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1.0 Introduction

The MicroGrid is a unique distribution system and as such needs careful assessment in all of its design aspects. A MicroGrid is subject to the same safety requirements as any other utility electric power system. This report presents the guidelines for operating a MicroGrid safely.

A fault in a MicroGrid may generate substantial ground potential rise, even if the energy sources operate at low voltage. This means grounding of the distributed energy sources, and the transformer connecting the MicroGrid to the utility network, must be carefully analyzed and appropriate rules need to be developed, so that the same level of safety as conventional systems is achieved. Also the earthing system of a MicroGrid must be able to deal with both interconnected and islanded operation.

It is very important to examine fault currents within the MicroGrid during both grid-connected and islanded operation. This knowledge is essential to plan for protection in a MicroGrid as well as to determine the step and touch voltages. The combination of the fault current, the earthing policy and the operating time of the protection gives rise to the step and touch potentials on which electrical safety requirements are based. These important parameters need to be calculated to ensure that they are within the legislative limits.

Potential gradients will be produced within and around a substation due to the flow of current into the earth during ground fault conditions. A grounding system has to be designed in such a way as to ensure that no electrical hazards exist outside or within the substation during normal and fault conditions.

Chapter 2 of this report presents the findings of an extensive literature review carried out on Low Voltage (LV) distribution network neutral earthing. The most suitable neutral earthing methods for a MicroGrid are proposed along with the means for earthing the micro-sources in a MicroGrid.

In the initial section of Chapter 3, the fault current contribution from converters is studied in view of most of the micro-sources in a MicroGrid being connected through power electronics. Then the fault current distribution in a MicroGrid is investigated for different fault scenarios for each of the earthing system proposed in chapter 2. The fault current investigation presented in this chapter is based on a study carried out by UMIST using the grounding software tool, CDEGS.

Chapter 4 investigates the performance of each earthing system in a MicroGrid. This chapter is based on the findings of a study carried out by ICCS/ NTUA using the analytical software tool EMTP.

Chapter 5 is based on the analysis of the performance of the MicroGrid grounding system. A substation grounding system for a typical MicroGrid is designed and its safety and adequacy is evaluated in terms of touch voltage, step voltage and ground potential rise.

2.0 EARTHING OF A MICROGRID

The earthing of an electricity supply network requires its network plant and customer electrical equipment to be connected to the earth in order to promote safety and reduce the possibilities of damage to equipment. Effective earthing prevents long-term over voltages and minimizes risk of electric shock hazards. Earthing also provides a predetermined path for earth leakage currents, which are used to disconnect the faulty plant or circuit by operating the protective devices. Research and experience show that both earthed and unearthed electrical systems can be safe. However, earthing of the source neutral is the common practice in Low Voltage (LV) systems.

Two reports have been produced identifying the earthing practices in LV networks and installations and reviewing national earthing practices. The UMIST report outlines the LV neutral earthing in the UK and mainly refers to the legislations ESQ&C2002, ESR88 (superseded and replaced by ESQ&C Regulations 2002) and BS7671 [1]. The NTUA report reviews the European practices and quotes IEC60364 and French Standard NF C 15-100 [2]. Sections 2.1- 2.5 of this chapter summarises the points raised in these two reports. Section 6 presents the proposed earthing systems for a MicroGrid with their advantages and disadvantages. Section 2.7 discusses the earthing of the generators in the MicroGrid.

2.1 Types of earthing systems

A LV distribution system may be identified according to its earthing system. These are defined using the five letters T (*direct connection to earth*), N (*neutral*), C (*combined*), S (*separate*) and I (*isolated from earth*). The first letter denotes how the transformer neutral (supply source) is earthed while the second letter denotes how the metalwork of an installation (frame) is earthed. The third and fourth letters indicate the functions of neutral and protective conductors respectively. There are three possible configurations:

1. TT: transformer neutral earthed and frame earthed
2. TN: transformer neutral earthed, frame connected to neutral
3. IT: unearthed transformer neutral, earthed frame.

The TN system includes three sub-systems: TN-C, TN-S and TN-C-S, as discussed in the following sub-section.

2.1.1 TN system

In a TN system, the supply source (transformer neutral) is directly connected to earth and all exposed conductive parts of an installation are connected to the neutral conductor. Safety of personnel is guaranteed, but that of property (from fire, damage to electrical equipment) is less so. The three sub-systems in TN are described below with their key characteristics.

2.1.1.1 TN-C earthing system

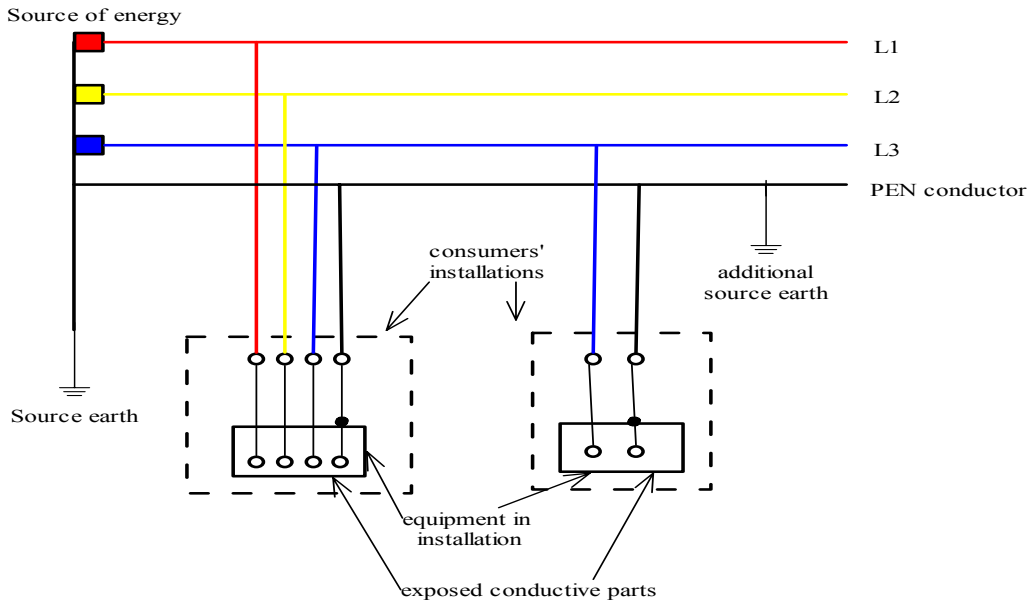


Figure 2.1: TN-C earthing system

- Neutral and Protective functions are combined in a single conductor throughout the system. (PEN – Protective Earthed Neutral).
- The supply source is directly connected to earth and all exposed conductive parts of an installation are connected to the PEN conductor.
- Particularly used in Anglo-Saxon countries
- Currently not recommended in premises equipped with communicating electronic systems as currents in the neutral and thus in the PE cause potential references to vary.

2.1.1.2 TN-S earthing system

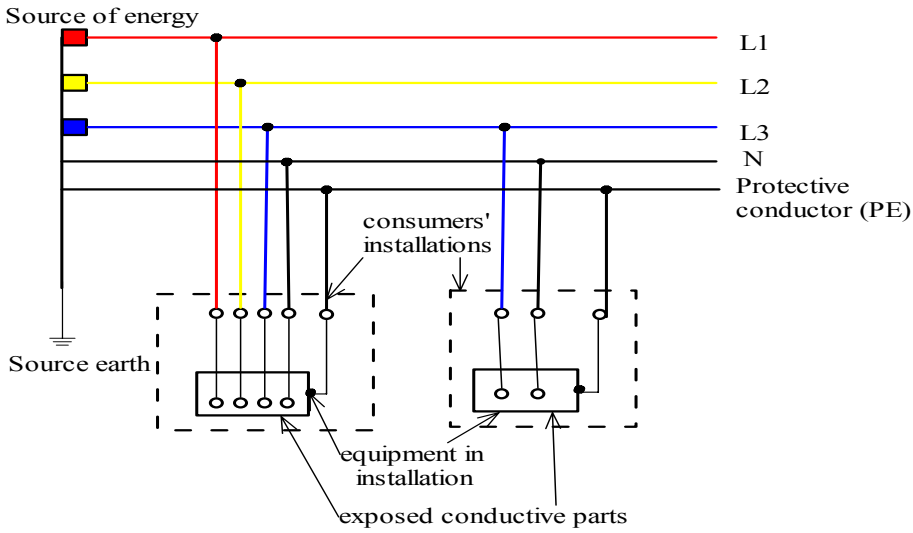


Figure 2.2: TN-S earthing system

- A TN-S system has separate neutral and protective conductors throughout the system.
- The supply source is directly connected to earth. All exposed conductive parts of an installation are connected to a Protective conductor (PE) via the main earthing terminal of the installation.
- This system is compulsory for networks with conductors of a cross-section $\leq 10mm^2Cu$

2.1.1.3 TN-C-S earthing system

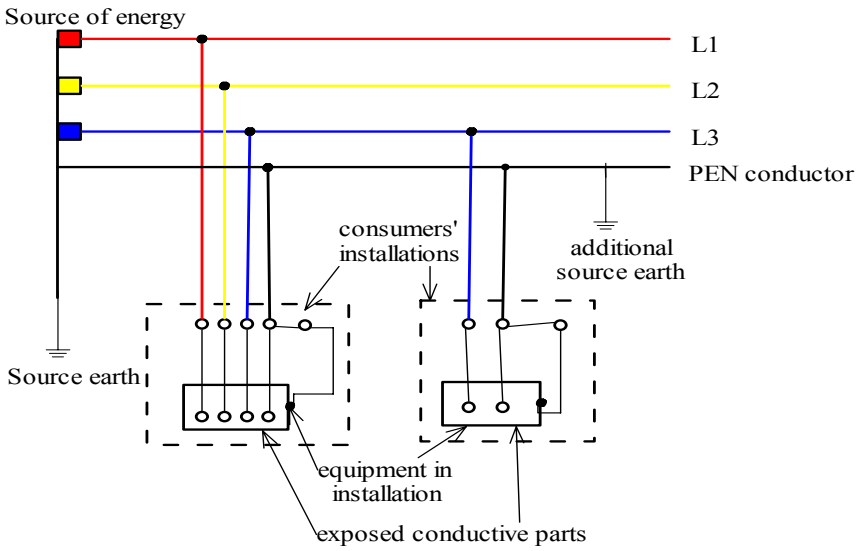


Figure 2.3: TN-C-S earthing system

- Neutral and protective functions are combined in a single conductor in a part of the TN-C-S system. The supply is TN-C and the arrangement in the installation is TN-S.
- All exposed conductive parts of an installation are connected to the PEN conductor via the main earthing terminal and the neutral terminal, these terminals being linked together.
- This is also known as Protective Multiple Earthing (PME) and the PEN conductor is referred to as the Combined Neutral and Earth (CNE) conductor. The supply system PEN conductor is earthed at several points and an earth electrode may be necessary at or near a consumer's installation.

2.1.2 TT system

The supply source has a direct connection to earth. All exposed conductive parts of an installation also are connected to an earth electrode that is electrically independent of the source earth.

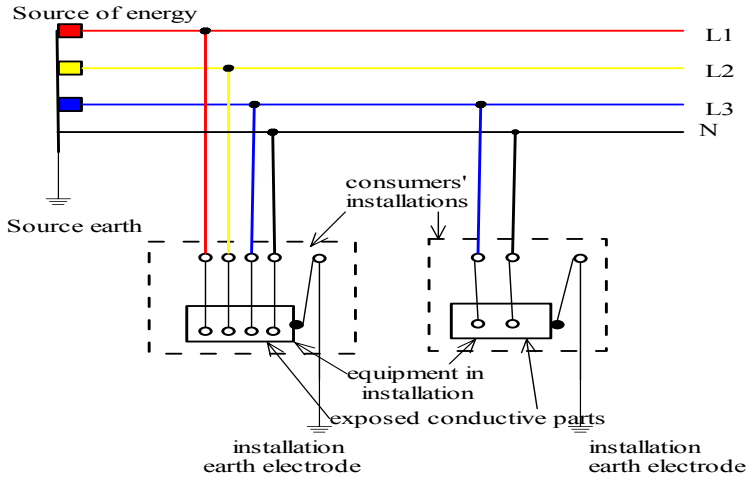
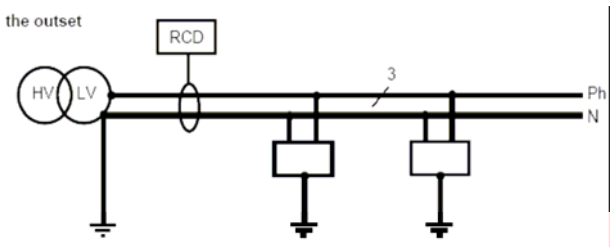


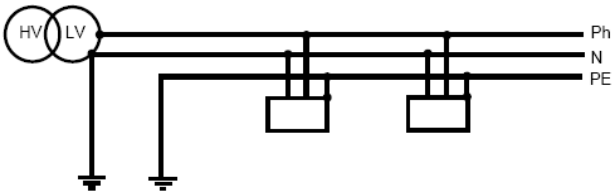
Figure2.4: TT earthing system

The evolution of the TT system is illustrated below in Figure 2.5[3].

a) At the outset

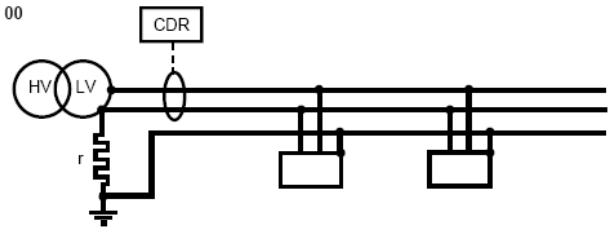


b) In 1990



PE distributed as in TN-S and IT. In some installations, the two earth connections are joined.

c) In 2000



To retain the advantage of the small fault current, an impedance-earthed TT (r ≈12 Ω/Id = 20 A) has emerged with a single earth connection. This system requires the use of a surge limiter if the MV zero sequence current exceeds ≈80 A

Figure 2.5:Evolution of TT earthing system [3]

(a): at the outset *(b): In 1990's* *(c): In 2000*

2.1.3 IT system

The supply source is either connected to earth through deliberately introduced high earthing impedance (Impedance earthed IT system) or is isolated from earth. All exposed conductive parts of an installation are connected to an earth electrode.

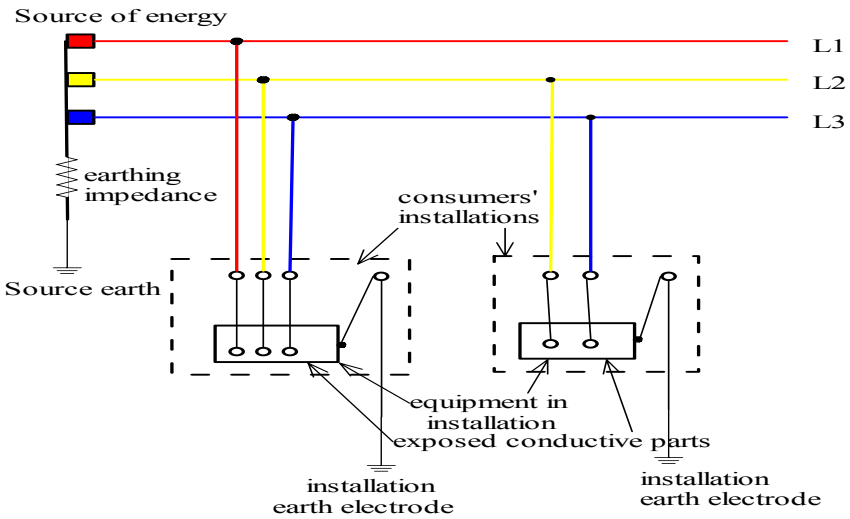


Figure 2.6: IT earthing system

Every exposed-conductive part shall be earthed to satisfy the following condition for each circuit

$$R_b * I_d \leq 50V$$

Where

R_b = The resistances of the earth electrode for exposed conductive-parts

I_d = Fault current which takes account of leakage currents and the total earthing impedance of the electrical installation

Each earthing system can be applied to an entire LV electrical installation or several earthing systems may be included in the same installation. Figure 2.7 shows an example of various earthing systems included in the same installation.

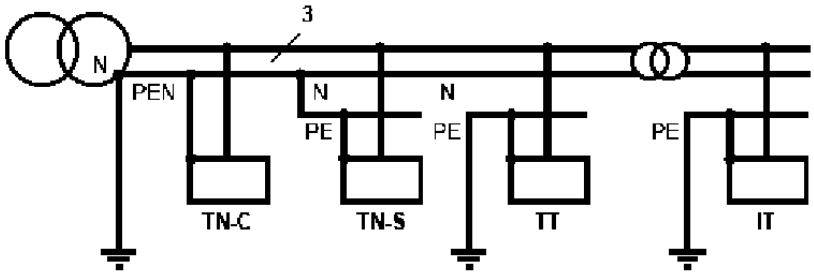


Fig. 2.7: example of the various earthing systems included in the same installation

2.2 Fault behaviour and characteristics of different earthing systems

An insulation fault in an electrical installation presents hazards to humans and equipment. At the same time it may cause unavailability of electrical power. The fault currents and voltages differ from one earthing system to another.

2.2.1 A fault in a TN system

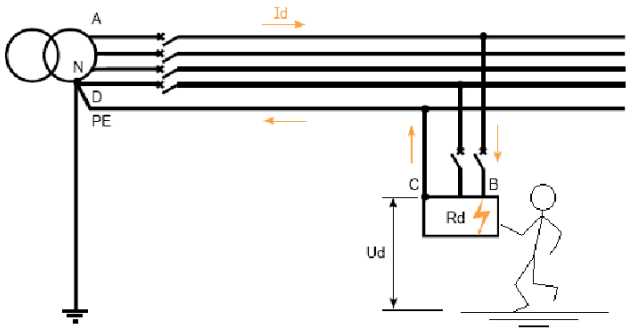


Figure 2.8: A fault in a TN system

- When an insulation fault is present, the fault current Id is only limited by the impedance of the fault loop cables
- Short Circuit Protection Devices (SCPDs - circuit breaker or fuses) generally provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time (depending on phase-to-neutral voltage Uo). Typical breaking times in a TN system are tabulated in Table 2.1 according to IEC 60364.

Uo (volts) phase/neutral voltage	breaking time (seconds) U_L = 50 V	breaking time (seconds) U_L = 25 V
127	0.8	0.35
230	0.4	0.2
400	0.2	0.05
≦ 400	0.1	0.02

Table 2.1: breaking time in TN system (taken from IEC 60364 tables 41 and 48A)

2.2.2 A fault in a TT system

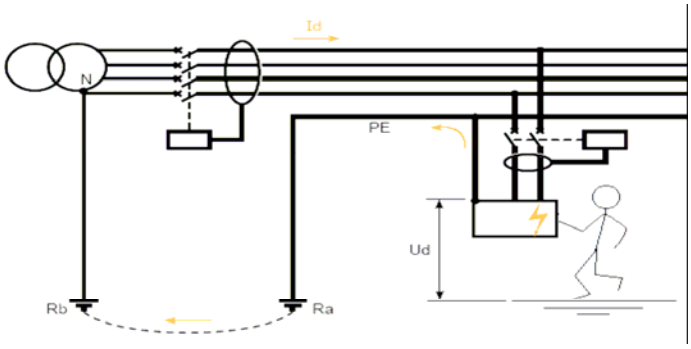


Figure 2.9: A fault in a TT system

- When an insulation fault occurs, the fault current Id is mainly limited by the earth resistances
- At least one Residual Current Device (RCD) must be fitted at the supply end of the installation. In order to increase availability of electrical power, use of several RCDs ensures time and current discrimination on tripping.

$I\Delta n \leqslant \frac{U_L}{Ra}$	maximum resistance of earth connection	
U_L	50 V	25 V
3 A	16 Ω	8 Ω
1 A	50 Ω	25 Ω
500 mA	100 Ω	50 Ω
300 mA	166 Ω	83 Ω
30 mA	1,660 Ω	833 Ω

Table 2.2: upper limit of the resistance of the frame earth connection not to be exceeded according to RCD sensitivity and limit voltage UL [I Dn = F(Ra)]

2.2.3 A fault in an IT system

First fault on an IT system

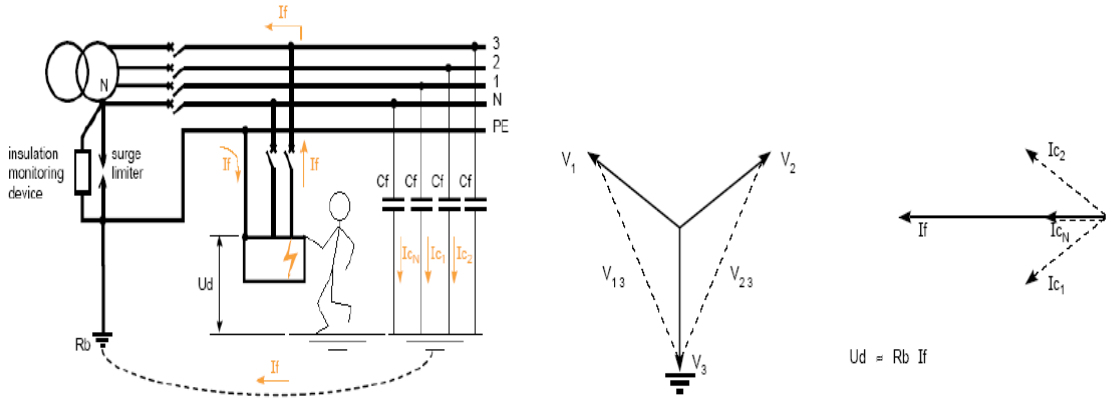


Fig. 2.10: first insulation fault current in IT system

- The fault voltage is low and not dangerous. Therefore it is not necessary to disconnect an installation in the event of a single fault.
- However it is essential to know that there is a fault and to track it and eliminate it promptly, before a second fault occurs. To meet this need the fault information is provided by an Insulation Monitoring Device (IMD) monitoring all live conductors, including the neutral. Locating is performed by means of fault trackers.
- When the neutral is not distributed (three-phase three-wire distribution)

$$Z_s \leq \frac{0.866U_0}{I_a}$$

- When the neutral is distributed (three-phase four-wire distribution and single phase distribution)

$$Z_s^1 \leq \frac{0.5U_0}{I_a}$$

Where

Z_s = Earth fault loop impedance comprising the phase conductor and the protective conductor

Z_s^1 = Earth fault loop impedance comprising the neutral conductor and the protective conductor

I_a = Fault current

Second fault on an IT system

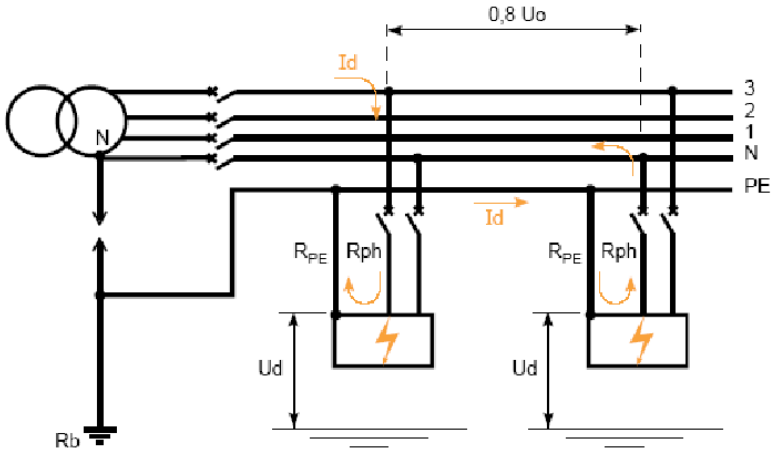


Fig. 2.11: 2nd insulation fault current in IT system (distributed neutral) and relevant feeders with the same cross-section and length.

Maximum disconnection times for an IT system are given in Table 2.3 (as in IEC 60364 tables 41B and 48A).

Uo/U (volts) Uo: phase/neutral voltage U: phase to phase voltage	U_L = 50 V breaking time (seconds) Neutral not distributed	 Neutral distributed	U_L = 25 V breaking time (seconds) Neutral not distributed	 Neutral distributed
127/220	0.8	5	0.4	1.00
230/400	0.4	0.8	0.2	0.5
400/690	0.2	0.4	0.06	0.2
580/1 000	0.1	0.2	0.02	0.08

Table 2.3: Maximum disconnection time in IT systems (second fault)

2.2.4 Fault characteristic quantities of earthing systems

In order to overview the quantities characterising the various earthing systems, as regards protection of persons, the main formulas are listed in Table 2.4.

		Id	Ud	Lmax	continuity of service
TN		$\frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\frac{0.8\ Uo}{1+m}$	$\frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	vertical discrimination
TT		$\frac{Uo}{Ra+Rb}$	$\frac{Uo\ Ra}{Ra+Rb}$	no constraint	vertical discrimination
IT	1st fault	< 1 A	<< U_L		no tripping
	double fault with neutral	$\leqslant \frac{1}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\leqslant \frac{m}{2}\ \frac{0.8\ Uo}{1+m}$	$\frac{1}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	vertical discrimination and possibility of horizontal discrimination to the advantage of hich current feeders
	double fault between phases	$\leqslant \frac{\sqrt{3}}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ L}$	$\leqslant \frac{m\ \sqrt{3}}{2}\ \frac{0.8\ Uo}{1+m}$	$\frac{\sqrt{3}}{2}\ \frac{0.8\ Uo\ Sph}{\rho\ (1+m)\ Ia}$	

Remember that:

- $\rho = 22\ 10^{-6}\ \Omega/mm^2/m$ for Cu (36 for Al);
- $m = \frac{Sph}{S_{PE}}$;
- PE cross-section, normally equal to phase cross-section, can be equal to half of phase cross-section when the latter exceeds 35 mm^2.... thus increasing Ud in TN and IT.

Table 2.4: Characteristic quantities of earthing systems [4]

Where

U_L = Limit voltage/ safety voltage

U_d = Fault voltage

R_a = Resistance of the installation earth

R_b = Resistance of the source earth

I_d = Fault current

I_a = Automatic breaking current

U_0 = Phase-to-neutral voltage

L_{max} = Maximum length in m

The standard values for fault currents in traditional LV earthing systems are as follows.

TN:	Id ≈ 20 kA	IT	(1st fault):	Id < 1 A;
TT:	Id ≈ 20 A		(2nd fault):	Id ≈ 20 kA.

2.3 Suitable switchgear selection

Suitable switchgear has to be selected for protection purposes. These are described below for each earthing system.

2.3.1 TN system

Short-Circuit Protection Devices (SCPDs - circuit-breaker or fuses) generally provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time.

2.3.2 TT system

The low fault currents do not allow the SCPDs to protect persons against indirect contact. Residual Current Devices (RCDs) need to be used, associated with circuit breakers or switches.

2.3.3 IT system

Insulation Monitoring Devices (IMDs) are used for locating the first fault. In the occurrence of a second fault, automatic breaking is vital due to the electric shock risk: this is then the role of the SCPDs backed up by the RCDs if required. This system must also be protected against risks of insulation faults between MV and LV by a surge limiter.

2.3.4 Neutral Protection

A multi-pole device must break the neutral

- In TT and TN, if the neutral cross-section is less than phase cross-section
- In terminal distribution in view of the Neutral/ Phase reversal risk.

The neutral must be protected and broken

- In IT for intervention of the protection device on the double fault, with one of the faults possibly on the neutral
- In TT and TN-S if neutral cross-section is less than phase cross-section
- For all earthing systems if the installation generates harmonic currents of order 3 and multiples (especially if neutral cross-section is reduced).

In TN-C, the neutral, which is also the PE, cannot be broken which would be dangerous as a result of its potential variations, due to load currents and insulation fault currents. To prevent risks, local equipotential bonding and an earth connection must be provided for each zone/consumer.

Figure 2.11 shows which types of circuit breaker should be used for which earthing system [4]. Note that TT and TN can use the same devices, with an additional RCD in TT systems.

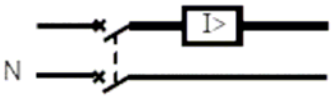
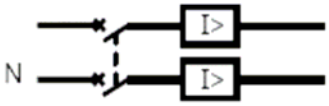
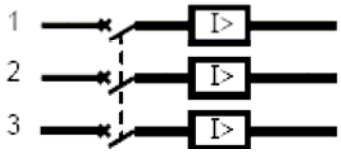
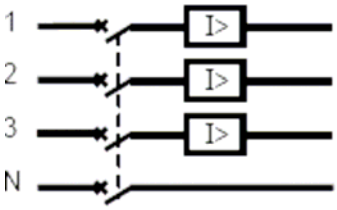
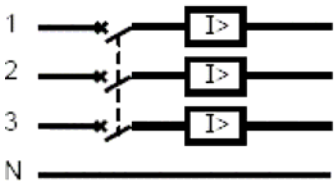
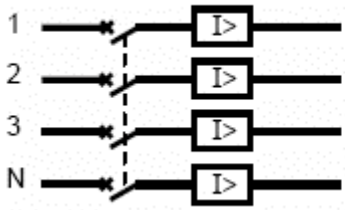
circuits	diagrams TN-C	TN-S	TT	IT
single phase circuits				
single phase circuits with one protected pole	no	yes	yes	no
 two-pole circuit-breaker (1 protected pole, 2 de-energized poles)				
phase to neutral circuits with two protected poles	no	yes	yes	yes
 two-pole circuit-breaker (with 2 protected poles)				
three-phase circuits without neutral				
with two-pole protection	yes	yes	yes	yes
 three-pole circuit-breaker				
three-phase circuits with neutral				
without overcurrent detection on neutral	no	yes	yes	no
 four-pole circuit-breaker with three protected poles				
 three-pole circuit-breaker	yes	yes	yes	no
with overcurrent detection on neutral	no	yes	yes	yes
 four-pole circuit-breaker with four protected poles				

Figure 2.12: Examples of circuit breakers according to earthing systems [4]

2.4 Review of International Standards and Practices in LV earthing

Table 2.5 gives the various earthing systems used in LV public distribution systems in different countries

country	LV earthing system	observations
Germany 230/400 V	TT and TN-C	the TN is the most commonly used; R_T must be < 2 Ω; earth connection at the consumer's, even in TN
Belgium 230/400 V	TT	Ru < 100 Ω 30 mA RCD for sockets
Spain 230/400 V	TT	Ru < 800 Ω with 30 mA RCD at supply end of the installation
France 230/400 V	TT	Ru < 50 Ω, (100 Ω shortly) 30 mA RCD for sockets
Great Britain 240/415 V	TT and TN-C	- town areas: TN-S and TN-C (New Est installations: 15 %), the earth connection (< 10 Ω) of the neutral is provided by the distributor - rural areas: TT
Italy 230/400 V	TT	RCD with IΔn as a function of Ru (IΔn < 50/Ru). For consumers without earth connection 30 mA RCD
Japan 100/200 V	TT	Ru < 100 Ω, frequent use of 30 mA RCD, no search for equipotentiality
Norway 230/400 V	IT	premises in insulating materials and poor earth connections account for this choice. homes with signalling 30 mA RCD. tripping of connection circuit breaker if 2 faults.
Portugal	TT	Ru < 50 Ω (100 Ω as from 1995).
USA 120/240	TN-C	earthing of neutral at LV consumers (all earth connections are connected to the source substation).

