Broken PEN conductor in the context of rural South African households

Devadasan Pillay

971164189

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Academic Supervisor: Dr A K Saha

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

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“At times our own light goes out and is rekindled by a spark from another person. Each of us has cause to think with deep gratitude of those who have lighted the flame within us.” — Albert Schweitzer

To my wife, Lizan, my kids, Brielle, Matthew and James, thank you keeping the flame in me alight; your love and support motivated me to complete this project. A special thanks to my mum for giving me the foundation of life and education that brought me to this point.

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ABSTRACT

Low voltage distribution systems often receive the least attention as faults affect fewer customers and the elemental value of the network is insignificant compared to other parts of the grand electrical system. Ironically, this component of the grid defines the safety of the customer which is dependent on the earthing practice employed. The three primary low voltage earthing practices used worldwide, Terre-Terre, Isolated-Terre and Terre-Neutral are characterised by differences in the low voltage source and service installations earthing. South Africa implements the Terre-Neutral-Combined-Separated earthing system in which the neutral and protective earth conductors are combined on the utility side but separated on the customer side. A broken protective-earth-neutral conductor on such system with unbalanced load creates a hazardous condition at single-phase service-installations which may lead to loss of life and damage to property. The risk to rural households is compounded due to the use of overhead reticulation networks and the high probability of unbalanced systems. Simulation and experimental studies observed that during an incidence of a broken PEN conductor, a typical rural household experiences close to phase-phase voltages at the single-phase installation and the exposed conductive parts are energized up to 191 V (r.m.s.) even when an appliance is off but still plugged into the mains socket. Touch potentials in excess of 35 V (r.m.s.) are considered dangerous. The scenario of a child standing on a muddy floor in contact with a stove chassis revealed, via simulations, that currents in the order of 368 mA flows through the kid undetected by the earth leakage device and the utility and household over-current protection systems. This current-flow may lead to ventricular fibrillation and eventually death as prolonged exposure to currents in excess of 6 mA is considered harmful. A multiple-earthed neutral conductor provides a pragmatic supply-side solution to lower touch potentials at households but is ineffective at mitigating out-of-limits phase-to-neutral voltages. A more complete solution would be to install a voltage operated device at the household distribution box to monitor the voltage between neutral and true-earth and disconnect live and neutral supply to the house when the voltage exceeds 35 V (r.m.s.). It is recommended that these proposals be explored for feasibility through future work and consideration be given for regulations to make the voltage sensing device in the distribution box mandatory.

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LIST OF ABBREVIATIONS

AC:	Alternating Current
DB:	Distribution Board
ECP:	Exposed Conductive Part
EXCP:	Extraneous Conductive Part
IMD:	Insulation Monitoring Device
IT:	Isolated Terre
LV:	Low Voltage
MCB:	Miniature Circuit Breaker
NRS:	National Regulatory Standards
PE:	Protective Earth
PEN:	Protective Earth Neutral
R.M.S.:	Root Mean Squared
RCD:	Residual Current Device
TN:	Terre Neutral
TN-C:	Terre Neutral Combined
TN-CS:	Terre Neutral Combined Separated
TN-S:	Terre Neutral Separate
TT:	Terre-Terre or earth-earth
UAP:	Universal Access Plan
U.K.:	United Kingdom
U.S.A.:	United States

Chapter 1. Introduction

1.1 Background

The TN earthing system is one of three primary earthing arrangements applied on LV distribution systems worldwide [1]. The TN-CS system (a derivative of TN) features three phase-conductors and a combined neutral and earth (PEN) conductor which is solidly-earthed at the neutral point of the distribution transformer and splits into constituent earth and neutral conductors at the entrance to LV service installations [2]. South African electricity utilities apply the TN-CS system as required by regulation [3] notwithstanding that it is preferred due to lower installation costs from not running a separate earth conductor as in a five-wire TN-S system. There are however inherent risks peculiar to the system.

Unbalanced three-phase TN-CS systems are undesirable as the unbalanced load causes a large current to flow in the PEN conductor. The cross sectional area of the PEN conductor is permitted by regulations to be fifty percent of that of a phase conductor as in an ideal balanced system the instantaneous neutral currents sum up to zero [4]. High magnitudes of currents in the PEN conductor may increase the incidence of thermal related failures.

A PEN conductor failure on an unbalanced three-phase system with single-phase loads creates a hazardous condition at customer (service) installations. The hazard is characterised by abnormal phase-to-neutral voltages that are beyond regulatory limits and dangerous touch potentials that may cause electrocution to a human. The excessive voltages may also cause household appliances and utility equipment to fail.

It is common for a high degree of unbalanced loading on typical South African rural electrification transformers due to the incongruent geographical layout of the load, the preference of the use of three-phase transformers to lower costs, the retrospective addition of loads to existing transformers without engineering from first principles, illegal connections and the general oversight of design engineers.

There is thus a high probability that a rural household is most likely to experience a condition of a broken PEN conductor on the utility’s LV network. The consequences of the ensuing risks are also stacked against rural households as they usually draw very little load which worsens the case and also have poor floor insulation as floors are generally mud and raw earth; this consequently increases the chance of electrocution. There is a need to quantify the level of exposure of typical rural households to the risk emanating from a broken PEN conductor given that the existing LV protection systems are unable to detect the condition. It is also required that some pragmatic recommendations are offered to industry for consideration.

1.2 Importance of the research

The existing South African regulations on LV earthing practices does not fully cater for a condition of a broken PEN conductor on the utility LV network which may setup non-compliant phase-to-neutral voltages and dangerous touch potentials at a customer's installation and the condition is also undetected by existing over-current and earth-fault protection systems on both the utility and customer side. Electricity utilities in South Africa are currently connecting millions of households to the electricity grid as part of the government's Universal Access Plan to provide services to rural homesteads. The homesteads are mostly informally constructed with mud floors, wood and mud walls and thatch roofs which increases the consequences related to this dangerous condition. The situation is exacerbated by the notion that if a human were to touch the exposed conductive part while standing on the household floor, injury or death may occur as a result of the current that would flow through the human body to ground. The lack of insulation from not having a proper floor and the highly probable instance of a kid making contact only serves to increase the consequences of such an event. The non-compliant phase-to-neutral voltages may lead to appliance failures and may also cause fires. The rural communities are also not fully aware of the dangers of electricity due to unfamiliarity with the product. The importance of the research is to define the risk present at a typical rural household due to an incidence of a broken PEN conductor and to offer a few pragmatic considerations on the detection or mitigation of such a condition.

1.3 Hypothesis

A human in contact with an exposed conductive part at a typical South African rural household during an incidence of a broken PEN conductor on a utility's unbalanced system will experience an electric shock that may be fatal. The phase-to-neutral voltages will also be outside of the regulatory limits and the dangerous condition cannot be detected by the utility over-current protection and the household over-current and earth-leakage protection systems.

1.4 Research problem statement

To demonstrate by simulation and experimental tests that a typical load model of rural households supplied from a utility LV distribution network with a broken PEN conductor and a high degree of unbalanced loading results in non-compliant phase-to-neutral voltages and dangerous touch potentials that are undetected by existing over-current and earth-fault protection systems on both the customer and utility side. To provide an overview of pragmatic considerations for industry to either mitigate or detect this dangerous condition.

1.5 Delimitations

This research reviews and recommends a few pragmatic considerations for the detection and/ or mitigation of the dangerous phenomenon; these recommendations are however not fully tested for all other supply-compliance requirements and therefore, only serve to stimulate future research on the feasibility and effectiveness of the proposed solutions.

1.6 Outline of Chapters

Chapter two of this dissertation reviews the various system earthing practices across the globe and provides an overview of the current opinions of broken PEN conductors on a TN-CS LV earthing system and its manifestation of risk. It also reviews the safe exposure limits of voltage and currents to the human body.

Chapter three presents the relevant theoretical aspects of LV distributions systems and orientates he reader to interpret the discussions and dialogues presented while chapter four simulates the condition of a broken PEN conductor on various supply configurations utilizing Matlab Simulink. Chapter five is an experimental setup of the simulation under laboratory conditions; this is to ratify the simulation model which is used in chapter six to evaluate and review preliminary mitigation and detection options for industry.

Chapter seven finally rounds up the passage of dialogue and summarises salient recommendations for industry.

Chapter 2. Literature Review

2.1 Introduction

It is important for utilities to have an effective earthing system as it is critical for the safety of persons, protection of equipment and reliability of supply [5]. Utility protection systems are configured to prevent the presence of excessive voltages and the flow of current at exposed conductive surfaces either due to direct or indirect contact [6]. The presence of voltage or the flow of current at conductive surfaces creates a risk of shock to humans or animals if contact is made to those conductive surfaces [6]. There are varying earthing practices applied on LV distribution systems worldwide, each with inherent benefits and weaknesses relating to the protection of life and property.

2.2 Review of international systems, including protection and earthing

There are three primary system-earthing arrangements applied worldwide, viz. the TT, IT and TN systems [7]. The TN system is further subdivided into the TN-C, TN-S and TN-CS subsystems. The TT system-earthing arrangement is characterised by the transformer neutral being solidly earthed while the exposed conductive parts of customer installations are directly earthed via a local ground electrode independent of the utility-side earthing [8]. The earth essentially provides a return path for earth-fault current. This system is utilised in several countries including Belgium, Denmark, Portugal, Italy, Greece, Spain, Turkey, Luxemburg, Japan, Morocco and Kenya [9]. One of the disadvantages of this system is that the loss of the earth connection is not automatically detected; this system is not considered for application in South Africa due to high soil resistivity and high incidence of earth conductor losses [3].

In an IT system the source is either unearthed or connected to ground through high impedance. The customer installations have a separate and independent earth electrode and all exposed conductive parts at the installation must be electrically bonded to the earth electrode [8].
A primary advantage of the system is the availability of supply to the system during the occurrence of a single fault; the protection will however operate when another fault occurs on a different phase [9]. One of the drawbacks is that line-to-neutral loads are not possible. This system may be found in certain applications in South Africa such as hospitals and continuous process plants and not a feature of LV residential applications [3].

The TN system is subdivided into the three subsystems

a) TN-C: The neutral and protective-earth (PE) conductors are combined (PEN)
b) TN-S: The neutral and PE conductors are separate
c) TN-CS: The neutral and PE conductors are combined (PEN) upstream but becomes a TN-S downstream, i.e. the neutral and PE conductor are separate [1].

The TN-CS is the preferred method of low-voltage system earthing in South Africa and other countries such as Germany, Australia, Sweden, the U.K. and the U.S.A. although the latter countries apply a variation with the PEN conductor earthed multiple times in the circuit [2]. In South Africa, the TN-CS earthing system is applied with only the neutral point of the transformer being solidly connected to the ground, the rest of the system, including the customer’s installation, is dependent on this solitary point of earthing [3].

There are differing opinions on the safety of a multi-grounded neutral system; [10] considers the system hazardous due to the uncontrolled flow of electric current over the earth posing a risk to animals and humans citing that currents exceeding nine milli-amperes may be hazardous to humans. According to [11], some European utilities’ choice to earth the PEN conductor multiple times along the circuit in their application of the TN-CS system is to prevent dangerous touch potentials and the possibility of an electric shock should a human come into contact with energized enclosures during a broken neutral fault on the utility side. The European practice of multiple earths along the PEN is successful due to low effective earth resistances as a result of good soil resistivity. The South African soil conditions makes it difficult to easily attain low resistance values hence multiple earthing of the neutral is not implemented [11].

2.3 The South African earthing system

The South African earthing practice is regulated by [4] which states that only the TN-S and TN-CS earthing systems may be used in South Africa although the TN-CS is preferred. In a typical rural electrification application, the TN-CS earthing system is utilised. Regulation [4] stipulates that the PEN conductor must be earthed at the source transformer, while at the service installation, the PEN conductor must split into constituent neutral and protective earth conductors prior to the residual current device (RCD). The application of this requirement is confirmed in [12]. The advantage of a combined neutral and earth protective conductor is the financial savings from not running a separate protective earth conductor. From a protection perspective, there is an added benefit that over-current protection also protects against earth faults as phase-to-earth faults are seen as phase-to-neutral faults and so the impedance of the fault is low enough such that a high fault current will cause the over-current protective device to operate [13]. Further, the provision of a separate earth conductor (yet connected to the neutral) at the service installation allows for the effective functioning of a RCD which operates if the difference between the currents flowing in the neutral and live conductors are greater than 30 mA [14]. One of the main disadvantages of the TN-CS system is that a neutral conductor failure on the utility side may result in excessive voltages at single-phase supply terminals and dangerous touch potentials at the exposed conductive parts under certain load conditions, yet undetected by existing over-current and earth-fault protection systems on both the utility and customer side [15].

In 1993, [11] detailed this risk and went on to recommend that the earthing practise in South Africa be reassessed from first principles and that the regulations be amended to allow a wider choice of earthing systems specifically related to safety. In 2013, a new South African regulation, [4], governing the earthing of LV distribution systems was promulgated. Alas, the regulation clearly highlights the risk yet no prescriptions are made on how to prevent or totally mitigate this condition.

2.4 Broken PEN conductor in the context of rural South African households

In determining the risk to the South African community, it is important to refer to material that specifically relate to the South African application of the TN-CS earthing system as international papers ([10], [13] and [2]) generally articulate risks of the system with a multiple grounded PEN conductor while in South Africa the PEN conductor is only grounded at the source. There are therefore questions whether the risks are applicable to the South African context. In a South African publication and on reviewing the South African application of the TN-CS earthing system, [15] states that there is indeed an impending risk to service installations if a PEN conductor fails on the utility side and that:

a) The risk is confined to a three-phase system serving single phase loads
b) The consequences are dependent on the load balance and position of the PEN conductor failure on the LV network.
c) The consequences include overvoltage (up to phase-to-phase) at single-phase installations and hazardous touch potentials at exposed conductive parts.
d) The hazard is not detectable by existing protection on both the utility and customer side.
e) This may lead to appliance failures, fires and injury or loss of life.
f) The risk of a broken PEN conductor on the utility side does not extend to a single phase installation derived from a single phase source or transformer.

The risk to South African households have also been confirmed by [11] while [16] confirms this and further highlights that the hazards associated with a broken PEN conductor (on the utility side), also extends to single-phase installations derived from a single-phase source contrary to what [15] stated. Despite inadequate regulation and protection systems to deal with this risk and for good reason, South Africa has engaged on mass electrification since 1994 based on a principle of low cost connections in a quest to provide electricity to millions of citizens previously deprived. Electricity, in these communities, serve the purpose of basic lighting and heating and so may even be considered as a basic human right. The strategy of electrification is to achieve the maximum number of connections at the cheapest cost and in the shortest possible timeframe due to political and social pressures.

To lower costs, application designers prefer the use of three-phase transformers as more customers may be connected per unit cost. Due to the random layout of households, load balancing is not always attained. In some instances customers migrate to an area that is already electrified whereupon these customers are added (at a later stage) to the closest point on the network resulting in a potential of further load unbalance. Illegal connections are also rife in the South African context as customers are impatient to wait years for electricity and so resort to connecting themselves onto the utility network; this again contributes to the load unbalance [16]. The probability of an unbalanced load in a rural area is therefore high.

