MITIGATION FOR FLOATING NEUTRAL IN DISTRIBUTION SYSTEMS

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A dissertation submitted in partial fulfillment of the requirements for the degree

Of

Master of Science in Electrical Engineering

College of Agriculture, Engineering and Science, University of KwaZulu-Natal

2019

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ACKNOWLEDGEMENTS

Let me begin by thanking God the almighty for the blessing of wisdom, courage and intellectual capacity that assisted me to complete my research.

I express my sincere appreciation and gratitude to the following people who contributed immensely for the successful completion of my Masters Programme:

Dr A Saha who is an Associate professor, Electrical Engineering Academic Leader Research and Higher Degrees in school of Engineering. The support, guidance and continuous encouragement contributed so much under difficult conditions for me to complete the programme.

Eskom Centre of Excellence in HVDC Engineering based at University of KwaZulu-Natal, Eskom management for allowing me to conduct the research on a subject relating to the impact of the product that Eskom supplies to our valuable customers. Mr Dumisani Mtolo and Mr Shawn Papi from Eskom Research Institute for allowing me to use your test laboratory to conduct the research.

My colleagues and friends for your interest in the work that I was doing as well as the continuous support that you gave me. I dedicate this dissertation to my family, especially my wife, Colleen and my three boys (Hlulani, Katekani and Nkhesani) for their support, understanding and patience when I almost became an absent father for the period that I was busy with my studies. I will forever be indebted to you for the quality time sacrificed to complete my studies.

ABSTRACT

The rollout of electrification programme in deep rural communities has significantly improved the quality of life for people of South Africa, some who never anticipated that they would have access to electricity. Most rural community members start saving and buy electrical appliances like refrigerators and televisions as soon as they become aware that they are going to have aces to electricity in the following year. A broken neutral conductor in the electrical network always leaves a devastating impact to the customers connected to that network especially in poor rural communities. The resultant damage to their electrical appliances is regrettable especially considering that the majority of electrification beneficiaries cannot afford to install their own protection devices. An engineering solution integrated to the current protection philosophy was required to mitigate against such type of network failures.

The main aim of the study was to have a better understanding of the current network protection philosophy of the electrification projects, protection capabilities of the current installed devices and equipment and recommend improvements to address gaps identified with the purpose of improving customer's experience of the services that some waited for lifetime to receive. The literature review and laboratory experiments conducted revealed that the current protection philosophy focused more on protection against over current and earth leakage faults. There was minimal effort on overvoltage and under-voltage protection on the customer's point of supply. Over voltage and under voltage are normally the fault conditions experienced by customers when the neutral conductor in the distribution system is broken.

The current protection philosophy and practice in distribution were tested against the regulatory and statutory requirements. The philosophy and practices complied with the regulatory and statutory requirements. However, the compliance does not take way the impact the fault have on customers. A responsible supply authority can go an extra mile to protect the customer's equipment they supply from network faults though it is not a minimum requirement. Considering the social status of the electrification beneficiaries, the provision of the overvoltage and under voltage protection to distribution customers will be a social contribution of a responsible supply authority and a minimal cost to the company compared to the consequential damage that floating neutral have on customers. Current available technology in the market as well as simulations conducted on Multisim and PSIM demonstrated that there are implementable viable solutions to mitigate and minimize the risk of damage against broken neutral conductor faults. The analysis of the results obtained during the study confirmed that current protection is not adequate and that there is a need to relook at the protection requirements to cover over voltage and under voltage protection. Refinements in the current minimum protection requirements were recommended for implementation.

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LIST OF ABBREVIATIONS

A	Ampere
ABC	Aerial Bundled Conductor
AC	Alternating Current
CIU	Customer Interface Unit
COC	Certificate of Compliance
CSP	Complete Self Protected (Transformer)
DC	Direct Current
ECU	Electricity Control Unit
ED	Electricity Dispenser
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPC	Insulated Piercing Connector
IT	Terre Isolated
kV	Kilo Volt
kVA	Kilo Volt Ampere
kW	Kilo Watts
L_{in}	Line in
L_{out}	Line out
LPU	Large Power Users
LV	Low Voltage
MV	Medium Voltage
MVA	Mega Volts Ampere
MW	Mega Watts
N	Neutral
NERSA	National Electricity Regulator of South Africa
NGL	Normal Ground Level
NRS	National Regulatory Services
OHL	Over Head Line
OPAMP	Operational amplifier
PE	Protective Earth
PEN	Protective Earth and Neutral
PTB	Pole Top Box
Q	Transistor
R	Resistor

RCD	Residual Current Device
RV (VR)	Variable Resistor
SABS	South African Bureau of Standards
SANS	South African National Standards
SPU	Small Power Users
TN	Terre-Neutre
TN-C	Terre Neutre – Combiné
TN-C-S	Terre Nezutre–Combiné–Séparé
TN-S	Terre Neutre – Séparé
TT	Terre-terre
V	Voltage
V_{in}	Input Voltage
V_{out}	Output Voltage
V_{REF}	Reference Voltage
V_s	Supply Voltage
W	Watts

CHAPER 1: INTRODUCTION

1.1 Background

A floating neutral occurs when the neutral conductor of the distribution system supplied by two phase or three phase is broken resulting in phase to neutral voltage rising up to the line voltage or dropping drastically up to almost zero voltage. A broken neutral conductor in the electrical network always leaves a devastating impact to the customers connected to that network especially in poor rural communities because the over voltage or/and under voltage created has a potential to damage connected customer appliances. The rollout of electrification programme in deep rural communities has significantly improved the quality of life for people of South Africa, some who never anticipated that they would have access to electricity. The damage to customer appliances when a floating neutral conductor occurs especially in poor rural communities is regrettable and there is a need for Eskom and other supply authorities to look at technical solutions that can assist to mitigate the risk.

1.2 Importance of the research

The drive for mass electrification roll out in South Africa is more of a social responsibility than being profit driven. Considering that the beneficiaries of the programme are mostly poor people who cannot afford sophisticated installations that will ensure protection of their equipment against power surges. As responsible corporate citizens, supply authorities need to consider inclusion of over voltage and under voltage protection in the network as minimum requirement to cover for such eventualities. Eskom is a customer centric organization, minimising or totally eradicating damage to customer equipment and appliances will definitely have a positive impact of how the customers perceive the electricity distributor. It will also have a positive benefit of reduction in litigation cost as well as settlement of public liability claims for damage equipment due to broken neutral faults.

1.3 Aim of the research

The main objective of the study is:

- Review of current available literature to have better understanding of what floating neutral is and what are the causes.
- Evaluate the adequacy of the current protection systems in addressing the identified problem.
- Conduct laboratory tests on listed devices to determine level of protection they offer.

- Investigate other means of protection based on the short comings that would have been identified on current available technologies for further research and development.

1.4 Hypothesis

The current protection philosophy employed in distribution systems is not adequate to protect the customer equipment against over voltage and under voltage caused by floating neutral in distribution systems.

1.5 Research question

The main research question is:

What refinements are required in the current distribution systems for protection of residential customers against floating neutral condition?

1.5.1 Subsidiary questions

In order to answer the main question raised above, the following key questions below need to be addressed.

- What is the impact of a broken neutral in distribution systems?
- Which part of the network on the distribution system will be impacted by a broken neutral condition and under which circumstances?
- What are the main causes of broken/floating neutral?
- What can be done to prevent a broken/floating neutral condition?
- What protection systems are currently available in the market to mitigate for a broken neutral condition?
- What are the limitations with the currently available protection systems and equipment?
- What can be done to improve on the current available protection systems and equipment?

1.6 Thesis structure

Chapter 1 gave background and over view of the project and what the research aim to achieve. Important questions that need to be answered in order to achieve the research objectives are also outlined in the chapter.

Chapter 2 covers literature review related to the problem of floating neutral in distribution systems, work that has already been done on the subject and areas that still require attention. The dangers as well as the causes of the fault condition are covered in the chapter.

Chapter 3 deals with the research methodology outlining the methods and techniques used to test the hypothesis. It also look at the current distribution low voltage network layout and protection philosophy.

Chapter 4 covers the metering units capability tests where laboratory testing was conducted to determine the level of protection available in the distribution networks. Data analysis was conducted followed by detailed discussion of the results obtained from the laboratory experiments conducted. The results were then be compared with the hypothesis and information gathered from the literature review.

Chapter 5 outline the design of the circuit that was designed aimed at addressing the identified gaps on existing protection philosophy. Simulations were also conducted with Multisim to verify and confirm functionality as well as comparing with the circuit that was built.

Chapter 6 finally concludes the research with summary of the results obtained with scope for future research that can be undertaken which were identified during the research.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Literature review was conducted to determine the amount of research already conducted on of mitigation for broken neutral conductor in distribution systems and to minimize duplication on the work that has already been covered [1]. From the literature study conducted, it became very clear that there was limited academic sources available on mitigation for broken neutral conductor in distribution systems. However, there were available studies on impact and consequences of broken neutral conductor in distribution systems [2] [3] [4]. Due to limited availability of research on mitigation for broken neutral in distribution systems, the researcher used an approach of focusing on the consequences of broken neutral conductors as well as the causes of such network failures to get to the mitigation measures. Broken neutral conductors in distribution systems has a devastating impact on connected customers especially those in rural communities with limited knowledge about electricity. Research on impact of broken neutral in distribution systems identified the risk of damage to connected customer loads and creation of hazardous touch voltages on exposed conductive parts [2] [4]. The damage to connected customer appliances are because of voltage fluctuations, which result in both over voltage and/or under voltage. Power quality in electrical systems often results in public liability claims mostly when they end up damaging customer's valuable electrical appliances and equipment.

Since the promulgation of the consumer act in 2008, customers have become more conscious about their rights and they explore all possible avenues for compensation when they experience poor quality of supply [3] [5]. In the 2016/2017 financial year, Eskom Enhanced Maxi Care perception survey score declined across all segments. The most common complaints related to how well Eskom informed customers about planned electricity interruptions and the number of power surges and voltage dips in the electricity supply that affected customers [6]. According to the South African distribution network code: "*the distributor's protection system shall be appropriately designed and maintained to ensure discrimination, safety and minimum interruptions to customers*". Customers are also expected to make provision for protection of their own equipment from faults or conditions that may occur at the point of supply [7]. The minimum and maximum voltage limits that will ensure that customer's equipment does not get damaged are well specified in the wiring of premises for low voltage installations and the quality of supply requirements to be 10% of the nominal voltage (between 207 V and 253 V) [8] [9].

The literature review will focus on three important elements identified as being the main impact of broken neutral conductor: (a) Damage to customer equipment – Overvoltage and under-voltage

(b) Dangerous touch voltages on exposed conductive surfaces.

2.2 IMPACT OF BROKEN NEUTRAL IN DISTRIBUTION SYSTEMS

The impact of broken neutral conductor in distribution systems was clearly documented by [2] and field experience was observed by [3]through customer claims that were submitted because of broken neutral conductors. The above were supported by simulation studies as well as laboratory experiments conducted at the University of Kwa-Zulu Natal by [4]. The risk of broken neutral in distribution systems was also acknowledged by [10] with the promulgation of the amended revision to allow wider choice of earthing systems [4].

2.2.1 Damage to customer equipment

Over voltage and under-voltage were identified as the main causes of damage to customers equipment during broken neutral conditions [2] [11]. The [8] as well as the [12] prescribe overload protection as well as earth leakage protection for wiring of premises. Although the voltage limits are prescribed in [9], the enforcement of compliance become very difficult since it is also expected of the customers to provide protection of their equipment against noncompliance of the distributors during fault conditions [7]. It would be good if the distributors were able to advise customers on availability of devices that customers could install to protect themselves against voltage fluctuations. However, customers has to fend for themselves to ensure protection of their equipment. Considering that the government took decision to provide universal access to electricity, the victims of broken conductor failures are the poorest of the poor who know very little about electricity residing in deep rural areas [13]. Most of the electrification programme beneficiaries are dependent on social grants and it will almost be imposable for them to afford installation of protection devices in their houses. According to [14] on the document published by the technical review care group: "*as a responsible corporate citizen, Eskom has a duty to care for its customers and cannot just walk away from incidents*" that occur in the network. Some of the network faults and failures on the network are due to actions or lack of action on the Eskom side or beyond the point of supply.

The current distribution network protection philosophy does not have any over voltage or under voltage protection from the distribution transformers up to the customer installation [12] [15]. A broken neutral conductor fault in the system will remain undetected by the current protection systems installed. That expose unsuspecting customers to the risk of losing valuable appliances bought with life savings and other life threatening risk of dangerous touch voltages [11] [16]. The introduction of split metering system as well as smart meters paved a way for cheaper options for protection of customers against the potential damage as minimum cost to both the distributors and customers. Minimum adjustments to the current prepayment meters specification were proposed for consideration [17]. The exclusion or omission of voltage protection in distribution networks is not only a South African phenomenon, the literature reviewed does not indicate that there is any country that is installing voltage protection as a minimum standard, though there are protection devices readily available in the market [16] [18]. The overvoltage protection that is provided for is the lightning surge protection, which would not assist in case of the broken neutral condition due to the magnitude of the voltage level [19] [20].

The impact of a broken neutral is very much dependent on the type of distribution system used as a well as the position or location of the neutral failure in the network. The study will focus on TN-C-S system since it is the system widely used in South African distribution networks especially in rural electrification [21] [2] [22]. TN-C-S power system is becoming more widely used across the globe for distribution of low voltage electric power due to economic benefits since the neutral and earth are combined in one conductor. PEN conductor failure on unbalanced three-phase system creates a hazardous condition at single phase installations causing phase to neutral voltages to go beyond regulatory limits and elevated touch potentials that may result in electrocution of people [2] [4].

2.2.1.1 Single phase customers on three phase supply under normal conditions

Figure 2.1 below displays a three-phase distribution network with a combined neutral and earth (PEN). Single-phase customers are connected between any of the phase conductors and a neutral. The phase-phase voltage in the circuit will be 400V and the phase to neutral voltage supplied to the customer houses will be 230V. It is imperative to balance the load while connecting the single-phase customers along the three-phase network to ensure that there is no unbalance created on the three phases. That is done to ensure that the neutral current is as close as possible to zero [23] [18] [24] .

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{400\ V}{\sqrt{3}} = 230\ V \qquad (2\text{-}1)$$

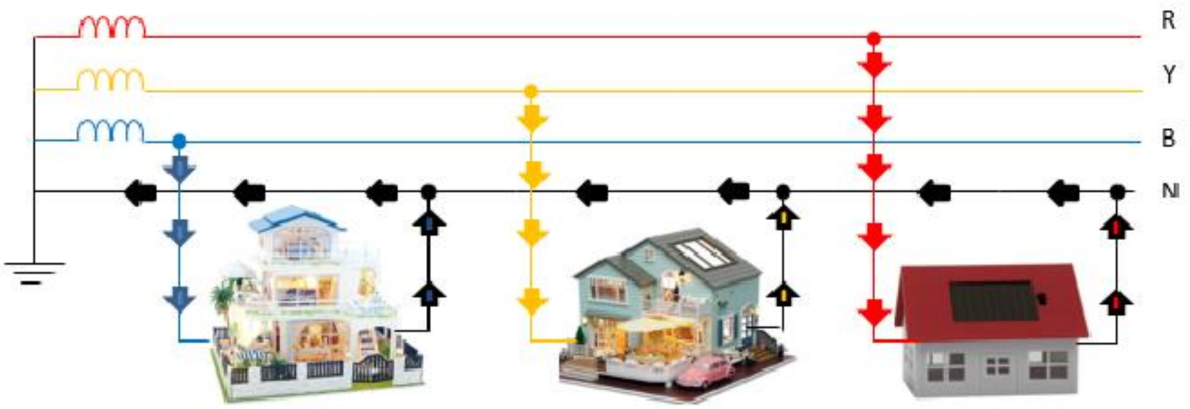

Figure 2.1 Power flow on three-phase supply with single-phase customers under normal conditions

Figure 2.1 above shows the flow of power from the different connected phases to the load under normal operating conditions. For all the connected loads, the neutral is the return path for the current flow resulting in all the customers connected between phase and neutral conductor. The voltage experienced by all customers is the phase voltage, which is 230 V.

2.2.1.2 Single phase customers on three phase supply under broken neutral condition

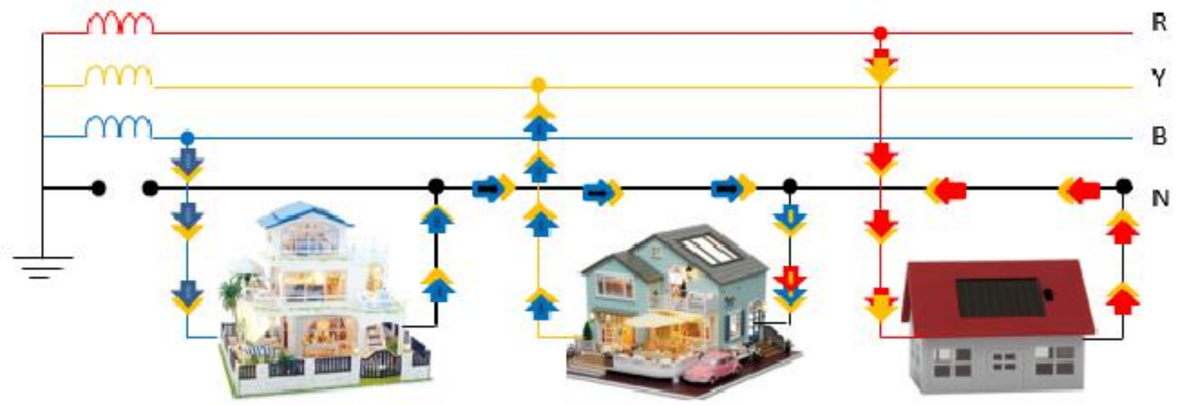

Figure 2.2 Power flow on three-phase supply with single-phase customers under broken neutral conditions

A broken neutral in a distribution network will result in an abnormal situation since there will be no continuity of current flow back to the neutral point as demonstrated in figure 2.2 above. The current from the blue phase that was supposed to use the neutral as a return path end up being directed to return via the red and yellow phase, resulting in them connected to phase-phase conductors instead of phase to neutral. That result in customers connected to the network experiencing voltage fluctuations up to the line voltage instead of the standard phase to neutral voltage of 230V or voltages close to 0 V depending on the load at different customer installations [4] [11].

