltages and $N$ indicates the turns ratio also seen in Figure 2.18 with the object of determining a common ratio.

$$V_1^{pri} = N_1 \text{x} V_1^{sec}$$ **Equation 2.6**
$$V_2^{pri} = N_2 \text{x} V_2^{sec}$$
$$V_1^{pri} = V_2^{pri} = V^{pri}$$

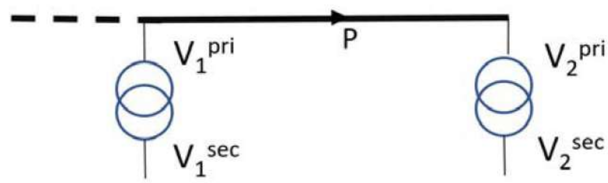


**Figure 2.18: Primary network connection** (Ashok et al., 2020)

Therefore, as $N_2$ x $N_1$ is a constant, the secondary voltage should also remain a constant, as seen in Equation 2.7.

$$V_1^{sec} / V_2^{sec} = N_2 x\, N_1 = constant$$ **Equation 2.7**

However, with practical considerations, a small voltage drop can be considered during peak loading periods. This can be accounted for by updating the equation and formulating this into a linear progression. In this case $\sum(P)$ equals the sum of the power downstream of $V_2^{pri}$ and accounts for the voltage drop between the 2 transformers. $\beta_1$ is an indication of the transformer ratio and $\beta_2$ is proportional to the resistance of the voltage cable between the two transformers. This is shown in Equation 2.8.

$$V_1^{sec} = \beta_1 V_2^{sec} + \beta_2 \sum(P) / V_2^{pri} + \in$$ **Equation 2.8**

**Results**

This paper was able to demonstrate a robust method for DT insulation and health monitoring using existing smart meter voltage and power measurement data. There was therefore also no need for invasive additional sensors to be installed. The results for the sample DTs showed that it was possible to identify transformers with degradation in the high voltage insulation. The algorithm deployed averaged the alarms over multiple neighbour DTs for increased accuracy and avoided false positives that were caused by normal operation, such as voltage tap changes and solar injection.

### 2.6.3 ER case 3 – Transformer monitoring using IoT (LoRa)

A paper by Kumar & Ajitha (2017) has been included in the research as it presents a different view of using IoT (LoRa) for monitoring and diagnosing the condition of transformers by using sensors and devices. The LoRa communication method is deployed at the sensor level.

**Sample size**

This sample consisted of 9 DTs.

**Methodology deployed**

The methodology deployed depended on the addition of sensors to monitor voltage, current, oil and winding temperature, oil level, and status of the silica gel in the breather of the transformer. All the sensors, S1 to S6, interfaced to an Arduino Uno microcontroller board that used ATmega328 and operated in edge mode to perform calculations. All this functionality is described in Figure 2.19, where the DT measurements were performed and communicated by the LoRa WAN network to the software platform that was cloud platform based.

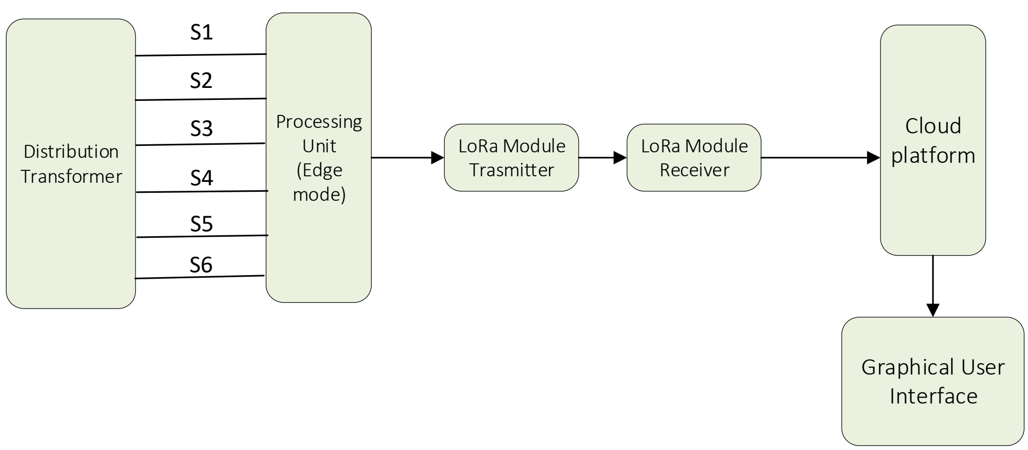


**Figure 2.19: LoRa WAN DTM solution** (Kumar & Ajitha, 2017)

**Results**

The Internet of Things (IoT) based solution for monitoring the transformers remotely was seamless and effective compared to manual monitoring methods. Continuous monitoring of DTs with timely alerts is an advantage of this method. This is seen by one of the transformer measurements in Table 2.6, where S. No 5 exceeded the current threshold defined. In a similar fashion all the DTM values can be measured, and threshold parameters defined.

**Table 2.6: DTM values measured**

| S. No | Voltage (V) | Current (A) | Oil temperature (℃) | Winding temperature (℃) | Oil level (cm) | Silica gel status |
|---|---|---|---|---|---|---|
| 1 | 5 | 1.02 | 30 | 30 | 21 | Unsaturated |
| 2 | 5 | 1.02 | 30 | 28 | 24 | Unsaturated |
| 3 | 5 | 1.02 | 29 | 28 | 20 | Unsaturated |
| 4 | 5 | 1.02 | 29 | 28 | 18 | Unsaturated |
| 5 | 5 | 1.5 | 29 | 28 | 18 | Unsaturated |
| 6 | 4.9 | 1.02 | 29 | 28 | 18 | Unsaturated |
| 7 | 4.98 | 1.02 | 30 | 30 | 18 | Unsaturated |
| 8 | 5 | 1.02 | 31 | 28 | 18 | Unsaturated |
| 9 | 5 | 1.02 | 30 | 28 | 18 | Unsaturated |

### 2.6.4 ER case 4 – DT monitoring as part the development of an automated distribution grid.

In their paper, Chaves et al. (2022) described some of the solutions developed by ENEL Distribution São Paulo to automate electricity distribution with new technologies. It entails the installation of sensors for the monitoring and protection of both the overhead and underground electricity grid with the focus on digitalisation of the primary substation communication infrastructure improvements, to attempt complete automation.

**Sample size**

ENEL Distribution São Paulo installed 10 distribution transformer sensing (DTS) units between 2019 and 2020.

**Methodology deployed**

The components were installed in a panel that was mounted on the same pole as the transformer to be monitored. The measuring components included current and ambient temperature sensors, where the voltage levels were derived from the panel supply. The remote terminal unit (RTU) acted like a local computer as it received the field measurements and, in real time, performed the calculations required. As listed in Figure 2.20, these the items pointed towards the RTU, and if any of these exceeded the predefined thresholds, the equipment sent an alert.

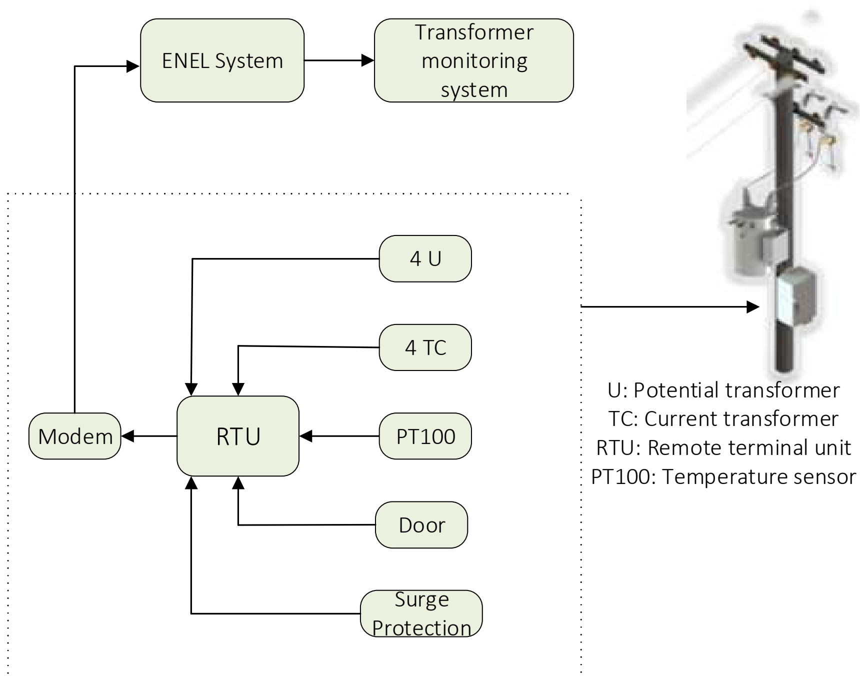


**Figure 2.20: ENEL Transformer monitoring solution** (Chaves et al., 2022)

**Results**

The DTS solution therefore aimed to provide data to the utility regarding the status of the DTs, which had become increasingly important due to increased penetration of renewable energy in the electricity distribution network. In the case of monitoring one DT, the data found was quite significant, as seen in Figure 2.21, where the number of defects is indicated for each type of defect.

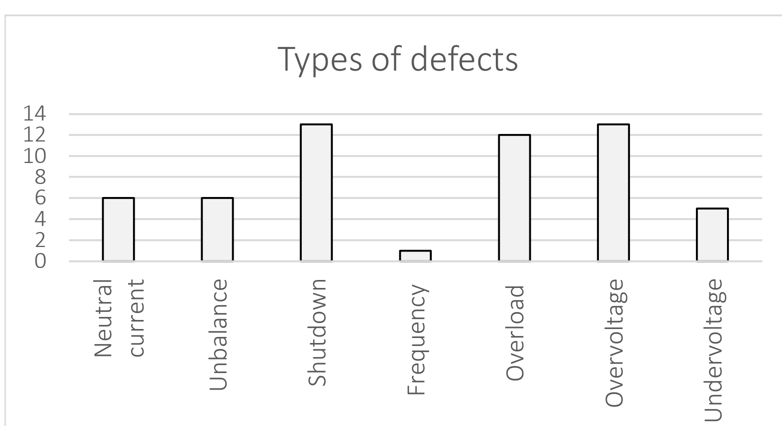


**Figure 2.21: ENEL Type of defects** (Chaves et al., 2022)

### 2.7 Research gap

The literature review has now extensively covered various ranges of DTM solutions. The first part was described in section 2.5, where DTM commercial solution cases were explored. These included four different types of solutions with various characteristics as described in the DTM cases summary in Table 2.5, with different criteria. This was followed by empirical research where four research papers were explored with various approaches to performing transformer monitoring.

These are all encapsulated in Figure 2.22, where the DTM commercial cases and ER cases are mapped to the progression. Starting on the left, DTM case 4 is linked to category 1, as only the engineering metering software comes into play. ER cases 1 and 2 are linked to category 2, where the existing smart metering system is used. ER case 3 and DTM case 2 involve additional monitoring features. Finally, ER case 4 and DTM cases 1 and 3 involve integrated monitoring and control of the DTs.

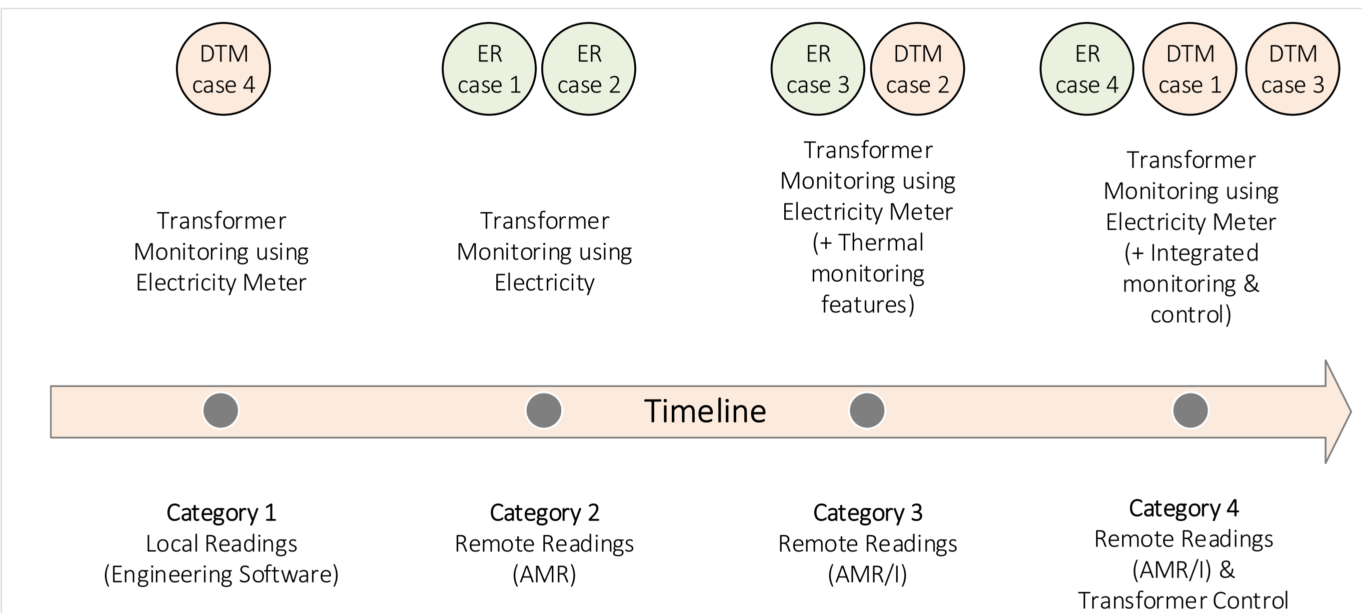


**Figure 2.22: Progression with DT monitoring solution overlap**

The research gap identified is to explore category 2, as there are no additional devices required except for what is already available at the meter and system level. This is also the status of most electricity meters installed at municipalities and utilities. Focusing on this area will therefore yield the best results.

## 2.8 Conclusion

The literature review conducted has now covered the global need for monitoring DTs. The theoretical principles of DTs have been covered extensively, in terms of the supporting theory and the wide range of DT types available with their applications. This was followed by smart metering principles with different approaches and applications. Comparisons of different DTM solutions and empirical research followed, where four solutions and cases were studied respectively. The literature review concludes by reviewing the most effective area to explore the research gap and addressing it most effectively. The area to be addressed is found in category 2 of the transformer monitoring progression, Figure 2.22. The research methodology chapter, therefore, continues with this in mind.

# CHAPTER THREE

## RESEARCH METHODOLOGY

## 3.1 Introduction

The aim of the research is to analyse the current state of distribution transformers globally and in the South African context, further by exploring smart metering developments for monitoring critical measurements to estimate their health and aging factor; moving from a broader global context search; and then specifically researching municipalities or utilities that use DTs. This research methodology chapter starts with the research philosophy and approach, describing the type of research being undertaken. The research design, sampling, and data collection methods are then described further. The measurements section is a significant portion of the chapter, as it describes the measurement criteria of all the components of the DTMS. The laboratory equipment section describes the equipment utilised to perform the testing. This chapter is then summarised.

## 3.2 Research philosophy and approach

The research methodology applied is positivism, as scientific methods will be utilised with the research being objective, reliable, and replicable. This is also a quantitative study as there are measurable elements to consider. Relevant data will be studied on smart metering advancement in the monitoring of DTs. Quantitative analysis is a suitable approach as it addresses the evaluative and historical questions asked, as well as involves the collection of measured data. The data itself can be collected with a high degree of accuracy.

The quantitative research is characterised as follows:

- Data gathering is obtained by using structured research instruments.
- Research can be duplicated with a high degree of reliability.
- The research question is clearly defined, and the objectives are stated.
- The research methodology can be carefully designed before data is collected.

The quantitative study research design will therefore continue with the research design section.

## 3.3 Research design and sampling strategy

The research design is largely descriptive as it focuses on describing existing conditions without manipulating any variables. The research methodology will therefore only perform data collection of existing condition sets. Following this, the sampling strategy fits in the probability sampling category as opposed to non-probability sampling. Probability sampling is more appropriate as a representation of the DT population and the associated monitoring capability will be researched.

### 3.4 Data collection method

The data collection approach is cross-sectional as it aims to look at data collection at a single point across various stages of DT conditions. This is shown in Figure 3.1, where the electricity network condition can change and therefore the DT can be impacted differently.

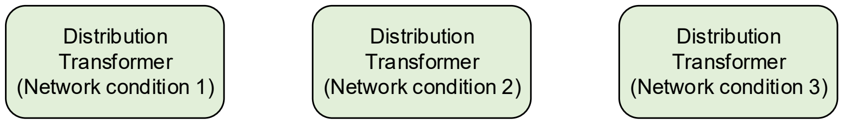


**Figure 3.1: Cross-sectional data collection method**

### 3.5 Measurements

Data will be collected by considering the measurements that contribute to the monitoring of DTs. The typical AMR system flow in Figure 2.10 will be considered in this case and mapped to the relevant measurement. The data measurement will be discussed first and then followed by the methodology approach. The measurements described in Table 3.1 were obtained at the DT level using smart metering capability. The measurements are listed with their relevant reading and real-time notification possibilities. The functionality was derived from the Itron electricity meter documentation (Itron, 2022) and is elaborated in the following paragraphs.

**Table 3.1: DT Measurements**

| No | Measurement | Meter Reading | Real-time notification |
|---|---|---|---|
| 1. | Demand reading | Apparent energy<br>excess demand register | Yes |
| 2. | Phase balance | Phase current register<br>Phase unbalance threshold monitor | Yes |
| 3. | Quality of supply | Phase cut, sag, swell threshold monitor | Yes |
| 4. | Power factor | Power factor register | No |
| 5. | Total harmonic distortion (THD) | THD monitor | No |
| 6. | Ambient temperature | Temperature register | No |
| 7. | Line frequency | Frequency register | No |

### 3.5.1 Demand reading

The demand reading is critical when monitoring the output of the transformer compared to its kVA rating. Apparent power is important as it measures the highest demand utilised by the transformer and is a measurement that can be easily obtained from the electricity meter. The power triangle in Figure 3.2 has the following measurements: apparent power, reactive power, and true power are now described. Apparent power (S) is the power supplied to the load of an electrical circuit with measured power in volt-amperes (VA) and is considered the generator output. Resistive loads consume true power (P) in the electrical circuit and are measured in watts (W) and is considered usable power. Then reactive power (Q) is the result of inductive and capacitive loads in the electrical circuit and is considered wasted or stored power. The phase angle θ is an indication of the inefficiency of the AC circuit and is the relationship to the total reactive impedance (Z) to the current flow in the circuit (DoE United States, 1992).

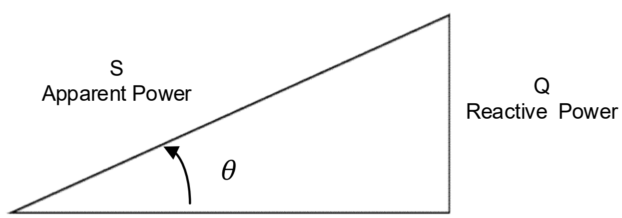


**Figure 3.2: Power triangle**

Apparent power is mathematically presented in Equation 3.1, where S is apparent power measured in VA, I is root mean square (RMS) current measured in A, E is RMS voltage measured in V and Z is impedance measured in Ω.

$$S = I^2 Z = IE$$ **Equation 3.1**

True power is mathematically presented in Equation 3.2 where P is true power measured in watts, I is RMS current measured in A, E is RMS voltage measured in V, R is resistance measured in Ω and θ is the angle between E and I cos waves.

$$P = I^2 R = EI \cos\theta$$ **Equation 3.2**

Figure 3.3 provides an illustration of the effect of phase shift on the active power. The phase shift range was $0^0$, $30^0$, $45^0$, $60^0$, $90^0$, $120^0$, $135^0$, $150^0$ and $180^0$.