The largest utility in South Africa installs a pre-wired distribution board to rural electrification customer households; the distribution board features a 20 A miniature circuit breaker (MCB) and a residual current device (RCD) earth leakage unit. The risk in essence is that neither the RCD nor the MCB operates when the neutral wire attains the potential of a phase conductor and exposed conductive parts become energised during the incidence of a broken PEN conductor on the utility side [17]. It still does not operate even after a human completes the circuit between the ECP and earth resulting in current flow through the human. The RCD cannot clear the fault as the neutral and live currents flowing through it balance to zero [17]. The non-operation of the RCD is not peculiar to the 20 A distribution board but is a limitation of the orientation of residual current devices in its application on a TN-CS system.

Urban suburbs are commonly supplied by underground cable systems; the ensuing risk to urban households from a broken PEN conductor fault is minimal because it is unlikely to lose the PEN conductor without losing the phase conductor as well [4]. In rural South Africa, overhead LV circuits are utilised; the conductors are fully exposed to the harsh South African conditions and further exposed to societal elements as detailed in [16] which may precipitate failure of the PEN conductor.

The chances are further exacerbated by the notion of high magnitudes of current flowing in the neutral conductor due to the common occurrence of unbalanced load. The PEN conductor is rated at only 50% of the phase conductor electrical specification [4]; the abnormal continuous current-flow in an already underrated conductor may cause the PEN conductor to fail due to thermal stresses.

Extraneous conductive parts in an urban application are bonded to the supply earth terminal and in almost all cases connected to some metal pipes and structures that are connected to the ground. In the rare event of a loss of the PEN conductor, the neutral point in the distribution box still has a reference to true earth and therefore there will be limited current flow though the human. The current will be further limited by the fact that urban households have concrete floors and tiles or carpets which sets up a larger resistance to ground making the path through the human inopportune [18].

In rural homesteads, extraneous conductive parts are not bonded to the supply earth terminal moreover the houses have mud floors rather than concrete and tiles; these mud floors contribute to a lower resistance to ground which is further lowered when the floors are wet during rainy weather. The total resistance to ground between an ECP and true earth comprises a human in series with the ground resistance; it is common in a rural setup for a kid to be barefooted when in contact with an exposed conductive part of an appliance. Consequently, an even lower resistance to ground is offered setting up higher magnitudes of current-flow through the human for a given touch potential; this is a recipe for disaster.

The following supply-side interventions, as stated by [11], may be considered to mitigate or possibly eliminate the problem:-

a) Earthing the ends of LV feeders via the PEN conductor where low earth resistances are attainable.
b) Consider a duplicate neutral conductor.
c) The adoption of a TN-S system with sensitive earth fault relay on the utility side [11].

The following load or customer-side interventions, as stated by [15], may be considered to mitigate against the risk:-

a) Install “devices to detect and operate under phase to neutral voltage rises above critical level”.
b) Install “devices that detect and operate a rise in the potential of the neutral conductor above critical level”.

In addition to the above, [16] recommended enhancing the aforementioned proposals with higher degrees of sophistication through integration of smart meters and additional current and voltage transducers, the following are however unique contributions:

a) "Monitor load current & voltage at multiple points on the system"; this with a view to integrate into smart meter technologies.
b) "Interconnect PEN's of different transformer zones with one another".

2.5 Touch potentials, current flow and the impact to the human body

Direct electrical contact with live parts in normal service or indirect electrical contact with exposed conductive parts of electrical equipment may cause physical harm to persons. Direct contact may be defined as coming into contact with a conductor that is normally live while indirect contact may be classified as a person coming into contact with an exposed conductive part that is not normally live but has become live due to a fault or malfunction of the system. The term "basic protection" refers to "protection against direct contact" while "fault protection" refers to "protection against indirect contact" [19]. The term touch potential refers to the voltage between an exposed conductive part and true-earth.

Voltage is an important factor in determining whether an object which is energized can deliver current through a body [20]. The threshold of a safe touch potential range is 50 V r.m.s. and below; this may be used for protection in the case of a fault either due to direct or indirect contact [21]. According to [10], a lower voltage of approximately 35 V r.m.s. across dry skin is sufficient to force electricity into the human body while an even lower voltage is sufficient for a woman's dry skin. Although voltage is the driving force, it is the current that causes injury or death to humans and animals. For a 60 Hz alternating current, a human may feel a slight sensation at 0.3 mA, while painful shock may occur at only 6 mA for a woman and 9 mA for a man while the likelihood of injury increases the longer the current flows through the body [10]. The flow of current through the chest cavity is considered the most damaging path by [10] who states that prolonged exposure to a 20 mA current (or more) at utility frequency, may be fatal.

Ventricular fibrillation occurs when electric current flows through the heart muscle impacting the heart's rhythmic contractions. Pumping of the muscle will eventually stop and the pulse disappears due to the derangement of the heart function rather than the actual damage done to the muscle. Ventricular fibrillation is considered the most dangerous result to electric shock since death ensues within a few minutes as the brain becomes deoxygenated. Treatment consists of immediate and continuous application of artificial respiration.

The minimum commercial frequency electrical current which results in ventricular fibrillation is considered to be directly proportional to body weight and inversely proportional to the square root of the duration of the shock itself [22]. The human skin has both resistance and capacitance components; skin capacitance causes impedance to decline with increasing frequency [20]. Therefore, the impedance may be considered mostly resistive at low frequencies. The duration of exposure to current flow, the impedance of the path through the human body and the applied voltage level determines the overall effect of the current flow and ultimately the impact to the subjected human.

2.6 Conclusion

There are inherent weaknesses and benefits of the various earthing systems utilised on electrical systems worldwide; the TN-CS system utilised on the South African LV grid is no different. A broken PEN conductor on a TN-CS system is documented in research to be dangerous under certain conditions yet there is an opportunity to quantify the risk to a typical rural South African application and ascertain whether the prevailing conditions in a rural application increases the risk to households by either augmenting the probability of drivers or the consequences of the outcome. Literature has also provided several generic solutions yet none have been confirmed to be applicable in the South African context. There is, thus, opportunity to also review the effectiveness of a set of commonly proposed solutions with a view to guide a utility on pragmatic considerations for the mitigation of the various manifestations of PEN conductor failures on LV distribution systems.

Chapter 3. LV distribution systems and safety – theoretical aspects

3.1 LV System earthing arrangements

The three primary LV earthing practices used worldwide, Terre-Terre (TT), Isolated-Terre (IT) and Terre-Neutral (TN) are characterised by the method of earthing the secondary of the LV transformer and the method of earthing the exposed conductive parts of service installations. Their naming convention comprises two letters, one defining the utility-side earthing and the other the service-installation-side earthing.

3.2 TT Earthing system

The neutral conductor in a TT system is solidly grounded at the utility LV source and thereafter distributed to single-phase loads. At the service installation (customer's premises) the exposed conductive parts (ECP) are bonded together and connected to a local earth electrode such that the service installation earth is independent of the utility earth, i.e. the customer provides one's own earth as the utility is unable to safely provide a means of earthing for its customers. [9]

The earth electrode of the utility and that of the house are connected together via the ground which forms a return path for the operation of protection. A feature of the protection system is that it sustains the earth fault but limits the consequences by employing RCDs on the utility side that operate for an imbalance between the neutral and phase current, typically in the case of an earth fault.

Figure 3-1 illustrates the key components in circuit during a phase-to-ECP fault in an appliance at a customer's service installation. The utility transformer earth electrode resistance and the installation earth electrode resistance dominate the impedances of the source, phase conductor and protective earth conductor in the fault loop denoted by the red dotted line in Figure 3-1.

The touch potential at the ECP at the customer's premises may be obtained from equation 3-1on applying Millmann's theorem to the circuit in Figure 3-1.

$$V_{ST} = \frac{\left(\frac{V_{ph}}{R_{UG}}\right)}{\left(\frac{1}{R_{IG}}\right)+\left(\frac{1}{R_{UG}}\right)} = V_{ph} \times \frac{R_{IG}}{R_{IG}+R_{UG}} = \frac{1}{1+(\frac{R_{UG}}{R_{IG}})} \qquad 3\text{-}1$$

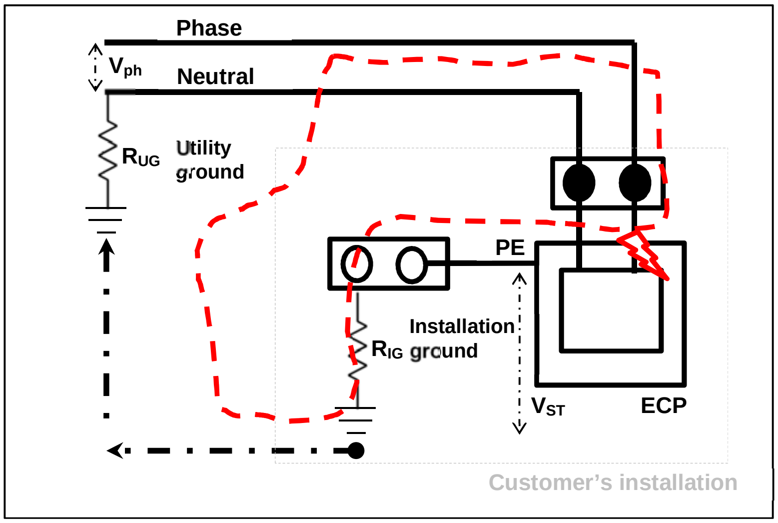


Figure 3-1: TT system highlighting the earth-return path

On analysing Equation 3-1, it is evident that the touch potential is inversely proportional to the utility ground resistance and directly proportional to the installation ground resistance. Therefore, the utility ground resistance should be as large as possible and the installation ground resistance should be as small as possible to achieve low touch potentials such that it is harmless to persons. It is generally difficult to achieve low enough earth resistance values at the customer installations; on the other hand it is also not possible to increase the earth resistance at the transformer indefinitely as the functioning of protection systems and the ground potential rise during faults become issues of concern. Ultimately, the magnitude of the ground-fault current during a fault such as that in Figure 3-1 is determined by the magnitude of the utility and the installation ground impedances. Safety is therefore achieved by providing a combination of over-current and residual protective devices.

If the neutral conductor is broken on a TT system, the neutral wire downstream of the break must be considered live as it attains the same potential as the live conductor supply. The exposed conductive parts however do not attain the same potential as the neutral conductor as in the case of a TN-CS system; this is because the neutral conductor of the supply is not connected to the earth terminal of service installation. Nonetheless, a broken neutral conductor on a three-phase TT system exhibits a similar risk as the TN-CS system in that single-phase installations are at risk of possible over-voltage as two installations may be sourced in series by a phase-to-phase voltage which will divide across the installations based on the respective loads.

3.3 IT Earthing system

In an IT system the neutral point of a transformer is not solidly connected to earth however the insulation from earth is achieved via a high resistance grounding resistor connected to the neutral point on the secondary side of the transformer. At the customer’s premises, the ECPs are either grounded individually or collectively.

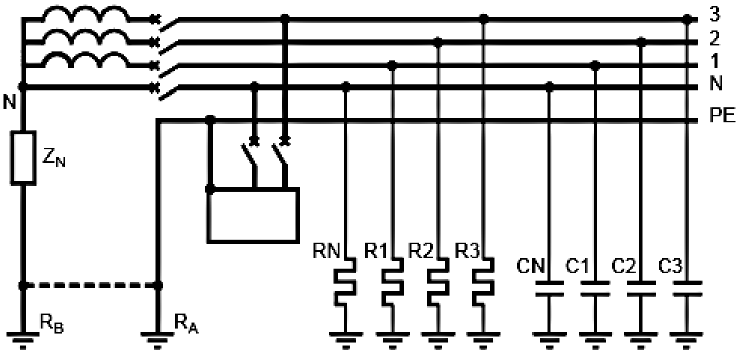


Figure 3-2: Equivalent circuit of an IT system [23]

In Figure 3-2, the neutral point of the supply-transformer is earthed via a high impedance resistor Z_N of resistance 1 kΩ to 2 kΩ; the equivalent earth resistance is indicated by R_B. At the customer’s premises the ECP is earthed via a resistance of R_A. The supply-side earth and the load-side earth may be interconnected but is considered to be separate if they are more than 8 m apart. The common mode impedance of the live and neutral cables is depicted by a resistor and capacitor in parallel from each conductor to earth representing the leakage capacity and resistance of the insulation to earth. A key feature of the IT system is its ability to maintain availability of supply to the system even after an earth fault is experienced on condition that the touch potentials at ECPs not exceed 50 V, if this voltage is exceeded then the protection system is configured to automatically disconnect the load-circuit from the supply. When a second earth fault is experienced while the first fault is still unresolved, the equivalent circuit appears as a short circuit to the protection system which operates to clear the fault.

Although the system is able to ride through the first earth fault, it is important that the fault is detected and resolved as soon as possible as the occurrence of a second fault may create a hazardous condition where an ECP at an installation may experience up to phase-to-phase voltage before the protection system interrupts the system. The detection of the initial fault also improves the overall reliability of the system as there would be no need for the system to trip if faults are detected and resolved before the occurrence of a second fault. Detection of the initial fault is achieved by the use of an insulation monitoring device (IMD) which monitors the impedance to ground at the neutral point of the circuit, if the impedance drops below a certain value then an audible or visual alarm is initiated which alerts the repair crew to the presence of the fault. The IT system is an intricate system that requires skilled maintenance teams but offers superior availability of supply when compared to the TT and TN systems. It is therefore preferred in applications such as hospital theatres and industrial processes.

3.4 TN-CS Earthing system

The TN-CS system is a derivative of the TN system of earthing. It is characterised by a combined neutral and earth conductor (PEN) that is distributed to service installations and connected to the star point of the supply-transformer which is solidly earthed at this point. The PEN conductor splits into constituent neutral and protective earth conductors at the entrance to service installations prior to the main distribution box. The purpose of earthing the neutral point of the transformer is to limit over-voltages during fault conditions and to provide a reference to the system operating voltage.

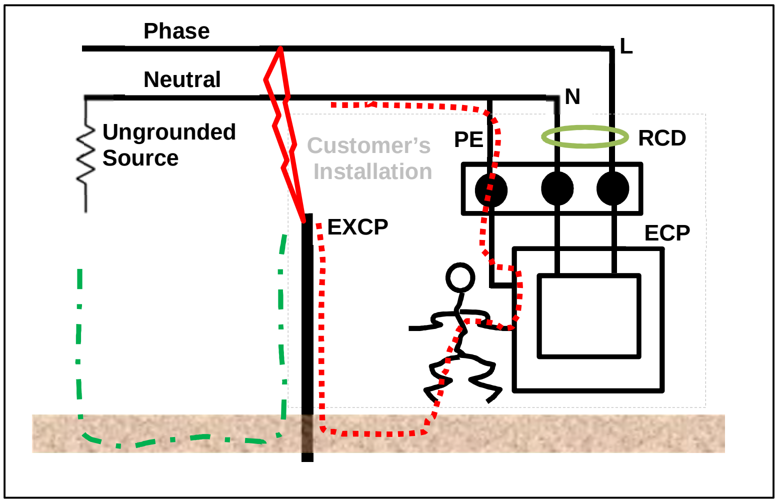


Figure 3-3: Ungrounded system with a fault

Figure 3-3 represents an ungrounded utility source with a fault between the phase conductor and an extraneous conductive part (EXCP), typically a metal post in the ground at a customer's installation. The fault loop is shown by the red dotted line: from phase conductor via the EXCP, into ground, via the human in contact with an ECP which is connected to the PE conductor that completes the loop back to the source via the PEN conductor. The only form of protection on the utility side is the overcurrent device which may or may not operate depending on the magnitude of the fault current. If the impedance between the EXCP to ground to the human is high, the resultant current may be lower than the threshold of the over-current pick-up. The green dotted line depicts the fault path if the neutral was appropriately earthed at the utility source-transformer; in this instance the path through the human becomes less opportune. This scenario illustrates the importance of the utility source-transformer-earth in the context of safety to households.