Table 2.5: Public distribution examples worldwide – LV earthing systems [3]

According to the above table, TT seems to be the most common earthing system used. At the same time, we have to make note of two points. Firstly, where both TN and TT systems are found (for example, Germany and Great Britain), TN is the principal earthing system and TT is not used often. Secondly the recent trends show that many countries are moving away from TT and adopting TN systems (for example, Netherlands and Portugal) for the reason of greater reliability.

2.5 Selection of the suitable earthing system

Choice of the LV earthing is usually determined by the normal practice in the country. Although the design engineers make the decisions, electrical power users and network operators should influence this choice. Users and operators both demand absolute

dependability. The elements making up installation dependability are safety, availability, reliability and maintainability. In addition, electricity must not disturb the numerous low current devices.

These are the criteria used to make the best choice and it is summarized in Table 2.6 for each earthing system [3].

	TN-C	TN-S	TT	IT(1)	IT(2)	Observations
safety						
■ of persons	+	+	+	++	-	Uc # 0 on 1st fault (IT)
■ fire	- -	-	+	++	-	TN-C not recommended
■ explosions	- -	-	+	++	-	TN-C strictly prohibited
availability- (further to 1 fault)	+	+	+	++	+	depends on discrimination of the SCPDs or RCDs (easier to implement)
maintenability	-	-	+	++	-	the IT authorises preventive and even predictive maintenance
reliability of the installation	-	+	++	++	+	advantage for small Ids (damage- electrodynamic forces)
disturbances						
■ radiation transmission EM	-	-	+	++	-	advantage for small Id
■ equipotentiality of PE	- -	+	++	+	+	pay attention to harmonics in TN-C

(1) : 1st insulation fault.
(2) : 2nd fault.

Table 2.6: comparison of the earthing systems [3]

In safety terms**,** the TT is the best option while IT gives the greatest availability**.** In maintainability terms**,** fault locating is fast in TN (thanks to the SCPD) but repair time is often long. Conversely, in IT, locating the first fault may be more difficult, but repairs are quicker and less costly. The TT is a good compromise. In disturbance terms, the TT is to be preferred to the TN-S whose high fault currents may be the source of disturbance. All the earthing systems are approximately equivalent in terms of complete cost over 10 – 20 years

In some countries, for some buildings or parts of a building, the choice of the earthing system is laid down by legislations or standards, e.g. for hospitals, schools, naval places, worksites, mines, etc. In other cases, certain earthing systems are strictly prohibited, for example the TN-C in premises with explosion risks. Apart from these

compulsory choices, the dependability objectives should determine which earthing system is chosen for a specific building type. The degree of development of the country should also be taken into consideration, as should be national practices, climate. It should also be noted that it is possible and even advisable to mix the earthing systems

2.6 Neutral earthing in the MicroGrid

A range of options is available to earth the MicroGrid network as explained in the above sections. The most common systems are TT and TN; a few countries, in particular Norway, use the IT system. Generally, global use of different earthing systems is as follows;

- Mainly TN in Anglo-Saxon countries;
- TT often used in the other countries;
- IT used when safety of persons and property, and continuity of service are essential.

When selecting the neutral earthing method for a MicroGrid, the following factors need to be considered initially.

1. *What is the normal practice in the country?*

   If an alternative system were to be introduced in the MicroGrid, all involved personnel would have to be trained on the new system. They might not be willing to deviate from the system they are accustomed to and the training programmes will introduce additional costs.

2. *What are the legislations to be adhered to?*

   Most countries apply or derive the systems from standard IEC 60364. However, each country might have their particular statutory orders. For example, "Electricity, safety, Quality and Continuity Regulations 2002 (ESQ&C2002)" and BS 7671 are the key legislations in UK in this field.

3. *What are the foremost needs of the MicroGrid customers?*

   The choice of the earthing system would depend on the needs of the network consumers. If availability is essential above all else, IT system might have to be used. If safety is the chief requirement, TT is probably the best option.

It has to be remembered that the MicroGrid could adopt a single earthing system or a combination of systems according to its individual needs. Taking all factors into account, the most appropriate earthing system for a typical MicroGrid is either TN (most specifically TN-C-S) or TT. This choice could be different for individual MicroGrids in keeping with the above-mentioned three issues. The pros and cons of these two systems are summarized below.

2.6.1 TN System in a MicroGrid

2.6.1.1 Advantages of a TN system

1. A TN system always provides a low impedance return path for faults in the LV grid (Lower earthing resistance of the PEN conductor).
2. The grounding conductors at the transformer and at all customers are interconnected. This ensures a distributed grounding and reduces the risk of a customer not having a safe grounding.
3. TN systems have the advantage that in case of an insulation fault, the fault voltages are generally smaller than in TT systems. This is due to the voltage drop in the phase conductor and the lower impedance of the PEN conductor compared with the consumer earthing in TT systems
4. No overvoltage stress on equipment insulation
5. TN-S system has the best EMC properties for 50Hz and HF currents, certainly when LV cable with a grounded sheath is applied
6. TN systems could be operated with simple overcurrent protection
7. High reliability of disconnection of a fault by overcurrent devices
8. Highest attainable protection level could be achieved with an overcurrent device along with a RCD if required.
9. Compensation of the earthing effect of old gas and water pipes, which are now made of plastic materials

2.6.1.2 Disadvantages of a TN system

1. Faults in the electrical network at a higher voltage level may migrate into the LV grid grounding causing touch voltages at LV customers.

2. A fault in the LV network may cause touch voltages at other LV customers
3. Potential rise of exposed conductive parts with the neutral conductor in the event of a break of the neutral network conductor as well as for LV network phase to neutral and phase to ground faults and MV to LV faults
4. The utility is not only responsible for a proper grounding but also for the safety of customers during disturbances in the power grid
5. Protection to be fitted in case of network modification (increase of fault loop impedance)
6. TN-C system is less effective for Electromagnetic Compatibility (EMC) problems

2.6.2 TT system in a MicroGrid

2.6.2.1 Advantages of a TT system

1. The most commonly found earthing system
2. Faults in the LV and MV grid do not migrate to other customers in the LV grid
3. Good security condition, as the potential rise of the grounded conductive part must be limited at 50 V for a fault inside the installation and at 0V for a fault on the network.
4. Simple earthing of the installation and the easiest to implement.
5. No influence of extending the network.

2.6.2.2 Disadvantages of a TT system

1. Each customer needs to install and maintain its own ground electrode. Safety and protection depends on the customer, thus complete reliability is not assured.
2. High overvoltages may occur between all live parts and between live parts and PE conductor
3. Possible overvoltage stress on equipment insulation of the installation
4. For large customers it is impossible to apply a TT system, since the disconnecting time of the over-current protective device is too long

2.7 Earthing of the micro-sources

An embedded generator could operate with its neutral point earthed or not earthed [5-7]. However, the provision of an earthing reference is important for the micro-sources, for both grid-connected operation and islanded operation. This is an important fact to consider in design of the MicroGrid.

Several options for generator neutral point earthing and relevant legislations are described in Engineering Technical report ETR113 and the British Standards BS7430 [5, 8]. The methods available to earth the generators are given below.

1. Switched neutral point earthing
2. Impedance earthing
    a. Direct (solid) earthing
    b. Resistance earthing
    c. Reactor earthing
3. Via a Voltage Transformer (VT) with residual voltage or neutral voltage displacement protection
4. Transformer earthing

According to current legislations, LV generators may be earthed or unearthed when operating in parallel with the distribution system. The usual practice is not to earth the generator neutral point in parallel operation.

A MicroGrid is designed to operate when interconnected to the distribution system as well as when disconnected from it. A simplified model of a MicroGrid with a single micro-source and a single load is shown in Figure 2.13. However in a typical MicroGrid there would be several generators dispersed throughout the system. If all or some of these generator neutrals are connected to the earth, the following technical issues have to be considered due to multiple earthing [9].

- Control of earth fault currents
- Maintaining predetermined paths for earth fault current
- Detection of earth leakage currents
- Effectiveness of network earthing
- Limiting circulating currents at fundamental and harmonic frequencies
- Avoiding interference to communication systems

Due to the above issues, earthing of micro-sources in grid-connected operation is not considered desirable.

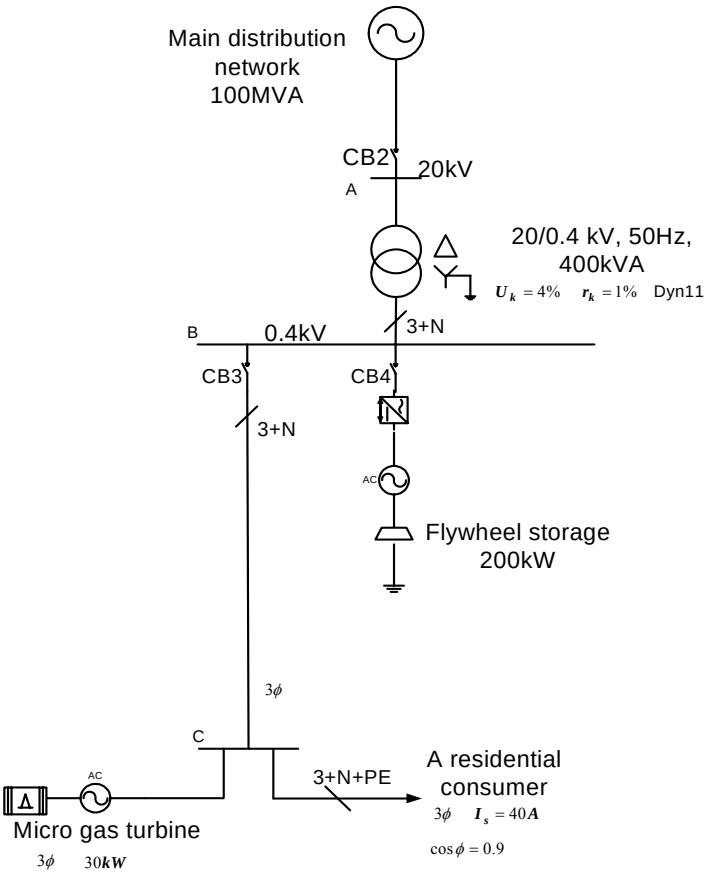


Figure 2.13: Simplified model of a MicroGrid

In the case of the generators in a MicroGrid not being earthed, we must ensure that an earth reference point is provided when the MicroGrid is disconnected from the main grid. One possible solution is to operate the generator with an unearthed start point when grid-connected and then automatically reconnect the start point to neutral/ earth connections when the MicroGrid is islanded. The MicroGrid Central Controller (MGCC) could send down a signal to all the micro-sources when the MicroGrid is disconnected from the distribution system or when it is reconnected. The generator neutral earth could be switched according to this signal.

There is another solution, which is simpler. It is obvious that the problem of a single earth reference point is prevalent in islanded operation as the distribution transformer neutral earthing is obviously available in grid-connected operation. Proposed protection schemes for a MicroGrid describe three operating scenarios according to the location of the fault [10].

1. For a fault on the distribution system, the MicroGrid will continue to operate in an island by opening the circuit breaker upstream of the main distribution transformer (CB2).
2. For a fault on the MicroGrid network, the whole MicroGrid will discontinue its operation. Sectionalising of a general MicroGrid is not advised.
3. For a fault at a residential consumer, the relevant consumer would be disconnected from the MicroGrid, and normal operation would continue.

According to above protection guidelines, the MicroGrid would not lose the source earth at the distribution transformer in any event. The transformer neutral earthing is retained in islanded operation as the MicroGrid is disconnected from the main grid by opening the circuit breaker CB2, which is upstream of the transformer. Therefore, the micro-sources could be operated safely without earthing their respective neutral points.

Protective earthing of the micro-sources is achieved by connecting the generator frame, all exposed conductive parts and extraneous conductive parts to a main earthing terminal.

2.8 Conclusions

A MicroGrid must achieve the same level of safety as any other conventional distribution system. Therefore the grounding of the distributed energy sources, and the transformer connecting the MicroGrid to the utility network, requires to be carefully analyzed and appropriate rules need to be developed. An extensive literature review had been carried out. According to this analysis, the most suitable earthing systems for a MicroGrid are identified as follows in the order of their suitability.

1. TN-C-S
2. TT
3. IT

As per proposed protection guidelines for a MicroGrid, the source earth at the distribution transformer would not be lost in any event. The MicroGrid should be

disconnected from the main grid only by opening the circuit breaker upstream from the transformer. Then the micro-sources could be operated safely without earthing their neutral points locally. Protective earthing of the micro-sources is achieved by connecting the generator frame and all conductive parts to a main earthing terminal.

The performance of each of these earthing systems in a MicroGrid is further investigated via simulation in the following chapters of this report.

2.9 References

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9. Rogers, W J S., Notes on "Protection of Distribution Systems with Distribution Generattion", UMIST MSc Module: Integration of Distributed Generation, 8th –12th March 2004.
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3.0 FAULT CURRENT CONTRIBUTIONS

Most conventional distribution protection is based on short-circuit current sensing. Conventional rotating generating plants provide considerable fault currents in the event of a short circuit. This high fault current capability of synchronous generators is very useful in detecting the occurrence of a fault. A majority of the micro-sources in a MicroGrid would be interfaced through power electronics. These power electronic based micro sources cannot normally provide the conventional high levels of short-circuit required. Typically they may only be capable of supplying twice the load current or less to a fault, unless the inverters are specifically designed to provide high fault current. Some conventional over-current sensing devices will not respond to this level of over-current, and those that do respond will typically take many seconds to respond, rather than the fraction of a second that is required.

A MicroGrid is required to operate when islanded as well as when grid-connected. In the grid-connected mode, the main distribution system would contribute to the short-circuit current and the use of traditional protection relays should not pose a problem. Using current based fault detection in an islanded MicroGrid however would be a great concern due to the low short circuit to load current ratios. Sufficient fault current sources within the MicroGrid are a requirement for successful operation of over-current protection.

A MicroGrid must achieve the same level of safety as any other conventional distribution system. Therefore the grounding of the distributed energy sources, and the transformer connecting the MicroGrid to the utility network, requires to be carefully analyzed. According to the previous chapter, the most suitable earthing systems for a MicroGrid are TN-C-S, TT and IT in the order of their suitability. The performance of the above earthing systems in a MicroGrid needs to be further investigated via simulation.

The fault current contribution from converters is analyzed in the first section of this chapter. In the second section, fault current distributions in a MicroGrid are examined for different neutral earthing systems.

3.1 Fault current contribution from converters

Clearing faults with conventional over-current devices in low voltage load circuits will require an available fault current of at least 3 times the maximum load current of the circuit [1]. Hence a study of the technical and commercial implications of using inverters with conventional over current protection was carried out with the objectives of investigating:

1. The fault current contribution available from various converter designs
2. The possibility of increasing their short circuit capability at a reasonable cost. (At least 3 per unit fault current lasting between 1-3 seconds).

A report was produced based on this study and is presented in the Appendix V of this report. The summary of its contents is given in the following subsections.

3.1.1 Short circuit capability of power modules

Each inverter design will have different parameters and the basic characteristics of each unit depend on the design goals of a particular manufacturer and/or application. The selection of power modules for any application is subject to the consideration of voltage rating, current carrying capacity (under realizable cooling conditions and with reference to the switching frequency) and safe operating areas (SOA).

The maximum continuous collector current I_c, indicated in the datasheets as typical currents for module designation and as maximum ratings may be calculated for a stationary fully controlled IGBT-module at a case temperature, T_{case}, according to the following formula [2].

$$I_c = \frac{\left(T_{j(\max)} - T_{case}\right)}{\left(V_{CEsat} \times R_{thjc}\right)}$$

Where

T_{case}	=	Case temperature
T_j	=	Junction temperature
V_{CEsat}	=	Collector Emitter saturation voltage
R_{thjc}	=	Thermal resistance, junction to case

3.1.1.1 Fault currents

Fault currents are collector currents, which exceed standard operating values of a certain application due to control or load errors. They might lead to damage of the power semiconductors by the following mechanisms [2, 3, 4, 5]:

- Thermal destruction by high power dissipation
- Dynamic avalanche
- Static or dynamic latch-up

Components used in power electronics must be protected from non-permissible stress in any operational state. In other words, they are not allowed to leave the safe operation areas (SOA) indicated in the datasheets. Operating outside SOAs will cause damage and, therefore, reduce component life. In the worst case, the component might be destroyed immediately.

3.1.1.2 Behaviour of IGBT's during short-circuit conditions

Short circuit is a fault condition that will drive the operation of the IGBT outside its safe operating area [4]. When considering short circuits experienced by IGBT's, two different cases of short circuits have to be distinguished [2, 4, 6].

Short circuit I – Hard Switching Fault (HSF)

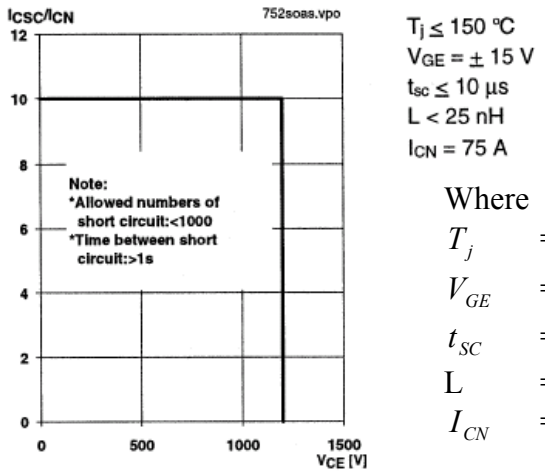
In case of a Hard Switching Fault, the transistor is turned on to an existing short circuit. The IGBT is in the linear mode operation. The rate at which the device begins to conduct current and the magnitude of the fault current are related to the charging rate of the input capacitance and the gate drive voltage. The stationary short-circuit current adjusts itself to a value that is determined by the output characteristic of the transistor. Typical values for IGBTs are up to 8-10 times the rated current.

Short circuit II – Fault Under Load (FUL)

In this case the transistor is already turned on, before the short circuit occurs. The IGBT is operating in the saturated mode. Compared to Hard Switching Fault, this case is much more critical with respect to transistor stress.

Hard Switch faults (HSF) result in much lower fault currents than the fault under load (FUL). Most manufacturers use HSF to quote the short-circuit capability of their devices because this test is less stressful on the device and yields more flattering results [4].

Figure 3.1 is a typical SOA-diagram at short circuit (SC SOA) shown in the IGBT datasheets. This shows the limits for safe control of a short circuit [2]. According to this SOA diagram, an IGBT is capable of delivering up to 10 per unit fault current. But these values are given for a short-circuit duration that is less than $10\,\mu s (t_{sc} \leq 10\mu s)$. There is no possibility of a conventional over-current relay responding in such a brief time interval. We require at least 3 per unit fault current lasting 1-3 seconds to operate existing over-current relays.



Where

T_j = Junction temperature

V_{GE} = Gate Emitter voltage

t_{SC} = Short-circuit duration

L = External collector inductance

I_{CN} = Nominal collector current

Figure 3.1: SOA at short circuit of an NPT-IGBT (SC SOA) - Normalized short-circuit current versus collector-emitter voltage (SKM100GB123D) [2]

According to our findings, the only way to achieve this performance is to increase the rating of the power module. If a fault current in the order of 3 p.u. is required, the rating of the module has to be increased by three times its load rating.

3.1.2 Cost of increasing the rating of a power module

Price/ cost predictions of power modules in general are difficult to make since they tend to be strongly influenced by market forces. We can, with some assumptions, identify trends. The actual cost of a power module is dictated by its current rating because all other things being equal, the cross sectional area of silicon required

increases in proportion to current. Therefore if we neglect the market distortions, the cost of an IGBT should be approximately proportional to its current rating.

According to a study carried out by Williamson, S., et al, [7, 8], 77% of the module cost is for IGBTs and freewheel diodes, which depends mainly on the silicon cross section required. These costs would increase proportionally to the current rating of the module. The bulk of the other costs (gate drive circuit costs, total wire bonding costs, labour and test, factory overheads and materials overheads) could be assumed to be constant for a unit and not change with an increased rating.

Based on these assumptions, the expected variation of actual price of a power module was analytically calculated and plotted [9, 10]. According to this analysis, a module with 3 pu short circuit capability could be achieved at less than three times the original cost. These expected prices are compared with the actual retail prices. Figure 3.2 and Figure 3.3 show the comparison between expected price based on cost and actual price of power modules with voltage ratings of 600V and 1200V respectively.

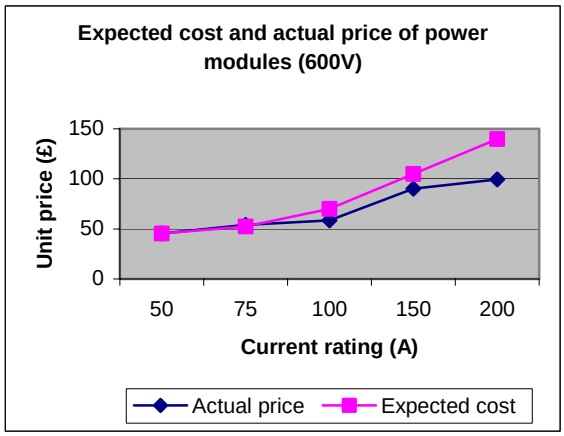


Figure 3.2: Comparison of expected price and actual price of a power module (600V)

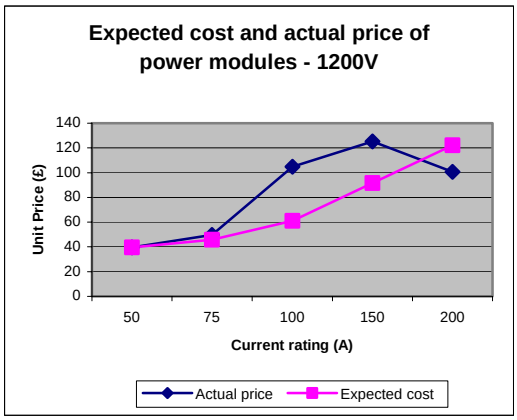


Figure 3.3: Comparison of expected price and actual price of a power module (1200V)

The above two figures clearly indicate that the actual price of a unit does not reflect the expected cost calculated based on the incurred cost. It is quite obvious that economy of scale/ market forces play a major role in the determination of the price of a power module. Although it is evident that we will have to incur a higher cost to install inverters with a higher rating, it is difficult to quote a specific amount at present.

3.2 Fault current distribution in a MicroGrid

The fault current distribution in a MicroGrid for different neutral earthing systems had been investigated in two independent studies. ICCS/ NTUA have carried out this study using the software package EMTP while UMIST have used the specialist grounding software CDEGS for their investigation [11, 12]. The NTUA study is presented in chapter 4 of this report and the UMIST study is presented in the subsequent sections of this chapter.

The most suitable earthing systems for a MicroGrid were identified as TN-C-S, TT and IT in the order of their suitability. The performance of each of these earthing systems in a MicroGrid needs to be further investigated via simulation. The IT system was eliminated as a probable candidate for the MicroGrid earthing as it is so rarely used in practice. Therefore further investigation was carried out only on TN-C-S and TT systems.

A substation grounding system is designed as a path to carry electric currents into the earth under normal and fault conditions and to ensure the safety of a person in the vicinity of the substation. The safety of the design is determined by limiting the step and touch voltages to safe levels for personnel within the substation area. The step and touch voltages are directly proportional to the magnitude of the fault current component discharged directly into the soil by the grounding network. It is therefore important to determine the fault current distribution in the system.

The fault current distribution is dependent on the neutral earthing method of the system (TT or TN). A portion of the fault current would return to its source via the neutral wire in a four-wire system. The current discharged into the substation grounding system is smaller than the maximum available fault current in such a system. Therefore it is required to study how the fault current is distributed between the neutral and the earth in order to calculate the step and touch potentials in and around the substation.

3.2.1 Methodology

A MicroGrid in its simplest form was considered for this study. The main distribution network was assumed to have a short circuit level of 100MVA and a X/R ratio of 5.

The MicroGrid consists of a flywheel (200kW), a single micro source (a micro gas turbine, 3ph, 30 kW) and a single load. The MicroGrid is connected to the main distribution network through a transformer (20/0.4 kV, 400kVA). There are three general faults that could occur in a MicroGrid network. They are a fault on the main distribution network (F1), a fault on the MicroGrid network (F2) and a fault at a load (F3).

A MicroGrid with the above-mentioned faults is shown in Figure 3.4.

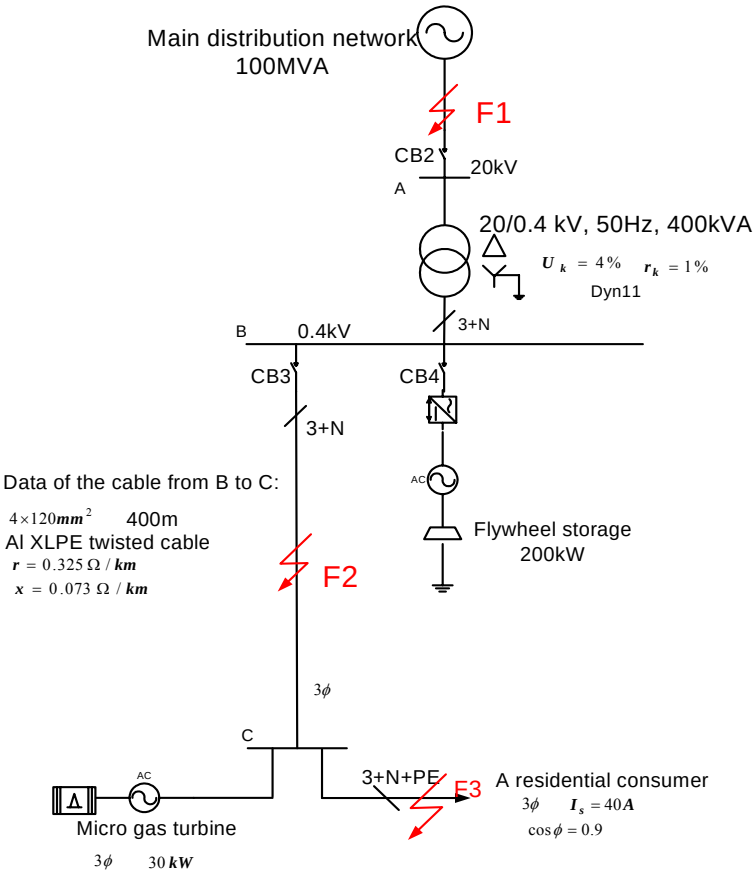


Figure 3.4: A simple MicroGrid model with typical fault locations

The aim of this study is to evaluate the performance of different earthing systems in this MicroGrid. TN-C-S and TT are the two earthing system proposed for the MicroGrid [13].

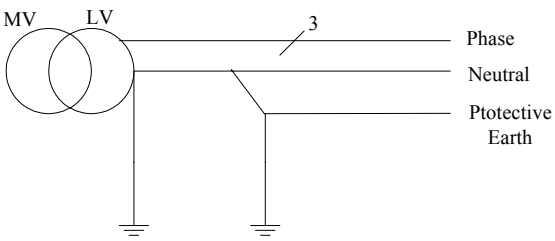


Figure 3.5: TN-C-S system

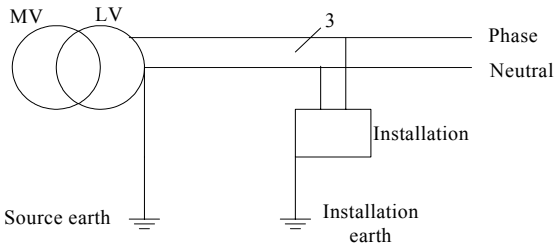


Figure 3.6: TT system

Figure 3.5 shows a TN-C-S system. In this earthing system, the transformer neutral is earthed and the supply feeder consists of a TN-C system, where the neutral conductor and the earth conductor are combined. The earthing arrangement in the installations (consumers) is TN-S, with separate neutral and earth conductors. A TT system is illustrated in Figure 3.6. In a TT system, the transformer neutral and the consumer installation have independent earth electrodes.

Two scenarios (Case 1 and Case 2) of the MicroGrid were investigated. In Case 1, the MicroGrid is connected to the main network. In Case 2, the MicroGrid operates in islanded mode. Three different faults (F1, F2 and F3) were applied to the MicroGrid. A single-phase-to-ground fault was assumed for the study, as this is the most common type of fault likely to occur.

The specialist grounding software, CDEGS, was used for the computer modelling. One of its subsystems, SPLITS, was used as the simulation tool in this particular study to determine the fault current distribution [14, 15]. The simulation data and the CDEGS reports for all the faults described below can be found in the original report on "Fault Current Distribution in a MicroGrid" presented in Appendix VII.

3.2.2 Fault current calculation

When a single-phase-to-earth fault occurs, the fault currents can be calculated using symmetrical components theory. The equivalent circuit for a single-phase-to-earth fault is derived as follows. Figure 3.7 shows a fault circuit with a single-phase-to-earth fault on its phase C.

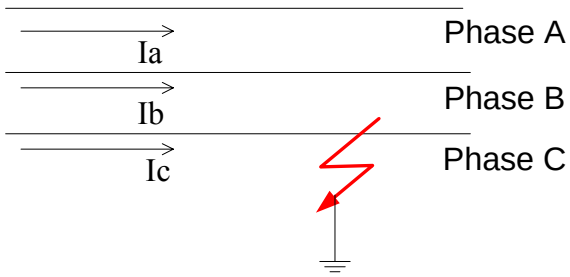


Figure 3.7: The fault circuit (phase C-to-earth fault)

If assumed that the faults are through zero impedance, the equations defining this fault circuit are

$$I_a = 0$$
$$I_b = 0$$
$$V_c = 0$$

The above set of equations can be converted in to sequence quantities as follows [16, 17].

$$\bar{I}_1 = \bar{I}_2 = \bar{I}_0 = \frac{1}{3} * I_c \qquad \text{Equation (3.1)}$$

$$\bar{V} - \bar{I}_1 * \bar{Z}_1 = \bar{I}_2 * \bar{Z}_2 + \bar{I}_0 * \bar{Z}_0 \qquad \text{Equation (3.2)}$$

According to Equation (3.1) and Equation (3.2), the equivalent circuit for a single-phase-to-earth fault can be obtained by connecting the positive, negative and zero sequence networks in series. This equivalent circuit is shown in Figure 3.8.