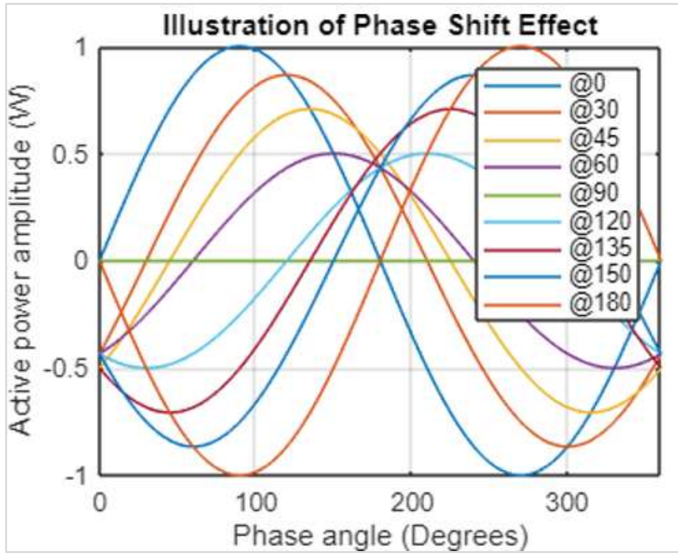


**Figure 3.3: Illustration of the phase shift effect on the active power**

Reactive power is mathematically presented in Equation 3.3 where Q is reactive power measured in VAR, I is RMS current measured in A, X is net reactance measured in Ω and θ is the angle between E and I sin waves.

$$Q = I^2X = EI\sin\theta$$ **Equation 3.3**

Apparent power in Equation 3.4 is therefore the square root of the sum of the squares of the active and reactive powers, measured and calculated in volt-ampere (Eskom, 2023).

$$S = \sqrt{P^2 + Q^2}$$ **Equation 3.4**

In order to determine the threshold of demand reading to simulate, the following factors were considered. DTs are typically less efficient than power transformers that are normally operated at full capacity. DT efficiencies are typically 75% to 80% of the rated load (Daelim Belefic, 2023). Transformers also by design will have energy losses that occur due to eddy currents that are produced because of the alternating magnetic flux and copper losses due to electrical resistance in the primary and secondary windings.

**Demand thresholds derived**

Based on the typical efficiency of the transformer and full loss watts the demand threshold was calculated as follows:

Normal demand is apparent power at a perceived normal level and mathematically presented below with transformer rating as $tr$ and full load loss as $fls$.

$$Demand_{Normal} = 0.8\ x\ tr - 0.8\ x\ fls$$ **Equation 3.5**

Exceeding demand is apparent power at a perceived exceeding level and mathematically presented below with transformer rating as $tr$ and full load loss as $fls$.

$$Demand_{Exceed} = 0.9\ x\ tr - 0.9\ x\ fls$$ **Equation 3.6**

### 3.5.2 Phase balance

Phase balance is a critical measurement as it will determine whether the transformers are operating optimally on all three phases and therefore providing the required expected output. Typical measurement parameters of Itron meters (Itron, 2022) include network voltage unbalance, load unbalance and no consumption. An unbalance voltage can cause the current drive to increase, resulting on greater power losses (ABB, 2015).

The voltage unbalance value in Equation 3.7 is derived by the unbalance threshold value subtracted from the nominal voltage.

$$V_{unbalance} = V_{nom} - V_{unbalance_{threshold}}$$ **Equation 3.7**

The load unbalance value in Equation 3.8 is derived by the unbalance threshold value subtracted from the nominal current.

$$I_{unbalance} = I_{nom} + I_{unbalance_{thresh}}$$ **Equation 3.8**

### 3.5.3 Quality of supply

Quality of supply (QoS), or power quality, has an impact on the transformer performance and monitoring these parameters is important. The severity level and frequency of the power quality events can have a direct impact on the transformer performance. The voltage quality standard IEC 61000-4-30 (ELSPEC, 2024) is considered when calculating the respective thresholds. Voltage sag, swell and cut events will be considered for this exercise, as shown Table 3.2.

**Table 3.2: Voltage supply measurements – IEC 61000-4-30**

| No | Measurement | Defined in IEC 61000-4-30 | Notes |
|---|---|---|---|
| 1. | Voltage sag | Decrease in RMS voltage of 10% or more below the nominal voltage for a period of 1/2 cycle to 1min. | Possible causes are a sudden large change of loads through the source impedance such as in a motor startup, or short circuit events. |
| 2. | Voltage swell | A brief increase in RMS voltage of 10% or more below the recommended range for a period of 1/2 cycle to 1min | Possible causes are ungrounded or floating ground delta systems, or when a large load is turned off. |
| 3. | Voltage cut | This is not defined by the standard and is meter manufacturer-specific. | - |

#### 3.5.3.1 Phase sag

A phase sag wave will be considered with the following points in mind: where the phase cut start and end thresholds are important points to monitor as shown in Figure 3.4, with the sag start Equation 3.9, and sag end Equation 3.10.

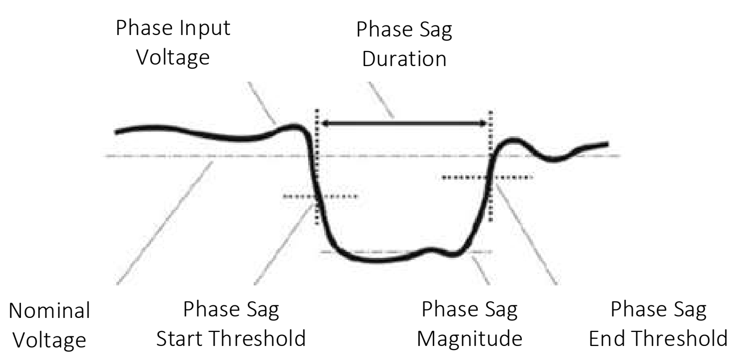


**Figure 3.4: QoS phase sag** (Itron, 2022)

$$V_{sag\_start} = V_{nom} \, x \, V_{sag\_start\%}$$ **Equation 3.9**

$$V_{sag\_end} = V_{nom} \, x \, V_{sag\_end\%}$$ **Equation 3.10**

As an illustration Figure 3.5 shows how a 40 % sag in the voltage will appear.

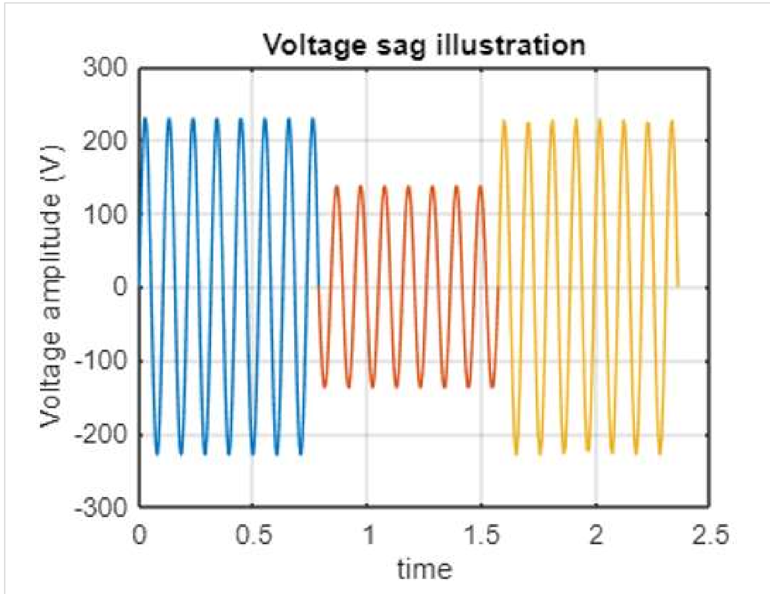


**Figure 3.5: Phase sag illustration**

#### 3.5.3.2 Phase swell

A phase swell wave will be considered with the following points in mind: where the phase swell start and end thresholds are important parameters to monitor, as shown in Figure 3.6, with the swell start Equation 3.11, and swell end Equation 3.12.

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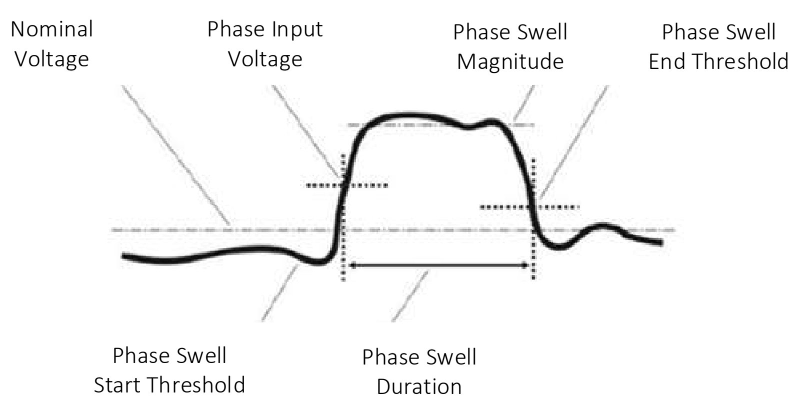


**Figure 3.6: QoS Phase Swell** (Itron, 2022)

$V_{swell\_start} = V_{nom} \: x \: V_{swell\_start\%}$ **Equation 3.11**

$V_{swell\_end} = V_{nom} \: x \: V_{swell\_end\%}$ **Equation 3.12**

As an illustration Figure 3.7 shows how a 40 % swell in the voltage will appear.

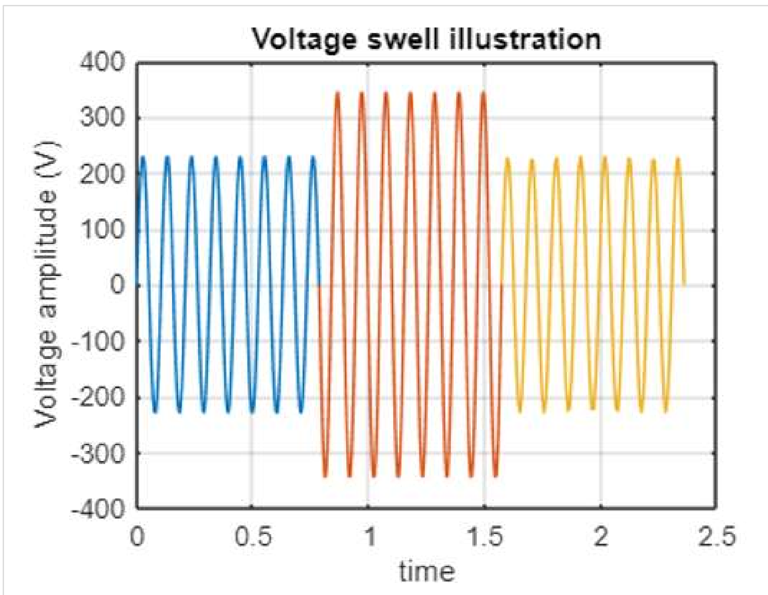


**Figure 3.7: Phase swell illustration**

### 3.5.3.3 Phase cut

A phase cut wave will be considered with the following points in mind: where the phase cut start and end thresholds are trigger points to monitor, as shown in Figure 3.8, with the cut start Equation 3.13, and cut end Equation 3.14.

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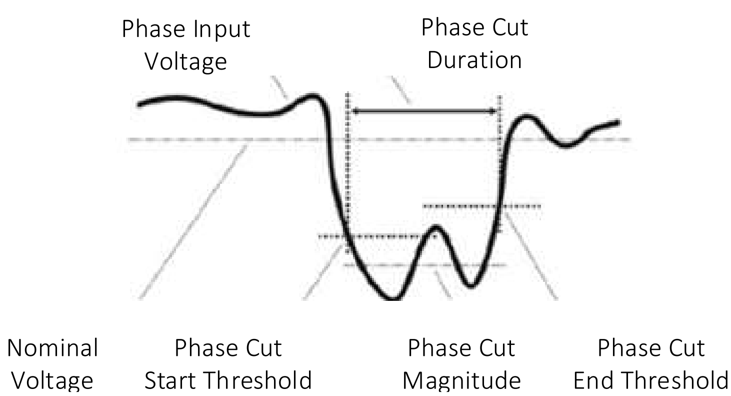


**Figure 3.8: QoS Phase Cut** (Itron, 2022)

$$V_{cut\_start} = V_{nom}\ x\ V_{cut\_start\%}$$ **Equation 3.13**

$$V_{cut\_end} = V_{nom}\ x\ V_{cut\_end\%}$$ **Equation 3.14**

### 3.5.4 Power factor

The power factor is a critical measurement as it is an indication of the magnitude of the reactive power. Power factor is ratio of true power over apparent power. True power is what is considered to be consumed by an AC circuit, whereas reactive in broad terms is considered to be what is stored in an AC circuit. Cos θ is the power factor of an AC circuit and is the ratio of true power to apparent power. The variation of the ratio is referenced as the phase angle θ, between the applied voltage and current sine waves, as well as between P and S on a power triangle.

Power factor *cos θ* is mathematically presented in Equation 3.15 where P is true power measured in watts and S is apparent power measured in VA.

$$\cos\theta = \frac{P}{S}$$ **Equation 3.15**

The power triangle in Figure 3.2 clearly shows that a poor power factor will increase the apparent power that will subject the transformer to a higher kVA reading. Another consideration is that the transformer operating under no load conditions inherently has a low power factor as the transformer by nature is almost purely reactive (Roderick, 2021). A power factor of greater than 0.96 will be considered good and less than < 0.96 as tending towards a poor power factor (Eskom, 2020b).

### 3.5.5 THD measurement

The THD measurement is described by the algorithm and distortion factor below.

#### 3.5.5.1 THD calculation algorithm

Non-linear loads can lead to DTs being subjected to total harmonic distortion (THD). Excessive THD can lead to temperature increases that can result in power loss and inefficiency of the transformer (Ulinuha & Sari, 2021).

The Fourier series applies for the harmonic equation, as seen in Equations 3.16 to 3.22.

$$f(\omega t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} ()a_n \cos(n\omega t) + b_n \sin(\omega t)$$ **Equation 3.16**

The following Fourier series coefficients apply:

$$\frac{a_o}{2} = \frac{1}{2\pi}\int_0^{2\pi} f(\omega t) d\omega t$$ **Equation 3.17**

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\cos(n\omega t) d\omega t$$ **Equation 3.18**

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\sin(n\omega t) d\omega t$$ **Equation 3.19**

Performing these integrals yield the coefficients' values as follows:

$b_n = 0$ and $\frac{a_o}{2} = 0$ **Equation 3.20**

$$b_n = \begin{cases} 0, n\,\epsilon[2,4,6,\dots] \\ \frac{4V_{DC}}{n\pi}, n\,\epsilon\,[1,3,5,..] \end{cases}$$ **Equation 3.21**

$$v_{on}(\omega t) = \sum_{1}^{\infty} \frac{4V_{DC}}{n\pi} \sin(n\omega t)$$ **Equation 3.22**

The RMS value of the nth harmonic is therefore as per Equation 3.23.

$v_{on}(\omega t) = \frac{4V_{DC}}{n\sqrt{2}\pi}$ **Equation 3.23**

From Equation 3.23, the harmonics can be portrayed as in Figure 3.9, where the n^th^ harmonic is described as below.

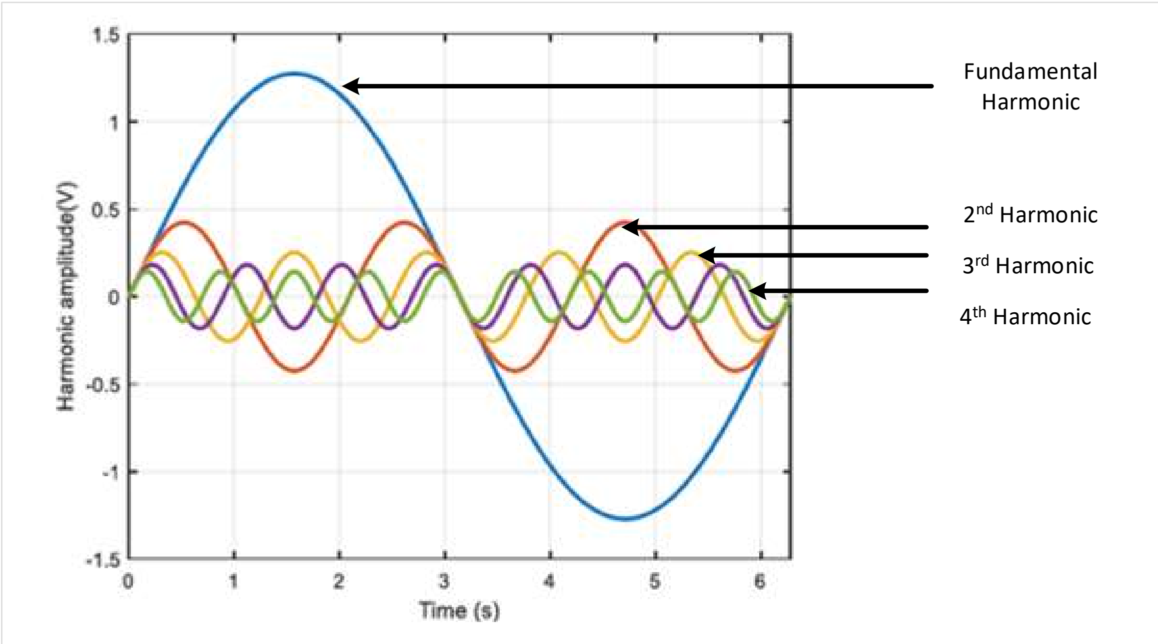


**Figure 3.9: Harmonic nth illustration**

#### 3.5.5.2 Total harmonic distortion

The distortion factor is a factor of the distortion residues, once filtering of the output voltage has taken place, as shown in Equation 3.24, where $V_1$ and $V_n$ are the RMS value of the fundamental and $n^{th}$ harmonic.

$$DF = \frac{1}{V_1}[\sum_{n=2}^{\infty}\frac{V_n}{n^2}]^2$$ **Equation 3.24**

The harmonic amplitude value is illustrated in Figure 3.10.

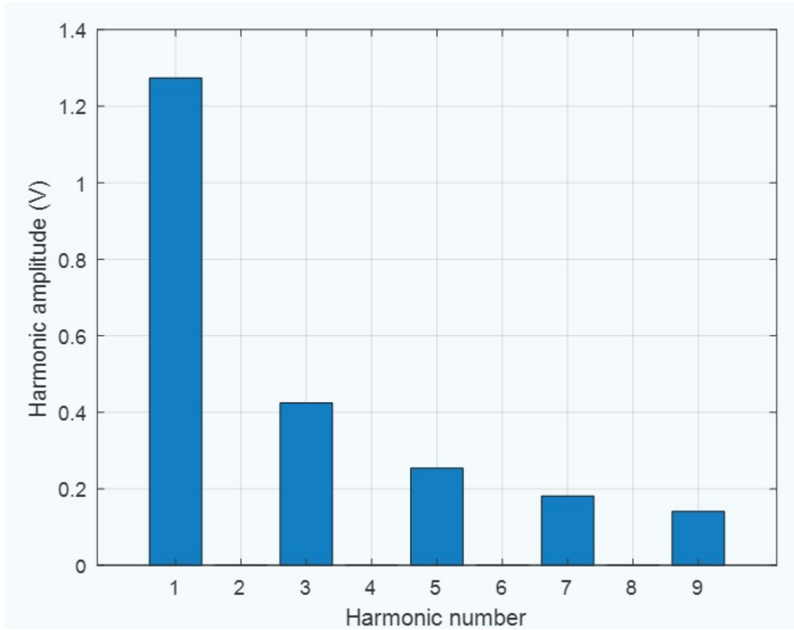


**Figure 3.10: Harmonic amplitude (V) nth illustration**

The contribution of the nth order component in the distortion is therefore given by Equation 3.25.

$$DF_n = \frac{V_n}{n^2 V_1}$$ **Equation 3.25**

The harmonic factor of the n<sup>th</sup> component is the ratio of the n<sup>th</sup> component over the RMS value of the fundamental component as seen in Equation 3.26.

$$HF = \frac{V_n}{V_1}$$ **Equation 3.26**

This factor helps assess the contribution of each harmonic component and identifies which component is dominant.