The South African application of the TN-CS system is distinguished by the LV system only being earthed at the utility supply-transformer, earthing at a customer's installation is not permitted due to poor soil resistivity and the consequent dangers of elevated touch potentials.

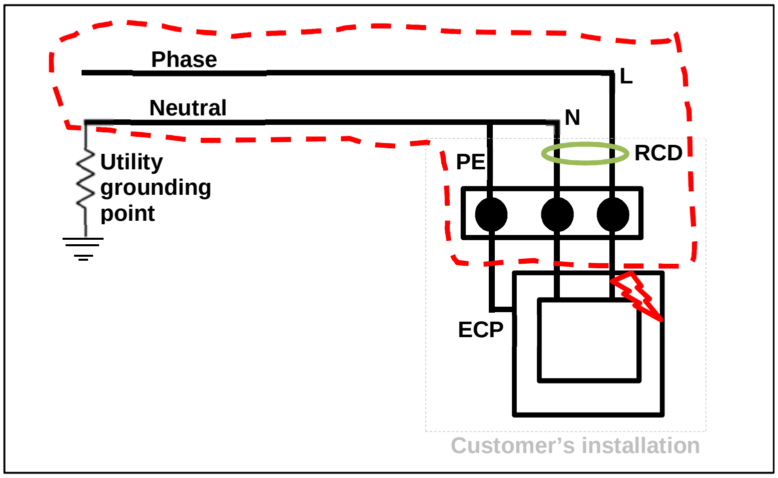
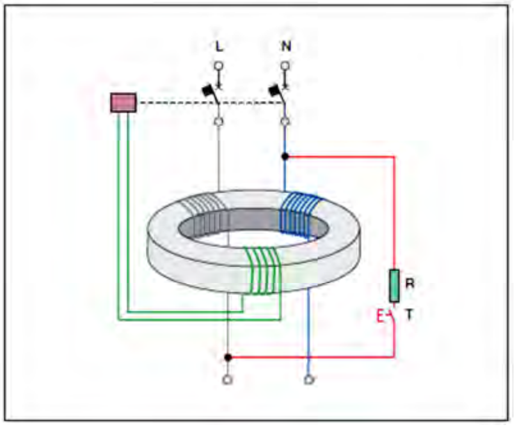


Figure 3-4: A TNCS system as applied in South Africa

Figure 3-4 shows a single-phase installation derived from a three-phase supply; the neutral conductor is solidly earthed and thereafter distributed to the service installation where it splits into the neutral and protective earth conductors. The protective earth conductor is connected to the earth terminal at the distribution box; ECPs and EXCPs are bonded to the earth terminal at the installation. During a short-circuit fault where the ECP becomes live, the fault loop is denoted by the red dotted line in Figure 3-4. If the fault is close enough to the source, the low impedance of the phase and PEN conductors results in high fault currents which enable the effective operation of over-current devices such as breakers and fuses. However there are situations such as at the end of a long LV network where the fault current may not be large enough to effectively operate the over-current devices. In these instances a RCD (denoted by the green ellipse in Figure 3-4 is employed at service installations as an added dimension of safety.

3.5 Residual current devices

An earth leakage device may be voltage operated or current operated; current operated devices are termed residual current devices and as per South African regulation, [3], it is mandatory at all low-voltage service installations. Residual current devices (RCD) are utilised to provide protection against electric shock arising from either direct or indirect contact.



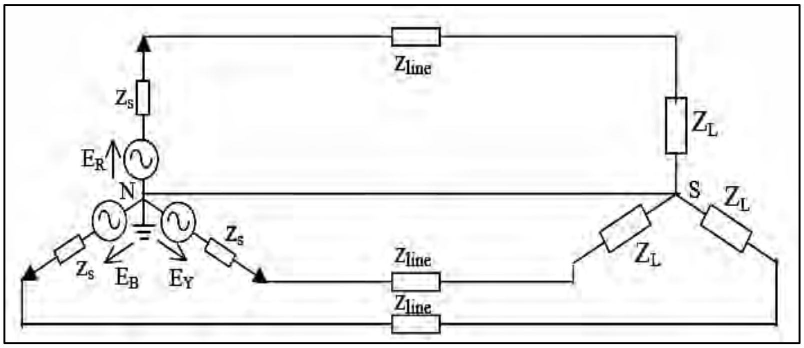
[24]

Figure 3-5: Operating principle of a RCD

In a TN-CS application, the RCD operates on the principle of monitoring the difference between the currents flowing in the neutral and live conductors by means of a toroid transformer as illustrated in Figure 3-5. Under normal conditions, the vectorial sum of the live and neutral currents is zero however when the sum is non-zero and greater than a residual rated current ($I_{\Delta N}$), the current differential is perceived to be a leakage to earth. This results in the secondary side of the toroid activating a dedicated tripping coil which disconnects both the live and neutral supply to the installation.

According to [25], RCDs are classified according to the type of current they can detect and their operating time. An AC-type RCD detects residual sinusoidal alternating currents, either suddenly applied or slowly rising while an A-type RCD operates for the same but with further capability to detect residual pulsating direct currents. The B-type RCD operates for residual direct currents, residual sinusoidal alternating currents and residual pulsating direct currents, whether suddenly applied or slowly rising. The two genres of operating-time types are undelayed-type and time-delayed-type. RCDs are also distinguished by the residual current rating and the number of poles it interrupts for example two-pole or four-pole. 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.

3.6 Broken PEN conductor on a three-phase system



[26]

Figure 3-6: Balanced three-phase star system

Figure 3-6 depicts a three-phase star connected system sourcing a balanced three-phase load where the phase voltages and currents are 120° displaced and equal in magnitude. In the case of single-phase loads derived of the three-phase system, the neutral conductor is common to each of the phases and forms the return path for the currents returning to the supply-transformer. Kirchoff's Current Law states that the algebraic sum of the currents entering a node is zero. Considering that the currents are sinusoidal waveforms, 120° displaced and of equal magnitude then equation 3-2 represents the vectorial sum of the current in the neutral conductor. Therefore the sum of the currents flowing in a balanced three-phase system is zero.

$$\sin(x) + \sin(x + 120) + \sin(x + 240) = 0 \qquad 3\text{-}2$$

Figure 3-7 represents a three-phase system with a broken PEN conductor; two single-phase loads (LD 1 and LD 2) and a three-phase load (LD 3) are supplied from this system. During an incidence of a broken PEN conductor, the single-phase loads appear in series to the voltage between phases A and B, i.e. V_{AB}. This is indicated by the red dotted line in Figure 3-7. The three-phase load is unaffected by this incident.

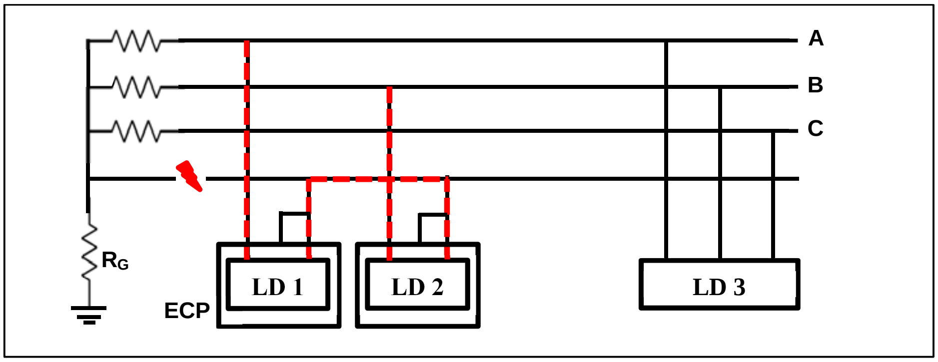


Figure 3-7: Three-phase system with a lost PEN conductor

Figure 3-8 is an equivalent circuit of the two loads sourced by the phase-to-phase voltage V_{AB}. With a phase-to-phase r.m.s. voltage of 415 V and Z_{LD1} and Z_{LD2} 23 Ω and 60 Ω respectively, the r.m.s. voltage at LD1 and LD2 will be 115 V and 300 V respectively.

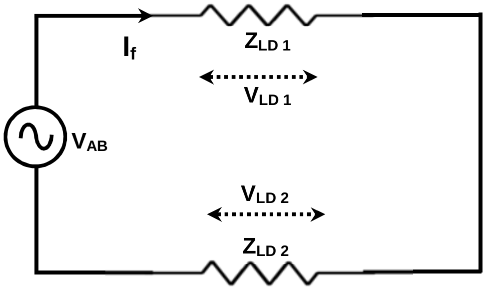


Figure 3-8: Voltage division circuit

It follows that the installation with the higher impedance will experience higher voltages. If the loads were of equal impedance then the voltage will divide equally almost mimicking a standard phase-to-neutral voltage. The apportionment of voltage with respect to size of the loads gets more complicated with additional loads but the principle of unbalanced loads causing high voltages at single-phase installations during an incidence of a PEN conductor failure still holds true.

Chapter 4. Simulation study on a PEN conductor

4.1 Introduction

A typical rural electrification supply comprises a 50 kVA three-phase transformer supplying single-phase households with 20 A meters via an overhead LV network. This chapter replicates the above system in Matlab where the manifestation of risk from a broken PEN conductor is observed closely for various cases of unbalanced load.

4.2 System model

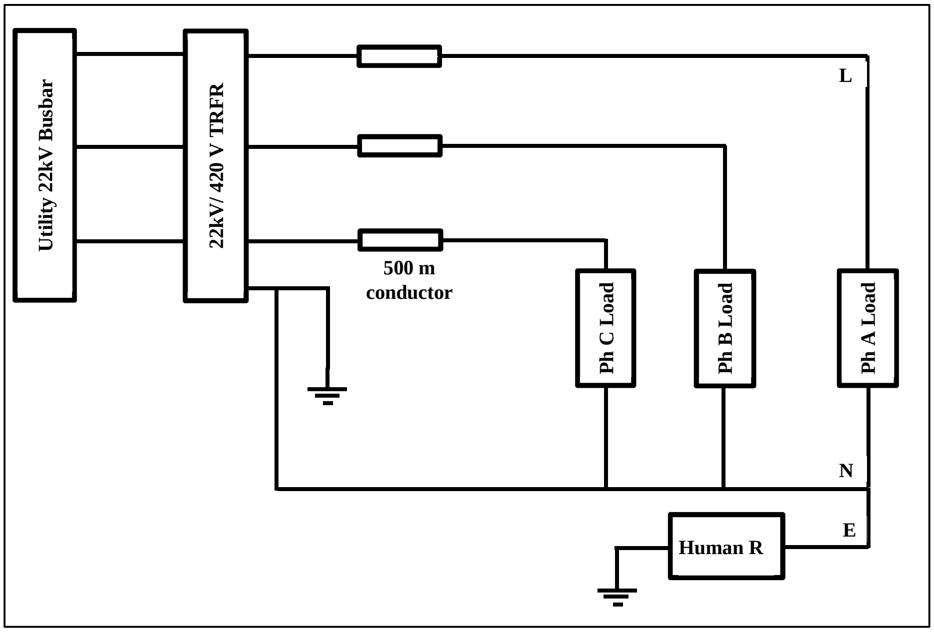


Figure 4-1: Equivalent model of an electrifcation scheme

Figure 4-1 is an equivalent single-line diagram of three single-phase loads derived from a three-phase LV transformer being fed from a medium voltage infinite busbar. The transformer supplies a LV network comprising five-hundred metres of LV network, typically the extent of LV conductor in a rural electrification scheme. Three single-phase purely-resistive lumped loads are initially utilised to collectively represent households connected per phase on the network. The loads are later disaggregated into constituent household-loads in the second set of simulations in chapter six.

The PEN conductor on phase-A is explicitly modelled to separate into neutral and protective earth conductors upon entering the distribution box at a service installation, as required by the South African regulation for the wiring of LV systems [3]. This configuration is characteristic of a TN-CS system as defined in [2]. The installation on phase-A is consequently modelled as three wires (live, neutral and earth) sourcing a two-plate stove appliance. Live and neutral conductors are connected across the stove element represented by a resistor and the earth conductor is connected to the chassis of the appliance as required by regulation [3]. A Matlab Simulink model was compiled for the system depicted in Figure 4-1; this system is used to simulate several scenarios of balanced and unbalanced loads and broken PEN conductors as detailed in the upcoming discussions. The model comprises the following components:-

a) The input voltage for the model is a three-phase AC supply with an r.m.s. voltage of 22 kV at 50 Hz.

b) A 50 kVA, 22 kV / 415 V, dyn11 distribution transformer was utilised. The secondary side of the transformer is solidly coupled to earth at the star point from which a PEN conductor is derived to supply single-phase loads.

c) A 7.85 mm diameter LV conductor of length five-hundred metres was utilised. The equivalent line parameters have been built into the model.

d) The stove chassis resistance was physically measured to be 1 Ω but a 6 Ω resistor was used to cater for variations in the type of metal surface.

e) The combined human and ground resistance selection was guided by [20] which states that 802 Ω represents a typical foot-to-foot human body resistance which is further influenced by conditions such as bare-feet and wet conditions. Wet conditions may cause the skin resistance to decrease by fifty percent [20], while bare-feet, a smaller human body (such as that of a kid) and a different conduction path (such as the trunk-to-foot path) may decrease the resistance even further. In the case of rural homesteads, consideration was given to lower the resistance further as floors are generally mud and raw-earth rather than concrete and tiles. With the above in mind, the initial combined resistance was chosen to be 500 Ω and 800 Ω such that it covers the case of a kid with bare feet standing on a wet and muddy floor and the generally-accepted value as stated in [20]. The second set of simulation-studies to identify detection and mitigation options considers the LV transformer earth-electrode resistance which is in the range of 30 Ω to 70 Ω [27]. At power frequencies, the ground resistance dominates the impedance. Pole-earths with typical soil resistivity may therefore be classified as predominately resistive [28].

f) Three single-phase lumped loads are initially utilised to collectively represent typical households in a rural electrification scheme. The loads are modelled as purely-resistive given that rural homestead appliances are generally incandescent lighting and heating elements. Rural domestic loads may be considered as current sinks with a large resistive heating component resulting in a power factor close to unity [29].

g) The load sizes were selected to represent combinations of lightly loaded phases and heavily loaded phases to create an unbalanced condition. The lumped loads are later disaggregated into constituent household loads.

This case study considers unbalance loadings on the phases of the utility LV transformer and varying the resistance of the human body from five-hundred ohms to eight-hundred ohms. It was of importance to observe the current flow through the human body as the conditions change from one to the other. Other associated parameters in the system such as the phase-to-neutral voltages, the touch potentials, the current flowing through the respective loads and the currents returning on the PEN conductor and the transformer earth electrode were also measured to observe any significant changes in them and whether they are contributing to the hazardous situation.

