Verification procedures to ensure consistent energy measurements

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It all starts here ™

ABSTRACT

Title: Verification procedures to ensure consistent energy measurements

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The majority of energy conservation measures (ECM) implemented by South African Energy Service Companies (ESCOs), are funded by the Eskom Demand Side Management (DSM) initiative. In 2013 Eskom reported a total DSM savings of 595 MW. To measure this effect power usage data needs to be recorded. A slight variance with the accuracy of measurement will however have a significant impact on the reported savings. It is therefore of critical importance to ensure consistent energy measurements throughout the life cycle of the ECM.

A literature study was conducted in order to investigate the individual effects each step of the measurement process contributes toward the overall accuracy. Components investigated include instrumentation transformers, the ADC process and the different signal processing techniques available. The study also investigated different power loggers and their impact on the overall accuracy.

The study found that each component has the potential to affect the accuracy of the measurement. However, the most significant risk to accuracy was not any specific component, but rather the process of installation and setup of the equipment. This prompted the development of a new procedure to address the verification of measurements. The verification procedure consists of three main parts namely, Verify measurements of temporary power logger (1), Evaluation of data recorded (2) and Verification of permanent power logger (3).

The first part verifies the accuracy of the temporary power logger and assists with initial installation on site. Part two focuses on verifying the measurements of the temporary power logger with independent data. It then uses the temporary power logger to verify the measurements of the newly installed permanent power logger. The third part verifies the measurements of a permanent power logger post-implementation of the energy conservation measure.

The new verification procedure was tested on several industrial projects. The procedure identified an omitted load of 1 MW with a potential annual cost impact of R 4.8 million. The procedure also identified several examples of incorrect CT ratios amounting to a combined daily error of 3.4 MW were also identified. This relates to a direct impact of R 16.3 million for the project stakeholders per annum.

There is currently no procedure in place which mentions the need to compare the pre- and post-implementation data. This highlighted the importance for a new verification procedure. Case studies were used to verify the new procedure which was then validated by comparing theoretical calculations and installed capacity ratings. The verification procedure had a significant impact on the overall accuracy ratings of the projects.

ACKNOWLEDGEMENTS

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Thank you to TEMM International (Pty) Ltd and HVAC International (Pty) Ltd for the opportunity, financial assistance and support to complete this study.

In the words of Tennesee Ernie Ford, "Load sixteen tons, what do you get? Another day older and deeper in debt. Saint Peter don't you call me, cause I can't go, I owe my soul to the company store".

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analogue to Digital Conversion
CFL	Compact Fluorescent Lamp
CT	Current Transformer
CVT	Capacitive Voltage Transformer
DSM	Demand Side Management
ECM	Energy Conservation Measure
ESCOs	Energy Service Companies
IEC	International Electro-technical Commission
M&C	Marketing and Communication
M&V	Measurement and Verification
PC	Personal Computer
RMS	Root Mean Square
SCADA	Supervisory Control and Data Acquisition
ST	S-Transform
STFT	Short Time Fourier Transform
THD	Total Harmonic Distortion
VT	Voltage Transformer
WT	Wavelet Transform

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CHAPTER 1

"If you can't explain it simply, you don't understand it well enough." – Albert Einstein

1. INTRODUCTION

1.1 Demand side management background

The majority of energy efficiency projects implemented by Energy Service Companies (ESCOs) in South Africa, are partially or in some cases fully funded by the Eskom Demand Side Management (DSM) initiative [1]. The Eskom DSM office with the collaboration of ESCOs identifies energy savings opportunities in allocated Eskom DSM sectors. There are three major Eskom DSM sectors, namely residential, commercial and industrial, which focus on energy usage. The intention of DSM projects is to positively affect the pattern and/or amount of electrical energy used by the consumers [2]. Where some of the main objectives of the energy efficiency projects are:

- Reduce costs of electricity generation thereby improving efficiency

- Decrease the rate of scarce resources used to generate electricity (coal and water)

- Reduce greenhouse gas emissions

- Create jobs through development of ESCOs

- Ensure the sustainability of implemented energy savings projects

The DSM initiative in South Africa consists of the following components [3]:

- Policy and legislative aspect which are government driven

- Funding component

- Marketing and Communication (M&C) campaign

The funding component as well as the M&C campaign are administered and lead by the Eskom DSM initiative. The goal of M&C is to create sustainable projects whilst at the same time generating awareness of energy efficiency projects.

There are two strategic options that are supported by Eskom DSM for energy efficiency projects. The strategic options are namely, energy efficiency and load management initiatives. Energy efficiency, represented in Figure 1, strategies implemented improve the overall energy usage throughout the day. The idea behind this strategy is to use less electrical power while maintaining the same benefits, thereby not negatively affecting production.
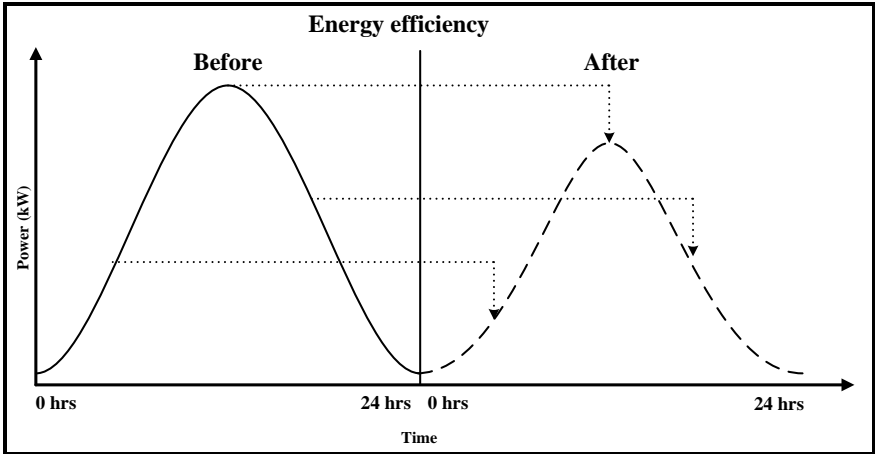
Figure 1: Energy usage made more efficient [1]

Load management consists of the following three strategies; load shifting, peak clipping and valley filling. Load shifting, represented in Figure 2, consists of moving a load out of Eskom's peak electricity periods to off-peak periods. The overall electricity usage for the end user remains the same with the load shifting strategy. The consumer also benefits financially as the majority of the electricity usage is during off-peak periods, where the price per kWh is less than it is during peak periods.
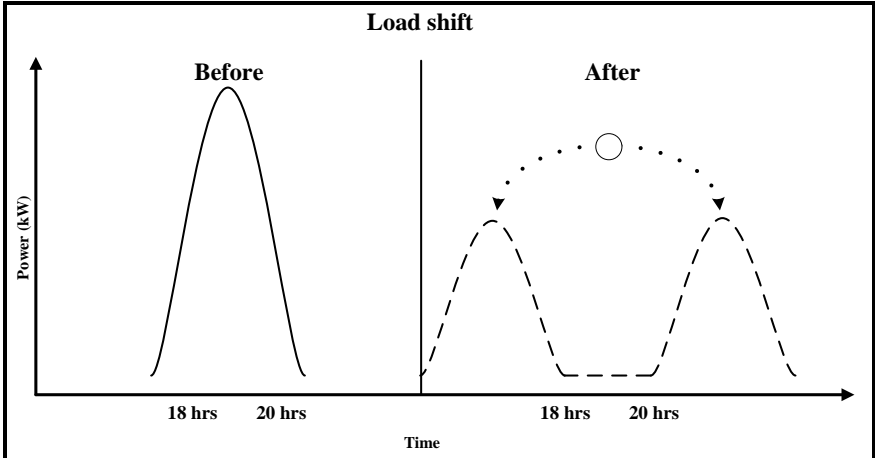
Figure 2: Energy usage moved to different times [1]

Peak clipping, shown in Figure 3, consists of reducing the peak period load, thereby reducing the electricity demand.
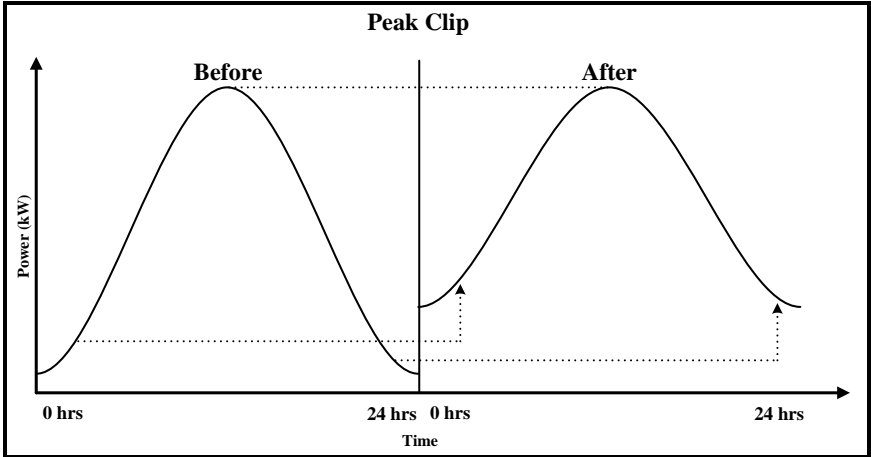
Figure 3: Energy usage shifted to off-peak periods [1]

Figure 4 represents the valley filling strategy, where the off-peak loads are strategically increased instead of increasing the peak load. Once again this strategy will benefit the consumer financially and Eskom as the peak load is not increased.
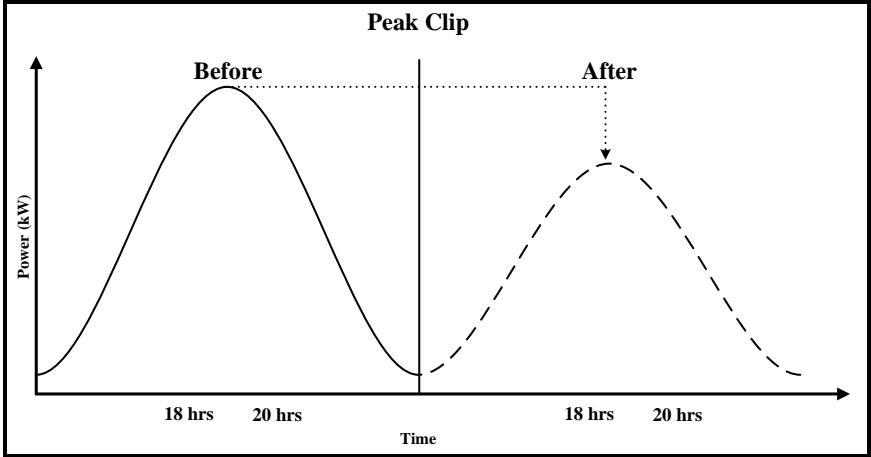
Figure 4: Increasing energy usage during off-peak periods instead of peak periods [1]

In order to understand how the power savings is reflected during the energy savings initiative, it is important to understand the life cycle of the initiative. First power usage data is collected, which will later be used to calculate the power savings for the project.

1.2   The life cycle of a project

In order to measure the effects of the energy strategies that are implemented [4], pre-implementation and post-implementation energy data needs to be recorded. Pre-implementation energy measurements will be processed to represent a typical 24 hour profile of the energy consumed. This is otherwise known as the baseline report, which takes place during the baseline development period. The post-implementation measurements record the overall energy usage on site after the energy management strategy has been implemented. Figure 5 is a basic flow chart that represents the life cycle of an energy project.
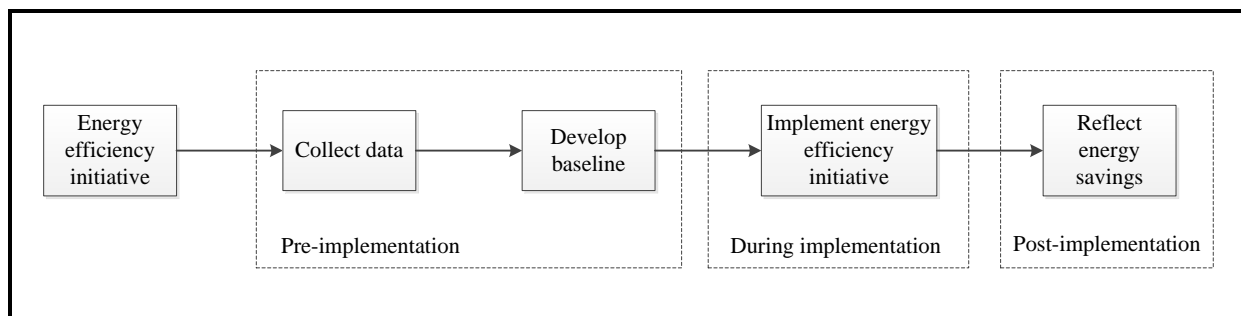
Figure 5: Life cycle of an energy efficiency project

Any energy management projects will include a life cycle that contains a before, during and after implementation stage. Figure 6 represents the way in which the different stages of the life cycle affect each other, as well as the purpose of the energy savings initiative (highlighted with thicker arrows in Figure 6).

The different stages of the life cycle are explained below [5]:

- **Pre-implementation**

   The baseline development period measures and records power usage before implementation. This process consists of gathering power usage data from all sources available. In some cases power data is not recorded electronically and is only obtainable from log sheets and/or from chart recorders. The process is important as the baseline cannot be developed after the energy intervention, as changes have been made to the system.
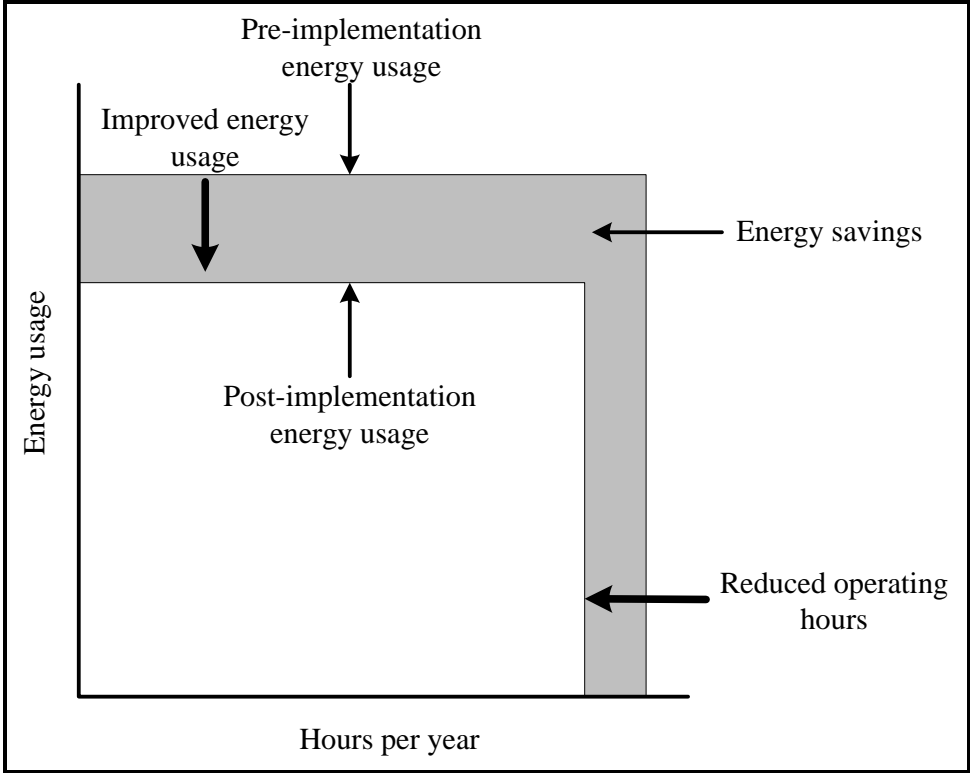
Figure 6: Energy savings reflected against the life cycle of a project [5]

- **During implementation**

  After all installations for the energy savings initiative are complete, the new equipment needs to be commissioned. The commissioning process ensures that the equipment is installed and functioning correctly.

- **Post-implementation**

  This stage of the project occurs after the necessary installations have been completed. It is used to reflect whether the implemented energy conservation measure (ECM) initiative can achieve its predicted power savings. Therefore no further installations are required.

Protocols have been setup to govern the method of recording and reflecting the power usage data. One of the protocols is described below.

1.3   Measurement and Verification

1.3.1   Background

The process of Measurement and Verification (M&V) includes determining the overall degree of measurement accuracy, which all stakeholders need to agree upon [6]. The stakeholders include the ESCO, the utility company (Eskom) and the client (consumer). The objective of involving an M&V team is to ensure an impartial and credible view of the impact that the energy savings initiative achieves. This process must be repeatable in order to apply it to numerous similar energy initiatives.

ESCO's and the client seek to financially benefit from the implementation of the energy saving projects. ESCO's or the clients generally identify the potential for energy savings projects. It is therefore necessary that the impact of the energy savings initiative is objectively determined by an outside third party, hence the M&V team.

The overall purpose and reason for involvement of M&V teams is to [5]:

- Accurately reflect the energy savings

- Reveal risks to respective stakeholders

- Decrease unknown variables

- Monitor equipment performance

- Investigate additional savings

- Increase productivity and maintenance initiatives

- Verify achieved energy savings

- Include the possibility of future adjustments

Recorded data is generally verified by reflecting the energy savings against the production data. The M&V team needs to adhere to certain codes and laws regarding the accuracy of all measuring equipment and data recorded.

The M&V team is responsible for the baseline development of the project. They need to ensure that the data used, accurately reflects the true power usage of the energy savings initiative. An accurate reflection of the power used is important to ensure that neither the ESCO, client nor Eskom is negatively affected when it is reported.

There are numerous types of energy savings projects that ESCOs can implement. In order to level the process of all the energy measurements, which is used later to reflect the energy savings, a specific standard needed to be setup. Pre- and post-implementation energy data can be determined using four different M&V methods mentioned in numerous M&V guidelines including report [7]. Once the necessary data has been collected, using one of the methods, the savings can be reflected and reported. It is important to reflect the true energy savings in projects as ESCOs are generally paid according to the savings generated.

Some of the standards that all ESCOs have to follow will include baseline development, CT, VT and power monitor accuracy standards, correct installations for different network configurations, available memory and housing for the energy meter. A procedure that is internationally used and recognised is the M&V process [8], [9] and [10]. The M&V process for energy management projects is widely used to reliably reflect the actual energy savings for a project.

1.3.2   Baseline development and calculating energy savings

To develop an accurate baseline model all aspects that affect the project need to be reflected. Factors that should be included in the development process are namely any independent variables, static influences and energy data.

Independent variables are circumstances or conditions that neither the ESCO nor the client can control. For example ambient temperature will have a direct effect on the power consumption of a fridge plant on a mine. The static influence of energy usage also needs to be accounted for. This will include the development of specific winter and summer baselines for projects. It will also include any adjustment in the baseline for equipment that could not be measured during the baseline period.

The baseline is used to calculate energy savings once the energy saving intervention has been implemented. There is no method to reflect energy savings after the implementation of an ECM

without a baseline. Figure 7 represents the baseline development period and reporting period which contains an adjustment to the baseline. Baseline adjustments are usually caused by either static influences or independent variables that may have changed.
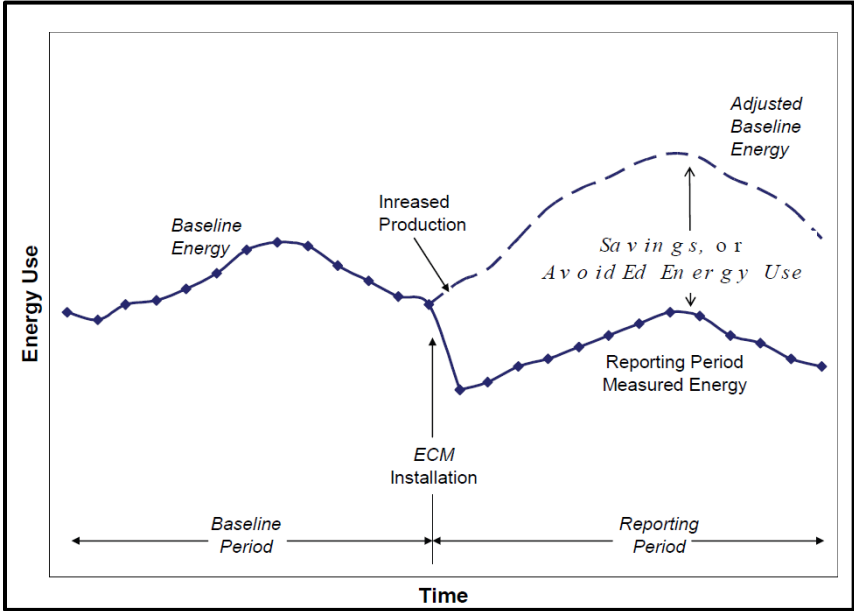
Figure 7: Baseline and reporting periods in an energy conservation measure [7]

The savings is calculated using a standard formula regardless of the baseline adjustment during the reporting period. The formula is:

$$E_{savings} = E_{baseline} - E_{usage} \pm Adj \qquad \qquad (1)$$

Where:

$E_{savings}$ = Calculated energy savings after ECM (kW)

$E_{baseline}$ = Measured energy baseline, before ECM (kW)

E_{usage} = Current energy consumption, after ECM (kW)

Adj = Any adjustments that need to be accounted for after original baseline development (kW)

Energy savings is calculated using pre-implementation power usage data, which is compared against data after the energy savings initiative, is implemented. There are numerous methods that

have been developed over the past 100 plus years to record power usage data. Each method has its own level of accuracy and its own dependencies, which is discussed next.

1.4 Methods used to record power usage

1.4.1 Log sheets

One of the earliest methods used, and is still in use today, is log sheets. Log sheets rely strictly on human interaction where values are generally recorded in hourly intervals. Recording at hourly intervals has its disadvantages as an accurate average over the interval might not be reflected. If an electrical motor is started half way through the hour the log sheet will not reflect the correct average, instead it will show that the motor has been on or off for the entire hour. This method really measures the instantaneous electrical power used on the hour.

However this method can be used to verify power measurements from different sources, as stated in [11]. The differences in measurements recorded and reflected against log sheets can be due to the low resolution (hourly intervals) of the log sheets. The low resolution does not always account for fluctuations in the data, but this can attribute towards a stable dataset.

Log sheets are also dependent on human interaction. It is easy for the person recording the data, to omit an hourly interval. This directly affects the quality of the data being recorded. However the accuracy of the data whilst using this method is not essential as it is generally used to reflect operating hours for the equipment.

1.4.2 Chart recorders

Chart recorders have been used since the early 1890s [12]. There are numerous different types of chart recorders, examples are shown in Figure 8. A chart recorder is defined as a device which produces a permanent representation of the analogue signal it is recording. The recorded analogue signal can either be intermittent or continuous. This ensures a higher resolution for the dataset as the overall average power usage is recorded throughout the day. It will reflect the total power usage for the day and will show when and if an electrical machine has been turned off.
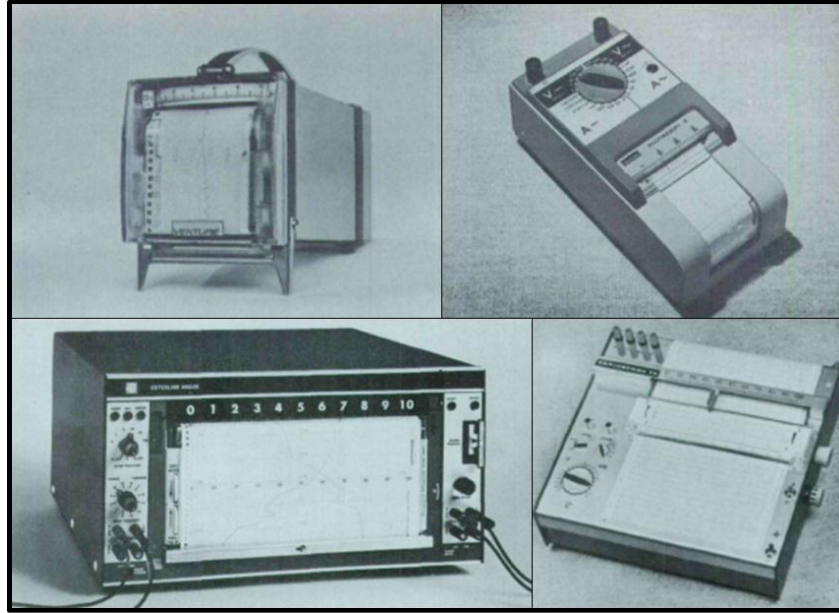
Figure 8: Example of different chart recorders used from 1870 [12]

The only human interaction required with this method is to change the chart paper once it has been filled. The main disadvantage with the log sheet method and the chart recorders is the difficulty in electronically processing the data. All the recorded power data needs to be manually typed into a computer program for electronic processing.

1.4.3   Power loggers

Power loggers are generally used to record data that will be used to generate a typical power usage profile for the project. The data recorded is also used to reflect the power savings of the energy strategy. It is advantageous as the recorded data is generally electronically available. This makes processing the recorded data less time consuming and more accurate. Some power loggers can be installed for a short time period and others can be installed for longer periods of time.