Finally, the THD shown in Equation 3.27 represents the ratio of the total harmonics to the RMS value of the fundamental component. This quantity also helps evaluate how close the waveform is to the perfect waveform.

$$THD = \sqrt{\frac{\sum_{n=1}^{\infty} V_n^2}{V_1}}$$ **Equation 3.27**

The IEC standard, IEC 61000-4-7 (IEC, 2007), provide a guideline as to what the VHD limits are (Table 3.3):

**Table 3.3: Voltage distortion limits – IEC 61000-4-7**

| Voltage | Individual Harmonic (%) | Total Harmonic Distortion THD (%) |
|---|---|---|
| $V \leq 1.0$ kV | 5.0 | 8.0 |
| 1 kV $< \boldsymbol{V} \leq$ 69 kV | 3.0 | 5.0 |
| 69 kV $< \boldsymbol{V} \leq$ 161 kV | 1.5 | 2.5 |
| 161 kV $<$ V | 1.0 | 1.5 |

### 3.5.6 Temperature measurement

The temperature measurement of the DT is an important consideration as transformer loading and ambient temperature impacts the transformer age. The IEEE standard C57.91-2011 is the temperature model applicable, as previously described in chapter 2.

### 3.5.7 Network frequency measurement

The network frequency is important as it determines the stability of the electricity grid and shows potential network frequency drift experienced during standard and heavy loading conditions.

## 3.6 Laboratory equipment

The equipment to perform the measurement is listed with a brief description of their functionality and the measurement areas where they apply.

### 3.6.1 Itron SL7000 Electricity meter

The electricity meter consists of the components shown in Figure 3.11. The current signal is measured by utilising mutual conductance transformers that measure instantaneous current per phase. The voltage signal is derived by measuring the distribution network voltage across a resistor divider. These analogue signals are fed into an analogue-to-digital converter that is processed by a microcontroller where the energy values are derived. The microcontroller then records energy registers that are stored independently and are always available in the flash memory. Register contents are displayed as total and instantaneous values on the meter LCD.

Data transfer is also possible through various inputs and outputs, metrological LEDs and infrared port.

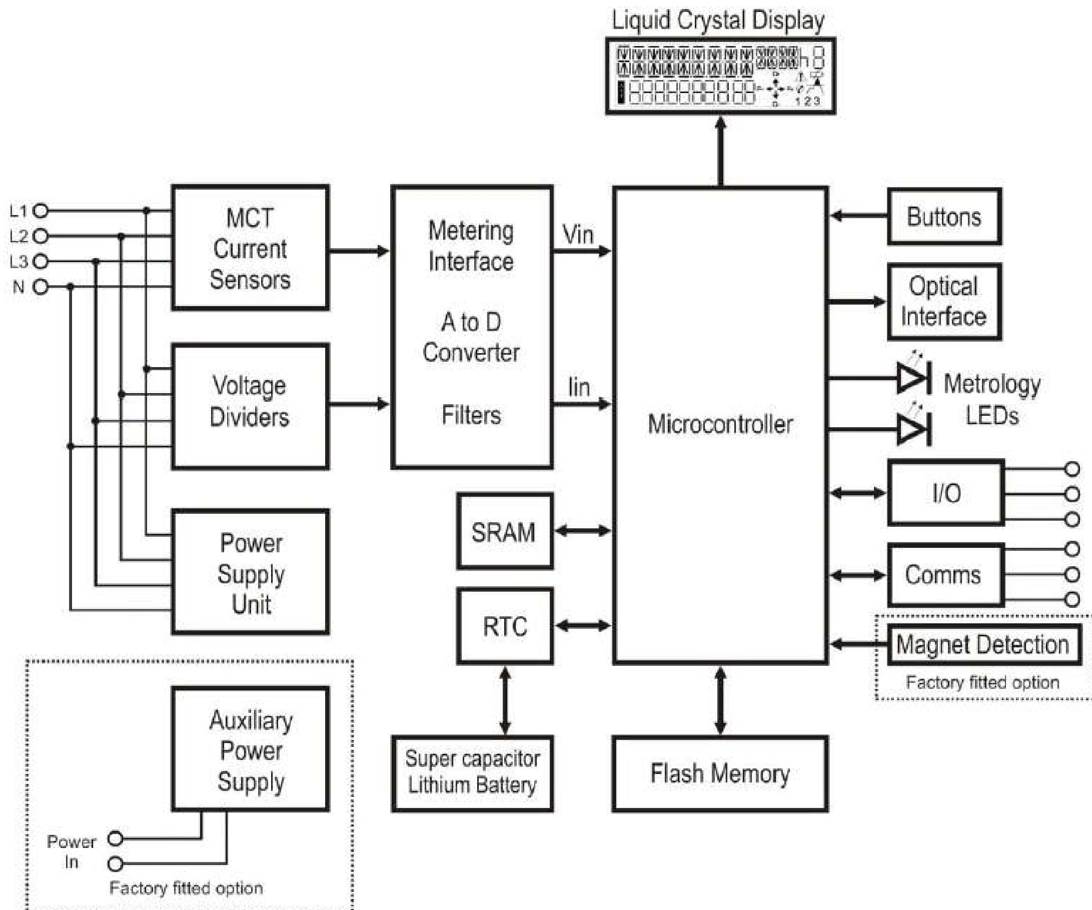


**Figure 3.11: Electricity meter components** (Itron, 2022)

### 3.6.2 KoCos EPOS 300

The EPOS 300 power supply and current injection unit accommodates three voltage signal sources denoted as U1, U2 and U3, and three current signal sources denoted as I1, I2 and I3 with variable amplitude, phase and frequency outputs, as shown in Figure 3.12. The EPOS 300 power supply is driven using panel controls or EPOS software by RS232. Each test point can therefore be configured to simulate a test condition.

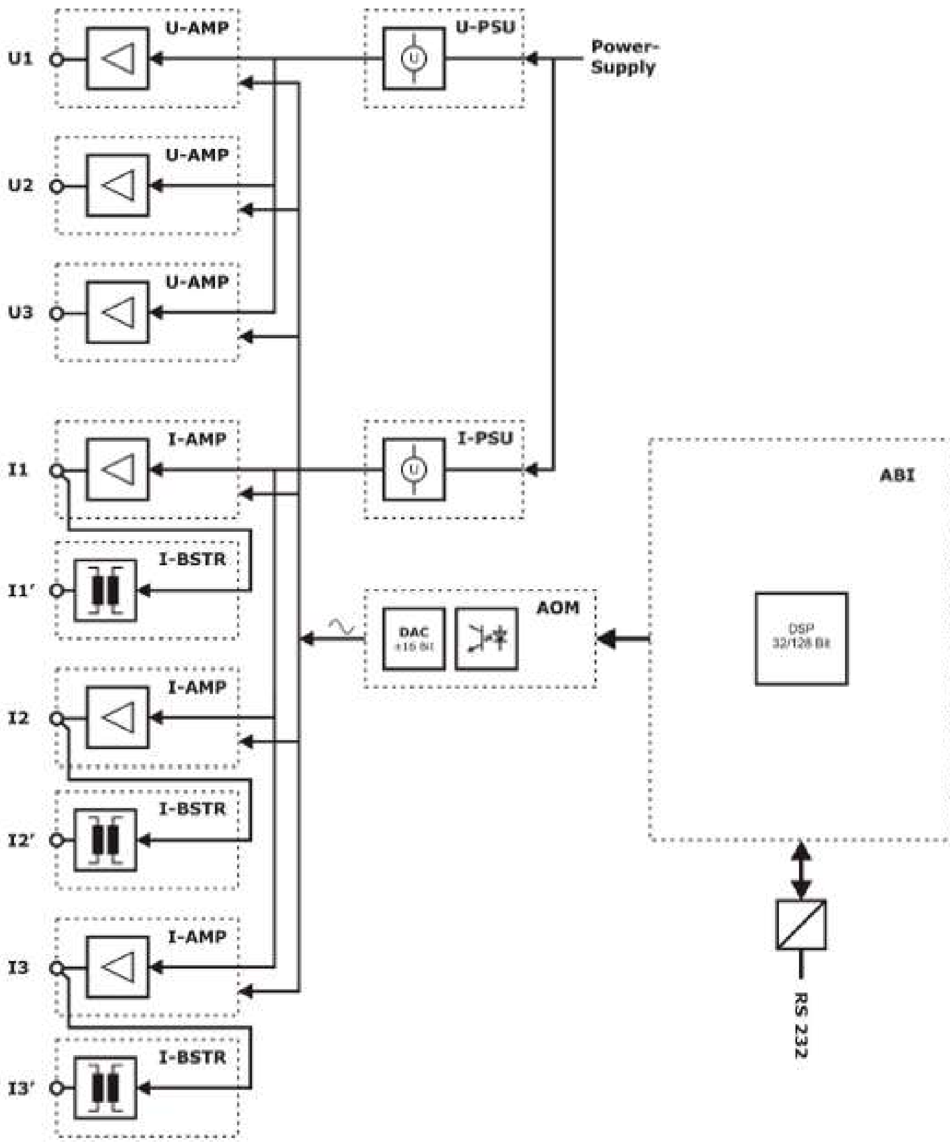


**Figure 3.12: KoCos EPOS 300 component block diagram (Kocos, 2025)**

### 3.6.3 Itron Sparklet modem

The Itron Sparklet modem has been designed for AMR applications and was used for the laboratory testing chapter. The Sparklet modem diagram is shown in Figure 3.13. The modem utilises a quadband Global System for Mobile Communications (GSM) engine, enabling remote communications for devices such as electricity meters. This band covers the frequency range of 850, 900, 1800, and 1900 MHz. The meter interface facilitates the handshaking connection between the modem and meter. The GSM services supported by the modem include Circuit Switched Data (CSD), Short Message Service (SMS) and General Packet Radio Service (GPRS). For this application, GPRS mode was used for transparent transfer of data. GPRS (ECEFast, 2016) was the preferred mode over CSD for the following reasons:

- CSD uses circuit switching instead of packet switching while it transmits data using a single radio time slot within the GSM network.
- GPRS, on the other hand, divides data into smaller packets and transmits these efficiently over the GSM network. It allows for faster data transfer compared to CSD.

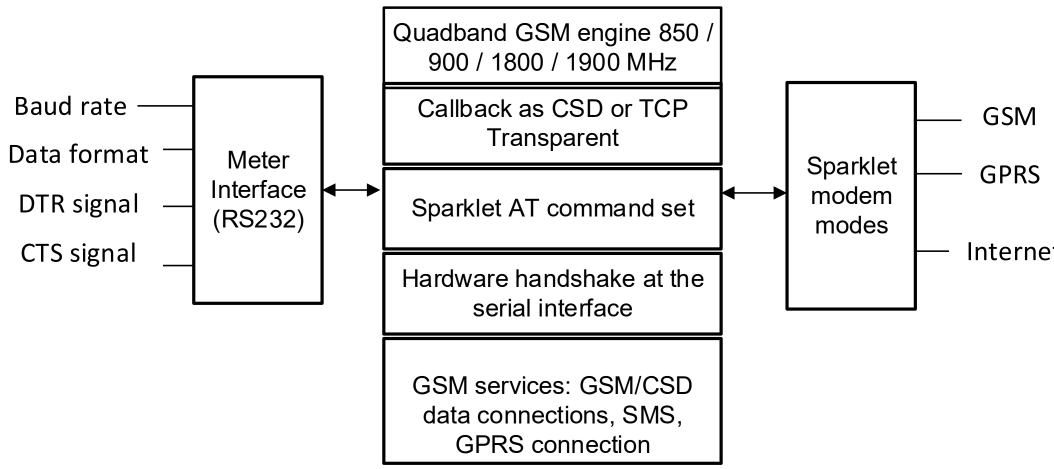


**Figure 3.13: Sparklet modem diagram** (Itron, 2022)

### 3.6.4 Meter reading software

Measurements were configured and read by Itron ACE Pilot engineering metering software (Itron, 2022). The software could connect to the meter by different communication methods that include optical, modem, and TCP/IP.

The following system functionality was important for this dissertation:

- Creating, editing and managing meter data.
- Programming of meters.
- Reading data from meters (billing information and configuration)

### 3.6.5 AMR Software

PNPSCADA (PNPSCADA, 2024) is the AMR software that was used for reading the DT measurement testing. This is a multi-vendor platform that supports electricity meters such as

Elster, Enermax, Landis&Gyr, EDMI, PRI, Wavenis and Itron SL7000. A simple web interface supports both Internet Explorer and Mozilla Firefox, with no additional plug-ins such as ActiveX or Applets, and where full functionality is available through a flexible web interface that includes real-time functions.

The following system functionality was important for this dissertation:

- User-friendly web interface
- Profile graph to navigate and view the important DT measurements
- Real-time notification
- Carbon consumption extrapolations by factoring in the $CO_2$ emissions of the type of fuel used.

### 3.7 Conclusion

This chapter started with a reminder of the objectives of this dissertation in addressing the research problem. This was followed by the research philosophy and approach that was utilised. Detailed descriptions of measurements pertaining to DTs were explained, with their mathematical calculations expressed. Finally, the laboratory equipment was described and their relevant functions and capabilities were discussed. The next chapter will test the measurements using the applicable laboratory equipment.

# CHAPTER FOUR

## TESTING OF DTM PERFORMANCE

## 4.1 Introduction

The focus of the research is to explore smart metering developments for monitoring critical measurements of DTs to assess their health and aging factors. As chapter 3 described the research methodology, chapter 4 continues with the testing of the different measurements that could impact the DT performance. The scope of the testing was associated with the hardware that was available at the time of the research and correlates with category 2 of Figure 2.11, which was found to be most effective in addressing the research problem. As a reminder, category 2 utilises the existing metering functionality. Each measurement starts with a description of the equipment setup required for testing in the laboratory. This is followed by the theoretical calculations and configuration applied to the test equipment. The DT measurement results are then collated, summarised, and the chapter concluded.

## 4.2 Laboratory test bench approach

The laboratory test bench approach describes how the DT measurements listed below were measured using the applicable test equipment.

1. Testing of normal and excess demand reading
2. Testing of network unbalance
3. Testing of QoS
4. Testing of poor power factor
5. Testing of THD measurement
6. Testing of temperature measurement
7. Testing of frequency measurement

The testing of the specific DT measurement was covered using the DT measurement description, mathematical calculations, equipment configuration, and finally, the test outcome. The KoCos EPOS 300 was at the heart of the setup as it was the equipment driving the phase voltages and currents for the different test points. All the equipment properties were described in detail in section 3.6.

## 4.3 Laboratory test setup

The laboratory test setup consisted of the main components, namely the power supply and current injection set, electricity meter, communication device, and finally the AMR system, as shown in Figure 4.1. This was overlayed with the DT components consisting of electricity network conditions, DT, communication network and smart metering system.

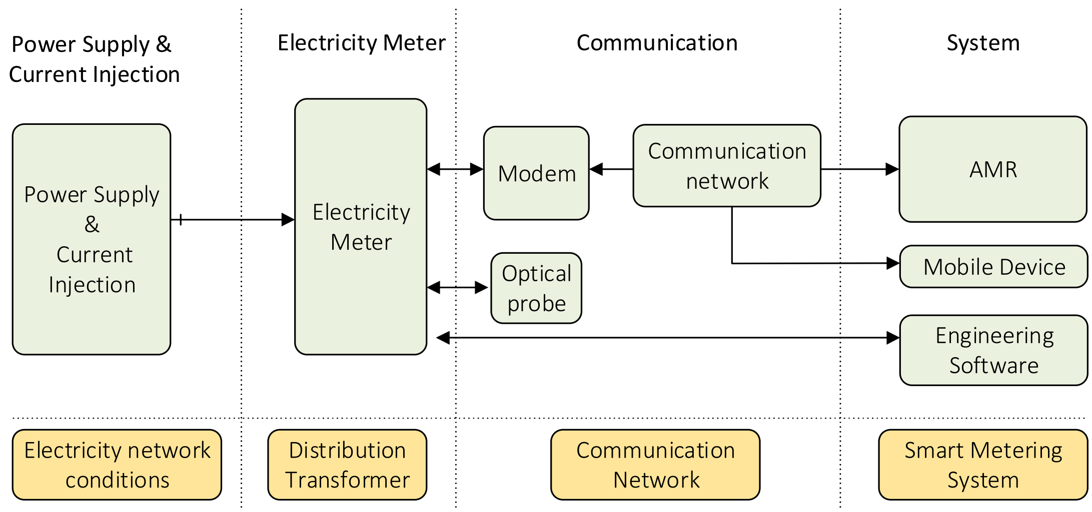


**Figure 4.1: Laboratory test setup diagram**

The physical test setup was assembled in the laboratory of Ontec Systems in South Africa as shown in Figure 4.2.

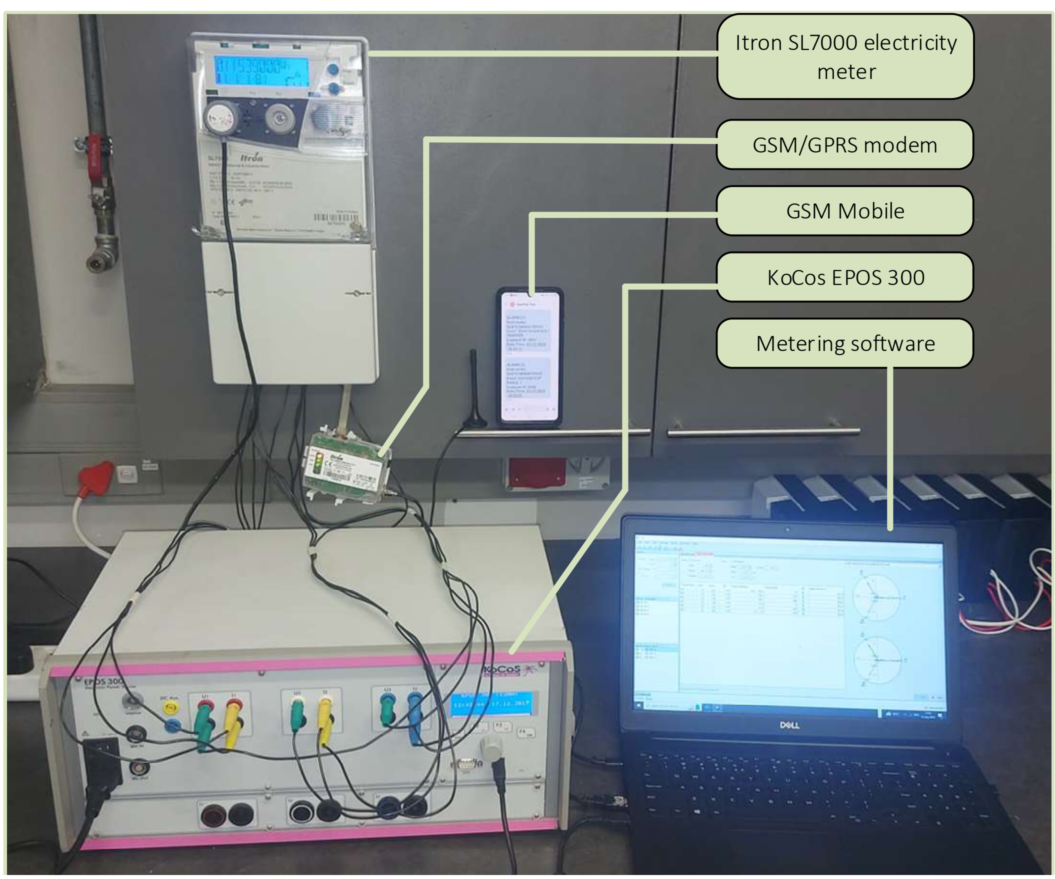


**Figure 4.2: Test setup in laboratory**

### 4.4 Testing of DT measurements

The testing of the DT measurements is covered next and outlined as described earlier.