4.3 Utility supply with LV transformer, LV network and no-load

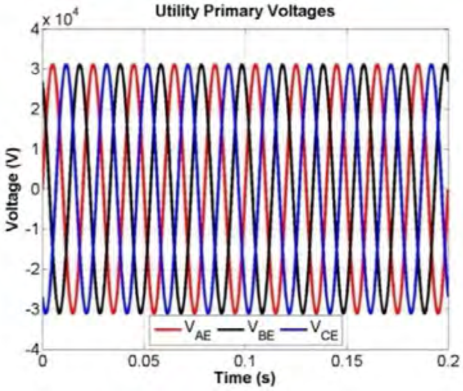


Figure 4-2: Primary instantaneous voltage

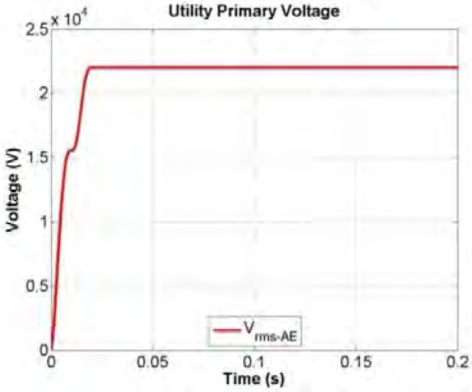


Figure 4-3: Primary r.m.s. voltage

At the outset of the simulation, a basic model of the infinite busbar, LV transformer and LV network was considered to observe the voltages at points of interest. Figure 4-2 illustrates the instantaneous phase voltages of the medium voltage busbar of the utility supply whereas the r.m.s. voltage of the same is shown in Figure 4-3. The magnitudes of the voltages and phase angles were found as expected corresponding to the parameters chosen for the system. Similarly, the instantaneous phase voltages and r.m.s. voltage at the secondary of the transformer are shown in Figure 4-4 and Figure 4-5 respectively. The r.m.s. voltage at the secondary of the transformer was found to be as expected.

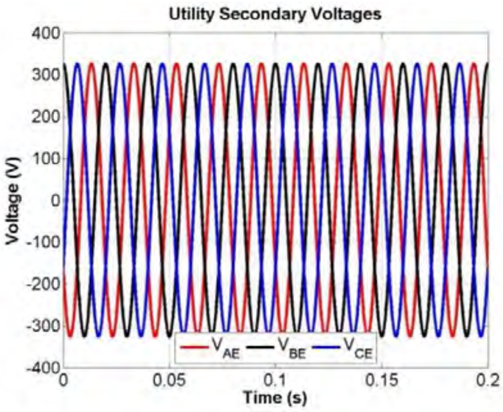


Figure 4-4: Secondary instantaneous voltages

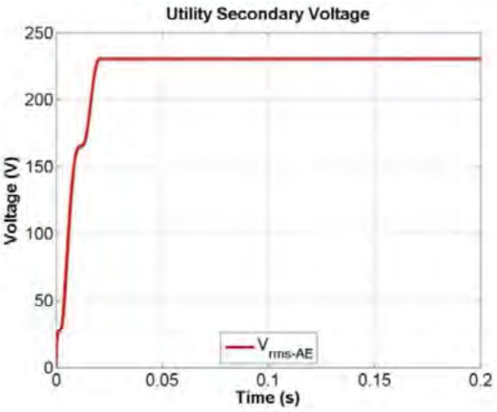


Figure 4-5: Secondary r.m.s. voltage

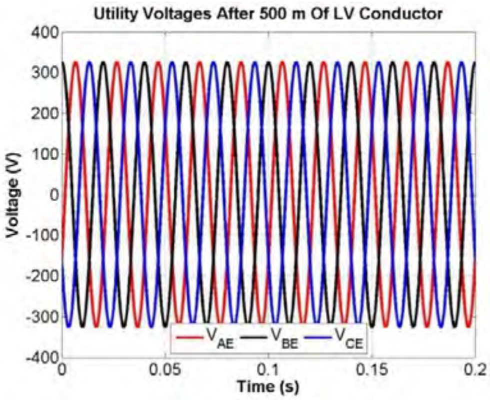


Figure 4-6: Instantaneous voltages at the end of the LV network

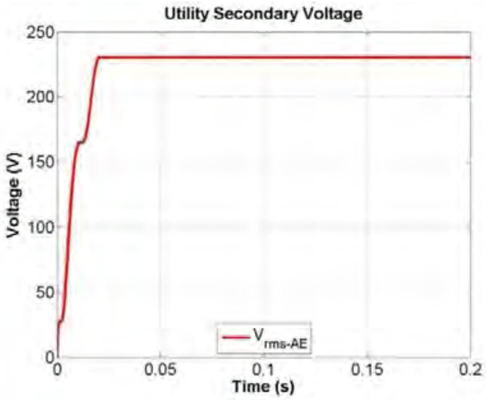


Figure 4-7: R.M.S. voltage at the end of the LV network

Figure 4-6 shows the instantaneous phase voltages at the end of the LV network. As expected, there is no volt drop across the conductor as no load is connected to the system. The phase-to-earth r.m.s. voltage at the end of the conductor is shown in Figure 4-7. In the no-load scenario, the phase-to-earth r.m.s. voltage on phase-A is 230.6 V.

4.4 Balanced three-phase load

In this scenario, three equal single-phase loads are applied to the three-phase system. The load on phase-A is of particular interest as it is modelled as a typical household where the PEN conductor on the utility side splits into separate earth and neutral conductors in the house distribution box as characterized by a TN-CS system. The house (used interchangeably to refer to load on phase-A) is, therefore, supplied from three conductors emanating from the distribution box, viz. live, neutral and earth.

The phase-to-neutral r.m.s. voltage at phase-A is illustrated in Figure 4-8. There is a 2.6 V voltage-drop when compared to the no-load voltage; this is due to the load current that flows via the five hundred metre conductor. Figure 4-9 illustrates the r.m.s. voltage between live and earth at the house; there is a 0.07 V difference between phase-to-neutral and phase-to-earth voltages. This is because the human resistance is in circuit as well. These two voltages become a focal point in the unbalanced load condition with a broken PEN conductor.

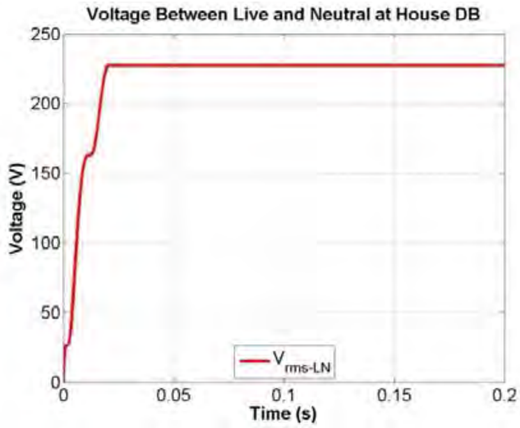


Figure 4-8: Phase-A-to-neutral r.m.s. voltage

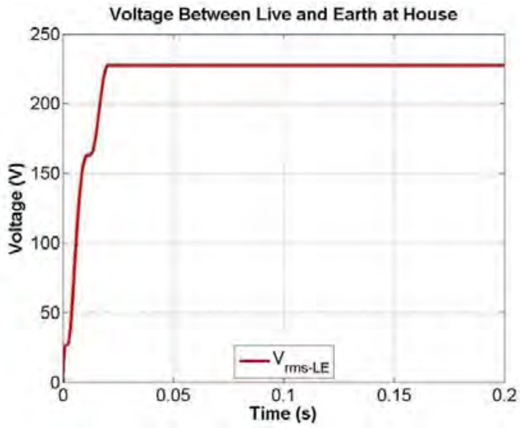


Figure 4-9: Phase-A-to-earth r.m.s. voltage

The r.m.s. current flowing through the 30 Ω load on phase-A was 7.58 A, this is illustrated in Figure 4-10. A two-plate stove, typically used in rural households represents a 30 Ω load. In the balanced three-phase model, a 30 Ω load was applied across phases A, B and C resulting in equal currents on all 3 phases as confirmed by the simulation results.

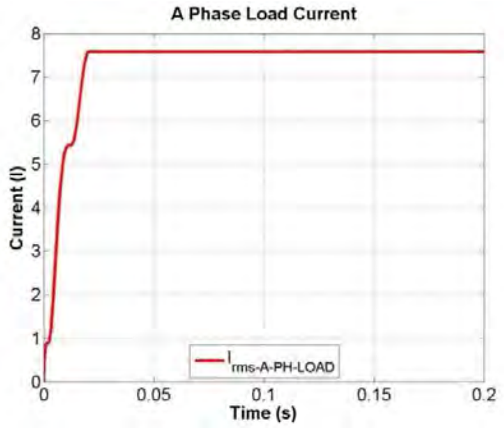


Figure 4-10: Phase-A load current (r.m.s.)

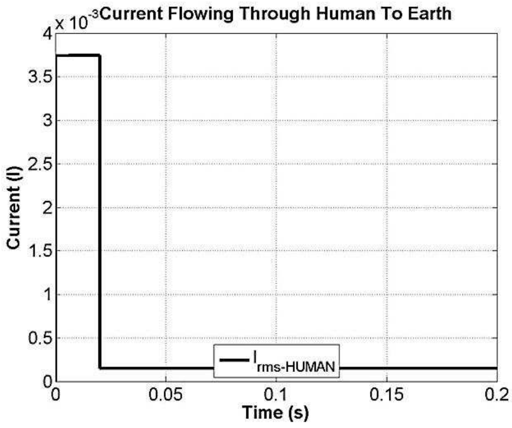


Figure 4-11: R.M.S. Current via human

Figure 4-11 displays the current-flow through a human of body-resistance 500 ohm in contact with the chassis of a stove which is connected to the earth point of the DB. The magnitude of the r.m.s. current observed was 0.16 mA which is considered not harmful to humans. The step in current after the first 20 ms is merely an artefact of the simulation initialization. Figure 4-12 is the equivalent circuit of the stove-load and a human touching the stove chassis while standing on a house floor. The human resistance is in series with the stove-chassis resistance which are in the earth-return path to the utility transformer. The earth-return path and the neutral-return path are in parallel; the current division to each path is therefore based on the resistance of each path. Under normal conditions, when the PEN conductor is intact, the neutral return-path resistance is far lower than the high impedance path through the human and earth hence very little current flows through a human even though the human is always electrically in the circuit. From the equivalent circuit in Figure 4-12, it is expected that the magnitude of current that flows through the human is equal to the magnitude of current that flows to the transformer earth electrode.

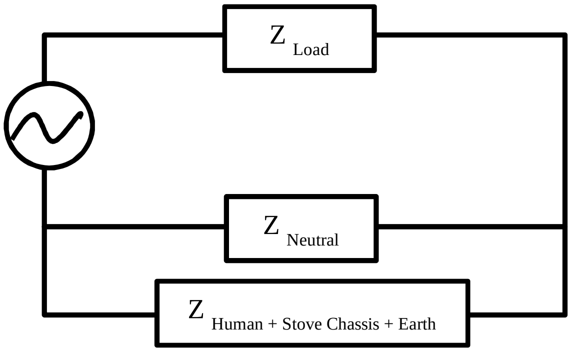


Figure 4-12: Equivalent circuit of a stove load and a human touching the stove

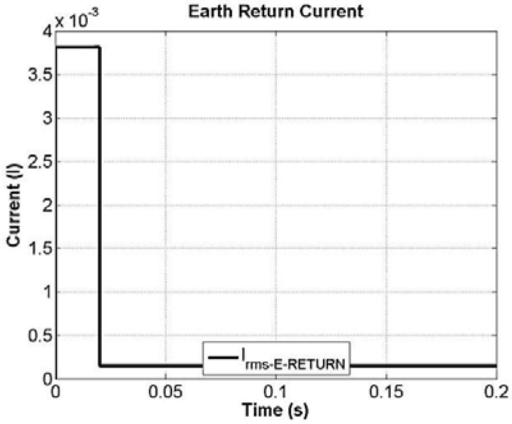


Figure 4-13: Earth return r.m.s. current

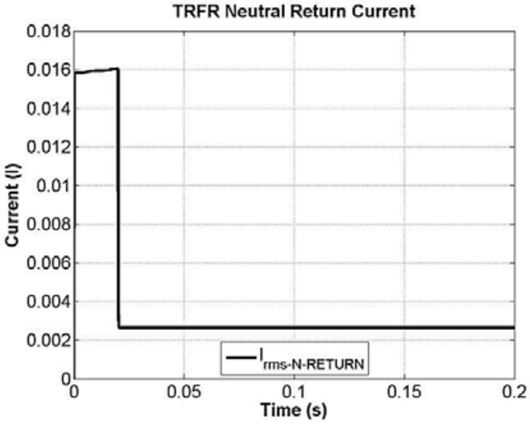


Figure 4-14: Neutral return r.m.s. current

Figure 4-13 displays the transformer earth-return current which is observed to be exactly as Figure 4-11 which represents the current-flow through the human. In a balanced three-phase load configuration the vector sum of the instantaneous neutral currents on the PEN conductor ideally sums up to zero. For the case under consideration, the magnitude of the resultant current in the PEN conductor is shown in Figure 4-14 to be in the order of 3 mA. The deviation from the perfect condition may be attributed to the minor load difference on phase-A which is that of the human, of 500 Ω resistance, present in the circuit.

4.5 Unbalanced three-phase load

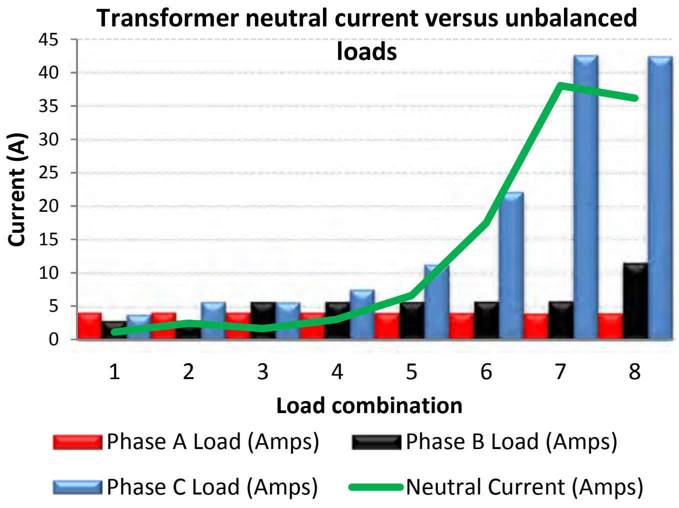


Figure 4-15: Combination of loads used to model the degree of unbalance

Unbalanced loads were simulated using load combinations 1-to-8 (in Figure 4-15) to observe the consequence to the current in the PEN conductor. Other system parameters such as phase-to-neutral voltages and touch potentials were also measured to determine if an unbalanced load condition creates a hazardous condition. Figure 4-15 depicts the resultant current in the PEN conductor as a green line which is observed to increase as the bars in the figure become more disproportionate. The bars represent the different loads on phase A, B and C; hence the disproportionality of the bars indicates the degree of unbalanced load on the system. A key observation, therefore, is that the degree of unbalanced load on a three-phase system determines the magnitude of current flowing in the PEN conductor. Load combination seven yielded the highest neutral current; this load combination forms the basis of the discussion ahead.

The degree of unbalanced load on the system is further illustrated by the difference in peak amplitude of the instantaneous voltage profiles of the three-phases as in Figure 4-16. The phase-to-neutral r.m.s. voltage on phase-A was 223.3 V, as depicted in Figure 4-17. The remaining phase-to-neutral r.m.s. voltages were also observed to be within the ± 10% range from nominal as required by South African regulation [30]. Although within regulatory range, phase-C experienced the highest voltage depression as indicated by the blue profile in Figure 4-16; this was expected because of the highest load being served. The r.m.s. voltage between phase-A and true-earth at the household-load was observed to be within the 10% range from nominal as well.