2.2.2 Dangerous touch voltages on exposed conductive surfaces

The greatest danger identified by [2]on the consequences of a broken neutral conductor in distribution system is the creation of dangerous touch voltages on exposed metallic surfaces and objects. The risk was confirmed by [4] in his Matlab simulations while conducting a study on broken PEN conductor in the context of rural South African household. According to [8]and [12], the installation of RCD or earth leakage protection is a minimum requirement for all electrical installations in South Africa. The need for installation of earth leakage devices to protect people against fatal electrical shock was initially identified in the 1950's, by the underground mining industry of South Africa. That was in response to an electrocution incident where a woman made contact with a standing lamp [14].

All earth leakage devices are supposed to comply with [24]. The biggest electricity distributor in South Africa has more than 5.5million customers with 94% of the customers connected via prepaid meters and the remaining 6% being conventional meters shared by small power users and large power users [25]. The 5.2 million prepaid customers are connected via different technology options depending on the load requirement and the period at which the installation was done. 20A customers who were connected before 2016 are connected via ECU's (Electricity Control unit) and 60A customers were connected using ED's (Electricity dispensers). Customers connected from 2016 are connected via split metering units for both 20A and 60A customers.

According to [8], every electrical installation shall be inspected, tested, and a COC issued to the owner. The supplier shall ensure that an accredited person has issued the COC before connecting to the supply [26]. All 60A customers requesting or applying for connection to the grid need to ensure that the house has been wired with a COC already issued by an accredited person. 20 A customers who are connected via an ECU or split meters are issued with a ready board by the supply authority, which come with an earth leakage unit (ELU) incorporated in it. In 1999, Eskom applied to the chief inspector for exemption on issuing COC's for ECU installations. The ready board that installed in the customer's installation come completely prewired and an abridged COC is issued by the manufacturers of the ready boards, which are completed by the person doing the connection to the house. The person doing the ECU connection does not have to be an accredited person [26] [14].

2.3 IMPACT OF BROKEN NEUTRAL AT DIFFERENT POSITIONS IN THE NETWORK

The impact of neutral failure is very much dependent on the type of distribution network and earthing as well as the position in the network. The South African networks predominantly uses the TN-C-S power system and the study focus more on that system [27] [8]. The Impact of broken neutral conductor on different sections of the network affects the connected load differently as discussed below:

2.3.1 Broken neutral at the reticulation transformer

The neutral failure in distribution transformers is dependent on the type of transformer used, single phase, dual phase or three phase transformation. Table 2.1 below give the summary of the neutral conductor failure on networks connected to different transformer sizes and configurations used in electrification projects. The details of how the different transformer sizes and configurations are affected by neutral conductor failures are discussed in the subsections of 2.3.1 below:

Table 2.1 Reticulation transformers used in distribution and potential failure impact [3] [21]

Transformer Size	Potential Damage to equipment	Dangerous Touch voltages
Single Phase Transformers	Only risk of dangerous touch voltages	
16kVA	No	Yes
Dual Phase Transformers	Potential damage to equipment & dangerous touch voltages	
32kVA	Yes	Yes
64kVA	Yes	Yes
Three Phase Transformers	Potential damage to equipment & dangerous touch voltages	
200kVA	Yes	Yes
100kVA	Yes	Yes
50kVA	Yes	Yes
25KVA	Yes	Yes

2.3.1.1 Single phase transformers

Single-phase transformers consist of only one phase and a neutral point. The secondary voltage of a single-phase transformer is 230 V between the connected phase and the neutral point. The impact of broken neutral on networks supplied from single-phase transformers is that the customers will lose supply, as the return path to the source would have been broken. There will be no risk of over voltage or under voltage to the connected customers. However, there might be dangerous touch voltages on exposed conductive parts that can be harmful to people [11] [4].

2.3.1.2 Dual phase transformers

Dual phase transformer are connected between two-phase conductors. The secondary side of the transformer is 230V, measured between any of the connected phase and neutral. The voltage across the phase-phase conductors is 460 V. A loss of neutral on a dual phase source will cause the neutral to float resulting in voltage fluctuations between -240V and + 240V. Customers connected to the network might experience voltage up to 460V. There can also be a potential of dangerous touch voltages on exposed conductive parts that can be harmful to people [11] [4].

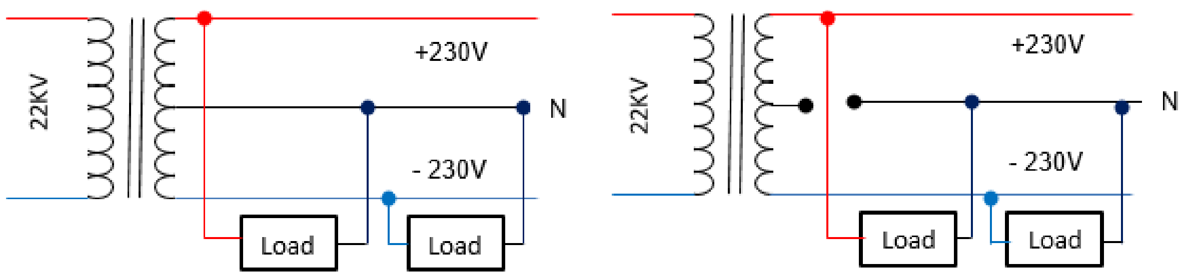

Figure 2.3 Power flow on a dual phase transformer under (a) normal condition and (b) broken neutral condition

2.3.1.3 Three phase transformers

In a three-phase transformer, all the phases of the electrical supply point are connected. The secondary output of the transformer is 230 V between any of the 3 phases and neutral point and 380 V phase-phase. A loss of neutral on a three-phase transformer will cause the neutral to float. The voltage experienced by the connected customers can fluctuate up to line voltages depending on the load balance on the connected load. Some customers will experience under voltage, while others will have under voltage experience. There can also be a potential of dangerous touch voltages on exposed conductive parts that can be harmful to people [11] [4].

2.3.2 Broken neutral on low voltage conductors

Low voltage conductors carry voltage from the transformer to the pole top boxes / pillar boxes supplying the customers or connected loads. The voltage would be 400V/460V phase to phase on three phase and dual phase conductors respectively. The phase to neutral voltage will be 230V for single phase as well as dual phase and three phase [15].

The impact of broken neutral conductor on low voltage conductors will be very much dependent on the type of network as well as the position where the neutral is broken. There will be potential dangerous touch voltages on exposed conductive surfaces connected to the network. For single-phase conductors, a broken conductor would be very similar to opening of a switch in a circuit, which would just result in loss of power. There will be no damage to customer’s connected equipment. In a network which is connected through a dual phase or three phase conductors, a broken neutral would result in downstream customers experiencing voltage fluctuations up to phase to phase voltage which has a potential to damage customers equipment connected to the network [4] [21].

2.3.3 Broken neutral on service conductor

A service conductor is a link between the pole top box and the customer’s installation. Depending on the type of metering unit used. It can be connected between the circuit breaker in the pole top box to the customer meter inside the house or between the split metering unit on the pole top box and the customer’s ready board or distribution box. The voltage on the service conductor would always be 230V irrespective of the source voltage. A broken neutral conductor on the service conductor would not damage the customer’s equipment connected. The customer will just experience a no supply since the return path would have been broken [3] [21].

2.4 CAUSES OF FLOATING NEUTRAL IN DISTRIBUTION SYSTEMS

Neutral integrity problems are more common in developing countries due to combination of aggressive environmental conditions, vandalism and in some cases questionable workmanship [2]. Material quality as well as poor workmanship or incorrect application of installation standards were also identified as major causes or contributors to neutral conductor's failure in Eskom distribution networks. Poor maintenance practices and temporal supply restoration measures that are applied especially when customers report no supply faults especially late at night also exacerbate the problem [11]. Different types of neutral failures on the distribution system and their causes identified during the period of the study were recorded as follows:

2.4.1 Neutral failure on transformer bushing

Neutral conductor failures on the transformer bushings are mostly caused by poor workmanship as well as the use of incorrect or non-standard material. The standard requires that all neutral connections needs to be connected directly to the neutral bushing. Figure 2.4 below shows the transformer neutral bushing connection on the network. The first picture on 2.4 (a) shows a direct neutral connection method using a transformer lug and It can be seen on the picture on figure 2.4 (b) that the 16mm2 copper insulated conductors is connected via the neutral surge arrester not directly on the neutral bushing. The pictures in 2.4 above were taken at Phokwane village electrification project in Limpopo during the project quality inspection. If the bridge piece between the surge arrested and the neutral bushing can be compromised, the network will be exposed to the risk of floating neutral. There was a time where there was a high rate of bimetallic lugs connecter failures due to the quality of the materials that were used. The connectors were failing at the point where the aluminum was joint with copper. That left a number of customers connected to the network exposed to the risk of floating neutral.

Figure 2.4 (a) Direct neutral connection & (b) Neutral connected via the surge arrester

2.4.2 IPC connections and neutral conductor failure


Figure 2.5 (a) IPC Connection and (b) IPC removed from ABC

Figure 2.5 (a) above shows a connection of an IPC on bare and insulated neutral conductors. The standard requires that the IPC's should be tightened until the IPC torque nut sheared off. That is done to ensure that there is a proper connection between the connector and the conductor to prevent conductor failure [15]. The use of incorrect tools result in poor connection on the IPC because it will not sheared off and create a hot connection in future. The standard also requires that two neutral IPC's must be used for connection on a neutral conductor. That is done to mitigate for the risk of poor connection and serve as backup should one connector fail. [15]. On figure 2.5 (a) above , it can be seen that only one connector has been used instead of two as required by the standard and that put the network at risk of neutral conductor failure. The other picture in figure 2.5 (b) shows the marks on the phase conductor where IPC's were removed for unknown reasons. Ingress of moisture or water due to rain will result in arcing between the phase conductor and the bare neutral, which would ultimately lead to conductor burn off. The pictures were taken during the public liability claim investigation at Botlokwa village in Limpopo during customer claim investigation.

2.4.3 Flying jumpers failure

Flying jumpers refers to connection or bridging of two conductors mid-span without a supporting structure as depicted in figure 2.6 below which was taken at Elliotdale in Eastern cape during electrification project quality inspection. The conductor movement due to wind and other mechanical forces that can cause movement on any of the conducts create friction between the conductor and jumpers. The movement combined with increased temperatures due to atmospheric as well as the heat generated by the electrical load on the conductor create a very conducive environment for the conductor failure. It is not standard practice to have flying jumpers on the network and such non-standard installations require normalization.

Figure 2.6 Flying jumpers connection on aerial bundled conductors

2.4.4 Clearance

The construction of overhead electrical networks must comply with the minimum clearances requirements to other structures and normal ground level (NGL) as specified by law. That is done to ensure that the electrical infrastructure will not pose danger to members of public and animals. Different clearance requirements for different voltage levels, road crossings, railways crossings and other objects that does not form part of the power lines are specified [15] [28]. Non adherence to minimum conductor clearances especially on road crossings exposes the conductors to the risk of being hooked by trucks. Almost every village and townships have bottle stores or liquor selling outlets where delivery trucks that are often loaded to capacity cross under the lines. If the clearance is not as per the required standard, there is a high risk of conductors being damaged by trucks.

Figure 2.8 below shows the conductor that was hooked and damaged by a truck at Skhunyani village due to non compliance to minimum clearance requirement. The conductor which is prone to be damaged first is the CNL because it is used for both current transfer as well as attachment point of the conductor to the line hardware. According to minumum clearance requirements for OHL as in figure 2.7 below, low voltage conductors are supposed to be a minimum of 4.9m above ground level and 6.1m for road crossing structures. The maximum permisible height for trucks with load in South Africa is 4.3m with the exception of high cube containers that are approximately 4.6m and double deck buses which are 4.65m. There was a moratorium that was issued in South Africa for banning carriage by road of high cube containers. The ban on the carriage by road of high cube containers was temporarily lifted until January 2019 after consulations between the Road Freight Association and the Department of Transport

[29] [30]. Considering the specified maximum heights, the minimum ground clearance of 4.9m and 6.1m on road crossings is more that adequate for low voltage OHL. Non adherence to the minimum clearances can result in injury to the road users as well as members of the public when vehicles and trucks make contact with the OHL. If the neutral conductor can be broken first, the connected customers might suffers damage to their electrical equipment due to over voltage or under voltage caused by the floating neutral [2] [4].

1	2	3	4	5	6	7	8	9	10
Highest system r.m.s. voltage kV	System nominal r.m.s. voltage kV	Safety clearance phase-to-earth m	Safety clearance phase-to-phase m	Minimum vertical clearances: Ground clearance		Minimum vertical clearances: Roads in townships, and proclaimed roads, railways	Minimum clearances any direction m: To tele-communication lines and between power lines	Minimum vertical and horizontal clearances m: To buildings, poles, structures not part of power lines and vegetation m	Tower-top clearances at maximum insulator swing and minimum clearances at extreme wind conductor blowout m
<1	–	–	–	4,9[a]		6,1	0,6[a]	3,0[a]	0,1[a]
7,2	6,6	0,15	0,2	5,5		6,2	0,7	3,0	0,1
12	11	0,20	0,3	5,5		6,3	0,8	3,0	0,1
24	22	0,32	0,4	5,5		6,4	0,9	3,0	0,1
36	33	0,43	0,5	5,5		6,5	1,0	3,0	0,1
48	44	0,54	0,61	5,5		6,6	1,1	3,0	0,15
72	66	0,77	0,89	5,7		6,9	1,4	3,2	0,20
100	88	1,00	1,14	5,9		7,1	1,6	3,4	0,24
145	132	1,45	1,68	6,3		7,5	2,0	3,8	0,35
245	220	2,1	2,7	7,0		8,2	2,7	4,5	0,6
300	275	2,5	3,6	7,4		8,6	3,1	4,9	0,7
362	330	2,9	4,3	7,8		9,0	3,5	5,3	0,86
420	400	3,2	4,8	8,1		9,3	3,8	5,6	1,0
800[b]	765	5,5	8,9	10,4		11,6	6,1	8,5	1,9
d.c. 533 kV[c]	–	3,7	–		8,6	9,8	4,3	6,1	

NOTE The assumption on which the values are based, is given in C.2.

[a] For insulated power lines complying to SANS 1418-1 and SANS 1418-2 (Aerial bundled conductor systems) or SANS 1507-6 (concentric cable) no minimum safety clearances are required here. The same will apply to technologies for which compulsory SANS safety standards may be developed.

Figure 2.7 OHL minimum clearances [15]

Figure 2.8 Broken conductor after being hooked by a truck at Skhunyani village

2.4.5 Poor maintenance practices

Different maintenace phylosophies for different types of networks are applied by different utilities ranging from preventative maintenance, predictive maintenance, real time monitoring and reactive maintenance. Low voltage networks are mostly not given attention that they deserve and as a result, they are mostly in a very bad condition. Utilities mostly focus on High voltage (HV) and Medium voltage (MV) networks as well as substations and ignore the Low voltage (LV) networks where millions of customers are connected. Reacive maintenance which is also referred to as run to failure maintenance strategy is mostly employed on low voltage networks by most utilities. The maintenance strategy applied to low voltage networks in Eskom is time based inspection with consequential repairs [31] [32].

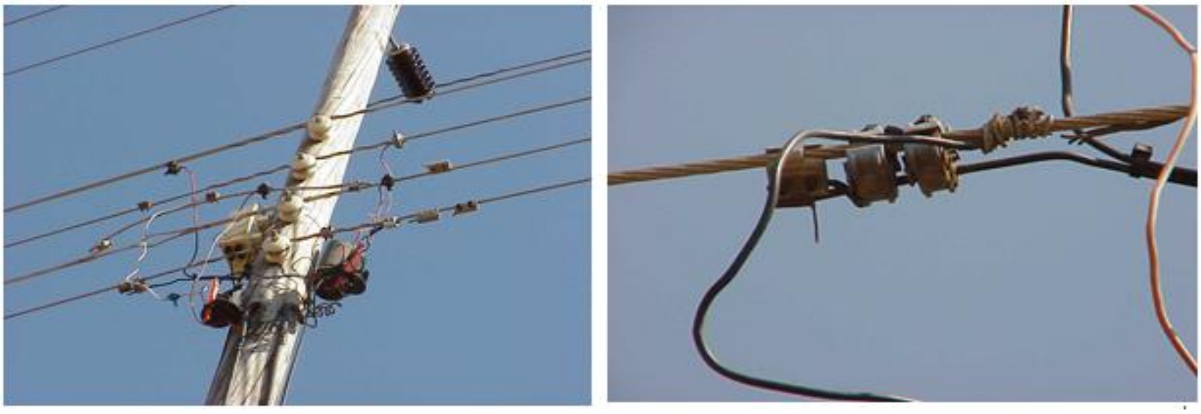

Figure 2.9 State of some low voltage networks

Eskom Distribution aims to ensure that the electricity delivery networks and associated electrical system are maintained in such a manner that the customer requirements, internal stakeholders and legal authorities related to such networks are met at minimum life cycle cost [32]. We have low voltage networks that are older than 40 years and have way exceeded their life span. The networks are mostly bare LV conductors and they are prone to failures especially on the connectors. Mitigation measures and standards implemented today were not in place when such networks were constructed. The replacement and refurbishment of old non-compliant networks is currently underway but the exposure remains high on those that are still in existence. The picture in figure 2.9 above was taken at Botlokwa village during the public liability claim incident investigation where customers claimed for damaged equipment due to an electrical fault on the network.