#### 4.4.1 Normal and excess demand reading test

The demand reading is critical when monitoring the output of the transformer compared to its kVA rating. The demand measurement is covered in two parts: normal demand and excess demand. The objective was to simulate normal and excess demand readings, and observe the measurements and notifications associated with these.

A 500 kVA three-phase transformer was considered with the following specifications, rated in the product datasheet (Actom, 2022). The voltage rating of 11 kV is typical for a distribution transformer that supplies 415 V consumers. A 500 kVA rated DT typically supplies 40 kVA and 100 kVA consumers such as hospitals, business parks, and food stores. The no-load losses rating is the watt losses considered during no-load conditions, and the full load losses rating is the watt losses that include heat losses and eddy currents that occur in the windings of the transformer.

- 11 kV / 415 V three-phase step down
- Transformer rating: 500 kVA
- Voltage: 415 – 420 V
- No load loss watts: 1 100 W or VA
- Full load loss watts: 5 400 W or VA

##### 4.4.1.1 Normal demand mathematical calculation

The normal demand is calculated considering a transformer rating of 80% with a full load loss of 80% as described in Equation 4.1 and considering a 500 kVA transformer for testing, where the transformer rating is indicated as *tr* and full load loss as *fll*.

$$Demand_{normal} = 0.8tr - 0.8fll \quad \textbf{Equation 4.1}$$

$$Demand_{normal} = 0.8 * 500\ kVA - 0.8 * 5.4\ kVA$$

$$= 400\ kVA - 4.32\ kVA$$

$$= 395.68\ kVA$$

$$\sim 400\ kVA$$

In order to simulate this demand reading using the equipment, the power for a star-connected load is mathematically calculated in Equation 4.2, where $I_l$ is the line current and $V_\Phi$ is the phase voltage. The total power $P_T$ is then derived using 240 V as the line voltage. The actual total power is finally calculated by including the current transformer (CT) factor.

**Equation 4.2**

$$I_l = I_\Phi \text{ and } V_\Phi = \frac{\sqrt{3} * V_L}{3}$$

$$P_T = \sqrt{3} * V_L I_L cos\theta$$

$$P_T = \sqrt{3} * 415 * 1.38 * cos\theta \; [Assume\ cos\theta = 1]$$

$$= 991{,}94 \text{ W}$$

$$P_{T\,(with\,CT\,factor)} = 991.94 * 400 \left[CT\ factor = \frac{2000}{5}\right]$$

$$= 397\ 440\ W$$

#### 4.4.1.2 Excess demand calculation

The excess demand is calculated considering a transformer rating of 90% with a full load loss of 90% as described in Equation 4.3 and considering a 500 kVA transformer for testing, where the transformer rating is indicated as *tr* and full load loss as *fll*.

**Equation 4.3**

$$Demand_{normal} = 0.9tr - 0.8fll$$

$$Demand_{normal} = 0.9 * 500\ kVA - 0.8 * 5.4\ kVA$$

$$= 450\ kVA - 4.32\ kVA$$

$$= 445.68\ kVA$$

$$\sim 450\ kVA$$

Therefore, as 4.32 kVA is a negligible amount in relation to the transformer rating and assumption of 90% load, the normal demand reading will remain as 450 kVA.

In order to simulate this demand reading using the equipment, the power for a star-connected load is mathematically calculated in Equation 4.4.

$$I_l = I_\Phi \; and \; V_\Phi = \frac{\sqrt{3} * V_L}{3}$$ **Equation 4.4**

$$P_T = \sqrt{3} * V_L I_L cos\theta$$

$$P_T = \sqrt{3} * 415 * 1.57 * cos\theta \; [Assume \; cos\theta = 1]$$

$$= 1128{,}51 \text{ W}$$

$$P_{T\,(with\,CT\,factor)} = 1128{,}51 * 400 \left[CT\; factor = \frac{2000}{5}\right]$$

$$= 451\,404 \; W$$

#### 4.4.1.3 Normal and excess demand equipment configuration

To simulate normal and excess demand conditions, the test equipment had to be configured with the required settings. The power source, EPOS 300, was set to simulate 397.440 kVA in Table 4.1 to simulate a normal demand condition. This was achieved by a voltage and current input of 240 V and 1.38 An as shown in Equation 4.2.

**Table 4.1: Power source (EPOS 300) normal demand**

| Channel... | State | Ramp mode | | Range amplitude | Range phase | | Range frequency |
|---|---|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 240 V | 0° | | 50 Hz |
| U2 | ☑ | | 1.000 | 240 V | 120° | | 50 Hz |
| U3 | ☑ | | 1.000 | 240 V | 240° | | 50 Hz |
| I1' | ☑ | | 1.000 | 1.38 A | 0° | | 50 Hz |
| I2' | ☑ | | 1.000 | 1.38 A | 120° | | 50 Hz |
| I3' | ☑ | | 1.000 | 1.38 A | 240° | | 50 Hz |

Simulating excess demand of ~ 450 kVA was achieved by setting the voltage and current input of 240 V and 1.57 A in Table 4.2, as shown in Equation 4.4.

**Table 4.2: Power source (EPOS 300) excess demand ~ 450 kVA**

| Channel... | State | Ramp mode | | Range amplitude | Range phase | | Range frequency |
|---|---|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 240 V | 0° | | 50 Hz |
| U2 | ☑ | | 1.000 | 240 V | 120° | | 50 Hz |
| U3 | ☑ | | 1.000 | 240 V | 240° | | 50 Hz |
| I1' | ☑ | | 1.000 | 1.57 A | 0° | | 50 Hz |
| I2' | ☑ | | 1.000 | 1.57 A | 120° | | 50 Hz |
| I3' | ☑ | | 1.000 | 1.57 A | 240° | | 50 Hz |

The electricity meter, Itron SL7000, was configured to measure demand expressed as import apparent aggregate in kVA and kW seen in Table 4.3 point 1. The excess demand threshold was set for 400 kVA, to enable events and notifications of exceeding demand in point 2. The alarm setting was enabled for the excess demand for LCD symbol on the meter display and assigned to person ‘1 informed’, whose mobile number was assigned. This person would therefore receive the notifications by SMS as seen in point 3.

**Table 4.3: Electricity meter (Itron SL7000) demand register settings**

**Electricity meter setting**

**1**

| Channel | Quantity | Scaler | Decimals | Unit | Number of Rates | Fluid | Memory Use |
|---|---|---|---|---|---|---|---|
| 1 | Import Apparent Aggregate | Kilo | 0 | VA | 1 | Electricity | 4 |
| 2 | Import Active Aggregate | Kilo | 0 | W | 1 | Electricity | 4 |

**2**

| Number | Quantity | Rate | Threshold | Scaler | Unit |
|---|---|---|---|---|---|
| I | Import Apparent Power Aggregate | 1 | 400 | Kilo | VA |

**3**

| Name | LCD Symbol Active | Control Output | 1 informed | 2 informed | 3 informed |
|---|---|---|---|---|---|
| Absence of energy consumption | ☑ | ☐ | ☑ | ☐ | ☐ |
| Absence of energy consumption on pulse inputs | ☐ | ☐ | ☐ | ☐ | ☐ |
| Aggregate energy reverse direction detected | ☐ | ☐ | ☐ | ☐ | ☐ |
| Alarm raised on control input | ☐ | ☐ | ☐ | ☐ | ☐ |
| Configuration inconsistency | ☑ | ☐ | ☐ | ☐ | ☐ |
| Energy reverse direction detected on phase 1 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Energy reverse direction detected on phase 2 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Energy reverse direction detected on phase 3 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Excess demand | ☑ | ☐ | ☑ | ☐ | ☐ |

The normal demand results are displayed in the load profile view of the AMR software (Figure 4.3) where 396 kVA was measured. The calculated value was 397.440 kVA in Equation 4.2. The measured value was therefore within 1.44 kVA or 99% of the calculated value and acceptable for the testing. At this level, the alarm was not activated as no excess was recorded. The graph displays the reading at 30-minute intervals, with a highlighted area at 17:00 15/04/2024 showing the reading at 396 kVA to the left of the graph.

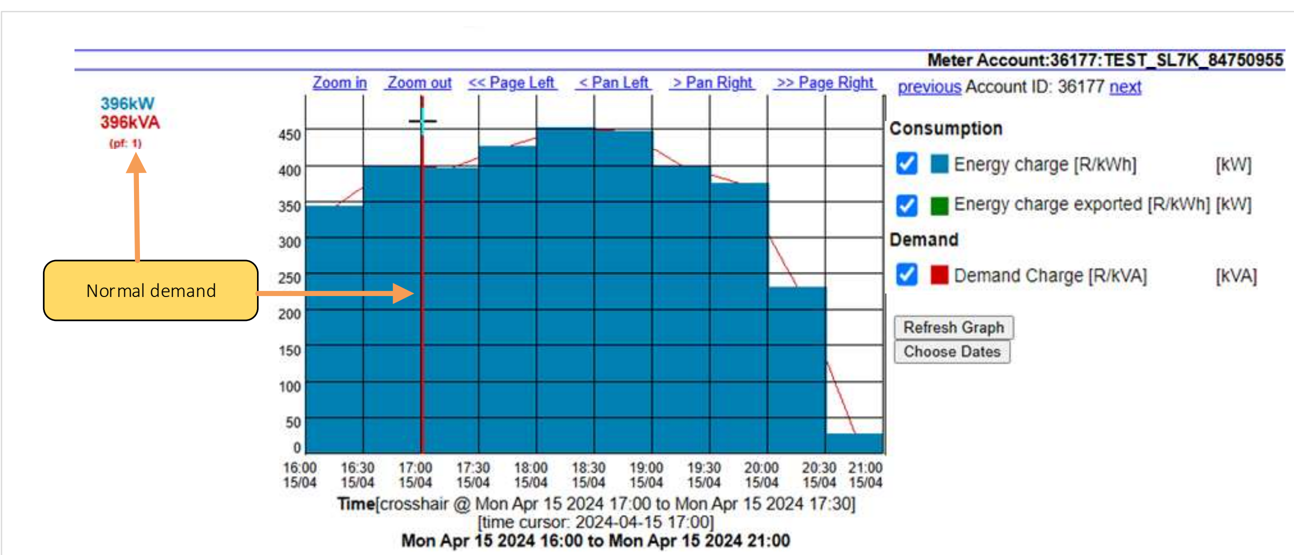


**Figure 4.3: AMR system normal demand**

The excess demand results are displayed in the load profile view of the AMR software (Figure 4.4) where 452 kVA was measured. The calculated value was 452.160 kVA in Equation 4.3. The measured value was therefore equal to the calculated value and acceptable for testing.

At this level, the alarm was activated as excess was recorded. The graph displays the reading at 30-minute intervals, with a highlighted area at 18:30, 15/04/2024, showing the reading at 446 kVA to the left of the graph.

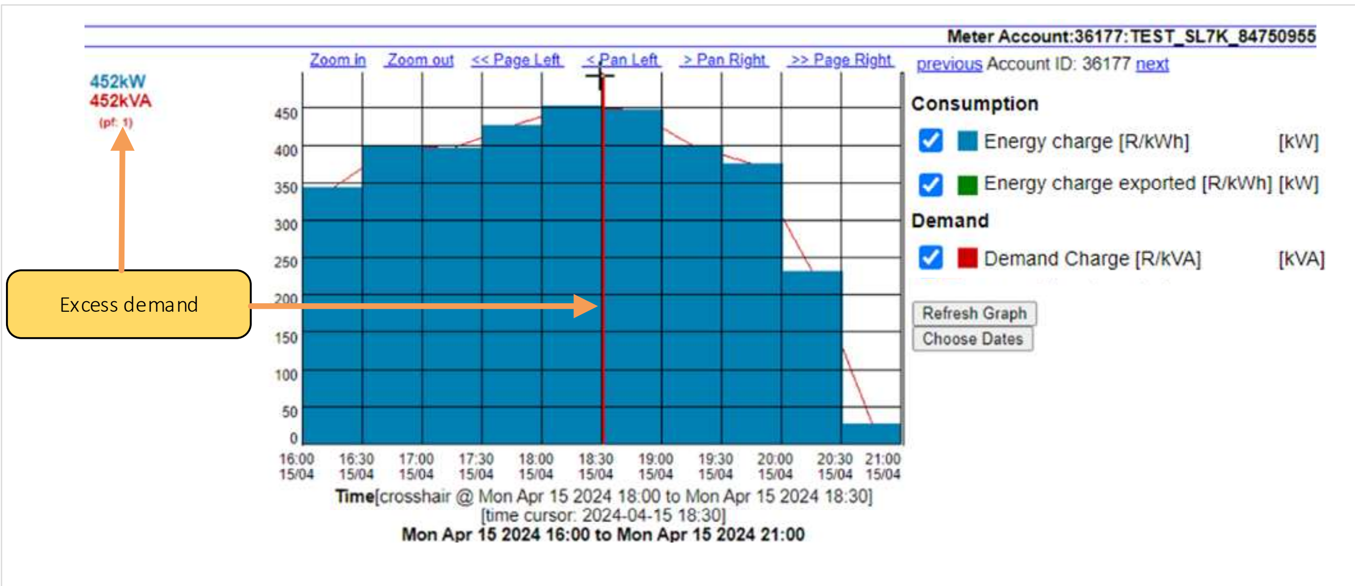


**Figure 4.4: AMR system excess demand**

The demand monitoring events were also logged by meter, as seen in Table 4.4, and could be read by the metering software. The excess demand alarm was raised at 18:09 15/04/2024, which corresponds with the AMR reading period when 446 kVA was reached.

**Table 4.4: Metering software excess demand**

| Type | Setting | ID | Date | Time |
|---|---|---|---|---|
| **Non-fatal alarm raised** | Alarm Type: EXCESS DEMAND | 2420 | 15 April 2024 | 18:09:01 |
| **Register data saved in flash memory** | PERIODIC SAVE | 2419 | 15 April 2024 | 18:00:03 |
| **Non-fatal alarm disappearance** | Alarm Type : EXCESS DEMAND | 2418 | 15 April 2024 | 18:00:00 |
| **Periodical end of interval (demand)** | | 2417 | 15 April 2024 | 18:00:00 |

The alarm event was sent by SMS to the mobile number of the allocated person '1 informed' as seen in Figure 4.5. The alarm ID 2420 could be cross-referenced to the meter logbook ID indicating consistent notification references with a time stamp of 04-15-2024 18:09:01. The associated alarm event of excess demand was flagged for electricity meter SLB761MA84750955.

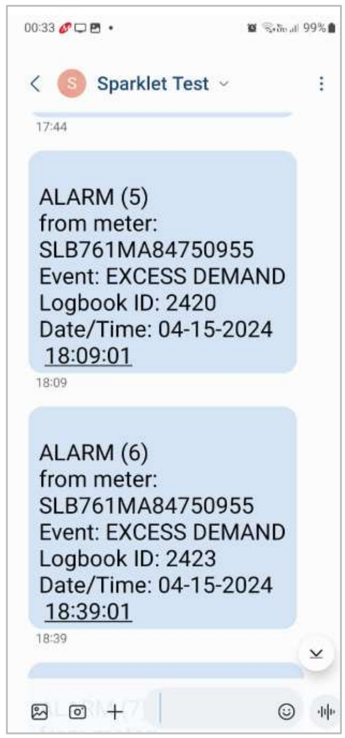


**Figure 4.5: Mobile SMS excess demand notification**

#### 4.4.1.5 Normal and excess demand test summary

The normal and excess demand test summary proves that monitoring of a defined demand kVA threshold is practical for the Itron SL7000 electricity meter. Under normal demand conditions, there are no notification and reporting of excess, but when excess is detected, it is communicated with the time recorded of the event. The demand threshold is configurable in increments of 1 kVA and can be adjusted for the electrical network environment.

### 4.4.2 Network unbalance test

The network unbalance is a critical measurement as it will determine whether the transformers are operating optimally on all three phases and thereby providing the required expected output. Network voltage and load unbalance are simulated in this section.

#### 4.4.2.1 Network voltage and load unbalance calculation

The network voltage unbalance threshold was set for 30 V with a nominal voltage of 240 V, as shown in Equation 4.5.

$$V_{unbalance} = V_{nom} - V_{unbalance_{thresh}}$$
$$V_{unbalance} = 240\ V - 30\ V$$
$$= 210\ V$$

**Equation 4.5**

#### 4.4.2.2 Network voltage and load unbalance configuration

To simulate voltage unbalance, the power source, EPOS 300, was set to ramp from 190 V to 240 V for phase 1 and remain constant at 240 V for phase 2 and 3, creating a 20 V difference, as seen in Table 4.5.

**Table 4.5: Power source (EPOS 300) voltage unbalance settings**

| Channel ... | State | Ram... | | Range amplitude | Range phase | | Range frequency |
|---|---|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 190 ... 240 V | 0° | | 50 Hz |
| U2 | ☑ | | 1.000 | 240 V | 120° | | 50 Hz |
| U3 | ☑ | | 1.000 | 240 V | 240° | | 50 Hz |
| I1' | ☑ | | 1.000 | 0.5 A | 0° | | 50 Hz |
| I2' | ☑ | | 1.000 | 0.5 A | 120° | | 50 Hz |
| I3' | ☑ | | 1.000 | 0.5 ... 6 A | 240° | | 50 Hz |

The load unbalance threshold current was set at 1 A, which means that if a 1 A delta was found amongst the phase currents, then the event would be logged.

$$I_{unbalance} = I_{nom} + I_{unbalance_{thresh}}$$
$$I_{unbalance} = 0.5\ A + I\ A$$
$$= 1.5\ A$$

**Equation 4.6**

To simulate a load unbalance condition, the power source, EPOS 300, was set at 0.5 A for two phases and one phase varying from 0.5 A to 6 A, as seen in Table 4.6.

**Table 4.6: Power source (EPOS 300) load unbalance settings**

| Channel Na... | State | Ramp mode | | Range amplitude | Range phase |
|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 230 V | 0° |
| U2 | ☑ | | 1.000 | 230 V | 120° |
| U3 | ☑ | | 1.000 | 230 V | 240° |
| I1' | ☑ | | 1.000 | 0.5 A | 0° |
| I2' | ☑ | | 1.000 | 0.5 A | 120° |
| I3' | ☑ | | 1.000 | 0.5 ... 6 A | 240° |

The electricity meter, Itron SL7000, was configured to monitor the network, with the settings as described in Equation 4.5 and 4.6 and the unbalance voltage threshold set at 20 V and load. The current unbalance threshold was set at 1 A. The alarm setting was enabled and assigned to person '1 informed', whose mobile number was assigned. This person would therefore receive the notifications by SMS as seen in point 2 of Table 4.7.

**Table 4.7: Electricity meter (Itron SL7000) voltage and current unbalance settings**

| | Electricity meter setting |
|---|---|
| 1 | NETWORK VOLTAGE UNBALANCE THRESHOLD 20.0 V<br>LOAD UNBALANCE THRESHOLD 1.00 A<br>NO CONSUMPTION THRESHOLD 1 Days |
| 2 | (see below) |

| Name | LCD Symbol Active | Control Output | 1 informed | 2 informed | 3 informed |
|---|---|---|---|---|---|
| Internal RAM memory fatal error | ☑ | ☐ | ☐ | ☐ | ☐ |
| Load unbalance detected | ☑ | ☐ | ☑ | ☐ | ☐ |
| Load unbalance detected (trapped) | ☑ | ☐ | ☑ | ☐ | ☐ |
| Low battery voltage or battery missing | ☑ | ☐ | ☑ | ☐ | ☐ |
| Magnet sensor | ☑ | ☐ | ☐ | ☐ | ☐ |
| Main cover opening | ☑ | ☐ | ☐ | ☐ | ☐ |
| Missing APS | ☐ | ☐ | ☐ | ☐ | ☐ |
| Network voltage unbalance detected | ☑ | ☐ | ☑ | ☐ | ☐ |

#### 4.4.2.3 Network voltage and load unbalance results

The network voltage unbalance results are displayed in the load profile view of the AMR software Figure 4.6 where the phase voltages were measured. At this level the alarm was activated as a network unbalanced voltage was recorded. The graph displays the reading at 30-minute intervals, with highlighted area at 20:00 17/08/2024, showing the phase voltage readings to the left of the graph.