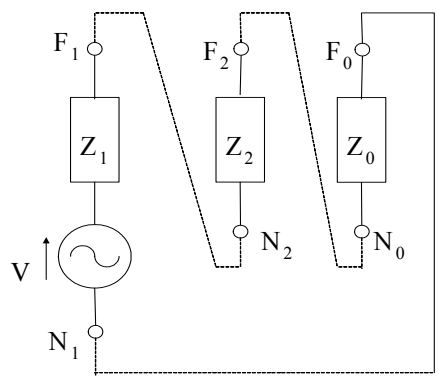


Figure 3.8: The equivalent sequence circuit for a single-phase-to-earth fault

From Figure 3.8, $$\bar{I}_1 = \bar{I}_2 = \bar{I}_0 = \frac{V}{Z_1 + Z_2 + Z_0} \qquad \text{Equation (3.3)}$$

From Equation (3.1) and Equation (3.3), the fault current magnitude

$$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0} \qquad \text{Equation (3.4)}$$

Where

V = Phase to earth voltage

Z_1 = Positive sequence impedance

Z_2 = Negative sequence impedance

Z_0 = Zero sequence impedance

It can be assumed that $Z_1 = Z_2$ for a passive network Equation (3.5)

According to "Protective Relays Application Guide" [17], the zero sequence impedance

$$Z_0 = 3 * Z_N + Z_1 \qquad \text{Equation (3.6)}$$

Where Z_N = the impedance of the earth return path

3.2.2.1 Fault current calculation for a TN-C-S system

The fault current distribution for a TN-C-S system is shown in Figure 3.9. A major portion of the fault current returns to the source through the neutral conductor ($I_{Neutral}$). Only a small fraction of the fault current would be conducted in to the ground (I_{earth}). Thus the main earth return path for a TN system is the neutral conductor.

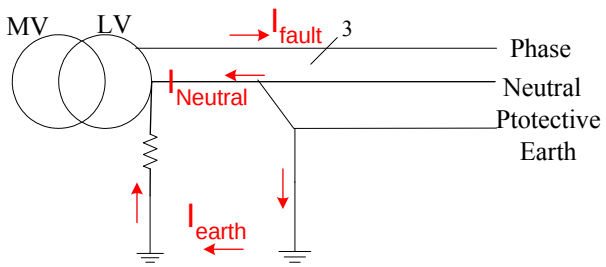


Figure 3.9: Fault current distribution for a TN-C-S system

Therefore the zero sequence impedance for a TN-C-S system is,

$$Z_{0_TN} = 3 * Z_{Neutral} + Z_1 \qquad \text{Equation (3.7)}$$

From Equation (3.4), the fault current magnitude for a single-phase-to-earth fault

$$I_{fault-TN} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

From Equations (3.5) and (3.7), the fault current magnitude for a single-phase-to-earth fault on a TN-C-S system

$$I_{fault-TN} = \frac{V}{Z_{Neutral} + Z_1} \qquad \text{Equation (3.8)}$$

3.2.2.2 Fault current calculation for a TT system

Figure 3.10 shows the fault current distribution for a TT system. The fault current returns to the source through the earth.

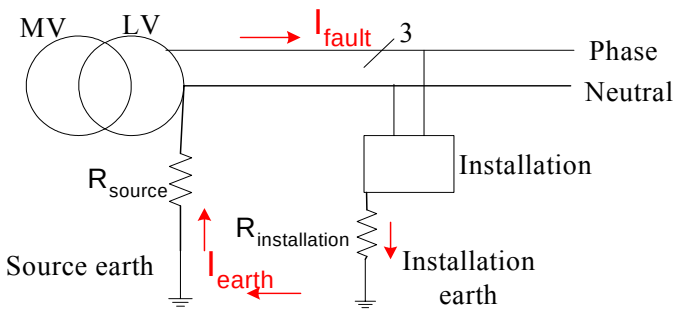


Figure 3.10: Fault current distribution for a TT system

The impedance of the earth return path for this TT system is given by

$$Z_{N_TT} = R_{source} + R_{Installation}$$

Therefore the zero sequence impedance for a TT system is,

$$Z_{0_TT} = 3 * \left(R_{source} + R_{Installation}\right) + Z_1 \qquad \text{Equation (3.9)}$$

From Equations (3.1), (3.2) and (3.6), the fault current magnitude for a single-phase-to-earth fault on a TT system

$$I_{fault-TT} = \frac{V}{R_{source} + R_{Installation} + Z_1} \qquad \text{Equation (3.10)}$$

3.2.3 Grid connected operation

The fault current distribution for the three faults F1, F2 and F3 was investigated when the MicroGrid is interconnected to the main distribution network. A single phase to earth fault was considered in each instance.

3.2.3.1 A fault on the main distribution network – F1

A MicroGrid network with the fault F1 (please refer to Figure 3.4) was simplified as follows. The main distribution network was represented by a voltage source behind a reactance and the primary side of the connection transformer represented the MicroGrid side. This simplified circuit is given in Figure 3.11.

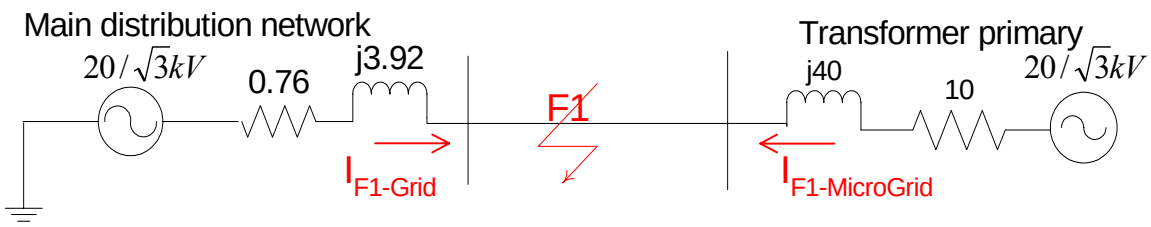


Figure 3.11: The simplified network for a fault on the main distribution network (F1)

Both the main distribution network and the MicroGrid network feed in to the fault. The fault current from the main grid is denoted by $I_{F1-Grid}$, and the fault current contributed by the MicroGrid is $I_{F1-MicroGrid}$.

3.2.3.1.1 Simulation results

The fault current magnitudes were determined by simulating a phase-to-earth fault on the phase C using SPLITS. The total fault current is shown in Figure 3.12 and is equal to 3073 A.

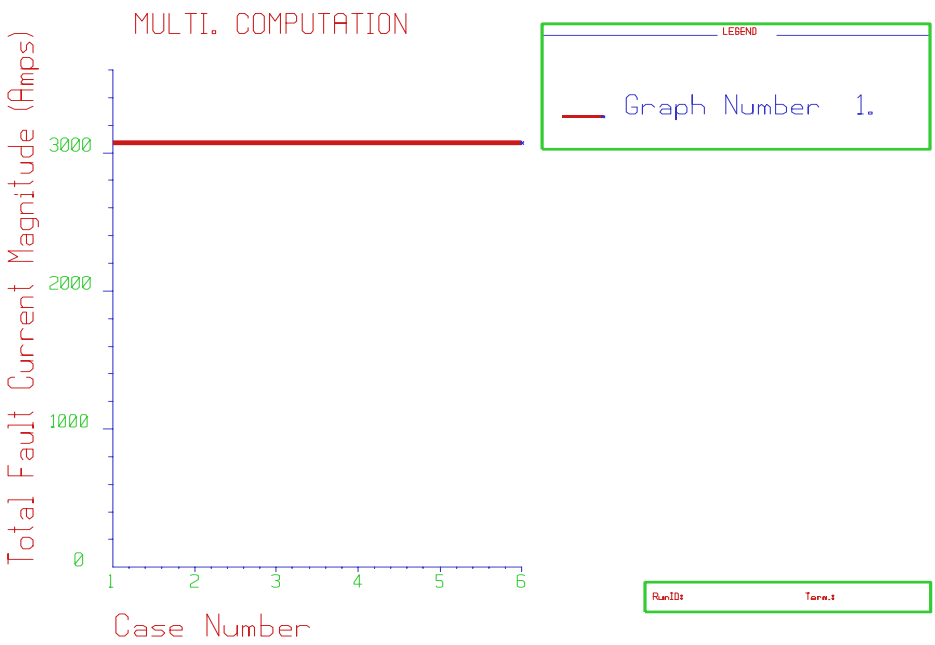


Figure3.12: Total Fault current for a fault on the main grid (F1)

The fault current from the main distribution network $I_{F1-Grid}$ is shown in Figure 3.13 and is approximately equal to 2890A. The fault current contribution from the MicroGrid $I_{F1-MicroGrid}$ is around 180A and is shown in Figure 3.14.

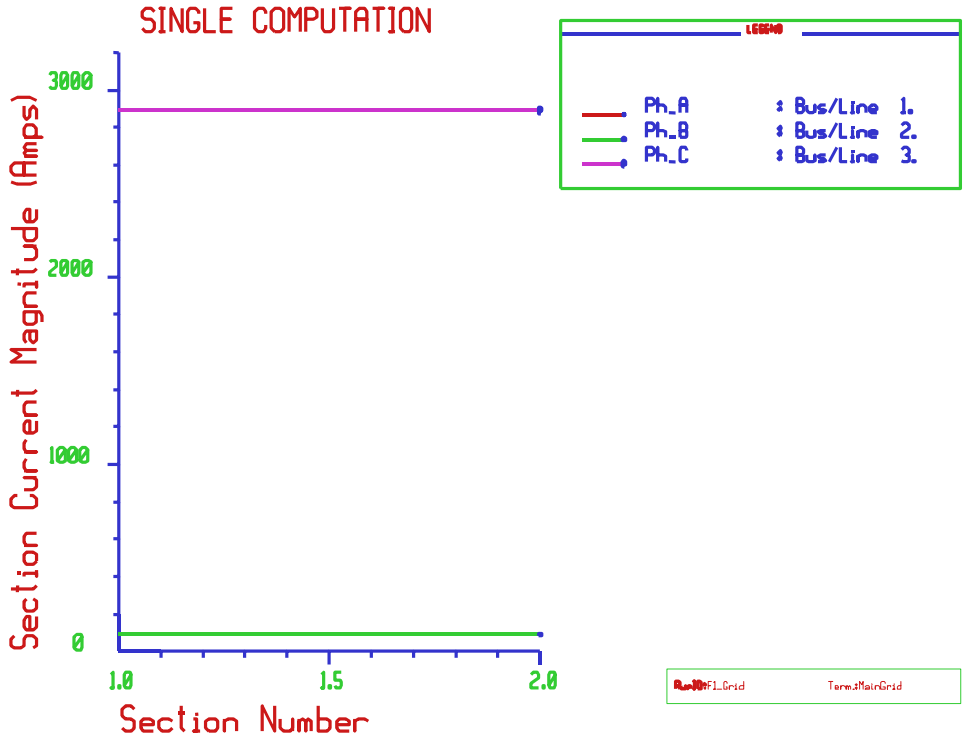


Figure 3.13: Fault current contribution from the main grid for F1

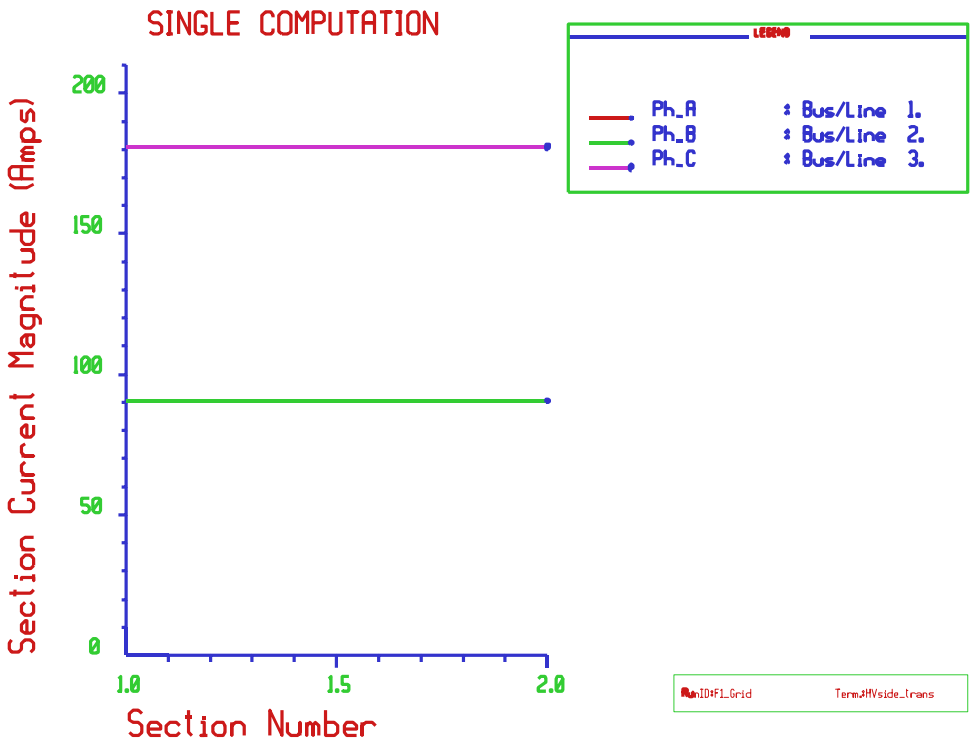
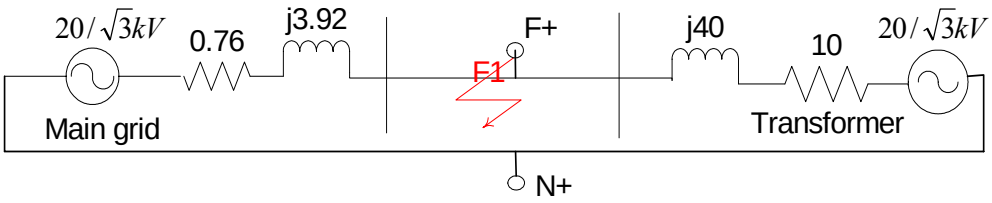


Figure 3.14: Fault current contribution from the MicroGrid for F1

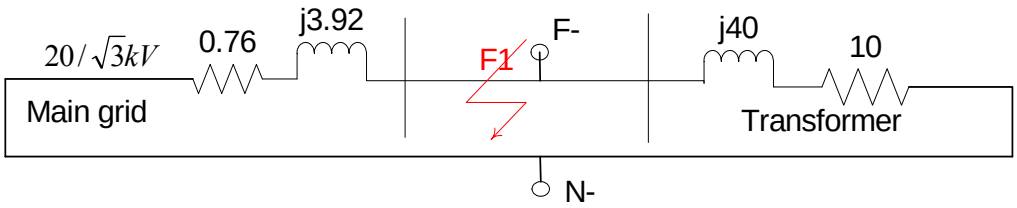
3.2.3.1.2 Manual calculation

Fault calculation presented in section 3.2.2 was based on the assumption of a single fault current source. However there are two fault current sources for F1, F2 and F3. Therefore the theoretical value for each type of fault is calculated separately with the aid of sequence circuits.

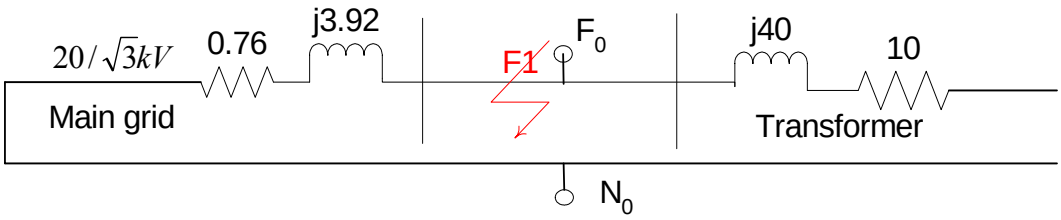
The positive sequence network for F1



The negative sequence network for F1



The zero sequence network for F1



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.76+j\,3.92) \text{ parallel to } (10+j\,40)$$

$$= 3.64 \angle 78.8$$

Assuming that the 20kV neutral is solidly earthed

$$Z_0 = 3*0 + (0.76 + j3.92)$$

From Equation (4), the rms value of the fault current,

$$I_{F1} = 3073\angle -79A \qquad \text{Equation} \quad (3.13)$$

3.2.3.2 A fault on the MicroGrid network – F2

A MicroGrid network with a fault F2 on its network feeder was shown in Figure 3.4. It was assumed that the flywheel converter does not provide any fault current contribution in gird-connected operation. Therefore the only fault current sources for this scenario are the main distribution network and the micro gas turbine connected to the MicroGrid.

Hence a simplified model was obtained as follows. The transformer secondary represented the main grid side and the MicroGrid network consisted of a 400m long feeder and the micro-source at the end of the feeder. The micro-source neutral was unearthed according to the proposed guidelines for earthing in a MicroGrid [13]. The fault F2 was assumed to be at the beginning of the feeder. This simplified network is presented in Figure 3.15. Please note that all the impedances have been calculated at the voltage 0.4 kV.

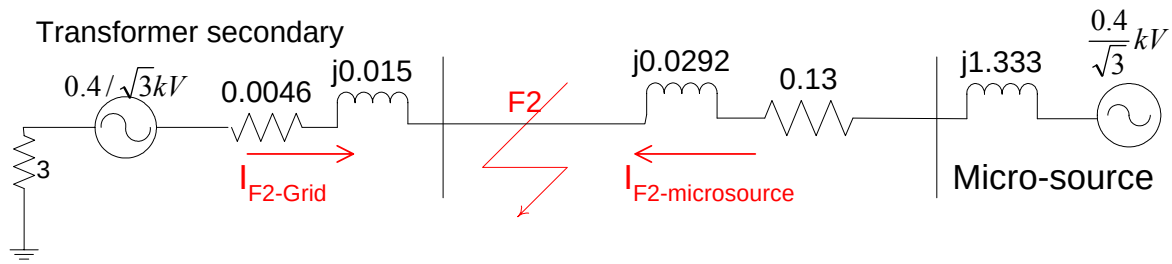


Figure 3.15: The simplified network for a fault on the MicroGrid network – F2

3.2.3.2.1 Simulation results

The fault current magnitudes were determined by simulating a phase-to-earth fault on the phase C using SPLITS. The fault current contribution from the main grid is $I_{F2-Grid}$ and the fault current contribution from the micro-source is $I_{F2-MicroSource}$.

The fault current distribution of a network is mainly determined by its Low Voltage neutral earthing system. Therefore a fault on a MicroGrid network (F2) with a TN-C-S system was simulated first to find out the fault current magnitudes. Then the same fault was modelled in a MicroGrid with a TT system.

TN-C-S system

The total fault current is shown in Figure 3.16 and is equal to 14, 828A at 0.4 kV voltage. The fault currents $I_{F2-Grid-TN}$ and $I_{F2-MicroSource-TN}$ for a fault F2 on a MicroGrid with a TN-C-S earthing system are shown in Figure 3.17 and Figure 3.18 respectively. $I_{F2-Grid-TN}$ is approximately equal to 14, 800A while $I_{F2-MicroSource-TN}$ is just above 110A.

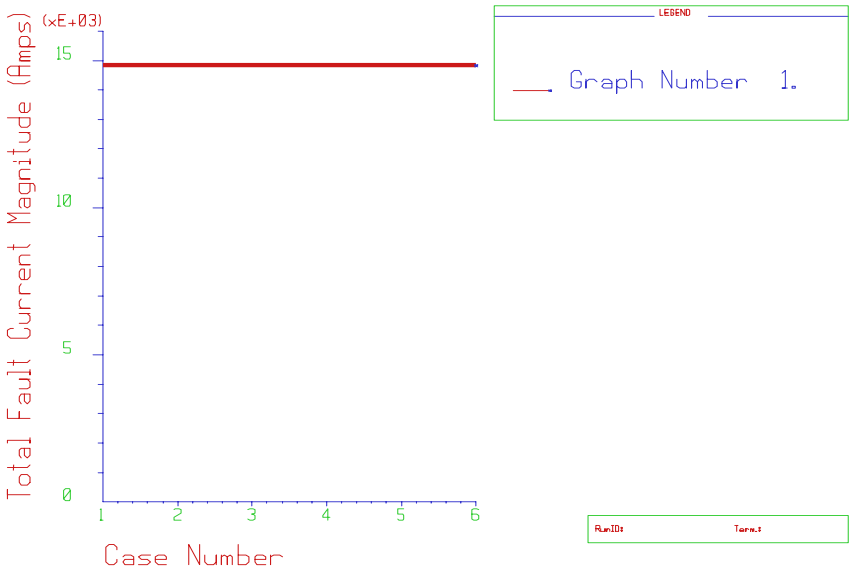


Figure 3.16: Total fault current for a fault on the MicroGrid network, TN system (F2)

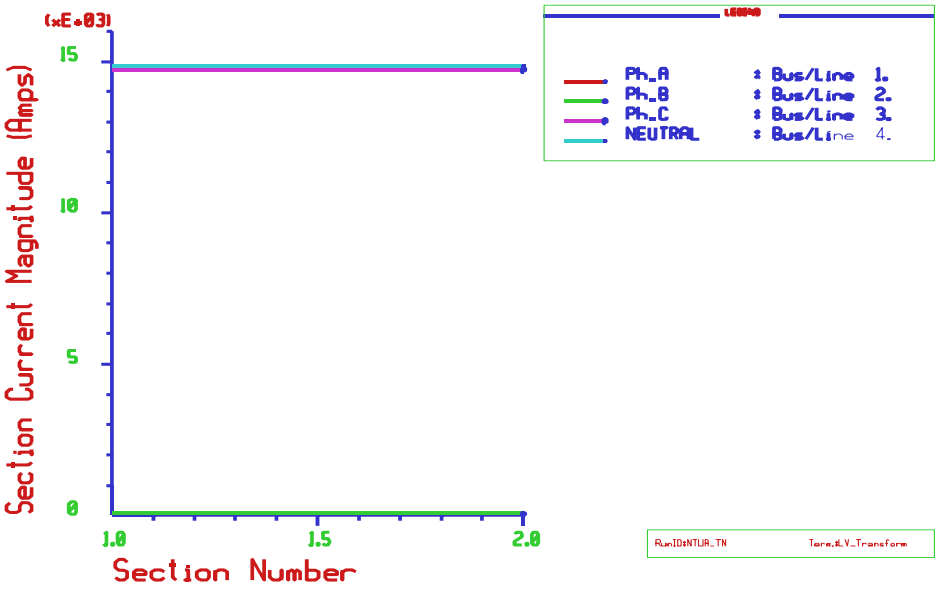


Figure 3.17: Fault current contribution from the main grid for F2, TN system

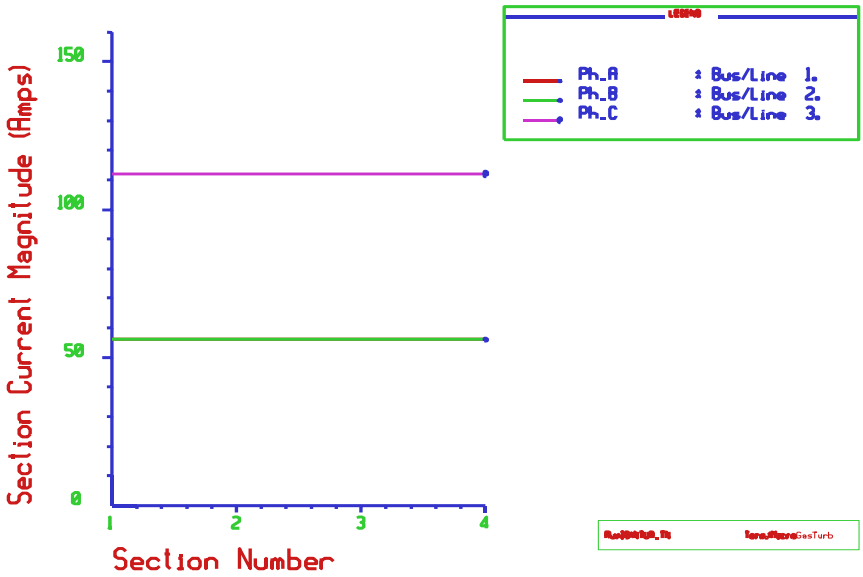


Figure 3.18: Fault current contribution from the micro-source for F2, TN system

TT system

The total fault current is approximately 18A and is shown in Figure3.19.

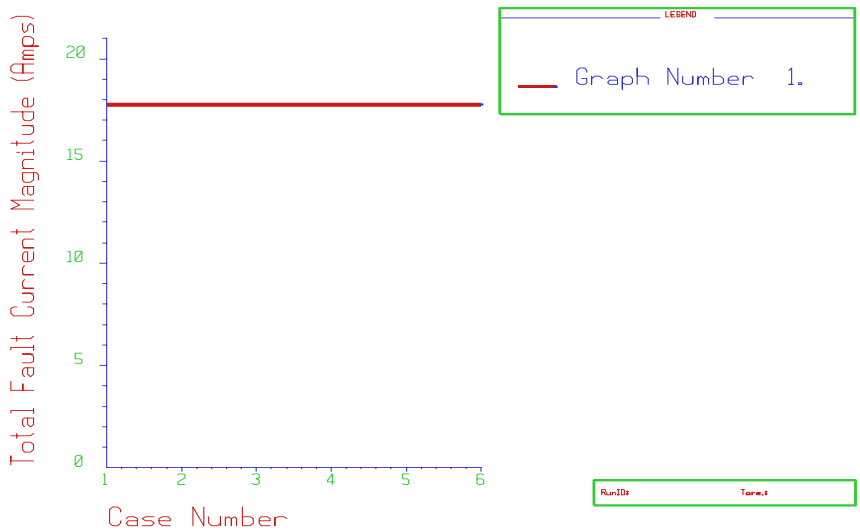


Figure 3.19: Total fault current for a fault on the MicroGrid network, TT system (F2)

The fault currents $I_{F2-Grid-TT}$ and $I_{F2-MicroSource-TT}$ for a fault F2 on a MicroGrid with a TT earthing system are shown in Figure 3.20 and Figure 3.21 respectively. $I_{F2-Grid-TT}$ is approximately equal to 18A while $I_{F2-MicroSource-TT}$ is almost zero.

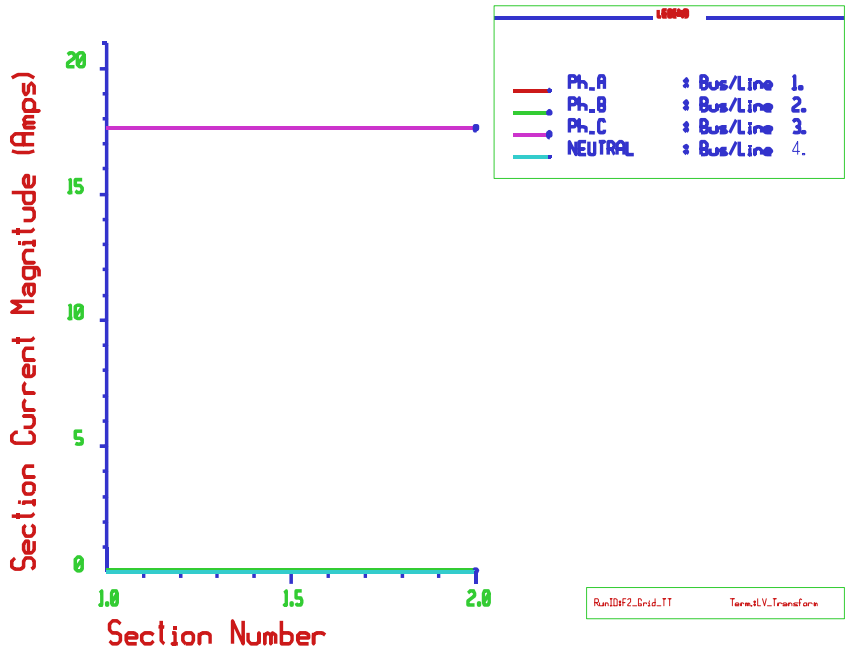


Figure 3.20: Fault current contribution from the main grid for F2, TT system

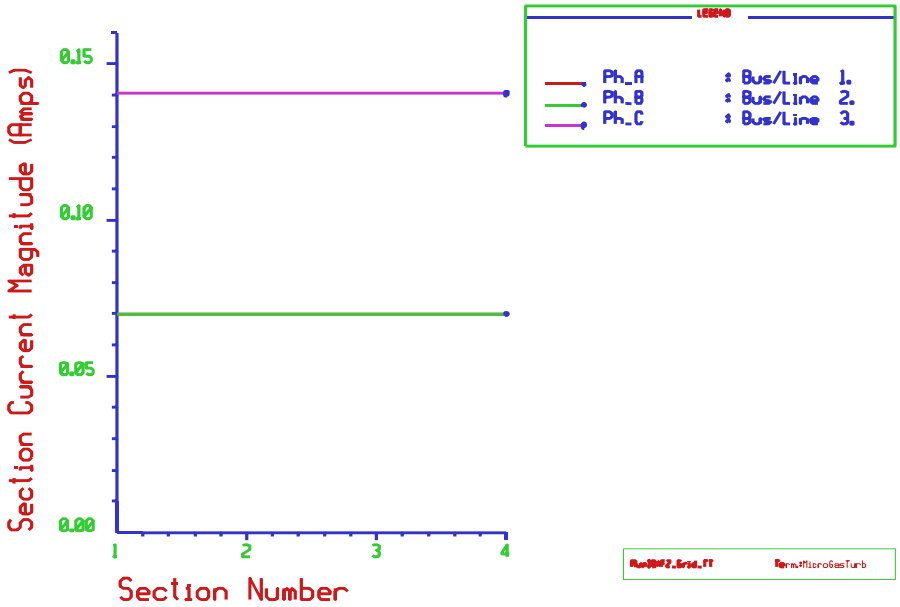


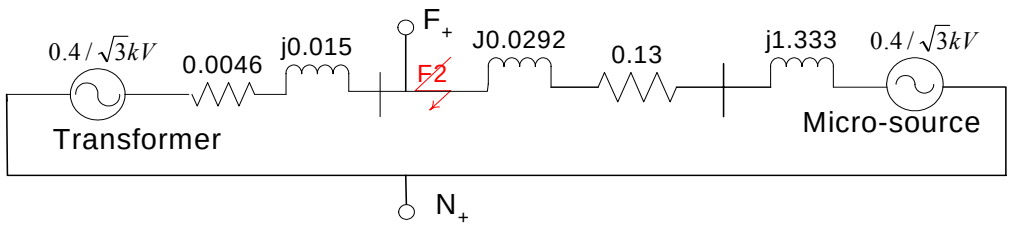
Figure 3.21: Fault current contribution from the micro-source for F2, TT system

3.2.3.2.2 Manual calculation

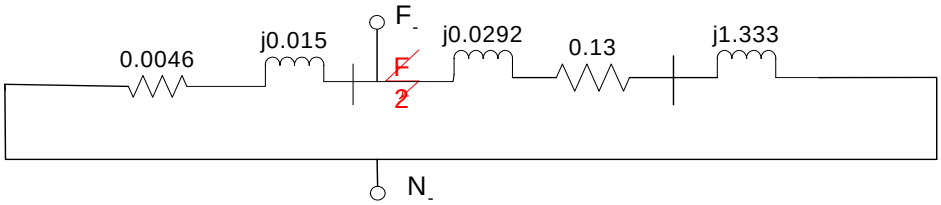
The fault currents for the fault F2 are calculated with the use of sequence networks.