2.4.6 Network overloading and unbalanced loads

Network overloading mostly due to illegal connections expose both the legal customers and illegal consumers to high risk of equipment damage due to neutral conductor failures. The problem is exacerbated by poor load balancing since the illegal connector does not consider phase balancing and connect to the nearest accessible phase conductor as in figure 2.10 below. Eskom specified a reduced neutral conductor size for low voltage aerial bundled conductor (ABC) [33] [28]. This is based on the assumption that, if the network is properly designed and constructed, there must be minimum current flow in the neutral conductor. Theoretically, the current flow on the neutral conductor is zero because of the cancellation due to 120° phase displacement of the phase currents [23] [34] [18]. The neutral wire is a return path for the unbalanced currents.

$$I_N = I_R \angle 0° + I_Y \angle 120° + I_B \angle -120° \quad (2\text{-}2)$$

Figure 2.10 Network overloading

From the formula in 2.2 above, under balanced load condition, the sum of all the currents in the three phases is Zero due to the phase displacement [35] [36]. If the load is unbalanced, there is a neutral or imbalance current flow. Current imbalance cause voltage unbalance and if there is no monitoring of the system probability of neutral conductor failure become high. When the network is unbalanced coupled with overloading, the system end up with a lot of current flowing in the neutral conductor resulting in thermal burn off. Considering that the neutral conductor has the smallest size, it become the weakest link in the circuit [23] [37] [35]. The picture was taken at Mbambamencisi village during the campaign for removal of illegal connections on the network.

2.4.7 Lightning

A number of neutral conductor failures has been observed in in networks with low voltage conductors constructed using ABC with bare neutral conductors, in areas with high lightning density especially in coastal areas and areas with high pollution levels. Investigation conducted discovered that direct lightning strikes as well as indirect lightning strikes has a potential to punch pinholes on the ABC insulation. Oxidation and corrosion due to electrolytic process create a conducive environment for leakage between the live and neutral conductor, which ultimately leads to conductor failure. Installation of ABC with insulated neutral conductor in risky areas where there is prevalence of high lightning density and pollution was recommended to mitigate for the identified risk [38] [39].

2.4.8 Conductor theft

The theft of nonferrous metals has become a serious challenge in South Africa due to economic as well as social impact it has on the country. The combined annual financial loss to Eskom, Transnet and Telkom due to copper theft was reported to be in excess of R10 billion rand. In recent years, there has been an increase in number of electricity network failures as a result of conductor theft for resale to scrap metal dealers [40] [41]. The neutral conductor being used as an attachment point of the conductor to the supporting structures (poles) is at high of being cut first when the conductor is stolen. For the duration that the phase conductors are still live and neutral conductor cut down, the connected customers remain exposed to the floating neutral condition [15] [33].

2.5 MEASURES IN PLACE TO MITIGATE THE RISK OF BROKEN NEUTRAL

According to [4], the existing South African regulations on LV earthing practices does not fully cater fort the condition of a broken PEN conductor on the utility LV network which may results in non - compliant voltage fluctuations and dangerous touch voltages at the customers point of supply. The statement is collaborated by [2] and [21] on the study conducted on a similar subject. The low voltage protection philosophy is also very silent in addressing the identified risk. The distribution network code acknowledges the prevailing risk and highlight the protection requirements but does not go to the details of how that is supposed to be achieved [7].

2.5.1 Overvoltage and under-voltage protection

Overvoltage and under-voltage were identified as the cause of damage to customer equipment during floating neutral fault condition [2] [3] [4]. Current protection requirements in South Africa does not specify voltage protection as a minimum requirement [26] [8] [12]. The only voltage requirement specified in the standards is surge protection which covers protection against lightning surges which have a total voltage characteristics and cannot protect the customers against floating neutral condition [19] [12]. The specification for prepayment metering systems covers overcurrent and earth leakage as mandatory protection requirements and voltage protection can be included as an optional requirement dependent on the metering unit manufacturers [42].

2.5.2 Earth leakage protection

Installation of residual current devices is a mandatory requirement for all electrical installations in South Africa [8] [26]. Residual current devices are utilised to provide protection against electrical shock arising from direct contact and indirect contact. *"In a single-phase residential application, a 30 mA, two-pole, undelayed AC-type device is used. Under most conditions, a 30mA RCD will be effective at preventing harm to humans in the event of direct or indirect contact and also provide reasonable protection against appliance damage and fires* [4]*".*

2.5.3 Installation of multiple earths along the PEN Conductor

The study that was conducted by [4] concluded that; *"The installation of multiple earths along the PEN conductor of LV distribution systems were observed via simulation studies to lower the touch potentials at households during an incidence of a PEN conductor failure".* The installation of multiple earths does not address the risk of possible damage to customer equipment during broken neutral condition since the voltage will still rise above the nominal voltage or drop significantly to the values that can damage customer equipment [16] [43].

2.6 SUMMARY OF OTHER MITIGATION MEASURES IMPLEMENTED

There is a number of mitigation measures implemented to deal with the problem of broken neutral conductors in distribution systems. Some are more preventative in approach and others are reactive once the neutral conductor is broken. The preventative measures are the preferred ones but it the event that the proactive means implemented fail to prevent the neutral conductor failure, the reactive measures need to kick in as a backup.

2.6.1 Proactive/preventative measures implemented

(a) Installation of double connectors in all neutral connections to minimize risk of failure

(b) Multiple earth application on low voltage network

(c) Periodic inspection of low voltage networks and immediate correction of identified faults as well as planned maintenance based on network condition.

(d) Training of construction teams on correct installation of LV networks with correct accessory applications.

(e) Monitoring of the type of connectors used for neutral connections

2.6.2 Reactive/corrective measures implemented

(a) The reactive measures includes what installation of overvoltage and under voltage protection units.

(b) Installation of residual current devices

2.7 CONCLUSION

The literature review conducted confirms that neutral conductor failure in distribution networks has got a serious potential to damage customers connected loads as well as creating dangerous touch voltages on exposed conductive parts that can be life threatening to people. An ideal solution to the problem would be to construct networks that will not be prone to broken neutral conductors. Number of mitigation measures are in place to reduce the probability of neutral conductors' failures. However, the impact of a broken neutral is so serious that for the minimum exposures still present, it warrants further mitigation measures to deal with the problem when the situation arise.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter covers the research methodology that was employed to investigate the impact of a broken neutral conductor as well as the mitigation for the associated risk [44] [4]. Relevant information relating to the network failures associated with a broken neutral conductor was looked at as well as the current network configuration and protection philosophy. The aim was to verify the protection adequacy in dealing with broken neutral conductor faults in the network. [45] [46]. The emphasis was more on South African networks configuration though there are references made to other networks.

Current available literature indicates that there is a serious risk in the network when a broken neutral fault occurs. There is potential damage to electrical equipment due to over voltage or under voltage created [44] [47], as well as danger to the public because it results in exposed metallic objects bonded to the electrical systems being live. The later risk has a potential to take people's lives depending on the body size of the person involved as well as the ground resistance [4] [48].

The research scope included testing the capability of the current electrification standard minimum protection requirements in Eskom, by means of theoretical analysis and benchmark against local as well as international standards [49] [50] [51]. Laboratory test and experiments were conducted to verify the performance as well as the limitation of the current protection units employed. That was done to validate the information gathered during literature review. The test samples were limited to the current metering units used in Eskom and municipalities in South Africa.

3.2 ANALYSIS OF SOUTH AFRICAN DISTRIBUTION RETICULATION NETWORK

The South African distribution reticulation network analysis was conducted to evaluate the design, technology used and benchmarking against international standards [46] [50]. The analysis were focused on identifying how the network design and technology utilization contribute to the impact of broken neutral conductor in distribution systems, with the aim of proposing improvements for mitigating against the short comings identified [44] [4] [47]. The analysis focused on the points tabulated below:

- Review of the current distribution network layout up to the customer point.
- Review of the current distribution network protection.
- Review of the distribution network earthing.
- Laboratory experiment to test current protection equipment for broken neutral fault conditions.
- Power simulations to propose mitigation measures.

3.2.1 Distribution network layout

A typical distribution network in South Africa is shown in figure 3.1 below. The network take off point is from the medium voltage network which is normally 11 kV or 22 kV. In rare cases we do get 33 kV networks being used for medium voltage reticulation but majority of the networks are 11 kV and 22 kV [49]. Overhead lines are mostly used for rural electrification medium voltage distribution and underground cables are mostly used for urban reticulation [52]. The medium voltage is then stepped down with a reticulation transformer to low voltage, which is: 400 V line voltage for three phase supplies, 420 V line voltage for dual phase supplies and 230 V phase voltage for single phase supplies [52] [53]. Bare low voltage conductors or Aerial Bundled Conductors (ABC) are used for low voltage reticulation and can be three phase, dual phase or single phase depending on the type of transformer used. Customers are connected to the network from the pole top boxes which are mounted on the LV poles. A service distribution cable (airdac) is used to connect the customer houses to the network [54]. The figure 3.1 below shows the network layout as well as the boundaries between Medium voltage, low voltage and customer installation. The customer installation point is also referred to as a service point in the document

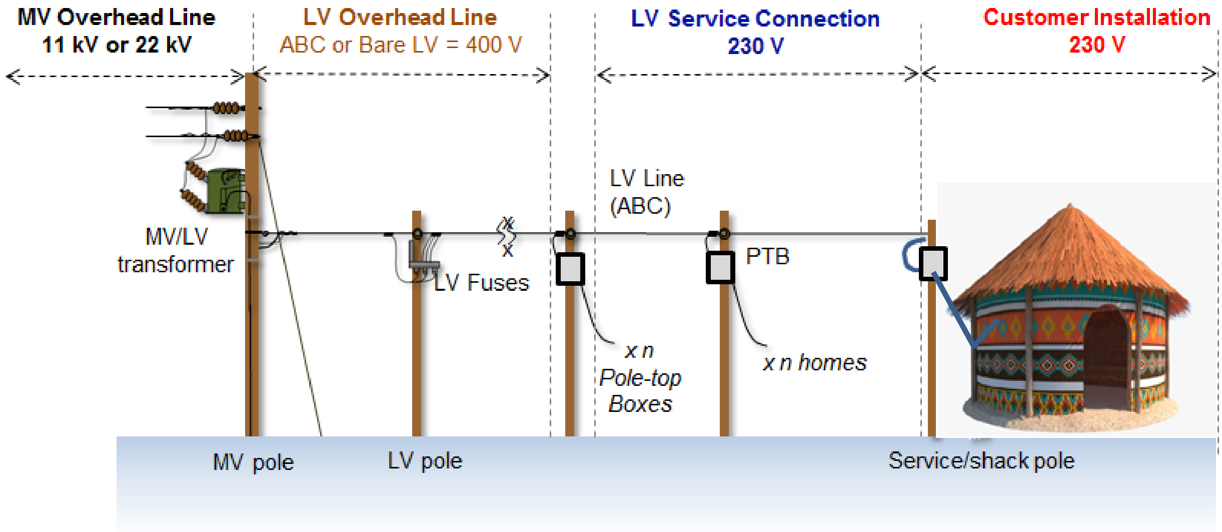

Figure 3.1 Distribution network model

3.2.1.1 Medium Voltage (MV)

The reticulation transformer is supplied from the medium voltage network, which then step down the voltage from 22 kV to 400 V phase to phase and 230 V phase to neutral for three phase transformers. On dual phase transformers, the transformation will be 22 kV to + 230 V, - 230 V and 22 kV to 230 V in 16 kVA single phase transformers. A similar transformation will occur for 11 kV and 33 kV networks with the only variance on the input voltage [52] [49].

The Medium Voltage (MV) side of the transformer is protected against faults inside the transformer using drop out fuses which are mounted on the cross arm above the transformer [52] [45], as shown in figure 3.2 below. There are few transformers in the network with internal oil immersed circuit breaker known as Complete Self Protected Transformers (CSP). Both the fuse and circuit breaker on the transformer MV side are meant for over current protection [55] [45]. Three MV surge arresters are also installed in parallel with the bushings of all three phases to protect the transformer against lightning surges [52]. The transformer is adequately protected against both over current and over voltage fault conditions that has got potential to damage the transformer.

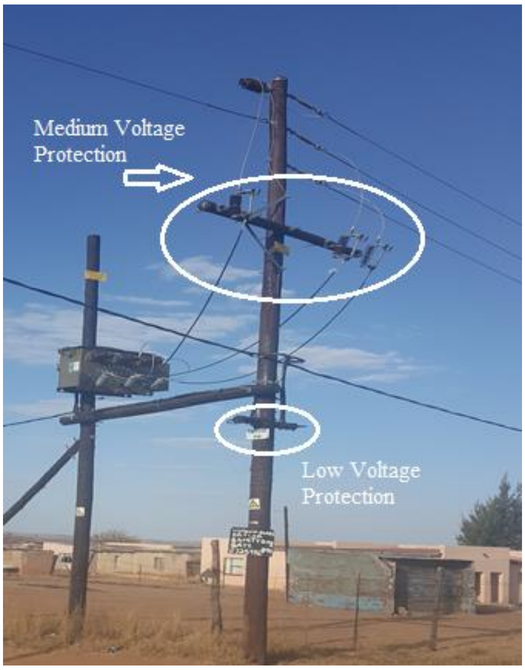

Figure 3.2 Reticulation Transformer Protection

3.2.1.2 Low voltage (LV)

The output of the transformer is connected to the Low Voltage (LV) conductors thorough the Low Voltage fuses (Morsdoff fuses). A low Voltage circuit breaker can also be used as an alternative to the fuses. Fuses are preferred due to initial capital cost though circuit breakers might prove to be economical considering the total life cycle costing [49] [45]. The fuses are meant to protect the transformer against faults on the LV conductors. The sizes of fuses used are dependent on the transformer size [45].

For dedicated customer loads (SPU's and LPU's), circuit breakers are used for LV protection. It should be noted that both circuit breakers and fuses are current operating devices which are meant for protection against overload and short circuit condition. Only over current protection is offered by both

Low Voltage fuses and Low Voltage circuit breakers installed in the network. There is no protection against undesirable voltage conditions in the network [45] [53].

The Low Voltage conductors can either be overhead (Aerial Bundled Conductor or Bare Conductors) or underground cables [53]. Overhead conductors are preferred in electrification projects because the cost is much lower in comparison to underground cables [56]. Where three phase transformers are used, the voltage on the LV conductors is 400 V phase to phase and 230 V between phase and neutral conductor. For dual phase networks, the voltage on the LV conductors will be + 230 V and - 230 V phase to phase = 460 V and 230 V phase to neutral. In a case of single phase transformers, the LV conductors voltage is 230 V [53] [49].

3.2.1.3 Services connections

The house connections or service connections are connected from the pole top box which is mounted on the LV pole through a concentric service conductor (airdac) as in figure 3.3 below. Service connections are protected against faults on the service cable by means of a 50 A circuit breaker inside the pole top box. The 50 A circuit breaker can protect up to four houses connected to the network [45]. The circuit breaker can only protect the network against Over Current and short circuit conditions and would not operate under over voltage or over voltage conditions [57].

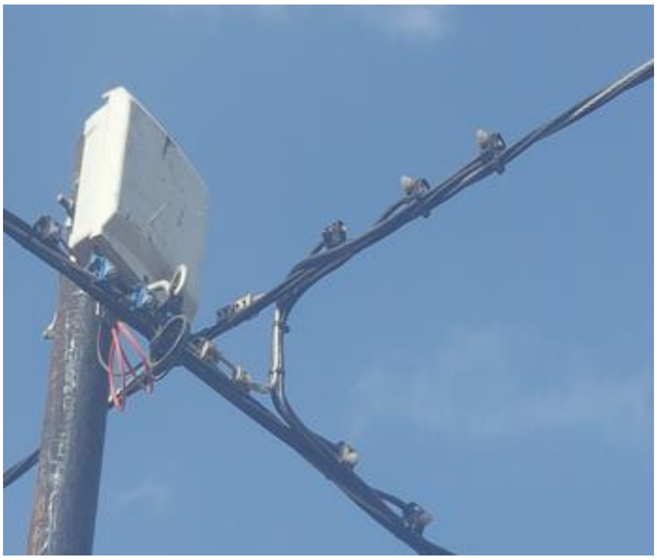

Figure 3.3 and 3.4 Service Pole Top Box

Figure 3.3 above shows a 4 way pole top box with two customers connected and both supplied from a single 50 A circuit breaker. The most common standard service connection applied in electrification today where the houses are not wired is the prepaid split meter mounted in the pole top box and customer interface unit (CIU) and ready board installed in the customer house. Where the customer's house is already wired, only a prepaid split meter and the customer's interface unit are installed [54].

3.2.1.4 Customer installation

Over the years, there has been an evolution on the type of customer installations in South Africa, ranging from conventional meters, prepaid meters mounted outside the customer's house, prepaid meters mounted inside the house and recently split meters as well as smart meters. In all the different installations mentioned above, the protection provided for is earth leakage protection and over current protection [46] [45].

Figure 3.5 below shows a typical rural house connection with a ready board and a plug box mounted on a rail for ease of installation. A ready board is a low cost distribution board that act as a termination point from the utility supply point. The unit consists of an earth leakage and circuit breaker for over load protection [56]. In electrification houses where Eskom supplies the ready board for 20A customers, a surge arrester for lightning protection is also included inside the unit. All the above mentioned protection will not protect the customers against under voltage and over voltage faults [45] [54].

Figure 3.5 Services installation for 20A customers

The network pictures used in Figure 3.2 to 3.5 above were taken at Matsulu Electrification project in Mpumalanga during the electrification project site visit and quality inspections.

3.2.2 Distribution network earthing

Earthing is classified in two categories depending on what the purpose for that particular earth is. The first category is protective earth and equipment earthing. Protective earthing (PE) is a conductor that connects all the exposed metallic objects and conductive surfaces of equipment to ensure that they are at the same potential for the purpose of preventing accidental electric shock. Under normal circumstances the protective earth does not carry any current. That process of connecting the protective earth (PE) to non current carrying metal parts of the equipment is called equipment earthing. The second category of earthing is functional earth and system earthing. The functional earth is for protection and measurement purpose like the neutral in the electrical supply system which is current carrying. The neutral is connected to the earth at one point to avoid earth currents [58] [59]. Low voltage distribution systems are identified according to their earthing arrangements and configurations. They differ in the manner in which the transformer neutral is earthed and how the metallic objects in the customers installation are earthed. International electrical standards recognizes three methods of earthing arrangement that are in place around the world [51], which uses the two letter codes:

(i) TT- Transformer neutral earthed and metallic frames in the customer's point earthed.