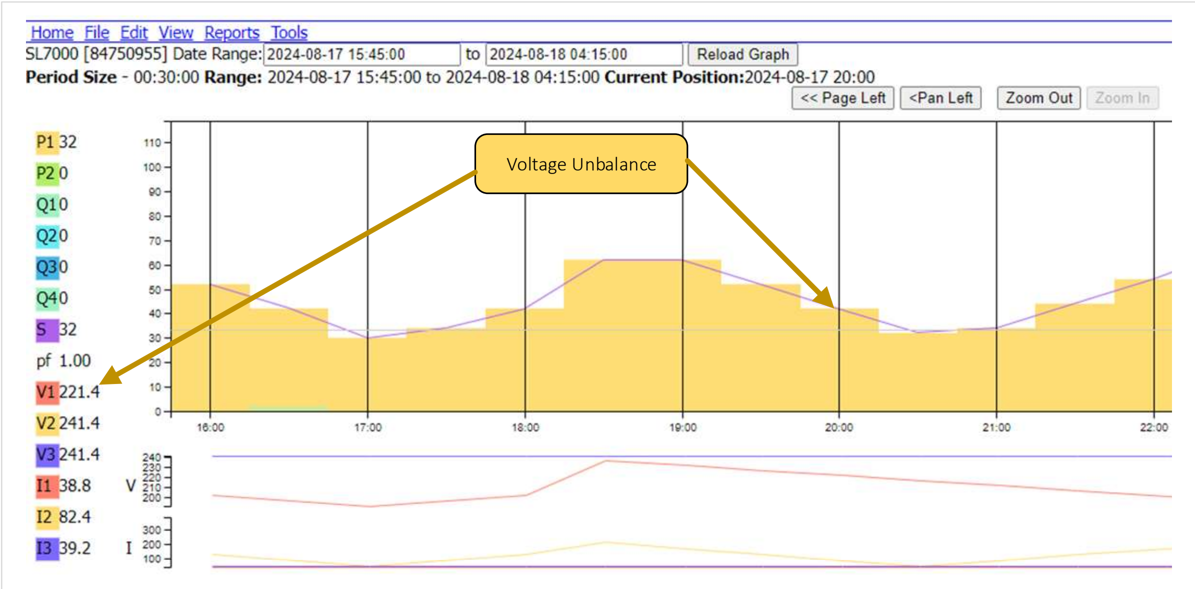


**Figure 4.6: AMR network voltage unbalance**

The network current unbalance results are displayed in the load profile view of the AMR software (Figure 4.7) where the phase currents were measured. At this level the alarm was activated as a network unbalanced current was recorded. The graph displays the reading at 30-minute intervals, with highlighted area at 17:00 12/05/2024 showing the phase current readings to the left of the graph.

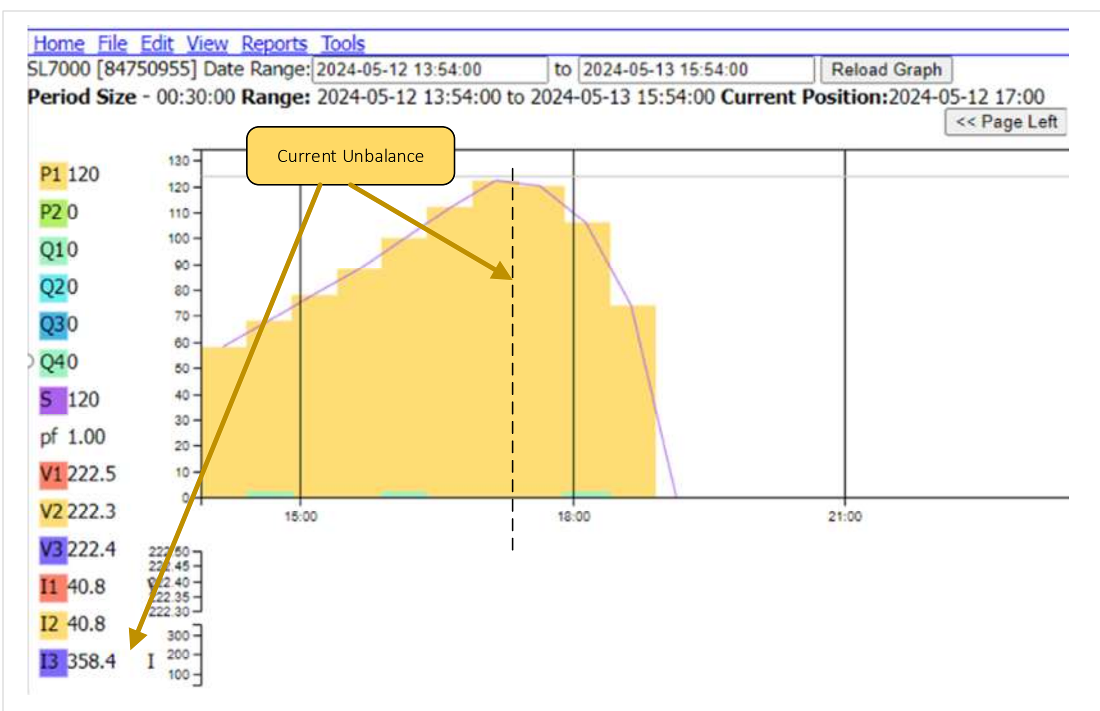


**Figure 4.7: AMR network current unbalance**

The network monitoring events were also logged by the meter as seen in Table 4.8 for voltage and Table 4.9 for current and could be read by the metering software. The zero sequence U alarm was raised at 20:10:07 on 17/08/2024 (Table 4.8), which corresponded with the AMR reading period when the network voltage unbalance alarm was raised. The zero sequence I alarm was raised at 16:44:11 on 12/05/2024 (Table 4.9), which corresponds with the AMR reading period when the network current unbalance alarm was raised.

**Table 4.8: Metering software network voltage unbalance**

| Type | Setting | ID | Date | Time |
|---|---|---|---|---|
| **Non-fatal alarm raised** | Alarm Type: ZERO SEQUENCE U | 4561 | 17 August 2024 | 20:10:07 |

**Table 4.9: Metering software network voltage unbalance**

| Type | Setting | ID | Date | Time |
|---|---|---|---|---|
| **Non-fatal alarm raised** | Alarm Type: ZERO SEQUENCE I TRAPPED | 3832 | 12 May 2024 | 16:44:11 |
| **Non-fatal alarm raised** | Alarm Type: ZERO SEQUENCE I | 3831 | 12 May 2024 | 16:39:11 |

The alarm event was sent by SMS to the mobile number of the allocated person '1 informed' as seen in Figure 4.8. For voltage unbalance, the alarm ID 4561 could be cross-referenced to the meter logbook ID, indicating consistent notification references with a time stamp of 17-08-2024 20:10:07. For current unbalance, the alarm ID 3832 could be cross-referenced to the meter logbook ID, indicating consistent notification references with a time stamp of 12-05-2024 16:44:11.

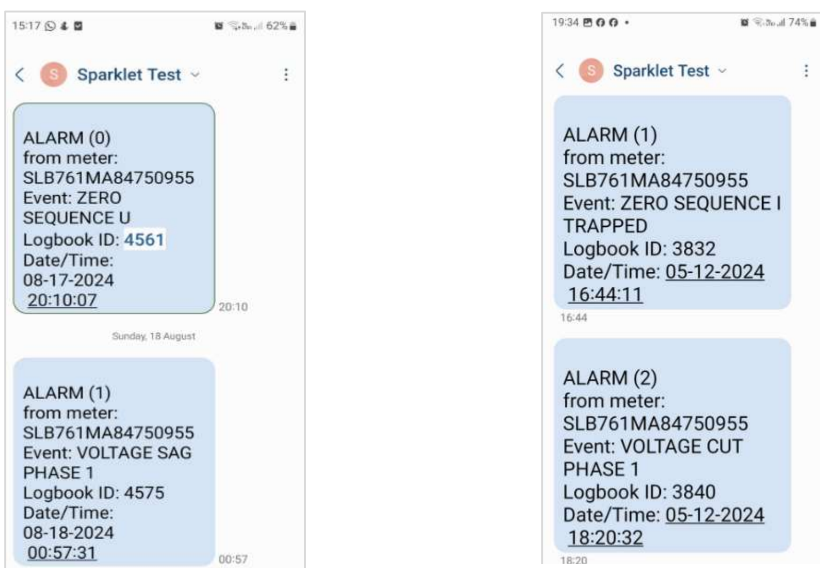


**Figure 4.8: Mobile SMS zero sequence U and I alarms**

#### 4.4.2.4 Network unbalance test summary

The Network Voltage Unbalance Test results show that monitoring deviances of any phase voltage from the nominal phase voltage is practical for the Itron SL7000 electricity meter, with notification and reporting communicated within real time of the event. The phase voltage deviance is configurable in increments of 0.1 V and can be adjusted for the electrical network environment (Itron, 2022). Load unbalance is treated the same with possible 0.01 A increments.

### 4.4.3 Quality of supply test

As introduced in chapter 3, the quality of supply (QoS) measurement has an impact on the transformer performance, and monitoring these parameters is therefore relevant (Itron, 2018). The QoS events of sags and swells are simulated as described in section 3.5.

#### 4.4.3.1 QoS calculation

The detailed QoS settings described in chapter 3 were applied with the default thresholds for the Itron electricity meter. These were linked to the standard IEC61000 that indicates a 10% threshold to the nominal voltage, of which Itron applied 15% as default percentages as listed in Table 4.10, from Equations 4.7 to 4.11.

**Table 4.10: QoS thresholds (Itron and IEC61000)**

| Type | Itron Meter Setting | IEC 61000 |
|---|---|---|
| Sag voltage | - 15% | -10% |
| Swell voltage | + 15% | +10% |

$$V_{nom} = 230\ V$$ **Equation 4.7**

$$V_{sag\_start} = V_{nom} * V_{sag\_start\%}$$ **Equation 4.8**

$$= 230\ V * 0.8$$

$$= 184\ \text{V}$$

$$V_{sag\_end} = V_{nom} * V_{sag\_end\%}$$ **Equation 4.9**

$$= 230\ V * 0.85$$

$$= 195.5\ V$$

$V_{swell\_end} = V_{nom} * V_{swell\_end\%}$ **Equation 4.10**

$= 230\,V * 1.15$

$= 264.5\,V$

$V_{swell\_start} = V_{nom} * V_{swell\_start\%}$ **Equation 4.11**

$= 230\,V * 1.20$

$= 276\,V$

### 4.4.3.2 QoS Configuration

To simulate a voltage sag, the power source, EPOS 300, was set to 180 V for all three phases, as seen in Table 4.11. This was necessary to raise the alarm for the sag start threshold of 192 V.

**Table 4.11: Power source (EPOS 300) voltage sag setting**

| Channel... | State | Ramp mode | | Range amplitude | Range phase | | Range frequency |
|---|---|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 180 V | 0° | | 50 Hz |
| U2 | ☑ | | 1.000 | 180 V | 120° | | 50 Hz |
| U3 | ☑ | | 1.000 | 180 V | 240° | | 50 Hz |
| I1' | ☑ | | 1.000 | 0 A | 0° | | 50 Hz |
| I2' | ☑ | | 1.000 | 0 A | 120° | | 50 Hz |
| I3' | ☑ | | 1.000 | 0 A | 240° | | 50 Hz |

To simulate a voltage swell, the power source, EPOS 300, was set at 270 V for all three phases, as seen in Table 4.12. This was necessary to raise the alarm for the sag start threshold of 192 V.

**Table 4.12: Power source (EPOS 300) voltage swell setting**

| Channel... | State | Ramp mode | | Range amplitude | Range phase | | Range frequency |
|---|---|---|---|---|---|---|---|
| U1 | ☑ | | 1.000 | 270 V | 0° | | 50 Hz |
| U2 | ☑ | | 1.000 | 270 V | 120° | | 50 Hz |
| U3 | ☑ | | 1.000 | 270 V | 240° | | 50 Hz |
| I1' | ☑ | | 1.000 | 0 A | 0° | | 50 Hz |
| I2' | ☑ | | 1.000 | 0 A | 120° | | 50 Hz |
| I3' | ☑ | | 1.000 | 0 A | 240° | | 50 Hz |

The electricity meter, Itron SL7000, was configured to monitor the network with the settings as described in Equations 4.8 and 4.11, with the voltage low sag threshold set at 184 V and the voltage high swell threshold set at 276 V. The alarm setting was enabled for the excess demand for LCD symbol on the meter display and assigned to person '1 informed', whose mobile number was assigned. These settings are listed in Table 4.13.

**Table 4.13: Electricity meter (Itron SL7000) voltage threshold settings**

| | Electricity meter setting | | |
|---|---|---|---|
| 1 | VOLTAGE QUALITY ACTIVATED ☑ | | |
| | LOW CUT THRESHOLD | 103.50 V | 45% |
| | HIGH CUT THRESHOLD | 126.50 V | 55% |
| | LOW SAG THRESHOLD | 184.00 V | 80% |
| | HIGH SAG THRESHOLD | 195.50 V | 85% |
| | LOW SWELL THRESHOLD | 264.50 V | 115% |
| | HIGH SWELL THRESHOLD | 276.00 V | 120% |

2

| Name | LCD Symbol Active | Control Output | 1 informed | 2 informed | 3 informed |
|---|---|---|---|---|---|
| Internal RAM memory fatal error | ☑ | ☐ | ☐ | ☐ | ☐ |
| Load unbalance detected | ☑ | ☐ | ☑ | ☐ | ☐ |
| Load unbalance detected (trapped) | ☑ | ☐ | ☑ | ☐ | ☐ |
| Low battery voltage or battery missing | ☑ | ☐ | ☑ | ☐ | ☐ |
| Magnet sensor | ☑ | ☐ | ☐ | ☐ | ☐ |
| Main cover opening | ☑ | ☐ | ☐ | ☐ | ☐ |
| Missing APS | ☐ | ☐ | ☐ | ☐ | ☐ |
| Network voltage unbalance detected | ☑ | ☐ | ☑ | ☐ | ☐ |
| Programming incoherency | ☑ | ☐ | ☐ | ☐ | ☐ |
| Real time clock lost | ☑ | ☐ | ☐ | ☐ | ☐ |
| Temperature excess | ☑ | ☐ | ☐ | ☐ | ☐ |
| Voltage cut detected on phase 1 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage cut detected on phase 2 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage cut detected on phase 3 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage sag detected on phase 1 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage sag detected on phase 2 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage sag detected on phase 3 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage swell detected on phase 1 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage swell detected on phase 2 | ☑ | ☐ | ☑ | ☐ | ☐ |
| Voltage swell detected on phase 3 | ☑ | ☐ | ☑ | ☐ | ☐ |

#### 4.4.3.3 QoS Results

The QoS results are displayed in the load profile view at 30-minute intervals on the AMR software. The voltage sag was 191 V measured at 16:30, 17/08/2024, as shown in Figure 4.9. As the calculated value was set at 192 V in Equation 4.8, the measured value was below the calculated value and acceptable for the test. At this measured value the alarm was activated.

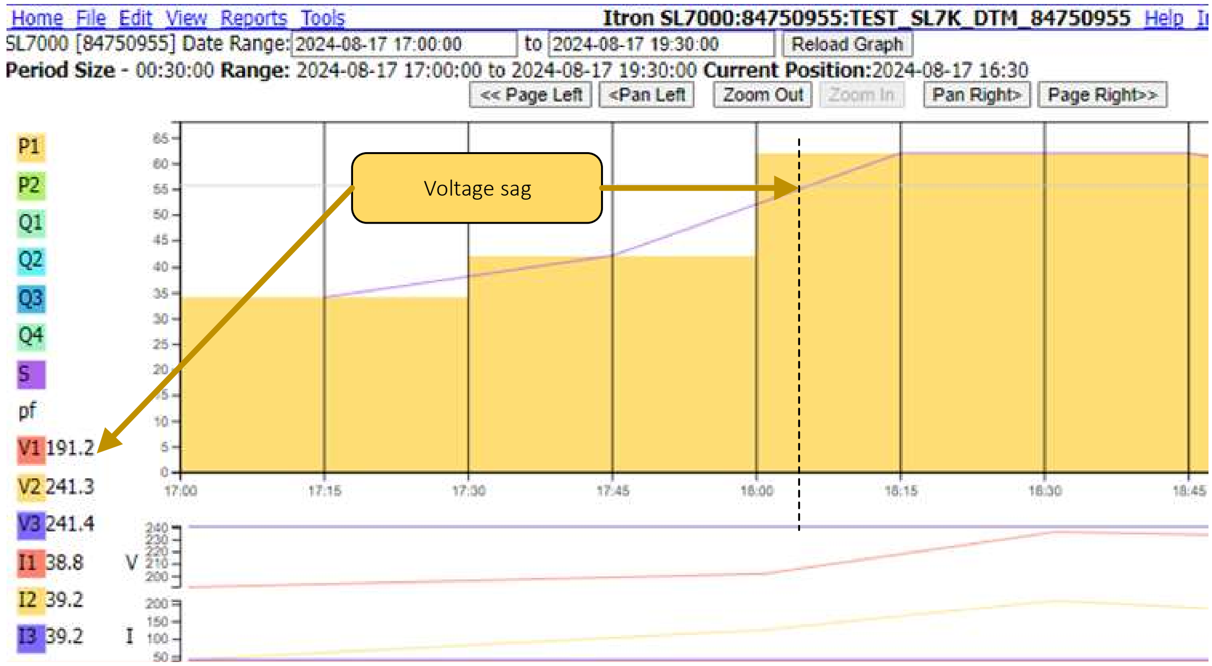


**Figure 4.9: AMR voltage sag load profile**

The voltage swell of 288 V was measured at 00:44:42 20/08/2024, as shown in Figure 4.10. As the calculated value was set at 276 V in Equation 4.11, the measured value was above the calculated value and acceptable for the test. At this measured value, the alarm was activated.