TN-C-S system

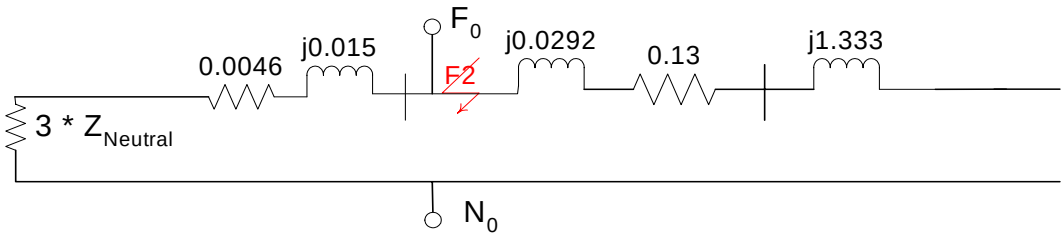
The positive sequence network for F2, TN network at 0.4 kV



The negative sequence network for F2, TN network at 0.4 kV



The zero sequence network for F2, TN network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.0046 + j\,0.015) \text{ parallel to } (0.13 + j\,0.0292 + j\,1.333)$$

$$= 0.0155 \angle 73.08$$

Since F2 is at the beginning of the feeder, $Z_{Neutral} = 0$

$$Z_0 = 3 * 0 + (0.0046 + j0.015)$$

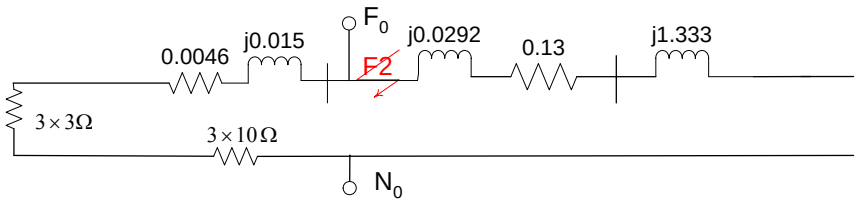
From Equation (3.4), the rms value of the fault current,

$$I_{F2-TN} = 14{,}778 \angle -73.0 A \qquad \text{Equation} \quad (3.14)$$

TT system

The positive sequence network and the negative sequence network for a TT system are identical to the ones for the TN system. However the zero sequence network parameters change according to the TT earthing method.

The zero sequence network for F2, TT network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.0046 + j\,0.015) \text{ parallel to } (0.13 + j\,0.0292 + j\,1.333)$$

$$= 0.0155 \angle 73.08$$

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance, $Z_0 = 3*(10+3)+(0.0046+j0.015)$

From Equation (3.4), the rms value of the fault current,

$$I_{F2-TT} = 18\angle 0A \qquad \text{Equation (3.15)}$$

3.2.3.3 A fault at a load – F3

The fault F3 occurs at a load in the MicroGrid. It is assumed that this load is located at the end of the MicroGrid feeder as shown in Figure 3.4. The fault current sources for this scenario are the main distribution network and the micro gas turbine because it is assumed that the flywheel is not providing any fault currents. Therefore a simplified model was obtained with the transformer secondary representing the main grid side and the MicroGrid network consisting of a 400m long feeder with a micro-source at the end of it. This simplified network is given in Figure 3.22.

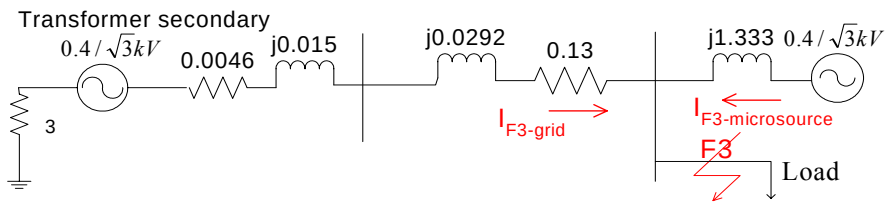


Figure 3.22: The simplified network for a fault at a load in the MicroGrid – F3

The fault current contribution from the main grid is $I_{F3-Grid}$ and the fault current contribution from the micro-source is $I_{F3-MicroSource}$. All the impedances are specified at 0.4 kV voltage.

3.2.3.3.1 Simulation results

The fault current magnitudes were determined by simulating a phase-to-earth fault on the phase C using SPLITS. The fault F3 was simulated on a MicroGrid network with a TN-C-S system and thereafter on a MicroGrid with a TT system to determine the fault current distribution.

TN-C-S system

The total fault current for the fault F3 in a MicroGrid with TN-C-S earthing system is shown in Figure 3.23 and is equal to 858A at 0.4kV.

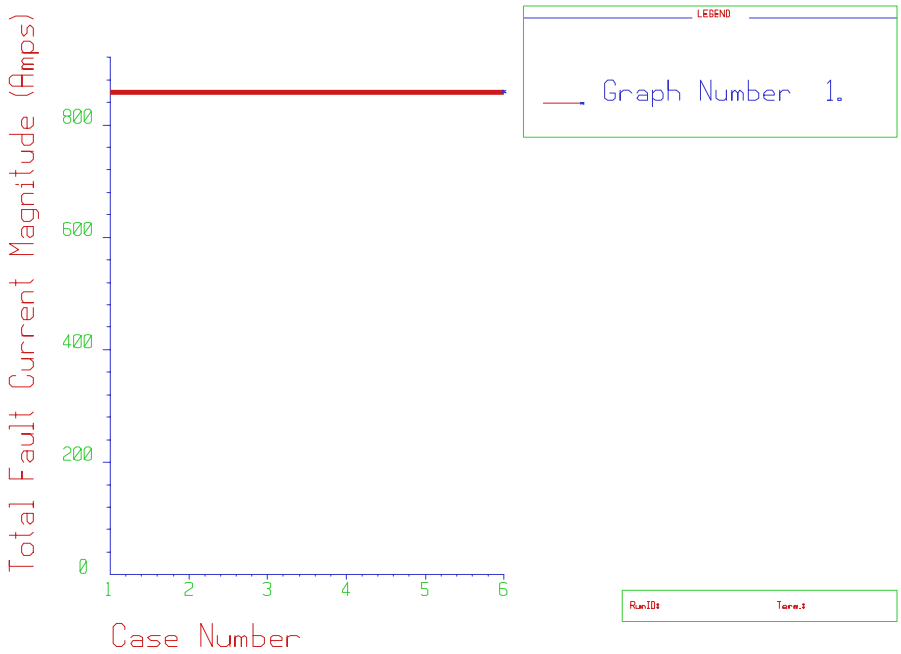


Figure 3.23: Total fault current for a fault at a load (F3), TN system

The fault currents $I_{F3-Grid-TN}$ and $I_{F3-MicroSource-TN}$ for a fault F3 on a MicroGrid with a TN-C-S earthing system are shown in Figure 3.24 and Figure 3.25 respectively. The fault current contribution from the main grid, $I_{F3-Grid-TN}$ is approximately equal to 840 A while the fault current from the micro-source, $I_{F3-MicroSource-TN}$ is just below 60A.

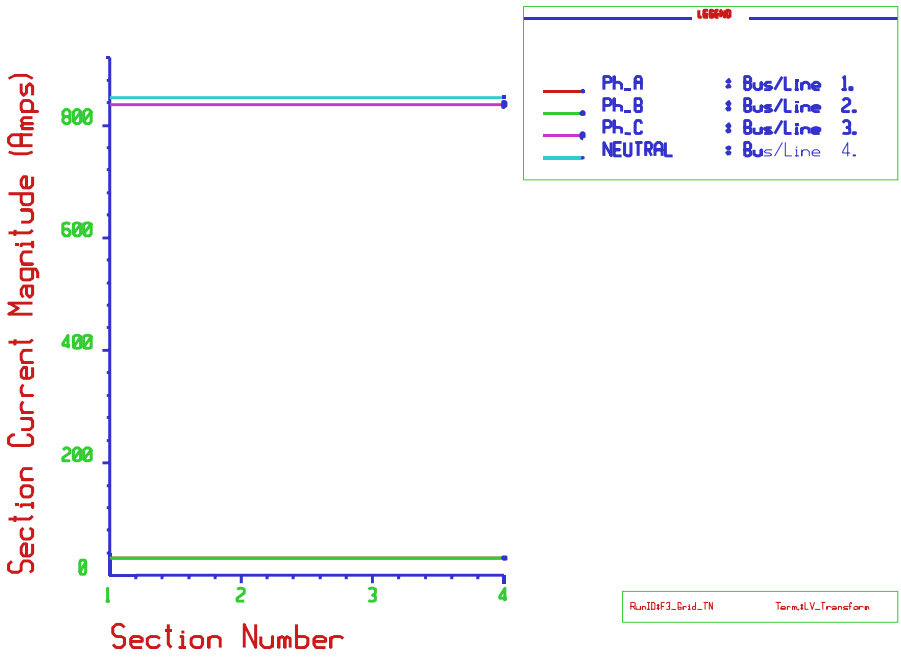


Figure 3.24: Fault current contribution from the main grid side for F3, TN system

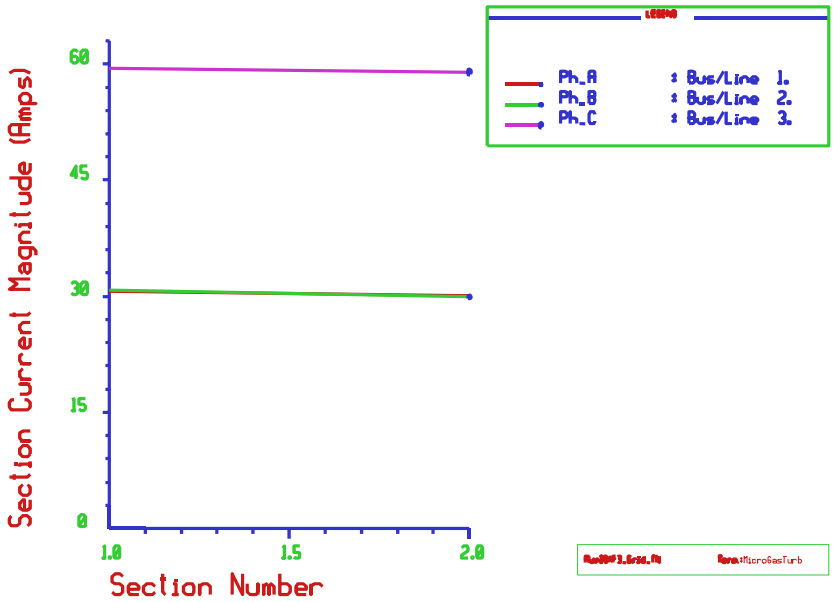


Figure 3.25: Fault current contribution from the micro-source for F3, TN system

TT System

The total fault current for the fault F3 on a TT system is shown in Figure 3.26 and is around 18A. The fault currents $I_{F3-Grid-TT}$ and $I_{F3-MicroSource-TT}$ are shown in Figure

3.27 and Figure 3.28 respectively. $I_{F3-Grid-TT}$ is approximately 17A while $I_{F3-MicroSource-TT}$ is around 1.2 A.

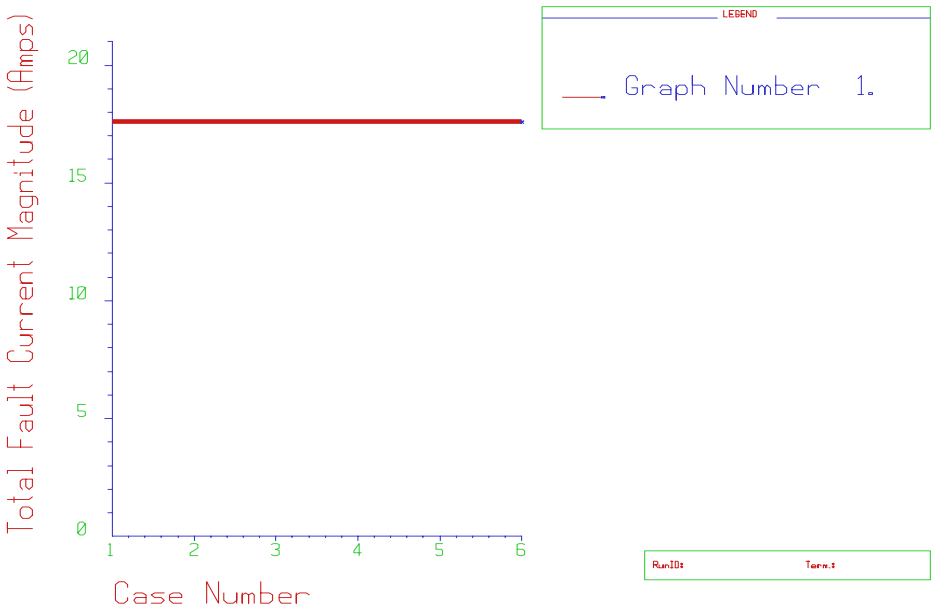


Figure 3.26: Total fault current for a fault at a load (F3), TT system

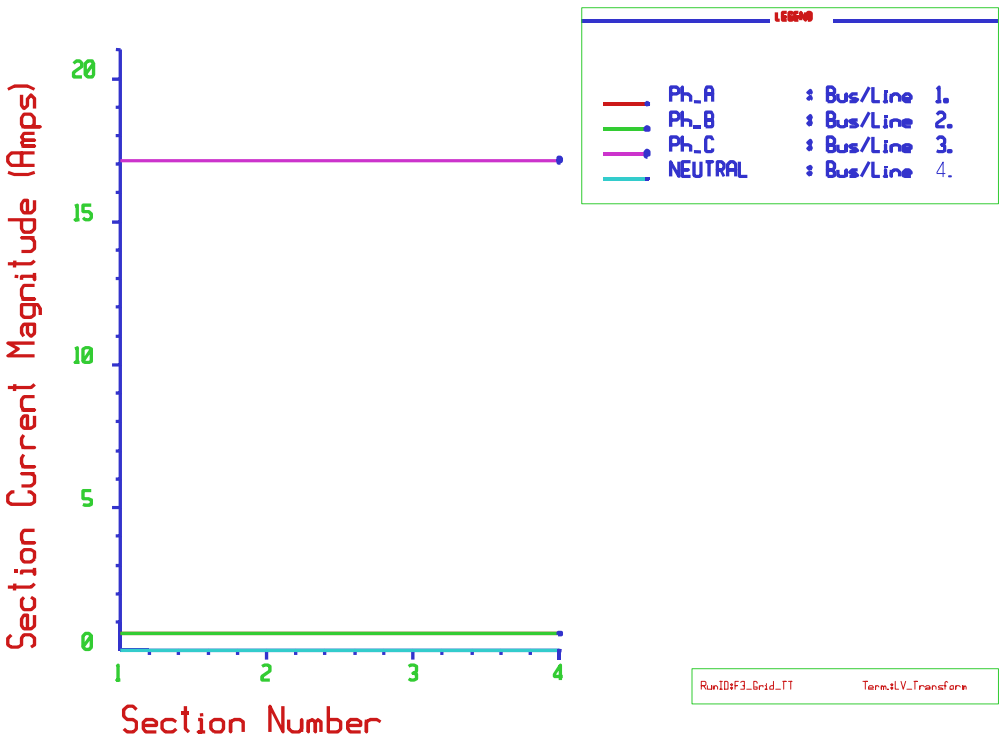


Figure 3.27: Fault current contribution from the main grid side for F3, TT system

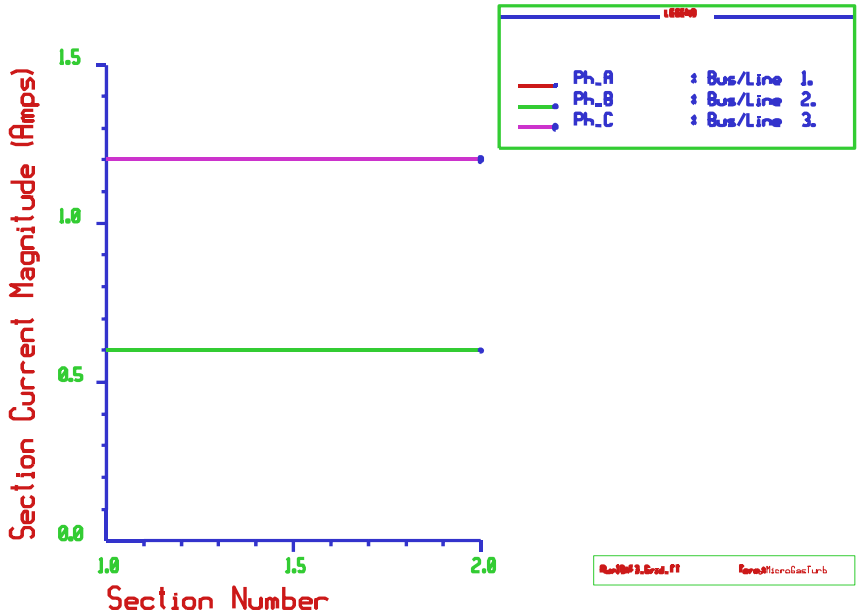


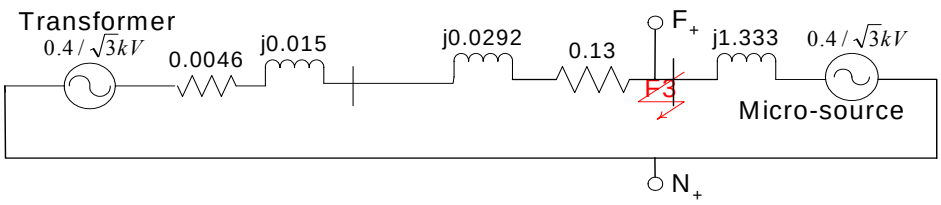
Figure 3.28: Fault current contribution from the micro-source for F3, TT system

3.2.3.3.2 Manual calculation

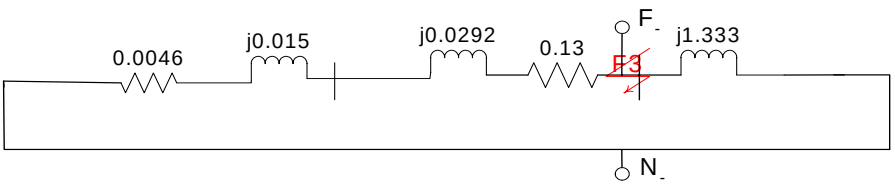
The fault currents for the fault F3 are calculated with the use of sequence networks.

TN-C-S system

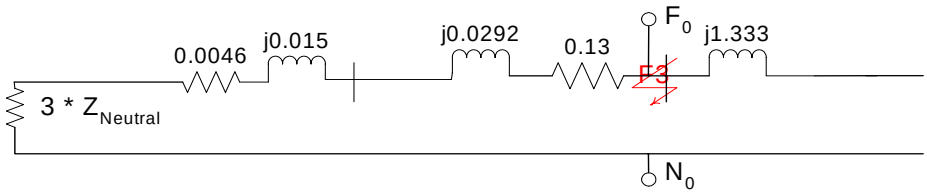
The positive sequence network for F3, TN network at 0.4 kV



The negative sequence network for F3, TN network at 0.4 kV



The zero sequence network for F3, TN network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.1346 + j\,0.0442) \text{ parallel to } (j\,1.333)$$

$$= 0.1319 \angle 27.8$$

Since F3 is at the end of the feeder, $Z_{Neutral} = (0.13 + j0.0292)$

$$Z_0 = 3 * (0.13 + j0.0292) + (0.1346 + j0.0442)$$

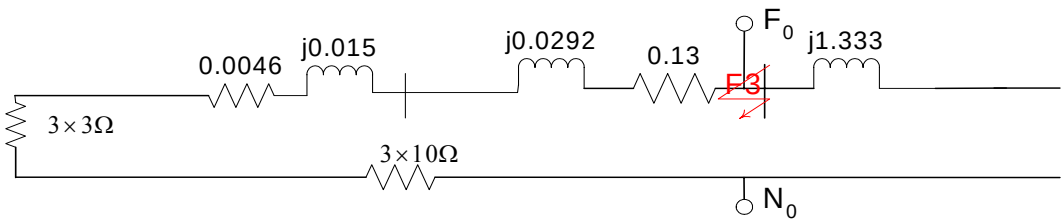
From Equation (3.4), the rms value of the fault current,

$$I_{F3-TN} = 863.8 \angle -18.6 A \qquad \text{Equation (3.16)}$$

TT system

The positive sequence network and the negative sequence network for the fault F3 remain the same as for those in the TN system. However the zero sequence network parameters change according to the TT earthing method.

The zero sequence network for F3, TT network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.1346 + j\,0.0442) \text{ parallel to } (j\,1.333)$$

$$= 0.1319 \angle 27.8$$

Consumer installation earth resistance is = 10 ohms. Then the zero sequence impedance, $Z_0 = 3 * (10 + 3) + (0.1346 + j0.0442)$

From Equation (3.4), the rms value of the fault current,

$$I_{F3-TT} = 17.53 \angle -0.2 A \qquad \text{Equation (3.17)}$$

3.2.4 Islanded operation

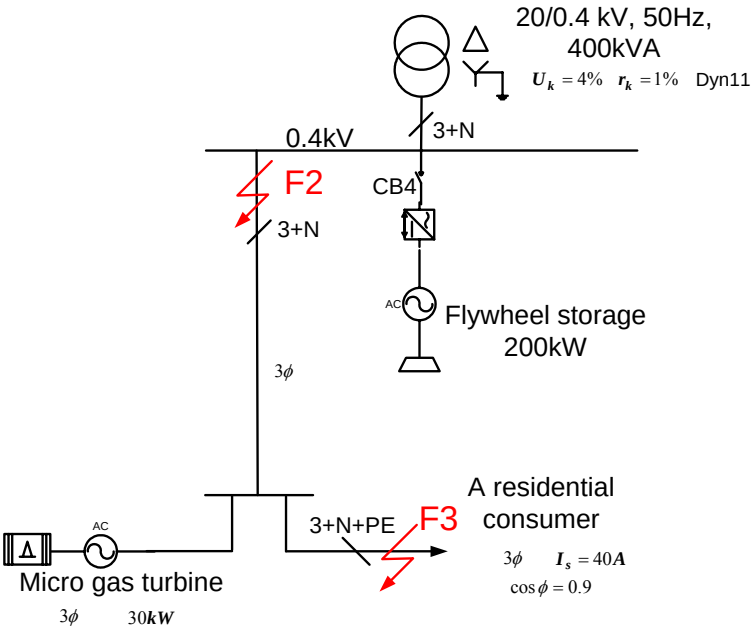


Figure 3.29: Faults F2 and F3 on the MicroGrid network for islanded operation

A MicroGrid network with the faults F2 and F3 in islanded operation is shown in Figure 3.29. According to the proposed control schemes for a MicroGrid, if a fault occurs on the main distribution network, the MicroGrid will continue to operate in an island by opening the circuit breaker upstream of the main distribution transformer [13, 18]. Therefore the MicroGrid would not lose the source earth at the distribution transformer in islanded operation. The flywheel is connected to the 0.4kV bus bar and CB4 is kept closed during islanded operation. The flywheel is considered as the main fault current source in the event of a fault in an islanded MicroGrid and provides either 3 per unit or 5 per unit of its rated current under fault conditions.

3.2.4.1 A fault on the MicroGrid network – F2

The flywheel acts as the main source of fault current and the transformer earth impedance, 3 ohms, is retained in the system. The fault current sources for this scenario are the flywheel and the micro gas turbine. Therefore a simplified model was obtained as shown in Figure 3.30. The flywheel parameters are given for the case where it provides 3 p.u fault current and it was assumed that the flywheel operates with unity power factor. All impedances are specified at 0.4kV voltage.

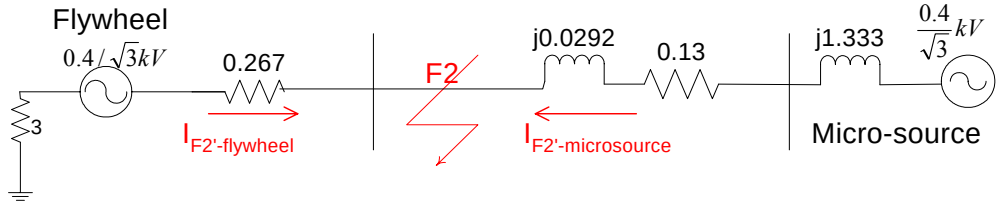


Figure 3.30: The islanded network for a fault on the MicroGrid network – F2

The MicroGrid network consists of a 400m long feeder and the micro-source at the end of the feeder. The micro-source neutral is unearthed according to the proposed guidelines for earthing in a MicroGrid [13]. The fault F2 is assumed to be at the beginning of the feeder.

3.2.4.1.1 Simulation results

The above network was modelled in SPLITS with TN and TT as the earthing system. The fault current magnitudes were determined by simulating a phase-to-earth fault on the phase C. The flywheel was assumed to provide 3 p.u. fault current. The fault current contribution from the flywheel is denoted by $I_{F2'-flywheel}$ and the fault current contribution from the Micro-source is $I_{F2'-MicroSource}$.

TN-C-S system

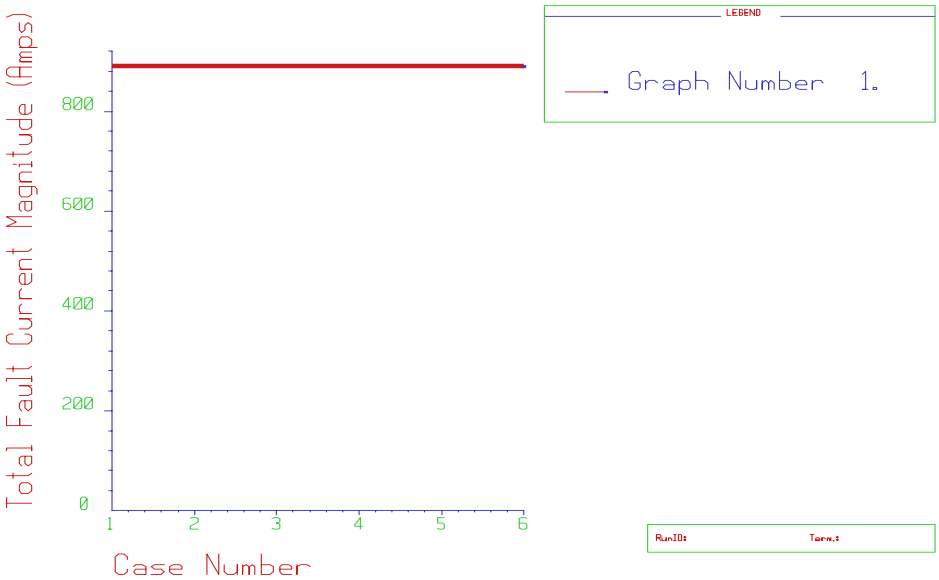


Figure 3.31: Total fault current for fault F2 in islanded operation, TN network

The total fault current is 889.5A and is shown in Figure 3.31. The fault currents $I_{F2'-flywheel-TN}$ and $I_{F2'-MicroSource-TN}$ for a fault F2 on an islanded MicroGrid with a TN-C-S earthing system are shown in Figure 3.32 and Figure 3.33 respectively. $I_{F2'-MicroSource-TN}$ is approximately 860A and $I_{F2'-MicroSource-TN}$ is about 112A.