(ii) TN - Transformer neutral earthed and the metallic frame in the customers point connected to neutral.

(iii) IT - The transformer neutral is unearthed with earthed metallic frames at the customers point.

3.2.2.1 TT Earthing system

The TT (terre-terre) earthing system is characterised by two or more independent and separate earth electrodes between the source and the customer. The neutral point of the supply is directly connected to an earth electrode with no physical connection to the local earth electrode installed at the customer point. The system has a high earth loop impedance, as a result a Residual Current Device (RCD) is strongly recommended as a first line of protection against earth fault. There is no risk in case of a broken neutral in a TT system. Where power is distributed using overhead infrastructure, earth conductors are not at risk of becoming live in case fallen trees and branches come into contact with the network [50] [58] .

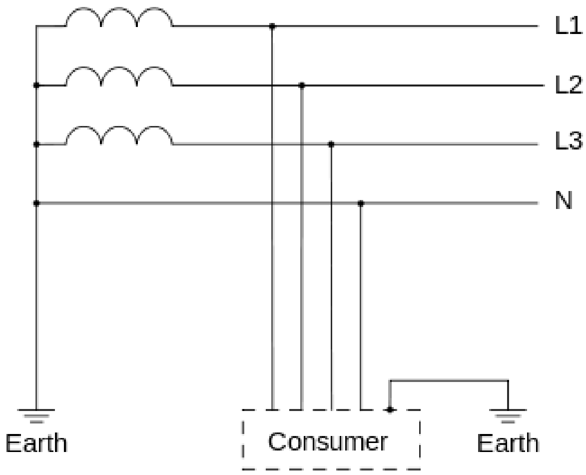

Figure 3.6 TT Earthing arrangement [58] [60]

3.2.2.2 IT Earthing System

The IT earthing system is very similar to the TT system explained in 3.2.2.1 above with the exception that the source is either isolated from the earth or connected to the earth through a high impedance. All exposed conductive parts in the customer's installation are connected to a local earth electrode as in Figure 3.7 below. The earthing of conductive earth parts is done to satisfy the condition that the voltage rise due to fault current on the earth electrode should be less than 50 V [58] [61]:

$$R_b * I_d \leq 50\ V \qquad (3\text{-}1)$$

Where R_b is the resistance of the earth electrode for exposed conductive parts

Id is the fault current which takes account of leakage currents and the total earthing impedance of the electrical installation.

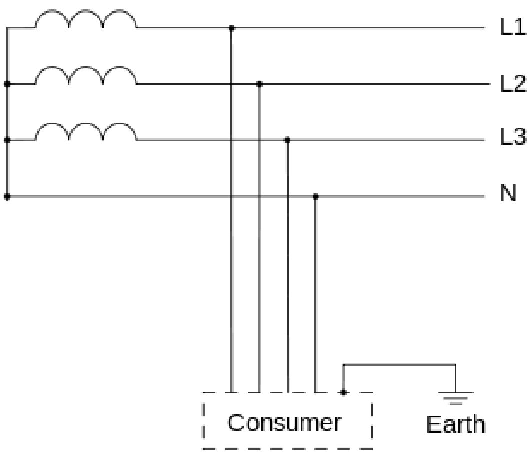

Figure 3.7 IT Earthing arrangement [60] [58]

3.2.2.3 TN Earthing system

The TN (Terre – Neutre) earthing system is characterised by having the source usually the star point directly connected to the earth electrode. The exposed metallic parts at the customer point of supply is called the Protective Earth (PE) and the conductor that connects to the start point on a three phase system or the return path for the single phase system is called the Neutral (N). The TN earthing arrangement can be arranged in three different configuration [60] [50] [62]:

(a) TN-S

Figure 3.8 below shows the earthing arrangement of the TN-S (Terre Neutre – Séparé) system. It consist of a separate protective earth (PE) and neutral (N) conductors from the source to the customer installation. The protective earth and neutral conductors remain separated through out the system and does not get connected at any point. The system consist of five separate conductors as a result it is the least cost effective though it is safer compared to the other systems. There is no additional earthing required at the customer point, the system is completely reliant on the source earth electrode [63] [56].

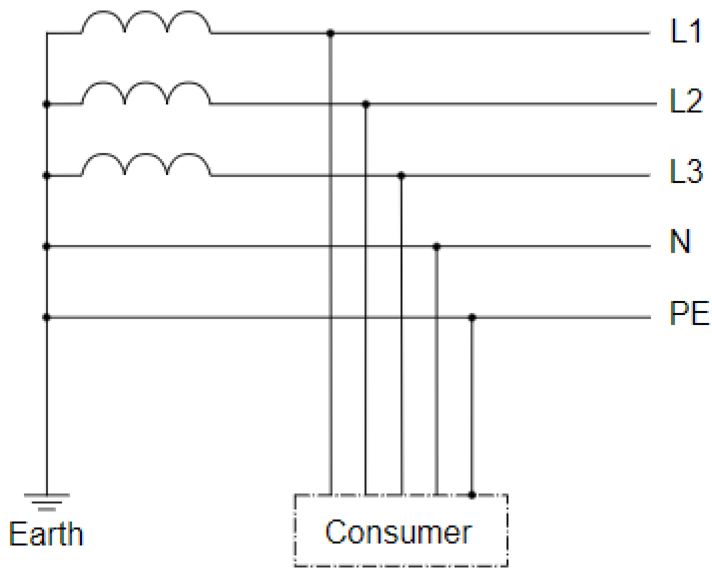

Figure 3.8 TN-S Earthing arrangement [60] [58]

(b) TN-C

The earthing arrangement of the TN-C (Terre Neutre – Combiné) system is different from the TN-S system in that the protective earth (PE) and neutral (N) conductors from the source to the customer installation are combined as depicted in Figure 3.9 below. The system consist of only four conductors which makes it more cost effective compared to the TN-S system. There is no additional earthing required at the customer point, the system is completely reliant on the source earth electrode as well [58] [61]

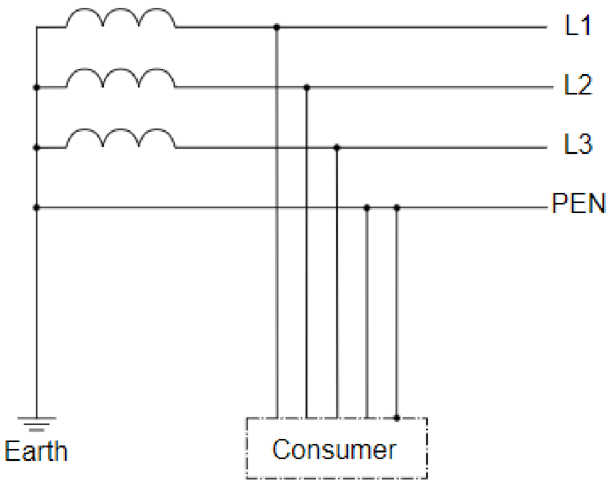

Figure 3.9 TN-C Earthing arrangement [60] [58]

(c) TN-C-S

The TN-C-S earthing arrangement (Terre Neutre–Combiné–Séparé) is a combination of TN-S system and TN-C system. The protective earth (PE) and neutral (N) conductors are combined from the source to the customer installation distribution point. From the distribution point, there is a separate protective earth (PE) and neutral (N) conductors. The wiring inside the customer premises run separate protective earth and a neutral conductors as well as all the flexible power cords utilised in the buildings. There is no local earth electrode required at the customer installation; the system is completely reliant on the source earth electrode [50] [62] [58].

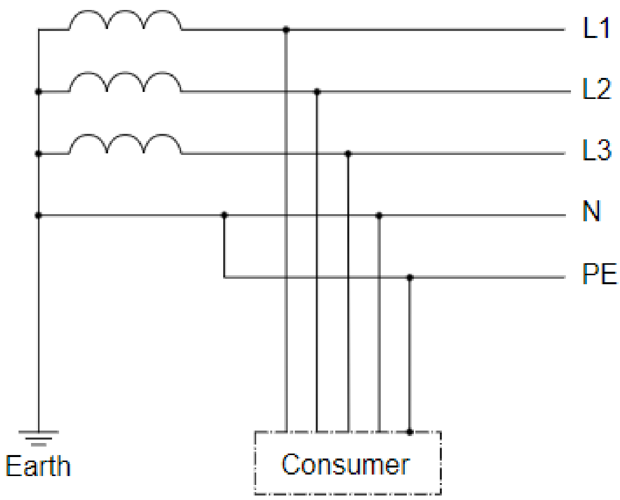

Figure 3.10 TN-C-S Earthing arrangement [60] [58]

3.2.3 Eskom distribution network earthing

LV distribution networks in Eskom are earthed in accordance with the TN-C-S earthing system philosophy [64], i.e. the neutral and protective functions are combined in a single conductor between the source and point of supply and are separated in a consumer's installation [4] [60] [62]. The main purpose of earthing is to provide a path to ground for dissipation of electrical currents into the earth under normal and fault conditions without exceeding any operating and/or equipment limits or adversely affecting continuity of supply [64] [63]. That is achieved by connecting all the parts which could become live to the general mass of the earth to provide a path for fault current and to hold the parts as close as possible to earth potential [60].

3.2.3.1 Medium Voltage & Low Voltage Earthing

Traditionally, the transformer MV and LV earth for reticulation transformer earthing in Eskom are applied at the transformer pole, with minimum separation distance of 5m between the two earths as in figure 3.11 below [64]. Where practically possible, the earths are installed on the opposite directions of the pole separated using an insulated 16mm^2 copper conductor and the actual earths using 16mm^2 bare earth conductors connected to 4 vertical earth spikes [60]. That is done to achieve the electrode resistance of less than 30Ω for both MV and LV [64]. The 30Ω earth electrode maximum limit is for ensuring that the fault in the network does not stay for longer period before sensitive earth fault protection operates to minimise the risk of people in close proximity to the network [59].

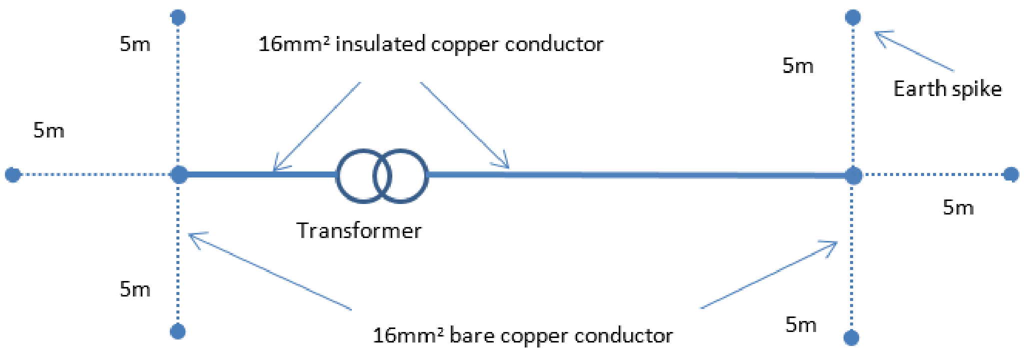

Figure 3.11 Transformer earthing with MV & LV on the same pole [64] [12]

3.2.2.2 Multiple LV Earthing

With the escalating risk of earth theft and the risk associated with having unearthed networks, multiple LV earths were introduced as a mitigation measure. Only MV earth is applied at the transformer pole and the LV earthed one pole away from the transformer as in figure 3.12 below. If the transformer zone consists of more than one LV feeder, each feeder is earthed one pole away from the transformer. In high risk areas, the LV earth electrodes can also be applied on the last pole of the LV feeders depending on the length of the LV feeders. In case of one earth being compromised, the risk of potential touch voltages in the system remains under control [53] [64].

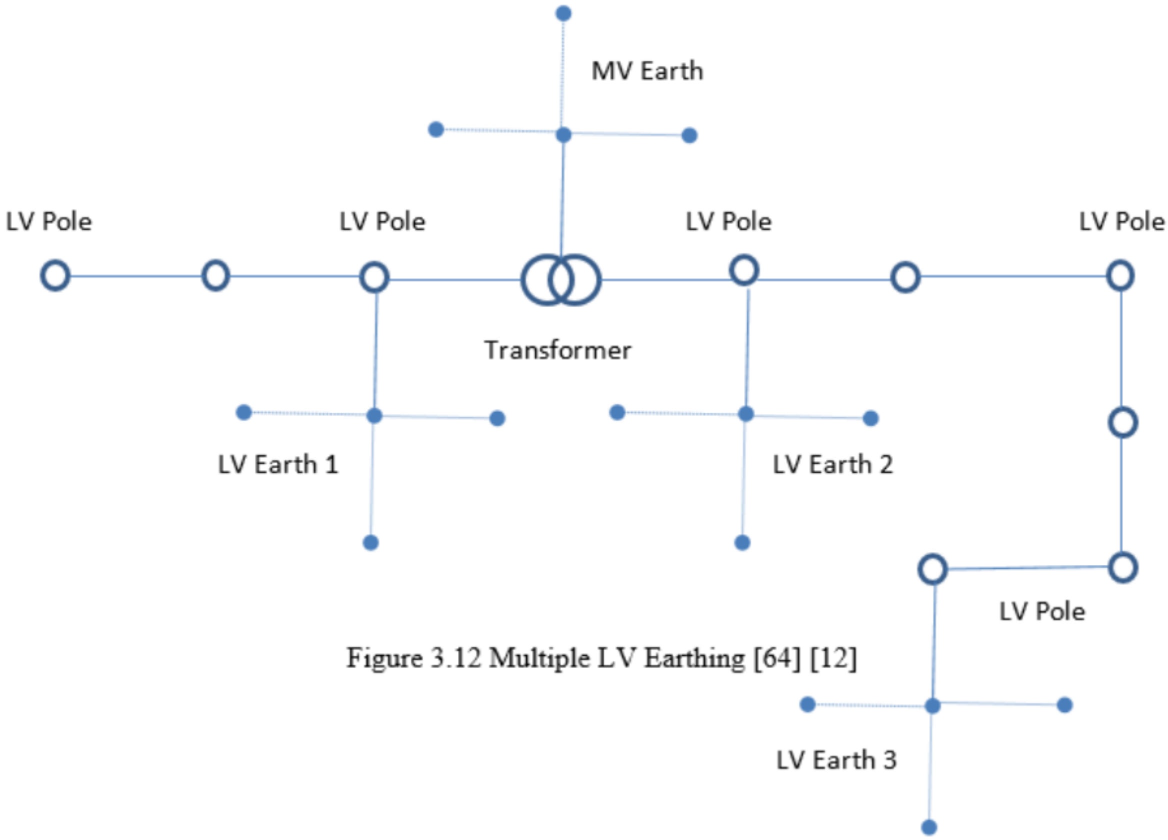

Figure 3.12 Multiple LV Earthing [64] [12]

Earthing is a fundamental component in any electrical system because of the role it plays in system and equipment protection, reduction of transient over voltages, operator and members of public protection as well as improved lightning protection. [59]. Effective earthing of a supply network requires the network equipment as well as the customer equipment to be connected to the earth at all material times to promote safety and reduction of damage to sensitive equipment. It provides a path for leakage currents which are used to disconnect faulty plant and equipment from the network by operating protective devices thereby reducing risk of electrical shock [61] . The introduction of multiple earthing as in figure 3.12 above will always ensure that the above benefits are not immediately lost with the earthing being compromised on a single point in an electrical network. There will always be a backup.

However, it is important that regular inspections are conducted to ensure that the areas that has been vandalized are corrected as quickly as possible [48].

3.3 CONCLUSION

The discussion above demonstrates that the current Low Voltage protection philosophy focus more on overload and short circuit protection. That leaves the customers very vulnerable to faults in the network that would not necessarily result in over loading or short circuit especially over voltage and under voltage.

It was also noted from the literature review that a broken neutral in the network can pose two dangers to the electricity users; fluctuating voltages that can be drop to voltages very close to 0V as well as rise up to the phase to phase voltages and potential touch voltages on exposed conductive parts [47].

The later risk has been adequately mitigated by the revision of the earthing standard to include installation of multiple earths on the low voltage network, thereby reducing the risk of potential touch voltages in case of a broken neutral [64]. However, customers remain very much exposed to the dangers caused by under voltage as well as over voltage mostly damage to sensitive equipment [4]. Mitigation measures implemented to mitigate the risk are explained in the next chapter

CHAPTER 4: METERING UNIT PROTECTION CAPABILITY TESTING

4.1 INTRODUCTION

Verifications of the current metering units used in Eskom and other electricity distributors in South Africa was done by testing different metering unit protection capabilities and limitations. The researcher requested three metering units from the largest suppliers of prepayment meters in South Africa for laboratory testing. The purpose of the experiment was to evaluate how the different meters responded to over voltage as well as under voltage conditions. Over voltage and under voltage are fault conditions experienced by customers when the neutral conductor in a distribution system is broken [4] [44]. Prepayment customers make up to over 93.5% of the total customer base in South Africa. Conventional metered customers contribute less than 7% which is divided into 6.2% SPU (Small power users) and about 0.3% LPU (Large power users). Electricity distribution utilities in South Africa are migrating to prepayment system with the aim of totally replacing all conventional meters with prepayment meters due to the culture of poor payments on conventional metering system [65]. Conventional meters also does not have any protection incorporated in them as a result the protection capability test was only limited to prepayment meters. Electrical appliances used by distribution customers are designed to operate at specified voltage limits in line with the National Electricity Regulator. Exposing them to over voltages and under voltages for extended periods can result in damage to such electrical appliances [44] [4] [47].

The outcome of the experiment conducted on the metering units were recorded and technically analysed to formulate mitigation measures for the shortcomings identified as well as proposing enhancements to the protection philosophy being used. Considerations were given to the risk of nuisance tripping as well as network compliance to the minimum voltage requirements when solutions were proposed. Results were also shared with the metering units manufactures for them to make enhancements for improved customer experience. Eskom distribution technology was also advised for revision of the protection philosophy standard and specifications review.