The overall accuracy of a power logger is dependent on the whole system, represented in Figure 9. The way in which the logger is setup, the accuracy and age of the Current Transformers (CTs) and Voltage Transformers (VTs) used, as well as the overall accuracy of the power logger is crucial to the measurement accuracy.
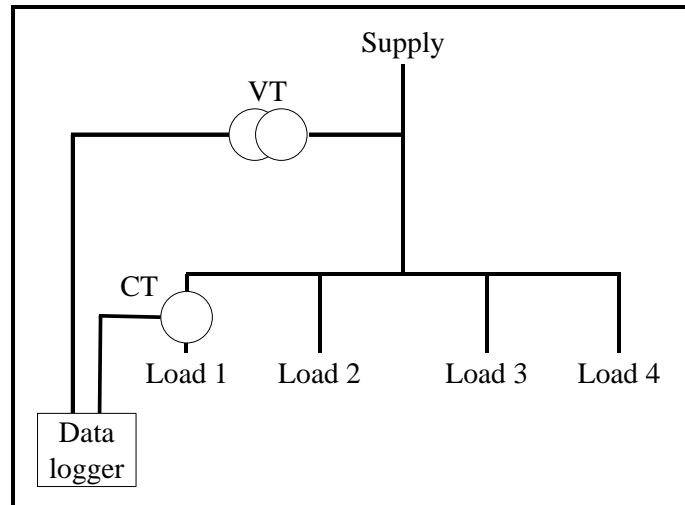
Figure 9: Overview of a single phase system for data loggers [13]

1.5   The effect of measurements in DSM projects

Measuring a projects' performance is crucial. It reflects the power savings a project is achieving and the cost benefit to the client. This reflects the feasibility of implementing the energy management project, as it is a factor of the payback period. The payback period is the length of time it will take for the electricity cost savings to effectively pay for the energy strategy.

If the power savings is measured incorrectly either the national electricity utility (Eskom) loses money or the client (mine) is paying more than expected. Some ESCOs are paid according to the electricity savings achieved during the project. If the energy metering is implemented incorrectly the ESCO might lose money and the energy strategy might not reflect its true savings potential.

For example a project has a baseline power usage of 20 MW, which is typical for an industrial project. The measuring equipment used has an overall measuring accuracy of 0.5%, which is fairly accurate. This means the measurement could either be negatively or positively biased by 0.5% of 20 MW, or +/- 100 kW. The 100 kW bias can result in an R 481 000 financial impact per annum, if it occurs over a 24 hour period. The ESCO, the client or Eskom can lose this kind of money yearly due to the effects of accuracy or lack thereof.

This might not sound like it could have a big impact. But if this happens in 10 different industrial projects, then 1 MW is not quantified through accuracy of the measuring equipment. This can almost be considered as a small energy savings initiative.

Bonesa [14] is an example used to reflect the gravity of one small energy initiative that was implemented, in the residential sector. It is a true representation of how strength comes in numbers. Bonesa was funded by the Global Environmental Facility and Eskom over a course of three years. The main purpose was to replace the traditional inefficient filament (incandescent) light bulbs with the more energy efficient Compact Fluorescent Lamps (CFLs), shown in Figure 10. Eskom DSM reported an average energy savings of 64 MW for 2004 as a result of this initiative alone.
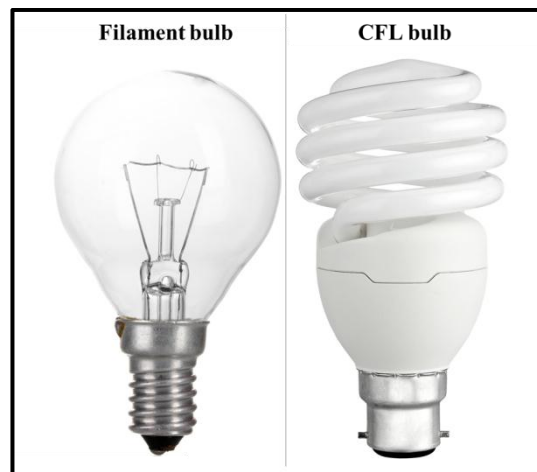
Figure 10: Example of filament[1] and CFL[2] light bulbs

The Eskom light bulb initiative replaced 4.5 million of the targeted 5 million fluorescent bulbs, during the second phase between 1 April 2013 – 30 September 2013 [15]. The traditional filament light bulb uses an average of 100 W, which is small. After replacing 4.5 million light bulbs Eskom saved a verified 17.7 MW. The first phase of this initiative saved a verified 81 MW in a period of six months.

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[1]Image taken from http://www.butlerrural.coop/content/incandescent-lighting
[2] Image taken from http://www.johnlewis.com/home-garden/lighting/light-bulbs/view-all-light-bulbs/cfl=lightbulbtype-lightbulbs-6000031120/c700006520/pg-view-all

When one considers the impact that small energy saving initiatives can have, then the overall accuracy of the measuring equipment cannot be ignored. "You cannot manage what you do not measure" – Jack Welch, CEO of General Electric [4].

1.6 Overview of dissertation

The first chapter focuses on background information for the different parties and aspects that are involved in the life cycle of an energy savings initiative. It highlights the importance of accurately measuring power consumption.

It is suspected the overall measuring accuracy is fundamentally related to the setup and installation of the measuring equipment used. Before this can be proved, all the characteristics of the different components used to measure energy need to be investigated.

In order to understand the individual effects which each component contributes towards the overall measuring accuracy, a literature study was carried out in the second chapter. The accuracy of each component used to record energy usage was investigated. Components investigated include CTs, VTs, Analogue to Digital Conversion (ADC) process and the different signal processing techniques available. Introductory information was used for each component to provide the reader with a thorough background of the components.

The third chapter presents a verification procedure that will help identify common issues that can affect the measuring accuracy. The procedure focuses on the setup and installation of the components mentioned in the second chapter. It also presents a procedure to verify the measurements of temporary power loggers, in hope to improve the accuracy of the results during baseline investigation period.

Whilst the investigation was underway common issues were identified, using the proposed procedure, and is presented in the fourth chapter. This chapter focuses on the setup and installation of the power loggers used to measure energy usage. It highlights the importance of data validation and verification during the life cycle of the project.

The conclusion for the study is drawn in the fifth chapter. The results are summarised and future recommendations for the study are mentioned.

CHAPTER 2

"Imagination is more important than knowledge. Knowledge is limited; imagination encircles the world" – Albert Einstein

2. MEASURING ENERGY

2.1 Introduction

In order to question the accuracy of any data capturing process, the entire system needs to be viewed. Figure 11 represents a breakdown of the general data capturing process for power measuring systems. The process consists of voltage and current transformers, power loggers, analogue to digital (ADC) conversions and signal processing techniques.
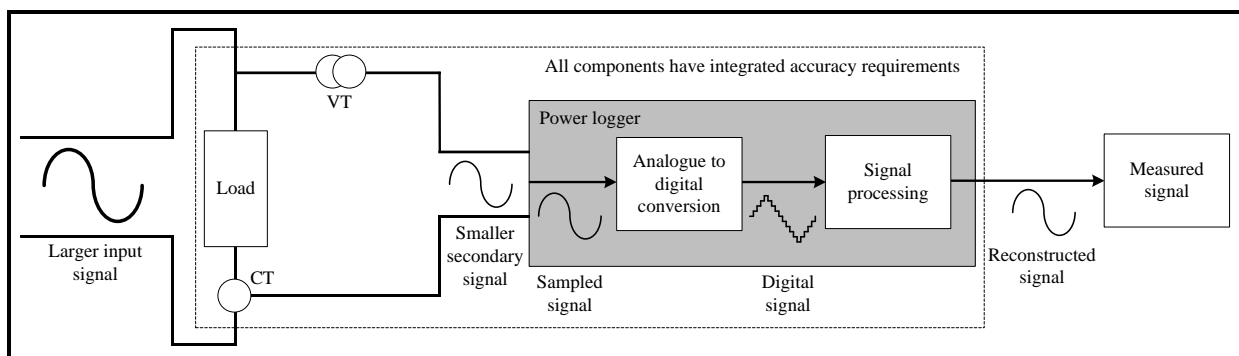
Figure 11: Overview of data capturing process

Instrumentation transformers used with power loggers consist of current and voltage transformers. The purpose of the instrumentation transformers is to reduce the high currents and voltages in order to measure them at safer levels. Instrumentation transformers are susceptible to certain issues such as, insolation aging, over burdening and saturation that may affect their accuracy. There are however a few solutions that one can implement to help reduce the impact of the issues. Solutions include the addition of external circuitry and development of specific algorithms.

The accuracy of the power loggers which are used is also a vital part to consider. All digital power loggers will need to do an ADC. The accuracy and precision of the ADC is dependent on the quantisation levels available and whether the correct ADC input range was chosen.

Once the signal has been digitised, different types of signal processing techniques are used to reconstruct the waveform that is being measured. The different types of techniques used differ in

speed, ease of implementation and sensitivity. In some cases numerous techniques need to be used to calculate the different characteristics (RMS, average, peak, etc.) of the input waveform.

The various accuracy requirements are governed by the M&V and Eskom protocols. The protocols suggest particular accuracy requirements for the instrumentation transformers that are used for numerous circumstances. It also suggests that particular tests and calculations are carried out to ensure the accuracy of the measurements.

Total Harmonic Distortion (THD), unbalanced phases, wye and delta connections may influence the accuracy of the power data reading. For the purpose of this study only the measuring process will be researched. The effect that errors in signals have on the data will be neglected. It is therefore assumed that the signal measured has little to no errors and will not affect the accuracy of the reading.

2.2   Components used to measure energy

2.2.1   Instrumentation transformers

Introduction to Current Transformers

CTs consist of a magnetising core, primary and secondary windings. They are used in two different applications in AC electrical circuits, namely for protection and metering purposes [16]. Protection CTs are used to recognise faults in circuitry, if a fault occurs it can isolate the circuit via use of a relay. Protection CTs isolate the circuitry in the case of high (peak) currents and therefore sacrifice accuracy [17]. Protection CTs need to maintain a reasonable accuracy as well as linear readings over a wide current range [18].

Metering CTs need higher accuracy requirements as they are used to measure and record current in the circuitry. Due to the higher accuracy requirements they generally do not handle high (peak) currents and tend to focus on smaller current ranges.

Figure 12 represents a fundamental circuit for CTs, it illustrates the way in which CTs scale down a high primary current ($I_{Primary}$) to a lower secondary current ($I_{Secondary}$) within a general region of 0A -5A [19]. This makes readings more practical and safer.
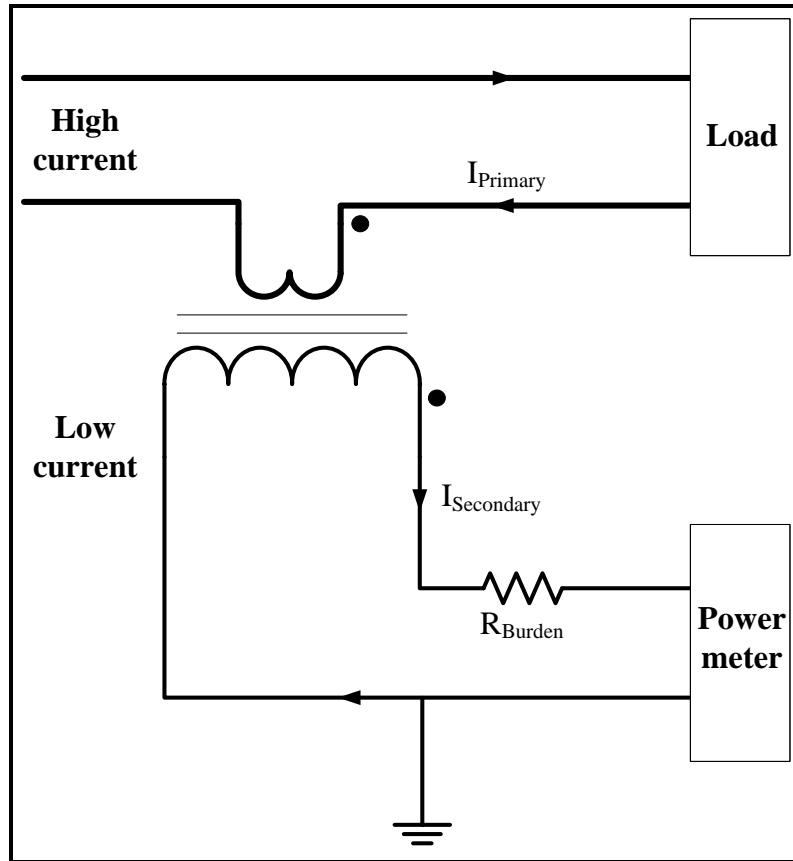
Figure 12: CT fundamental circuit [3]

The primary and secondary currents are related to one another via a turns ratio. A wire is wrapped around the primary and another on the secondary side of the magnetising core, which is represented in Figure 13. Where the primary side consists of the measured high current load and the secondary contains the lower current output. Each side (primary or secondary) of the core has a specific number of turns or windings. There is no physical connection between the primary and secondary windings, as it is purely based on magnetic fields (flux) [20].

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[3]Image adapted from http://www.scribd.com/doc/27914215/Basics-of-CT-and-PT
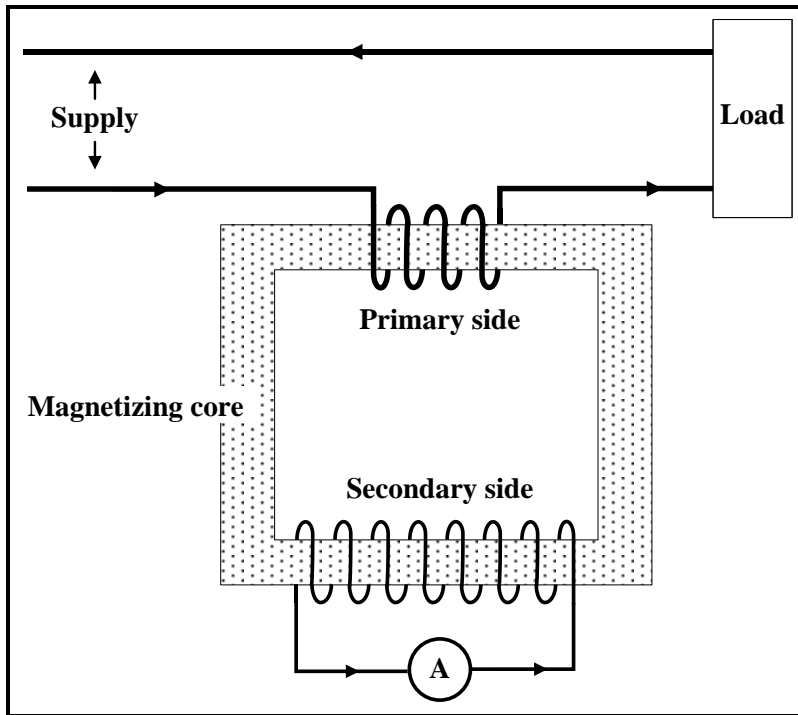
Figure 13: CT windings on a core [4]

The turns ratio effects the magnitude of the current on the output (secondary side), where primary and secondary currents are linearly related under normal conditions. Majority of measuring CTs only have a single primary winding, where the load is simply used as a single winding.

Figure 14 represents the primary and secondary windings on a solid magnetising core. The conductor (load) that passes through the middle of the core acts as a single turn on the primary side. Current which passes through the core induces a potential difference (voltage) across the secondary windings. The secondary voltage induces a current on the secondary side, which is related to the primary current via a turns ratio.

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[4]Image adapted from http://www.scribd.com/doc/27914215/Basics-of-CT-and-PT
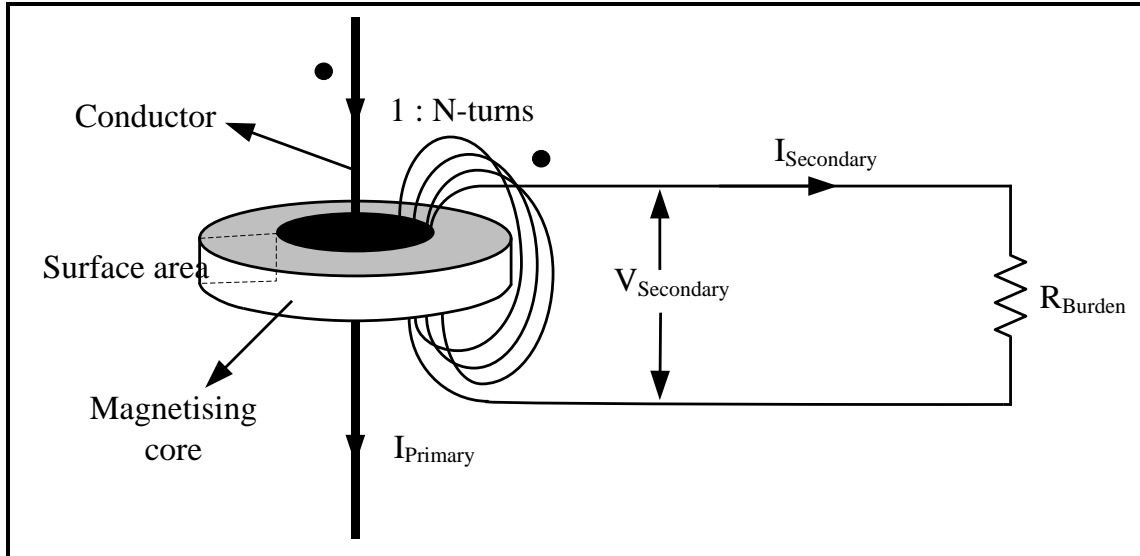
Figure 14: Fundamentals of a CT [15]

Equation 2 represents the relationship between the primary and secondary currents, which is related by the turns ratio. Turns ratio is the inverse amount of turns on the secondary winding, if the load conductor is not turned around the CT.

$$I_S = \frac{I_P}{N_R} \qquad (2)$$

Where:

I_S= Secondary current (A)

I_P = Primary current (A)

N_R = Rated turns ratio

Accuracy of the CT refers to the error in the current measured on the secondary side. The error is comprised of the effective turns ratio, the phase shift and whether the measurement falls within the linear region of the CT. Measuring phase shift is important when the CT is used to measure real power and power factor.

The accuracy of a CT is also directly dependant on the magnetic core used. Numerous materials are used to manufacture magnetising cores including; silicon steel, nickel alloy and ferrite cores.

Each core type has its own accuracy rating which is related to the material used and its price range.

The different type of materials mentioned above can be used to make either split or solid type cores. The major difference between the two cores is the ease of installation and price.

Split magnetising cores, shown in Figure 15, are easier to install as they can be temporarily opened. They are often referred to as open cores, it is therefore not necessary to disconnect the load when connecting the CT. If the load cannot be disconnected or turned off upon installation, then the CT can be temporarily opened and placed over a live primary conductor.

Figure 15: Example of a split type magnetising core [5]

Figure 16 is an example of a solid type core, often referred to as closed cores. The load needs to be disconnected in order to put the conductor through the solid core. They are generally cheaper, when compared to the split core. This is due to the manufacturing process being less complex, as it doesn't have an opening hinge which causes an air gap.

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[5]Image found on http://www.directindustry.com/prod/electrohms/split-core-open-loop-hall-effect-current-sensors-54132-367917.html

Figure 16: Example of solid type magnetising core [6]

Equation 3 shows the relationship the measured frequency, turns ratio, flux density and cross sectional area of the core has with the secondary voltage. The flux density is related to the type of material used to make the core. Cross sectional area is proportional to the thickness of the core.

$$V_S = 4.44\,FN_R BS10^{-8} \tag{3}$$

Where:

V_S = Transformed voltage on secondary winding (V)

I_S = Secondary current (A)

I_P = Primary current (A)

N_R = Turns ratio

F = Conductor frequency (Hz)

B = Flux density (T)

S = Core cross-sectional (m^2)

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[6]Image found on http://www.ayainstruments.com/solid_core_current_transformers.html

In any CT the secondary voltage is responsible for setting up the excitation current in the core and the current in the secondary side. The excitation current sets up the magnetising field in the core, whilst the current on the secondary side will pass through the measuring equipment.

It is important to note that the direction of the CT after installation needs to be correct. Polarity of the CT is crucial when it is used to measure energy usage. The measuring CT and VT should not measure signals that are more than 90° out of phase, when compared against one another. This will only happen if the CT is installed facing the incorrect direction. The direction that the protection CT faces is not as crucial, because peak and RMS values only need to be considered.

Table 1 represents a summary of the different types of CT outputs available along with the advantages and disadvantages thereof.

Table 1: Comparison of different CT types [19]

	Advantages	**Disadvantages**
5 A Output	• Industry standard • Readily available • Wide input range • Low cost (solid core) • Universal output	• High cost (split core) • Can be large and heavy • Limited range for small currents(< 50 A)
mA Output	• Highest accuracy • Low cost • Small • Safe output range	• Scale is dependent on metering equipment • Poor phase shift accuracy (split core) • Highly susceptible to burden for large current conductors
mV Output	• Low cost • Universal output • Safe output range	• Susceptible to noise • Lower accuracy • Poor phase shift accuracy • Only available in spilt cores • Fixed ranges

Accuracy requirements for Current Transformers

An international standard organization called the International Electro-technical Commission (IEC) has set standards for all metering devices. If a metering device has an accuracy rating of class 0.5, the device will have an absolute accuracy of +/- 0.5% of the full nominal rating. Absolute accuracy of all instrumentation transformers varies at the minimum and maximum ratings of the device. It is advised to use power meters which have a VA rating lower than 0.5 VA to help improve accuracy.

Furthermore all M&V guideline documentation have safety procedures that need to be followed when installing instrumentation transformers. In many cases the circuitry needs to be disconnected before installations. Please refer to reference [7] if any instrumentation transformers are to be installed.

All CTs have an apparent power (VA) rating. The higher the VA rating is the further a CT can be placed from the power meter. However as the VA rating for the CT increases the total accuracy decreases.

Accuracy requirements regarding CTs generally fall into two categories. The first category is when there are already CTs installed on site. The second category is when new CT needs to be installed on site.

It should be noted that it is not good practice to share CT circuits between different devices. If a CT is already installed in the correct position and is being used, then a 1:1 ratio (category one) CT can be installed on the existing secondary CT circuitry, as shown in Figure 17.
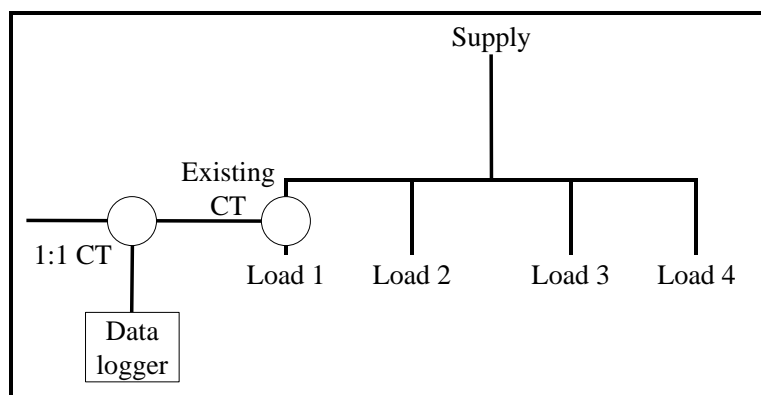
Figure 17: Installing a 1:1 ratio CT when existing CTs are available [13]

Specifications for category one CTs are:

- 1:1 current (A) ratio (primary current = secondary current)

- Class 0.5

- 2 VA or higher (refers to burden)

- Zero phase displacement (between primary and secondary current)

For the second category either solid type or split core CTs need to be installed on the input signal. Solid type CTs will be installed where the power cables can be disconnected on site. They are also generally cheaper and more accurate compared to the other types of CTs, because a higher VA rating can be achieved without affecting the accuracy.

Specifications for solid type CTs:

- 5 A secondary current rating

- Class 0.5

- 5 VA

- 600 V isolation

Split core CTs will be used in cases where the power cables cannot be disconnected from the load. They are generally more expensive and less accurate than solid type CTs.

Specifications for split core CTs:

- 1 A or 5 A secondary current rating

- Class 0.5

- At least 2 VA

All CTs need to adhere to strict wiring requirements in order to ensure accurate measurements. Wiring requirements for CTs include the wire thickness and length, the amount of other

connections between the CT and power meter. These requirements contribute towards the total resistance of the circuit. The following equations are used to calculate whether accurate measurements will be made after installation of the CT [13].

$$V_{Drop} = \frac{2 * V_{DropValue} * A * L_{cable}}{1000}$$ (4)

Where:

V_{Drop} = Total voltage drop across the wire (between CT and meter) (V)

$V_{DropValue}$ = Constant that is related to the thickness of the wire (V)

A = Maximum secondary current for the CT (A)

L_{cable} = Total length of the wire (between CT and meter) (m)
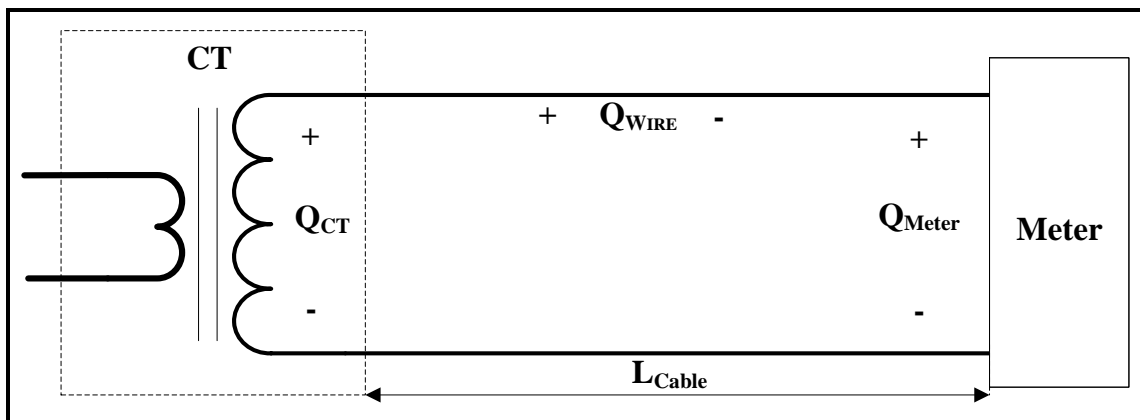
Figure 18: Basic circuitry for a CT anddata logger

The power summation of the circuit can be calculated using equation 5 [13].

$$Q_{wire} = Q_{CT} - Q_{meter}$$ (5)

Where

Q_{wire} = Available apparent power to drive the current (VA)

Q_{CT} = Apparent power rating for the CT (VA)

Q_{meter} = Apparent power rating for the meter (VA)

To find the potential difference the wire can handle in the circuit equation 6 was used.

$$V_{wire} = \frac{Q_{wire}}{I}$$ (6)

Where

V_{wire} = Voltage across CT wires (V)

Q_{wire} = Available apparent power to drive the current (VA)

I = Current in the wire (A)

To guarantee an accurate current measurement V_{Drop} should be lower than V_{wire}. If V_{Drop} is greater than V_{wire}, an improved accurate measurement can be achieved by either:

- substituting the power meter with another that has a lower VA requirement

- substituting the CT with another that has a higher VA rating

- use of a thicker wire in the circuit (between CT and meter)

Issues experienced with Current Transformers

There are a number of factors that can influence the accuracy of a CT. Factors such as; unbalanced lines, higher than expected currents and aged CTs can all lead to saturated secondary current waveforms [21]. The saturated waveform on the secondary side, affects the accuracy of the reading.