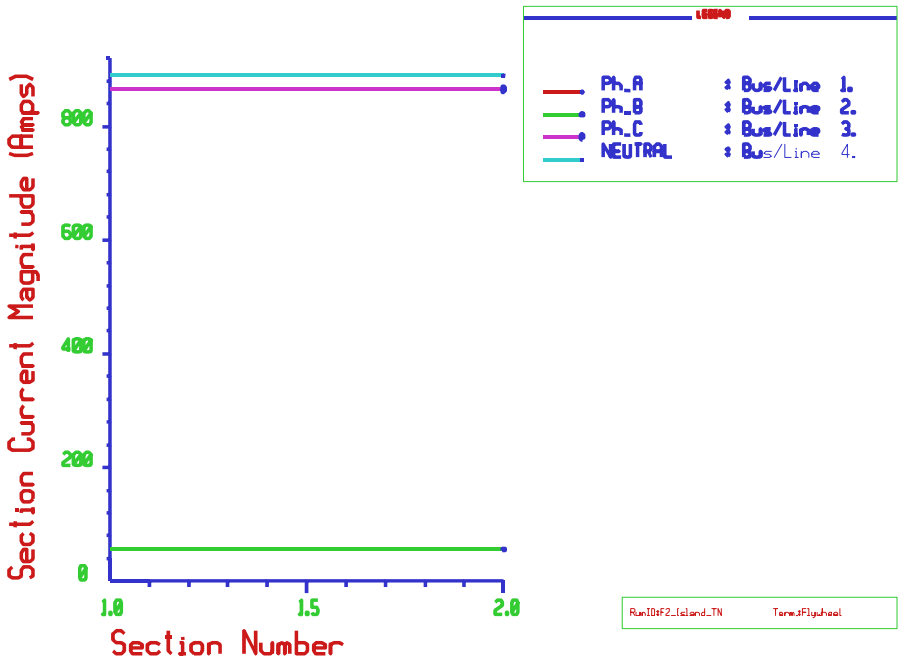


Figure 3.32: Fault current contribution from the flywheel for F2, islanded, TN

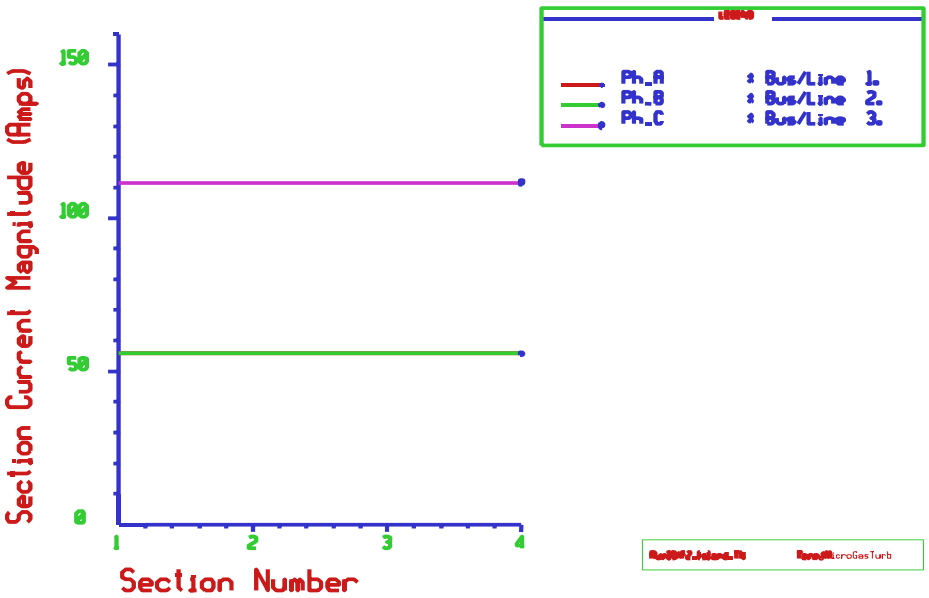


Figure 3.33: Fault current contribution from the micro-source for F2, islanded, TN

TT system

The total fault current is around 17A and is shown in Figure 3.34. Figure 3.35 and Figure 3.36 show the fault currents provided by the flywheel and the micro-source for a fault F2 on an islanded MicroGrid with a TT earthing system. The fault current from the flywheel is approximately 17A and the fault current contribution from the micro gas turbine is around 2A.

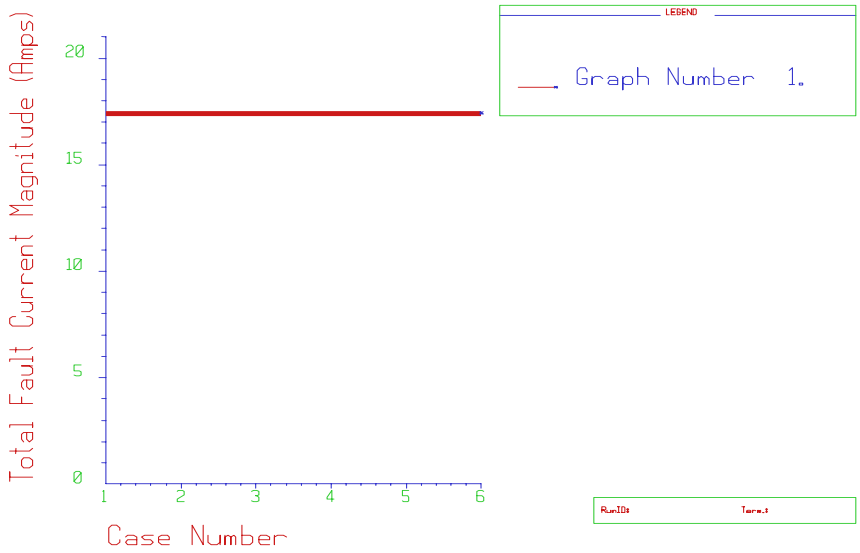


Figure 3.34: Total fault current for fault F2 in islanded operation, TT network

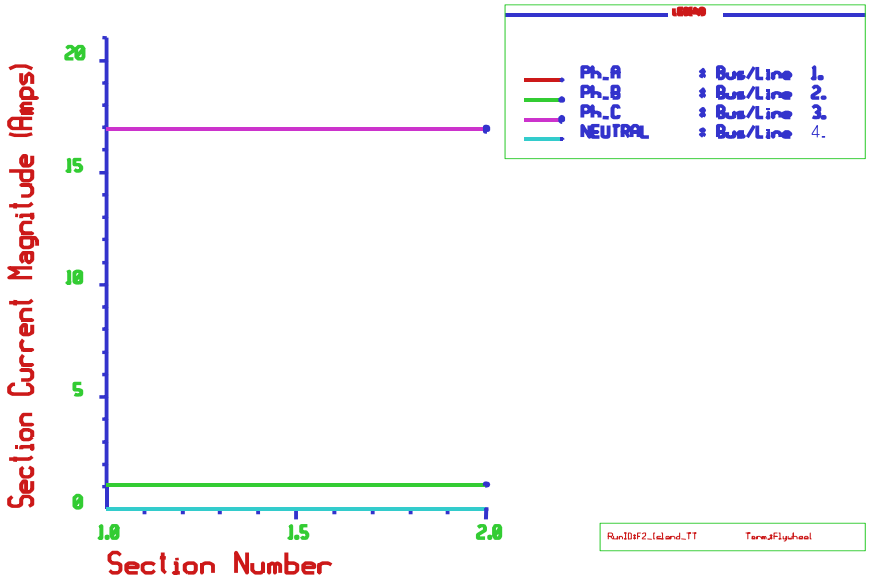


Figure 3.35: Fault current contribution from the flywheel for F2, islanded, TT

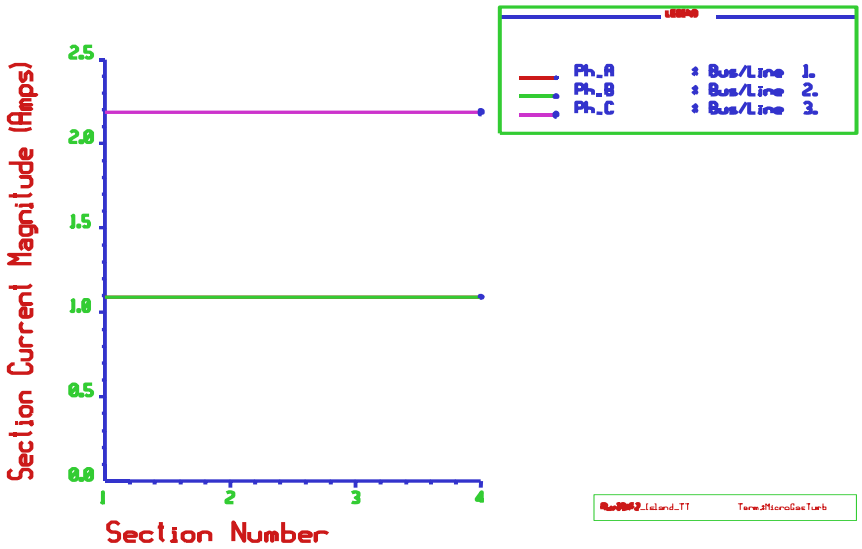


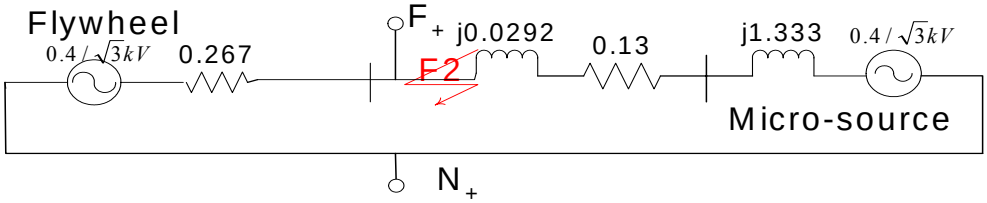
Figure 3.36: Fault current contribution from the micro-source for F2, islanded, TT

3.2.4.1.2 Manual calculations

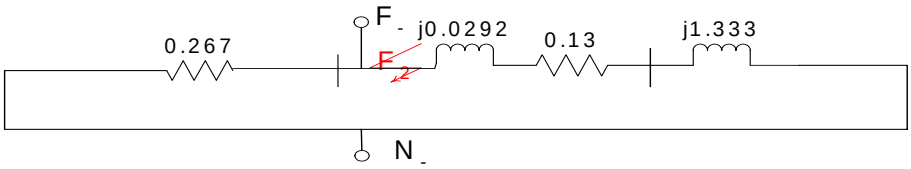
The fault currents for the fault F2 in islanded operation are calculated in this section. The same approach taken for grid-connected operation is carried out with the use of sequence networks.

TN-C-S system

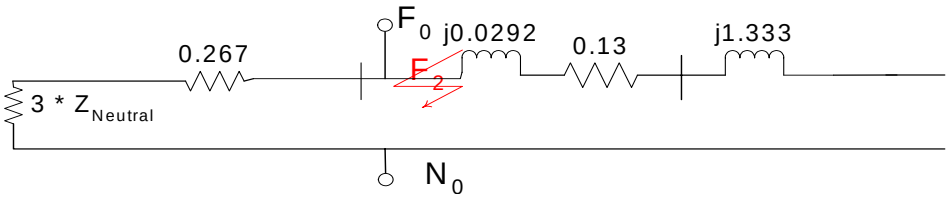
The positive sequence network for F2, islanded, TN at 0.4 kV



The negative sequence network for F2, islanded, TN at 0.4 kV



The zero sequence network for F2, islanded, TN at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.267) \text{ parallel to } (0.13 + j\,1.3622)$$

$$= 0.257 \angle 10.8$$

Since F2 is at the beginning of the feeder, $Z_{Neutral} = 0$

$$Z_0 = 3 * 0 + (0.267)$$

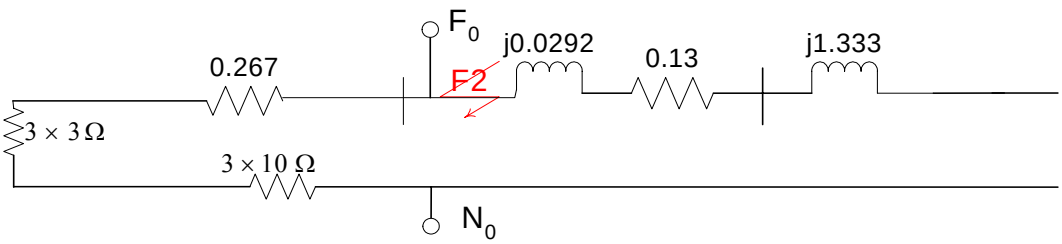
From Equation (3.4), the rms value of the fault current,

$$I_{F2'-TN} = 886.9 \angle -7.0 A \qquad \text{Equation} \quad (3.18)$$

TT system

The positive sequence network and the negative sequence network remain the same as for that in the TN system. However the zero sequence network parameters change according to the TT earthing method.

The zero sequence network for F2, islanded, TT at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.267) \text{ parallel to } (0.13 + j\,1.3622)$$

$$= 0.257 \angle 10.8$$

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance,

$$Z_0 = 3 * (10 + 3) + (0.267)$$

$$Z_0 = 39.267$$

From Equation (3.4), the rms value of the fault current,

$$I_{F2'-TT} = 17.35 \angle 0 A \qquad \text{Equation (3.19)}$$

3.2.4.2 A fault at a load – F3

The fault F3 occurs at a load located at the end of the MicroGrid feeder (please refer to Figure 3.29). The fault currents are fed in to the fault by the flywheel and the micro gas turbine. A simplified network of the above MicroGrid is shown in Figure 3.36 where it is assumed that the flywheel provides 3 p.u of its rated current for a fault at unity power factor.

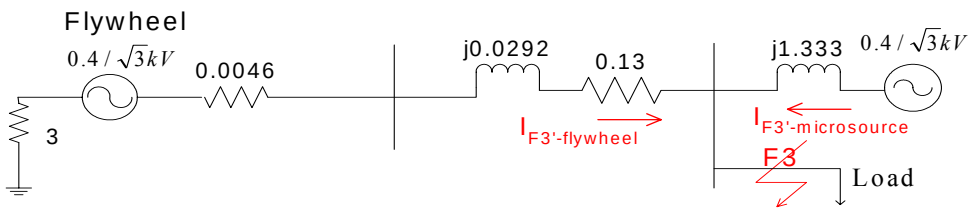


Figure 3.36: Simple network for fault at a load in an islanded MicroGrid

3.2.4.2.1 Simulation results

The fault current magnitudes were determined for a single-phase-to-earth fault on the phase C of the above system. The flywheel was assumed to provide 3 pu fault current. Two cases of the system were simulated, one with TN-C-S earthing and the other with TT earthing. The fault current contribution from the flywheel is denoted by $I_{F3'-flywheel}$ and the fault current contribution from the micro-source is $I_{F3'-MicroSource}$.

TN-C-S system

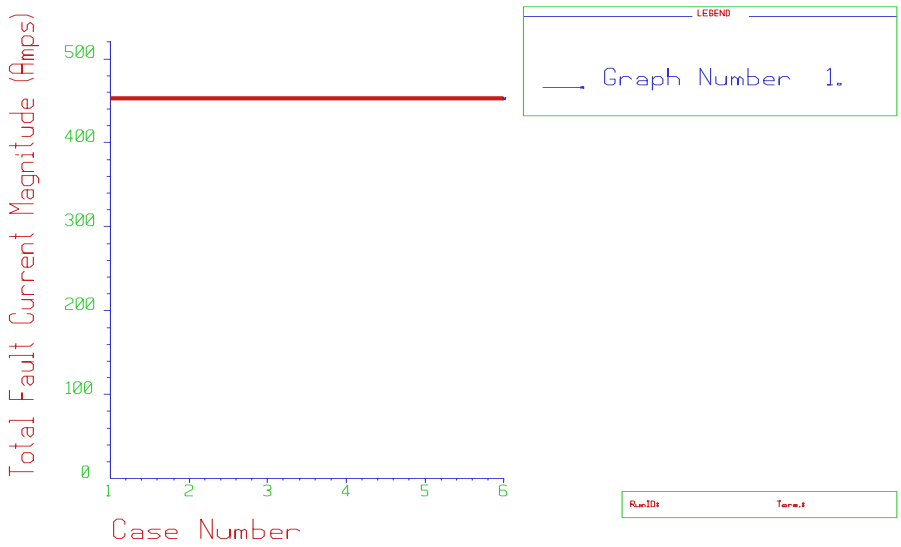


Figure 3.37: Total fault current for a fault at a load in an islanded MicroGrid, TN

The total fault current for the fault F3 in a TN system in islanded operation is about 453A and is illustrated in Figure 44. The fault current from the flywheel $I_{F3'-flywheel-TN}$ is shown in Figure 45 and is approximately equal to 430A. The fault current from the micro gas turbine $I_{F3'-MicroSource-TN}$ is around 85A as shown in Figure 46.

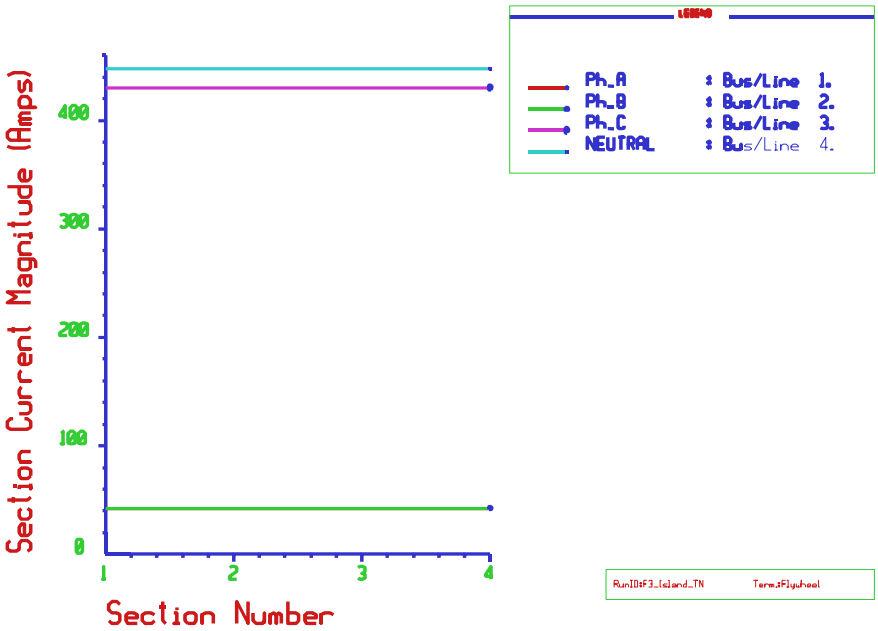


Figure 3.38: Fault current contribution from the main grid side for F3, islanded, TT

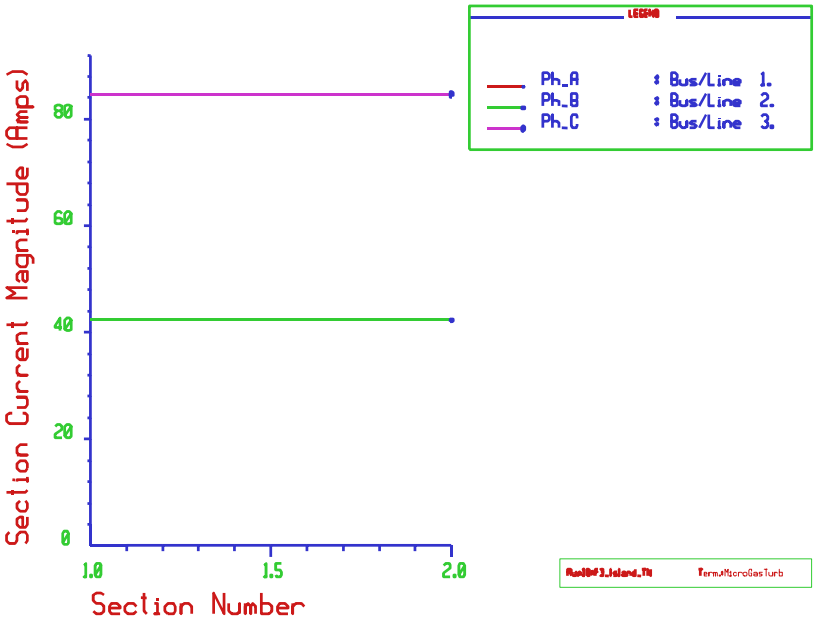


Figure 3.39: Fault current contribution from the micro-source for F3, islanded, TN

TT system

The total fault current for the fault F3 in a TT system in islanded operation is approximately 17A, as shown in Figure 3.40. The fault currents $I_{F3'-flywheel-TT}$ and $I_{F3'-MicroSource-TT}$ for a fault F3 on an islanded MicroGrid with a TT neutral earthing system are shown in Figure 48 and Figure 49 respectively.

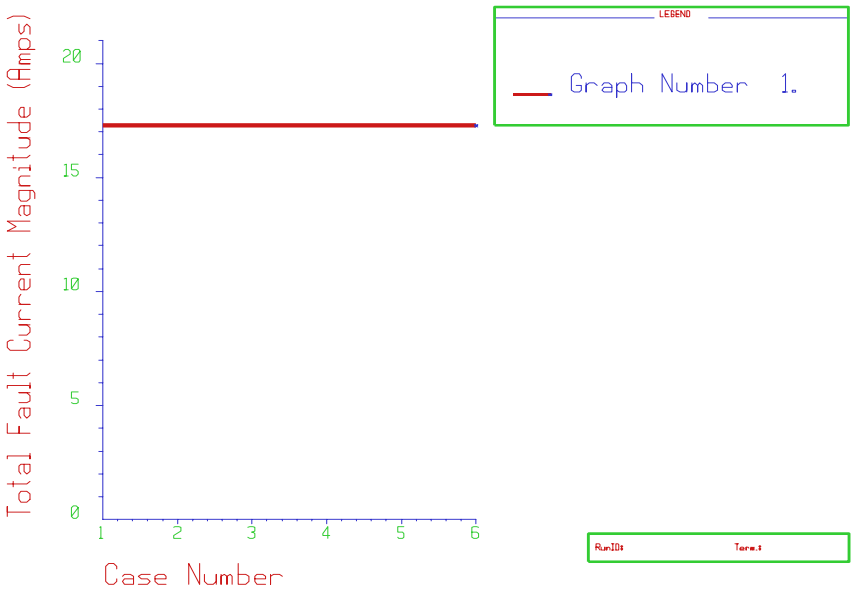


Figure 3.40: Total fault current for a fault at a load in an islanded MicroGrid, TT

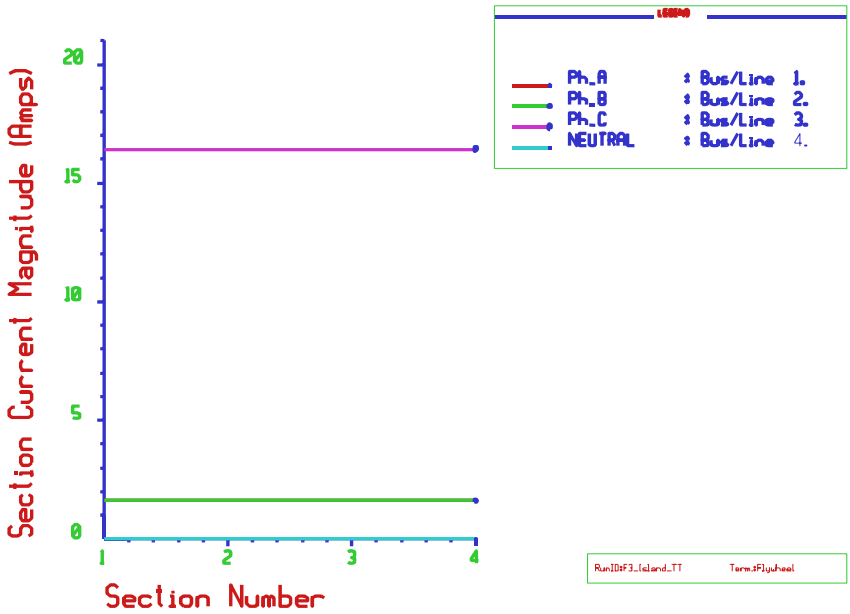


Figure 3.41: Fault current contribution from the main grid side for F3, islanded, TT

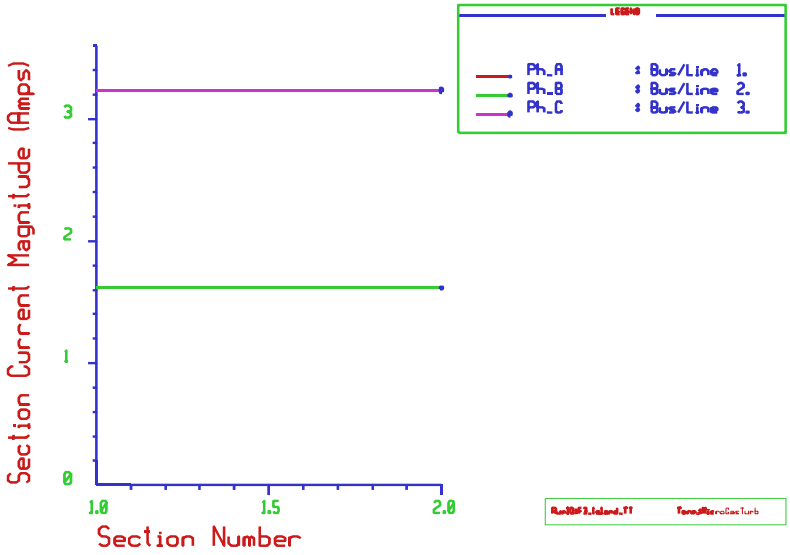


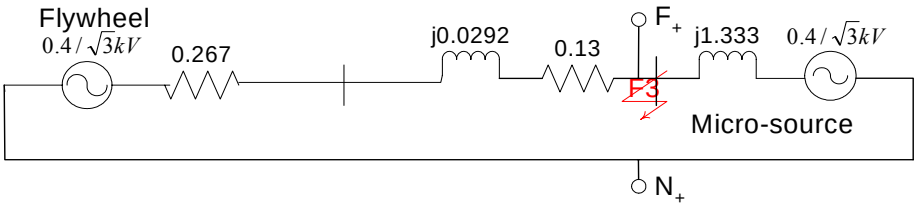
Figure 3.42: Fault current contribution from the micro-source for F3, islanded, TT

The fault current from the flywheel is approximately 16A and the micro gas turbine provides about 3A of fault current.

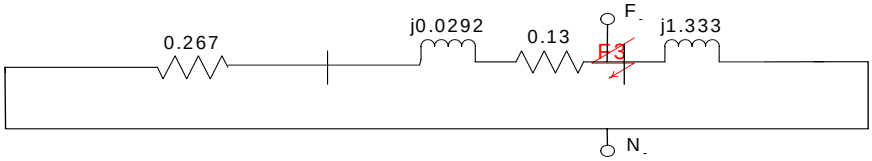
3.2.4.2.2 Manual calculation

TN-C-S system

The positive sequence network for F3, islanded, TN at 0.4 kV



The negative sequence network for F3, islanded, TN at 0.4 kV



The zero sequence network for F3, islanded, TN at 0.4 kV

The positive and negative sequence impedances,

$Z_1 = Z_2$ = (0.397+ j 0.0292) parallel to (j 1.333)

= 0.376 $\angle 27.8$

Since F3 is at the end of the feeder, $Z_{Neutral} = (0.13 + j0.0292)$

$$Z_0 = 3 * (0.13 + j0.0292) + (0.397 + j0.0292)$$

$$Z_0 = (0.787 + j0.1168)$$

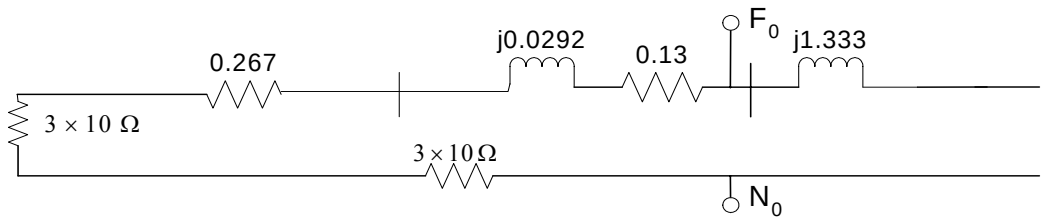
From Equation (3.4), the rms value of the fault current,

$$I_{F3-TN} = 452.3\angle -17.8A \qquad \text{Equation (3.20)}$$

TT system

The positive sequence network and the negative sequence network remain the same as for that in the TN system. The parameters for the zero sequence network are changed according to the TT earthing method.

The zero sequence network for F3, islanded, TT at 0.4 kV



The positive and negative sequence impedances,

$Z_1 = Z_2$ = (0.397+ j 0.0292) parallel to (j 1.333)

= 0.376 $\angle 27.8$

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance, $Z_0 = 3 * (10 + 3) + (0.397 + j0.0292)$

$$Z_0 = (39.397 + j0.0292)$$

From Equation (3.4), the rms value of the fault current,

$$I_{F3-TT} = 17.22\angle -0.5A \qquad \text{Equation (3.21)}$$

3.3 Conclusions

With conventional over-current protection of a MicroGrid, especially when islanded, Voltage Source Converters must contribute 3 p.u fault current in the least for a minimum duration of one second. A study was carried out to determine the fault current contributions from various converter designs. According to the findings of this study, the only way to achieve this performance is to increase the rating of the power module. If a fault current in the order of 3 p.u is required, the rating of the module has to be increased by three times its load rating. This option implies incurring greater cost.

The fault current distribution in a MicroGrid for different faults in grid-connected operation and islanded operation had been studied. A single-phase-to-earth fault had been simulated using SPLITS sub module of CDEGS software. The fault currents have been derived through simulations and hand calculations. The fault current contributions from each source for different faults have been presented.

Operating mode	Earthing system	Fault type	Total Fault current (A)		CDEGS results	
			CDEGS simulation result	Manually calculated value	Total earth current	Neutral current
Grid connected	TN	F1	3,073	3,073	-	-
	TN-C-S	F2	14,828	14,778	0	14,828
		F3	858	864	8.7	850
	TT	F2	17.8	17.7	17.8	0
		F3	17.6	17.5	17.6	0
Islanded (3 pu flywheel current)	TN-C-S	F2	889	887	0	889
		F3	452	452	4.6	452
	TT	F2	17.4	17.6	17.4	0
		F3	17.3	17.2	17.3	0
Islanded (5 pu flywheel current)	TN-C-S	F2	1462	1458	0	1462
		F3	558	557	5.7	552.8
	TT	F2	17.5	17.5	17.5	0
		F3	17.4	17.3	17.4	0

Table 2: Fault currents in a MicroGrid

Summary of the results are presented in Table 2. The simulation results and the calculated values for the case where the flywheel provides 5 p.u of its rated current also have been included. Please note that the fault currents for the fault F1 are specified at 20 kV line voltage while all other currents are based on 0.4 kV line voltage.

This study has re-confirmed the following facts regarding the performance of each earthing system.

1. The return path for the fault current in a TN-C-S system is the neutral conductor and only a small current is directed in to the earth.
2. The return path for the fault current in a TT system is the earth and the total fault current flows in to the earth.
3. The fault currents in a TN system are high due to the low impedance of the fault loop impedance (the fault return path being the neutral)
4. The fault current values in a TT system are very low compared to TN systems, due to the high earthing impedance in the fault loop.

It is also interesting to note the following observations about the fault current distribution in a MicroGrid.

- In grid-connected operation, the major fault current contributor is the main distribution network with the micro-source providing only a small fraction of the fault current.
- The flywheel plays a very important role in islanded operation as the main source of fault currents. It is apparent that the micro-source cannot provide enough fault currents in the event of a fault to operate conventional overcurrent protection devices.

Since the fault currents in a MicroGrid have been calculated, the step and touch voltages can be evaluated now to assess the safety of the MicroGrid grounding system.