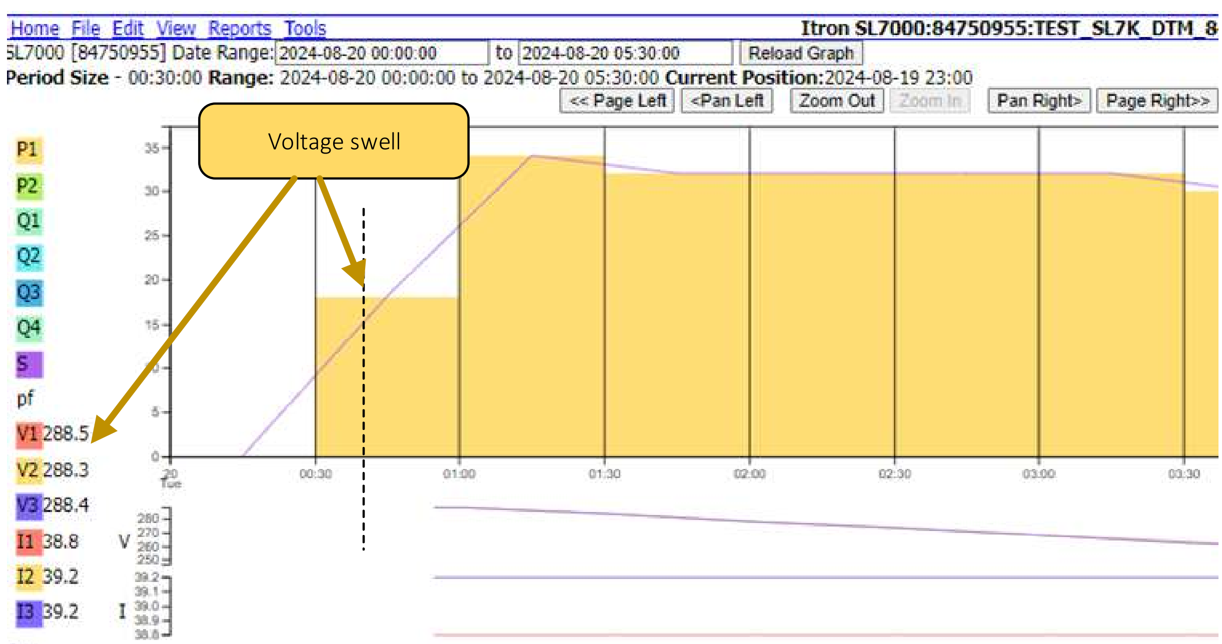


**Figure 4.10: AMR voltage swell load profile**

The network monitoring events were also logged by the meter as seen in Table 4.14 for voltage sag and Table 4.15 for voltage swell and could be read by the metering software. The voltage sag alarm was raised at 18:09:15 on 08/17/2024, which corresponded with the AMR reading, and the voltage swell was raised at 00:44:42 on 08/20/2024.

**Table 4.14: Metering software network voltage sag**

| Type | | Setting | ID | Date | Time |
|---|---|---|---|---|---|
| **Non-fatal alarm raised** | | Alarm Type: VOLTAGE SAG PHASE 1 | 4522 | 17 August 2024 | 18:09:15 |

**Table 4.15: Metering software network voltage swell**

| Type | Setting | ID | Date | Time |
|---|---|---|---|---|
| **Non-fatal alarm raised** | Alarm Type: VOLTAGE SWELL PHASE 2 | 4853 | 20 August 2024 | 00:44:42 |
| **Non-fatal alarm raised** | Alarm Type: VOLTAGE SWELL PHASE 2 | 4852 | 20 August 2024 | 00:44:42 |

The alarm event was sent by SMS to the mobile number of the allocated person '1 informed' as seen in Figure 4.11. For voltage sag, the alarm ID 4522 could be cross-referenced to the meter logbook ID, indicating consistent notification references with a time stamp of 18-09-2024 18:09:15. For voltage swell, the alarm ID 4853 could be cross-referenced to the meter logbook ID, indicating consistent notification references with a time stamp of 20-08-2024 00:44:42.

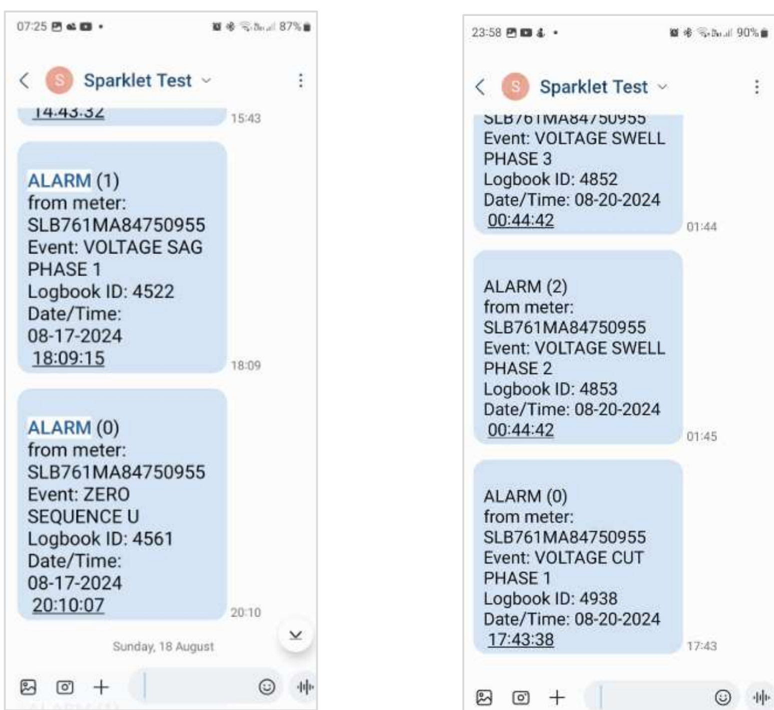


**Figure 4.11: Mobile SMS voltage sag and swell alarms**

#### 4.4.3.4 QoS summary

The QoS test results show that monitoring of QoS parameters can be defined to different thresholds as per standard IEC 61000 or a variation of this. The Itron SL7000 electricity meter measures these events with notification and reporting communicated within real time of the event. The QoS thresholds can be configured in 1% increments (Itron, 2022).

### 4.4.4 Power factor test

As introduced in chapter 3, the power factor is an important measurement to consider as it is an indication of the magnitude of the reactive power. The power triangle in section 3.2 clearly shows that a poor power factor will increase the apparent power, which will cause the transformer to drive a higher kVA output, as confirmed by Alnaseem & Adi (2011) in their study of the impact of power correction on the electrical distribution network.

#### 4.4.4.1 Power factor calculation

The power factor calculation was set as in Equation 4.12, and is a standard threshold as defined in chapter 3, where a poor power factor starts at less than 0.96.

$$pf = (\cos\theta\,L1 + \cos\theta\,L2 + \cos\theta\,L3)/3$$
$$= (\cos 340° + \cos 220° + \cos 100°)/3$$
$$= 0.939$$

**Equation 4.12**

#### 4.4.4.2 Power factor configuration

To simulate a poor power factor of less than 0.96, the power source, EPOS 300, was set at 230 V for all three phases, as seen in Table 4.16.

**Table 4.16: Power source (EPOS 300) power quality setting**

| Channel Name | Mode | Amplitude | X | Phase | X | Frequency | X |
|---|---|---|---|---|---|---|---|
| U1 | AC | 230.000 | ☑ | 0.000 ° | ☑ | 50.000 Hz | ☐ |
| U2 | AC | 230.000 | ☑ | 240.000 ° | ☑ | 50.000 Hz | ☐ |
| U3 | AC | 230.000 | ☑ | 120.000 ° | ☑ | 50.000 Hz | ☐ |
| I1' | AC | 1.000 | ☑ | 340.000 ° | ☑ | 50.000 Hz | ☐ |
| I2' | AC | 1.000 | ☑ | 220.000 ° | ☑ | 50.000 Hz | ☐ |
| I3' | AC | 1.000 | ☑ | 100.000 ° | ☑ | 50.000 Hz | ☐ |

The electricity meter, Itron SL7000, was configured to monitor the aggregate power factor as described in Equation 4.12 with the channel added under load profile in Table 4.17.

**Table 4.17: Metering software Electricity meter (Itron SL7000) power factor settings**

| Channel | Quantity | Scaler | Unit | Excess | Calculation Mode | Fluid | Memory Usage |
|---|---|---|---|---|---|---|---|
| 1 | Voltage RMS value Phase 1 | 10^-1 | V | ☐ | Average | Electricity | 0 |
| 2 | Voltage RMS value Phase 2 | 10^-1 | V | ☐ | Average | Electricity | 0 |
| 3 | Voltage RMS value Phase 3 | 10^-1 | V | ☐ | Average | Electricity | 0 |
| 4 | Current RMS value Phase 1 | 10^-3 | A | ☐ | Average | Electricity | 0 |
| 5 | Current RMS value Phase 2 | 10^-3 | A | ☐ | Average | Electricity | 0 |
| 6 | Current RMS value Phase 3 | 10^-3 | A | ☐ | Average | Electricity | 0 |
| 7 | Power Factor Aggregate | 10^-4 | No unit | ☐ | Average | Electricity | 0 |
| 8 | Frequency | 10^-2 | Hz | ☐ | Average | Electricity | 0 |

### 4.4.4.3 Power factor results

The power factor results are displayed in the load profile view at 30-minute intervals on the AMR software. The poor power factor level was 0.949 measured at 21:00 on 11/05/2024, as shown in Figure 4.12. As the calculated value was 0.939 in Equation 4.12, the measured value was acceptable for the test as it needed to be less than 0.96.

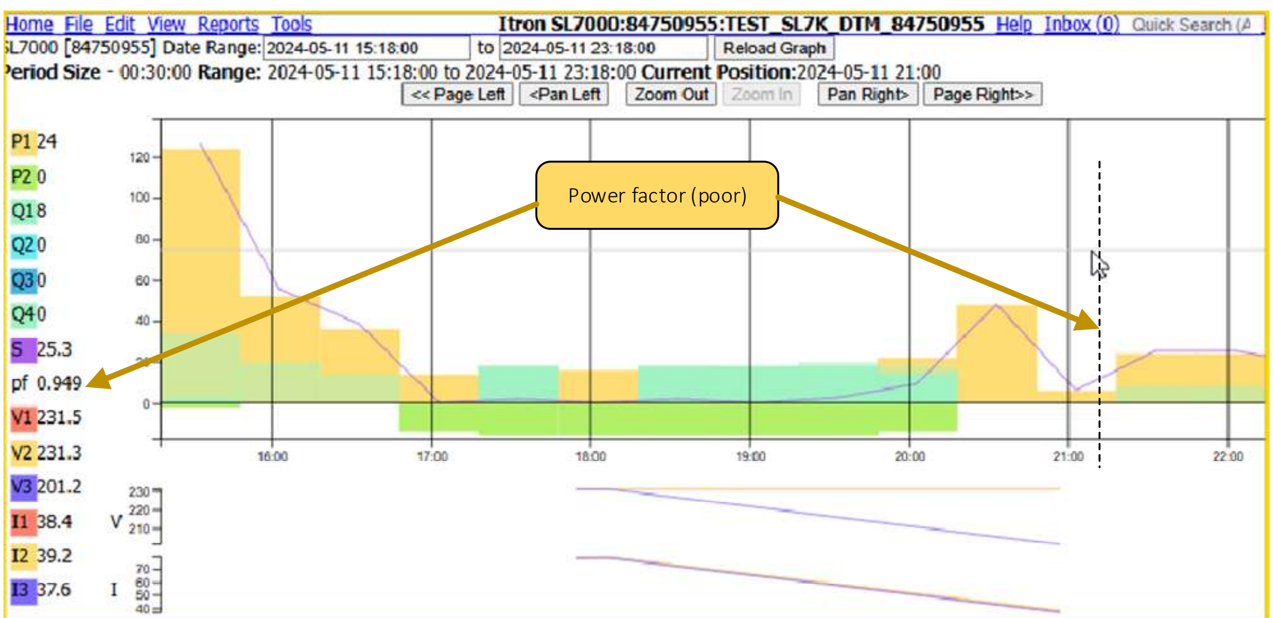


**Figure 4.12: AMR power factor load profile**

The power factor measurement was also logged by the meter (Table 4.18) that could be read by the metering software. The power factor reading of 0.944 was logged at 21:00 on 11/05/2024, which corresponded with the AMR reading.

**Table 4.18: Metering software power factor load profile**

| Date | End of Period | Channel 7 |
|---|---|---|
| 11 May 2024 | 00:30 | 0,9998 |
| | 20:29 | 0,9402 |
| | 21:00 | 0,944 |
| | 21:30 | 0,944 |
| | 22:00 | 0,9394 |
| | 22:29 | 0,9376 |

#### 4.4.4.4 Power factor summary

The power factor test results show that monitoring can be performed by the engineering software and AMR system, with poor power factor readings of less than 0.96.

### 4.4.5 THD measurement test

As introduced in chapter 3, the THD measurement has an impact on transformer performance, and monitoring these parameters is therefore relevant (Itron, 2018). The THD measurements for voltage and current were recorded and not simulated due to limitations of the laboratory test equipment. As the objective of the measurement was to determine the possibility of the function at the meter level, it was acceptable to measure existing conditions as a principle.

#### 4.4.5.1 THD measurement configuration

To measure THD, the electricity meter, Itron SL7000, was configured to monitor the THD voltage and current distortion between 4% and 99%, as seen in Figure 4.13.

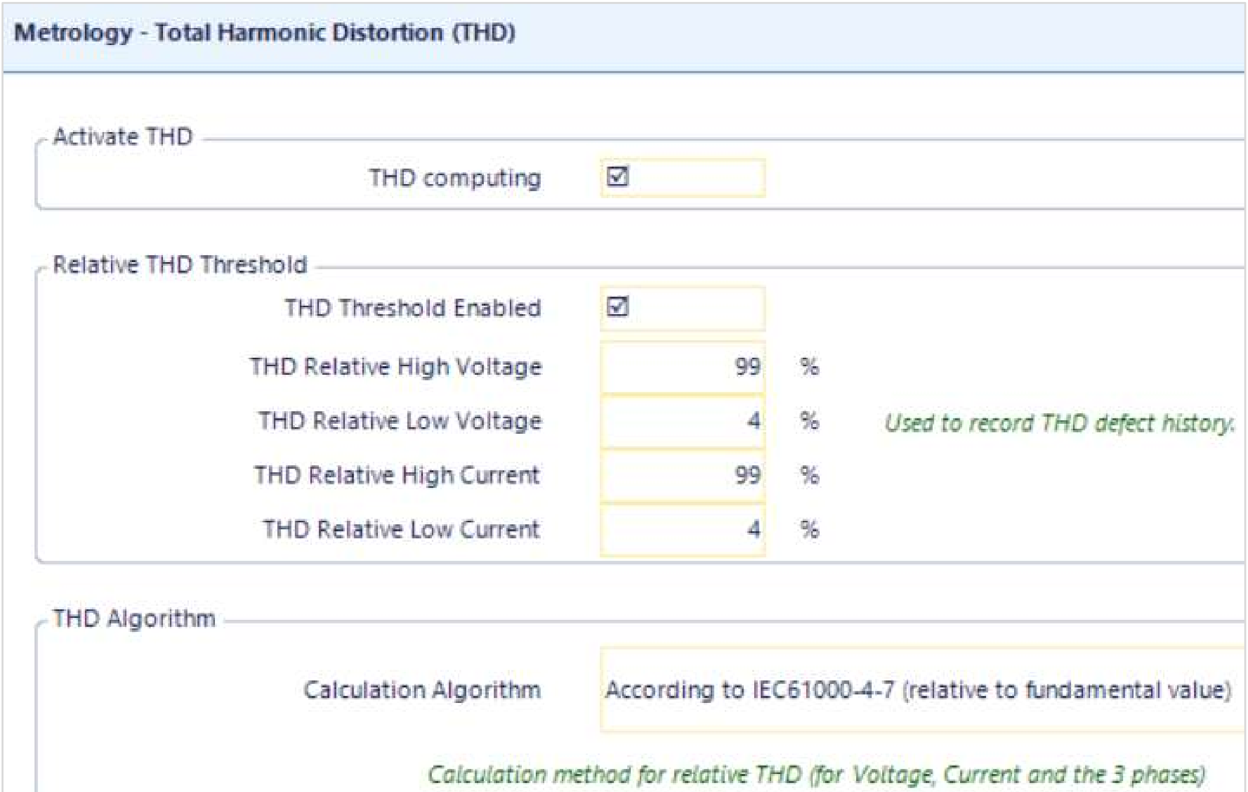


**Figure 4.13: Metering software THD configuration**

### 4.4.5.2 THD measurement results

The THD values recorded were below the defined thresholds of 4% and therefore did not report any THD faults, as seen in Table 4.19.

**Table 4.19: THD Values**

| Data per Phase | Fundamental Amplitude | Harmonic Distortion Amplitude | Rms Values | Relative THD by Phase | Notes |
|---|---|---|---|---|---|
| **Voltage phase 1** | 201,2 V | 0,4 V | 201,2 V | 0,1 % | Reading less than 4% |
| **Voltage phase 2** | 201,1 V | 1 V | 201,1 V | 0,4 % | |
| **Voltage phase 3** | 201 V | 0,5 V | 201 V | 0,2 % | |
| **Current phase 1** | 1,974 A | 0,021 A | 1,974 A | 1 % | |
| **Current phase 2** | 1,974 A | 0,021 A | 1,974 A | 1 % | |
| **Current phase 3** | 1,972 A | 0,021 A | 1,972 A | 1 % | |

### 4.4.5.3 THD measurement summary

The THD test results show that monitoring can be read by the engineering software and individual THD voltage and current faults of the threshold defined > 4% can be recorded. For this test the

THD measurement only recorded the distortion that was present on the line and not injected, as this was not possible with the laboratory equipment used. For this particular electricity meter, it was possible to monitor THD between 4% and 99%.

### 4.4.6 Temperature measurement test

As introduced in chapter 3, the temperature measurement has an impact on transformer performance, and monitoring these parameters is therefore relevant (Itron, 2018). The temperature measurement was recorded to measure the existing temperature.

#### 4.4.6.1 Temperature measurement configuration

To measure temperature, the electricity meter, Itron SL7000, was configured to monitor the temperature at 30-minute intervals as seen in Table 4.20.

**Table 4.20: Meter software temperature load profile 1**

| Channel Number | Description | LogicalNameChannel | Unit |
|---|---|---|---|
| 1 | Import Active Energy Aggregate | 1.1.1.29.0.255 | kWh |
| 2 | Export Active Energy Aggregate | 1.1.2.29.0.255 | kWh |
| 7 | Ambient Temperature | 1.1.149.27.0.255 | °C |

#### 4.4.6.2 Temperature measurement results

The temperature values were recorded in load profile 1 channel 7 (Table 4.21).

**Table 4.21: Metering software temperature load profile 1 results**

| | End of Period | Channel 7 (°C) |
|---|---|---|
| 2024/05/12 | 09:00 | 19 |
| | 09:30 | 23 |
| | 10:00 | 25 |
| | 10:30 | 27 |
| | 11:00 | 28 |
| | 11:30 | 28 |
| | 12:00 | 28 |
| | 12:30 | 29 |
| | 13:00 | 30 |

#### 4.4.6.3 Temperature measurement summary

The temperature measurement results show that monitoring can be performed by the metering software and is possible from 1, 5, 15, 30, 60, to 1440-minute intervals. However, this measurement is an indication of the ambient temperature and not the hot-spot temperature of the DT.

### 4.4.7 Line frequency measurement test

As introduced in chapter 3, the line frequency measurement has an impact on transformer performance, and monitoring these parameters is therefore relevant (Itron, 2018). For the sake of the measurement, the line frequency was recorded under existing conditions to show the reporting principles. It was not necessary to provide a wide range of line frequency variables.

#### 4.4.7.1 Line frequency configuration

To measure temperature, the electricity meter, Itron SL7000, was configured to monitor the frequency at 30-minute intervals as seen in Table 4.22.

**Table 4.22: Metering software frequency load profile 2**

| Channel Number | Description | LogicalNameChannel | Unit |
|---|---|---|---|
| 7 | Power Factor Aggregate | 1.1.13.27.0.255 | |
| 8 | Frequency | 1.1.14.27.0.255 | Hz |

#### 4.4.7.2 Line frequency measurement results

The temperature values were recorded in load profile 2 channel 8 (Table 4.23).

**Table 4.23: Metering software frequency load profile 2 results**

| | End of Period | Channel 8 (Hz) |
|---|---|---|
| 2024/05/12 | 09:00 | 49,96 |
| | 09:30 | 49,99 |
| | 10:00 | 49,91 |
| | 10:30 | 49,99 |
| | 11:00 | 49,99 |
| | 11:30 | 49,99 |
| | 12:00 | 49,99 |
| | 12:30 | 49,99 |
| | 13:00 | 49,99 |

#### 4.4.7.3 Line frequency measurement summary

The line frequency measurement results show that monitoring can be performed by the metering software.