Aged insulation on primary and secondary wires on a CT can affect the overall accuracy. Insulation usually ages over time, but this process can be sped up when the CT is exposed to currents higher than its rated current. Other factors that influence the aging of the insulation (epoxy) are large changes in the ambient temperature, rapid changes in the load, mechanical vibrations and high temperatures [22]. Worn insulation on wires influence the effective turns ratio between the primary and secondary sides. This in turn results in a ratio error, when the primary and secondary currents are no longer proportionally related.

In normal operation of the CT the magnetising current can be neglected, however it does play a significant role with ratio error. Ratio error influences saturation effects in the core of the CT. Once the core is saturated the error produced increases significantly as the knee-point is approached or passed.

The knee-point, signified with a "K" in Figure 19, of a CT can be defined as the point where a 10% increase of the primary voltage results in a 50% increase in the magnetising current. For this to occur the CT core needs to be saturated, which can occur when the primary voltage is higher than rated voltage.

When the knee-point has been reached the effective turns ratio is no longer similar to the rated turns ratio. The rated turns ratio states the desired ratio between the primary and secondary currents. As the saturation of the CT increases, so does the magnetising current in the core. An increase in the magnetising current will in turn bring a difference between the effective turns ratio and the rated turns ratio. This results in a ratio error measured on the secondary side.
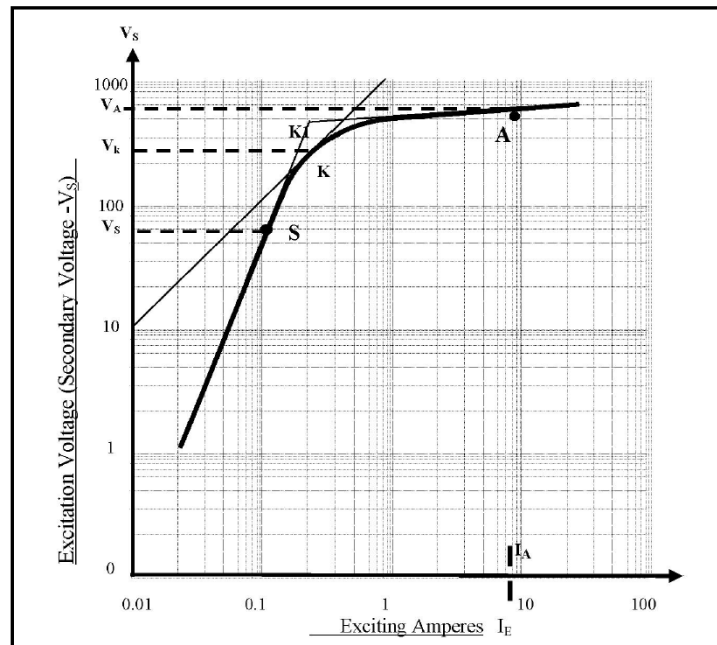
Figure 19: Knee-point on current transformer [16]

Distortion of the secondary current waveform can also be realised with the effects of burden on the CT [23]. The total resistance of the secondary side is related to the burden of the circuit. Total burden of the secondary side of a CT is affected by the total length of the wires between

the CT and power meter. Therefore the burden of the circuit would increase if the CT is installed far away from the power meter. CT saturation will be experienced when the effects of burden are too high.

The effects of burden can be seen in Figure 20, distortion of the secondary current waveform increases as the total burden of the circuit increases. If the total burden for the secondary circuit is too high the accuracy of the measurement will be affected.
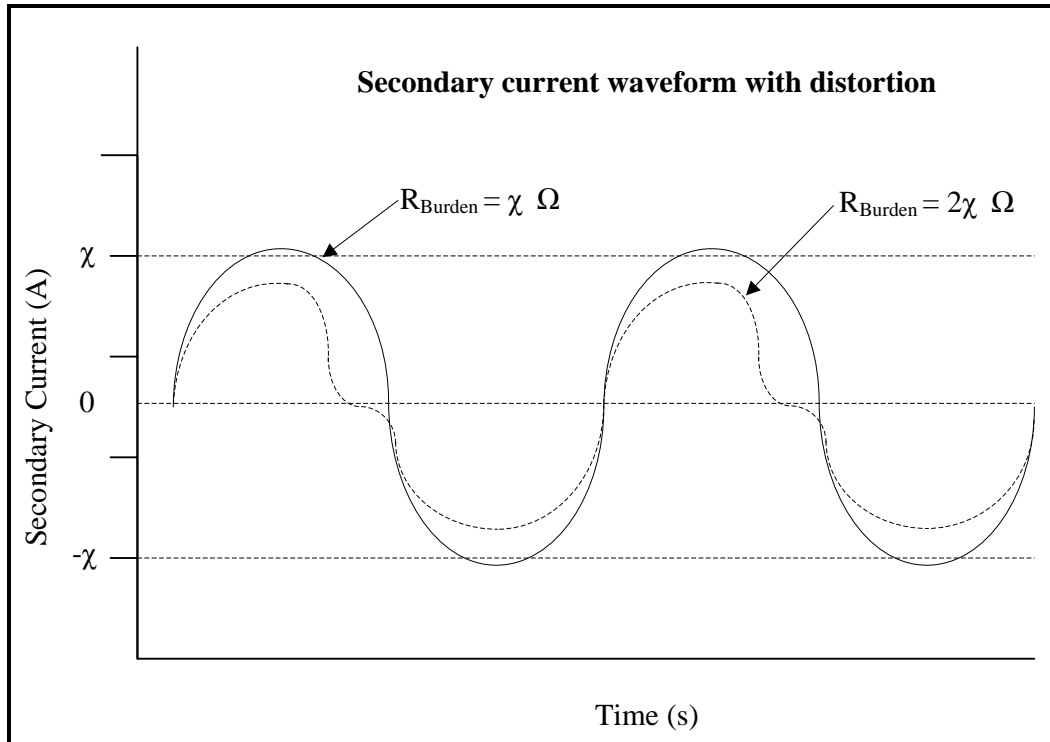
Figure 20: Distortion effects of burden on the secondary current waveform [23]

CTs can also be saturated at much lower primary current and voltage levels. This is caused by DC offset that is superimposed on the primary or secondary winding. The DC offset saturates the CTs magnetising core. It will also play a role in the saturation of the CT, because the average of the AC signal is not zero, which is demonstrated in Figure 21.
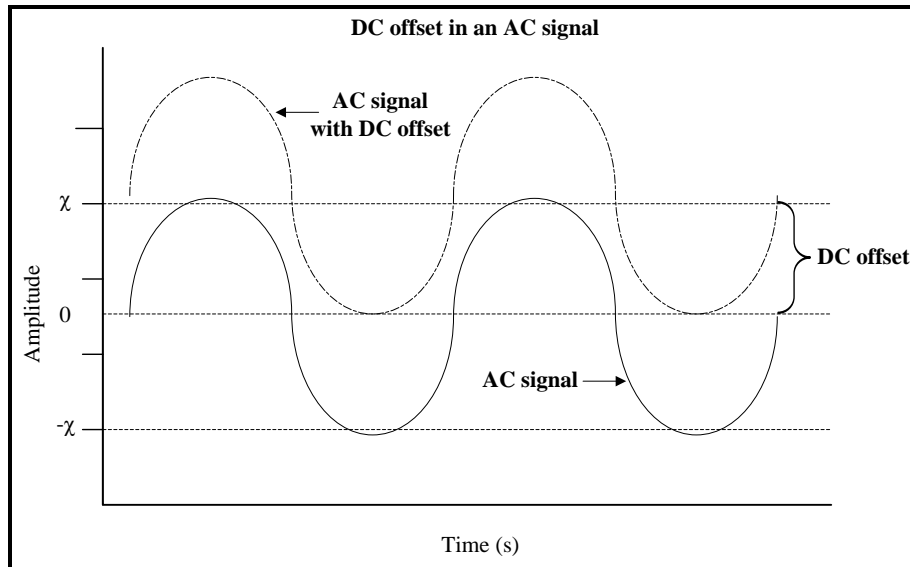
Figure 21: Example of DC offset in an AC signal [7]

Solutions for issues with Current Transformers

Compensation algorithms help resolve the effects of CT saturation. Each algorithm has its own reaction time, performance and additional circuitry if necessary. Plenty of these methods have been developed for maintenance issues experienced with CTs and can be found in but not limited to [20] [21] [24] [25]. A few examples of the developed and tested algorithms and circuits follow.

Figure 22 is an example of a distorted secondary current waveform. It can clearly be seen that there are two distinguishable parts to the waveform. Each period of the waveform consists of an unsaturated and a saturated part of the waveform. The unsaturated waveform is the ideal waveform. It is considered the perfect scenario with the highest accuracy. A saturated section of the waveform can be seen as it deviates from the ideal waveform, thus causing a reading with a lower accuracy.

Figure 22 also shows that the saturation effect of the CT reduces over time. As the saturation effect starts dissipating, the shape of the saturated waveform starts to replicate the unsaturated waveform. However the saturation effect does not disappear completely, the saturated points start to become repetitive in terms of placement. The repetitive nature of the distorted (saturated)

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[7]Image adapted from http://engineersphere.com/math/sine-functions.html

waveform can be used to reconstruct the ideal (unsaturated) waveform. Reference points can be determined after the waveform has differed from the ideal waveform (fault detection). The very first cycle of the waveform will not be considered, as a reference point, as the error is higher than the rest. The reference points that follow will be used to reconstruct the distorted waveform.
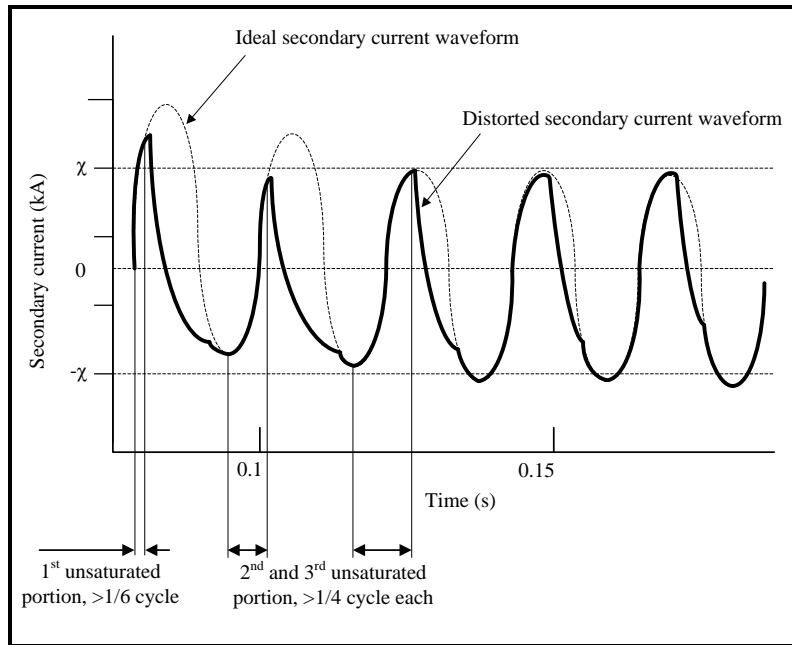
Figure 22: Distorted secondary current waveform [21]

The compensation algorithm mentioned above can be used effectively to increase the accuracy of a saturated CT. The algorithm is also easily adapted to different CT features and has been tested under various fault conditions. A flow chart of the way in which some compensation algorithms are implemented is shown Figure 23.
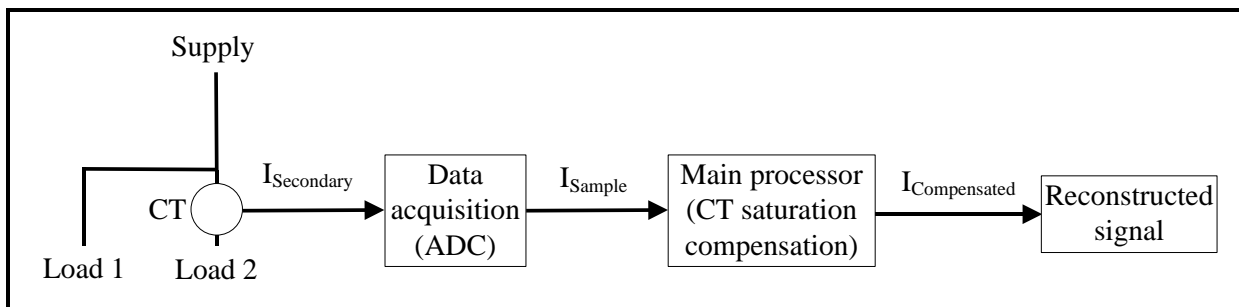
Figure 23: Compensation system for saturated CTs [21]

Other techniques can also be implemented to reduce the error in clamp on or split core CTs. Typical high accuracy instrumentation transformer design includes large magnetising cores, thick wires and even a technique which uses two magnetising cores and two secondary windings [26].

Larger cross sectional magnetising cores increase the impedance which reduces the magnetising current. Thicker wires reduce the series resistance of the secondary windings. The double magnetising core uses one secondary winding for magnetization purposes and the other for measuring. This design has a disadvantage though, as it makes the CTs bulky, heavy and expensive, when high accuracy is required.

Bulky CTs can make temporary installations more difficult, the design solutions to improve accuracy mentioned above are therefore not viable. The solution mentioned in [26] does not need a special magnetising core design or any fundamental changes made to the CT.

The solution proposes to measure the secondary voltage and current in order to realise the magnetising current. It can therefore be used on any existing CT. This method can be used to improve the accuracy of split core CTs.

When electronic circuitry, shown in Figure 24, is added to the metering CT, the accuracy of the split core CT can be improved. Experimental results proved that the electronic circuitry can improve the accuracy of a conventional split core CT by 100 times [26]. The increased accuracy is valid for a current range of 0.5A to 50A and a burden range of 0Ω to 100Ω.
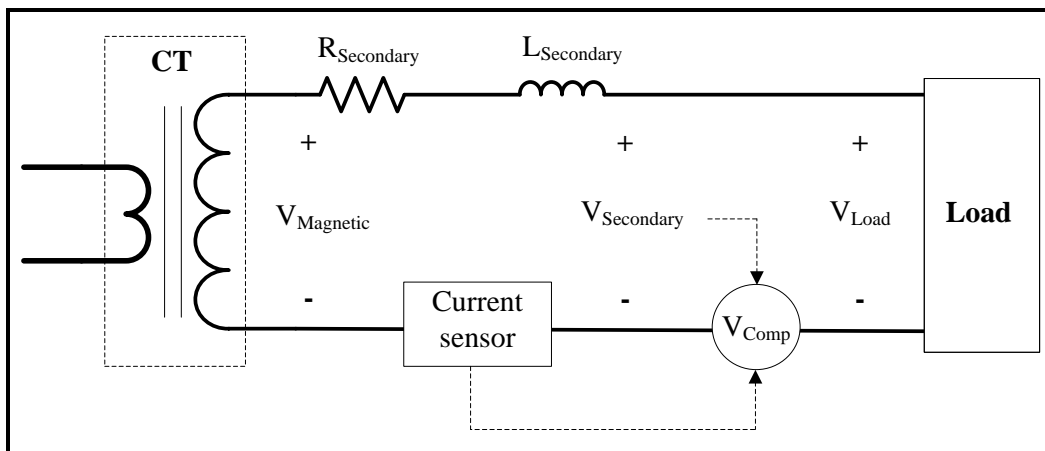
Figure 24: Simplified drawing of an error reduction system [26]

Introduction to Voltage Transformers

VTs are used to reduce and measure potential difference across the supply wires (conductor) [27]. They are also used to isolate and protect measuring equipment from the high voltages on the supply wires. There are, however, plenty similarities between VTs and CTs as the follow the same principles.

The primary difference between the two transformers is the way they are connected to the load which needs to be measured. VTs measure the potential difference across the supply wires. They can therefore be connected between the live and neutral wire, as shown in Figure 25, or between different phases. CTs on the other hand, are connected to a single wire as reflected in Figure 14, in order to measure the total current in the line.
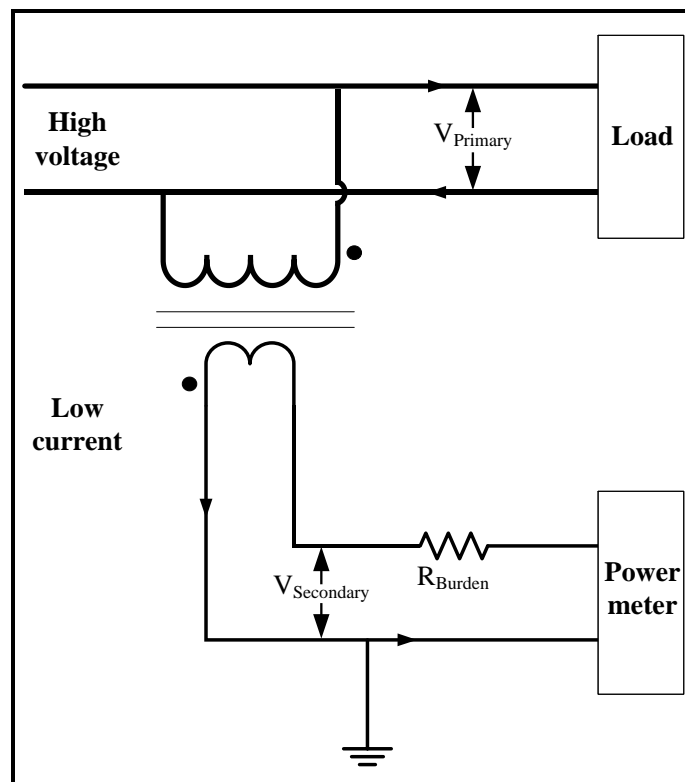
Figure 25: VT fundamental circuit [8]

In cases where the primary winding is subjected to high voltages it is generally cheaper to use Capacitive Voltage Transformers (CVTs). They are cheaper due to the smaller magnetic core

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[8]Image adapted from http://www.scribd.com/doc/27914215/Basics-of-CT-and-PT

that needs to be used when capacitors are implemented CVTs are generally not as accurate as the electromagnetic voltage transformers. The fundamental circuit of a CVT is shown in Figure 26.

Electromagnetic voltage transformers or voltage transformers (VTs) from here on, will be researched due to the higher accuracy characteristics. In order to obtain the high accuracy levels in VTs magnetic currents and secondary currents need to be kept as small as possible [28].
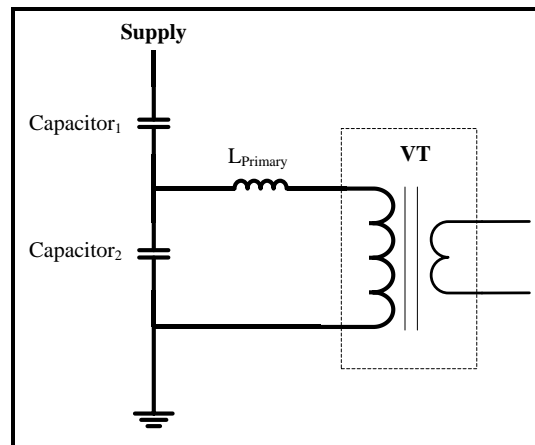
Figure 26: CVT fundamental circuit [9]

Due to the many similarities between CTs and VTs, the following section will not be as detailed as the CT section.

Accuracy requirements for Voltage Transformers

In cases where the voltage exceeds 400 V existing VTs should be used. When the voltage is 400 V or lower the VT can be connected directly to the power circuits. VTs and voltage meters have a high apparent power (VA) rating, typically, 50 VA and 8 VA respectively.

As with the CTs, when adding an additional VT to the metering circuit the additional burden needs to be considered. The addition of meters to the circuit may significantly affect the overall burden of the circuit. In order to calculate how long the terminals (wire) can be between the VT and power meter the same formulas used for CTs are used for the VTs. The only difference is that the length of the cable is calculated instead of a comparison of the voltage drop across the wire [13].

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[9]Image adapted from http://nikolaandi.com/nikola/capacitive-voltage-transformer/

$$L_{cable} = \frac{V_{drop}*1000}{V_{DropValue}*A*2} \qquad (7)$$

Where

V_{drop} = Voltage drop across the terminals should be smaller than the accuracy class of the meter (V) (Eg: Class 0.5 meter will have a V_{drop} of 0.318 V if the phase to neutral potential difference is 63.5 V)

Please refer to the equations above in Accuracy requirements for CTs for further definition of the different variables in the formula.

In the formula above the maximum secondary current (A) is calculated as follows:

$$A = \frac{VA}{V} \qquad (8)$$

Where

VA = Apparent power rating of the voltage meter (VA)

V = Phase to neutral voltage of the terminals (V)

If longer terminals are required between the VT and voltage meter one may need to consider using thicker wires.

Issues experienced with Voltage Transformers

All VTs can be susceptible to the effects of saturation, as all forms of transformers can be affected by it. Fault voltages will affect the accuracy of the voltage reading with both VTs and CTs, because the fault is generated from the source of the measurement. As the VT ages it also becomes affected by the ratio error. The VT however will have a ratio error regarding the primary and secondary voltages instead of the currents.

The error ratio for VTs can be calculated using the following formula, adapted from [17]:

$$R_{Error} = \frac{N_R V_s}{V_P} * 100\% \qquad (9)$$

Where:

R_{Error} = Ratio error

N_R = Nominal turns ratio

V_S = Secondary voltage (V)

V_P = Primary voltage (V)

Knee point saturation does not affect VTs as they generally operate far from magnetic core saturation [29].

To maintain the good accuracy characteristics of the VT the burden is kept large to keep the secondary current small. The exciting (magnetic) current of a VT is kept low by the high magnetising inductance of the core. This is a characteristic of the permeability and geometry of the magnetic core. The higher the permeability and larger the cross sectional area of the magnetic core, the more accurate the VT will be. This however makes the VT more expensive and bulky.

To improve accuracy of a VT without bulking the magnetic core up and without increasing the cost of manufacturing, some compensation algorithms focus on the hysteresis loops of the magnetic core.

Solution for issues experienced with Voltage Transformers

There are numerous compensation algorithms in use today which help reduce error in VTs. The compensation algorithm mentioned in [28] uses the hysteresis characteristics of the magnetic core. Hysteresis characteristics are subject to the material used to manufacture the magnetic core, such as ferrite and iron.

This compensation algorithm compensates for the error generated by the voltages across the primary and secondary windings. The voltage across the primary winding is dependent on the primary current, where the primary current is the addition of the secondary current with the magnetic (excitation) current. Secondary voltage is related to the secondary current.

The proposed method, mentioned above, calculates the potential differences across the primary and secondary windings of an iron core VT. To calculate the primary voltage the primary current is estimated using the core-loss current and magnetising current, which are properties of the iron magnetic core. Core-loss currents are associated with Eddy currents and resistance of the magnetic core. Whilst the magnetising current is estimated using a hysteresis loop similar to that shown in Figure 27. Hysteresis loop shows the relation between the flux linkage and magnetising current, in this case the flux is used to obtain the magnetising current.

The calculated primary and secondary voltages across the respective windings is then added to the measured secondary voltage. This new compensated voltage is then used to reduce overall error of the VT. This compensation algorithm meets the class 0.1 accuracy requirements.
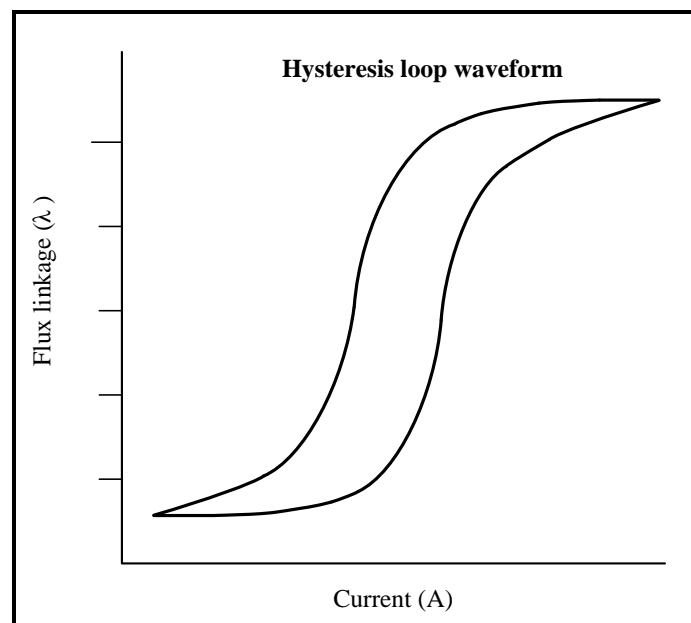
Figure 27: Example waveform of a hysteresis loop waveform [28]

2.2.2 Signal processing

Introduction to signal processing

In order to record and digitally store analogous signals an ADC needs to be implemented. The accuracy of the reconstructed analogue signal depends on numerous factors used in the ADC process [30]. It is crucial to use the correct sampling frequency, sample rate and signal

processing technique for the ADC to accurately reconstruct the analogue signal. It is therefore crucial to define what an analogue and digital signal are and what different types of signal processing techniques are available.