3.3 References

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4.0 NTUA study using EMTP

The analysis of the grounding requirements and protection implications of the MicroGrids necessitates the use of suitable modelling and simulation tools. One appropriate package for this purpose is EMTP, which is extensively used for the analysis of power systems and networks of all voltage levels, primarily for the study of fast electromagnetic transients. EMTP can provide a simulation platform with proven accuracy and more than adequate modelling capabilities of the various system elements and network topologies. The potential of utilizing EMTP for the analysis of MicroGrid earthing and protection issues has been explored by ICCS/NTUA within WPE and results from its application are presented in this report.

EMTP is first applied for the simulation of the voltages and currents in conceptual networks with TN and TT earthing systems in case of earth faults and its results are compared with the standard engineering calculations performed by hand. Then, EMTP is applied to the realistic study case LV network elaborated by ICCS/NTUA, both in its state without any distributed energy sources and in its envisaged MicroGrid development, with dispersed micro-sources. The two main earthing systems considered are TN and TT, since only these are used in public distribution networks (the IT scheme is applied only in private installations with increased continuity of supply requirements). The objective of this step is to explore the efficiency of EMTP in simulating more extended networks, as well as to obtain results on the performance of the existing earthing arrangements of the network in grid-connected or isolated mode.

4.1 EMTP application in conceptual TN and TT networks

4.1.1 TN System

The simplified TN network structure is illustrated in Figure 4.1. When an insulating fault is present, the fault current Id is only limited by the impedance of the fault loop cables (see fig. 4.1):

$$Id = \frac{Uo}{Rph_1 + Rd + R_{PE}} \tag{4.1}$$

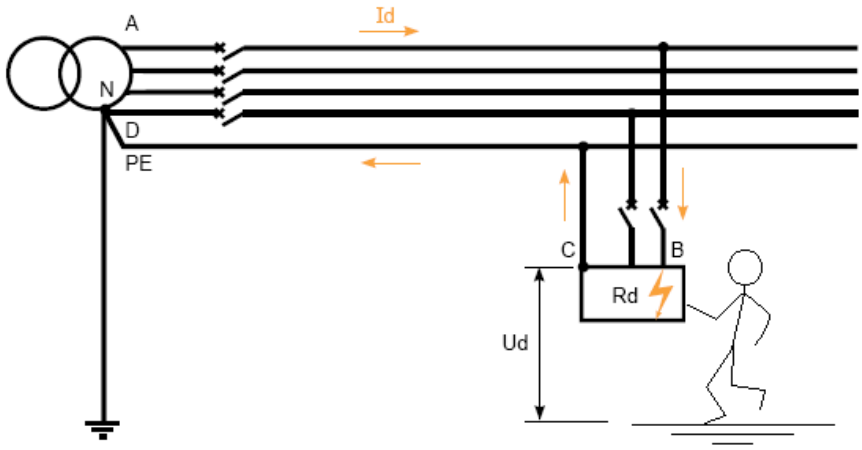


Figure 4.1: TN Earthing System.

For a feeder and a fault with Rd ≈ 0: $$Id = \frac{0.8 \cdot Uo}{Rph_1 + R_{PE}} \quad (4.2)$$

Where it is accepted that the impedances upstream the relevant feeder cause a voltage drop of around 20 % on phase-to-neutral voltage Uo, which is the nominal voltage between phase and earth. Id thus induces a fault voltage with respect to earth:

$$Ud = R_{PE} Id \quad (4.3)$$

Substituting Id from above, under the assumptions $R_{PE} = Rph$ and $Rd = 0$:

$$Ud = 0.8 \cdot Uo \frac{R_{PE}}{Rph_1 + R_{PE}} \Rightarrow Ud = \frac{0.8Uo}{2} \quad (4.4)$$

For 230/400 V networks, this voltage of around Uo/2 (if R_{PE} = Rph) is dangerous since it exceeds the safety limit, even in dry atmospheres (U_L = 50 V). The installation or part of the installation must then be automatically and promptly de-energised.

A simple circuit used to investigate the performance of the TN-S system is constructed using ATPDraw program and shown in Figure 4.2. The impedance of the voltage source in Figure 4.2 corresponds to a 400 kVA transformer with 1.13 p.u. resistance and 3.83 p.u. inductance (hence R = 0.0046 Ω, L = 0.048 mH). For the phase and neutral cables the series resistance is 0.320 Ω/km, the series inductance is 0.230 mH/km and the shunt capacitance 0.60 μF/km. The source neutral earthing

resistance is 3Ω, whereas the load earthing resistance is 10 Ω. The RLC load consists of a 6.793 Ω resistance connected in series with a 16 mH inductance.

The time domain solution of the network for the fault shown is illustrated in Figure 4.3. The switch closes at the time of fault, which is 0.008 s from the start of the simulation.

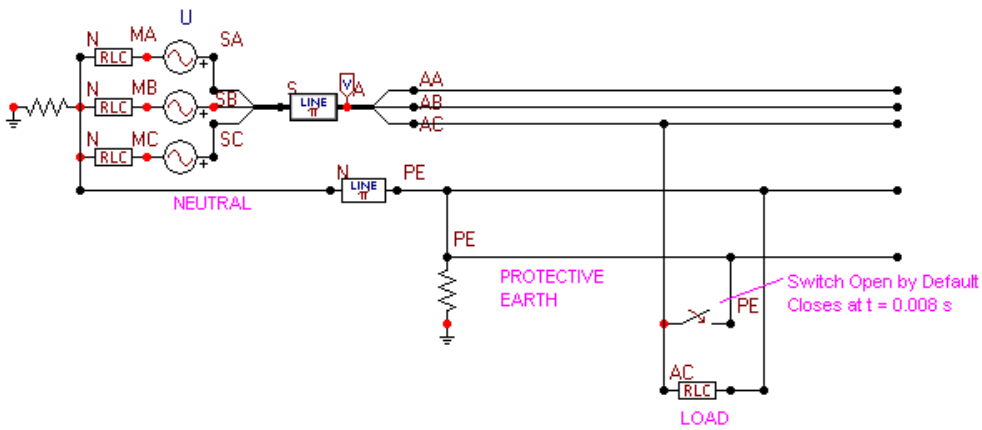


Figure 4.2: ATP Draw representation of the TN-C-S Earthing System.

Simulation results are in agreement with hand calculations. For example the max value of the total fault current Id can be estimated according to the previously proposed formula (4.1). In the TN-C-S example circuit shown in fig 4.2 the impedance of the neutral conductor needs to be added in the denominator resulting in the expression:

$$Id_{total} = \frac{Uo}{Rph_1 + Rd + R_{PE} + R_N} \tag{4.5}$$

It is:

$$Rph_1 + Rd + R_{PE} + R_N = \left(\left|0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3} + 0 + 0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3}\right|\right)\Omega$$
$$= 0.037\Omega$$

Consequently, from (4.5) the max total fault current is:

$$Id_{total} = \frac{Uo}{Rph_1 + Rd + R_{PE} + R_N} \approx \frac{326.5986\,\text{V}}{0.037\Omega} = 8428\text{A}$$

Where Uo = 230x$\sqrt{2}$ V.

More accurate calculation of Id_{total} involves the synthesis of grounding resistances at "N" and "PE", the fault loop cable impedances and the impedance of the source. The total fault loop current Id_{total} can be calculated then as:

$$Id_{total} = \frac{Uo}{Z_{total}} \tag{4.6}$$

Where $Z_{total} = Zph_1 + Zd + Z_{PE} + Z_N //(R_{NG} + R_{PEG}) + Z_{N-MC}$ (4.7)

R_{NG} and R_{PEG} are the grounding resistances of the grounding systems of the neutral and the protective earth, equal to 3Ω and 10Ω correspondingly.

Neglecting the capacitive term of the cables impedances it is:

$$Z_{total} = 0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3} + 0$$
$$+ \left(0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3}\right) // 13 + 0.0046 + j \cdot 2\pi \cdot 50 \cdot 0.048 \cdot 10^{-3}$$
$$Z_{total} = (0.041 + j \cdot 0.023)\Omega$$

Substituting to (4.6) it is $Id_{total} = \frac{Uo}{Z_{total}} = \frac{326.5986V}{|0.041 + j \cdot 0.023|\Omega} = \frac{326.5986}{0.047} A = 6949A$

The ATP calculation for the total fault current results in a max value of Id_{total} equal to 6984.7 A, as shown in Fig. 4.3.10.

The portion of Id_{total} dispersed into the ground, $Id_{ToEarth}$ is calculated as

$$Id_{ToEarth} = Id_{total} \cdot \frac{Z_N}{R_{NG} + R_{PEG}} = 6949A \cdot 1.42 \cdot 10^{-3} = 9.866A$$

And the max touch voltage Ud will be $Ud = Id_{ToEarth} \cdot R_{PEG} = 9.866A \cdot 10\Omega = 98.66V$

While from (4.4) it is Ud= 130.108V and from ATP calculations it is 99.026V as shown in fig. 4.3.1.

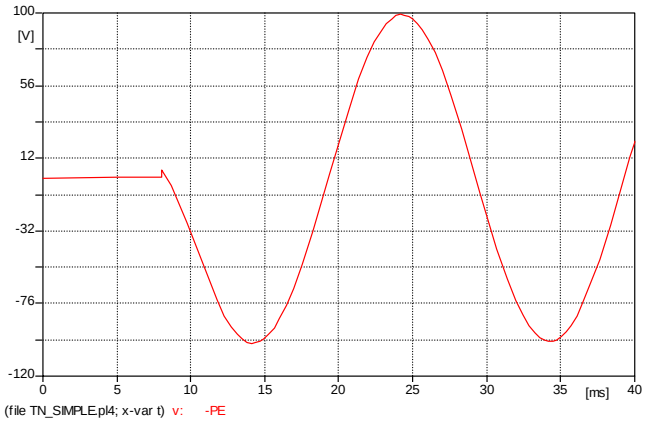


Figure 4.3.1: Voltage to Earth at "PE".

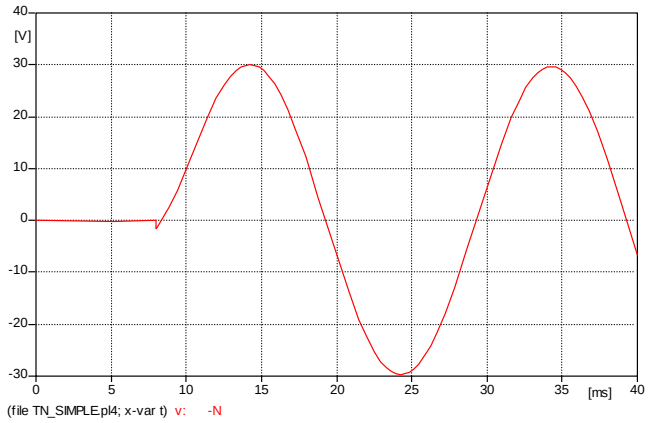


Figure 4.3.2: Voltage to Earth at "N".

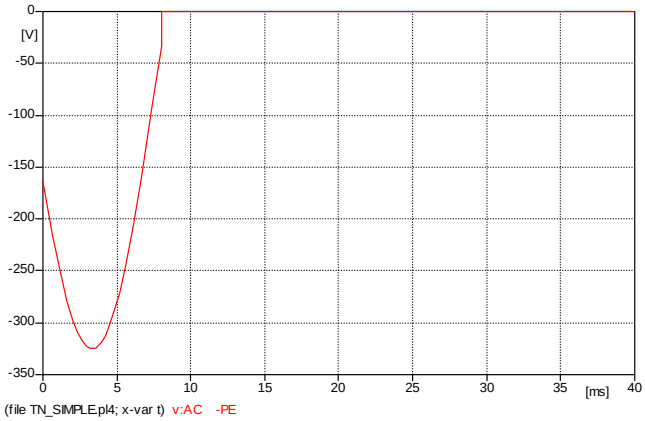


Figure 4.3.3: Voltage difference at Load ends.

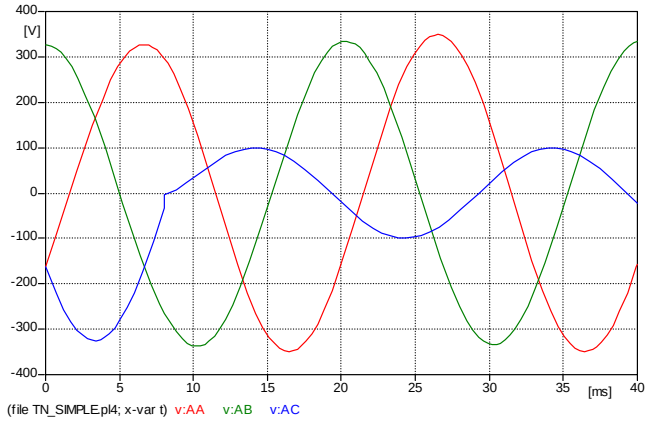


Figure 4.3.4: Voltage to Earth of Phases A, B and C.

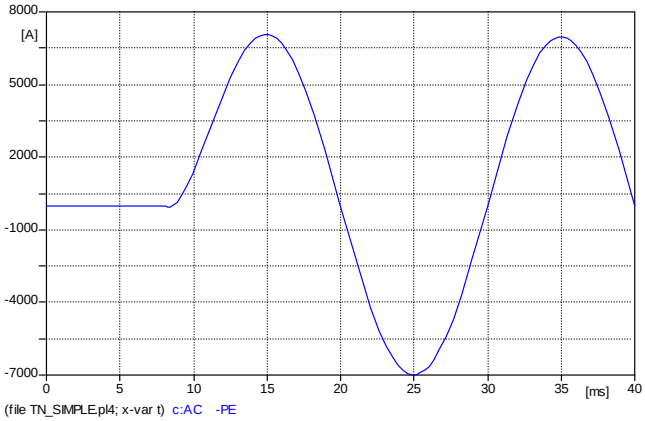


Figure 4.3.5:Branch current at the fault loop("AC to PE").

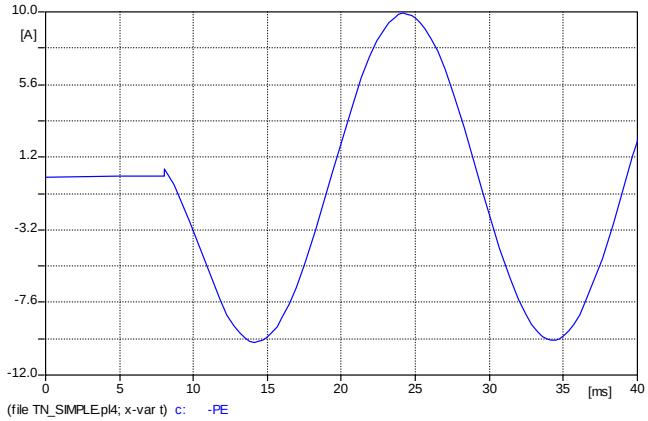


Figure 4.3.6:Current to earth from the PE earthing.

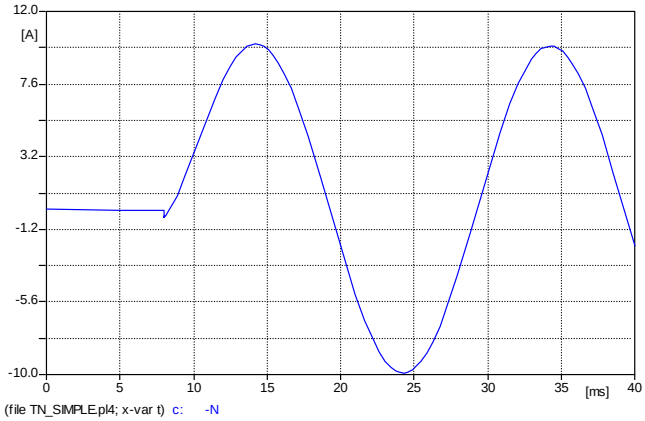


Figure 4.3.7: Current to Earth from Node "N".

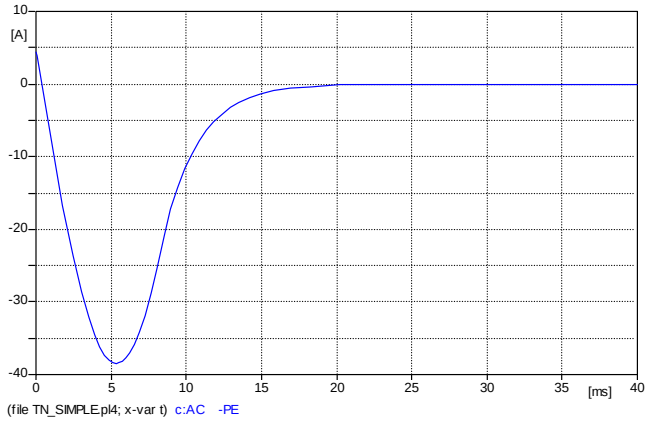


Figure 4.3.8: Branch current along the Load.

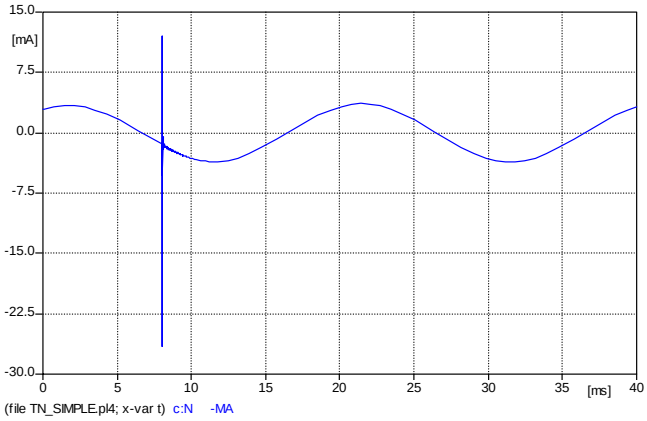


Figure 4.3.9: "N to MA" branch current.

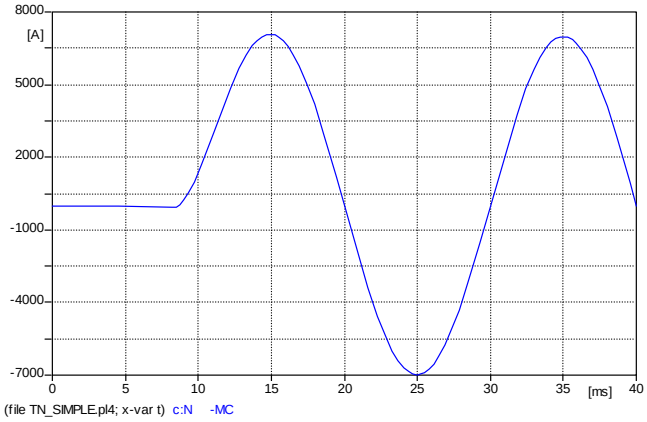


Figure 4.3.10: Branch current at the fault loop.

Figure 4.3. EMTP simulation results for the TN-C-S network of Figure 4.2.

4.1.2 TT System

The TT network structure is illustrated in Figure 4.4. When an insulation fault occurs, the fault current Id is mainly limited by the earth resistances (if the earth connection of the frames and the earth connection of the neutral are not associated). Assuming that the fault impedance is negligible, the fault current is:

$$Id \approx \frac{Uo}{Ra + Rb} \tag{4.8}$$

This fault current induces a fault voltage in the earth resistance of the applications:

$$Ud = Ra\ Id, \text{ or } Ud = \frac{Uo \cdot Ra}{Ra + Rb} \tag{4.9}$$

As earth resistances are normally low and of similar magnitude (≈1-10 Ω), this voltage of the order of Uo/2 (for equal resistances) and therefore dangerous. The part of the installation affected by the fault must be automatically disconnected.

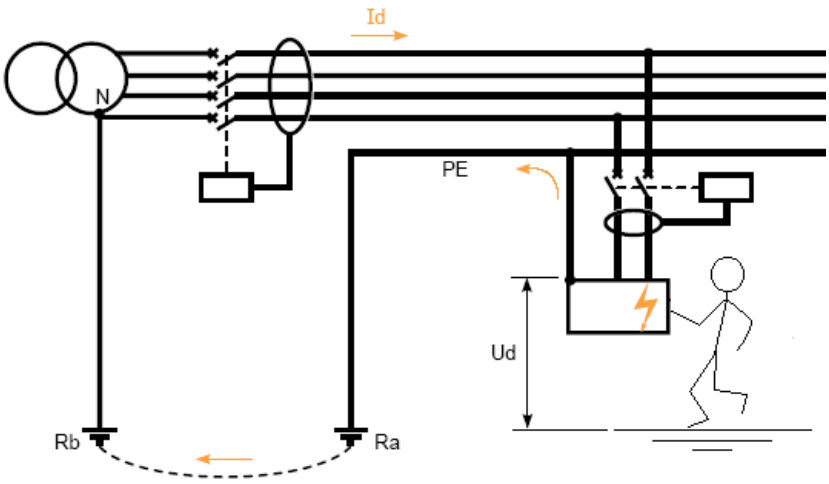


Figure 4.4: TT Earthing System.

The simple circuit used to investigate the performance of the TN-S system is constructed using ATPDraw program and shown in Figure 4.5. The input data for this circuit are the same as for the TN case of the previous section. The time domain solution of the network for the fault shown is illustrated in the diagrams of Figure 4.6.

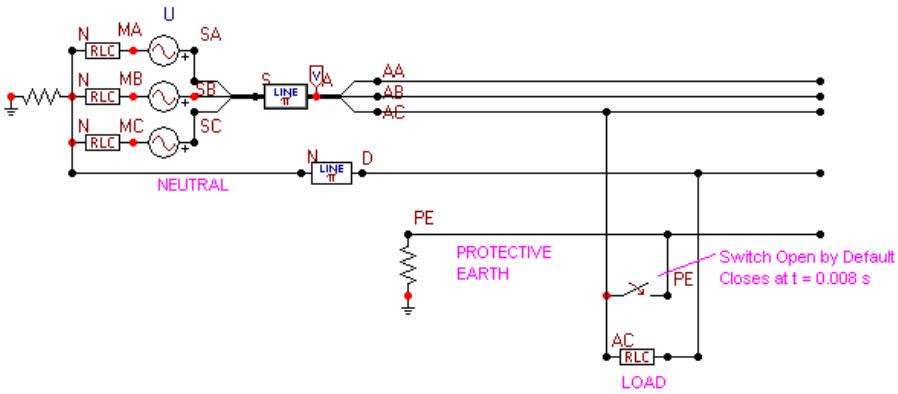


Figure 4.5: ATP Draw representation of the TT Earthing System.

Simulation results are in agreement with hand calculations. The max value of the fault current Id dispersed to ground can be estimated according to the previously proposed formula (2.8):

$$Id_{ToEarth} \approx \frac{Uo}{Ra + Rb} = \frac{230\sqrt{2}V}{13\Omega} = 25.021A$$

(2.10)

More accurate calculation of $Id_{ToEarth}$ involves the synthesis of grounding resistances at "N" and "PE", the fault loop cable impedances the impedance of the source and the impedance of the load. The total fault loop current Id_{total} can be calculated then as:

$$Id_{total} = \frac{Uo}{Z_{total}} \tag{4.11}$$

Where $Z_{total} = Zph_1 + Z_{N-MC} + (Z_N + Z_{LOAD})//(R_{NG} + R_{PEG} + Zd)$ (4.12)

R_{NG} and R_{PEG} are the grounding resistances of the grounding systems of the neutral and the protective earth, equal to 3Ω and 10Ω correspondingly.

Neglecting the capacitive term of the cables impedances it is:

$$Z_{total} = \left(0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3}\right) + \left(0.0046 + j \cdot 2\pi \cdot 50 \cdot 0.048 \cdot 10^{-3}\right) +$$
$$+ \left[(0.018 + j \cdot 2\pi \cdot 50 \cdot 0.013 \cdot 10^{-3}) + \left(6.793 + j \cdot 2\pi \cdot 50 \cdot 16 \cdot 10^{-3}\right)\right] // 13\Omega$$
$$Z_{total} = \left(5.011 + j \cdot 2.054\right)\Omega \tag{4.13}$$

Consequently the max current along the phase cable will be

$$Id_{total} = \frac{Uo}{Z_{total}} = \frac{326.5986V}{|5.011 + j \cdot 2.054|\Omega} = 60.307A$$

The ATP calculation results in 60.532A maximum current along the phase cable, as shown in fig.4.6.6

The total current Id_{total} is divided in two parts with the ratio

$$(Z_N + Z_{LOAD})//(R_{NG} + R_{PEG} + Zd) = 1.535 \tag{4.14}$$

Consequently the max fault current $Id_{ToEarth}$ dispersed into the ground through the grounding systems of the neutral and the protective earth is calculated 23.789 A

The ATP calculation results in max $Id_{ToEarth}$ = 25.077A as shown in figures 4.6.7 and 4.6.8.

Consequently the max touch voltage will be equal to $Ud = Id_{ToEarth} \cdot R_{PEG}$= 250.77V while from (4.9) it equals 250.207 and from ATP calculation it is 249.92 V as shown in fig.4.6.1.

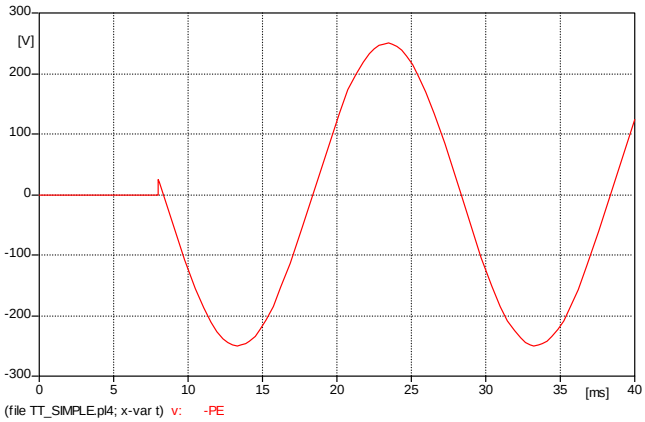


Figure 4.6.1: Voltage to Earth at "PE".

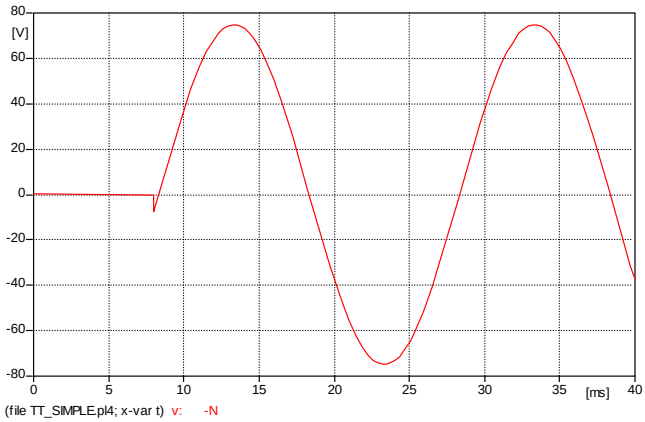


Figure 4.6.2: Voltage to Earth at "N".

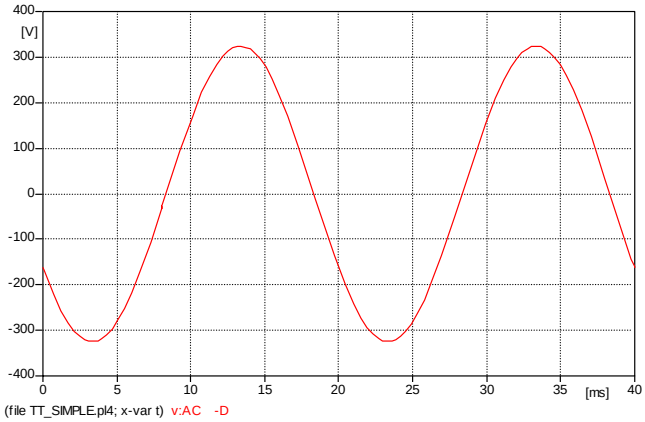


Figure 4.6.3: Voltage difference between Load ends.

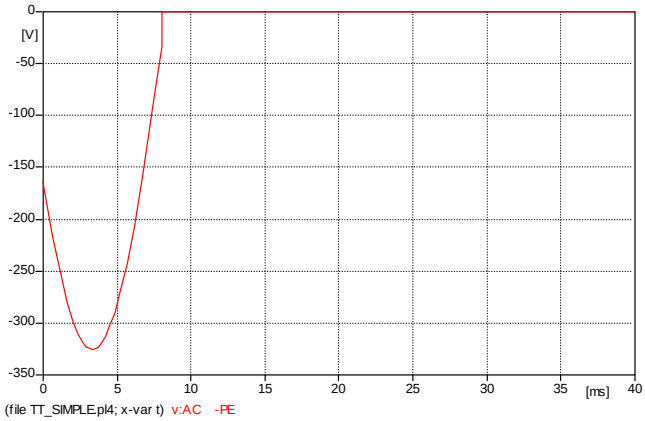


Figure 4.6.4:Voltage difference between "AC" and "PE"

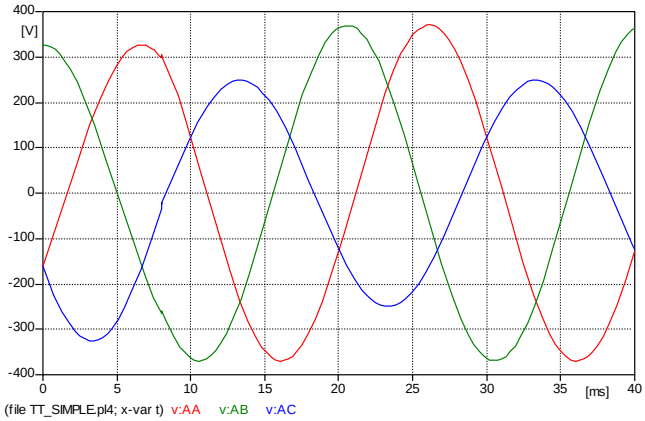


Figure 4.6.5: Phase Voltages to Earth.

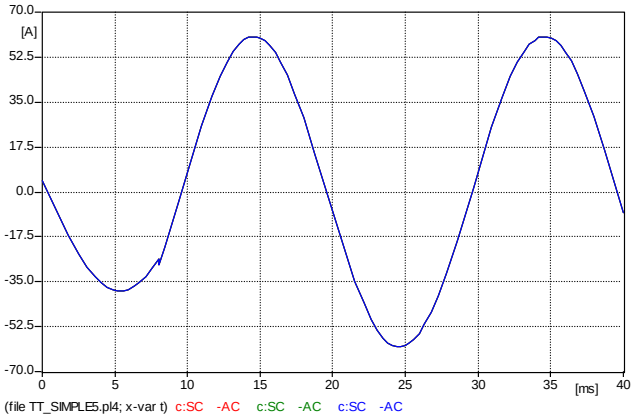


Figure 4.6.6: Branch Current along the phase cable.