4.2 PREPAYMENT METER PROTECTION TESTING

Figure 4.1 below illustrates the test bench arrangement with all the equipment that were used during the laboratory experiment for over voltage and under voltage conditions simulation. The details of the equipment used are given in the circuit diagram in figure 4.2 below. The purpose of the test was to observe the response of the different metering units when subjected to over voltage or/and under voltage as it happens during a broken neutral condition in electrical distribution system. The results obtained were recorded and analysis conducted to determine what the impact would have been if the meter was connected to the load. Comparison of the metering unit's performance to the manufacturer specification were done, to determine if the meters works as specified or if there were any deviations from the expected performance.

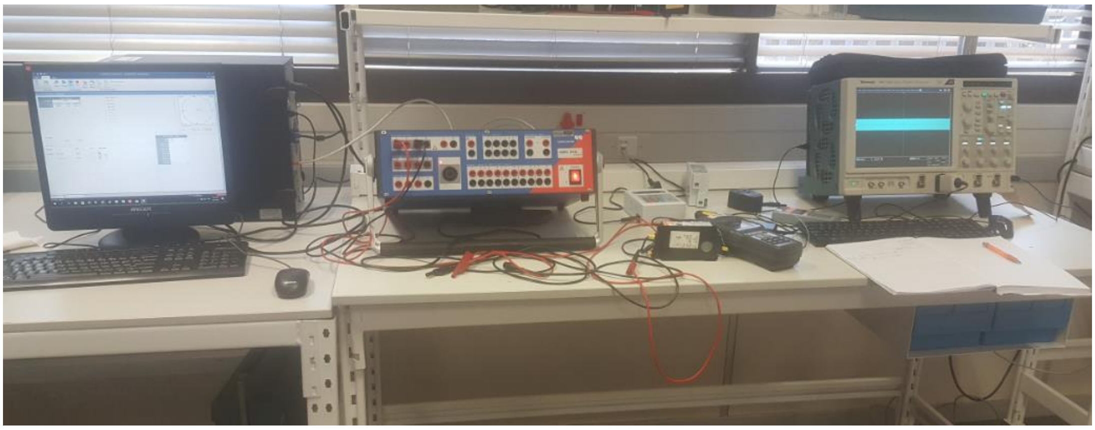

Figure 4.1 Overview of the meter testing setup

4.2.1 Test circuit Layout

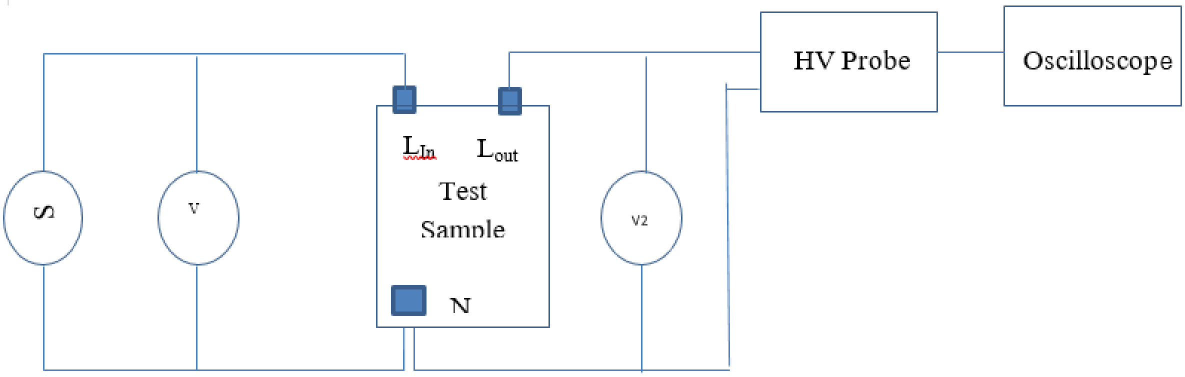

Figure 4.2 Single line diagram of the test circuit

A variable voltage supply was connected to the metering units that were tested to enable upward and downward voltage adjustment to simulate over voltage as well as under voltage conditions. Two voltmeters were also connected across the input and output terminals to measure the input voltage and output voltage. An oscilloscope was included in the circuit, to record the waveforms as well as the period between the changes in state of the metering unit.

4.2.2 Test sample meters

Figure 4.3 Pictures of the test samples

Figure 4.3 above shows the three metering units that were used for testing as well as the customer interface unit (CIU) that communicates with the meter. For the purpose of supplier information confidentiality, the metering units were randomly referred to as Meter A, Meter B and Meter C without necessarily following the order in which they are displayed. The random naming of the samples has been consistent trough out the report for accurate reporting and analysis of the outcome.

4.2.2.1 Prepayment metering minimum protection requirement specification

The minimum protection requirements for prepayment meters in South Africa is over current, surge protection and earth leakage protection for 20A customers because they are supplied complete with a ready board as part of the installation. 60A supply is only given to customers with a house which is wired and issued with a certificate of compliance for wiring of premises. The installation will be having over current as well as the earth leakage protection [66] [46]. There is no mandatory requirement for over voltage and under voltage protection. However, Eskom specified under general disconnection requirements that the meter may disconnect if the supply voltage is removed or falls below 80% of the rated voltage. This is on a condition that the meter will automatically reconnect and restore supply when the voltage is restored to more than 80% of the rated voltage [66]. The SPD (surge protection device) is intended to limit transient over voltages and divert surge current. Due to the rating of the surge protection device, it cannot protect against over voltages caused by a broken neutral in a distribution system [67] [68]. The clamping voltage of the SPD is above the line voltage limit and the waveform of the voltage caused by a broken neutral is different from the lightning surge which makes it not suitable for over voltage protection.

4.2.3 Over voltage protection test

The over voltage protection test was conducted to determine how the different metering units responded when voltage level which is above the rated voltage limit was applied across the meters [69]. Step voltage increase of 1% supplied to the meters from 230 V until the meter trip or reach the line voltage of 400 V. For compliance with the regulatory limits, the meter protection was expected to operate and cut off the supply to the load as soon as the voltage exceed 10% of the standard supply voltage. That means that any voltage above 253V was outside the maximum permissible voltage and the meter was supposed to disconnect the load. Operating equipment and appliances rated for 230 V above 253 V can puncture the insulation of such equipment and appliances resulting in damage to the components. It is important that customers are protected from exposure to over voltage when it does occur on the network to comply with regulatory requirements as well as maintaining good customer relations [69]. The Eskom specification prescribes the disconnection of load at 80% of the rated operating voltage, which is 10% above the National Regulator’s limit [66].

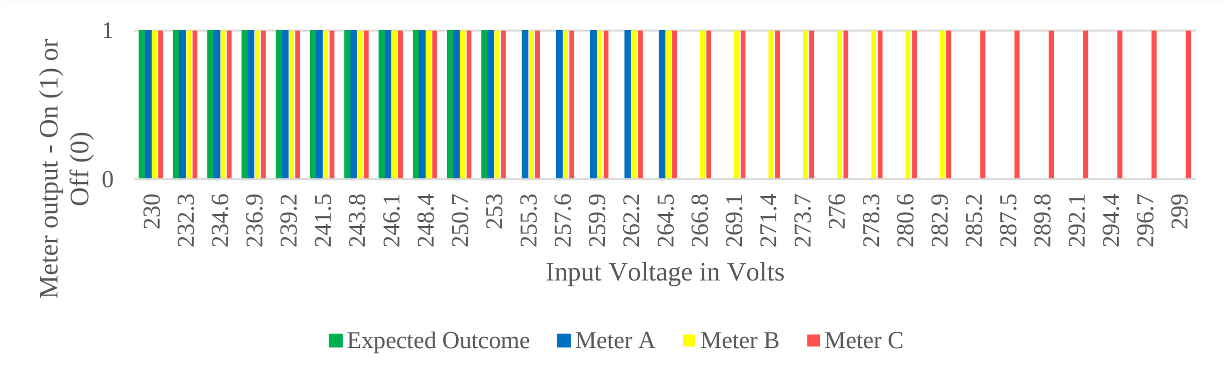

Figure 4.4 Over voltage protection graph

Figure 4.4. Above show the response of the three meters that were tested when subjected to over voltage condition. The results show that all the three metering units remain on above the 10% of the standard supply voltage (253 V). Metering unit A only responded at 16% (267 V) of the standard supply voltage and switched off the supply to the load. Metering unit B switched off at 24% of the standard supply voltage (285 V). Metering unit C remained on until the test voltage reaches the line voltage of 400 V. The ON state on the graph is represented by a 1 and the Off state is represented by a 0. The output voltage measured was the same as the input voltage, the graph only indicates the ON and OFF state.

The response time for metering unit A and B to disconnect the load when applying over voltage were 4 and 5.5 seconds respectively. There was no change in response time in both metering units A and B with increase in voltage. The response time remained constant irrespective of the over voltage applied above the maximum metering unit threshold.

The diagram 4.5 below shows the response of metering unit A when supplied with over voltage. The system remained stable between the rated operating voltage of 230 V and 265 V. At 267 V the metering unit tripped in 4 seconds and remained off. When voltage was ramped up to 230V, the system switched back on and stabilised after 30 seconds. As much as the meter operated outside the NRS limit of 10% variance, it was still within the 20% limit specified by Eskom as an optional protection requirement [66] [69]. The oscilloscope recorded a time difference of 40 seconds, the variance of 10 seconds was due to the time taken to reduce the voltage back to 230 V. There was no change in response time for all voltage ranges between 267 V and 400V. The tripping time on over voltage as well as time taken for system stabilization after restoring supply remained constant at 4 seconds and 30seconds respectively. Even though metering unit A continued to operate outside the maximum permissible voltage, the exposure to the load connected beyond the meter was limited since it operated at 16% (267 V).

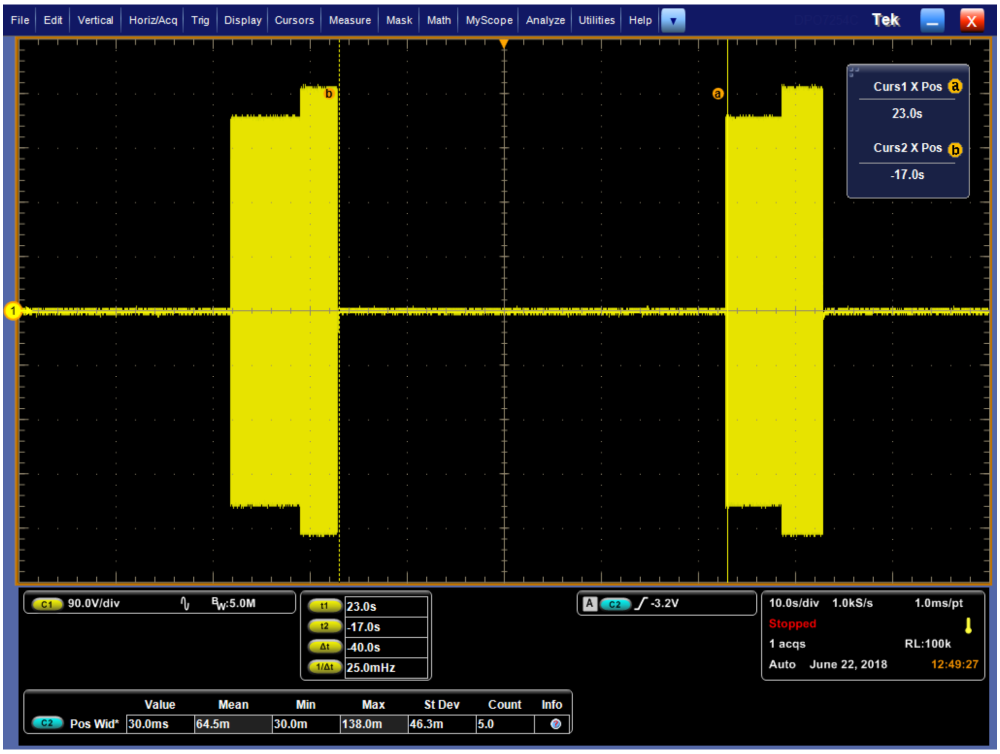

Figure 4.5 Metering unit A response on Over voltage

Figure 4.6 Metering unit B Over voltage response time

Metering unit B in figure 4.6 above shows that the metering unit responded to the over voltage applied in 5.5 seconds when voltages above 283 V were applied. The time taken for system stabilization after normalizing the supply voltage to 230 V was 30 seconds. Both the tripping time and stabilization time were also independent of the voltage level applied above 283 V.

4.2.4 Under voltage protection test

The test was conducted to determine the metering units response when voltage that is below the standard supply voltage of 230V was applied [69] [46]. Similarly, to the over voltage test above, the metering units were connected to the test circuit as in figure 4.2 above and supply voltage of 230V applied to the circuit. There was gradual voltage reduction in step changes of 1% at a time while recording and observing the metering units response. The minimum voltage supplied was not expected to be below 10% of the standard supply voltage which is 207 V [69] [46]. That meant that any voltage below 207 V was outside the minimum permissible voltage and was supposed to trigger the protection system to trip.

Figure 4.7 below shows the performance of the three metering units when subjected to under voltage supply at different levels from 230V up to 100 V. All the metering units tested remain on at voltages below 207 V. Metering unit A and B switched off at 195V and 115V respectively while metering unit C remained on at all voltage levels. The ON state on the graph is represented by a 1 and the Off state is represented by a 0. The output voltage measured was the same as the input voltage, the graph only indicates the ON and OFF state.

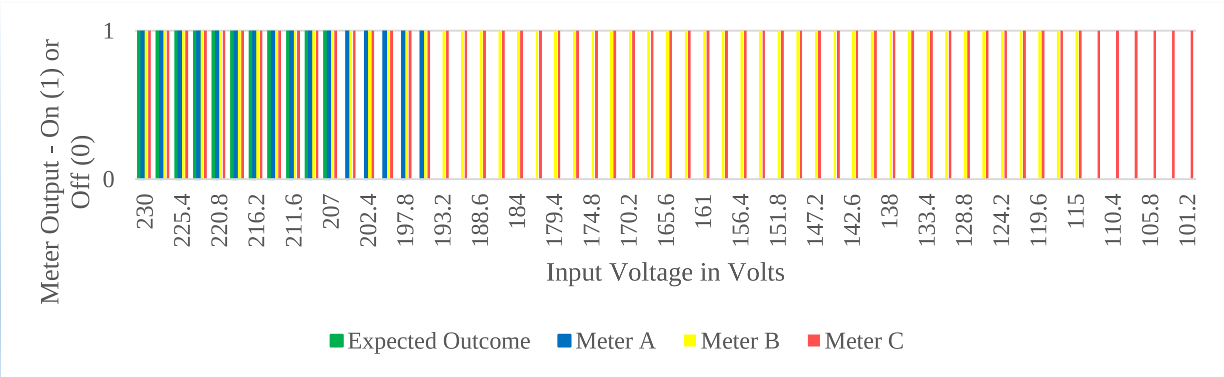

Figure 4.7 Under voltage protection graph

The response time for Metering unit A and B were 30 seconds and 6.5 seconds respectively. The reduction is voltage levels did not increase or decrease the response times for both metering units.

Figure 4.8 and 4.9 below shows the response of metering unit A & B when subjected to under voltage condition. Metering unit A switched off at 161 V (30%) in 30 seconds and metering unit B switched off at 115 V (50%) in 6.5 seconds. There was no relationship in response time to the over voltage above 30% and 49% respectively for both metering unit A and B. The response times remained constant at 30 seconds and 6.5 seconds respectively. The meters were all outside the NRS 048 limits as well as the Eskom limit of 80% of the rated voltage. Both units took 30 seconds to restore supply when voltage was increased from the under voltage ranges to the rated operating voltage of 230 V. Metering unit C did not operate for all under voltage conditions and it remained on outside the rated operating voltages.

Newer electronic devices and appliances are not at high risk of damage by under voltage because they have temperature sensors and protective devices build in them. Under voltage, causes increase in current, which results in over heating of components. For constant load electrical appliances, if the voltage suddenly drops and the appliance is required to maintain the same rated output power, the current will proportionally increase to compensate for the voltage drop [36] [70]. The increase in current results I^2R losses and temperature rise, which ultimately cause the components of electrical equipment to fail.

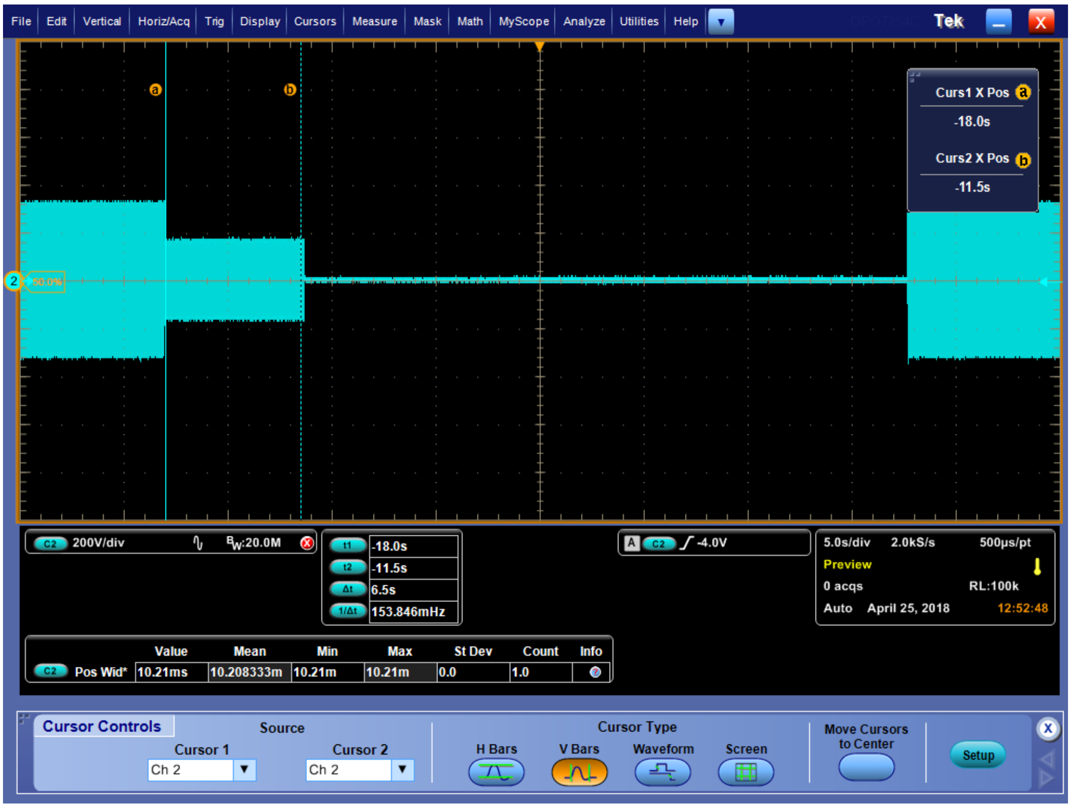

Figure 4.8 Metering unit B Under voltage response time

Figure 4.9 Metering unit A response on Under voltage

4.3 CONCLUSION

The laboratory experiment has demonstrated that over voltage and under protection in distribution systems is possible and can be implemented to protect electricity users against the dangers of floating neutral. Two of the three samples that were tested confirmed that the functionality is possible to implement though they were operating outside the voltage ranges. At the current moment, over voltage and under voltage protection is not a minimum requirement in metering unit's specification. The low voltage protection philosophy focus more on earth leakage, overload, short circuit and surge protection. That leaves the customers very vulnerable to faults in the network that would not necessarily result in over loading or short circuit especially over voltage and under voltage. The surge protection offered by the MOV's would not protect against over voltage since the clamping voltage of the device is at line voltage or above the line voltage.