Analogue signals are defined as a continuous waveform that can have any value [30]. Figure 28 is an example of an analogue waveform, where the amplitude of the waveform can be any real number. A digital waveform, shown in Figure 29, can only take on a finite amount of values.
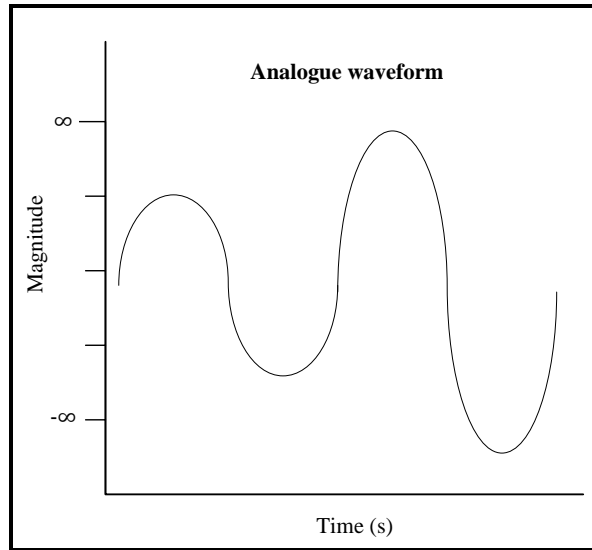
Figure 28: Example of an analogue waveform [30]
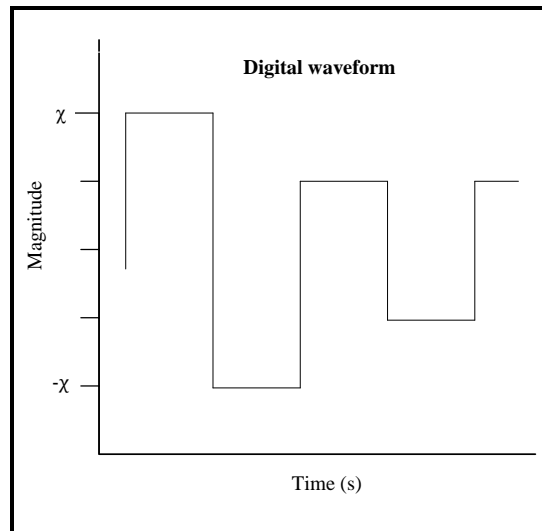
Figure 29: Example of a digital waveform [30]

The following terms need to be defined when considering the features of any measurements that are made. These terms all play important roles in defining measurements:

- Accuracy   How close the measured value is to the actual value

- Resolution   Is the smallest measurement that can be detected

- Precision   How often a certain measurement can be repeated when considering a finite amount of measurements

The overall accuracy of the ADC is dependent on the hardware used to capture the data [31], ie type of power logger used. Accuracy and resolution of the recorded data is specified by the manufacturers of the devices. Each measurement made by the ADC has to have sufficient resolution and accuracy.

An explanation of how an ADC works can be found in [30], as mentioned above an analogous signal can have an infinite amount values. A digital signal can only have a finite amount of values, which means analogue signals can be converted to digital through sampling and rounding off. Rounding off to the closest defined value is generally termed as quantisation levels, where quantisation is the approximation of a value, shown in Figure 30.
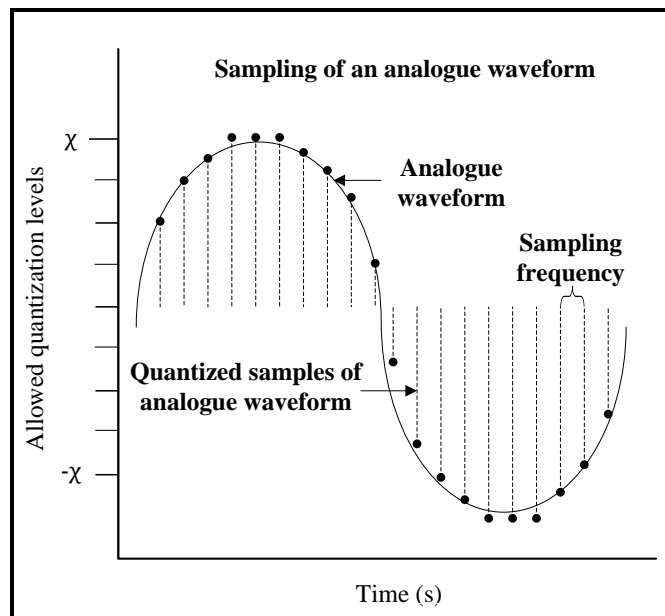
Figure 30: Quantisation levels of an analogue signal [30]

Figure 30 is an example of an analogous waveform that is sampled using a pulse. The frequency of the pulse is called the sampling frequency. The higher the sampling frequency the more digital information can be recorded of the analogous waveform. There are numerous waveforms used to sample continuous waveforms, the pulse is used here as a simple illustration.

Issues experienced with signal processing

Sampling of the analogue signal needs to occur at a specific frequency. If it doesn't meet a certain frequency criteria valuable information of the waveform can be lost. This is called aliasing. Figure 31 represents a reconstructed signal where the initial sample rate (frequency) is too low. To avoid losing important information, any signal should be processed at the Nyquist rate [30] or higher.
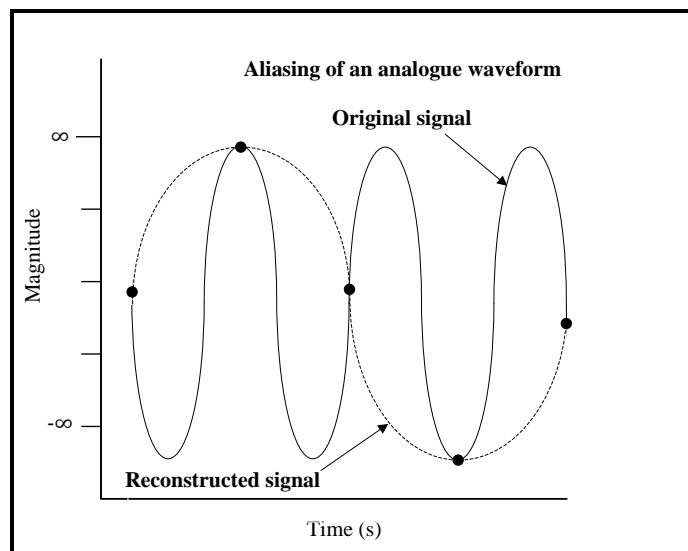
Figure 31: Example of aliasing on a signal

The Nyquist rate states that any analogous signal should be sampled at a rate of at least twice the frequency of the original signal. Anything below the Nyquist rate might cause aliasing and loss of vital information that could be used to reconstruct the waveform.

The above mentioned Nyquist rate is an example of a true theoretical analysis. In the real world rise and fall times of the pulse needs to be taken into consideration. Therefore for measurement purposes signals may need to be sampled at 100 or more times the Nyquist rate [31].

The hardware used for the ADC process needs to function in its region of linearity, whilst sampling the signal. There are two common issues related to the hardware used called clock and trigger jitter [31]. These errors, however, do not normally significantly affect normal operation unless the hardware is operating close to its rated frequencies.

The environment that the hardware (ADC circuit) is used in can affect the accuracy due to noise. Noise caused by the environment can be generated from nearby circuitry, lighting and higher voltage power lines. Once again, in most cases noise levels are not significant enough to affect the accuracy of the measurement. However, caution should be taken though to minimise the effect of noise, by implementing proper grounding techniques and using shielded wires and interconnects.

All ADCs are designed for an expected input range. Identifying the correct range the input signal will have is crucial for the overall accuracy. This is important because the infinite possibility of values, from the analogue waveform, need to be quantised to digital (finite) values for the ADC process. This will ensure that parts of the signal are not lost due to clipping the peak of the waveform.

Clipping of the waveform occurs when the input waveform consists of values out of the ADC range. ADC values can be out of range as only a finite amount of number are selected as estimates of the expected input waveform.

Fundamental characteristics of electrical signals can be reflected with the Root Mean Square (RMS) value of a measurement (current or voltage). RMS values are dependent on the size of the sample window used to record the measurement [32]. The smaller the sample window is the more irrelevant the RMS value becomes. The larger the sample window the better the signal can be averaged, as certain events are "hidden".

RMS values can be affected by the deviation of a voltage or current signal from the perfect sine waveform. Signals can be deviated from the norm with the following constraints [32]:

- Magnitude

- Frequency

- Distortion

- Short variations

- etc.

Figure 32 represents the effect of increasing the window size for a 1 minute sample of an input waveform. As the window size increases the RMS voltage waveform becomes smoother. The smaller the window size the noisier the RMS voltage waveform seems.
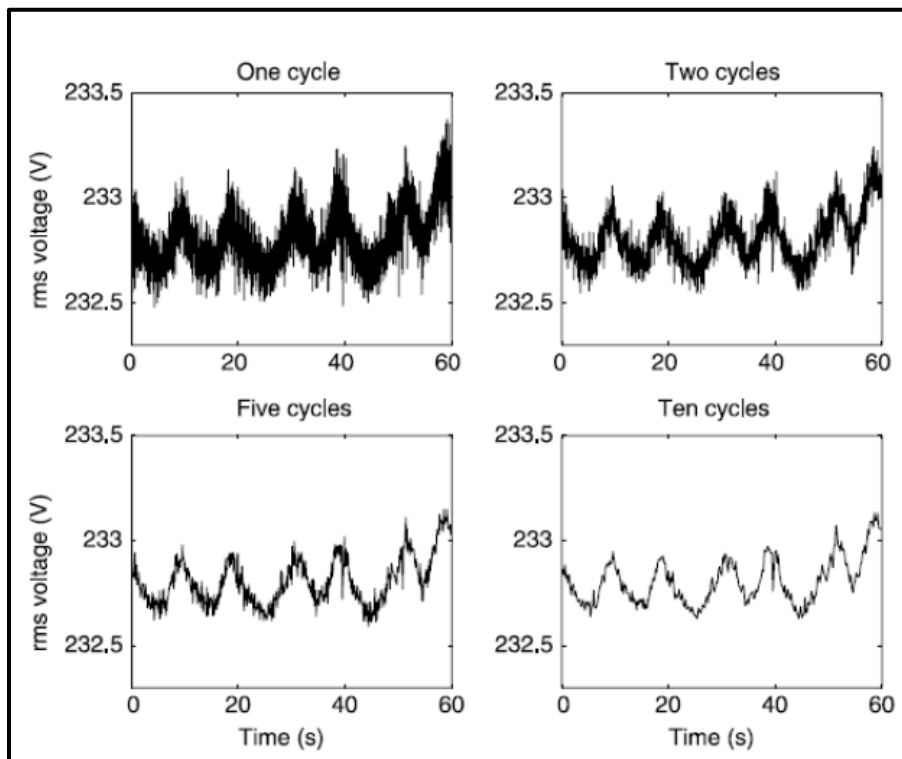
Figure 32: Effect of increasing the window size for RMS values [32]

There are analysis techniques which are used to reconstruct the digital waveform. These techniques include, but are not limited to, the Short Time Fourier Transform (STFT), Wavelet Transform (WT), S-Transform (ST) and Park's Vector approach [32]. There are other methods used, but they are not mentioned in this text.

Table 2 shows a summary of the different analysis techniques mentioned in this text. It is clear Park's Vector technique has a high sensitivity, is the quickest and is the easiest to use.

Table 2: Comparison between analysis techniques [32]

	STFT	Wavelet	S Transform	Park's Vector
Speed	Moderate	Moderate	Low	High
Sensitivity	Low	Moderate	High	High
Implementation	Difficult	Difficult	Difficult	Easy

2.3 Power loggers

2.3.1 Introduction to power loggers

In ECM projects two different types of power loggers are used namely temporary and permanent power loggers. Where temporary power loggers generally store the data locally and permanent power loggers connect to a Supervisory Control and Data Acquisition (SCADA) system to store data. Each type of power logger has certain characteristics that will influence and can improve the accuracy of the power loggers.

The ease of installation is one of the main contributions when temporary power loggers are considered. Due to the ease of installation temporary power loggers are generally used to record the baseline of a project. Temporary power loggers usually use clamp on CTs for the ease of installation and removal on site. CT and VT ratios, time as well as date settings are setup using a laptop with the respective software for the temporary power logger.

Permanent power loggers are installed during implementation of the ECM. It is not uncommon for them to have a local display where the voltage, current, power factor and power usage can be viewed locally. The screen helps with the local setup of CT and VT ratios and time and date settings too.

2.3.2 Temporary power loggers

Table 3 compares various temporary power loggers using the points below with supported reasons.

- CT compensation   CT compensation can improve overall accuracy of the current measurement if CTs show signs of saturation.

- Accuracy (kW)   Overall accuracy of the power measurement needs to be considered to see the overall performance of the temporary logger.

- Data resolution   Is a representation of the smallest measurement that can be recorded.

- Battery life   Reflects the amount of time the temporary power logger can be left on site to record power usage data.

- Sample rate   As the temporary power logger is a stand-alone unit, it is important to consider the rate at which data can be recorded

Only two temporary loggers in Table 4 had circuitry or software which contributed toward CT compensation. CT compensation helps combat issues experienced, such as saturation. The accuracy rating for the temporary loggers were fairly similar, besides for the 5% accuracy rating for the Logit LCV. Battery life for the loggers varied vastly, with two of the loggers using the voltages from site to keep the battery charged. (L1 and L2, in Table 3, represent the first and second phase for the voltage that is measured on site respectively, and is used to power the temporary loggers).

Table 3: Comparison of temporary power loggers

Temporary logger	CT Compensation	Accuracy power	Data resolution	Battery life	Sample rate
Dent Elite pro XC [33]	Y	< 0.2%	1 W/0.01 A	L1&L2	0.125 sec
Extech DL 160/162 [34]	N	2%	0.1 A	5 Days	1 sec
Extech Power Analyzer [35]	N	0.9%	0.1 W	N/A	0.1 sec
Logit LCV [36]	N	5%	0.1 A	20 Days	1 sec
Dent Power Scout [37]	Y	0.50%	1 W	L1&L2	0.5 sec

Figure 33 illustrates the sample rate plotted against the overall power accuracy of the different power loggers shown in Table 3. It indicates a general increase in accuracy the faster the power logger samples. In general, the lower the sample rate (higher sampling frequency) the higher the overall accuracy.
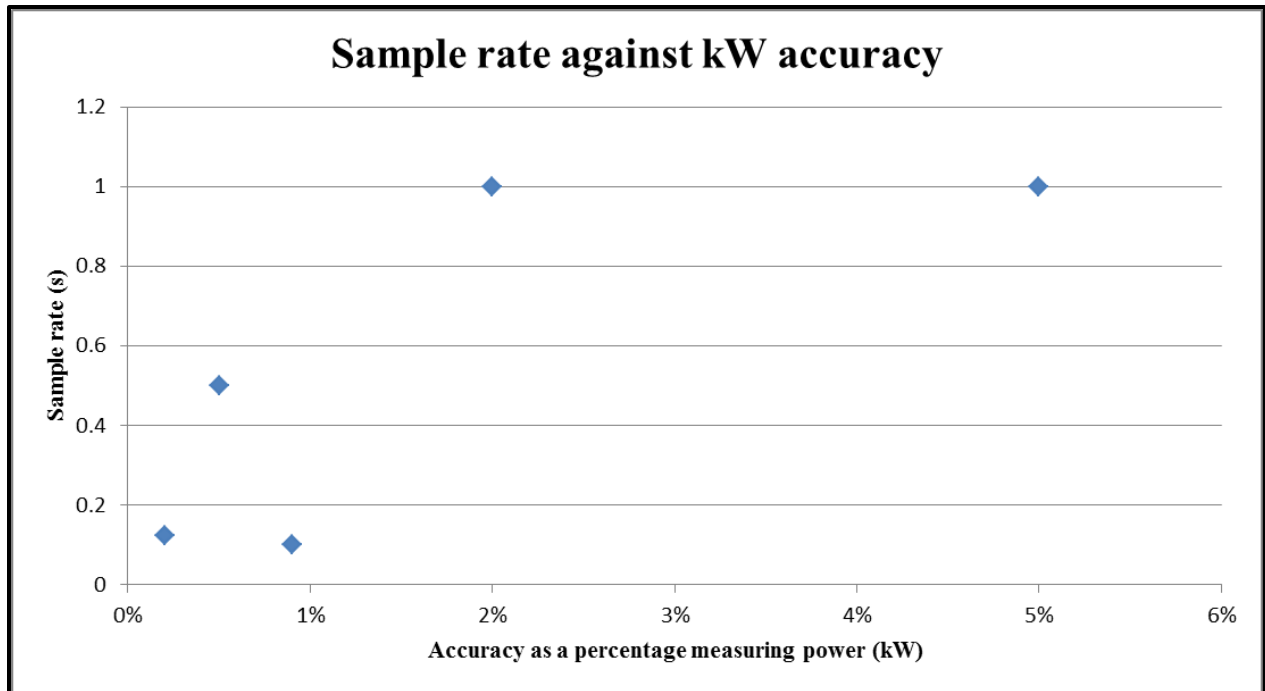
Figure 33: Sample rate against the overall power accuracy for temporary power loggers

Once all these parameters are considered a more generalised view of any temporary power logger can be painted. Table 3 also shows that the temporary power loggers, that were considered, have similar characteristics. The loggers have high accuracy ratings and sample rates to accurately record the required power measurements, besides for the Logit LCV.

2.3.3 Permanent power loggers

Different permanent power loggers from varying price brackets were compared against one another in Table 4. For the permanent power loggers the accuracy of each measurement that can be recorded was considered. Specification sheets for the permanent power loggers gave accuracy ratings for, voltage, current, frequency, active power and power factor. Each individual measurement considered can affect the overall accuracy of the power usage measurement. Equation 11 below represents the relationship between these parameters.

$$P = VI \cos(\alpha) \tag{10}$$

Where:

P = Active power (W)

V = Voltage (V)

I = Current (A)

α = Power factor (time difference between the voltage and current waveforms)

Table 4: Comparison of permanent power loggers accuracy ratings

Permanent logger	Voltage	Current	Frequency	Active power	Power factor
Merlin Gerlin PM700PMG [38]	0.50%	0.50%	0.01%	1.00%	N/A
Diris A10 [39]	0.20%	0.20%	0.10%	0.50%	0.50%
ABB M2M [40]	0.50%	0.50%	0.20%	1.00%	1.00%
Schneider PM750MG [41]	0.50%	0.50%	0.02%	1.00%	0.50%
Schneider PM1200MG [42]	1.00%	1.00%	0.10%	1.00%	1.00%
Schneider PM850MG [43]	0.375%	0.375%	0.02%	0.20%	0.10%
Siemens Sentron PAC4200 [44]	0.20%	0.20%	N/A	0.50%	0.50%
Schneider Power logic ION7550 [45]	0.10%	0.10%	0.005%	0.20%	0.20%
Siemens Sentron PAC3100 [46]	1.00%	1.00%	N/A	1.00%	N/A

It was fairly evident that as the overall accuracy for the permanent power logger increased so did its price range. Figure 34 shows that the majority of the power loggers considered have an active power accuracy measurement of 1%, but this varies over a price range of approximately R 5 800. There are however, power loggers available on the market for a fair price that offer competitive accuracy rates.
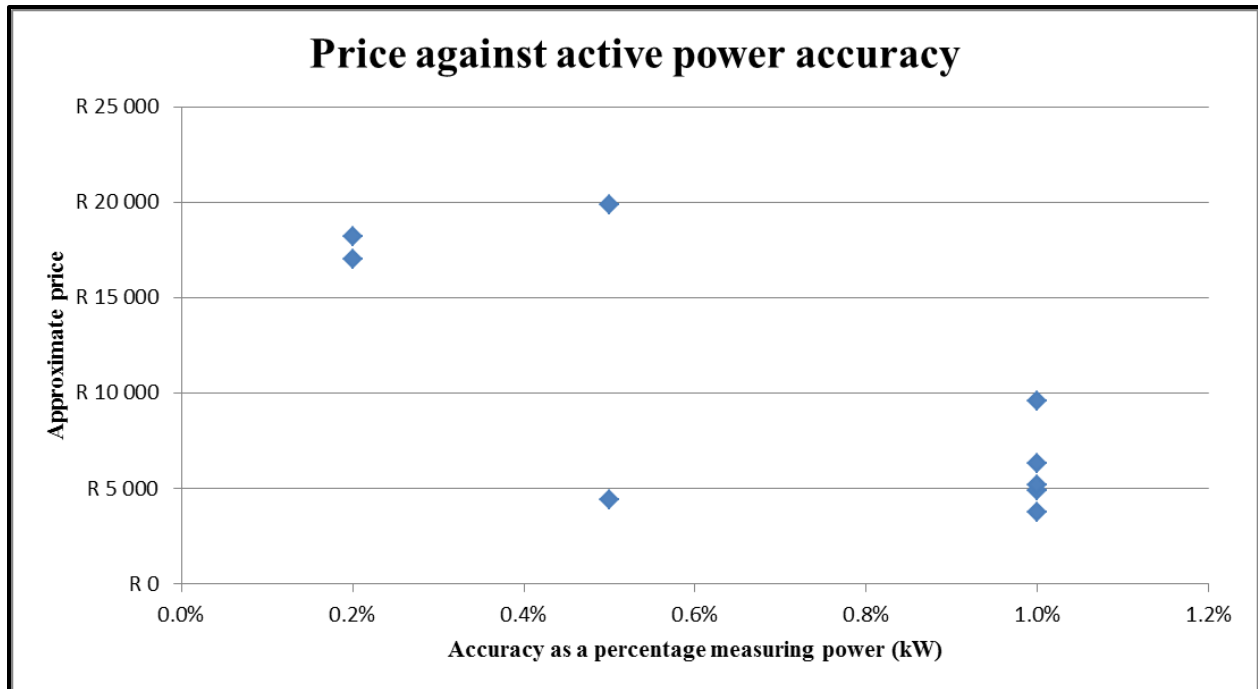
Figure 34: Price against active power accuracy for permanent power loggers

Although there is an evident difference between the accuracy specifications of various power loggers, the overall accuracy specifications have high ratings. All the permanent power loggers that were considered can record/log power usage with a high enough accuracy.

2.4   Holistic approach to measuring energy

2.4.1   Overall accuracy effects of measuring equipment

The way in which the overall accuracy is affected can be clearly described with the equations shown earlier in the chapter. Equation 3 is shown below for ease of access:

$$V_S = 4.44\, F N_R B S 10^{-8} \tag{3}$$

The following aspects of the equation can affect the overall accuracy of the secondary voltage (V_S):

- The effective turns ratio (N_R) decreases over time, due to the effects of aging

- Increasing the cross sectional (S) area can help improve accuracy, but makes the instrumentation transformers bulky

- Larger cross sectional area (S) increase the overall impedance of the magnetising core, which reduces magnetising current (improves accuracy)

- Secondary voltage (V_S) is responsible for setting up the excitation current in the core and secondary current (I_S)

The secondary voltage and current are directly related, therefore each of the factors will be affected by the aspects mentioned above.

2.4.2   The need for a metering procedure

There are protocols which can be followed to measure power usage accurately, but there is no mention of possible aging when using existing instrumentation transformers. If existing instrumentation transformers are saturated it will affect the accuracy of the reading. It is also normally assumed that all instrumentation transformers have been correctly installed. As reflected in this chapter, burden can play an important role when accuracy is considered.

There is also no mention of comparing measurements taken pre- and post-implementation. This is especially important as ESCOs generally use temporary power loggers during the baseline development, and permanent power loggers whilst reporting the energy savings. The two different power loggers used at the different stages of the project could generate results that differ with variations in accuracies. If this is the case it could be for the following reasons:

- The two different power loggers are not setup in the same manner

- Each power logger might be biased differently

- Incorrect or lack of burden calculations

- Not measuring the same electrical bus during the different stages of the project

In order to create an environment that compares apples with apples (before and after values), a procedure was developed and presented in Chapter 3. After implementing the procedure in

Chapter 3 there should be little difference between the baseline and reporting period energy measurements.

This procedure can be used at the start of the project or to verify that a project in progress is measuring energy usage accurately.

2.5   Conclusion

It is now evident that the components used today to measure energy usage have a high accuracy standard. Whilst effects of saturation and burden can hinder the accuracy of the instrumentation transformers and reduce the overall accuracy, there are methods and extra circuitry available to counter these effects.

Analogue to digital conversions and reconstruction of the signal with different Fourier methods cannot be considered as an issue regarding accuracy. There are several methods available, where the method with the poorest accuracy will still be accurate enough for power measurements.

The temporary and permanent power logger market is very competitive when overall accuracies are considered. Active power accuracies for permanent power loggers are generally better than 1%. Extensive development has been done for power loggers which make the choice of power logger fairly redundant in today's environment.

Several protocols have been setup to help ensure overall accuracies of the components used in the measuring process. These protocols ensure updated calibration certificates and correct methods to reflect the true energy savings. However, most protocols do not mention how saturated instrumentation transformers can affect the overall accuracy of the measurement.

There is also no mention of the need to compare the measurements of the permanent power logger against the temporary power logger. The measurements could be biased, which will not reflect the true power savings of the ECM. This can all be directly related to the installation and setup of the power loggers and its components during the life cycle of the project.

Instead of focusing on the accuracy of the equipment used to measure energy, the focus should be on the installation and setup of the measuring equipment. With all the aspects that can affect

the accuracy in mind, a verification procedure was developed to help identify possible issues experienced when installing power loggers.