## 4.5 Laboratory testing overall summary of results

In summary, there were two categories of testing performed. In the first category, conditions were simulated to trigger certain events, and in the second category, the existing conditions were measured and results recorded. In both categories, the reporting function was exercised.

Category 1 with measurements was performed under triggered conditions and events included: normal and excess demand; network unbalance of phase voltage and current; quality of supply; and power factor.

Category 2 measurements were performed under existing conditions and not triggered conditions. Events included: total harmonic distortion; ambient temperature; and line frequency.

## 4.6 AMR environmental impact measurements

The AMR software can calculate the environmental impact based on the electricity meter consumption. By applying the type of fuel used as coal, the environmental implications are derived. These factors include ash produced, $CO_2$ emissions, coal use, NOx emissions, particulate emissions, $SO_2$ emissions, and water use. An electricity meter with a consumption of 33157 kWh is considered for this measurement in Table 4.24. This breakdown of environmental implications can be evaluated against the SDG objective of supplying clean and reliable energy.

**Table 4.24: Environmental impact for meter with 33157 kWh consumption**

| Implication | 2025-01-01 to 2025-07-01 | Daily Avg | Monthly Avg |
|---|---|---|---|
| **Ash produced** | 5139.359334 kg | 28.394250 kg | 864.249998 kg |
| **CO2 emissions** | 32825.585429 kg | 181.356825 kg | 5520.048378 kg |
| **Coal use** | 17573.293209 kg | 97.090017 kg | 2955.177414 kg |
| **NOx emissions** | 138.596916 kg | 0.765728 kg | 23.306870 kg |
| **Particulate emissions** | 10.941861 kg | 0.060452 kg | 1.840016 kg |
| **$SO_2$ emissions** | 256.967966 kg | 1.419712 kg | 43.212499 kg |
| **Water use** | 46.420019 kl | 0.256464 kl | 7.806129 kl |

By considering the same electricity meter with 33157 kWh consumption, the $CO_2$ emissions used can be compared for the previous, current, and projected years as shown in Figure 4.14. Energy efficiency measurements relating to transformers can therefore be tracked in this manner. The $CO_2$ emissions total of 32825.58 kg was measured from January to June 2025, with previous year and projected points overlayed.

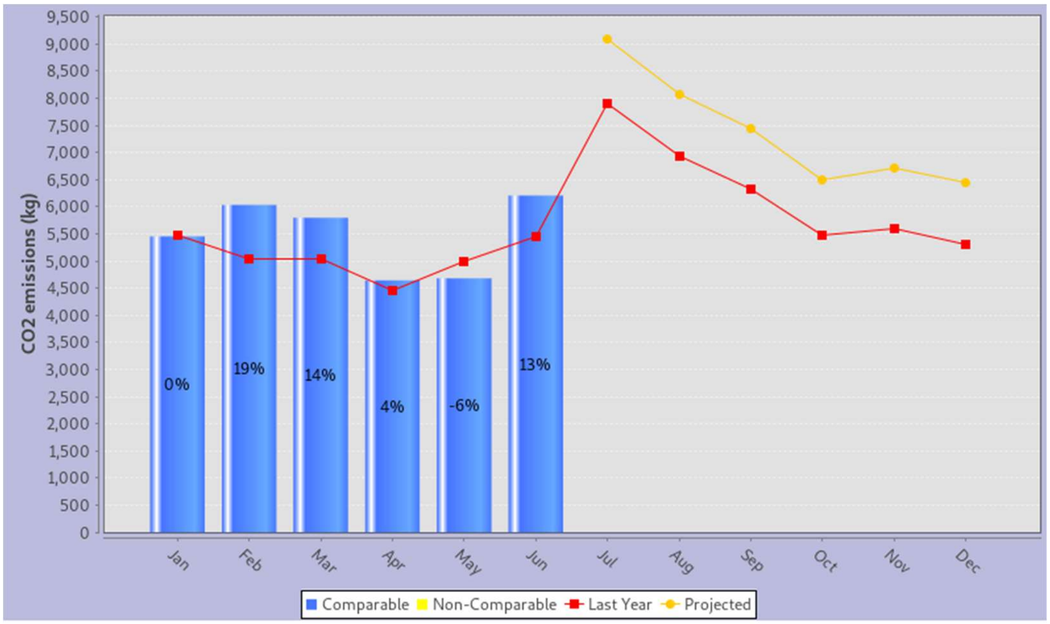


**Figure 4.14: $CO^2$ emissions tracking**

## 4.7 Conclusion

The testing was performed by using the Itron SL7000 electricity meter, which is considered a typical C&I meter in South Africa, where municipalities such as Stellenbosch (Stellenbosch Mmunicipality, 2024), Dawid Kruiper Municipality (Dawid Kruiper Municipality, 2024), City Power (City Power, 2024) and Nelson Mandela Bay (Nelson Mandela Bay Municipality, 2024) deployed these. Typical electricity meters include Itron, Elster, Landis+Gyr, Itron, and Hexing. The test results were found to be very rich in results. The next chapter consists of a detailed comparative analysis of the DTM commercial solutions and empirical research performed in chapter 2 and compares this with the laboratory testing performed in this chapter.

# CHAPTER FIVE

## DATA ANALYSIS AND DISCUSSION

## 5.1 Introduction

The research focus was to explore the smart metering developments for monitoring critical measurements of DTs to assess their health and aging factors. The data analysis chapter discusses the laboratory testing performed in chapter 4 and compares the results with the DTM solutions and empirical research discussed in chapter 2. These are all brought together in DT measurement comparison and DTM efficacy tables, where the laboratory testing is ranked and discussed fully as to its relevance in the body of research undertaken. Figure 5.1 provides a visual illustration of the ranking process. The DTM categories is firstly checked against DTM measurements in Block A with a DTM comparative analysis result, followed by the transformer health monitoring (THM) measurements in Block B with a DTM efficacy result, and lastly, the comparative and efficacy tables are combined and ranked in Block C. The chapter is then summarised and concluded.

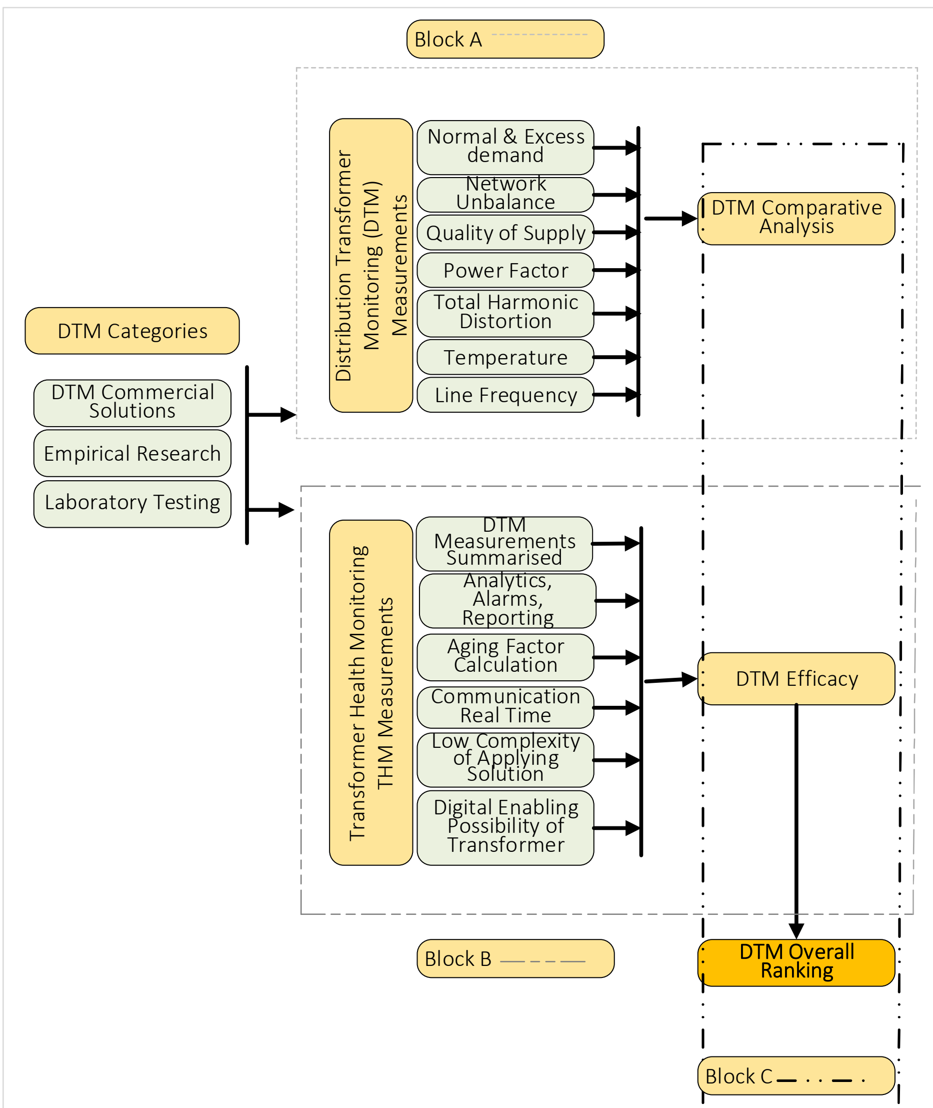


**Figure 5.1: DTM ranking process**

## 5.2 Data analysis of DTM measurements and transformer health monitoring

The seven DTM measurements consist of normal and excess demand, network unbalance, QoS, power factor, THD, temperature and frequency measurement. These were described in detail in section 3.5. Transformer health monitoring (THM) is an indication of how well the transformers are monitored to assess their aging factor. These DTM measurements and THM measurements are now compared against the DTM solutions, empirical research and laboratory testing.

### 5.2.1 DTM solutions comparative analysis

The DTM solutions are now discussed against the DTM measurements.

#### 5.2.1.1 DTM case 1: Hitachi TXpert™ asset management solution

For this DTM case there is no specific mention of performing these DT measurements. However, some of the diagnostics services provided are the inspection of dielectric fluid and temperature to analyse the condition of the transformer. So, other monitoring measures are therefore utilised (Hitachi Energy, 2024). The full solution is described in section 2.5.1 of the literature review.

- DT measurements: Based on the research it can be assumed that there are minimal DT measurements available.
- THM measurements*:* Temperature measurement and dielectric fluid measurements can contribute towards monitoring the transformer health.

#### 5.2.1.2 DTM case 2: Itron DTM metering solution

For this DTM case, specific mention is made of the following measurements in the literature review where they are discussed in detail. These include metrology, load profiles, power quality and billing registers. In terms of transformer health, monitoring is possible by a transformer load monitoring module, based on derived data to identify critical indicators such as accelerated aging and overheated exposure. The full solution is described in section 2.5.2 of the literature review.

- DT measurements: all the measurements are specifically mentioned and therefore covered.
- THM measurements: the transformer load module provides an indication of transformer health, but there is no direct transformer measurement.

#### 5.2.1.3 DTM case 3: Hexing iDMS solution

A fully integrated solution is described in this case, and with the assumption that Hexing metering is utilised, all DT measurements should therefore also be covered. The strength of this solution is monitoring, controlling and managing the distribution network from a central iDMS. There is no mention of direct transformer measurement. The full solution is described in section 2.5.3 of the literature review.

- DT measurements: all measurements are possible considering Hexing metering.
- THM measurements: the solution is focused on management and no direct transformer measurement is mentioned.

#### 5.2.1.4 DTM case 4: Meter software reading solution

As metering software is a manufacturer-specific configuration tool, all DT measurements are also configurable by this software and therefore covered for the common industry meters such as Elster, Landis+Gyr and Itron. With this case, it can also be considered that transformer monitoring can be derived, but not directly measured. The full solution is described in section 2.5.4 of the literature review.

- DT measurements: all measurements are possible considering common industry metering.
- THM measurements: the solution is focused on electricity metering capability and not direct transformer measurement.

### 5.2.2 Empirical research (ER) comparative analysis

The ERs are now discussed against the DTM measurements and THM.

#### 5.2.2.1 ER Paper 1: Overloading analysis using the temperature measurement model

Based on the IEEE C57.91-2011 standard, this research (Muthukaruppan et al., 2022) aims to estimate the winding hot-spot temperature, and the aging of transformer insulation life aim to predict transformer overloading status. As smart data forms the basis of this analysis, the assumption can be made that the smart meters are capable of at least the main DT measurements. The full research is described in section 2.6.1 of the literature review.

- DT measurements: given that smart data is available, it can be assumed that some of the DT measurements are possible such as voltage and power.
- THM measurements*:* by estimating the winding hot-spot and aging of the transformer insulation life, the transformer health can be monitored indirectly, as there is no direct transformer monitoring.

#### 5.2.2.2 ER Paper 2: DT health monitoring detecting high voltage insulation degradation

Research by Ashok et al. (2020) deploys an algorithm that considers the behaviour between primary and secondary voltages where the transformer turn ratios are calculated and smart data utilised such as voltage and power measurements. The full research is described in section 2.6.2 of the literature review.

- DT measurements: given that smart data is available, it can be assumed that some of the DT measurements are possible such as voltage and power.
- THM measurements*:* the voltage insulation degradation factor means that it is possible to have an indication of the transformer health, although there is no direct transformer measurement.

#### 5.2.2.3 ER Paper 3: Transformer monitoring using IoT (LoRa)

Research by Kumar & Ajitha (2017) deploys the use of a range of sensors to monitor various measurements of the transformer that includes voltage, current, oil and winding temperature, oil level and status. It uses the Arduino Uno microcontroller board using ATmega328 to perform edge mode calculations. The measurements are communicated by LoRa WAN communication to the cloud-based platform. The full research is described in section 2.6.3 of the literature review.

- DT measurements: a wide range of measurements is possible and therefore the DT measurement factor is high.
- THM measurements*:* the voltage, current, oil and winding temperature are measurements that contribute towards monitoring the transformer health.

#### 5.2.2.4 ER Paper 4: DT monitoring as part the development of an automated distribution

In their research paper (Chaves et al., (2022) deployed the use of various sensors such as voltage and currents, temperature and oil level. The sensors installed covered the monitoring of both the overhead and underground electricity grid. The full research is described in section 2.6.4 of the literature review.

- DT measurements: the paper has shown that DT measurements such power, voltage and current are possible.
- THM: measurements: the temperature measurement and oil level monitoring means that it is possible to have indications of transformer health.

### 5.2.3 Research methodology: laboratory testing

The laboratory testing was performed to ascertain how effective a standard metering solution deploying an MDC can address DT monitoring. Standard metering measurements were considered that could easily be obtained from industry standard metering. Measurements at the MDC included power, voltage, current and power quality events. Although temperature measurements were possible at the metering level, translating this to a transformer temperature reading was not possible. The laboratory testing was performed in chapter 4 of the paper.

- DT measurements: the testing has shown that standard DT measurements such power, voltage and current are possible.
- DTM: there is no direct measurement that can be used to indicate transformer health; however derived measurement data can be utilised.

## 5.3 DT measurements comparative analysis

The data analysis of DT measurements is consolidated in Table 5.1, where comparisons are drawn for all type DTM solutions, empirical research and the laboratory testing performed.

**Table 5.1: DT measurements comparison**

| | DT Measurement / DTM solution/ Empirical research/ Laboratory test | Normal and excess demand | Network unbalance | Quality of supply | Power factor | THD measurement | Temperature | Frequency |
|---|---|---|---|---|---|---|---|---|
| | **DTM Solutions** | | | | | | | |
| **1** | **DTM Case 1:** TXpert™ Asset Management Solution (Hitachi Energy, 2023) | ☒ | ☒ | ☒ | ☒ | ☒ | ✓ | ☒ |
| **2** | **DTM Case 2**: Itron DTM Metering Solution (Itron, 2017), (Itron, 2012) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **3** | **DTM Case 3**: Hexing iDMS Fully Integrated Solution(Hexing, 2023);(Hexing, 2024) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **4** | **DTM Case 4:** Meter Software Reading Solution (Itron, 2020), (Elster, 2015), (Landis+Gyr, 2024) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | | | | | | | |
| | **Empirical research papers** | | | | | | | |
| **5** | **ER Paper 1:** Overloading analysis using temperature measurement model (Muthukaruppan et al., 2022) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **6** | **ER Paper 2:** DT health monitoring using smart meter data (Ashok et al., 2020) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **7** | **ER Paper 3:** Transformer monitoring using IoT (LoRa) (Kumar & Ajitha, 2017) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **8** | **ER Paper 4:** DT monitoring as part the development of an automated distribution (Chaves et al., 2022) | ☒ | ✓ | ☒ | ☒ | ☒ | ✓ | ✓ |
| | | | | | | | | |
| **9** | Laboratory testing | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## 5.4 Data analysis DTM efficacy

The data analysis of DTM efficacy is consolidated in Table 5.2, where comparisons are drawn for all types of DTM solutions, empirical research and the laboratory test performed. Solutions denoted by a '1' can derive aging factors based on algorithms and not an actual temperature measurement.

**Table 5.2: DTM efficacy comparison**

| | **DTM efficacy criteria** / **DTM solution/ Empirical research/ Laboratory test** | **DTMS services** (Analytics, alarms and reporting) | **Transformer measurements** (QoS, harmonics, phase unbalances, energy and demand) | **Aging factor calculation** (Calculate the aging factor or life expectancy) | **Communication technology** (Reliable with real time reading capability) | **Low complexity of applying solution - can** solution be applied and what are the prerequisites? | **Possibility of digital enabled transformer** |
|---|---|---|---|---|---|---|---|
| | **DTM Solutions** | | | | | | |
| **1** | **DTM Case 1:** TXpert™ Asset Management Solution (Hitachi Energy, 2023) | ✓ | ☒ | ✓ | ✓ | ☒ | ✓ |
| **2** | **DTM Case 2**: Itron DTM Metering Solution (Itron, 2017), (Itron, 2012) | ✓ | ✓ | ☒[1] | ✓ | ✓ | ☒ |
| **3** | **DTM Case 3**: Hexing iDMS Fully Integrated Solution (Hexing, 2024) (Hexing, 2023; 2024) | ✓ | ✓ | ☒[1] | ✓ | ☒ | ☒ |
| **4** | **DTM Case 4:** Meter Software Reading Solution (Itron, 2020), (Elster, 2015), (Landis+Gyr, 2024) | ☒ | ✓ | ☒ | ☒ | ✓ | ☒ |
| | **Empirical research papers** | | | | | | |
| **5** | **ER Paper 1:** Overloading analysis using temperature measurement model (Muthukaruppan et al., 2022) | ☒ | ✓ | ☒[1] | ☒ | ✓ | ☒ |
| **6** | **ER Paper 2:** DT health monitoring using smart meter data (Ashok et al., 2020) | ☒ | ✓ | ☒[1] | ☒ | ✓ | ☒ |
| **7** | **ER Paper 3:** Transformer monitoring using IoT (LoRa) (Kumar & Ajitha, 2017) | ✓ | ✓ | ✓ | ✓ | ☒ | ☒ |
| **8** | **ER Paper 4:** DT monitoring as part the development of an automated distribution (Chaves et al., 2022) | ☒ | ✓ | ✓ | ✓ | ☒ | ☒ |
| **9** | **Research Methodology**: Laboratory simulation | ☒ | ✓ | ☒ | ✓ | ✓ | ☒ |

## 5.5 DTM Solution, Research and Laboratory Test Ranking

The DTM solutions, empirical research and laboratory test are now scored against the criteria defined and ranked in Table 5.3. The scores from Table 5.1 are denoted by a ‘1’ and Table 5.2 denoted by a ‘2’.