From the literature review, it was noted that a broken neutral in the network could pose two dangers to the electricity users; fluctuating voltages that can drop to voltages very close to 0V as well as rise up to the phase-to-phase voltages and potential touch voltages on exposed conductive parts. The later risk has been adequately mitigated by the revision of the earthing standard to include installation of multiple earths on the low voltage network as well as the RCD that is installed in all the customer installations. That reduce the risk of potential touch voltages in case of a broken neutral. However, customers remain very much exposed to the dangers caused by under voltage as well as over voltage, which can result in damage to sensitive equipment. Mitigation measures still need to be implemented to manage the risk.

CHAPTER 5: OVER VOLTAGE & UNDER VOLTAGE PROTECTION DESIGN

5.1 INTRODUCTION

Over voltage and under voltage occurs when the voltage in a distribution systems rise above or drops below the rated voltage limit. The impact of over voltage and under voltage in distribution systems has been thoroughly researched, It has been proven to have a detrimental effect on customer appliances and equipment [2] [4] [21]. Operating appliances at under voltage level results in devices drawing excessive currents, which increase heat on the device components. Over time, the heat damage the insulation of the equipment thereby shortening the life span of such equipment. The impact of an over-voltage condition on electrical appliances will differ from one appliance to the other depending on build in protection capabilities and exposure to such voltage levels. The extent of the damage might also vary from immediate equipment destruction to degrading of the equipment components causing circuit malfunctions, fire or failure over extended period.

There is a number of over voltage and under voltage protection units already available in the market that come as complete units that can be connected on the customer distribution board supplying the load. There is also units that can be plugged on the socket outlet and protect only the appliances connected from that socket. For the purpose of this academic project, the researcher opted for a circuit designed from basic principles instead of final products that come as complete units. The magnitude and duration of the over-voltage are some of the major considerations when designing an effective protection against fluctuation voltages. The protection involved setting a threshold voltage above and below which the control circuit shuts down the supply to the load.

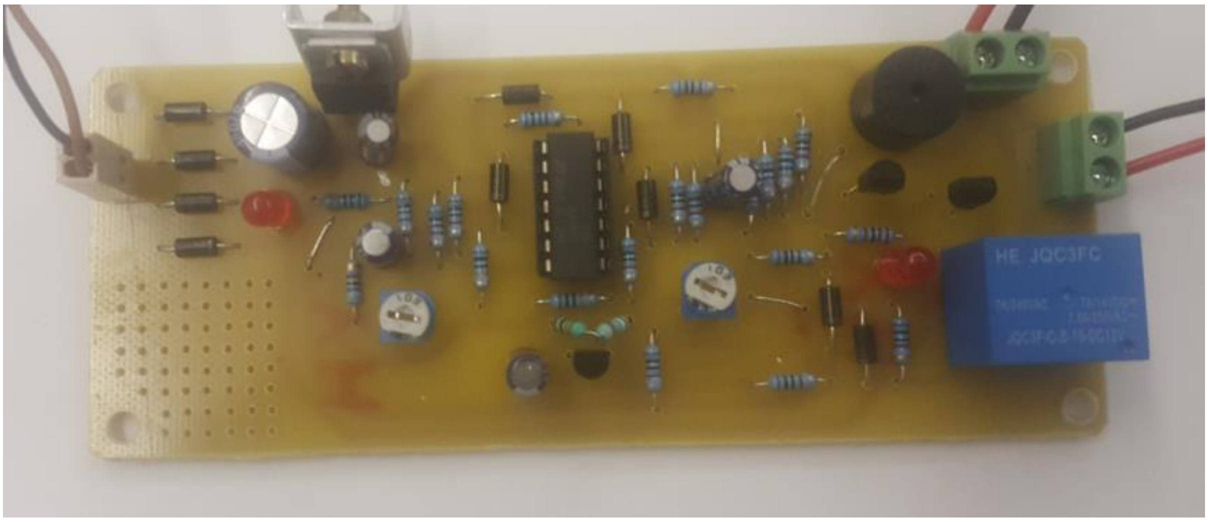

Figure 5.1 Over Voltage and Under Voltage protection circuit

Figure 5.1 above shows the picture of the over voltage and under voltage protection unit that was built to demonstrate how under voltage and over voltage protection in an electrical equipment and appliances can be done. The details of the circuit design and operation are covered in the subsections that follows. A laboratory bench test was conducted on the circuit and functionality was also verified using Multisim and Psim simulation tools.

5.2 CIRCUIT COMPONENTS

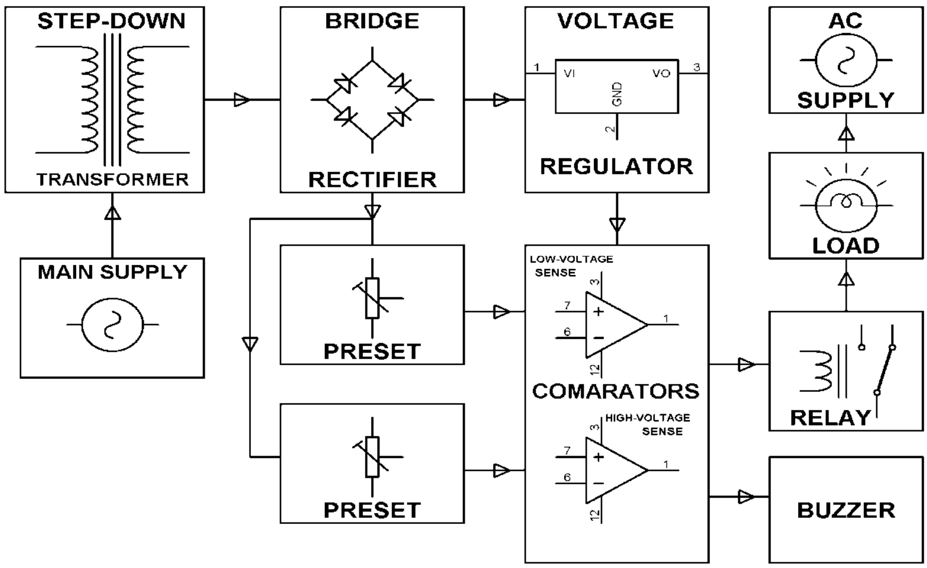

Figure 5.2 Block diagram of the protection circuit [71]

Figure 5.2 above is the block diagram of the over voltage and under voltage protection circuit with all the major components that makes up the circuit. The arrangement of the components in the block diagram show the manner in which power flows from one component to the other.

5.2.1 Power supply

The circuit was powered from a single-phase alternating current source with standard operating voltage of 230V. The over voltage and under voltage experiment to observe circuit response to over voltage and under voltage fault conditions, a variable voltage supply unit was used with capability to supply voltage from 0 V to 400 V. The point of connection considering the distribution network layout can be very much dependent on the level of protection requirement. It can be located, either on the pole top box or on individual customer’s installation. For experimental purpose, the unit was connected to the variable voltage supply unit to enable over voltage and under voltage testing with voltage range of 0V to 400V. The circuit that was used to simulate the results is displayed in figure 5.3 below with the output waveform in figure 5.4.

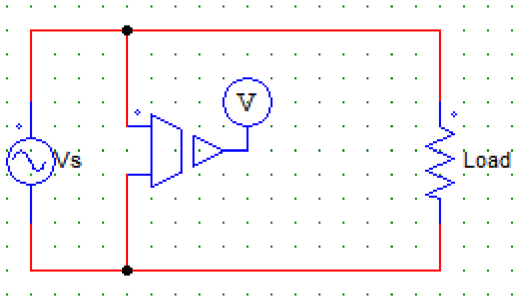

Figure 5.3 Power Supply Circuit

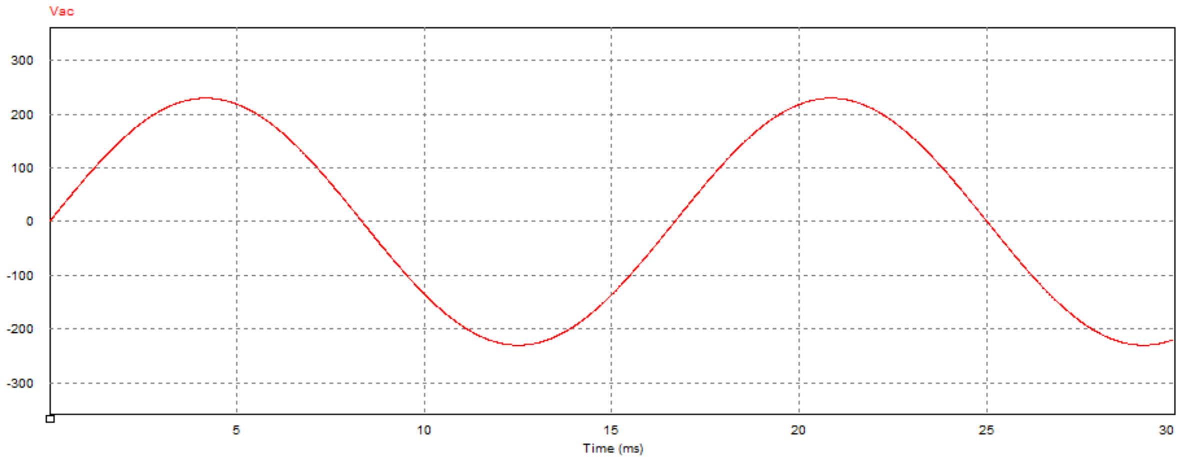

Figure 5.4 230 V Supply voltage wave form

5.2.2 Transformer

Figure 5.5 below shows the transformer connected to the AC power supply. A transformer with ratio of 19:1 was selected to give the desired secondary voltage of 12 V under normal condition when the supply voltage is 230 V. When the supply voltage fluctuates under broken neutral condition, the output voltage will proportionally increase or decrease in accordance with the supply voltage [43] [2]. The simulated input and output voltage waveforms displayed in figure 5.6 below shows input voltage of 230 V and output voltage of 12 V.

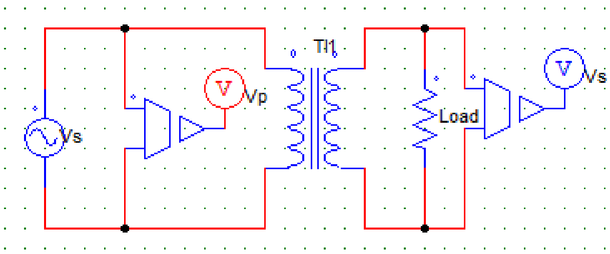

Figure 5.5 Transformer Circuit

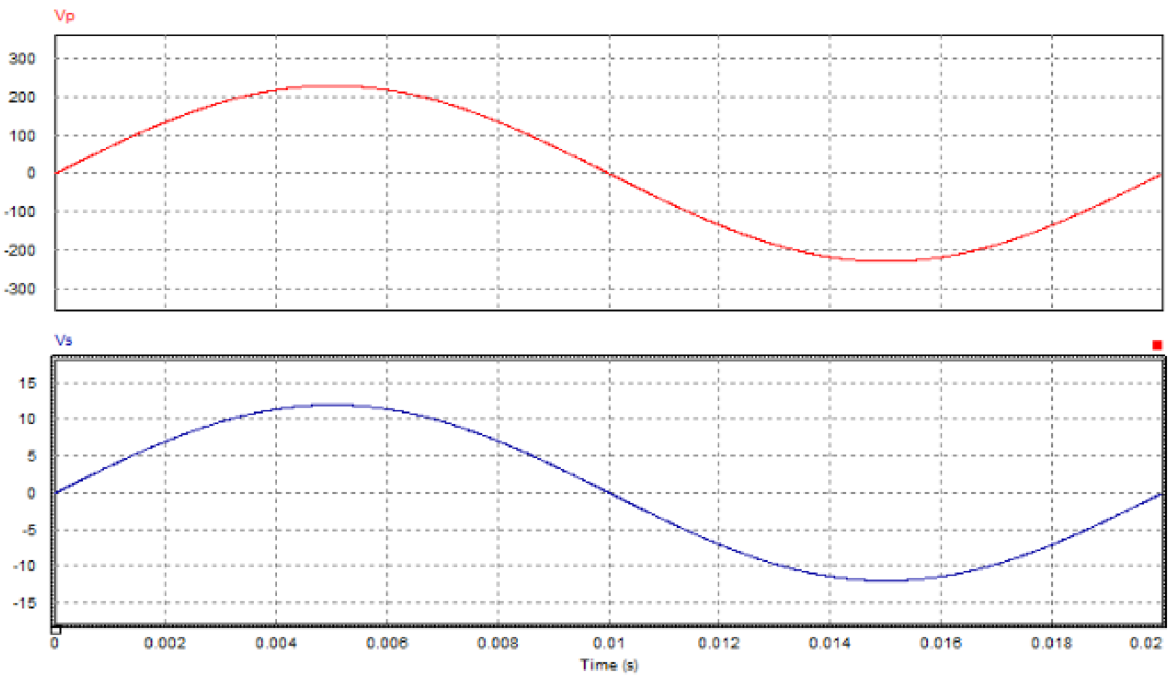

Figure 5.6 Transformer primary and secondary voltage waveform

5.2.3 Rectifier

The stepped down voltage from the transformer output of 12 V was connected the bridge rectifier which converted the Alternating Current (AC) to Direct Current (DC). The In the positive half cycle, two diodes conduct and in the negative half cycle the other pair of diodes conduct, there by converting AC into pulsating DC [23] [72]. Figure 5.7 below shows the AC voltage of 12 V rectified to 12 V DC as displayed in the voltmeter 4 connected to the circuit.

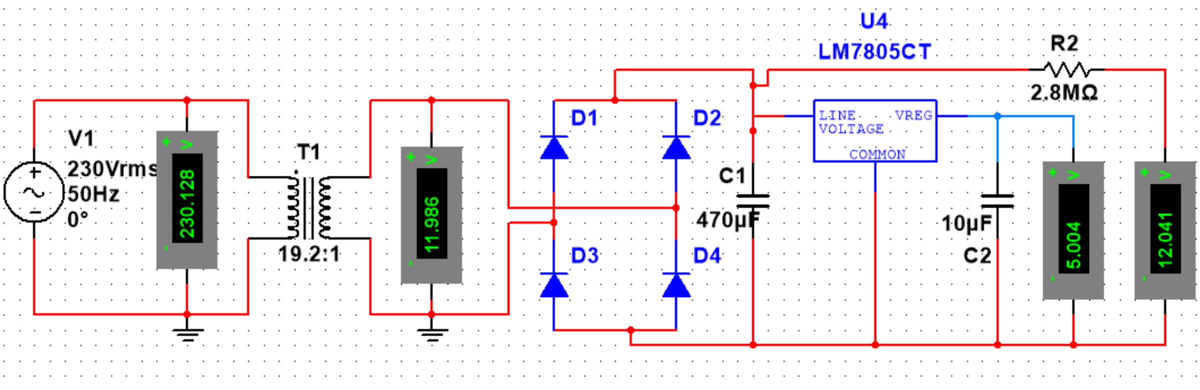

Figure 5.7 Bridge rectifier

5.2.4 Filtering capacitor

The output of the rectifier was pulsating DC with ripples. The capacitive filter C1 was used in the circuit to smoothen the DC output.

5.2.5 Voltage Regulator

The circuit required the use of two voltage DC supplies. The 12 V DC as measured in figure 5.7 above on voltmeter 4 and 5 V DC measured in voltmeter 3 for powering the operational amplifiers used as comparators. The LM7805 voltage regulator was used for regulating the 12 V DC output voltage to the required fixed 5V DC. The voltage regulator consists of internal current limiting function, thermal shutdown and safe operating area protection, which make it essentially indestructible. It has an output current of up to 1A, output voltage of 5 V.

5.2.6 Comparator circuit

In the circuit, an operational amplifier (OPAMP) was used as comparator. A comparator circuit compares two signals or voltage levels to determine the output. The circuit in figure 5.8 and 5.9 below shows the comparator in its simplest form connected to variable resistors and voltmeters. The variable resistors were used as a potential divider to adjust the voltage levels at the non-inverting input of the operational amplifiers (terminal 7) and the inverting input (terminal 6). The supply voltage was connected to $+V_{ss}$ (terminal 3) and $– V_{ss}$ (terminal 12) connected to ground.

The basic formula or operation logic of the comparator is that when the voltage at the non-inverting input is greater than the voltage at the inverting input, the output of the operational amplifier would be high as in figure 5.8 below. The variable resistor RV2 was set at 25% and RV1 set at 45% resulting in the voltage at the non-inverting input voltage of 3.75 V which is greater that the inverting input voltage of 2.75 V. That resulted in a logic high output for the operational amplifier to give 1.44 V.