CHAPTER 3

"We cannot solve our problems with the same thinking we used when we created them." – Albert Einstein

3. VERIFICATION PROCEDURES TO ENSURE CONSISTENT ENERGY MEASUREMENTS

3.1 Introduction

It was identified in Chapter 1 that overall measuring accuracy of an energy efficiency project is crucial. This can have a negative financial effect for the ESCO, the utility supplier or even the client. A study related to the achievable accuracy of the measuring equipment was done in Chapter 2. It concluded that current measuring equipment can achieve high standards when measuring accuracies are considered. A suggestion was also included in Chapter 2 to develop a procedure which will help identify discrepancies and improve overall measurement accuracy. The proposed procedure is described in this chapter.

If the proposed procedure is implemented through the chronological life span of an ECM project, shown in Figure 35 (moved here for convenience from Chapter 1, Figure 5), the three parts, reflected in Figure 36, will need to be followed. This will ensure the highest measuring accuracy is achieved. Parts one and two are dependent on one another, whilst part one and three need to be implemented together.
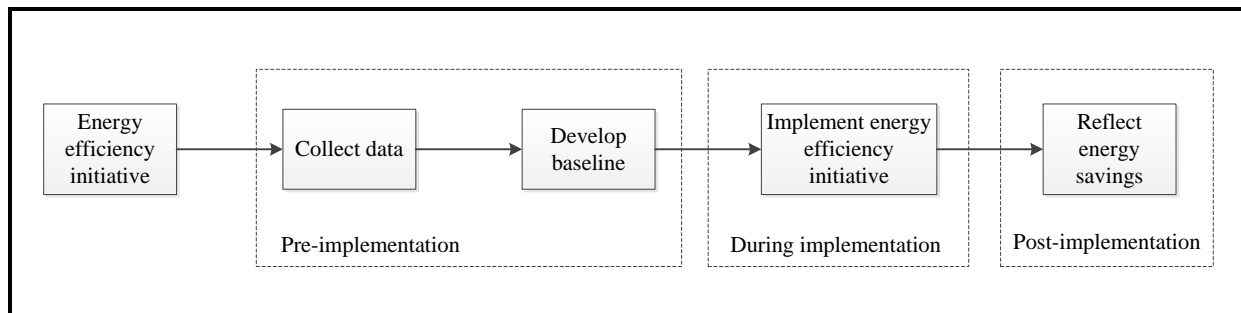
Figure 35: Life cycle of an energy efficiency project
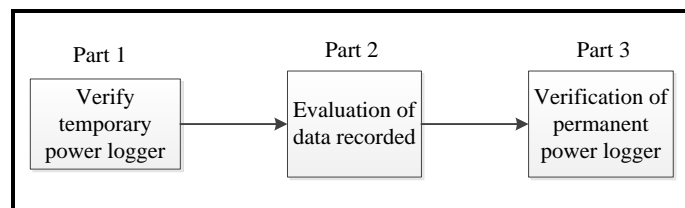
Figure 36: Main parts involved in the proposed procedure

The first part of the procedure consists of verifying the temporary power loggers' measurements. In order to verify the temporary power logger it either needs to be sent for laboratory calibration or alternatively can be verified against externally calibrated equipment. Client personnel need to be consulted to ensure the correct measurements are recorded by the temporary power logger. This all occurs during the pre-implementation stage of the project.

The second part of the verification procedure consists of the evaluation of the data recorded by the temporary and newly installed permanent power logger. Firstly the temporary power loggers' data is compared to log sheets or client SCADA data, which is used to confirm the correct place of installation. Once the place of installation has been confirmed, the temporary logger can be used to evaluate the data recorded by the newly installed permanent logger. This will confirm that the correct date and time and CT ratio has been used upon setup of the permanent power logger. All this occurs during pre-implementation and implementation of the project.

Part three of the procedure is used to verify permanent power loggers that have been installed on site for a period of time. This part is used long after the performance assessment of the project. It consists of comparing the permanent loggers' measurements to the temporary loggers' measurements. A comparison of the theoretical calculation as well as the installed capacity and client predicted power usage (if available) will be used as validation.

Figure 37 gives an overview of the proposed procedure and shows where each part fits in the life cycle of the ECM project. The three parts will be discussed in further detail throughout this chapter. Flow charts of each part will be given in the respective sections.
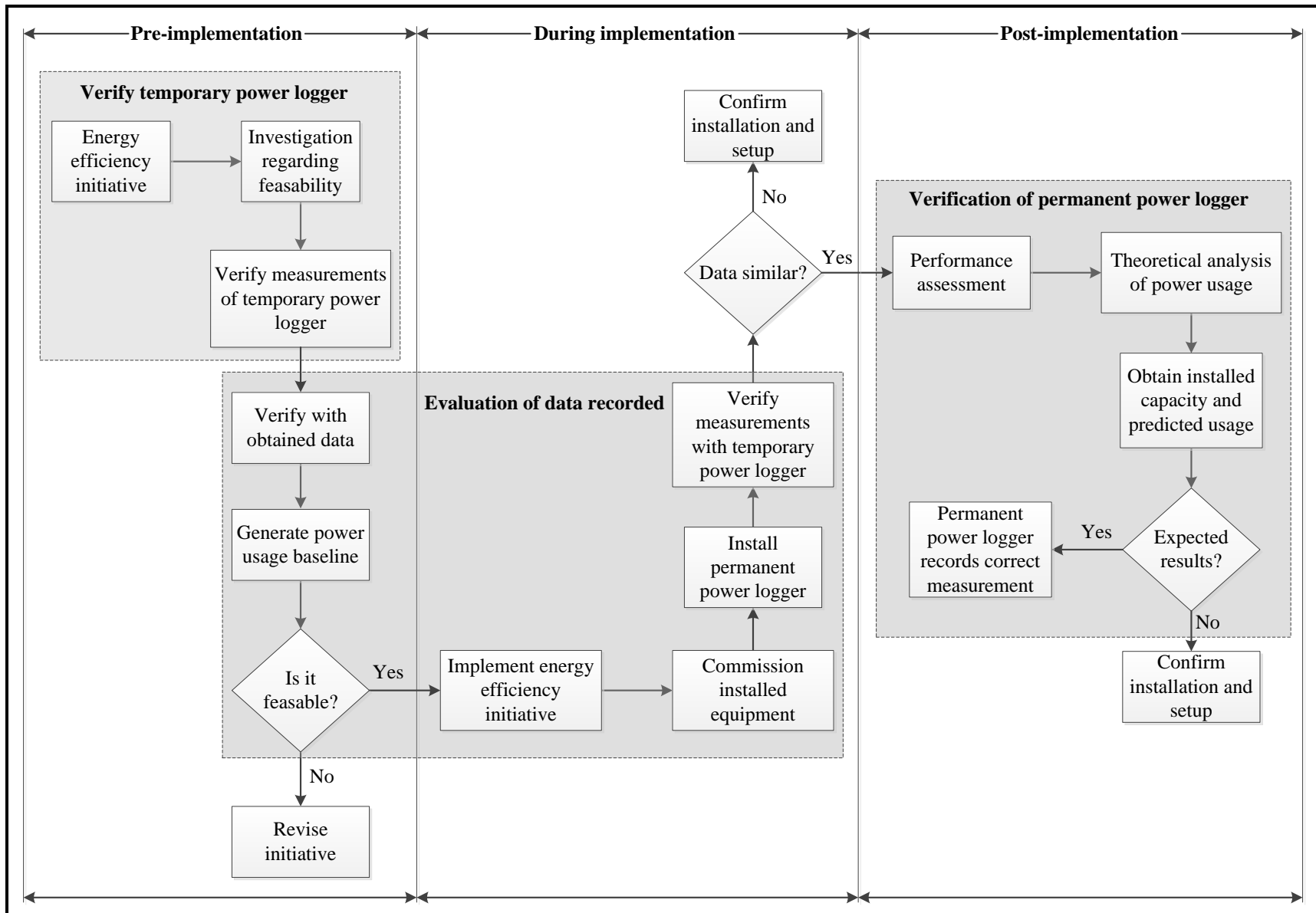
Figure 37: Overview of the verification procedure

3.2 Verify measurements of temporary power loggers

3.2.1 Overview

For the sake of clarity part one has been divided into two different subsections. The first subsection includes a verification procedure that can be used to quantify the accuracy of the temporary power logger. There are numerous methods that can be used to verify the measurements of temporary power loggers. The loggers can be sent for calibration or the results can be compared against other calibrated equipment. Verification of the temporary power logger should occur regularly and before installation on site.

The second subsection consists of basic checks that can be implemented upon installation of the temporary power logger. These checks will help identify possible issues that can be corrected immediately on site. Confirming installation and power logger setup aids towards the correct installation of the temporary power logger.

Figure 38 represents flow chart of the proposed procedure that should be followed before and during the installation of the temporary power logger. Both subsections will be described with more detail in the following two sections.
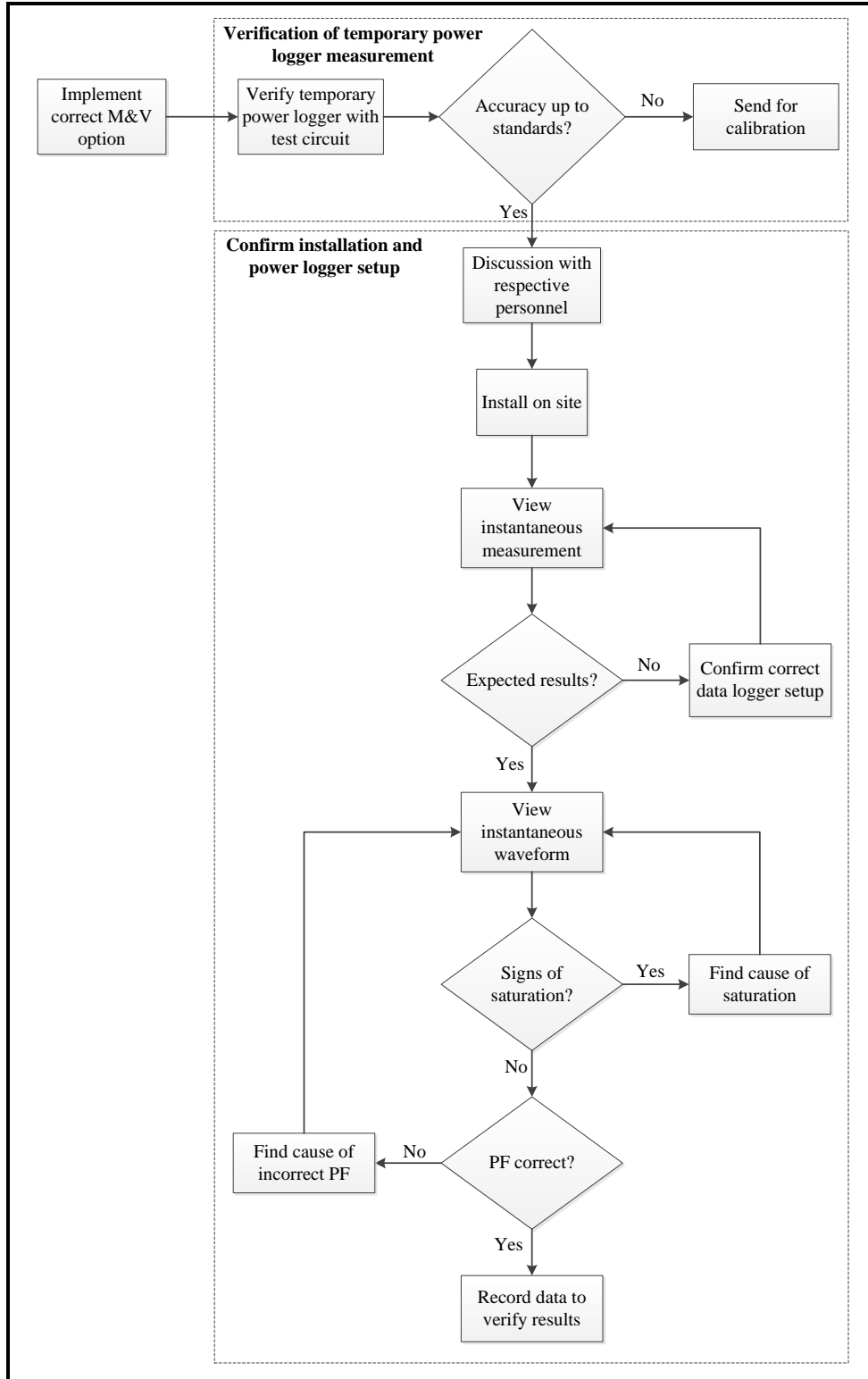
Figure 38: Procedure to verify the measurements of a temporary power logger

3.2.2 Verification of temporary power logger measurements

The accuracy of the temporary power logger and all of its components, shown in Figure 42, needs to be determined before any baseline reporting period can commence. Ideally the components can be sent for laboratory calibration. However calibration tests can be costly and may be time consuming, therefore the following procedure was developed to aid the verification process.
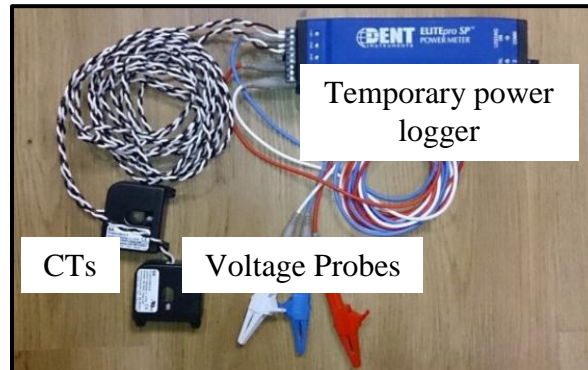
Figure 39: Example of a temporary power logger and its components [10]

The temporary power logger can be connected to a circuit (test circuit), to compare all the variables (voltage and current) against a calibrated device or known variables. This way the current, voltage and power factor measurements of the temporary power logger can be verified. If the measurements are within the specified accuracy[11] of the temporary power logger then it can be used on site. If the power logger does not achieve the specified accuracy it should be sent in for laboratory calibration. To make sure that the verified power logger is used, it is suggested that the verification of the measurements occur before the logger goes out to site.

The overall accuracy of the measurement is dependent on the type of temporary power logger and components that are used. As discussed in Chapter 2, there are different temporary power loggers available with different achievable accuracies. Chapter 2 also mentions that saturated instrumentation transformers can have an impact on the accuracy of the measurements.

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[10]Image taken and edited by Luke Meijsen
[11] Specified accuracy is related to the achievable accuracies reflected on the specification sheet of the temporary power logger.

After the measurements of the temporary power logger and its components have been verified, it can be installed on site. To ensure that the temporary power logger is installed on site correctly the following step needs to be taken.

3.2.3 Confirm installation and power logger setup

It is crucial to know what needs to be measured and what parameters will be affected after the ECM installation. If you do not know what you are measuring you will not be able to reflect the true savings potential of the ECM intervention.

Once all the parameters that need to be measured are known, the electrical foreman and/or electrician of the site should be consulted. The following topics should be discussed:

- Best place/places to measure all the parameters that will be effected after the energy intervention

- The place of installation of the permanent power logger

- Existing CT and VT ages if any are to be used

- Expected power usage (voltage and current magnitude)

- Measuring CT and VT ratios that will be used (needed for the setup of the power loggers)

Burden formulas, given in Chapter 2, should be used to guarantee accurate measurements. This will ensure that power meters and the instrumentation transformers are not placed too far from one another, and ensure that the correctly sized wires are used.

Correct installation guidelines need to be followed when installing CTs and VTs on site. This is to avoid any possible damage caused to the instrumentation transformers. The temporary logger CT and VT ratios need to be adjusted, during the setup of the power logger.

Directly after installation of the power meter, if possible, the instantaneous measurement should be viewed locally. Generally the instantaneous voltage and current measurements can be viewed on a laptop screen, using software provided by the temporary power logger manufacturers. The instantaneous measurement should be compared to what is expected on site, based on the

information discussed with the clients' personnel. If it is not correct the temporary power logger may have been setup incorrectly and the CT and VT ratios might need to be adjusted.

Whilst confirming the instantaneous measurement, the current and voltage waveforms should also be viewed locally. It will be easy to perceive whether there is any waveform distortion, as represented in Figure 40. The distortion can be caused by the following:

- Over burden in the circuit

- Saturated instrumentation transformers (CTs and VTs)

- Incorrect polarity (E.g.: CT that is installed in the incorrect direction)

- Harmonics (out of this scope for discussion)
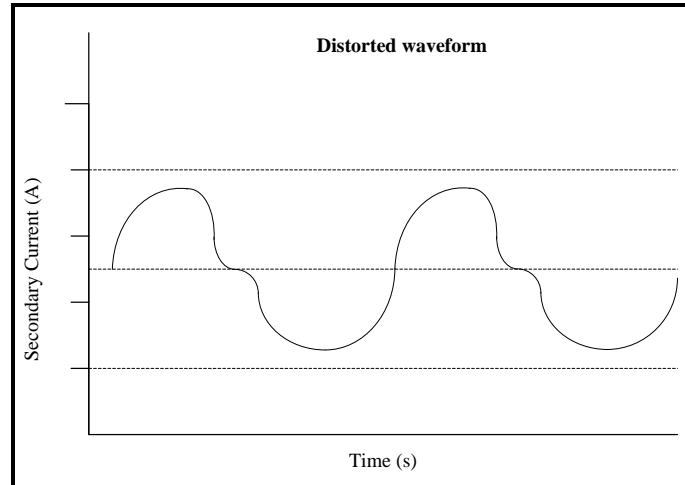
Figure 40: Example of a saturated waveform [23]

Whilst viewing the instantaneous waveform, the power factor (PF) should also be confirmed. The power factor should generally never be lower than 0.6, which is the worst case scenario, or be reflected by a negative value. Incorrect power factors can be displayed for the following reasons:

- CT is installed in the incorrect direction

- Incorrect line match-up (voltage for line 1[12] not matched with current for line 1)

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[12] There are three lines in a three phase system.

The procedure used to verify the measurement of the temporary power logger is summarised with a flow chart in Figure 38. This procedure should be followed when a temporary power logger needs to be installed on site. Part one is divided into two subsections, where the measurement of the temporary power logger is verified and the installation and setup is confirmed on site.

Ultimately part one is used to ensure that accurate measurements are taken with the temporary power logger. It is also used to confirm the installation of the temporary power logger on site. It will help avoid using inaccurate temporary loggers and avoid issues related to incorrect installation procedures. Confirming the logger setup also helps avoid using incorrect instrumentation transformer ratios and ensures the lines (phases) are matched.

3.3   Evaluation of data recorded

3.3.1   Overview

Part two, evaluation of data recorded, consists of two subsections namely verification of the temporary power loggers' place of installation and verification of the newly installed permanent power logger. This is shown in Figure 41. By comparing the client's data against the temporary power loggers' data its place of installation can be confirmed. If the temporary power logger is installed on the incorrect electrical bus the two data sets will differ. This is known, because the temporary power logger was setup correctly in Part one.

The second subsection is used to verify the measurement of the newly installed permanent power logger. The measurements can be compared to that of the temporary power logger, as the installation and setup have already been confirmed and verified.
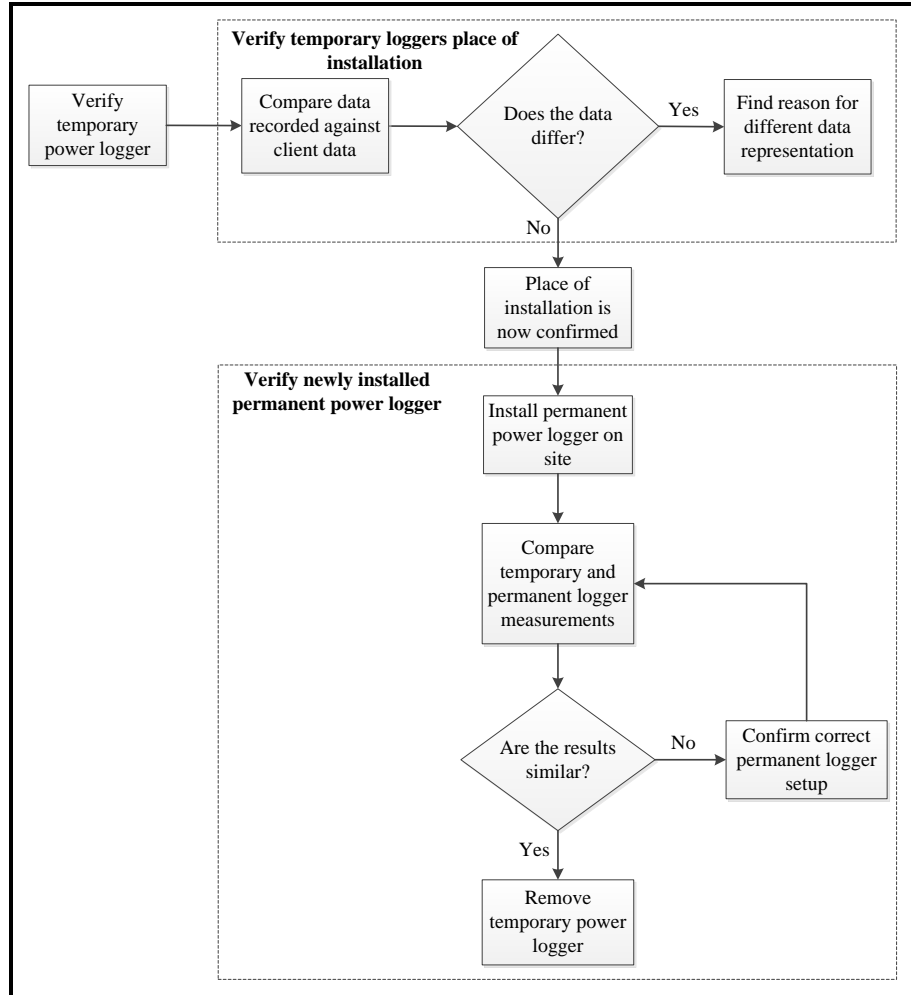
Figure 41: Flow chart representing the evaluation of data recorded

3.3.2 Verify temporary loggers' place of installation

During the pre-implementation (baseline period) and during implementation stages, where the baseline for the project is developed and used for the first time, it is suggested that further data/evidence is obtained from the client. The extra data will be used to confirm the reading recorded by the temporary logger.

Data taken either from the client's SCADA, log sheets or taco graphs, etc. should be used to confirm the temporary loggers' place of installation. After comparing data it will be quick to reflect whether the power logger is recording the correct measurements and whether it is setup correctly.

There are numerous reasons as to why the data might differ after comparison, these reasons are stated below:

- The temporary power logger is not setup correctly

- The burden in the temporary power logger circuit is too high

- Temporary power logger is installed on the incorrect electrical bus

- Client obtained data is faulty

- Saturated instrumentation transformers

Data recorded here will be used to develop the baseline for the project and used to verify the measurements of the newly installed permanent power logger, to come. The data therefore needs to be recorded as accurately as possible. The baseline will be used to reflect energy savings long after the project has been complete. The permanent power logger will be used to reflect the impact of the ECM intervention after the temporary power logger has been removed.

3.3.3 Verify newly installed permanent power logger

It should be protocol to leave the temporary power logger on site to compare the measurements against that of the newly installed permanent power logger. This is done after the temporary power logger's measurements have been verified, the correct place of installation has been confirmed and results have been compared to data requested from the client. The temporary power logger can then be used to verify whether the permanent power logger is recording the same measurements.

If the measured results are not similar, between the temporary and permanent lower loggers, it could be due to the incorrect setup of the permanent power logger. If so the following needs to be checked:

- Power loggers are installed on the same electrical bus

- Power loggers are using the correct CT and VT ratios

- Time and date settings on the power loggers are the same

The stage of comparing the two results is important, as the permanent power logger will measure energy usage after ECM implementation. At the end of the whole process it should seem as though only one power logger was used during the life of the project. That way when one compares the data during the reporting period to baseline data there will be no biased readings involved.

Figure 41 represents a summary of the verification procedure to evaluate the data recorded. It should be used to confirm the correct place of installation for the temporary power logger. Once this has been confirmed it will then be used to verify the measurements of the newly installed permanent power logger.

3.4   Verification of permanent power logger

Figure 42 is a summary of part three for the proposed procedure. It is used to validate the measurements of a permanent power logger that was previously installed on site. This part can only be implemented after part one of the procedure, which verifies the measurement of the temporary power logger.
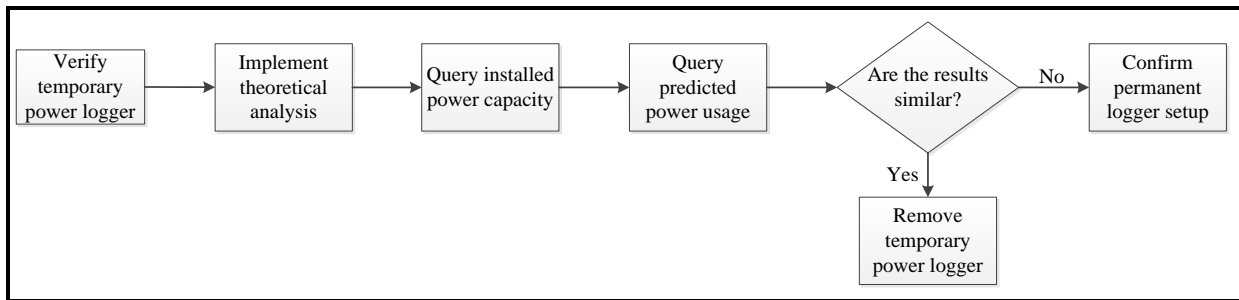
Figure 42: Verification of permanent power logger procedure

Verifying measurements of permanent power loggers during the post-implementation period bares a few complications. The age of the instrumentation transformers should not be assumed because one does not know how long the permanent power logger has been installed on site. It is also generally more difficult to obtain information from the client regarding the setup and installation of the power logger, as a long period of time could have lapsed since installation of the measuring equipment.