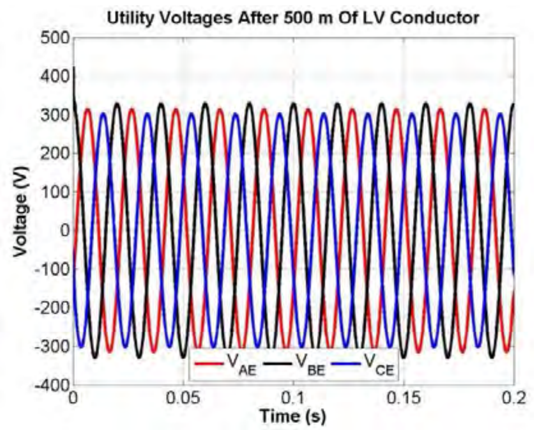


Figure 4-16: Instantaneous voltages - end of LV network

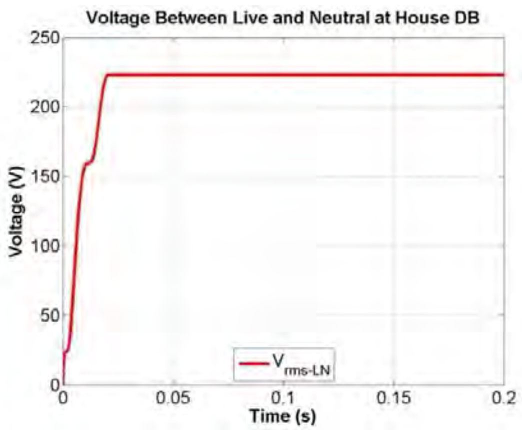


Figure 4-17: Phase-to-neutral r.m.s. voltage – end of LV network

The voltage difference between neutral and true-earth at the installation represents the voltage between an ECP and true-earth (interchangeably referred to as touch potential). All cases simulated yielded safe touch potentials. The safe touch potentials corroborates with the low magnitude of current observed to flow through the human at the service installation of phase-A.

Figure 4-18 illustrates that for the worst unbalanced condition, the magnitude of current through a human is approximately 0.75 mA, this for a body resistance of five-hundred ohms. This order of current is not harmful to humans irrespective of exposure time. Figure 4-19 displays the current returning on the PEN conductor after the vector summation of the neutral currents returning from each phase; as expected the magnitude is undesirably high at 38.07 A.

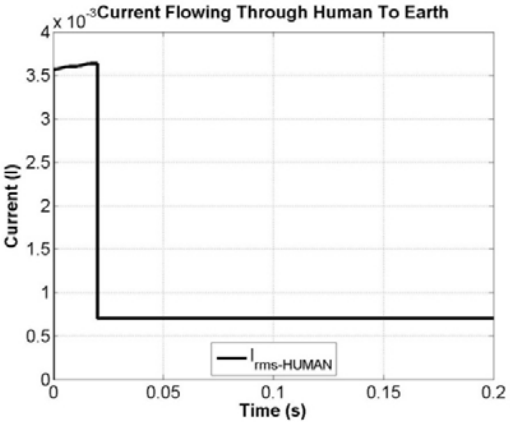


Figure 4-18: R.M.S. Current via human

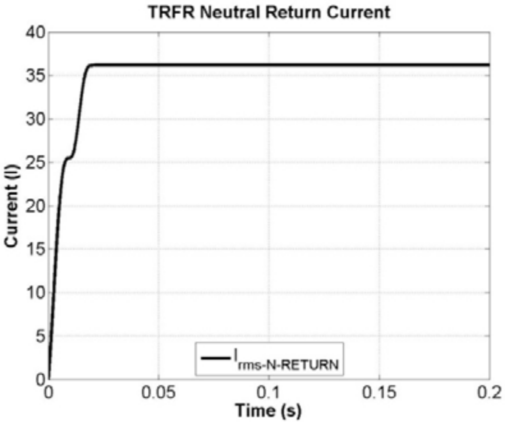


Figure 4-19: Neutral return r.m.s. current

4.6 Balanced three-phase load and broken PEN conductor

A broken PEN conductor was introduced to the balanced three-phase system to ascertain how the condition manifests itself by observing system parameters such as single-phase and three-phase voltages and touch potentials which indicates if a hazardous situation is created.

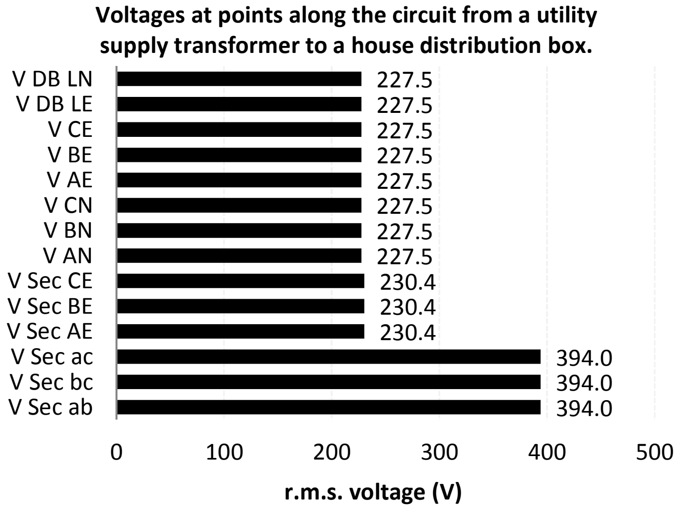


Figure 4-20: Utility r.m.s. voltages at various points along the LV network

Figure 4-20 is a summary of the r.m.s. voltages observed on the LV system during an incidence of a broken PEN conductor on the balanced three-phase system. The utility r.m.s. voltages are all within regulatory limits and do not display any uncharacteristic elements that may have been induced by the broken PEN conductor incidence. The balanced load condition allows the neutral to retain its reference point with respect to ground and it is not shifted to a position closer to a phase with higher loads as is with the phenomena of unbalanced conditions. The maximum r.m.s. touch potential observed at phase-A was 0.05 V. The load currents were also found to be parametrically correct and more importantly the current through the human to earth was only 0.10 mA; this magnitude of current is not harmful to humans, irrespective of the exposure time

The incidence of a broken or lost PEN conductor on a balanced three-phase system does not present hazardous conditions at single-phase installations. Utility r.m.s. voltages are within safe operating parameters and the touch potentials at households are safe. The neutral (although unreferenced to earth) essentially does not float and therefore unsafe voltages are not setup at installations.

4.7 Unbalanced three-phase load and broken PEN conductor

This case study considers unbalance loadings on the phases of the utility LV transformer by applying load combinations 1-to-8 as detailed in section 4.2. An incidence of a broken PEN conductor, close to the utility LV transformer, is introduced to the system by modelling the PEN conductor as open-circuit. It was of importance to observe the current flow through the human body as the conditions change from one to the other. Also, other associated parameters in the system such as the phase-to-neutral voltages, the touch potentials at ECPs, the current flowing through the respective loads and the currents returning on the PEN conductor and the transformer earth electrode were measured to observe any significant changes in them and whether they are contributing to the hazardous situation.

The hazard is characterised by:

a. Phase-to-neutral r.m.s. voltages (at customer installations) that are above the declared voltage limits as prescribed by the NRS048-2 regulation.
b. Dangerous voltages between true earth and exposed conductive surfaces at customer installations.
c. Current flow through a human standing on the ground while in contact with the exposed conductive surface.

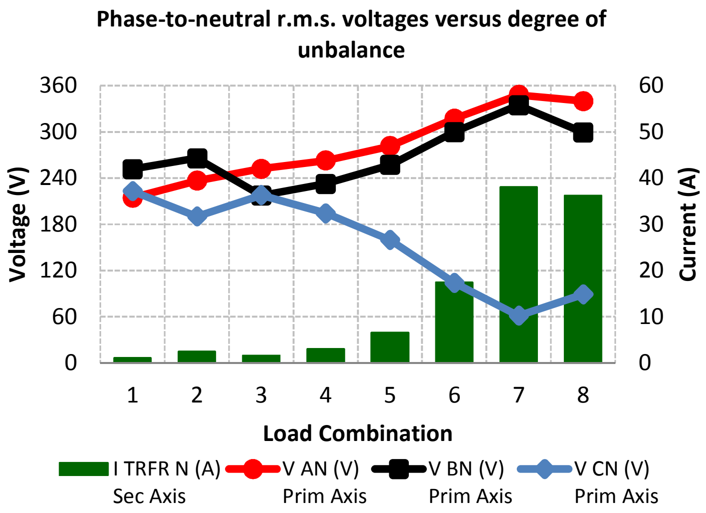


Figure 4-21: Phase-to-neutral r.m.s. voltages versus degree of unbalance

Figure 4-21 relates the degree of unbalance on the system to the phase-to-neutral r.m.s. voltages on each phase of the three-phase system. The transformer neutral currents obtained from the simulations in section 4.5 were used as a proxy for the degree of unbalance. The load combination 7 yielded the highest neutral current (in section 4.5.) and in this case also yielded the highest phase-to-neutral r.m.s. voltages at installations on phases A and B. Phase-C however experienced a severe voltage depression. Therefore, during an incidence of a broken PEN conductor on an unbalanced system, the greater the unbalance on the system (case 7 on Figure 4-21), the greater the deviation of the phase-to-neutral r.m.s. voltage from legally allowed limits.

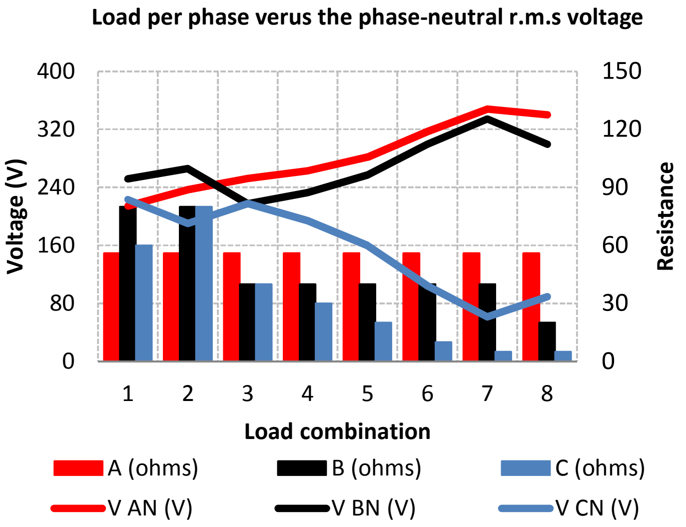


Figure 4-22: Load per phase versus the phase-to-neutral voltage

The relationship of load per phase and the degree of risk is further demonstrated in Figure 4-22 where it is observed that the phases with relatively higher resistance, i.e. lightly loaded, experience higher phase-to-neutral voltages while the heavily loaded phases experience lower voltages. The simulations results obtained from utilising load combination 7 (representing a high degree of unbalance) serve as a basis for the discussion ahead. The load on phase-A (herein referred to as household or house) was modelled to represent a typical rural load of a two plate stove and therefore the measurements observed from this iteration may be viewed as indicative of the actual risk a household may be subjected to.

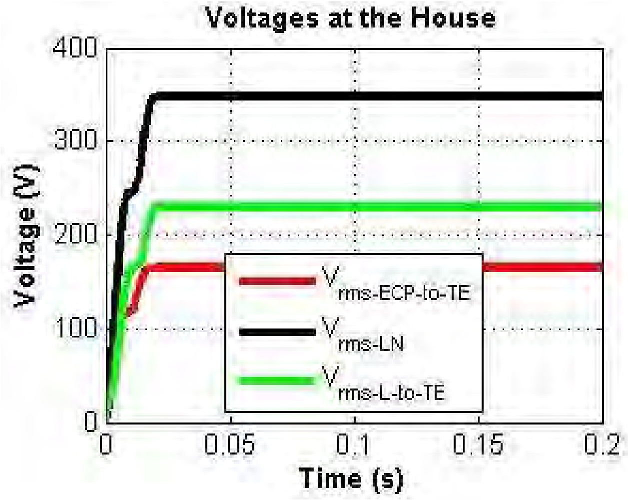


Figure 4-23: R.M.S. Voltages at phase-A installation

Figure 4-23 displays the r.m.s. voltages observed at the household during an incidence of a broken PEN conductor on a LV network with a high degree of unbalance. The voltages of interest are the touch potential represented by the red line, the phase-to-neutral voltage represented by the black line and the phase-to-true-earth voltage represented by the green line. The phase-to-neutral r.m.s. voltage at the house was 348.9 V, this is almost the full phase-to-phase voltage of the three-phase supply whereas the r.m.s. voltage between phase and true-earth was 229.6 V which is within the range of normal supply voltage. The touch potential was observed to be 165.2 V. The excessive phase-to-neutral r.m.s. voltage and the dangerous touch potential are serious risks and therefore expounded on further.

Figure 4-24 illustrates that a human may complete the circuit between an ECP and true-earth. This will result in current-flow through the human which is dependent on the touch potential and the human body resistance. A simple calculation based on Ohm's Law reveals that for a combined human, stove and ground resistance of 506 Ω and a voltage of 165.2 V, a current of

326 mA is expected to flow through the human. For the scenario above, the simulation produced a current of 326.4 mA flowing through the human and returning via the earth at the neutral point of the transformer. The human resistance varies with body size (adult or a kid) and the resistance to ground may vary if a person is bare-footed or with shoes or standing on a concrete floor versus a wet mud floor in a rural household. A simulation with human and ground resistance of 806 Ω was also conducted and a current of 205.6 mA was obtained, again yielding an acute risk.

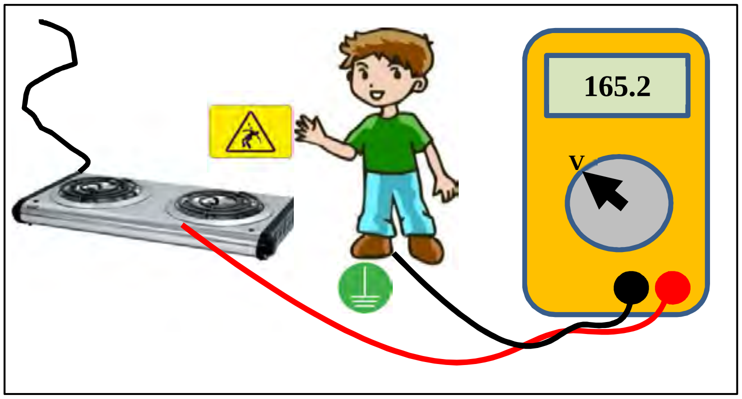


Figure 4-24: Illustration of a touch potential hazard at a house

The RCD at the household operates on a principle of measuring the current flow through the live and neutral conductors and if there is a difference between the currents then the RCD will operate and disconnect both the live and neutral supplies to the house. It was observed that the neutral and live currents were equal for the case in Figure 4-24 where the human touches the stove chassis during an incidence of a broken PEN conductor on a three-phase system with a high degree of unbalanced load. Despite the dangerous current-flow through the human, the RCD still does not operate due to the equality in the neutral and live currents.

The transformer neutral current and the load currents per phase are illustrated in Figure 4-25 where phase-A is shown in red, phase-B in black, phase-C in blue and the transformer neutral current in green. Of interest initially, is the phase-A load current which is just over 6 A; the over-current protection at the house is provided by a 20 A MCB on the ready-board. The household over-current protection therefore does operate for this dangerous condition as well. The utility LV protection from the transformer bushings to the point of common coupling at the customer’s installation is based on an elaborate philosophy that guides the selection of appropriate fuse and/or circuit breaker ratings at various points along the circuit. However, a crude interpretation of the philosophy is that to achieve the grading of over-current protection, all the upstream over-current protective devices must at least be greater than the 20 A MCB on the ready-board supplied to electrification households.