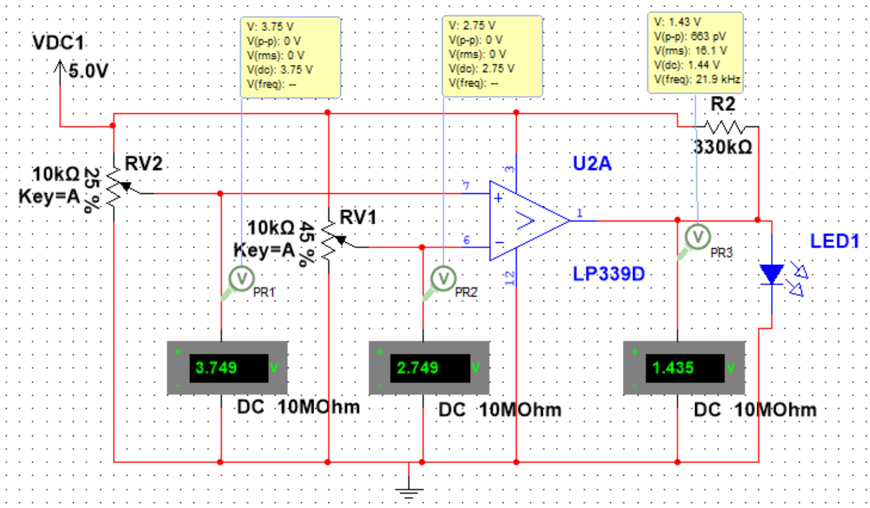

Figure 5.8 Comparator circuit with high output

When the resistance of the variable resistor RV2 was increased to 65% with the resistance of the variable resistor RV1 constant at 45%, the input voltage of the non-inverting input dropped to 1.75 V which was less than the inverting input voltage of 2.75 V. That resulted in a logic low output of 0 V, as in figure 5.9 below. It was demonstrated in the two circuits in figure 5.8 and 5.9 that: the operational amplifier only gives a high signal when the non-inverting input is greater than the inverting input and a low output when the non-inverting input is less than the inverting input.

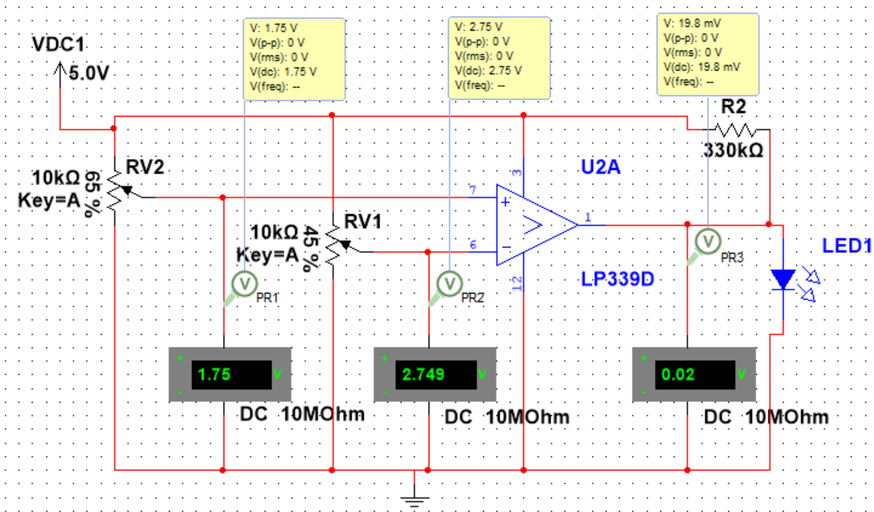

Figure 5.9 Comparator circuit with low output

The comparator that will be used in this over voltage and under voltage circuit is a LM 339. The LM 339 is a combination of four comparators integrated in one circuit. The circuit that will be used for the study uses three of the four Comparators. Comparator 2, 3 and 4 will be used and comparator 1 will not be connected. One unit is used for over voltage detection, the second one for under voltage detection and the last unit for a warning bell when the voltage goes beyond the pre-set limits.

5.2.7 Window comparator

The overvoltage and under voltage protection circuit uses two comparators that are connected in such a way that one comparator measures the overvoltage and the other one measures the under voltage as in figure 5.10 and 5.13 below. The inverting input of the overvoltage comparator is connected to the non-inverting input of the under voltage comparator and the common input voltage source. The other two terminals of the comparators are used as reference voltage for the overvoltage and under voltages. The window comparator only gave a high output when the output of both the over voltage and under voltage comparators are high. If any of the two comparators gives a low output, the circuit output will be low as demonstrated in figure 5.10 simplified window comparator diagram and the logic truth table in table 5.1. below [73] [74].

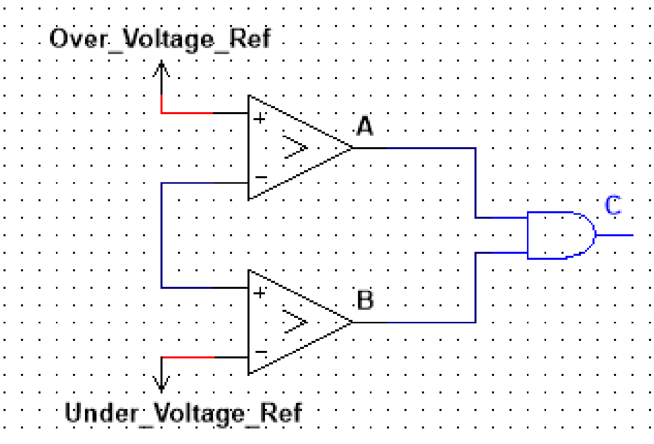

Figure 5.10 Window comparator simplified diagram

Table 5.1 AND gate C truth table

A	B	C = A.B
0	0	0
0	1	0
1	0	0
1	1	1

The truth table of the logic AND gate C in table 5.1 above shows that the comparator will only give a high (1) logic output only when both comparator A and B are having a high output logic. If any of the two comparators are low, the output become low as well.

5.2.7.1 Non-inverting comparator circuit

The setting for the under voltage reference limit was done on the non-inverting comparator circuit. The reference voltage equivalent to 206 V on the AC supply point was connected to the inverting input of the operational amplifier as in figure 5.11 below. The resistors forming the potential divider for the reference voltage are equal resulting in the reference voltage of 2.5 V since Vcc was fixed at 5V [75]. From the formula 5.1 below:

$V_{ref} = V_{cc}/2$ 5-1

$= 5\ V/2$

$= 2.5\ v$

The non-inverting comparator only give a high output when ;

$V_{in} > V_{Ref}$ 5-2

With the reference voltage set at a voltage equivalent to the Ac voltage of 206 V, the under voltage comparator only gave a high output for voltages above 206 V. With voltage of 207 V applied to the circuit, the comparator output saturated towards the positive supply rail, V_{cc} resulting in a high output [75]. For voltages equal to and less than 206 V, the operational amplifier comparator changed state and saturate at the negative supply rail with a low output as demonstrated in figure 5.11 below.

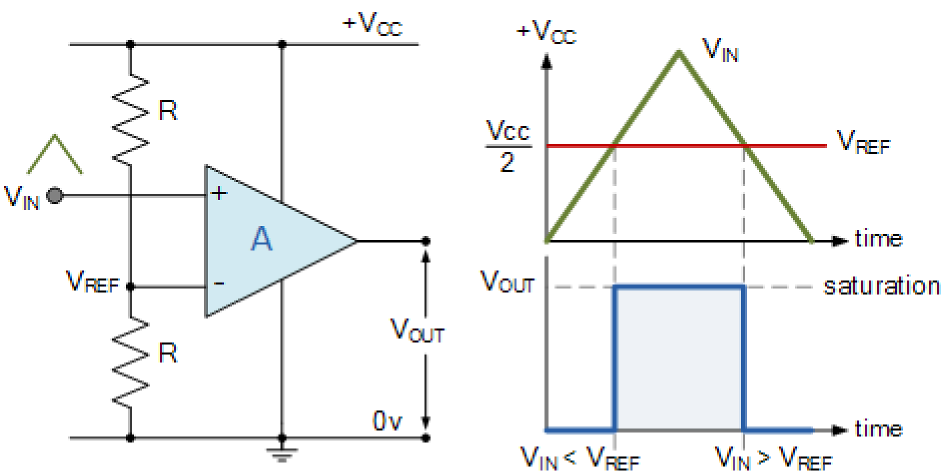

Figure 5.11 Non-inverting comparator circuit [75]

5.2.7.2 Inverting comparator circuit

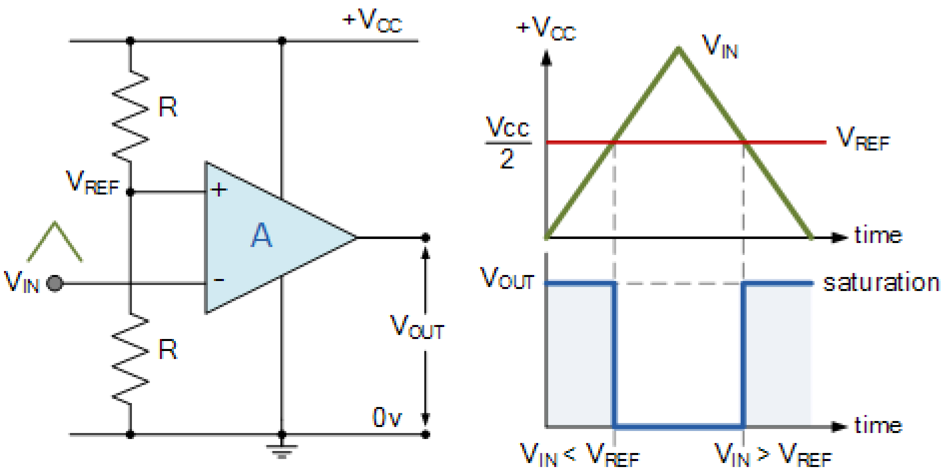

Figure 5.12 Inverting comparator circuit [75]

The inverting comparator circuit was used to set the over voltage limit of the protection circuit. Contrary to the non-inverting comparator circuit, the inverting comparator circuit gives a high output signal when the input signal is less than the reference voltage. From the formula in 5.1 above the reference voltage that was applied to the circuit was 2.5 V. The inverting comparator circuit gave the high output when:

$V_{in} < V_{Ref}$ 5-3

In the inverting configuration, the reference voltage was connected to the non-inverting input of the comparator and the input was connected to the inverting input via a variable resistor to adjust the input voltage. with the reference set at an equivalent AC voltage limit of 254 V, the comparator circuit only gave a high output for voltages up to 253 V. Any voltage above 253 V gave a low output since the voltage would have been higher than the reference voltage that was connected on the non-inverting input of the comparator [75].

5.2.8 Circuit operation

The overvoltage and under voltage protection circuit is meant to protect the connected load against over voltage and under voltage fault conditions which are mostly caused by floating neutral. The comparators in the circuit are supplied with fixed voltage of 5 V at the $+V_{ss}$ terminal (pin 3) and connected to the ground at the $–V_{ss}$ terminal (pin 12). The inverting and non-inverting input of the comparators were connected to the 12V supply voltage via the variable resistors RV1 and RV2. The other input terminals of the comparators were bridged and connected together to the over voltage and under voltage reference points. An equivalent of 206 V was applied to the circuit and the variable resistor RV1 adjusted until the inverting terminal of comparator 1(input) was below the non-inverting terminal(reference) input voltage to yield a high output of the comparator as detailed in 5.2.7.1. Similarly on comparator 2, 254 V was applied to the circuit and the variable resistor RV2 adjusted to set the upper voltage limit.

The overvoltage was set at 254 V and under-voltage set at 206 V to ensure that the voltage will not go beyond 253 V and below 207V in line with the code of practice and regulatory requirements [9] [8]. During normal operating conditions when the voltage is within the set voltage window of 207 V and 253 V, the output of both the comparators were high resulting in diodes D3 & D4 being reversed biased. Transistor Q1 then conduct as the drive is available through R14, R17, R13 to the base of transistor Q1. That energised the relay contact to close resulting in the connected load at the output having supply.

When the input goes above the upper limit of the pre-set 253 V, the voltage at the centre of RV1 goes above 2.5 volts DC. That resulted in output going low to forward bias the D3, which starts conducting and takes away the driving voltage from the transistor Q1 and Q2. While the Q1 is off the relay drops to cut off the load. At the same time the Q2 is also going off so that the pin 8 of the inverting comparator become higher than the non-inverting input voltage forcing PNP transistor Q3 to get biased so that the current flows through Q3 to sound the buzzer. Similarly, the circuit operation will be the same for the low voltage condition when the supplied voltage drop below 207 V.

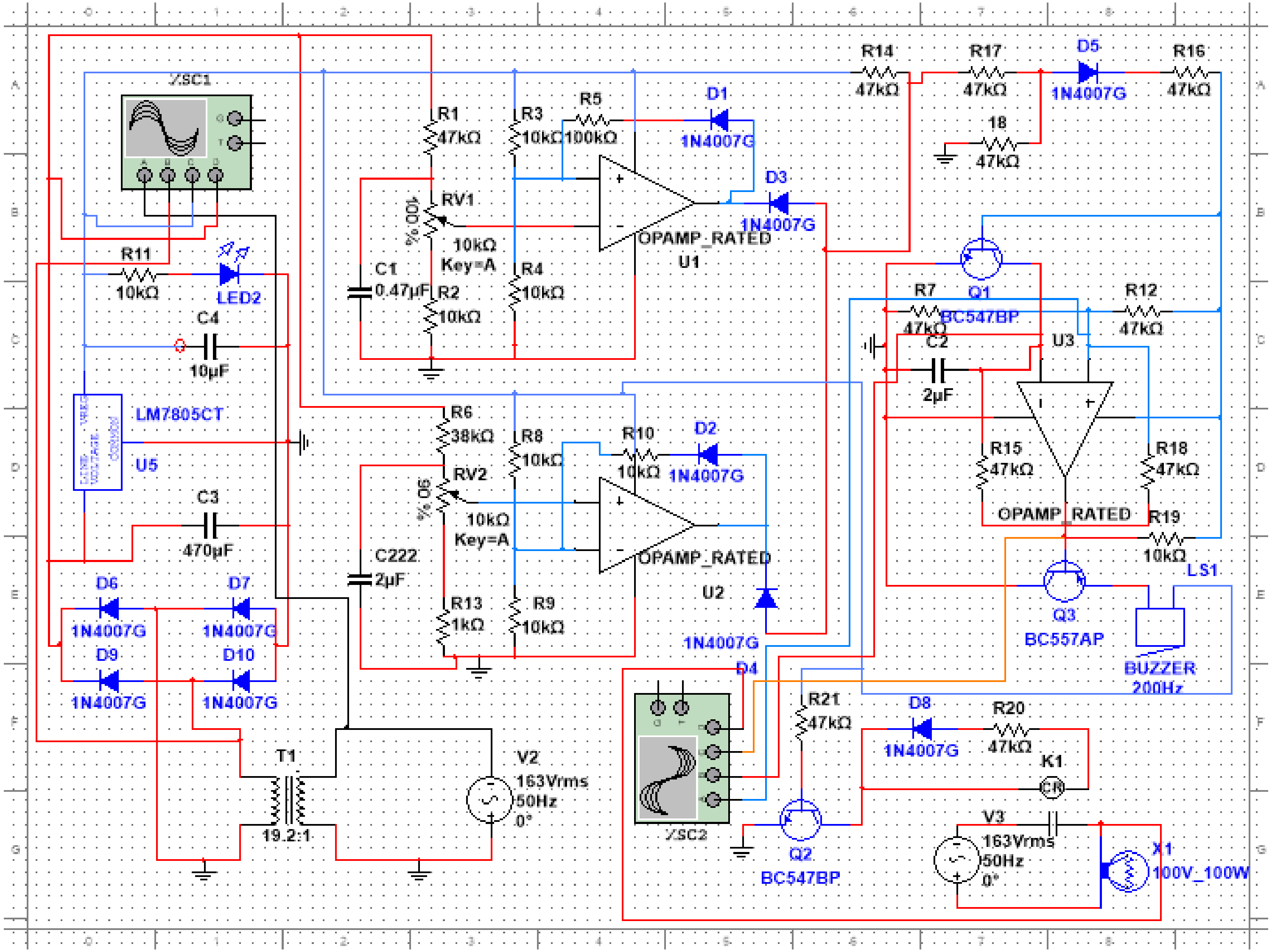

Figure 5.13 Overvoltage and under voltage protection circuit diagram

5.2.9 Results

The operation of the overvoltage and under voltage protection circuit was tested using Multisim simulation software as well as laboratory testing of the circuit that was constructed. Figure 5.17 below show the results of the laboratory tests that were conducted using the overvoltage and under voltage circuit that was constructed. The results were also collaborated by the Multisim results for the circuit diagram in figure 5.13 above. In both cases, it was possible to adjust the circuit to operate within the selected window parameters of 207 V to 253 V. That was achieved by adjusting the variable resistors until the circuit operate within the desired voltage levels. At voltages above 253 V, only comparator 2 (under voltage limit reference) had a high output. The circuit output and the comparator 1 (over voltage limit reference) had low output. The circuit required both comparators to have a high output for it to have a supply to the connected load. When the voltage was reduced below 253 V, the circuit output gave a high output and that was sustained until the voltage dropped below 207 V where only comparator 1 had a high output, resulting in an overall low circuit output.