The installation of a temporary power logger to verify the measurements of the permanent power logger is not sufficient. Installing the temporary power logger on the same bus might give similar results, as the age of the instrumentation transformers is unknown.

The measurements of the permanent power logger should therefore not just be verified with a temporary power logger, but also validated with other data. Validation of the old permanent power logger should be accompanied by a comparison against the theoretical calculations, installed capacity and predicted power usage (power budget) if available.

Theoretical calculations should provide a good approximation of the total power (kW) consumed by the load (compressor, fridge plant, etc.). This may entail research and educated estimates of certain values to be used in the formulas. The expected measured results of the power loggers should be between the theoretical calculation and installed capacity. If the power measurement recorded by the power logger is lower it could be due to the following reasons:

- Incorrect power logger setup (CT and VT ratios)

- Saturated instrumentation transformers

Installed capacity and the theoretical analysis should give a good estimate of the power usage. It is therefore used to validate the measurements of the temporary and permanent power logger readings. The measurements between the temporary and permanent loggers' should not differ by more than the accuracy which the temporary logger achieved during its verification test.

3.5   Conclusion

The purpose of this chapter is to create a verification procedure that can be used to help increase the overall measuring accuracy. An increase in measurement accuracy can be achieved through verification and validation procedures. The procedures can help identify discrepancies between two different data sources. Generally the two sources would be the temporary and permanent power logger measurements.

Part one of the proposed procedure, "Verify measurements of the temporary power loggers", focuses on the calibration and place of installation of the temporary power logger. Laboratory calibrations can be costly and time consuming; it is therefore proposed to use a test circuit to

verify the readings of the temporary power logger. Basic checks are proposed upon installation to assist with confirmation of the installation and power logger setup.

Part two, "Evaluation of data recorded", helps verify the place of installation for the temporary power logger. This is done by comparing client obtained data against the temporary loggers' data. Once the correct place of installation has been confirmed, the baseline power usage can be recorded for the ECM. After recording the baseline, the temporary logger will be used to verify the measurements of the newly installed permanent power logger.

Part three, "Verification of permanent power logger", is implemented when the measurements of a permanent power logger need to be verified during the post-implementation period of the project. The temporary power logger is installed to verify, whilst theoretical analysis is used to validate the measurements of both the power loggers.

The proposed verification procedure will be tested and implemented on industrial sized projects in the following chapter. Different DSM projects will be used to show the numerous issues that were identified in this chapter.

CHAPTER 4
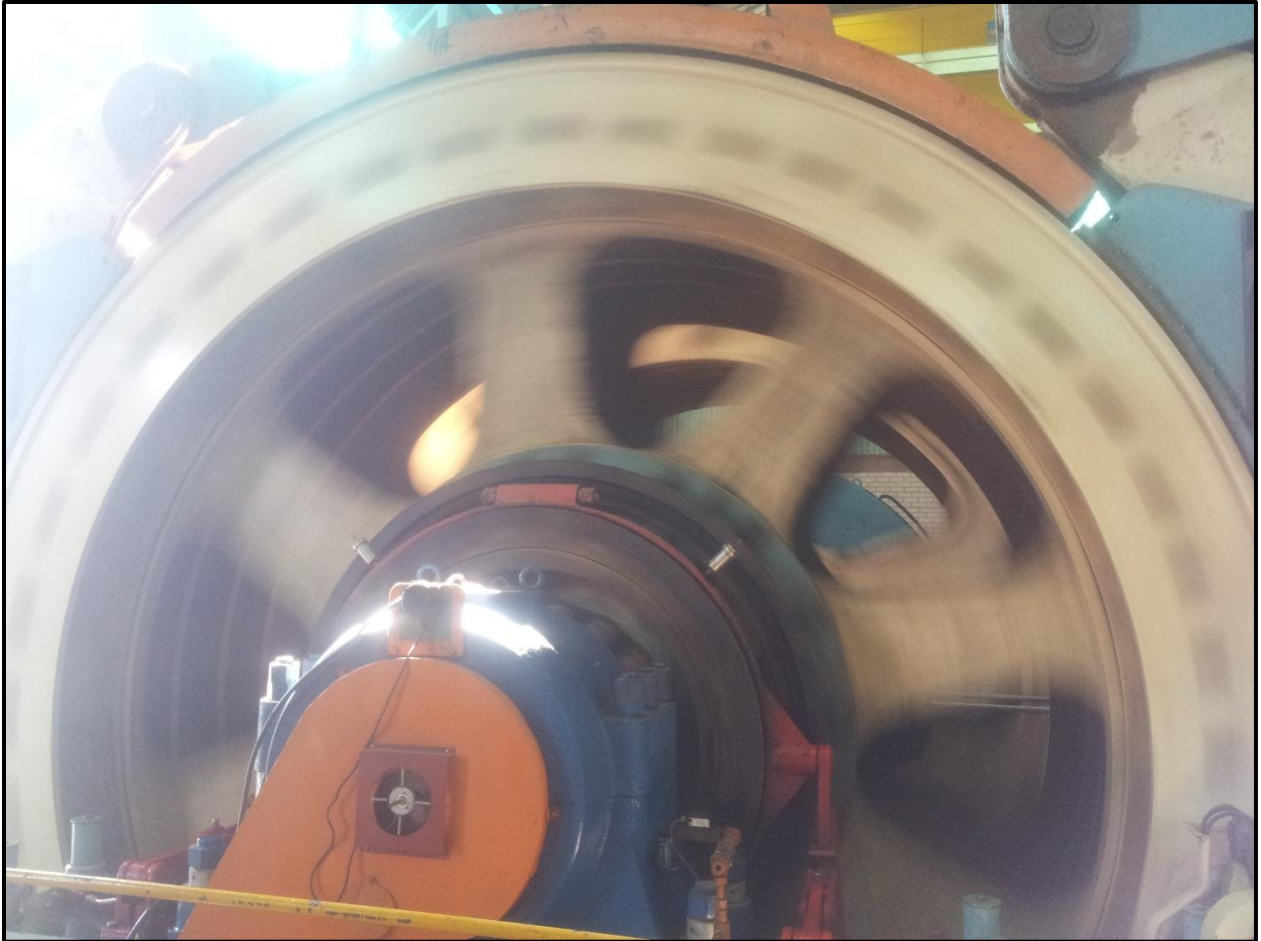
"Insanity: doing the same thing over and over again and expecting different results." – Albert Einstein

4. CASE STUDIES

4.1   Introduction to case studies

For the purpose of the case studies the procedure shown in Figure 37 will be followed, where the life cycle of a project is considered. The case studies start off with the verification of temporary power loggers' measurements[13] and the correct setup and installation of the logger. A few issues are also highlighted during this process.

Common issues experienced during the implementation stage of the ECM are reflected upon in the evaluation of data recorded section. Plausible explanations and possible solutions are given for the issues experienced in the different scenarios.

In order to not be tedious and show repetition each case study has been taken from different industrial projects. The industrial projects include power usage data recorded for mills in cement plants to air compressors used in gold mines. Brief case studies have been given to highlight common issues that were experienced during the study. A detailed case study will be given last to illustrate the full extent of the verification procedure.

4.2   Verify measurements of temporary power loggers

4.2.1   Overview

Subsection one of the first part, to the proposed procedure, is to verify the measurements of the temporary power logger. Without the verification measurements the need for calibration and current accuracy status of the temporary power logger would be unknown. Case Study 1 focuses on using a testing circuit that can be used to verify the measurements of a temporary power logger. A test circuit was constructed as part of the case study.

The second subsection guides the reader through the installation of the temporary power logger on site. It focuses on viewing the instantaneous measurements and waveforms which are then compared to what is expected on site. This helps confirm the place of installation and the setup

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[13]All data used for the case studies were evaluated by independent sources (M&V teams).

for the temporary power logger. Waveforms that were used to confirm saturation levels of the CTs are shown in Case Study 2.

4.2.2 Case Study 1 - Verification of temporary power logger measurements

Figure 43 has highlighted the part of the procedure which Case Study 1 focuses on. Temporary power loggers need to be calibrated at the earliest every six months. In order to receive a calibration certificate the temporary power logger needs to be taken off site and sent in to be calibrated. This process can be a costly and time consuming one. This case study presents an example of a test circuit.

The purpose of the test circuit is to realise the possibility of a simple verification circuit. Once the temporary power logger is connected to the test circuit different scenarios can be created. The different scenarios will be used to verify the results recorded by the temporary power logger. Appendix A, Test circuit, can be consulted for further information regarding the design and method used with the testing circuit.
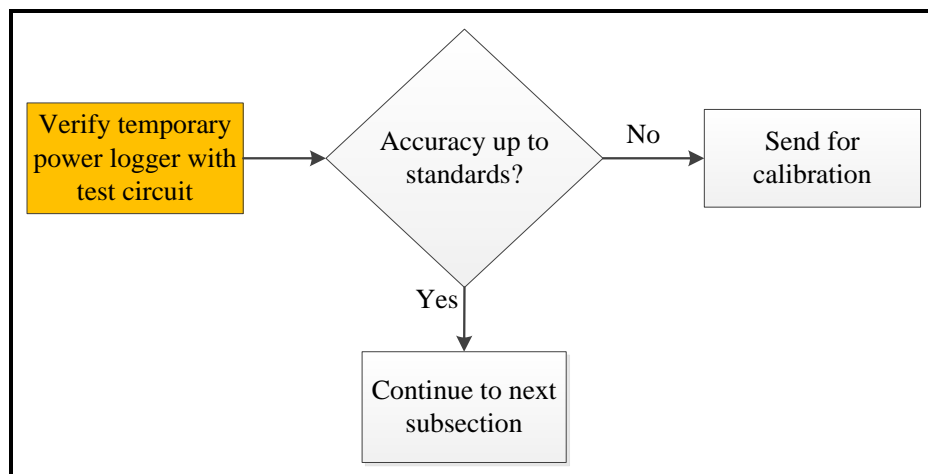
Figure 43: Verification of temporary power logger procedure

The measurements recorded by the temporary power logger will be compared to the measurements of an oscilloscope. Some oscilloscopes only need to be calibrated yearly. If the measurements between the temporary power logger and oscilloscope do not differ by more than

specified accuracy[14], then it is safe to assume that the temporary power logger is still within its calibration limits.

Figure 44 represents a circuit that was built to test and verify temporary power loggers, here after referred to as the test circuit. This will be used to verify whether the temporary power logger is recording accurate measurements and will not be regarded as a calibration test.

V_{ac}, in Figure 44, represents a variable Alternating Current (AC) power supply such as an auto-transformer (Variac). R is a variable resistor that has two different resistances and X_L is an inductor which has constant impedance.
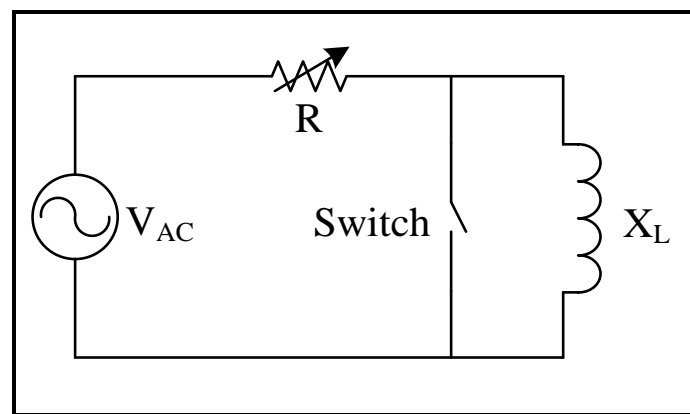
Figure 44: Test circuit

The variable power supply will be used to simulate different voltages that the temporary power logger may need to record on site. A variable resistor is used to alter the total current in the circuit. By varying both V_{ac} and R different power demands for the circuit can be generated. The inductor is placed in parallel with the switch to represent a changing power factor in the load. Power factor can be altered as X_L is bypassed or added to the circuit using the switch. Therefore two scenarios for the power factor can be tested, unity and that of which is reflected by the impedance of the inductor. The addition of the inductor in the load will not only change the power factor, but will also change the amount of reactive power used by the circuit.

The test circuit will be used to simulate different conditions that a temporary power logger might need to measure on site. It will be used to reflect the present accuracy of the temporary power

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[14]The specified accuracy is dependent on the overall accuracy that is achievable by the power loggers and needs to be agreed upon by all stakeholders.

logger. It is therefore necessary to confirm the measurements against something that has a calibration certificate. A measuring device such as an oscilloscope can be used to verify the measurements.

Although the oscilloscope also needs to be calibrated, there are still advantages to using the test circuit. An advantage is some oscilloscopes need to be calibrated once a year instead of every six months like most temporary power loggers.

The idea is to connect all measurement ports of the temporary power logger to the test circuit. The different conditions can be displayed on a Personal Computer (PC)/laptop using the present reading option of the temporary power logger. For example the software provided by Dent Logger is called ELOG; this software has an option where one can view instantaneous measurements on a PC screen.

The measurement should then be compared to that of the oscilloscope. Calibration can be verified if the measurements do not differ by more than the specified accuracy of the temporary power logger. All recording ports of the temporary power logger should give similar values, as the same point in the circuit will be measured.

Table 5 through to Table 9 shows the results of the Dent Loggers which were compared against the measurements from the test circuit, implementing the method mentioned in appendix A. Three tests were carried out on each temporary power logger, where the currents were changed to 0.1 A (Test 1), 0.5 A (Test 2) and 1 A (Test 3) respectively.

Table 5: Dent Logger 1 verified using the test circuit

	Dent Logger 1								
	Test 1			Test 2			Test 3		
	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy
$V_{RMS}(V)$	19	18.9	0.526%	78	77.3	0.9%	132	130.2	1.364%
$I_{RMS}(A)$	0.1	0.086	14%	0.499	0.496	0.601%	0.9	0.896	0.444
PF	0.95	1	5.263%	0.95	0.97	2.105%	0.95	0.97	2.105%

Table 6: Dent Logger 2 verified using the test circuit

	Dent Logger 2								
	Test 1			Test 2			Test 3		
	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy
$V_{RMS}(V)$	20.7	20.6	0.483%	76.8	76.1	0.911%	128	126	1.563%
$I_{RMS}(A)$	0.1	0.096	4%	0.502	0.506	0.797%	0.903	0.896	0.775
PF	0.942	0.98	3.924%	0.95	0.97	2.105%	0.95	0.97	2.105%

Table 7: Dent Logger 3 verified using the test circuit

	Dent Logger 3								
	Test 1			Test 2			Test 3		
	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy
$V_{RMS}(V)$	19.3	18.9	2.073%	74.9	74.3	0.801%	125	123.6	1.12%
$I_{RMS}(A)$	0.101	0.086	14.851%	0.507	0.506	0.197%	0.904	0.906	0.221%
PF	0.953	0.97	1.786%	0.95	0.97	2.105%	0.95	0.97	2.105%

Table 8: Dent Logger 4 verified using the test circuit

	Dent Logger 4								
	Test 1			Test 2			Test 3		
	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy
$V_{RMS}(V)$	19.5	19.2	1.538%	74.9	74	1.202%	123	121	1.626%
$I_{RMS}(A)$	0.102	0.086	15.686%	0.503	0.496	1.392%	0.907	0.906	0.11%
PF	0.958	0.97	1.197%	0.95	0.98	3.158%	0.95	0.97	2.105%

Table 9: Dent Logger 5 verified using the test circuit

	Dent Logger 5								
	Test 1			Test 2			Test 3		
	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy	Test bench	Elog	Overall measurement accuracy
V_{RMS}(V)	18.7	18.5	1.07%	74.1	73.4	0.945%	120	118	1.667%
I_{RMS}(A)	0.1	0.086	14%	0.51	0.504	1.176%	0.906	0.916	1.104%
PF	0.947	0.97	2.418%	0.95	0.98	3.158%	0.95	0.97	2.105%

When the overall accuracy for the project is discussed with all the stakeholders, the above results need to be considered. A better accuracy cannot be expected than what was achieved in the test for the temporary power logger. If the accuracy for the voltage and current overshoots the amount mentioned in the temporary loggers specification sheet[15] it should be sent in for calibration.

Test 1 for all Dent Loggers shows very poor current accuracy results, this is due to the measured current being lower than 0.5 A, which is below the 10% input range for the CT that was used. CTs have lower accuracy ratings when the current is 10% of rated current. Therefore the results can be ignored as the inaccurate measurements were expected.

The Test Circuit realised the possibility of verifying temporary power loggers with external calibrated equipment. It also proved to be quicker and cheaper than sending the temporary power logger and its components in for laboratory calibration, when the calibration might not be required. Temporary loggers can now be sent for calibration when it is known that the achievable accuracy is out of range.

4.2.3   Case Study 2 - Confirm installation and power logger setup

After the accuracy of the temporary power logger has been confirmed it can be installed on site. Once installation of the temporary power logger and all its components has been completed the procedure shown in Figure 45 should be followed.

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[15] Please refer to the following website http://www.dentinstruments.com/media/PDF/ELITEpro_datasheet.pdf for further details regarding the technical specifications for the Dent Logger which was used in the test.

The instantaneous measurements and waveforms were viewed locally on site once the temporary power logger was installed and setup. As highlighted in Figure 45, Case Study 2 represents an example of what instantaneous waveforms should look like. The waveforms should be viewed when the load is turned on, that way possible saturation effects of the CT can be seen.
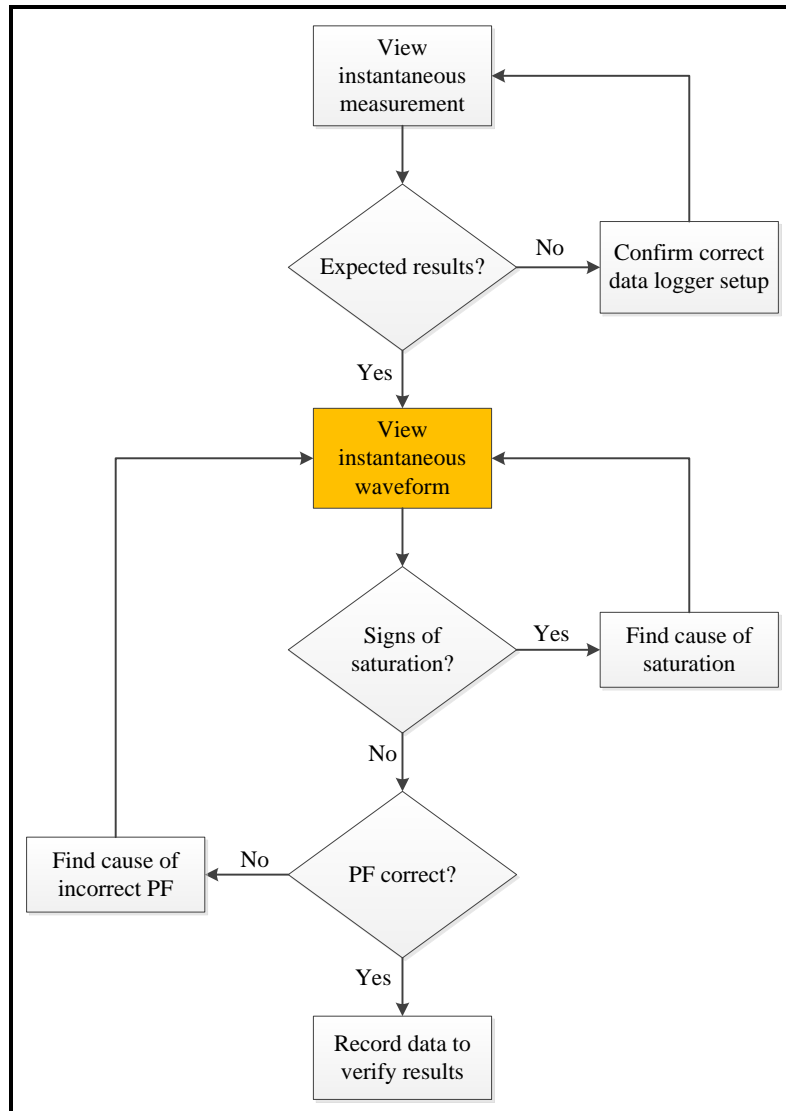
Figure 45: Confirm installation and power logger setup procedure

Figure 46 shows typical waveforms recorded by a temporary power logger. The three different waveforms namely the voltage (Volts), current (Amps) and power (kW) show no signs of saturation. This proves the instrumentation transformers which were utilised were not saturated and could be used to record power measurements.
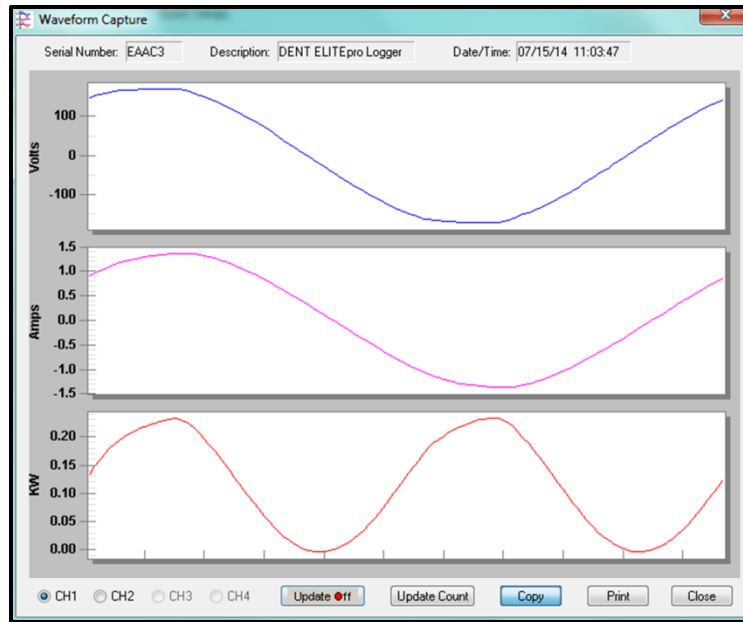
Figure 46: Example of an instantaneous waveform

4.3   Evaluation of data recorded

4.3.1   Overview

As with part one, part two of the proposed procedure is also divided into two different subsections. The first subsection is used to verify the temporary power loggers' place of installation. It will ensure all possible auxiliary loads are included in the power measurement. As the temporary power logger data is compared to data obtained from the client.

The second subsection is used to verify newly installed permanent power loggers. The overall purpose of this subsection is to confirm the setup of the permanent power logger. It can be used to identify whether the permanent power logger has been setup with the correct CT and VT ratios and has the correct date and time settings.

This part of the verification procedure stretches over two different time periods of the project. Therefore this section is divided into two different parts, where Case Study 3 focusses on the pre-implementation period (subsection one) and Case Study 4 focuses on the implementation period (subsection two). Numerous situations are given in each case study to help identify different possible scenarios.

4.3.2 Case Study 3.1 – Verify temporary loggers place of installation

After verifying the accuracy of the temporary power logger, it can be installed on site. Once installed on site the temporary logger's data needs to be confirmed again. This will confirm the correct place of installation and correct temporary logger setup. This part of the proposed procedure is highlighted in Figure 47, Case Study 3 is dedicated to this subsection.
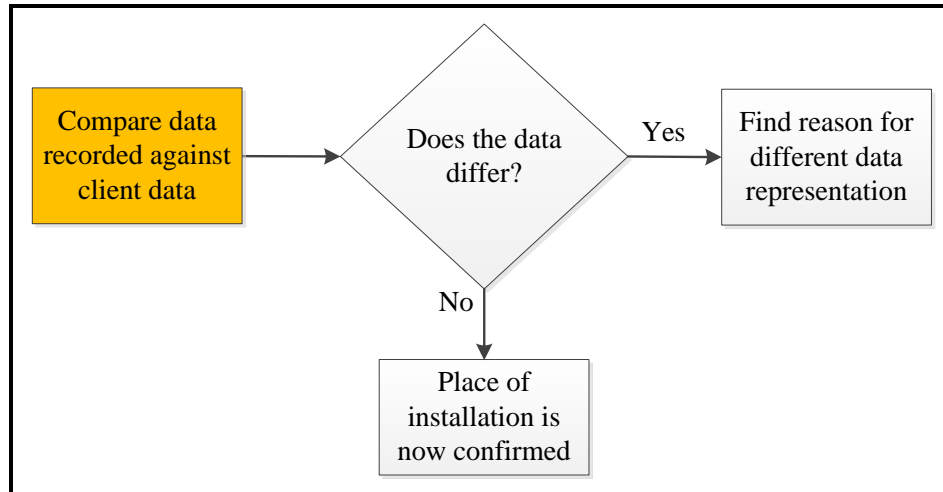
Figure 47: Verify temporary power loggers' place of installation procedure

Figure 48 represents a data set that compares the temporary power logger data with log sheet data. Highlighted in the figure are points of data which differ significantly. The temporary logger recorded the similar data, as seen by the matching profiles, but did not measure all the auxiliaries. When the additional auxiliaries were started the temporary power logger could not record their impact.