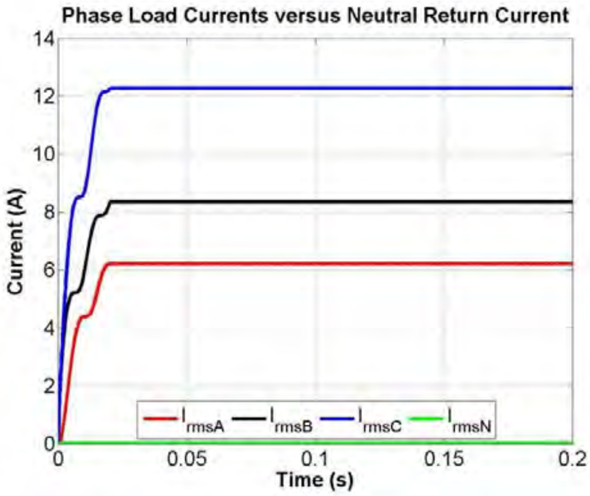


Figure 4-25: Load and transformer neutral r.m.s. currents

Figure 4-25 indicates that none of the phase r.m.s. currents exceeded 20 A, therefore the utility over-current protection would not have detected this dangerous condition. Incidentally, the transformer neutral current illustrated in Figure 4-25 simply confirms that the neutral conductor is broken as zero current returns to the transformer.

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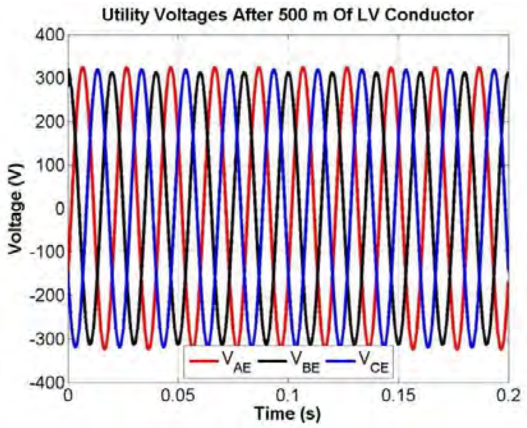


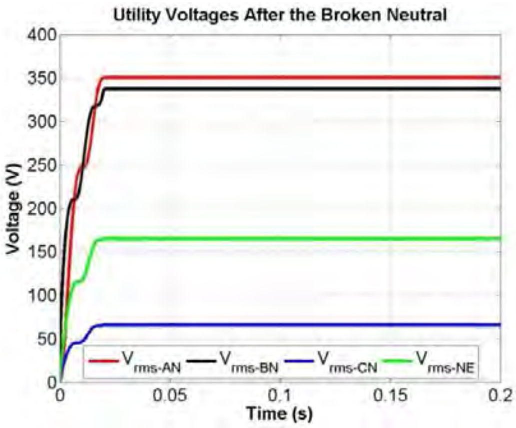


Figure 4-26: Utility instantaneous voltages

Figure 4-27: Utility r.m.s. voltages

The utility phase to earth instantaneous voltages, as depicted in Figure 4-26 offer very little opportunity for the detection of the broken PEN conductor phenomena as characteristics of the waveform in terms of amplitude and displacement of phases are very similar to that of a healthy condition on the network. There is, therefore, very little discrimination to uniquely identify the broken PEN conductor based on the supply-transformer voltages with respect to earth or neutral.

The phase-to-neutral voltages on the load side of the broken PEN conductor however do display variations in the voltage outside of the ± 10% range from nominal. Figures 4-27 and the earlier discussion confirm that when the PEN conductor is broken on an unbalanced three-phase system, the phase-to-neutral voltages are inconsistent and phases with higher loading experience a low voltage while phases with relatively lower loading experience higher voltages.

A final case of the household drawing no-load was considered based on the reasoning of the level of risk increasing with lower loading on a phase. A scenario of the stove drawing zero load (i.e. off) but still plugged into the wall-socket was simulated. This was achieved by modelling the live conductor to the stove element as open circuit.

The simulation of a broken PEN conductor on an unbalanced system with load magnitudes of infinite, forty and five ohms on phases A, B and C respectively, yielded the following results:-

a) The r.m.s. voltage between live and neutral at the installation on phase-A was 379.8 V
b) The r.m.s. voltage between the ECP (stove chassis) and true earth was 191.6 V
c) For a combined human, stove chassis and ground resistance of 506 ohms, an r.m.s. current of 368.68 mA was observed.
d) The household RCD and over-current protection system and the utility over-current protection system did not detect the dangerous condition.

4.8 Conclusion

A broken PEN conductor on the supply side of a balanced three-phase system does not create a hazardous condition at installations nor does an unbalanced load with an intact PEN conductor create a hazardous condition. However, a broken PEN conductor close to the supply-transformer on a LV network with a high degree of unbalanced load sets up very dangerous touch potentials and phase-to-neutral voltage variations at installations whereby neither the household over-current and earth-leakage protection systems nor the utility over-current protection system is able to detect the hazardous condition.

In the context of a rural household fed of a three-phase unbalanced system, it was observed via simulation that a bare-footed kid standing on a wet mud-floor and touching a two-plate stove chassis while it is plugged into the circuit but not necessarily drawing load, is at risk of fatal electrocution during an incidence of a broken PEN conductor close to the utility LV transformer. The risk is profound as the simulation of the 806 Ω scenario proved that during this hazardous condition even an adult is at risk of electrocution. The risk to property, although insignificant when compared to loss of life still poses an indirect threat to life through fires caused by phase-to-neutral r.m.s. voltages that are above the declared voltage limits as prescribed by the NRS048-2 regulation. In general, the phase-to-neutral voltage deviation from the declared nominal voltage is a function of the degree of unbalance on the system; the greater the unbalance, the greater the deviation from nominal voltage while customers connected to the phase with the lightest load are at highest risk, as the phase with the lightest load experiences the highest phase-to-neutral voltages.

Chapter 5. Experimentations on a broken PEN conductor

5.1 Introduction

The simulation results from chapter four were verified with an experimental model mimicking the same three-phase system with single-phase loads. A positive correlation between the physical results and the simulation results will give credence to the equivalent model utilised for the simulation. Upon proving the credibility of the equivalent model, a greater sense of confidence may be attached to the detection methods simulated but not actually physically tested. The model may also be utilised to take the area of study forward in discovering more sophisticated detection techniques.

5.2 System model

Figure 5-1 is the equivalent model utilised in the simulations; the discussion that follows explains how the model was setup in a laboratory facility.

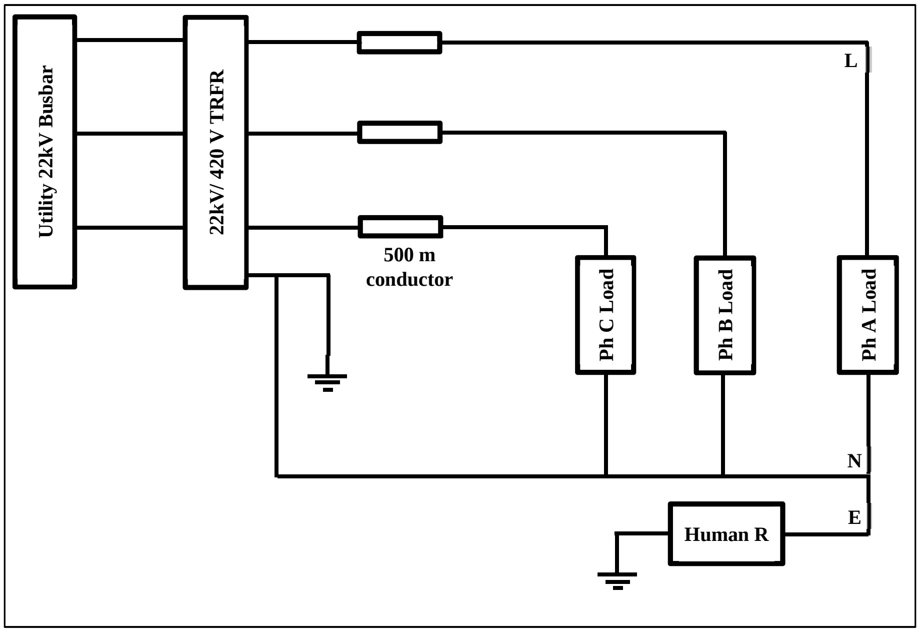


Figure 5-1: Equivalent model of the experimentation system

Figure 5-2 shows the three-phase 400 V supply with the neutral solidly earthed while Figure 5-3 is a picture of an actual 20 A ready-board utilized on electrification schemes. It consists of an overcurrent MCB rated at 20 A and an earth-leakage device rated to operate at 30 mA. Figure 5-4 depicts the splitting of the PEN conductor into protective earth and neutral conductors prior to the RCD.

Figure 5-3: Three-phase 400 V supply

Figure 5-2: The 20 A ready-board

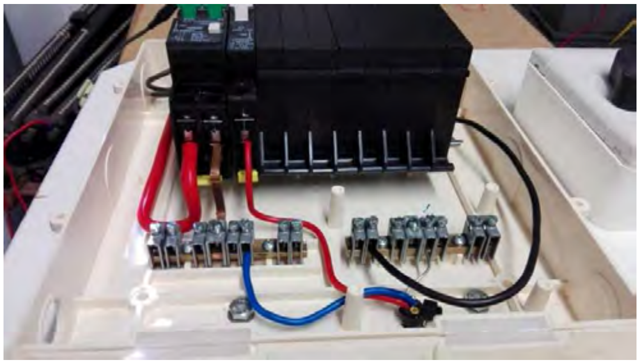


Figure 5-4: The DB wiring

Figure 5-5 displays the three resistive banks utilised to add load to phases A, B and C as per load combinations 1 to 8 in Figure 4-15. The resistive banks were rated at 240 V with a resistance range of 5 Ω to 80 Ω. The various resistances are achieved by selecting the black dials into position. Figure 5-6 shows the two-plate stove used for the test; each plate has a resistance of 56 Ω while both in parallel have an equivalent resistance of 28 Ω. Figure 5–7 illustrates the connection of the earth lead to the chassis of the stove.

Figure 5-5: Resistive banks

Figure 5-6: The two-plate stove

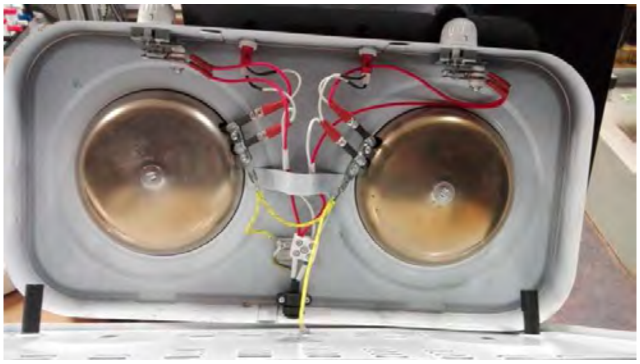


Figure 5-7: The stove internal aperture

Figure 5-8 is an overview of the experimental setup highlighting the resistor banks utilised to achieve the human resistance. One end of the resistor bank was connected to the chassis of the stove and the other to true earth. The resistor banks were tuned to 500 Ω and 800 Ω depending on the scenario under observation. Figure 5-9 illustrates some of the test measurement points. The limitation of the experimental setup was that the impedance of the phase and neutral conductors were not replicated. The non-ideal laboratory conditions may cause the experimental measurements to be quantitatively different from that of the simulations but should not cause the observations to be qualitatively different from the simulations conducted.

Figure 5-8: An overview of the experimental setup

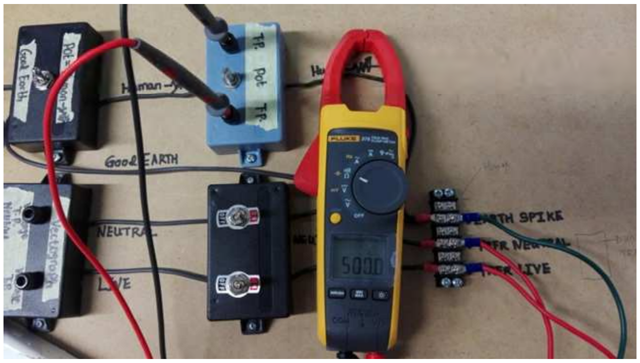


Figure 5-9: Various test points on the circuit

5.3 Utility supply with LV transformer, LV network and no-load

The initial test was to initiate a trip on the RCD by pressing the test-switch on the unit. The test successfully caused the earth leakage device to operate confirming the functionality of the device. The r.m.s. voltages obtained under the no-load test on the secondary side of the three-phase supply are shown in Figure 5-10. Phases A and C are incidentally lower than phase-B while the r.m.s. voltage difference between neutral and earth was measured to be 11.3 V.

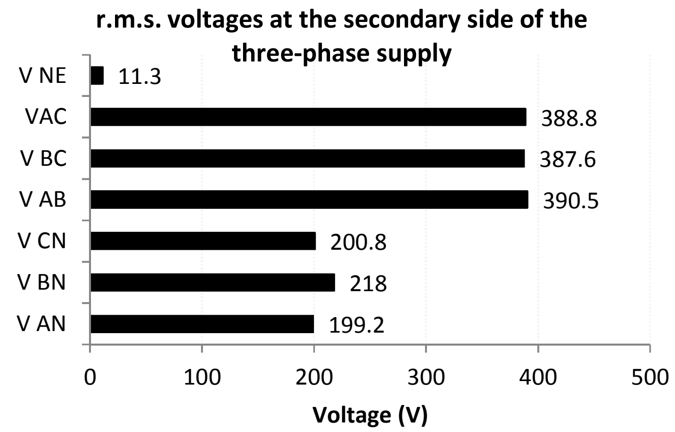


Figure 5-10: Utility secondary r.m.s. voltages

This deviates from the ideal power supply utilised in the simulation as a result of existing loads already connected to the respective phases in the laboratory building. The deviation however doesn't affect the ability of the experimental setup from ratifying the simulated results; it is expected that the absolute measurements will differ but the relationships observed during the simulations should still exhibit during the tests.