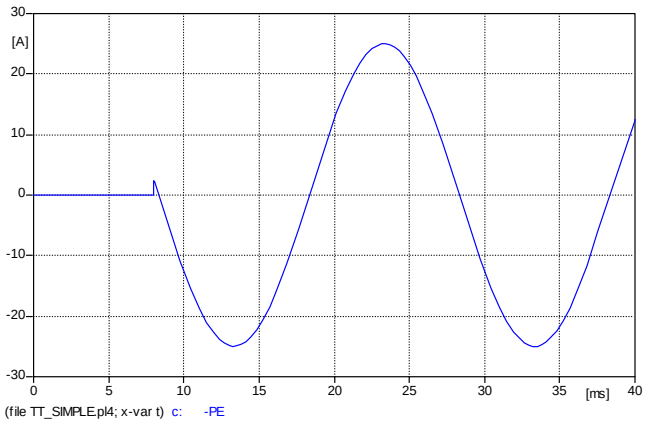


Figure 4.6.7: Current to earth from PE earthing.

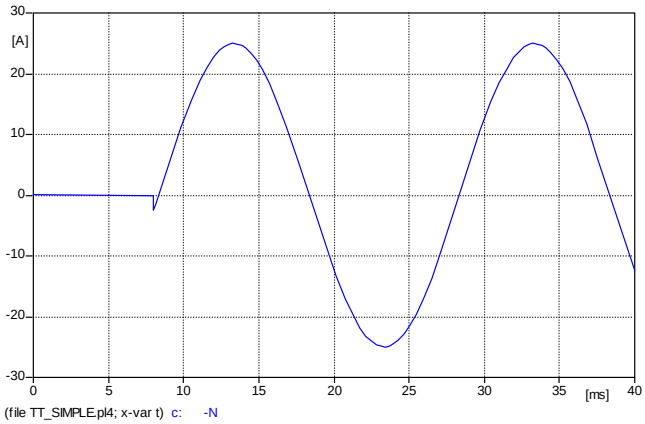


Figure 4.6.8: Current to earth from Neutral Earthing.

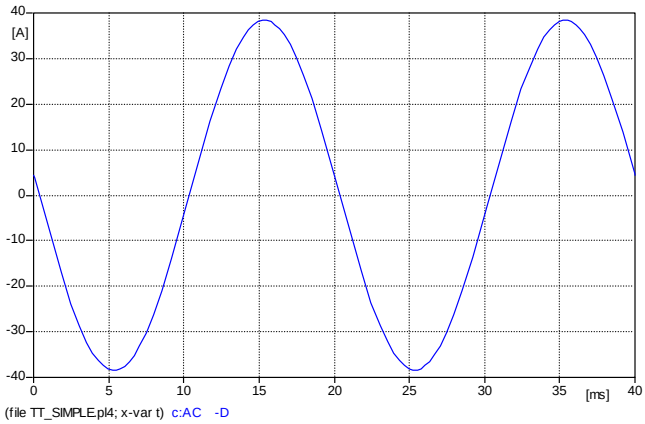
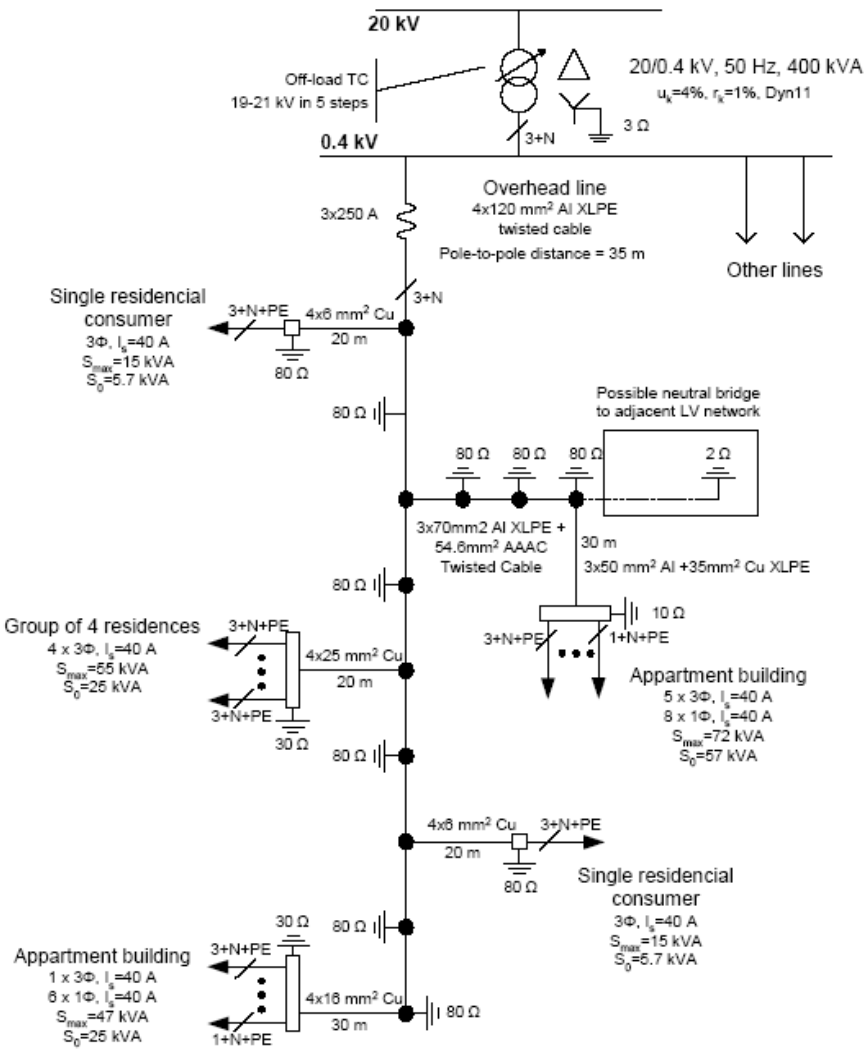


Figure 4.6.9: Branch current along the Load.

Figure 4.6. EMTP simulation results for the TT network of Figure 4.5.

4.2 Application to a realistic study case LV network

4.2.1 Study case description



Line type	R (Ω/km)	X (Ω/km)	R_n (Ω/km)
Overhead - Twisted cable 4x120 mm^2 Al	0.284	0.083	0.284
Overhead - Twisted cable 3x70 mm^2 Al + 54.6 mm^2 AAAC	0.497	0.100	0.630
Overhead – Conductors 4x50 mm^2 Al	0.397	0.279	
Overhead – Conductors 4x35 mm^2 Al	0.574	0.294	
Overhead – Conductors 4x16 mm^2 Al	1.218	0.318	
Underground – XLPE cable 3x150 mm^2 Al + 50 mm^2 Cu	0.264	0.071	0.387
Connection - Cable 4x6 mm^2 Cu	3.410	0.094	
Connection - Cable 4x16 mm^2 Cu	1.380	0.085	
Connection - Cable 4x25 mm^2 Cu	0.870	0.083	
Connection - Cable 3x50 mm^2 Al + 35 mm^2 Cu	0.462	0.077	0.526
Connection - Cable 3x95 mm^2 Al + 35 mm^2 Cu	0.410	0.071	0.524

Figure 4.7: One line diagram of the LV network used for simulations and line parameter values.

In Fig. 4.7 the LV study case network considered is illustrated. Regarding the earthing arrangements of the network, first the TN system is considered, as shown in Fig. 4.7. Then, the TT system is also examined, in which case neutral conductors are not bridged to the protective earth conductor at the connection point of each installation, as shown in Fig. 4.8. Further, for the TT system all network neutral grounding points are removed, except only for the main substation. All earthing resistances (substation and consumers) are the same as in Fig. 4.7.

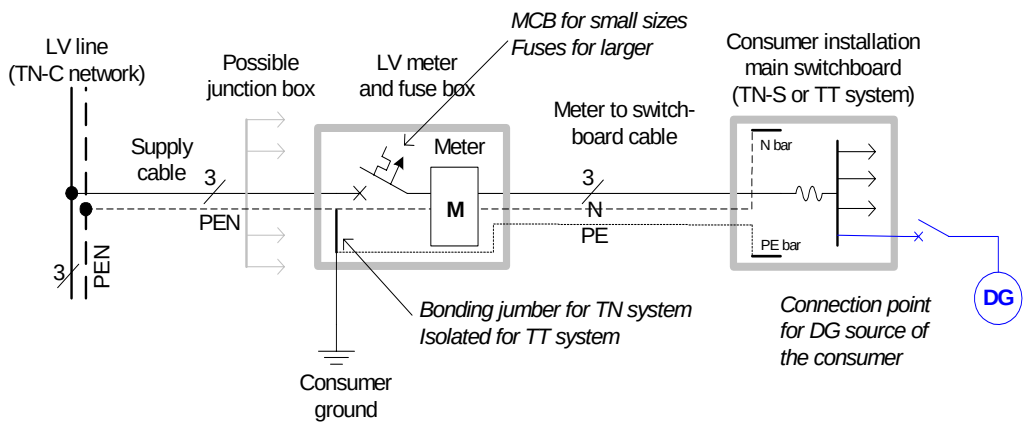


Figure 4.11. Customer connection arrangements.

The analysis includes the two basic operating modes, which is grid-connected and isolated. In the latter case, the gravest scenario is considered where not only the feeder breaker is open, but also the neutral conductor is interrupted (e.g. due to damage of the cable), which results in losing the low earthing resistance of the MV/LV substation.

In the grid-interconnected mode, micro-sources are not taken into account since their contribution to the fault is very small compared to the network's (by one order of magnitude in general). In the isolated mode, the network is assumed to be fed by a 50kVA three-phase central inverter (batteries or flywheel) installed at Node 2. The inverter provides a neutral conductor earthed at the supply point of the installation (earthing resistance 10 Ω). Other micro-sources are not included, mainly because suitable EMTP models were not available. This however does not affect the validity of the analysis, since the main fault current contribution is expected from the central inverter. For this inverter two distinct cases have been analysed: a) without restriction on its fault current magnitude b) with restriction on the fault current magnitude, taken equal to three times the its rated current.

The faults considered are single phase to ground faults, which are the most common in the consumer premises. Faults at the departure and at the end of the LV feeder are examined, being the remotest and closest to the source.

Based on the above, the following six study cases are simulated in the following:

- First Case: TN-S type of grounding. Short circuit at load 1. Grid-connected mode with no micro- sources in the network.
- Second Case: TN-S type of grounding. Short circuit at load 5. Grid-connected mode with no micro-sources in the network
- Third Case: TN-S type of grounding. Short circuit at load 1. Isolated mode with a 50 kVA central inverter at Node 2, without current limit.
- Fourth Case: TN-S type of grounding. Short circuit at load 1. Isolated mode with a 50 kVA central inverter at Node 2, with current limit equal to $3I_n$.
- Fifth Case: TT type of grounding. Short circuit at load 5. Grid-connected mode with no micro-sources in the network.
- Sixth Case: TT type of grounding. Short circuit at load 5. Isolated mode with a 50 kVA central inverter at Node 2, without current limit.

4.2.2 Simulation results

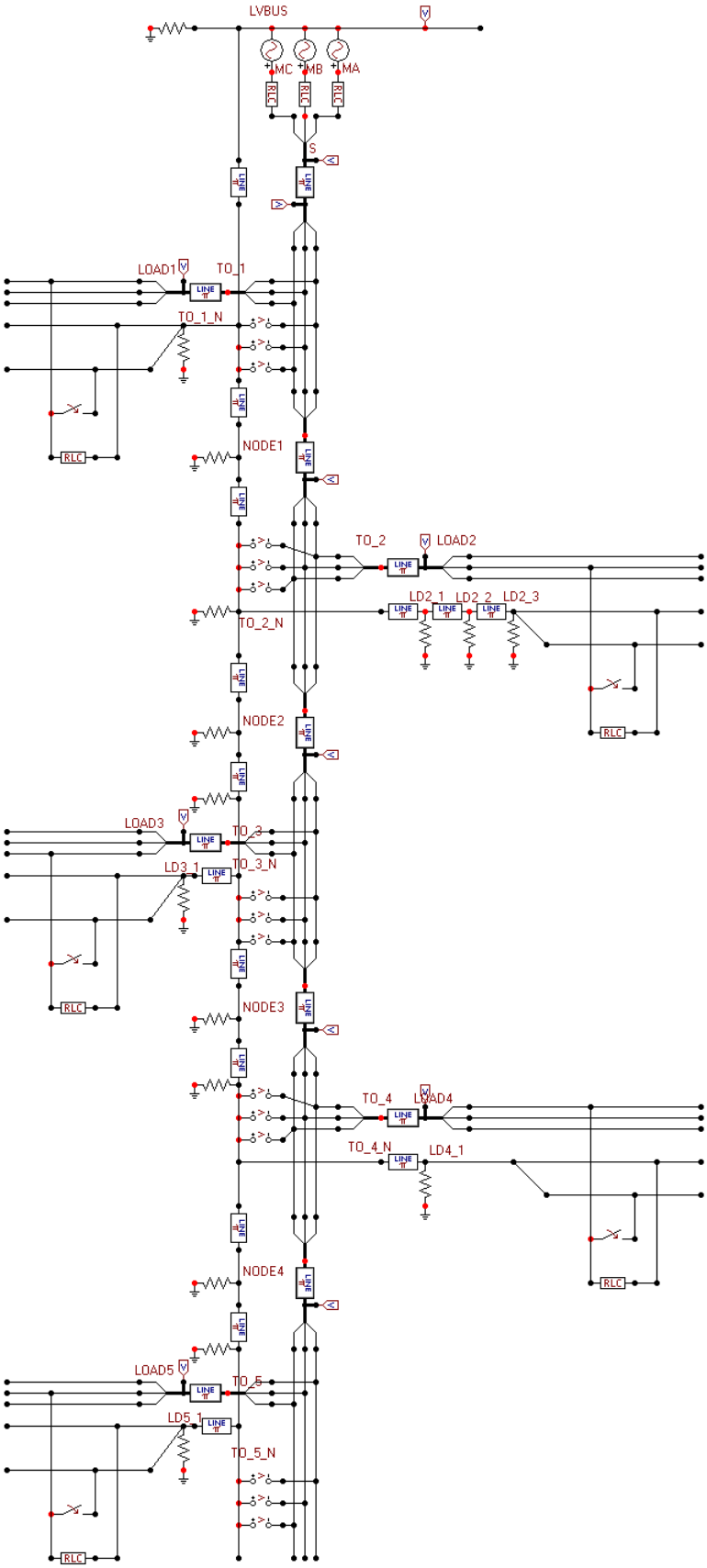


Figure 4.9: ATPDraw circuit representation of the LV network for the first and second study case.

1st Case

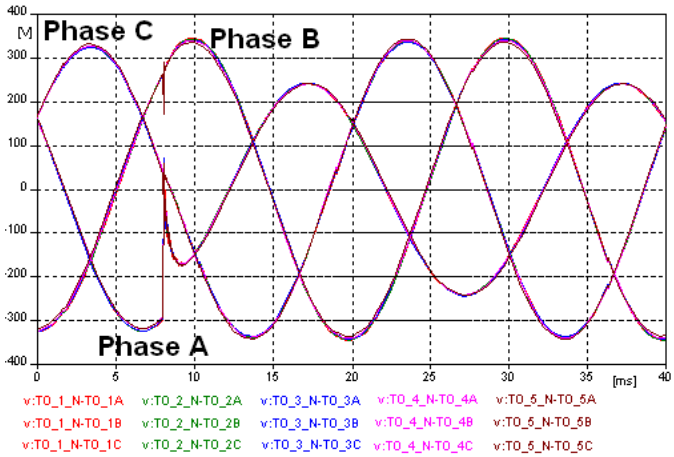


Figure 4.10.1: Phases to neutral voltages at various nodes of the circuit.

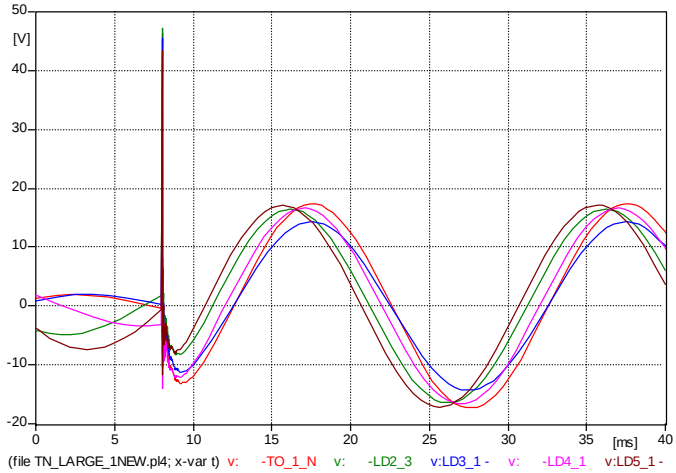


Figure 4.10.2: Touch voltages at various points of the circuit.

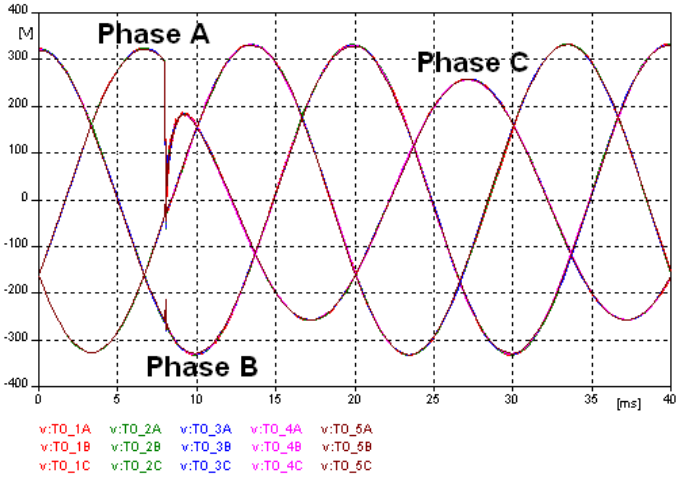


Figure 4.10.3: Phase voltages at various nodes of the circuit

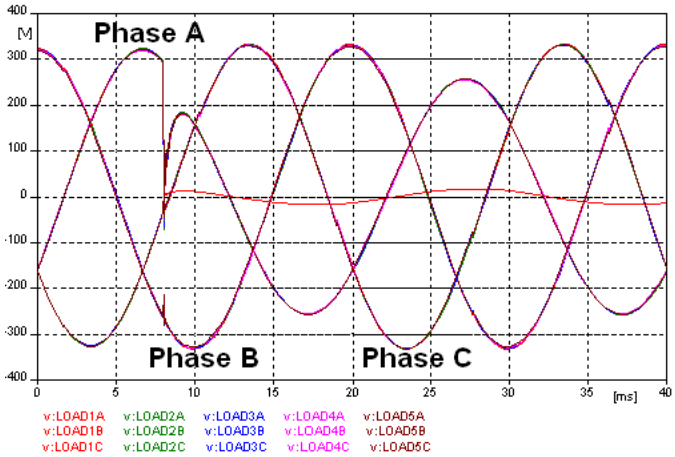


Figure 4.10.4: Phase voltages at load connection points.

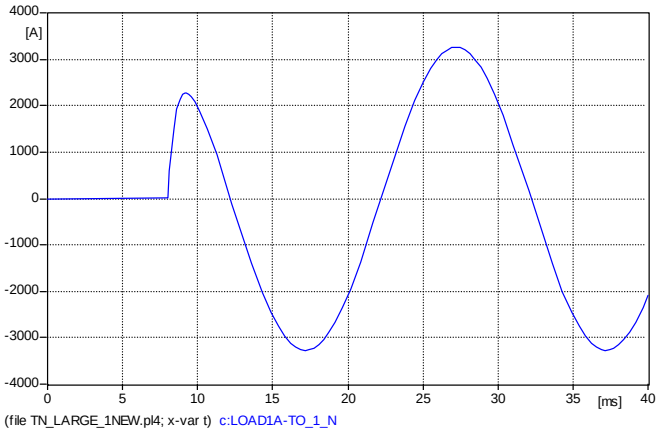


Figure 4.10.5: Fault Current.

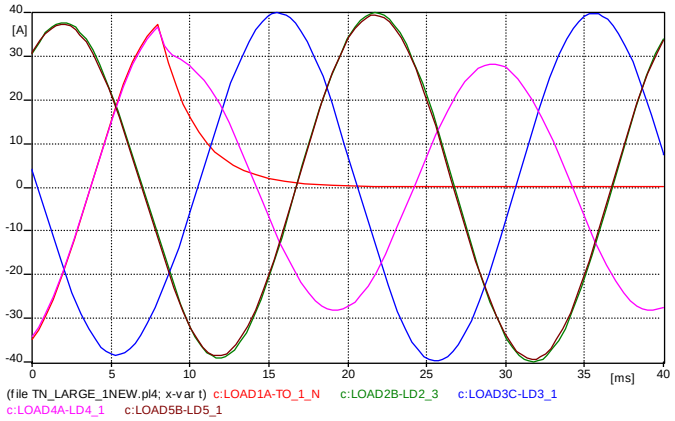


Figure 4.10.6: Currents along the loads.

Figure 4.10: ATP calculation results for the circuit of fig. 4.9, considering fault at load 1.

2nd Case

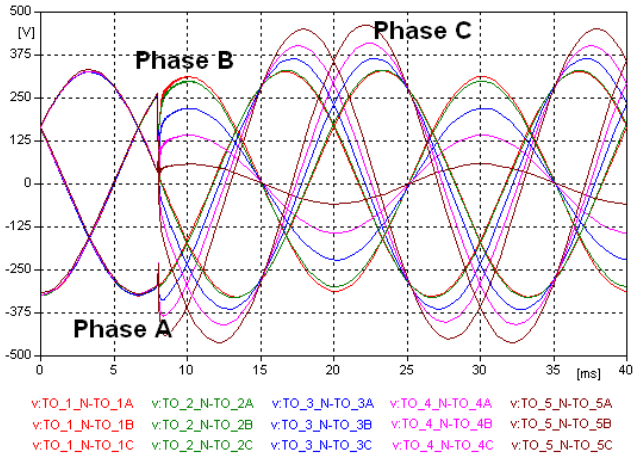


Figure 4.11.1: Phase to neutral voltages at various nodes of the circuit.

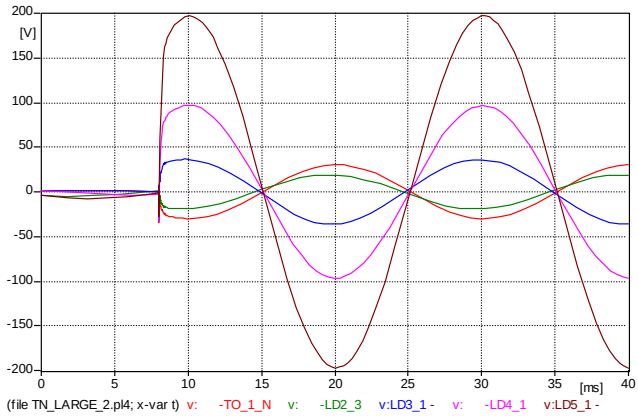


Figure 4.11.2: Touch voltages at various points of the circuit.

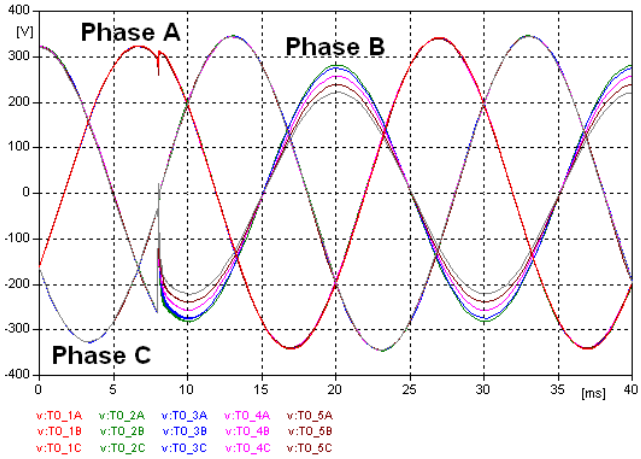


Figure 4.11.3: Phase voltages at various nodes of the circuit.

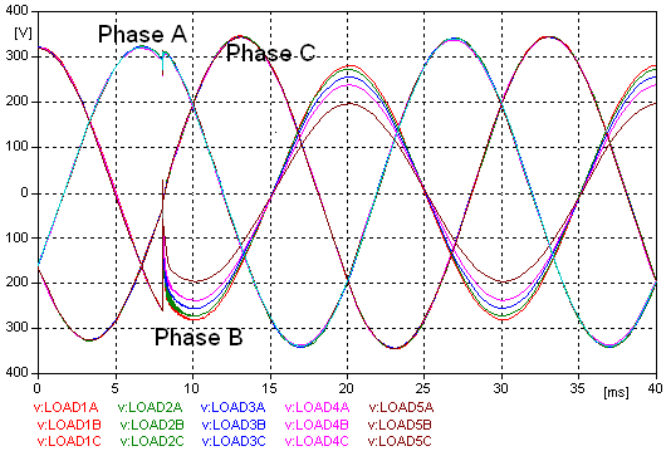


Figure 4.11.4: Phase voltages at load connection points.

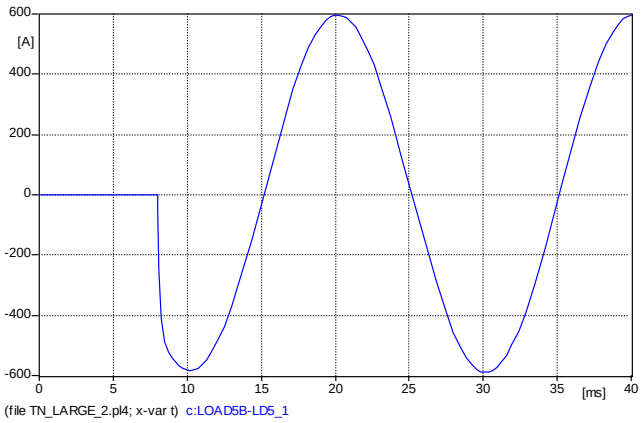


Figure 4.11.5: Fault Current.

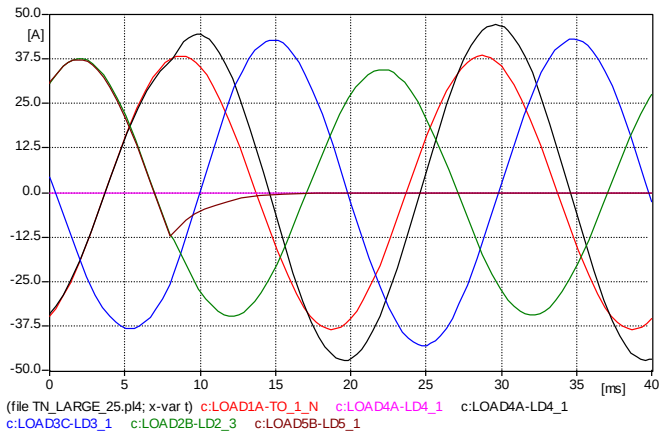


Figure 4.11.6: Currents along the loads.

Figure 4.11: ATP calculation results for the circuit of fig. 4.9, considering fault at load 5.

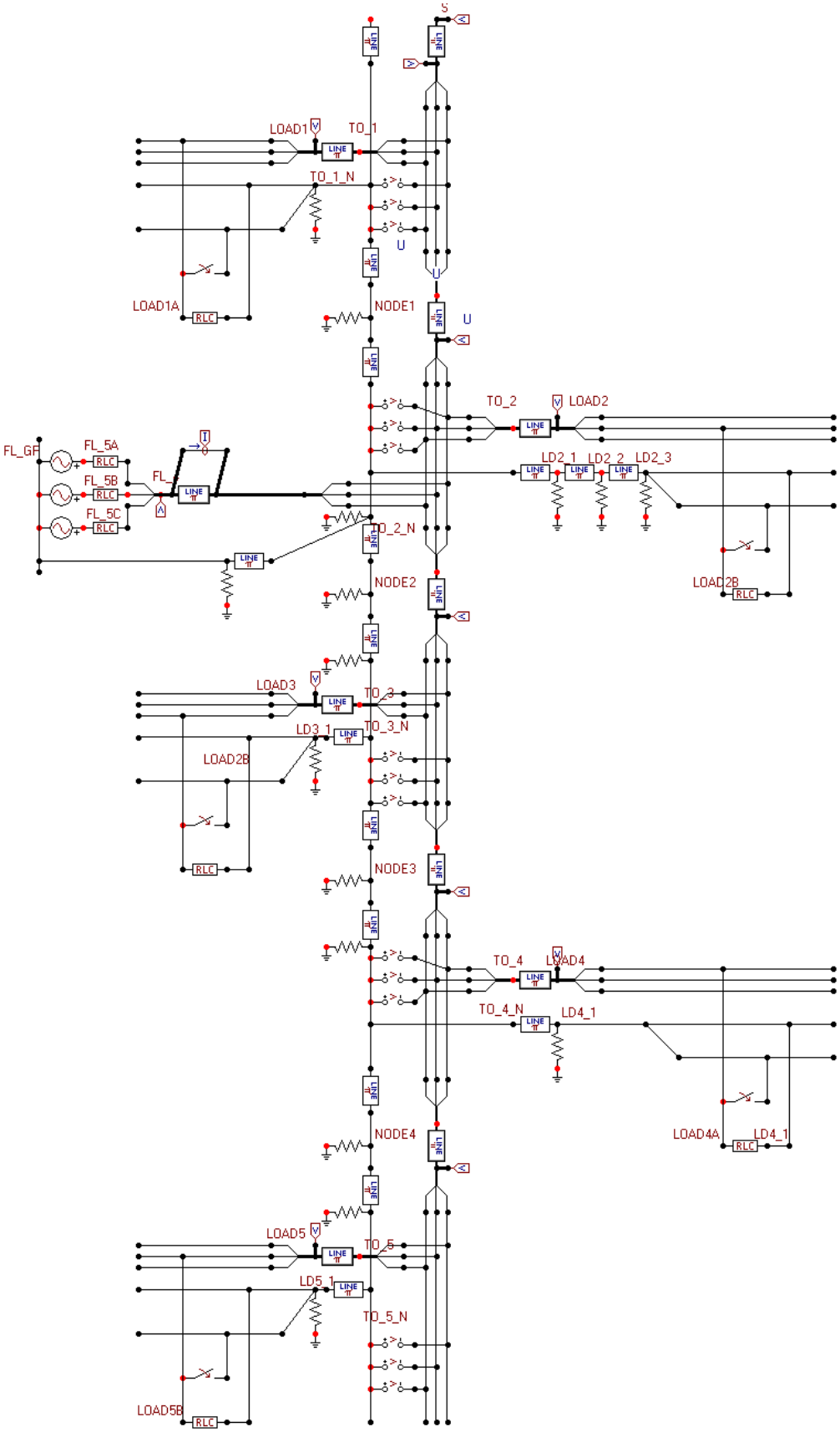


Figure 4.12: ATPDraw circuit representation of the LV network for the third study case.