This part of the proposed procedure can be used to identify if the temporary power logger is measuring the correct power usage for the ECM. The results will show either that the temporary power logger was setup incorrectly upon installation, where the data would be biased or have a time shift. Or that the temporary logger was installed on the incorrect feeder or bus, which generally results in data discrepancies as highlighted in Figure 48. If this is the case then the temporary power logger should be installed on the feeder which contains all the auxiliaries.
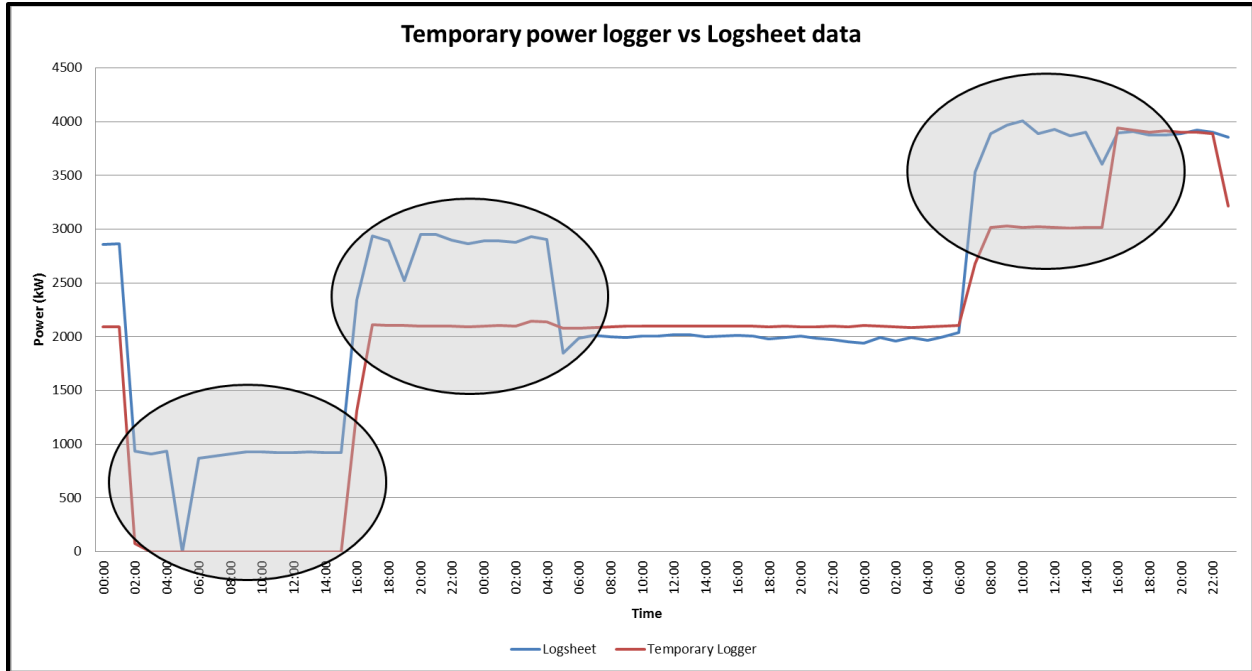
Figure 48: Temporary power logger not installed on correct electrical bus

4.3.3 Case Study 3.2 – Verify log sheet data with SCADA data

Electronic SCADA data might be available, but only for a short period of time in the worst case scenarios. In most cases however, log sheet data can date back for a few years. This case study provides evidence that log sheet data recorded in hourly intervals can closely represent data that is recorded by the SCADA. SCADA data is generally recorded every two minutes which can reflect a truer power usage average over an hour.

Data recorded in two minute intervals (high resolution) will give a closer representation of the average hourly power usage of the load, as mentioned in Chapter 2 regarding the sampling rate. Detail is sacrificed when data is recorded in hourly intervals. Therefore it is best to only use hourly recorded log sheets for a load that does not get turned on and off often within an hour.

Figure 49 represents a data comparison between SCADA and log sheet data. The highlighted sections differ due to the lower log sheet resolution. Log sheet data shows that the load has been turned off where the SCADA data shows a lower averaged power usage over the same period. This could be due to the load being turned on and off numerous times through the highlighted period.
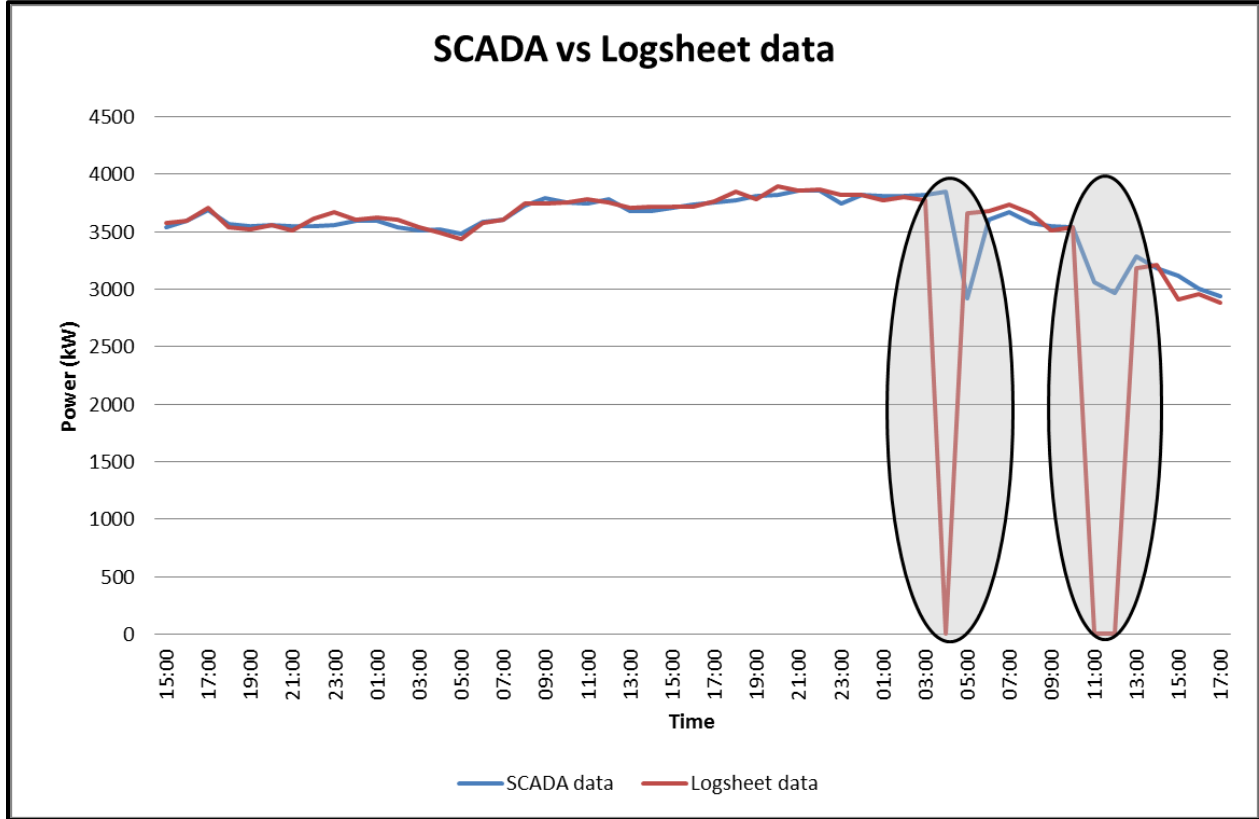
Figure 49: Log sheet data verified with SCADA data

The log sheet data represents the SCADA data with an overall accuracy of 5.19%, including the highlighted issues. Log sheet data, before the highlighted sections, represents the SCADA data with an overall accuracy of 0.25%. The majority of the error is therefore due to the resolution the data is recorded with.

The close fitting data proves that data obtained from the client, such as log sheet or SCADA data, can be used to verify the place of installation for the temporary power logger. If the load is turned on and off often during an hour, data recorded with a higher resolution than hourly intervals should rather be used.

4.3.4　Case Study 3.3 – Bias between temporary power logger and log sheet

A small bias or offset is not uncommon between temporary power logger recordings and log sheet data. Log sheets are commonly used to record load status and/or to reflect load running hours. Therefore when the data is recorded on the log sheet it can either be reflected with a 1 or a 0, which represents the load status on or off.

When power usage is calculated with log sheet data, the installed power capacity is often multiplied with appropriate load efficiency. An average overall bias of 103 kW is reflected in Figure 50, where the temporary power logger has the higher power reading.
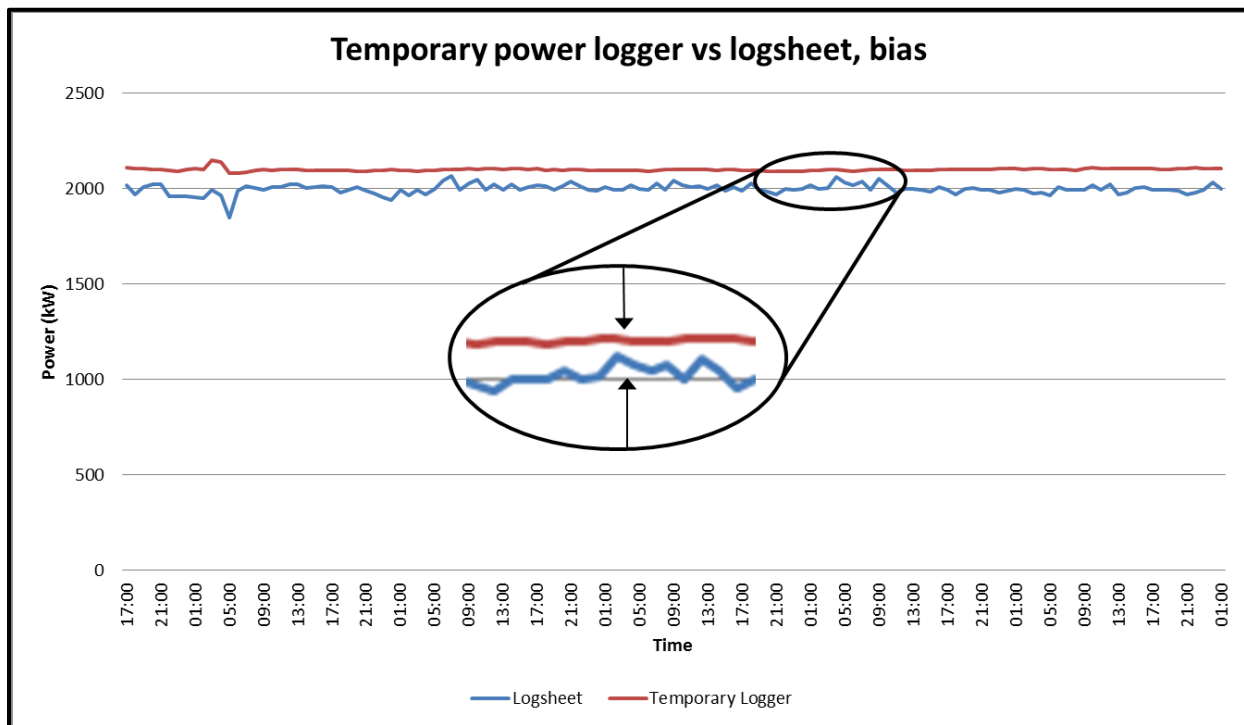
Figure 50: Biased results between a temporary power logger and log sheet

Biased results can negatively affect the reflected target savings in an ECM. The biased results can be caused by incorrect setup of CT and VT ratios on the temporary power logger. Or it could simply be based on a poor estimate of the load efficiency when calculating the total power used by the load.

4.3.5   Case Study 4–Verify newly installed permanent power logger

The part of the proposed procedure that is used in this case study is highlighted in Figure 51. During the implementation of the ECM a permanent power logger will be installed. The power logger will be used to reflect the savings of the initiative for the life of the project, post-implementation. Before the temporary power logger is removed from site, it is essential to compare the two different readings between the permanent and temporary loggers.
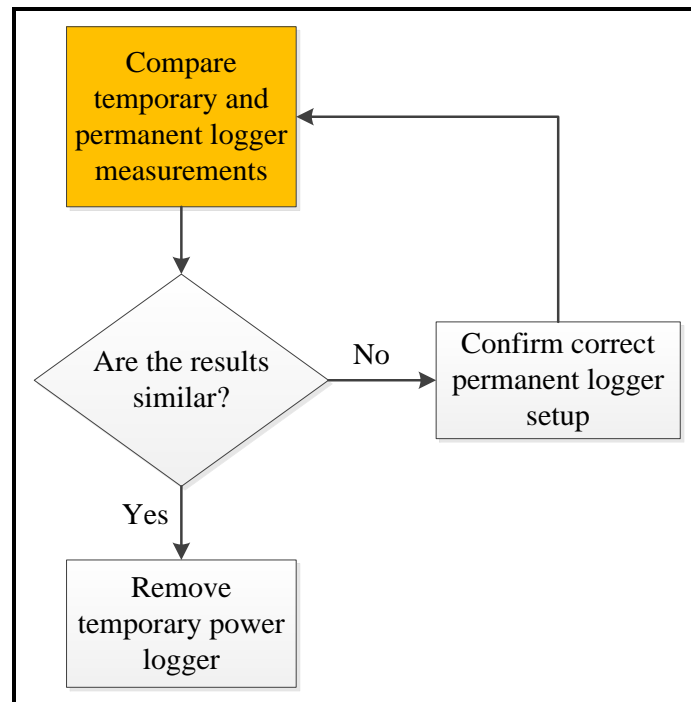
Figure 51: Verify newly installed permanent power logger procedure

Figure 52 shows the comparison of power usage recorded by a temporary and permanent power logger. The permanent power logger measurement is accurate to 2.28% of the measurement recorded by the temporary power logger. As the baseline was recorded with the temporary power logger, the future reflected energy savings will have an accuracy of 2.28%.

This is an important part to the procedure, as the baseline power usage was recorded using the verified temporary power logger. Future power savings for the project will be reflected using the power usage measured by the permanent power logger. If the results differ the overall reflected savings for the ECM will be negatively affected. Be it a smaller or larger reflected power savings

one of the stakeholders will be negatively impacted. The ESCO will be negatively impacted with the smaller power savings, whilst the power utility is negatively impacted with the "larger" power savings.
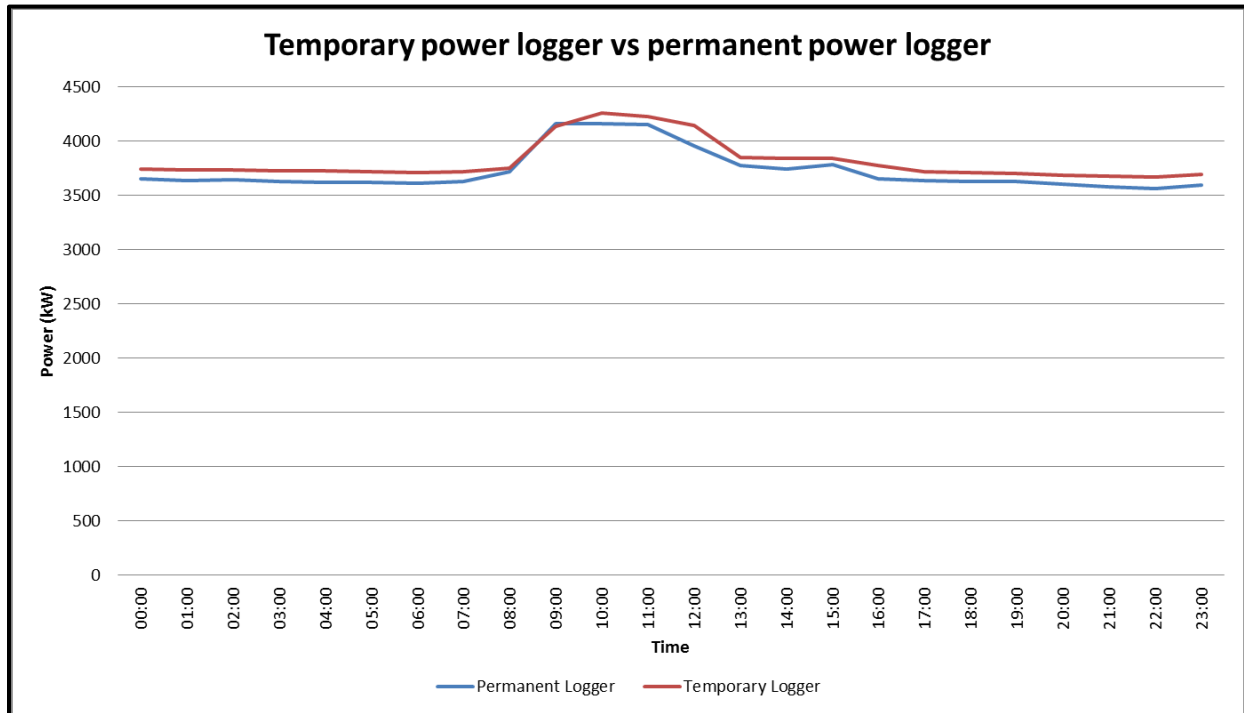
Figure 52: Comparison between temporary power and permanent power logger

4.4 Verification of permanent power logger

4.4.1 Overview

More detailed case studies are given for the third part of the proposed procedure. The steps for the verification of the permanent power logger that were focussed on are highlighted in Figure 53. Case Study 5.1 shows how the proposed procedure can be used to help identify differences between the temporary and permanent logger measurements.

In Case Study 5.2 the procedure helps identify an error with the setup on both the temporary and permanent power loggers. It lastly concludes reflecting how the correction of the setup impacted the power measurements.
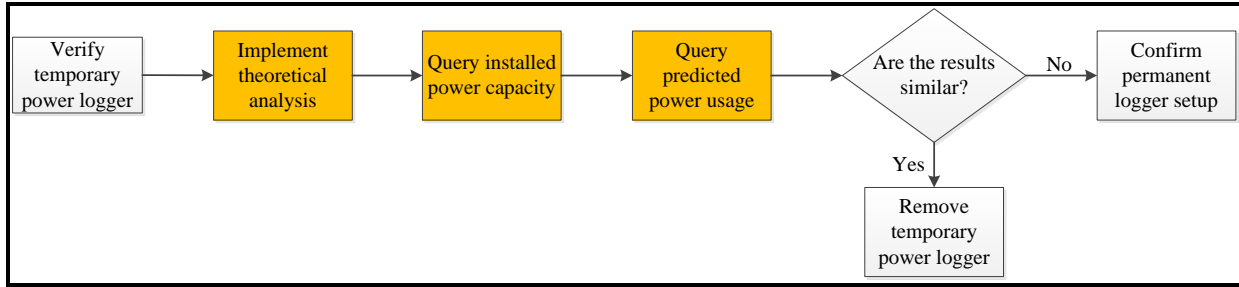
Figure 53: Verification of permanent power logger procedure

4.4.2 Case Study 5.1 –Incorrect CT ratio on permanent logger

Figure 54 represents the different daily averaged power usage values for an industrial sized air compressor namely, permanent power logger, temporary power logger, installed capacity and the results of a theoretical calculation. All formulas used for the theoretical calculation can be found in Appendix A, "Industrial compressor theoretical power usage calculation". A full description of the formulas can also be found there.

The installed capacity of the compressor is 3.95 MW, using the values listed in Table 10, the theoretical calculation reflected a power usage of 3.092 MW and the temporary power logger gave an average of 3.42 MW over the day. The permanent power logger recorded an average usage of 1.19 MW for the day. Therefore it is safe to conclude that there is an error with the permanent power logger. All power usage data points were obtained on the same day.
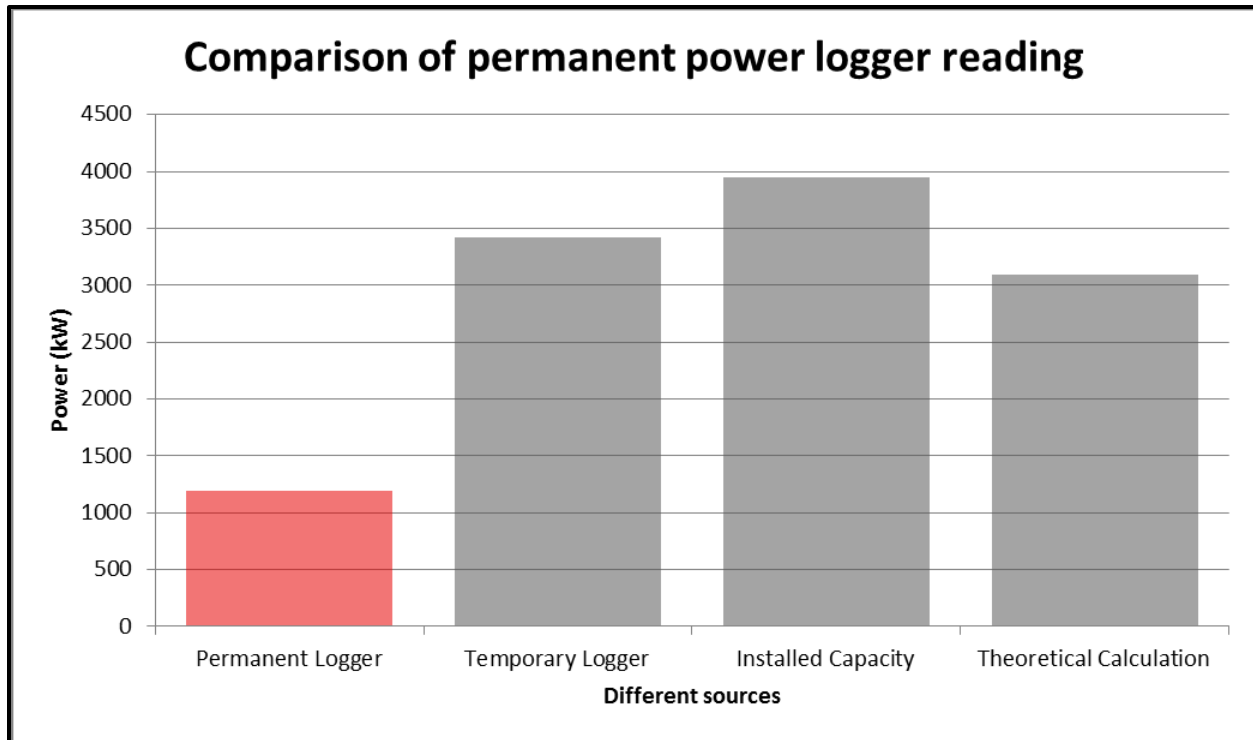
Figure 54: Verifying permanent power logger measurements

An external company came to a similar conclusion and found an error with the CT ratio on the permanent power logger[16]. The permanent power logger was setup incorrectly upon installation. The application of the procedure highlighted an issue with the permanent power logger. Case Study 5.2 will investigate the cause of a similar event in greater detail.

In this case the temporary power logger would have been sufficient to verify the incorrect measurements by the permanent power logger. The installed capacity and theoretical calculation was used to validate that the measurement was incorrect. If the measurement of the temporary power logger is between the calculated and the installed capacity, then it can be assumed that the instrumentation transformers are not saturated.

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[16]The author of this thesis can be contacted for further documentation if needed.

4.4.3 Case Study 5.2 –Time shift and incorrect CT ratio

The results of a permanent power logger that was installed on a rock winder at a gold mine needed to be verified. A temporary power logger was installed to verify the measurement of the permanent power logger. A two hour time shift between the temporary and permanent power logger was identified, shown in Figure 55.

Upon perusal of the time shift an external company later came to a similar conclusion and corrected the issue. It was found that the permanent power logger's time was two hours early. Figure 55 also shows little difference between the two power loggers' measurements, both loggers recorded approximately the same power usage for the rock winder.
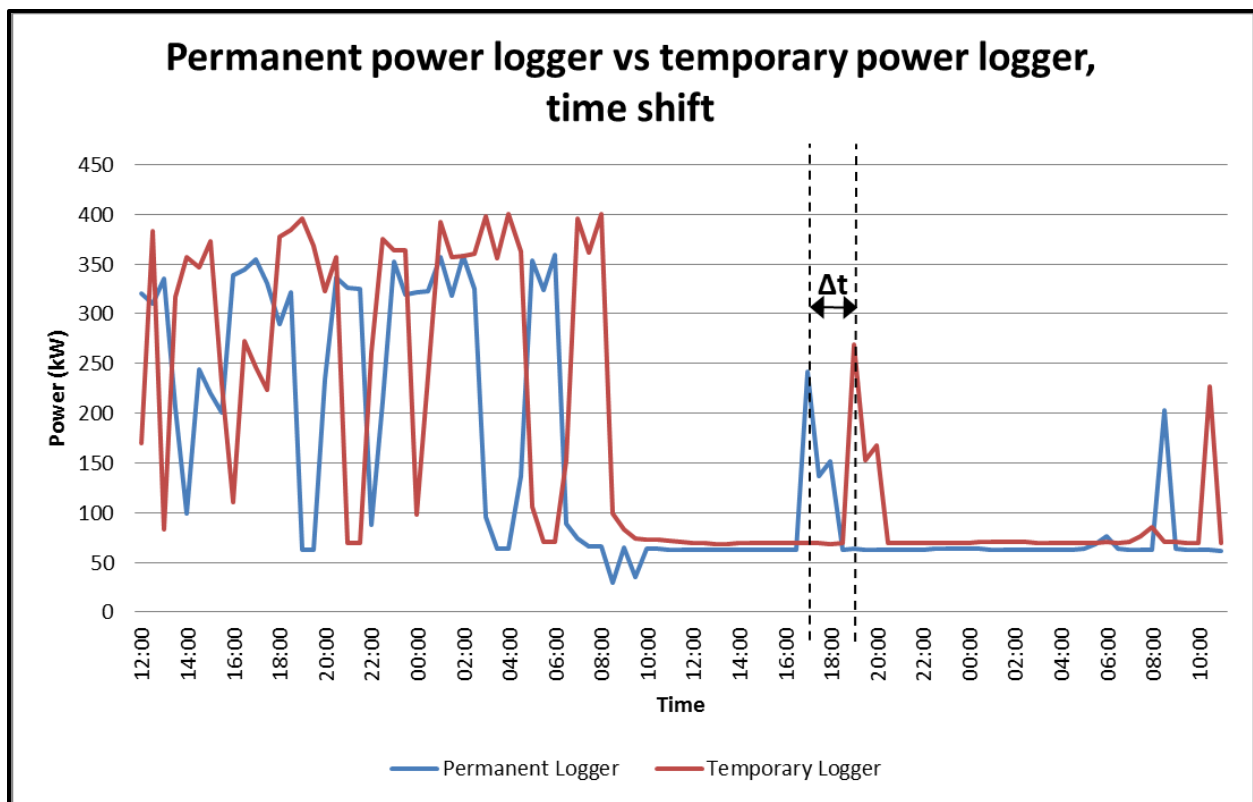
Figure 55: Using a temporary power logger to verify a permanent power logger

Following the proposed procedure, mentioned in Chapter 3, the next step is to validate the recorded power measurements with a theoretical calculation. The formulas used along with a

description there of can be found in Appendix A, "Rock winder theoretical power usage calculation".