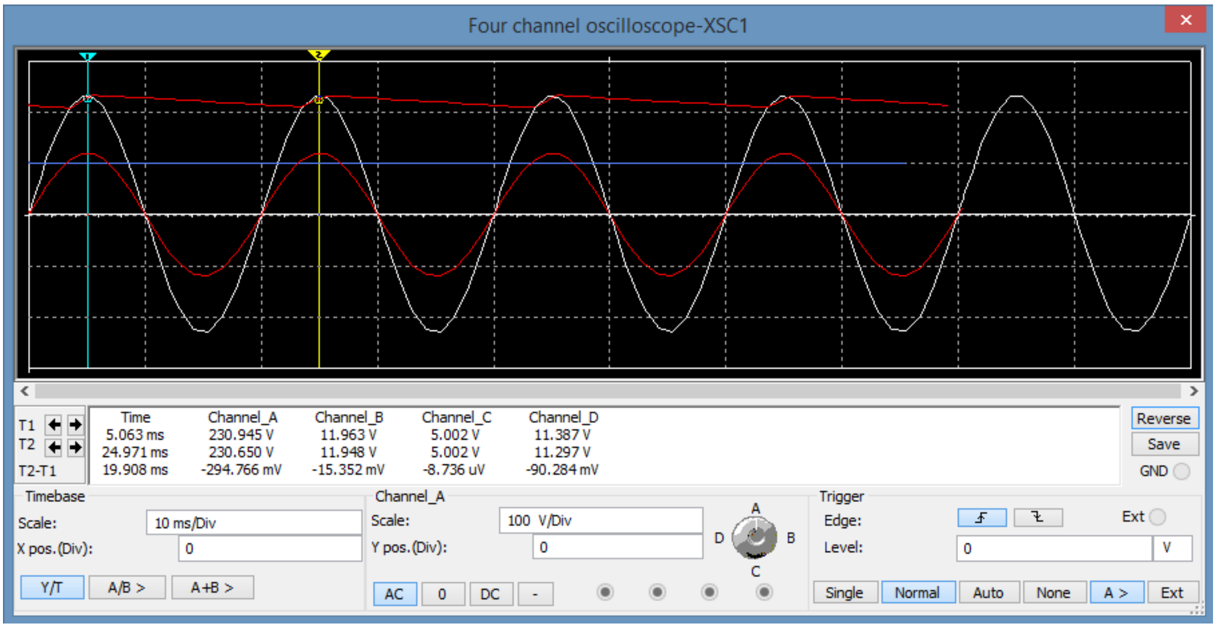

Figure 5.14 Transformer and rectifier output voltages

The above figure 5.14 shows the simulation results for the transformer primary voltage, transformer secondary voltage, rectifier DC output and the regulated DC output voltage. With the transformer primary voltage scale at 100 V/Div (white waveform in channel A), it can be seen that the circuit was supplied with 230 V AC. That resulted in the output voltage of 12V AC on the secondary side (Red waveform in channel B) with the scale set at 10V/Div. The AC voltage was rectified to 11.3 V DC as displayed by the orange voltage waveform in channel D with the scale at 5 V/Div. A voltage regulator was connected on the DC output to give constant output voltage of 5 V as displayed by the blue waveform in channel C with the scale of 5V/Div. The supplied voltage resulted in the output displayed in figure 5.15 below on the comparator circuit.

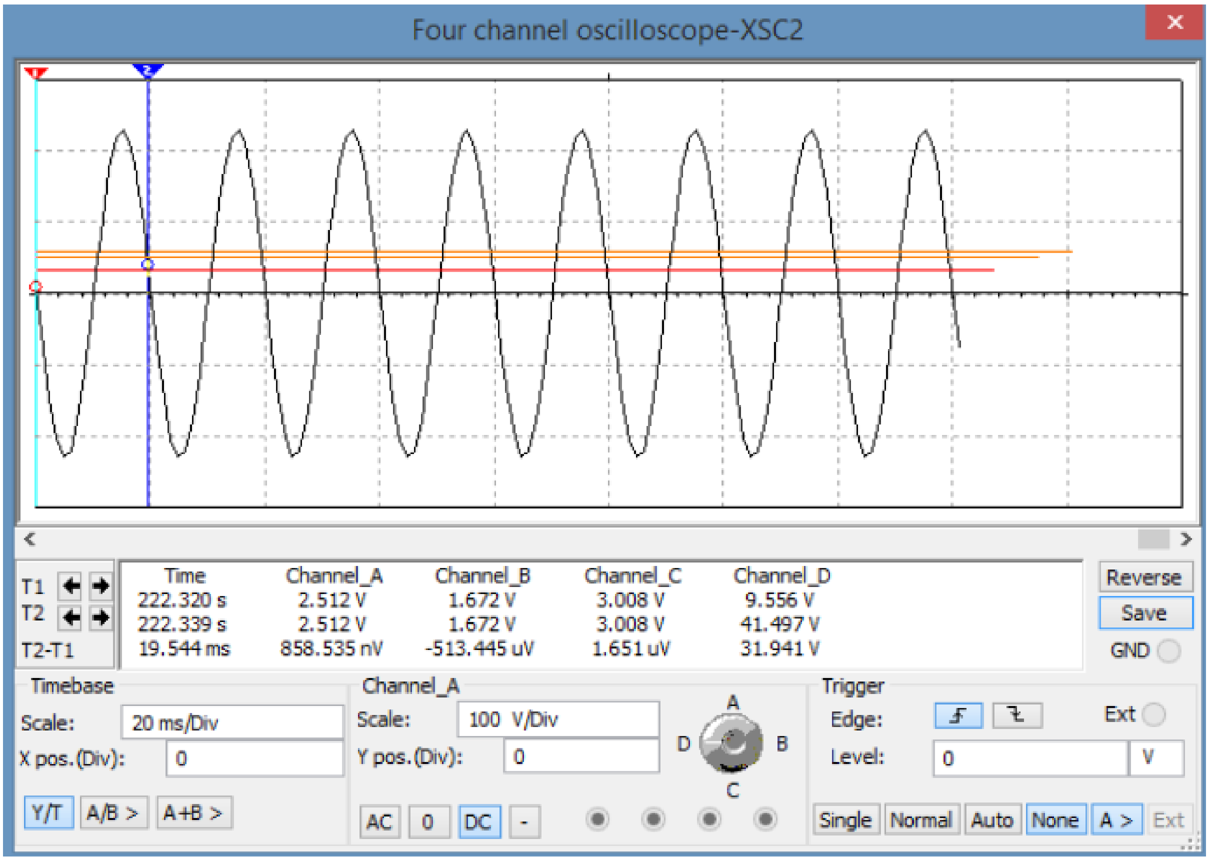

Figure 5.15 Window Comparator output voltage under normal condition

Under normal operating conditions, with the supply voltage between 207 V and 253 V, the non-inverting input voltage (yellow DC output voltage graph in channel A) of the comparator circuit was higher than the inverting input voltage (Orange DC voltage graph on channel B). That resulted on a high output (Blue DC output voltage graph in channel C). The high window comparator out activated the relay contact to close resulting in the connected AC load having a supply as displayed by the black AC voltage waveform in channel D.

When voltage increased beyond the upper voltage window limit of 253 V, the inverting input of comparator 1 increased beyond the reference value resulting in a low output of the comparator. Figure 5.16 below shows the reference voltage or the non-inverting input voltage of 2.25 V DC in channel A of the oscilloscope. The value is less than the input voltage at the inverting input of 2.75 V in channel B. With the inverting input voltage greater than the non-inverting input voltage, that resulted in low output voltage of 19.8 x 10^{-3} V in channel C.

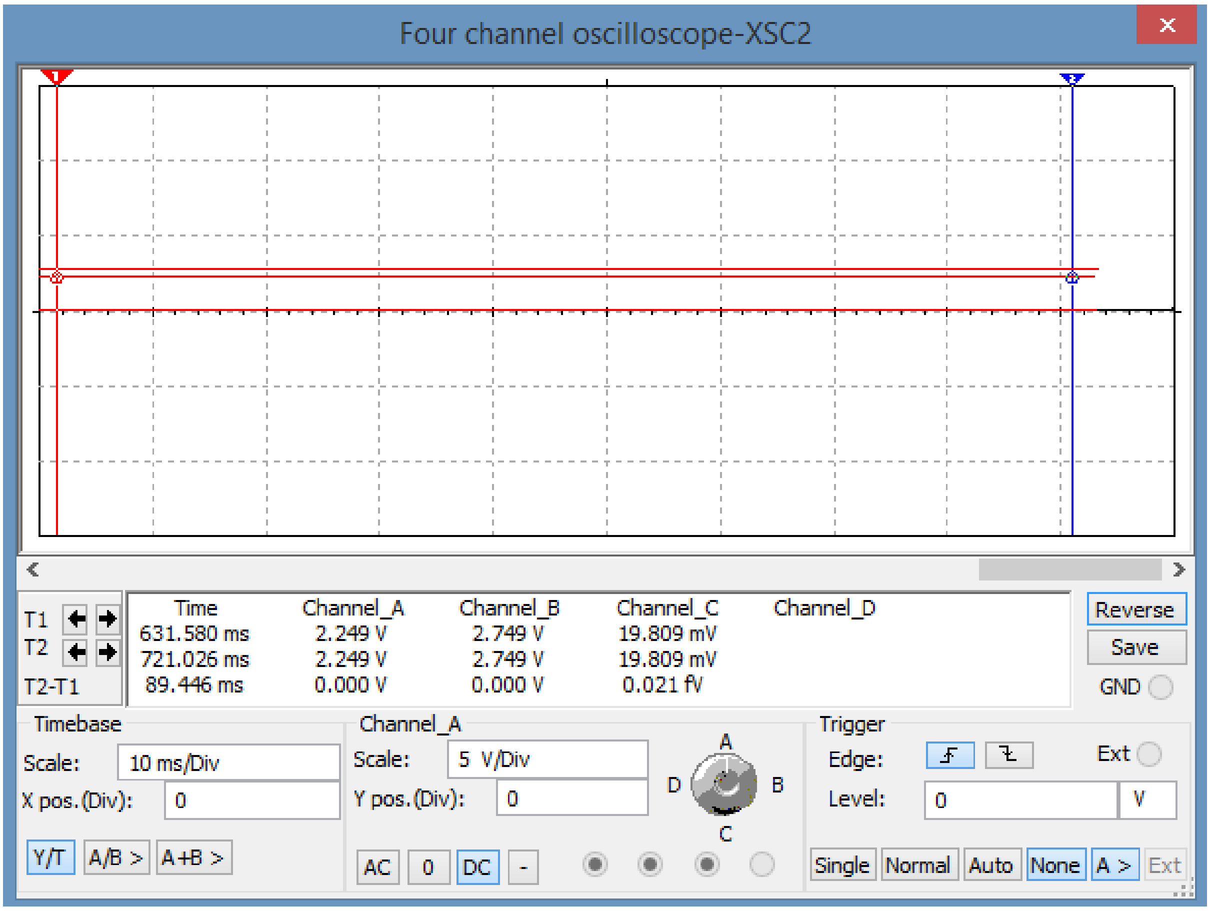

Figure 5.16 Window Comparator output voltage during over voltage condition

Similarly, when the voltage reduced below the reference voltage of the lower limit of 207 V equivalent on comparator 2, the non-inverting input, which was the input voltage, dropped below the reference voltage input voltage on the inverting input. That resulted in a low input on comparator 2 and an overall output of the circuit became low. The overall response of the window comparator circuit at different voltage levels depicted on figure 5.17 below with only comparator 2 having a high output above 253 V. Comparator 1was the only one with high output below 207 V. The circuit had supply when both comparator 1 and 2 were high at voltage levels between 207 V and 253 V.

Similar results in figure 5.17 below were observed with the electronic circuit that was built as per figure 5.1 above. The laboratory test proved that it was possible to set the voltage window where the circuit must operate as well as well as lower and upper voltage threshold where the circuit was supposed to be off.

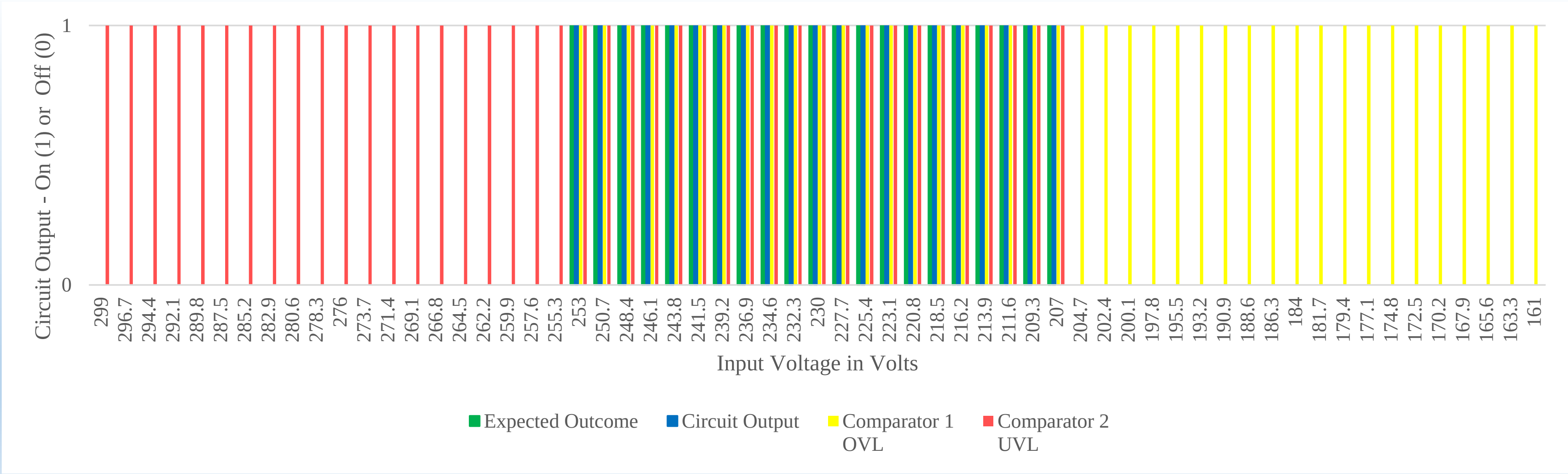

Figure 5.17 Protection circuit results

5.3 CONCLUSION

The capability of the overvoltage and under voltage protection circuit to switch off the load when the supply voltage stray outside the regulatory limit was confirmed. The laboratory bench test on the designed circuit confirmed that it was possible to set the lower and upper voltage limits using the variable resistors to switch on and off the load connected via the protection circuit. The results were also collaborated by the software simulations conducted using Multisim tool. The window comparator was able to switch off and disconnect the load at voltages below 207 V and voltages above 253 V. with distribution load connected via the protection circuit, protection of customers against overvoltage as well as under-voltage caused by broken neutral conductor and other fault conditions resulting in overvoltage or under-voltage can be achieved.

The laboratory tests conducted on the current metering equipment as recorded in chapter 3 has proven that one of the metering equipment was not having any protection at all and the other two had protection functionality though inadequate. The protection parameters were outside prescribed minimum and maximum requirements according to the NRS 048 limits. The findings of this research will address the gaps identified with the current metering equipment because it will ensure that only voltages that are within the regulatory requirements get to the customer installations. Anything outside the parameters will cause the supply to switch off to disconnect the load.

Literature review also revealed that a broken neutral that pose danger to the customers is the one that occurs on the transformer and low voltage conductors supplying the customers. Installation of the protection device on the pole top box will clear all potential damages to customer equipment caused by a broken neutral. A broken neutral on the service conductor between the pole top box and the customer house will only result in no supply with no danger of over voltage or under voltage.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The thesis has demonstrated that protection against floating neutral condition in the distribution system is possible. The dangers that are created in distribution networks when the neutral conductor is broken or compromised is voltage fluctuations that can rise up to line voltage or fall close to zero voltage, with detrimental effect of damage to customer equipment. Considering that there is no voltage protection on distribution network from the transformer up to the customer's house or point of supply, the customer connected electrical appliances and equipment remain vulnerable to broken neutral fault conditions.

The introduction of overvoltage and under voltage protection devices in the network will eliminate the risk of equipment damage when floating neutral fault condition occur. Some of the prepaid meters installed in customer's houses are equipped with built-in overvoltage and under-voltage protection. However, the protection is inadequate since they trip outside the required protection range. The solution proposed and build by the researcher uses window comparators. That protection circuit has proven to be very effective in protecting load against over voltage and under voltage fault conditions. In the circuit, it is easy to adjust the minimum and maximum operating voltage ranges using the variable resistors in the circuit. Laboratory experiments were conducted where it was demonstrated that the circuit was able to switch off the supply when voltage fall below 207 V and when voltage rise beyond 253 V. That only allows the supply to be on within the voltage levels prescribed by NRS 048 and as a result, the connected equipment guaranteed protection against voltage fluctuations even under broken neutral condition. The installation of the protection device on the pole top box to switch on and off supply from the circuit breaker can guarantee safety of the customer's equipment at a lower cost since one device can protect two, four or up to eight customers depending on the type of pole top box used.

The second danger of a broken neutral conductor in a distribution system is the creation of dangerous touch voltages that can cause injury and/or death to people in contact with exposed conductive parts. The electrical installation regulations in South Africa requires that electrical installations be equipped with an earth leakage protection or residual current device. The earth leakage protection does mitigate the risk of potential touch voltages that floating neutral in the network could create. The introduction of multiple earthing on the low voltage network increases the reliability of the residual current protection devices used to protect against earth leakage faults. The overvoltage and under voltage protection devices will ensure that the dangers of broken neutral conductors are completely mitigated at all times since both risk of potential dangerous touch voltages and voltage fluctuations would have been addressed.

The cost impact of including overvoltage as well as the under voltage protection in the network has not been quantified. As a result, the implementation of the recommendations will not happen immediately. The customers will remain exposed and vulnerable to the dangers of broken neutral conductors until implementation of the proposed mitigation measures.

6.2 RECOMMENDATIONS

The researcher recommended amendments on the current distribution protection philosophy and standards to include under voltage as well as over voltage protection as a mandatory requirement not as an option. The available options includes:

6.2.1 Installation of the overvoltage and under voltage protection circuit presented in the thesis on pole top boxes supplying the customers.

6.2.2 Updating the prepayment metering specification to ensure that overvoltage and under-voltage be specified as minimum requirements and all future contracts to accept only devices that operates within the prescribed minimum and maximum voltage ranges.

6.2.3 Creating awareness to all customers on dangers of broken neutral conductor in distribution systems as well as educating them on how they can protect themselves against the potential dangers.

6.3 FUTURE WORK

The functionality of the proposed solution simulated and tested in a laboratory only, there is still a need of incorporating the overvoltage and under-voltage protection circuit to the pole top box and test it in a real project as a pilot especially in areas where there is a high rate of neutral conductor failures. The results will assist with possible improvements that might be required before embarking on a mass roll out of the proposed solution.

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