5.4 Balanced three-phase model

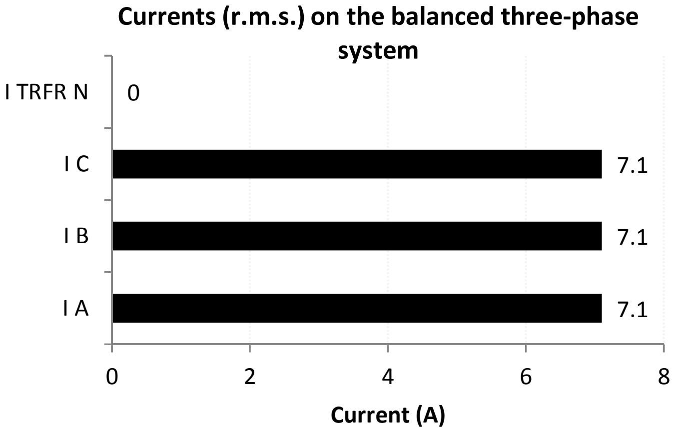
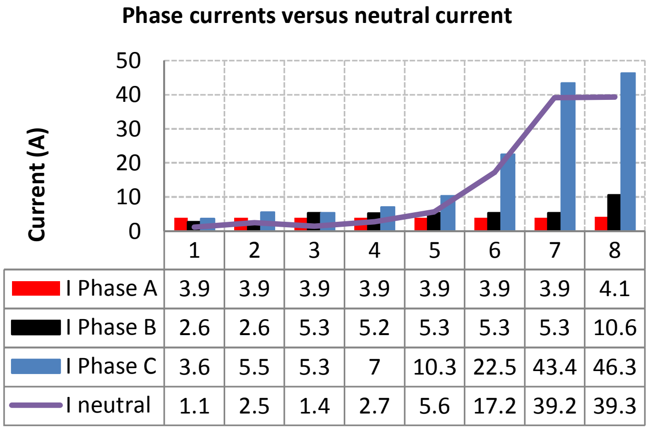


Figure 5-11: R.M.S. currents on the balanced three-phase system

Figure 5-11 displays the r.m.s. currents measured on phases A, B and C for the application of a 30 Ω load on the respective phases. The transformer neutral current was measured to be 0 A. The results exhibit a perfectly balanced system but this may have been incidental as the phase voltages displayed a degree of unbalance for the no-load condition.

5.5 Unbalanced three-phase model



	1	2	3	4	5	6	7	8
🟥 I Phase A	3.9	3.9	3.9	3.9	3.9	3.9	3.9	4.1
⬛ I Phase B	2.6	2.6	5.3	5.2	5.3	5.3	5.3	10.6
🟦 I Phase C	3.6	5.5	5.3	7	10.3	22.5	43.4	46.3
— I neutral	1.1	2.5	1.4	2.7	5.6	17.2	39.2	39.3

Figure 5-12: Phase and transformer neutral r.m.s. currents

Figure 5-12 illustrates the eight load combinations and the corresponding phase and neutral r.m.s. currents as obtained from the experimentation. It is observed that the transformer neutral current increases as the degree of the unbalance increases; the degree of unbalance is represented by the disproportionate bars in Figure 5-12. The results obtained from the experimental setup and the simulations displayed the same relationship between the transformer neutral current and the load unbalance. All other points of interest exhibited results of the same order to that of the simulation results.

5.6 Balanced three-phase model & broken PEN conductor

The physical measurements obtained for this experimental component produced phase-to-neutral voltages and phase-to-phase voltages all within the ± 10% range from nominal. The r.m.s. currents measured on phases A, B and C were 7.2 A, 7.1 A and 7.0 A respectively for the application of a 30 Ω load per phase. There were no significant deviations from the simulated results.

5.7 Unbalanced three-phase model & broken PEN conductor

For the case of a broken PEN conductor as applied on an unbalanced three-phase system, the phase-to-phase voltages remain close to 400 V and are unaffected by the broken PEN conductor as expected from theory and as simulated. The phase-to-neutral r.m.s. voltages however varied with the degree of unbalance on the system; of all the cases simulated, load combination 7 produced the highest phase-to-neutral voltages with phase-A obtaining the highest r.m.s. voltage at 336.4 V. Similar results were obtained from the simulations although the magnitudes of the voltages differ marginally. The experimental results also observed that the phase with the least load experienced the highest phase-to-neutral voltages while the phase with the highest load experienced severe voltage depressions. Two cases of human resistances of five-hundred ohms and eight-hundred ohms were applied; the current-flow through the earth return path to the transformer was observed by conducting a current measurement at the earth return electrode. R.M.S. currents of magnitude 314.5 mA and 195 mA flowed through the resistors representing human resistances of 500 Ω and 800 Ω respectively. The simulation results produced r.m.s. currents of 326.4 mA and 205.6 mA for the 500 Ω and 800 Ω human resistances respectively.

The case of no-load on phase-A was observed as a special condition identified during the simulation stage. The instance of the stove being off but plugged into the circuit proved to be more dangerous as higher currents flowed through a human than when the stove was on and drawing a load. Neither the MCB nor the RCD operated for any of the test iterations discussed above. Figure 5-13 shows the plate of the stove glowing during an over-voltage condition.

Figure 5-13: The stove during an overvoltage condition

5.8 Conclusion

The experimental results obtained corroborated very strongly with the simulation results in observing that a broken PEN conductor close to the supply-transformer on a LV system with a high degree of unbalance creates unsafe conditions at single-phase installations characterised by the risk of experiencing almost phase-to-phase voltages and elevated touch potentials that induce current flow through a human in contact with an ECP at that installation. In addition, neither the utility over-current protection system nor the household over-current and earth-leakage protection systems detect this dangerous condition.

Chapter 6. Detection and mitigation opportunities for future work

6.1 Introduction

The installation of multiple earths along the PEN conductor was reviewed for effectiveness in being able to fully mitigate all the risks associated with a broken PEN conductor. The results of the preliminary simulations are discussed however further research is required to build upon the findings from this study. Other opportunities for detection and mitigation are also discussed.

6.2 System model

The Matlab model was modified to represent the lumped-loads as single loads as depicted by households H1 to H9 in Figure 6-1. Seven points of PEN conductor failure were also introduced on sections of the LV network that sets up a unique level of risk to the different households. The points of failures are illustrated by the red blocks numbered 1-to-7 on Figure 6-1. These modifications were of importance and necessary to observe how each PEN conductor failure at the various locations manifests risks at the different households. It also provides a means to evaluate if a prospective solution totally eliminates the risks manifested at the households.

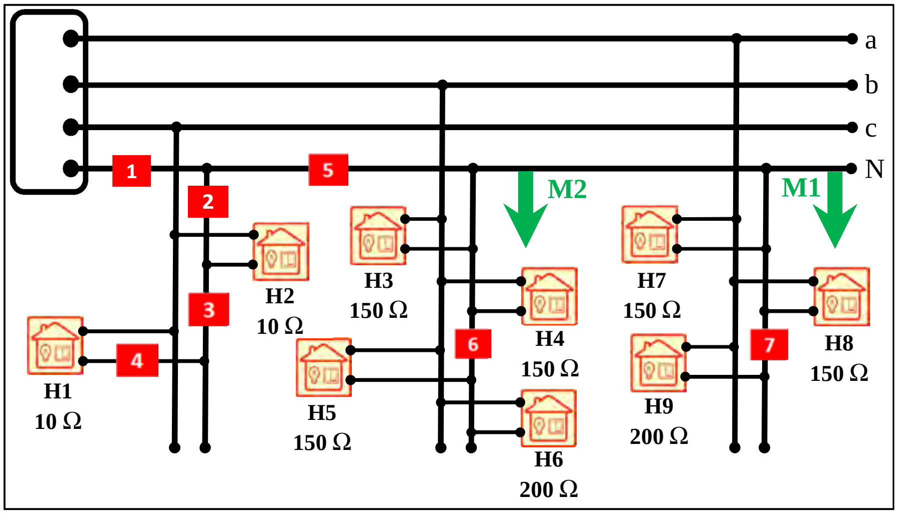


Figure 6-1: Single-line diagram with multiple PEN conductor failures

Figure 6-1 illustrates the PEN conductor failure points along the LV network where points 1 and 5 represent a failure on the main backbone, point 2 a failure at the beginning of a single phase tee-off, points 3, 6 and 7, a failure midway along the tee-off and point 4 a failure on the service cable of a single household.

6.3 PEN conductor location of failure versus detection limitations

Table 6-1 presents the touch potentials and phase-to-neutral r.m.s. voltages observed at households H1 to H9 (from Figure 6-1) for varying locations of PEN conductor failures on an unbalanced three-phase system. P1 to P7 correspond to red blocks 1-to-7 in Figure 6-1.

The red cells in Table 6-1 highlights any phase-to-neutral r.m.s. voltage that exceeds the ± 10% voltage band from nominal voltage and also highlights r.m.s. touch potentials that exceeds 35 V. Cells in green are within the allowable ranges while cells in amber are within range but demonstrate that it deviates from the norm.

Table 6-1: R.M.S. voltages observed at the different households

		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**
H1	**V_ECP_TE**	170	230	228	228	22	20	20
	V_LN	60	0	0	0	205	207	207
H2	**V_ECP_TE**	170	230	9	9	21	19	19
	V_LN	60	0	220	220	205	207	207
H3	**V_ECP_TE**	164	5	6	6	120	17	16
	V_LN	336	226	231	231	167	239	235
H4	**V_ECP_TE**	164	5	6	6	120	17	16
	V_LN	336	226	231	231	167	239	235
H5	**V_ECP_TE**	164	5	6	6	120	230	16
	V_LN	336	226	231	231	167	0	235
H6	**V_ECP_TE**	164	5	6	6	120	230	16
	V_LN	336	226	231	231	167	0	235
H7	**V_ECP_TE**	161	6	5	5	119	16	15
	V_LN	344	226	231	231	228	236	239
H8	**V_ECP_TE**	161	6	5	5	119	16	15
	V_LN	344	226	231	231	228	236	239
H9	**V_ECP_TE**	161	6	5	5	119	16	229
	V_LN	344	226	231	231	228	236	0

V_ECP_TE: R.M.S. voltage between exposed conductive part and true earth

V_LN: R.M.S. voltage between phase and neutral

It is noted that the incidence of a broken PEN conductor at various locations doesn’t always present itself with both non-compliant voltages and elevated touch potentials, it may be one or the other or a combination. It is therefore important that the detection or mitigation system caters for both risk conditions separately.

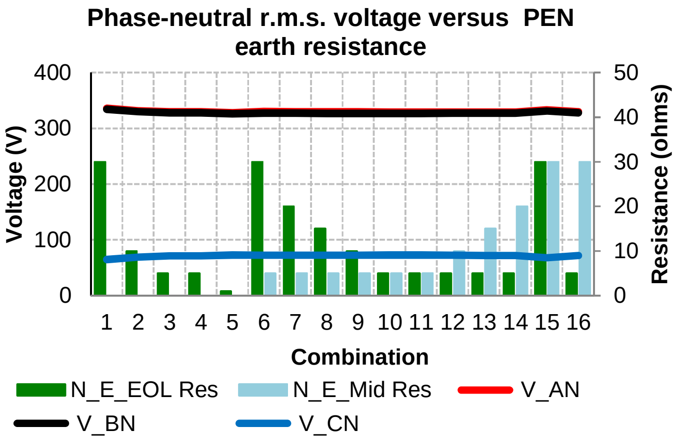
The summary below further illustrates the point:

a) Only households beyond the point of failure of the PEN conductor are affected by either elevated touch potentials or non-compliant phase-to-neutral r.m.s. voltages.
b) Dangerous conditions exist at households irrespective of the failure of the PEN conductor transpiring on the mainline, tee-off or service cable; the only variable that changes is the number of households affected.
c) Any detection or mitigation proposal must therefore cover PEN conductor failures on the mainline, tee-off and service cable.
d) The exclusive application of over-voltage detection at a customer’s installation is not sufficient at eliminating the risk at the household as there are situations where the phase-to-neutral r.m.s. voltage is within the acceptable range of nominal or even 0 V yet the touch potential is grossly above 35 V (r.m.s.).

6.4 Multiple-earthed PEN conductor

The following discussion is a review of the effectiveness of multiple-earthing on the PEN conductor and its ability to totally eliminate the consequent risk of non-compliant phase-to-neutral voltages and hazardous touch potentials resulting from a broken or lost PEN conductor on an unbalanced three-phase system.

The objective of earthing the PEN conductor at regular intervals is to clamp or hold the neutral voltage as close as possible to earth potential in the event the primary neutral-earth-point at the transformer is lost. The challenge however is that it is expensive to establish earth points at too many points along the circuit and so a trade-off of risk and cost is required. The pragmatic approach adopted for the simulation was to identify the minimum number of PEN conductor earth points that would alleviate risk. The first point of multiple-earthing on the PEN conductor is at the end of the main backbone as it provides for maximum coverage of the LV network while the second PEN conductor earth-point is at the middle of the main LV backbone, these are denoted by points M1 and M2 in Figure 6-1.



N_E_EOL Res: Neutral end-of-line earth resistance
N_E_Mid Res: Neutral middle-of-line earth resistance

Figure 6-2: Multiple earths along the PEN versus phase-to-neutral r.m.s. voltages

Figure 6-2 illustrates the impact of a multiple-earthed PEN conductor to the phase-to-neutral r.m.s. voltages experienced on the network during an incidence of a broken PEN conductor at point 1 on Figure 6-1; a transformer earth resistance of thirty ohms was used for this case. The bars represent the value of the PEN conductor earth resistance at the end and middle of the main backbone. The naming convention used in Figure 6-2 is retained for Figure 6-3 as well.

It is observed that the phase-to-neutral r.m.s. voltages are unaffected by the addition of multiple earths on the PEN conductor along the LV circuit; this is clearly demonstrated in Figure 6-2 by the change in magnitude of the bars yet the phase-to-neutral r.m.s. voltages represented by the lines remain unchanged. This solution therefore does not provide any mitigation against non-compliant phase-to-neutral voltages at households; the risks of appliances failing and fires possibly igniting are still very prevalent.

In Figure 6-3, the bars represent the varying resistances of the PEN conductors at the middle and end of the main backbone while the line profiles represent the r.m.s. touch potentials on the three-phases of supply during an incidence of a broken PEN conductor at point 1 in Figure 6-1 and for a transformer earth resistance of thirty ohms.

During an incidence of a lost or broken PEN conductor on an unbalanced system with a solitary earth at the neutral point of the supply transformer, the touch potentials at ECPs is depicted by combination 6 in Figure 6-3 which represents a very dangerous touch potential. The introduction of an additional PEN earth point at the end of the main backbone reduces the touch potentials to less than fifty volts r.m.s. for cases when the new PEN earth resistance is less than thirty ohms.

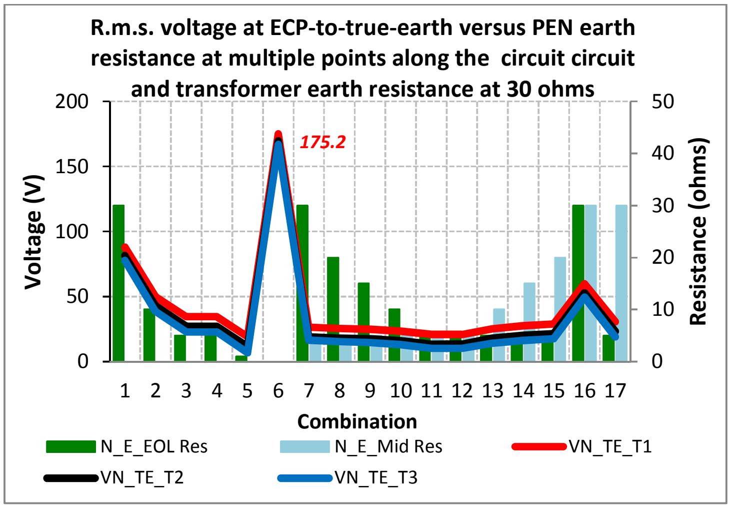


Figure 6-3: Multiple-earthed PEN versus neutral-to-true-earth r.m.s voltages

The best result achieved (with just one additional PEN conductor earth point) was when the end-of-line PEN conductor earth resistance was one ohm with corresponding touch potentials in the range of seven to nineteen volts r.m.s. on tee-offs three and one respectively. A resistance of one ohm is impractical to achieve and therefore higher resistances and an additional PEN conductor earth-point is considered. When the end-of-line PEN conductor earth resistance is increased to five ohms, the minimum and maximum touch potentials are twenty-two and thirty-four volts r.m.s. on tee-offs three and one respectively. To lower the touch potentials even further, a second point of PEN conductor earthing is introduced at the middle of the main low-voltage backbone. With both the PEN conductor end-of-line and middle-of-line earth-resistance at five ohms, the maximum and minimum touch potentials are twenty-one and ten volts r.m.s. on tee-offs one and three respectively. There is a reduction of approximately ten volts in the touch potentials from the addition of the second point of earthing.