It is important to mention that the calculation of the electrical power will always be lower than the measured power usage. The calculation for the rock winder power usage does not take into consideration any power that is used to keep it stationary. Therefore a 0 kW is calculated instead of the average 300 kW which is used to keep the rock winder stationary. It is therefore a good estimate which represents the lowest possible power usage for the rock winder.

After the time shift was corrected the permanent power logger data was compared to the theoretical calculation, the comparison is shown in Figure 56. The rock winder power usage calculation (SafeWind calculation) showed that the power recorded by the power loggers was incorrect. After further investigation it was found that the permanent and temporary logger was setup using an incorrect CT ratio. The power loggers were initially setup with a CT ratio of 600:5 instead of 600:1.
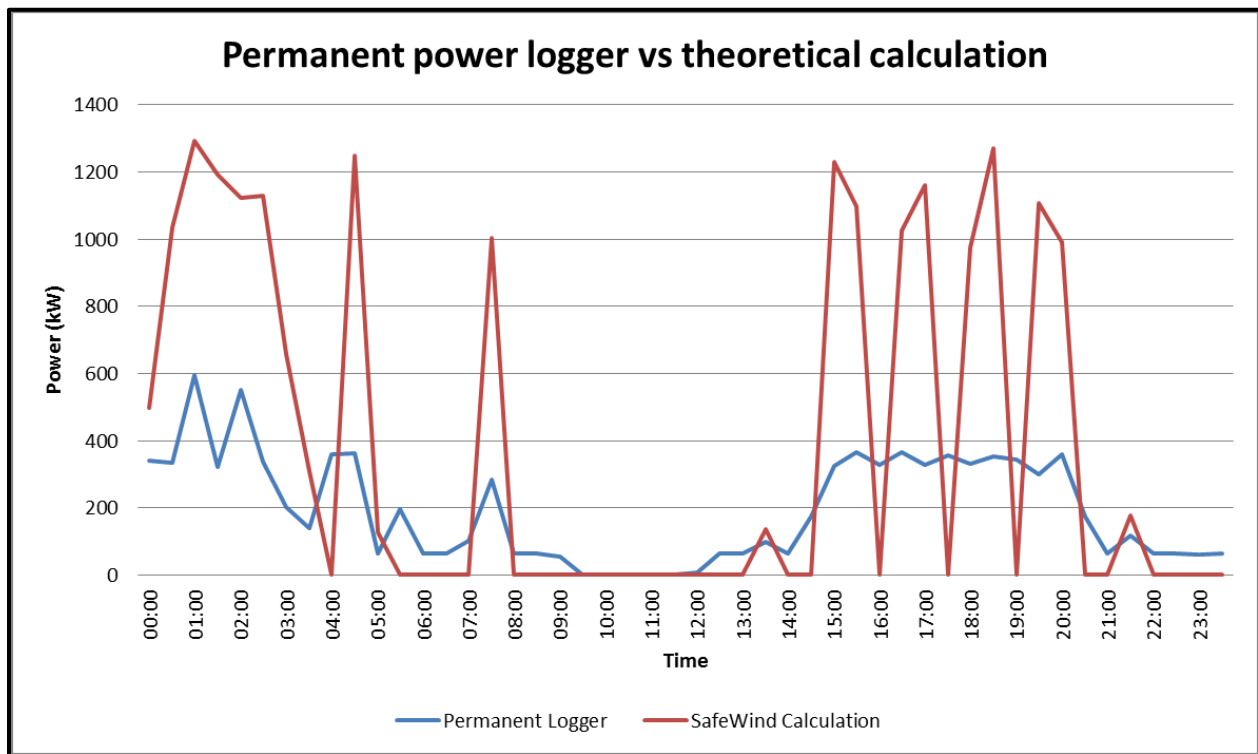
Figure 56: Comparison of theoretical calculation and measured results with incorrect CT ratio

Figure 57 shows the comparison of the permanent power logger data against the rock winder power usage calculation after the CT ratio was adjusted[17]. It was clear that the power usage recorded by the permanent logger was higher than the calculated result. This should not raise suspicion, as the theoretical calculation reflects the lowest possible power usage for the rock winder. The mines energy budget had predicted an average usage of 1.65 MW for the rock winder, which was close to what the permanent power logger was recording.
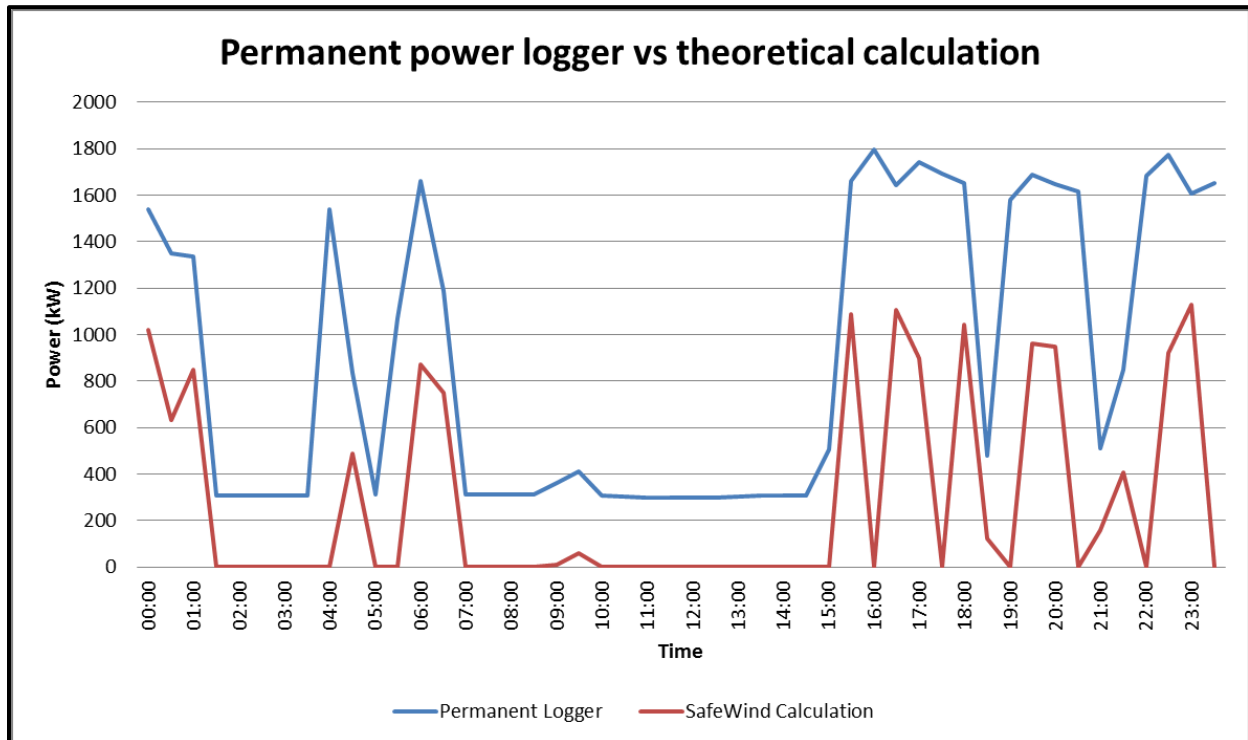
Figure 57: Comparison of theoretical calculation and measured results with correct CT ratio

A comparison of the instantaneous measurements is shown in Figure 58, for the rock winder power usage. Mine personnel predicted a power usage of 1.65 MW, which is represented in the bar chart by the red striped line on top. The bottom red striped line depicts the theoretical calculation of the power usage.

The red bars represent the measurements of the temporary and permanent power loggers before the CT ratio issue was corrected. It is clear that both measurements are well below the minimum

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[17]The CT ratio was changed by an external company.

theoretical calculation. As stated above, the power loggers' measurements should be higher than the theoretical calculation.

The grey bars represent the respective measurements after the CT ratio was corrected. These results are within the expected parameters; this is because both power loggers recorded power usage values between the theoretical and predicted values.
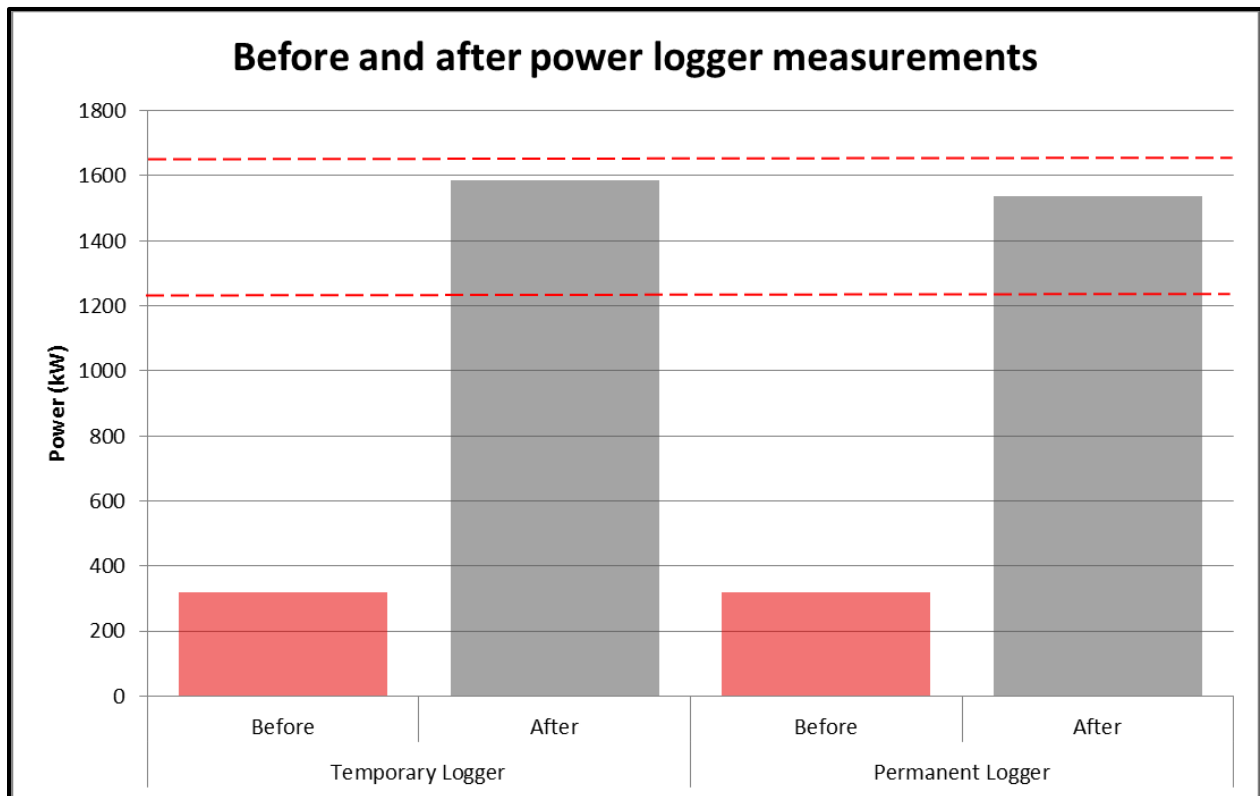
Figure 58: Comparison of measurements before and after incorrect CT ratio error

It was proven in this case study that the proposed procedure for the permanent power logger can not only find saturated instrumentation transformers, but can also identify power loggers that have been setup incorrectly. Client personnel might have forgotten the measuring CT ratios, because the permanent power logger might have been installed a long time ago. Therefore it is required to validate the measurements recorded by the power loggers with at least the theoretical analysis.

4.5 Conclusion

The proposed verification procedure can help identify possible issues that can be experienced whilst measuring power usage. This contributes toward increasing the overall accuracy of the measurements. A simple test circuit was built and used to verify the measurements of the temporary power loggers. Typical instantaneous waveforms that are expected on site were shown, where the waveforms showed no signs of saturation.

Evaluation of data recorded proved that log sheet and SCADA data can be used to confirm the temporary loggers' place of installation. Discrepancies between the data sources were highlighted with the plausible explanations covered by the proposed procedure. Expected results between the temporary power logger and the newly installed power logger were given, which was used to verify the measurements of the newly installed power logger.

The procedure used to verify a permanent power logger during the post-implementation period was used to identify incorrect power measurements recorded by permanent power loggers. The importance of validating the measurements of both the power loggers with the theoretical analysis was shown. As both the temporary and permanent power logger can be setup incorrectly or could be measuring with the same faulty instrumentation transformers.

The verification procedure was verified by implementation on actual industrial case studies. The results were further validated by comparing it against results obtained from external parties or alternative methods.

CHAPTER 5

"Education is not the learning of facts, but the training of the mind to think." – Albert Einstein

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Post-implementation power usage is compared against the pre-implementation power usage to reflect the achieved power savings of the ECM. Between the pre- and post-implementation stages power usage is measured using various components. Numerous components and methods can be used to measure and record power usage, where each method and component has different accuracies and weaknesses.

It is common for any ECM to use different power loggers during the life cycle of a project. Power measured from two different sources can differ significantly, which can impact the accuracy of the measurement over the life cycle of the project. If power is not measured accurately and consistently the ESCO, utility supplier or the client can be negatively affected.

Measuring power usage with temporary and permanent power loggers was the main focus of this dissertation/thesis. The accuracy of all the components and ADC process of the power loggers was investigated. A study was conducted on the background, issues experienced and current solutions for instrumentation transformers. Further investigation involved the achievable accuracies of the temporary and permanent power loggers available on the market today.

The conclusion for the literature study indicated that the reviewed equipment had generally acceptable accuracies. It however, found that accuracies can be affected during the installation of the measuring equipment. This identified the need for a verification procedure which can be followed to improve the overall measuring accuracy for any ECM.

A procedure was developed to identify any possible power data discrepancies and solve common issues experienced when measuring power. The procedure first highlights a need to verify the accuracy of the temporary power logger that will be used to measure the baseline. Once the accuracy of the temporary power logger is verified it can be installed on site, where the instantaneous measurements and waveforms are viewed locally. Viewing the instantaneous measurements and waveforms confirms the correct setup and installation of the temporary power logger.

The procedure then evaluates the place of installation for the temporary power logger. This is done by comparing the data against information obtained from the client. If any discrepancies are noticed during this stage it means the temporary power logger has been installed on the incorrect location.

After the baseline has been recorded a permanent logger is installed to replace the temporary logger. The permanent loggers' measurements are verified with the temporary logger, before it is removed. This way it can be ensured that the measurements during the reporting period and baseline period are similar. Current M&V protocols do not include the need to compare the baseline data to the reporting data. Therefore this step is of utmost importance to ensure overall measurement accuracy throughout the life cycle of the ECM.

Lastly the procedure develops a method to verify the measurements of a permanent power logger that has been installed for a long period of time. The method requires the installation of a verified temporary power logger, theoretical power usage calculation and querying the budgeted power usage and installed capacity. All the data is later compared and evaluated. The permanent and temporary loggers' measurements need to be between the theoretical calculation and the installed capacity to be acceptable.

The new procedure was applied to numerous case studies, to verify its effect. A test circuit was designed and built in Case Study 1. The test circuit was used to verify the measurements of temporary power loggers before installation. Case Study 2 shows what the typical instantaneous waveforms should look like on site, which assists with identification of saturated instrumentation transformers.

Case Study 3 compared log sheet data against the measurements recorded on a temporary power logger. The comparison identified a 1 MW auxiliary load that was not measured by the installed equipment. It also confirmed that the SCADA and log sheet data can reflect similar results, therefore SCADA or log sheets can be used to verify measurements of a temporary power logger. The last section in Case Study 3 identified an average bias of 103 kW, between a temporary power logger and log sheet data. The bias can negatively affect the reported savings. Therefore instantaneous measurements are inadequate to confirm the temporary loggers' place of installation.

Case Study 4 compared the results of the temporary power logger against that of a newly installed permanent power logger. The results differed by 2.28%, which roughly reflected a bias of 80 kW between the power measurements. This confirms the significant impact a potentially small deviation can have. The procedure is therefore very important to detect and mitigate potential issues.

The final part of the procedure was tested in Case Study 5. The first scenario identified a 2.2 MW difference between the temporary and permanent power logger measurements, due to an incorrect CT ratio. The data discrepancy was validated by comparing the measurements to a theoretical calculation and the installed capacity. Another scenario identified a time shift between the temporary and permanent loggers. After validation of the measurements, it was discovered that the temporary and permanent logger had incorrect CT ratios. The combined effect of the scenarios would have resulted in an R 16.2 million financial impact for the stakeholders. Validation of the measurements proved to be vital to avoid incorrect setup of power loggers and saturated instrumentation transformers.

The potential for a new verification procedure was identified after the literature study. There is no procedure that mentions the need to compare data recorded during the pre-implementation period, against data recorded during the post-implementation period. The functionality of the procedure was demonstrated in the case studies, where different scenarios were approached and reflected upon. This verified the new procedure which was then validated through comparison of theoretical calculations and installed capacity ratings. After the procedure was applied a significant impact was noted therefore the results can be extrapolated to a national level.

5.2 Recommendations

The study focussed on finding issues and discrepancies related to the measurement of power usage. It was assumed that the measured electrical signal was a pure waveform. There are many factors which can affect the clean electrical signal. Factors such as, unbalanced phases, harmonic distortion, etc. can affect the accuracy of the measurement. A further recommendation would be to study the expected measurement accuracies, with distortions in the signal.

The scope of this study can be increased to include the verification of flow meters, pressure transmitters, temperature probe, etc. measurements. The verification procedure can be adapted for different measurement devices to ensure accurate results.

A separate study can be implemented on external circuitry for instrumentation transformers, which can improve accuracy of old instrumentation transformers. An analysis can be carried out, where the cost of buying new instrumentation transformers is weighed against the costs of adding external circuitry to old instrumentation transformers. This study should include a risk and benefit analysis of how long the additional circuitry will positively affect the saturated instrumentation transformers.

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APPENDIX A

A.1 Test circuit

A.1.1 Preliminary design of the test circuit

Figure 59 shows the preliminary design for a test circuit. The adjustable resistor connector can either be plugged into the 100 Ω or 150 Ω connector affecting the total current in the circuit. A switch either by-passes the inductor or includes the inductor in the circuit. By-passing the inductor will give the circuit a unity power factor. Including the inductor should change the power factor to 0.95 if a 100 mH inductor is used. The connections labelled L1, L2, L3 and N in Figure 59are for the temporary power logger voltage leads.
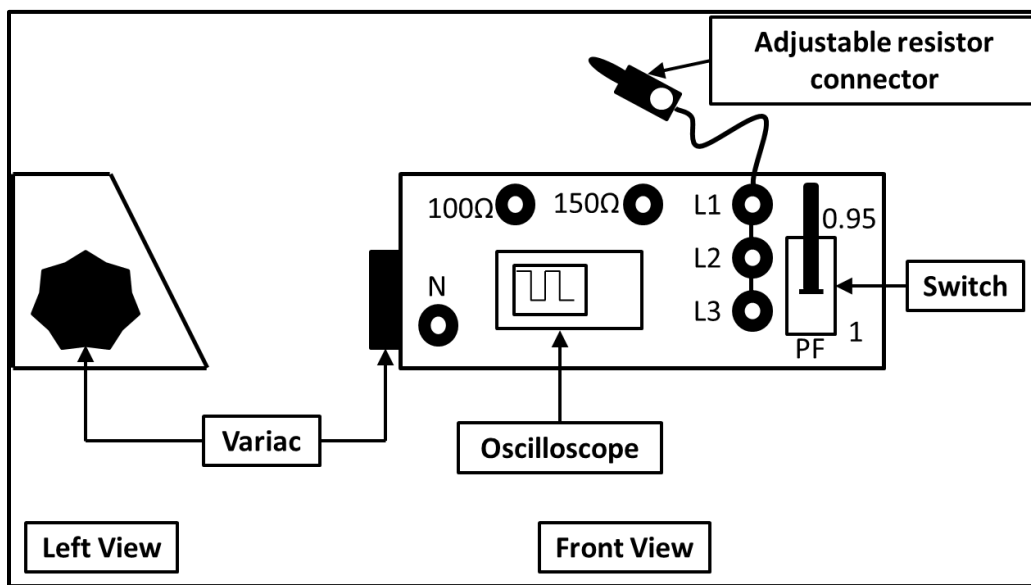

Figure 59: Preliminary design for the test circuit

A.1.2 Method for using the testing circuit

Please note the method stated below will be used for a Dent Logger.

The method requires a connection between the laptop and the Dent Logger. The user then needs to setup the present viewing option for the Dent Logger using the ELOG software on the laptop. Once the graphical present viewing option has been setup the Dent Logger can be connected to the relevant places of the test circuit. The CT's will be connected around the wire connected to

the adjustable resistor connector. L1, L2, L3 and N of the Dent Logger will be connected to the relevant places labelled on the test circuit. With the adjustable resistor connector attached to the 150 Ω port and with inductor by-passed (switch is at power factor 1).

The current probe and passive probe of the oscilloscope must then be connected in the same places where the Dent Loggers measuring leads are connected. The passive probe which measures the voltage must be connected to the L1 port and the current probe around the wire attached to the adjustable resistor connector. The test circuit can now be turned on and results can be compared between that read off the oscilloscope and that displayed on the laptop screen. Power factor can then be altered by switching the power factor switch to the 0.95 position and results can then be compared again.

For different power readings the testing circuit should be turned off and the adjustable resistor connector should be moved to the 100 Ω port. Power factor can then be toggled and results compared against one another. The voltage can also be adjusted between tests to compare different power usage scenarios.

The voltage and power factor were also compared during each test. Overall voltage accuracy was calculated using formula 11.

$$Acc = \left| \frac{Vt_{RMS} - Ve_{RMS}}{Vt_{RMS}} * 100\% \right| \tag{11}$$

Where:

Acc = Overall accuracy (%)

Vt_{RMS} = Voltage measured by the oscilloscope on the test bench (V)

Ve_{RMS} = Voltage measured by the temporary power logger (Elog software) (V)

The accuracy for the current and power factor were calculated similarly, where the current and power factor were substituted in the place of the voltage.

A.2   Theoretical calculations

A.2.1 Industrial compressor theoretical power usage calculation

A permanent power logger is used to record the power usage of an Oerikon[18] compressor at a gold mine needed to be verified. In order to do a theoretical calculation of the electrical power consumed by the air compressor, the following formulas were used, obtained from [47], [48], [49], [50] and [51]. To calculate the overall electrical power used by the motor:

$$P_{motor} = \frac{P_{cmp}}{\eta_{motor}} \tag{12}$$

Where:

P_{motor} = Electrical power consumed by motor for the compressor (kW)

P_{cmp} = Power consumed by compressor to compress air (kW)

η_{motor} = Electrical motor efficiency

In order to calculate the power consumed by the compressor, the following formula was used:

$$P_{cmp} = m_{air} W_{cmp} \tag{13}$$

Where:

P_{cmp} = Power consumed by compressor to compress air (kW)

m_{air} = Mass flow rate achieved by compressor (kg/s)

W_{cmp} = Mechanical energy used to compress air (kJ/kg)

To convert volume flow rate to mass flow rate the following formula was used:

$$m_{air} = Q\rho \tag{14}$$

---

[18]Make of an industrial air compressor.

Where:

m_{air} = Mass flow of air achieved by compressor (kg/s)

Q = Volume flow rate (m³/s)

ρ = Density of air subject to different temperatures (kg/m³)

Calculation of the mechanical power required the use of the next formula:

$$W_{cmp} = \frac{nRT_{in}}{\eta_{cmp}(n-1)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1-\right] \tag{15}$$

Where:

W_{cmp} = Mechanical energy used to compress air (kJ/kg)

n = Polytrophic constant for isentropic compression

R = Gas constant (kJ/kg.K)

T_{in} = Compressor inlet temperature (K)

η_{cmp} = Compressor efficiency

p_2 = Discharge pressure for compressor (kPa)

p_1 = Inlet pressure for compressor (kPa)

The following values, shown in Table 10, were used in order to calculate the theoretical power used by the compressor. Lower than normal efficiencies were used for the compressor and the electrical motor, this was due to the age of the air compressor.

Table 10: Constants and values used to calculate theoretical power used by the compressor

Parameter	Value used
n	1.4
R	0.278kJ/kg.K
T_{in}	300 K
η_{cmp}	0.65
p_2	480kPa
p_1	102kPa
Q	8m³/s
η_{motor}	0.75
ρ @ 30°C	1.16kg/m³ [19]

A.2.2 Rock winder theoretical power usage calculation

In order to do the theoretical power calculation for the rock winder the following formulas were used, obtained from [52] and [53]:

$$P_{winder} = \left[\frac{mgd}{3600}\right] S_{factor} \tag{16}$$

Where:

P_{winder} = Electrical power consumed by motor for the winder (kWh)

m = Mass of the load in skip (tonne)

g = Gravitational acceleration (m/s²)

d = Vertical hoist height for the winder (m)

S_{factor} = Scaling factor

The scaling factor can best be described by the following equation:

$$S_{factor} = \frac{1 + F_{factor}}{\eta_{factor}} \tag{17}$$

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[19]Parameters selected are based on information gathered from industry personnel.

Where:

S_{factor} = Scaling factor

F_{factor} = Friction factor, the friction load for the winder

η_{factor} = Efficiency factor, the efficiency of the winder

Table 11 represents the constants and variables used to calculate the power used by the winder. The mass of the load in the skip varies per hoist within the range of 0 and 35 tonne.

Table 11: Constants and values used to calculate theoretical power used by the winder [20]

Parameter	Value used
m	Varies per hoist (tonne)
g	9.81 m/s^2
d	1750.9 m
F_{factor}	0.18
η_{factor}	0.99

---

[20]Parameters selected are based on information gathered from industry personnel.