**Table 5.3: DTM solution, research, laboratory test ranking**

| | **Criteria** / **DTM solution/ Empirical research/ Laboratory test** | **DTM Measurement Ranking (%)** | **DTM Efficacy Ranking (%)** | **Total Ranking** | **Reference** |
|---|---|---|---|---|---|
| | **DTM Solutions:** | | | | |
| **1** | **DTM Case 1:** TXpert™ Asset Management Solution | (1/7)[1] 14% | (4/6)[2] 66% | (5/13) 38% | (Hitachi Energy, 2023) |
| **2** | **DTM Case 2**: Itron DTM Metering Solution | (7/7)[1] 100% | (4.5/6)[2] 75% | (11.5/13) 88% | (Itron, 2017; 2012) |
| **3** | **DTM Case 3**: Hexing iDMS Fully Integrated Solution | (7/7)[1] 100% | (3.5/6)[2] 58% | (10.5/13) 81% | (Hexing, 2023; 2024) |
| **4** | **DTM Case 4:** Meter Software Local Reading Solution | (7/7)[1] 100% | (2/6)[2] 33% | (9/13) 69% | (Itron, 2020), (Elster, 2015), (Landis+Gyr, 2024) |
| | | | | | |
| | **Empirical research papers:** | | | | |
| **5** | **ER Paper 1:** Overloading analysis using temperature measurement model | 7/7)[1] 100% | (2.5/6)[2] 42% | (9.5/13) 73% | (Muthukaruppan et al., 2022) |
| **6** | **ER Paper 2:** DT health monitoring using smart meter data | 7/7)[1] 100% | (2.5/6)[2] 42% | (9.5/13) 73% | (Ashok et al., 2020) |
| **7** | **ER Paper 3:** Transformer monitoring using IoT (LoRa) | 7/7)[1] 100% | (4/6)[2] 67% | (11/13) 85% | (Kumar & Ajitha, 2017) |
| **8** | **ER Paper 4:** DT monitoring as part the development of an automated distribution | 3/7)[1] 43% | (3/6)[2] 50% | (6/13) 46% | (Chaves et al., 2022) |
| | | | | | |
| **9** | Laboratory test | 7/7)[1] 100% | (3/6)[2] 50% | (10/13) 77% | |

The ranking of the solutions, research, and laboratory tests is now sequenced in Table 5.4. The percentages scored for these entities were measured in Tables 5.1 and 5.2 using the criteria defined. All 9 entities were evaluated on their own merits.

**Table 5.4: DTM solution, research, laboratory test ranking sequenced**

| Ranking | DTM solution, research, laboratory test | Percentage |
|---|---|---|
| 1 | DTM Case 2: Itron DTM metering solution | 88 |
| 2 | ER Paper 3: Transformer monitoring using IoT (LoRa) | 85 |
| 3 | DTM Case 3: Hexing iDMS fully integrated solution | 81 |
| **4** | **Research Methodology: Laboratory test** | **77** |
| 5 | ER Paper 1: Overloading analysis using temperature measurement model | 73 |
| 6 | ER Paper 2: DT health monitoring using smart meter data | 73 |
| 7 | DTM Case 4: Meter software local reading solution | 69 |
| 8 | ER Paper 4: DT monitoring as part the development of an automated distribution | 46 |
| 9 | DTM Case 1: TXpert ™ Asset management solution | 38 |

## 5.6 Conclusion

The data analysis chapter shows how the laboratory test bench results in particular ranks against the rest of the solutions and empirical research conducted. It is ranked fourth when combining the DT measurements and transformer health efficacy. One note is that analysing the aging factor is mostly derived from smart metering measurements and not based on a direct transformer measurement. In these cases, the DT health monitoring is derived from an algorithm deployed. The ranking weights of these specific cases were adjusted by half a point.

The research consisted of a mix of local and international papers and solutions that indicate the global relevance of the research problem. The laboratory test setup was focused on a local South African market, and ranking indicates a high efficacy factor. The results are positive and a definite consideration to explore further.

# CHAPTER SIX

## CONCLUSION

6.1 Introduction

6.2 Dissertation overview

6.3 Outcomes of research

6.4 Contributions made to research

6.5 Recommendations for future research

## 6.1 Introduction

The research aimed to analyse the current state of transformers globally and in the South African context and look at advances in smart metering for monitoring their health and aging factors. This conclusion chapter discusses briefly the chapters covered and the response to the aims and objectives set out in Chapter 1. The research question was positively answered, and the objectives were achieved. A summary of the experimentally measured outcomes and contributions is also presented, followed by recommendations for future research.

## 6.2 Dissertation overview

This dissertation started by highlighting conditions that the electricity grid is subjected to, impacting all electricity network equipment that includes DTs. Internal factors impacting the grid were discussed next, such as load shedding and the increased uptake of renewable energy. External factors covered climate control mandates and how this was linked to UN sustainable design goals. The aims and objectives continued and guided what the research aimed to achieve, and how. In summary, the aim was to research the existing state of DTs and consider smart metering developments for monitoring their health and aging factors.

The literature review covered in more detail the global need for monitoring DTs in developed and developing countries. Studying the research papers, it was confirmed that the topic is a global concern. The theoretical framework of DTs and smart metering detailed the electrical theory and smart metering systems. Once this framework was set, studies of a range of commercial DTM solutions and empirical research were performed to gauge approaches in solving the problem. These were measured against specific DT measurement criteria. A key outcome of the literature review was finding an obvious research gap. The research gap identified was to explore the category of DT monitoring where no additional devices were required, except for what was already available at the meter and system level.

The research methodology started with describing the research philosophy and approach as being quantitative and cross-sectional respectively. The DT measurements formed a significant part of this section as it benchmarked the various commercial DTM solutions and empirical research against the same criteria set. The theory of DT measurements was discussed and expressed mathematically. For reference, the DT measurements included demand reading, phase unbalances, quality of supply, power factor, THD, ambient temperature and network line frequency.

Next, the laboratory test and metering equipment were described in detail in terms of their functionality and how they could be configured to simulate certain network conditions. The laboratory testing chapter demonstrated the DT measurements detailed in the research methodology chapter. The testing was performed on an Itron ACE SL7000 meter, which was chosen as it was available for testing, as well as a good representation of a typical LPU meter installed by multiple municipalities in South Africa. It shares similar functionality with other industry standard meters, such as Elster, Landis+Gyr and Hexing, as they comply with the same metering standards such as IEC 62056-21, IEC 61000-4-30 and DLMS/COSEM. The test results were very extensive and expressed the richness of data available in existing meters and smart metering systems. Certain conditions tested triggered alarms that could be seen in the metering software, AMR platform, as well as cellular mobile SMS notification. It must be noted that the Itron ACE SL7000 meter used for testing is not the same meter variant used for the Itron DTM solution that incorporates an algorithm for DT temperature monitoring in conjunction with the system.

The data analysis and discussion chapter evaluated the commercial DTM solutions, empirical research papers, and the laboratory testing against the same scoring methodology. The scoring was performed under three categories that consisted of DT measurements comparison, DTM efficacy comparison, and finally, an overall ranking of the two. This chapter showed in particular how the laboratory testing category ranked against the rest of the solutions and empirical research conducted. As it was a favourable result, it demonstrated the benefit of exploring this category for DT monitoring.

## 6.3 Outcomes of research

One of the outcomes was the monitoring of DTs as a global concern that affects both developed and developing countries. This was significant, as it indicated a general concern for most countries to monitor and address DT health as an important measure for electricity grid stability. As much as transformer root cause failures varied per region, the common failures were due to electrical system issues, faults, damage, aging infrastructure, higher demand, and the impact of renewable energy integration.

The significant contrast of solutions ranging from very advanced to standard smart metering was another outcome. Available solutions ranged from being fully system-based with digital transformer controls and multiple measurement sensors to solutions that used existing smart metering data as a baseline. The input for solutions using standard data models to predict transformer health included electricity metering data, surrounding electrical line conditions, and available temperature data. While advanced solutions required greater investment to deploy, using existing infrastructure offered a practical solution to deploy in stages.

Lastly, the richness of existing smart metering data to perform DT monitoring was another outcome. This was significant as it showed excellent opportunities for utilities to deploy these features in existing metering. The study showed that most electricity meters comply with international measurement standards for the measurement of energy, demand, QoS, and power line data. In fact, for the range of solutions available, this category of using existing smart metering data was found to be most effective.

## 6.4 Contributions made to research

By performing an efficacy ranking of DTM solutions, this study provides utilities with insight as to how solutions with various degrees of complexity are implemented. This contribution made to research allows utilities to consider available solutions and case studies to gauge their unique requirements and map where they fit in the ranking, to then apply similar solutions.

Another contribution is that technology service providers can compare their solutions to others in the industry, hereby also considering enhancing certain metering functionalities that can be more DTM-friendly and thereby gaining further access to this sector. The functionality of interest includes incorporating inputs to sensors that interface easily with DT oil and temperature measurements.

Lastly, to perform DT monitoring to determine transformer health, the efficiency of transformers can also be compared to the manufacturer's specification and typical operational demand measurement. The smart metering software used for the laboratory testing can express energy efficiency and GHG emissions calculations. This, in turn, responded to an SDG objective as it refers to the supply of clean and reliable energy.

## 6.5 Recommendations for future research

One of the recommendations for future research is to perform a comprehensive comparative analysis for the same DT population set, with actual DT-specific sensors and ones only using derived data. Further, to then build a detailed efficacy comparison of transformer health monitoring between the two types, detailing how closely they track each other when comparing transformer health and aging.

Comparing the laboratory test data with live distribution environments should also yield some interesting results that might not have been anticipated under controlled environments.

Another recommendation for future research is to explore existing metering hardware in terms of DT monitoring with Input/Output (I/O) capability. The retrofitting of a temperature sensor can then be considered as a possible solution to measure the hot spot temperature of the DT. The analogue temperature measurement could be converted to a digital output by an Analog/Digital converter, which is fed to auxiliary inputs of existing smart meters equipped with I/O ports. Therefore, an actual temperature reading of the DT can be communicated using existing smart metering infrastructure. This is possible as some electricity meters can already interface with third-party external devices by pulsing.

Lastly, as the primary focus of this research was the study of low-voltage distribution transformers, a study on medium and high voltage transformers would further provide network quality data at these distribution levels.

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# APPENDICES

## Appendix A.1: Types of electricity meters and metering software – Elster.

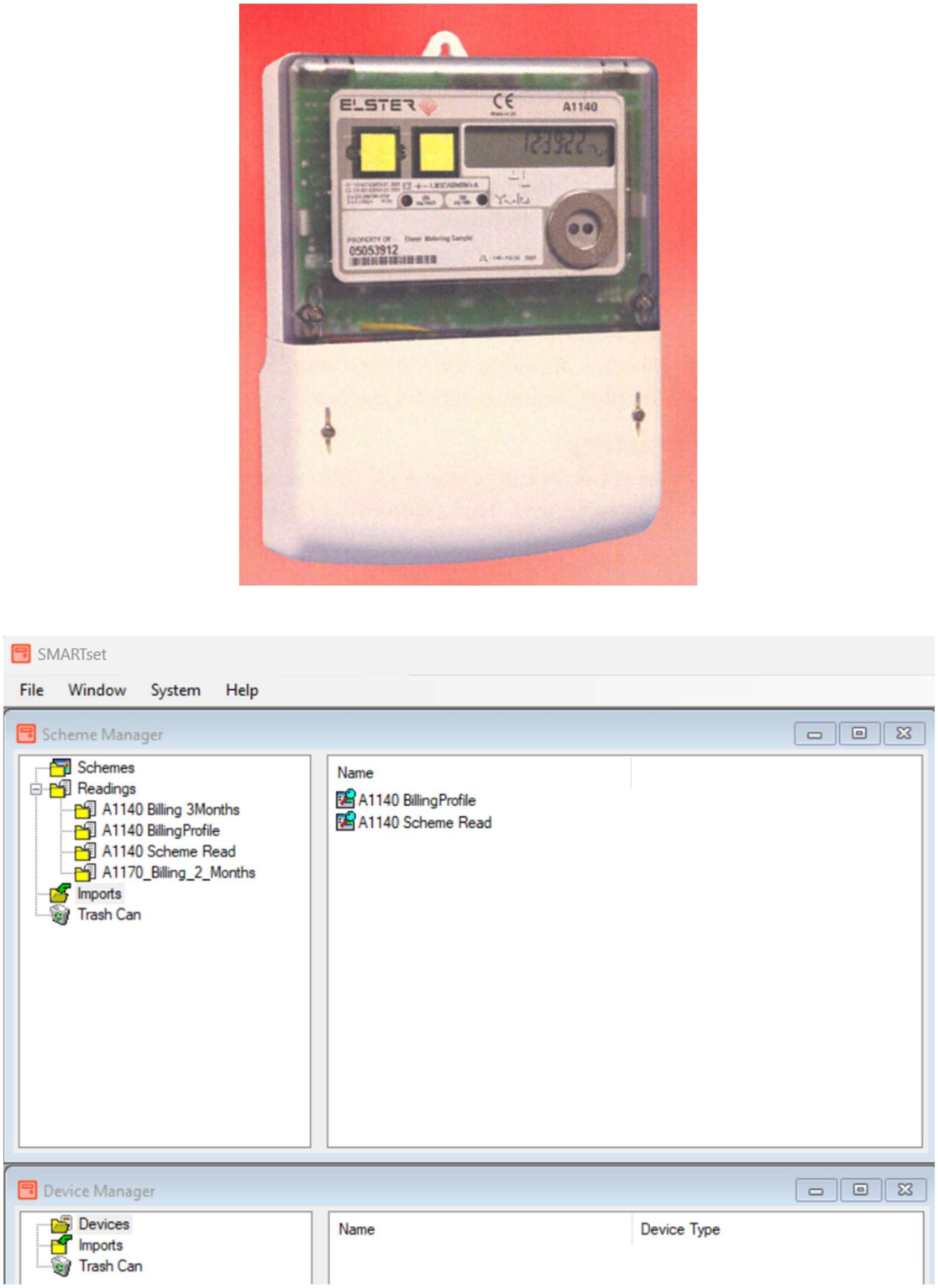


**Figure A.1: Electricity meter and software – Elster A1140/SmartSet (Elster, 2015)**

## Appendix A.2: Types of electricity meters and metering software – Landis+Gyr.


**Figure A.2: Electricity meter and software – E650/(.MAP110) (Landis+Gyr, 2024)**

## Appendix A.3: Types of electricity meters and metering software – Itron.

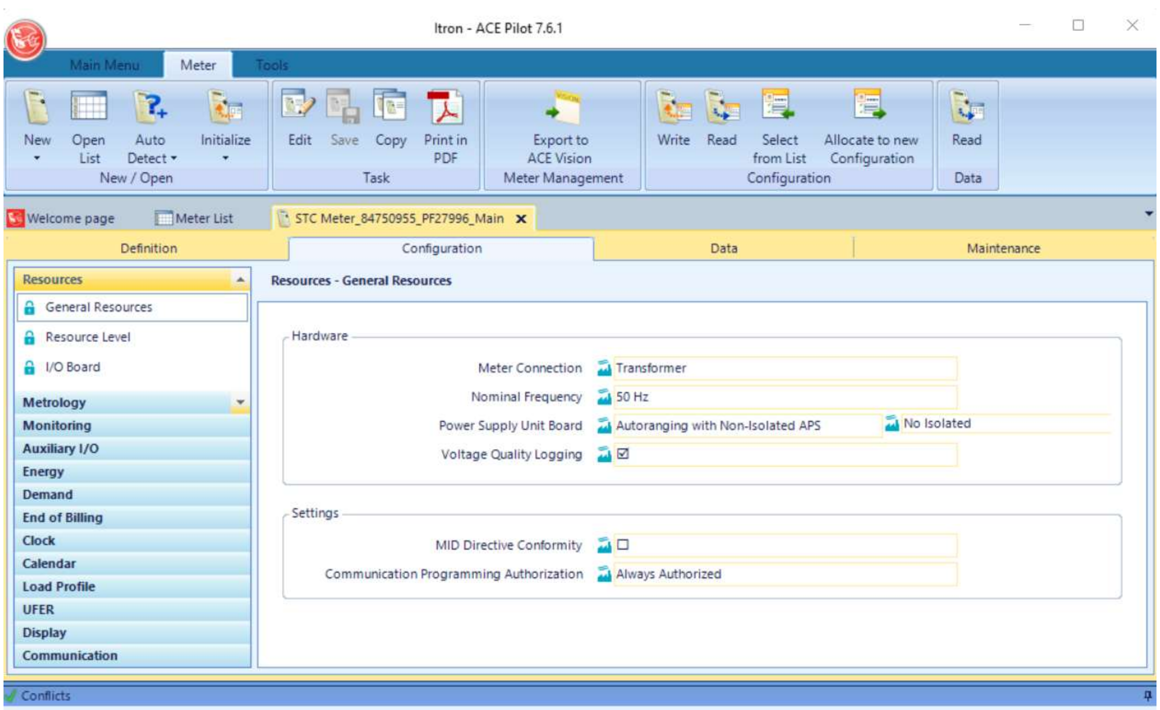


**Figure A.3: Electricity meter and software – SL7000/ACE Pilot (Itron, 2020)**

## Appendix A.4: Types of electricity meters and metering software – Hexing


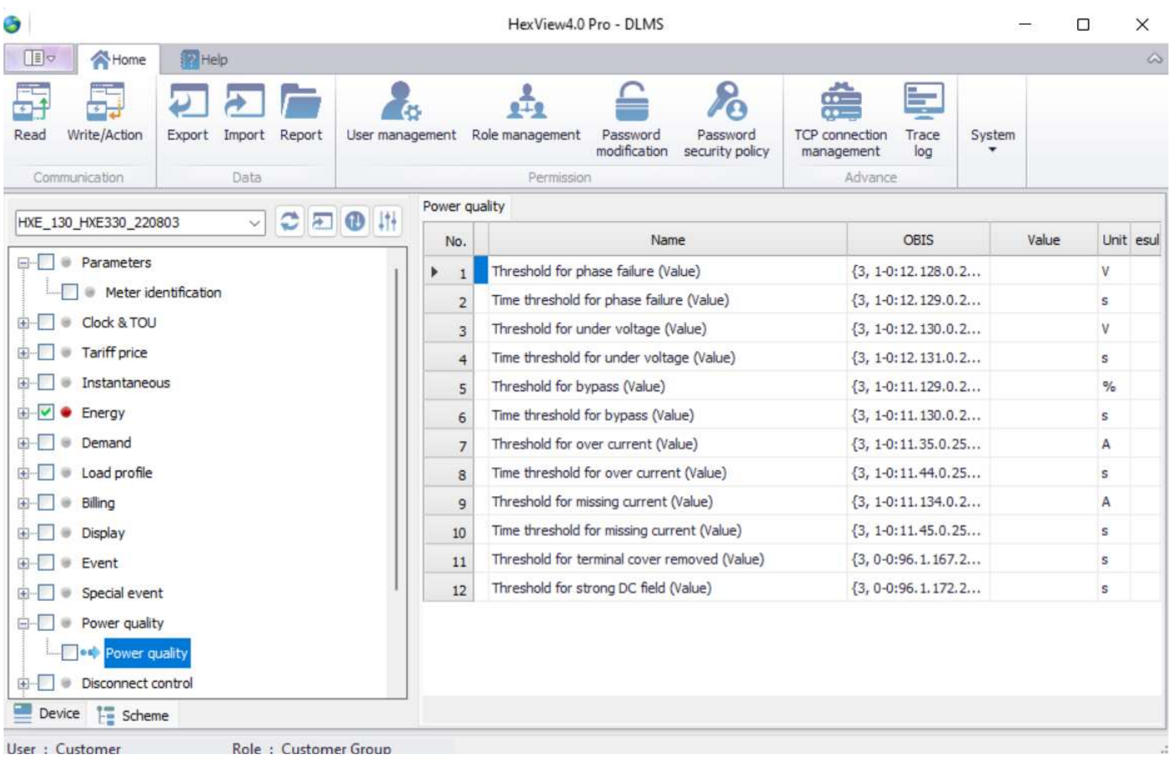


**Figure A.4: Electricity meter and software – HXF300/HexView ()**