Combinations seven to seventeen in Figure 6-3 illustrate the results of simulating varying magnitudes of resistance at the two PEN conductor earth points. The results advocate that with a transformer earth resistance of thirty ohms, both the PEN conductor earth points are required to be five ohms or lower to achieve safe touch potentials at household installations during an incidence of a broken PEN conductor failure on the network close to the utility supply-transformer. The addition of more PEN conductor earth-points will lower the touch potentials further but were not simulated as the intention was to merely review the effectiveness of the solution. The effect of varying the transformer earth resistance is however considered in the discussion that follows.

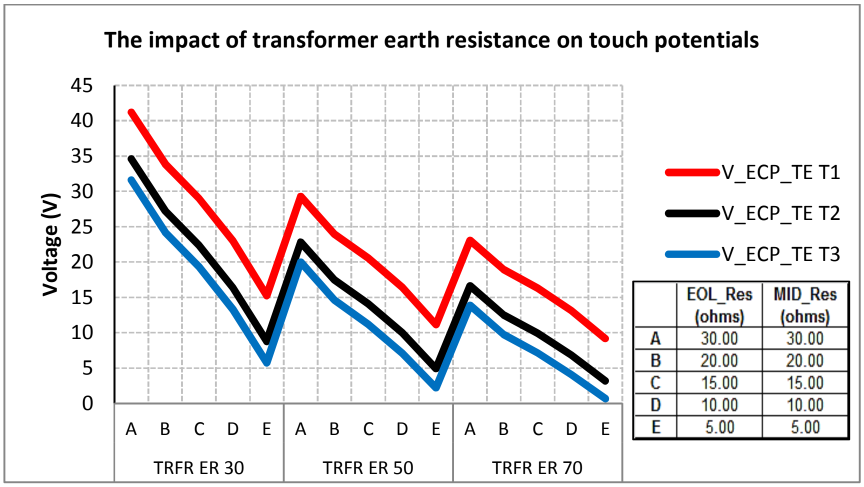


Figure 6-4: The impact of transformer earth resistance on touch potentials

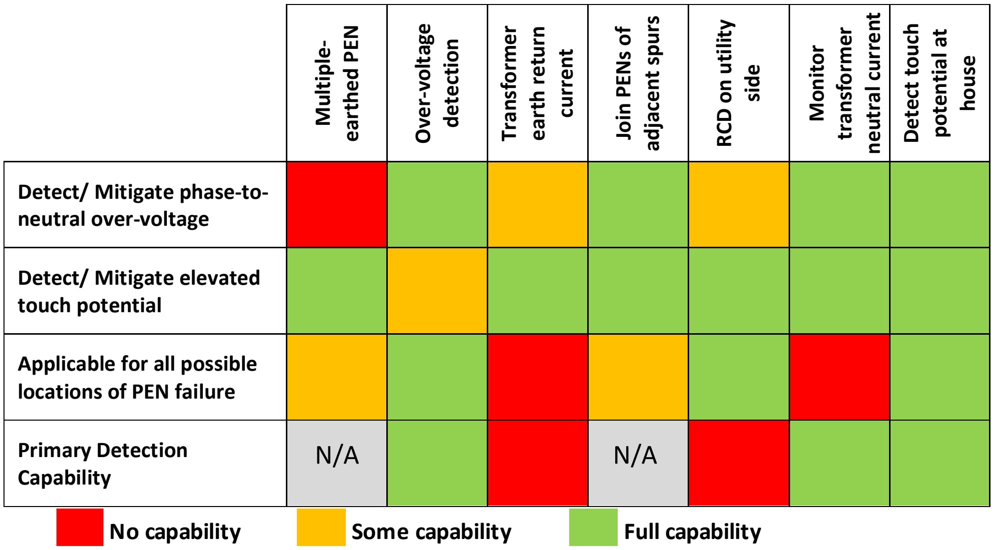
Figure 6-4 illustrates that as the transformer earth resistance is increased to the upper bound of seventy ohms, the touch potentials at households reduce for a given set of PEN earth resistances at the end and middle of the main LV backbone. The key observation is that there exists a relationship between the transformer earth resistance and the PEN conductor multiple earth resistances which may be exploited to provide a cost effective solution to alleviate dangerous touch potentials at households during an incidence of a lost or broken PEN conductor along the main LV backbone.

Another observation is that multiple earthing of the PEN conductor along the main backbone only provides a possible solution for incidence of broken PEN conductors on the main backbone; failures of the PEN on tee-offs are not covered by this solution and may require additional PEN earth points along the tee-offs. This therefore becomes an expensive venture as there are generally many tee-offs along the mainline. An alternate means of mitigation may need to be considered for failures along the tee-off.

6.5 Overview of effectiveness of detection and mitigation proposals

Table 6-2 presents an overview of some of the popular proposals as found from literature review and new proposals derived from this undertaking. Each proposal is briefly discussed in terms of its capability to detect or mitigate against phase-to-neutral over-voltages and elevated touch potentials, its effectiveness for all possible locations of a PEN conductor failure and whether it is able to detect the unsafe condition immediately.

Table 6-2: Review of effectiveness of various detection/ mitigation proposals



	Multiple-earthed PEN	Over-voltage detection	Transformer earth return current	Join PENs of adjacent spurs	RCD on utility side	Monitor transformer neutral current	Detect touch potential at house
Detect/ Mitigate phase-to-neutral over-voltage	🟥	🟩	🟧	🟩	🟧	🟩	🟩
Detect/ Mitigate elevated touch potential	🟩	🟧	🟩	🟩	🟩	🟩	🟩
Applicable for all possible locations of PEN failure	🟧	🟩	🟥	🟧	🟩	🟥	🟩
Primary Detection Capability	N/A	🟩	🟥	N/A	🟥	🟩	🟩

🟥 **No capability** 🟧 **Some capability** 🟩 **Full capability**

The multiple-earthed PEN was observed to be effective at lowering touch potentials at service installations although it depends on the number of earth points and the resistances of the transformer earth. It is however unable to mitigate against phase-to-neutral over voltage conditions experienced at installations. It also tends to be expensive when applied as mitigation for PEN conductor failures on single-phase tee-offs.

Over-voltage detection whether at the service-installation or on the utility side remains an effective means to detect phase-to-neutral over-voltages as a primary event, i.e. it does not depend on a secondary event, for example a human touching an ECP; it is however ineffective at totally alleviating elevated touch potentials as detailed in Table 6-1 where it is demonstrated that during the incidence of a broken PEN conductor on a single-phase tee-off, the phase-to-neutral voltages are within regulatory limits but the touch potentials attain dangerously high values.

The next possible solution is to monitor the transformer earth-return current neutral and disconnect both live and neutral conductors at a certain current threshold, most likely 30 mA as in the case of a house earth leakage device. This study observed that the current flow through a human to earth at an installation returns to the transformer via the earth connection to neutral. Although this solution provides the best economy of scale for the detection of the condition as a single RCD at the transformer provides protection for all customer installations supplied from that transformer. It is however subject to a few disadvantages: it does not have a primary detection capability and therefore relies on a secondary event of a human making contact with an ECP to activate protection. Once activated it may be effective at disconnecting a hazardous condition but further study is required to fully review its effectiveness. It is also prone to nuisance tripping due to harmonics and other system disturbances.

Joining the PEN conductor of adjacent tee-offs or spurs was simulated and it was observed that it provides effective risk mitigation for the condition of a broken PEN conductor anywhere along the same tee-off. It is however ineffective if the PEN conductor fails on the service cable entrance to the house (point 4 in Figure 6-1). It may also be ineffective if the PEN conductor fails at specific points along the mainline. It may prove to be a cumbersome solution as tee-offs don’t generally run in the same direction, it also has the disadvantage that the looped connection to the adjacent spur is not self-monitoring.

Another alternative is to introduce a RCD on the pole-top box prior to it entering the customer’s premises – this was simulated by measuring the difference between the neutral and live currents on the utility-side prior to entering the service installation distribution board. The neutral and live currents at this point present a residual difference when a human touches an ECP with an elevated voltage. The key to detection is that the RCD must be connected prior to the neutral and earth separation in a TN-CS system. Some utilities split the neutral before entering the customer’s premises, in these instances, the RCD must be installed further back just prior to the split. One major drawback of this proposal is that it does not have primary detection capabilities as it relies on a human subjected to a hazardous condition to activate the protection. Further limitations of this recommendation and other implicit risks were not evaluated.

Monitoring the transformer neutral current is a novel solution or proposal that did not feature in the literature review. From the study conducted, it was observed that the loss of a PEN conductor close to the utility transformer with an unbalanced load subjects all households supplied from that transformer to the hazardous condition. It was further observed that the loss of the PEN conductor results in zero current flow through it. If the phase currents and the neutral current are monitored at the transformer, it is possible to detect the broken PEN conductor as the phase currents will be greater than zero yet the neutral current is zero. Intelligent assimilation of these parameters may provide a cost effective means of detection. The limitation is that this solution will not be successful for all locations of PEN conductor failures.

It was observed that monitoring the touch potential at a house, i.e. measuring the voltage between neutral and true earth is the most effective way of addressing both the risks of phase-to-neutral over-voltages and elevated touch potentials. It is also relevant irrespective where on the network the PEN conductor fails. The proposed device should ideally monitor the touch potential and operate or disconnect the live and neutral supply to the house if the voltage exceeds a threshold, for example, thirty-five volts. It may not be the most cost effective solution as households all over the country will need to incorporate this device into the distribution board but it will definitely save lives. Further limitations of this recommendation and other implicit risks were not evaluated.

6.6 Conclusion

The location of a PEN conductor failure on an unbalanced three-phase system creates a hazardous condition at single-phase installations causing phase-to-neutral voltages beyond regulatory limits and elevated touch potentials that may result in electrocution of a person. The risk to each household depends on the location of the PEN conductor failure and may present itself as either non-compliant phase-to-neutral voltages or elevated touch potentials or both.

An effective detection or mitigation system must, therefore, be able to cater for all locations of PEN conductor failures and also have the ability to detect or mitigate independently a phase-to-neutral over-voltage condition or an elevated touch potential. It should ideally also have primary detection capability to respond to the risk elements as soon as it is presented to the system rather than depending on a secondary event stimulating or activating its operation. A secondary event in this case may be viewed as a human touching an ECP with an elevated touch potential resulting in current flow through the human which then activates the protection. A multiple-earthed PEN conductor was observed to be an effective mitigation option to lower touch potentials at service installations during an incidence of a broken PEN conductor. The solution however needs further study to specify the appropriate multiple earth resistances in relation to the transformer earth resistance and the consequential ground-potential rise at each earth point. The advantage is that it offers a supply-side solution that improves the safety at many households without interventions at each specific household. The disadvantage is that it is unable to mitigate against non-compliant phase-to-neutral voltages and so the risk of appliance failures and fires remain. Other mitigation and detection proposals were also reviewed for effectiveness with respect to the aforementioned capabilities. Of all the options reviewed, a protection system based on monitoring the voltage between neutral and true-earth at a service installation appeared to be most effective but an in-depth analysis was not conducted to consider other weaknesses, limitations and inherent risks of the proposed solution. There is therefore an opportunity for future work into each of the proposed solutions such that industry may be guided towards a robust and pragmatic solution for this very real and probable risk especially in the context of a rural homestead.

Chapter 7. Conclusion and recommendations

7.1 Conclusion

The phenomenon of a lost or broken PEN conductor on a TN-CS LV earthing system is widely documented in literature although there are differing opinions on whether the ensuing risk is only applicable to a three-phase unbalanced system or also present on a single-phase system. Literature also offers many mitigation and detection proposals but the risk to a typical South African rural homestead and the effectiveness of possible solutions has not been considered collectively.

The risk emanating from this phenomenon is generally undetected phase-to-neutral voltages that are beyond regulatory limits and dangerously high touch potentials at single-phase service installations derived of that supply system. A rural South African electrification application is a system riddled with elements that increase both the probability and consequence of this risk.

It is very probable that a high degree of unbalanced loading exists on a typical South African rural electrification transformer due to the incongruent geographical layout of the load, the preference of the use of three-phase transformers to lower costs, the addition of new customers to existing transformers through an abridged design process without reengineering from first principles and illegal connections. This large unbalanced load sets up a high current in the PEN conductor which may precipitate thermal failure.

Simulation and experimental studies were conducted to ascertain the risk to a typical South African rural household which observed that the household experiences approximately phase-to-phase voltages at the single-phase installation and that the exposed conductive parts are energised up to 191 V (r.m.s.) even when an appliance is off but still plugged into the mains socket. Touch potentials in excess of 35 V (r.m.s.) are considered dangerous. The scenario of a child standing on a muddy floor in contact with a stove chassis revealed via simulations that currents in the order of 368 mA flows through the kid undetected by the earth leakage device and the utility and household over-current protection systems. This current flow may lead to ventricular fibrillation and eventually death as prolonged exposure to currents in excess of 6mA is considered harmful. Regulations and industry needs to assume accountability for the safety of the public and quickly find a reliable and economical solution to address this veiled risk.

7.2 Recommendations

Rural South African homesteads are at highest risk from the hazardous conditions ensuing during a PEN conductor failure on both an unbalanced three-phase system and a single-phase application. Quick and pragmatic solutions are therefore required to immediately address the risk.

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 solution, at first glimpse, appears to be pragmatic in that it offers a supply-side solution that extends to the benefit of many households without interventions at each specific household. Industry must however invest in proper research and engineering studies to meticulously evaluate the proposal and lower the cost of a final solution. The multiple-earthed PEN conductor is however ineffective at detecting non-compliant phase-to-neutral voltages.

It was observed that monitoring the voltage between neutral and true-earth at a service installation is the most effective way of addressing both the risks of phase-to-neutral over-voltages and elevated touch potentials. It is also relevant irrespective where on the network the PEN conductor fails. The proposed device should ideally monitor the touch potential and operate or disconnect the live and neutral supply to the house if the voltage exceeds a threshold, for example, thirty-five volts. Further limitations of this recommendation and other implicit risks were not evaluated. It is however strongly recommended that regulations consider stipulating such device as mandatory once a tried and tested product is available.

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Appendix A – Component specifications

Table 7-1: Distribution transformer parameters

Parameter	**Value**
Winding 1 connection	Delta
Winding 2 connection	Star-Neutral
Nominal Power	50 kVA
Frequency	50 Hz
Winding 1 Parameters:	
Phase to phase voltage	22 kV
R1	58.08 Ω
L1	7.395 H
Winding 2 Parameters:	
Phase to phase voltage (r.m.s.)	415 V
R1	0.006889
L1	0.0087713
Magnetization resistance	$1.452 \mathrm{x} 10^7$ Ω
Magnetization inductance	46219

Table 7-2: Distributed line parameters

Parameter	Value
Number of Phases	3
Frequency	50 Hz
Resistance per unit length	0.786177 Ω/Km
Inductance per unit length	$1.178268\ 10^{-3}$ H/Km
Capacitance per unit length	$3.8778331\ 10^{-5}$ F/Km
Line Length	500 m