3rd Case

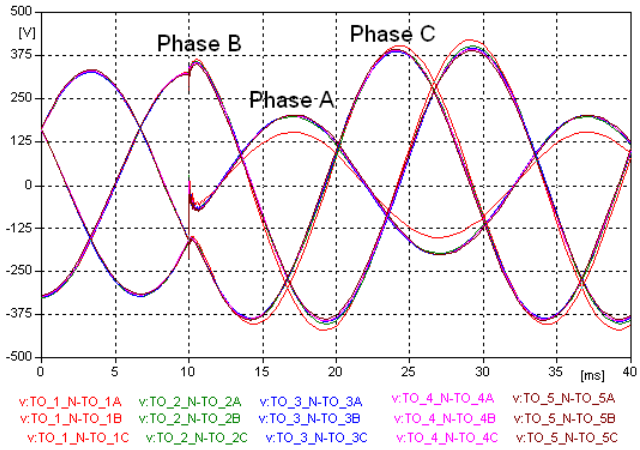


Figure 4.13.1: Phase to neutral voltages at various nodes of the circuit.

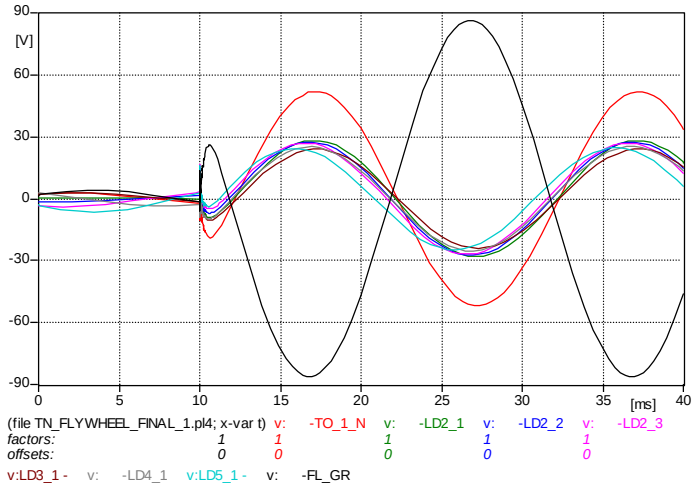


Figure 4.13.2: Touch voltages at various points of the circuit

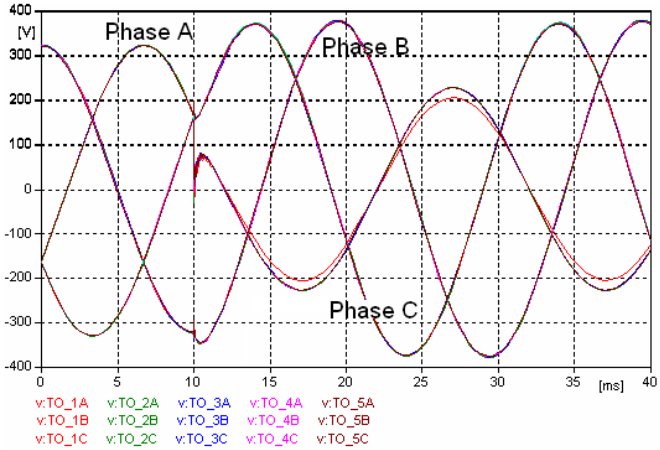


Figure 4.13.3: Phase voltages at various nodes of the circuit.

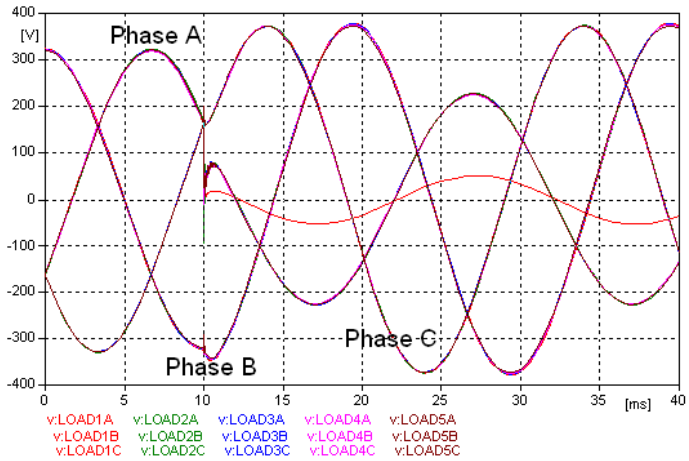


Figure 4.13.4: Phase voltages at load connection points.

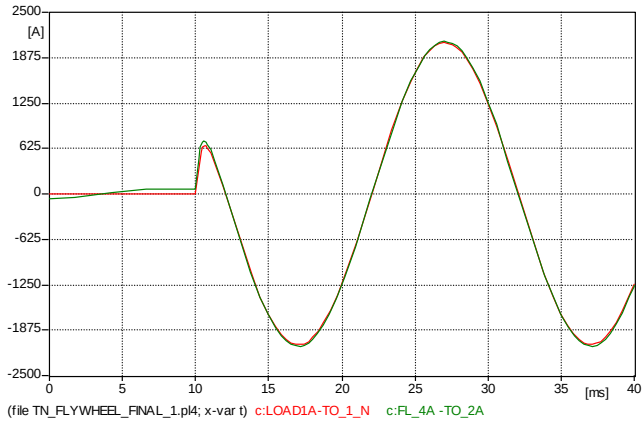


Figure 4.13.5: Fault Current

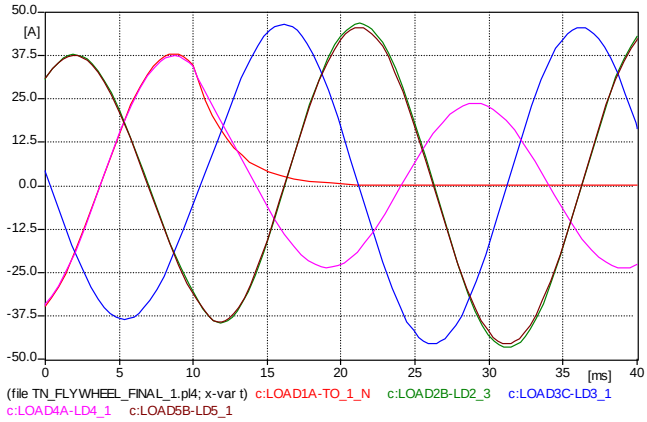


Figure 4.13.6: Currents along loads

Figure 4.13: ATP calculation results for the circuit of fig. 4.12, considering fault at load 1.

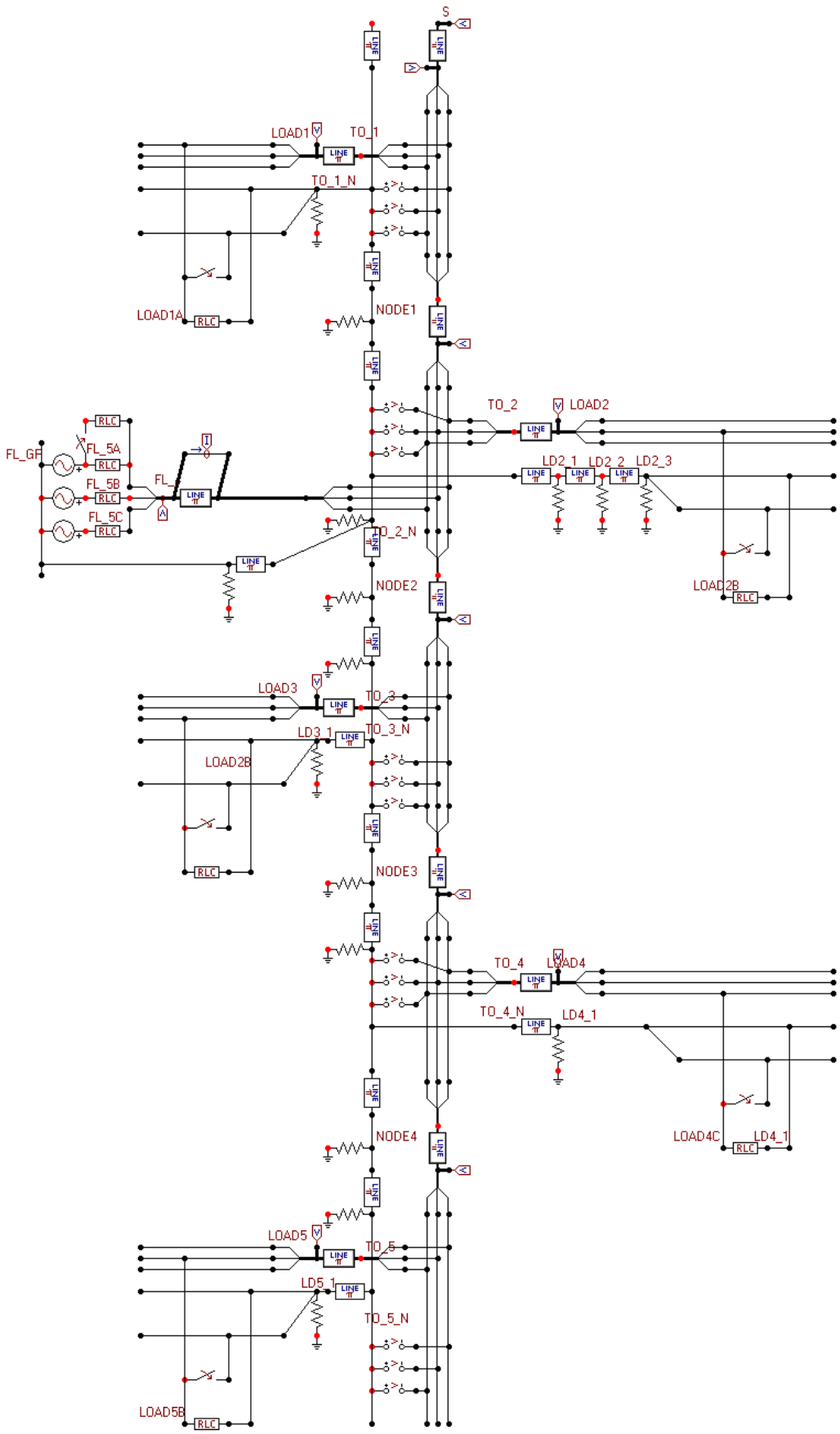


Figure 4.14: ATPDraw circuit representation of the LV network for the fourth study case.

4th Case

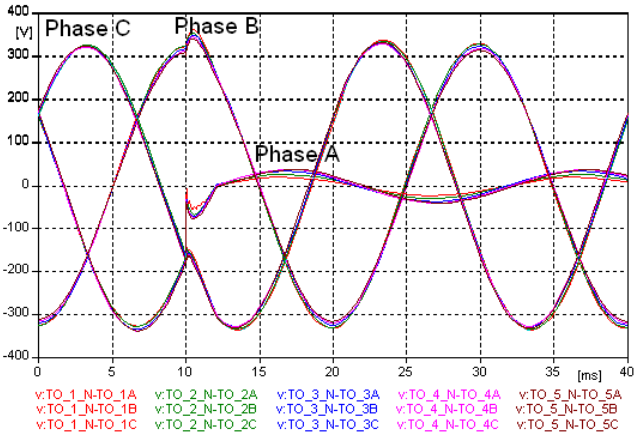


Figure 4.15.1: Phase to Neutral Voltages at various nodes of the circuit

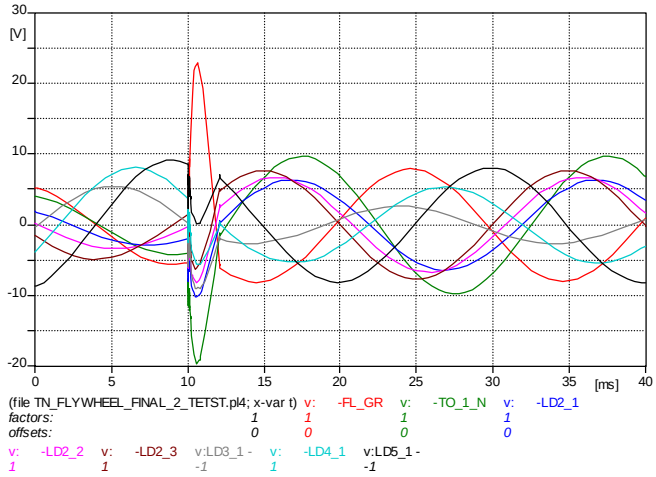


Figure 4.15.2: Touch voltages at various points of the circuit

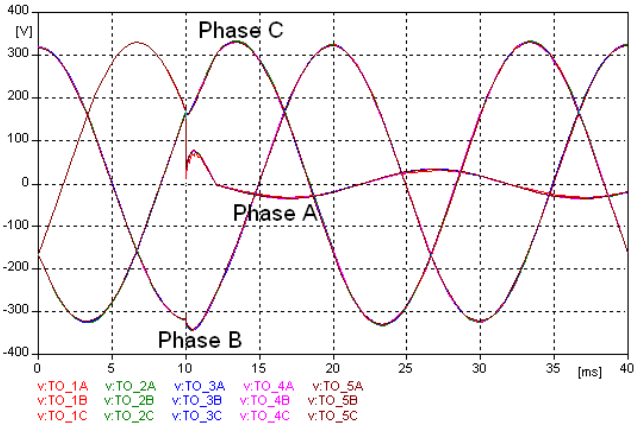


Figure 4.15.3: Phase voltages at various nodes of the circuit

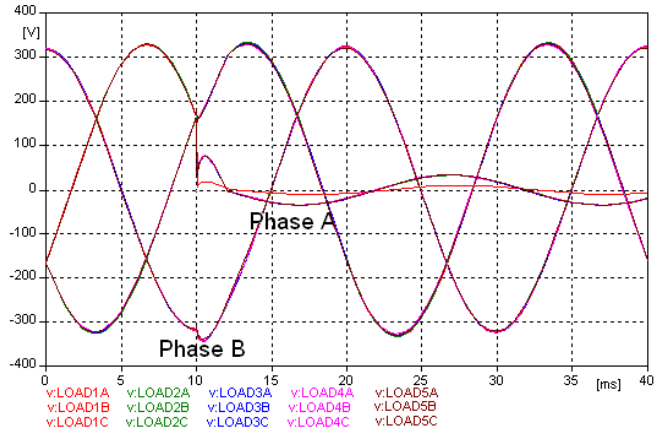


Figure 4.15.4: Phase voltages at load connection points

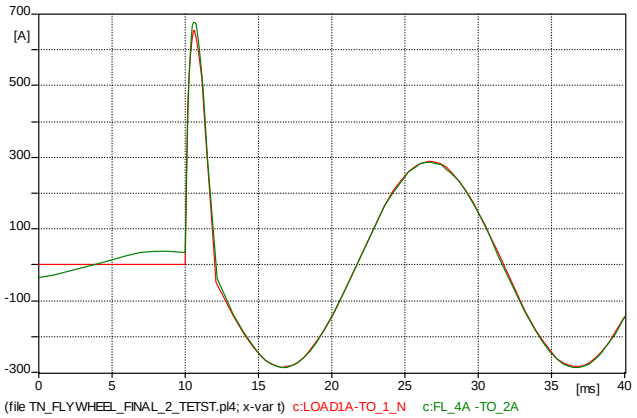


Figure 4.15.5: Fault Current

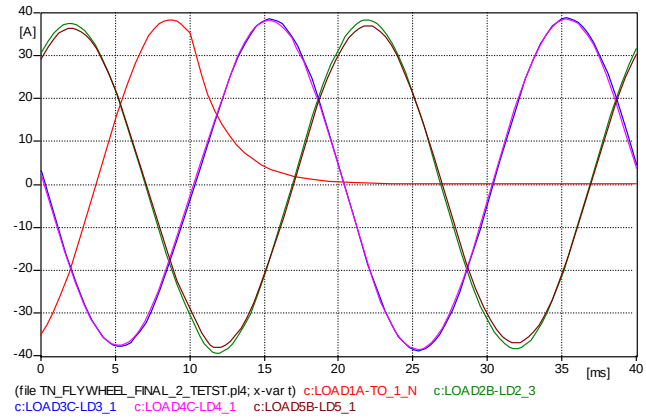


Figure 4.15.6: Current along the loads

Figure 4.15: ATP calculation results for the circuit of fig. 4.14, considering fault at load 1.

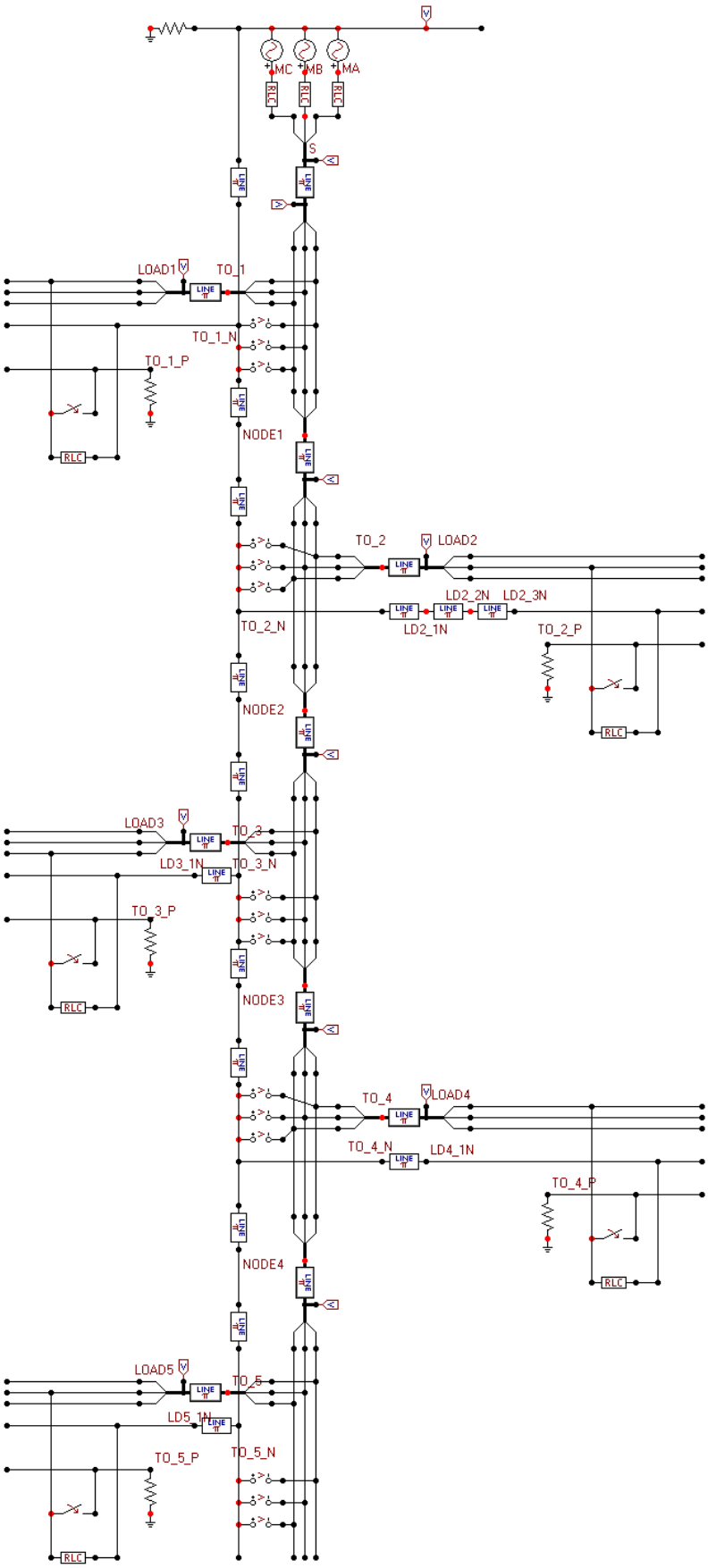


Figure 4.16: ATPDraw circuit representation of the LV network for the fifth study case.

5th Case

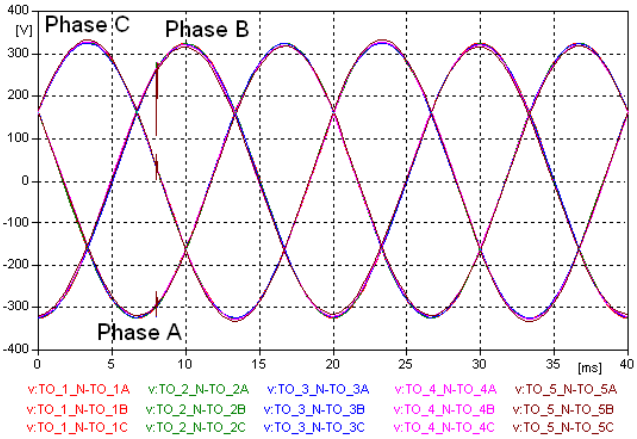


Figure 4.17.1: Phase to neutral voltages at various nodes of the circuit.

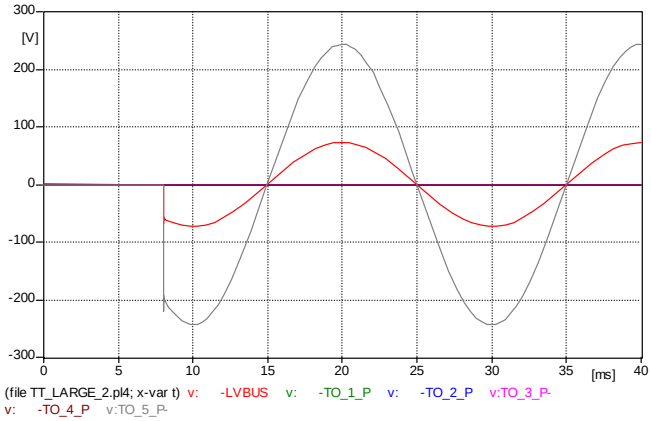


Figure 4.17.2: Touch voltages at various points of the circuit

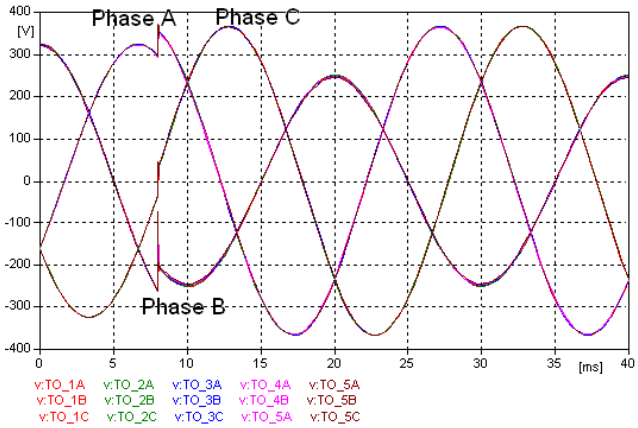


Figure 4.17.3: Phase voltages at various nodes of the circuit.

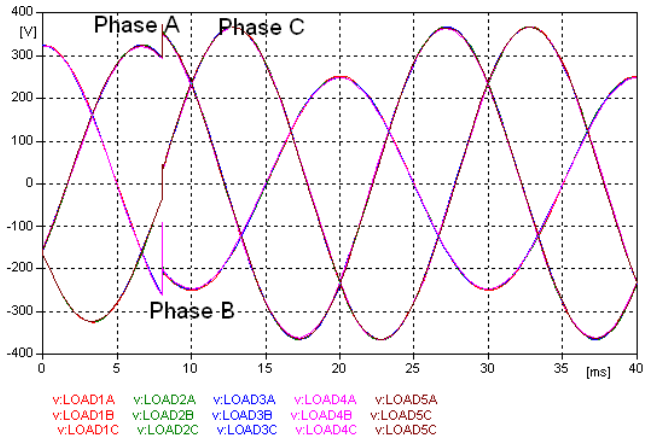


Figure 4.17.4: Phase voltages at load connection points

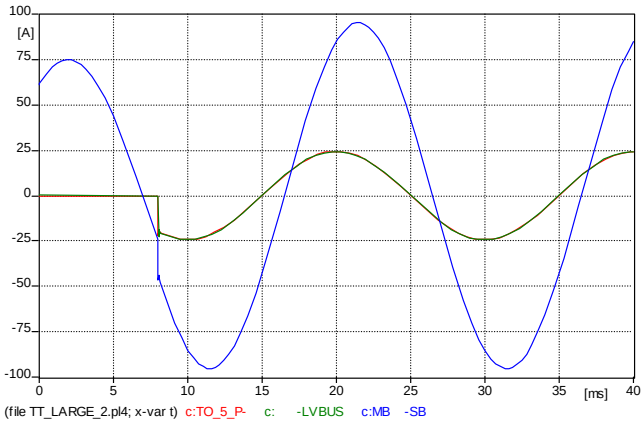


Figure 4.17.5: Fault currents

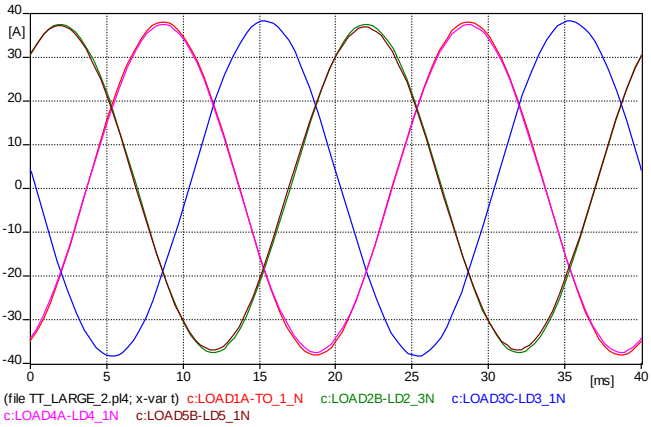


Figure 4.17.6: Currents along the loads

Figure 4.17: ATP calculation results for the circuit of fig. 4.16, considering fault at load 5.

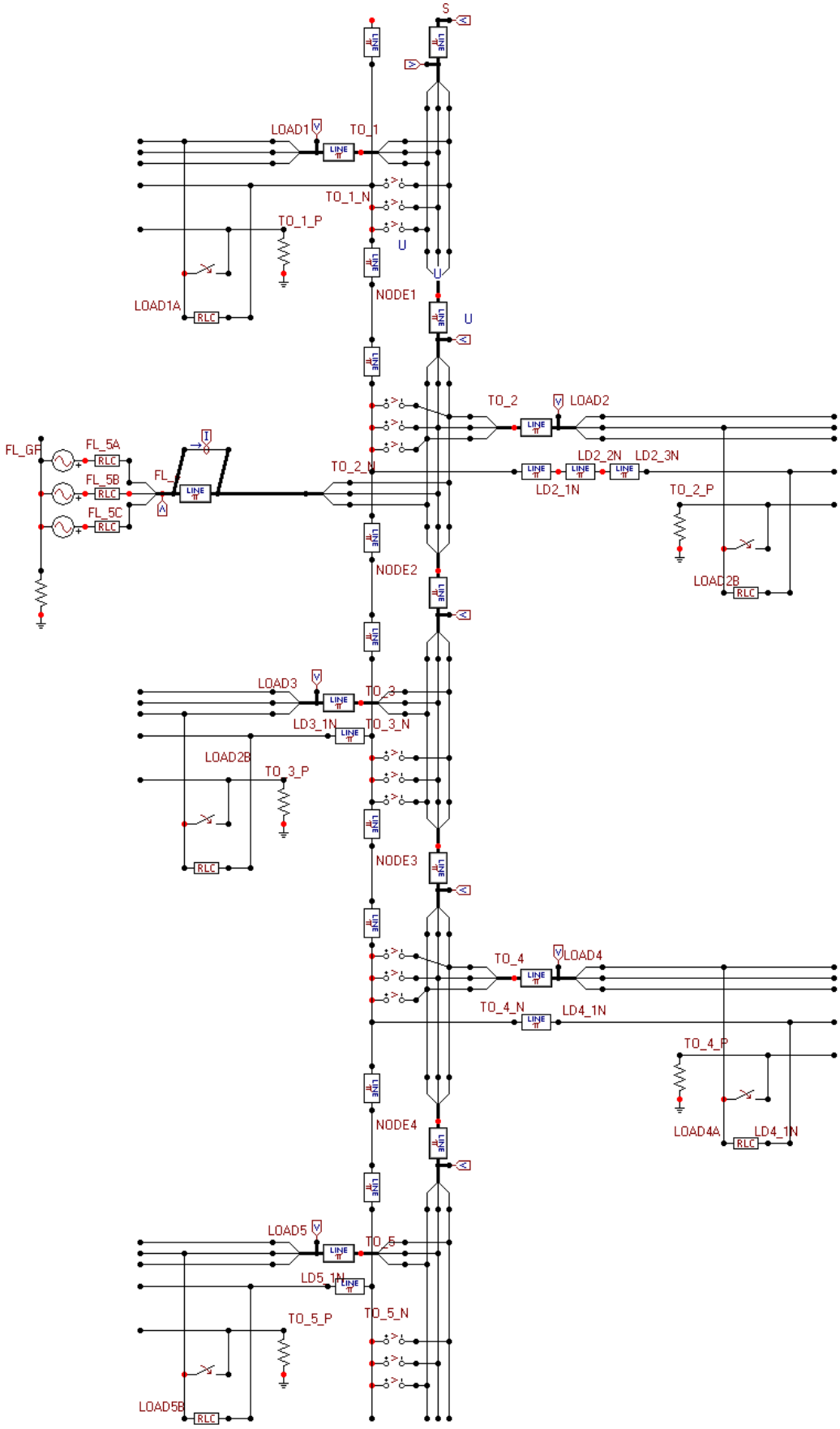


Figure 4.18: ATPDraw circuit representation of the LV network for the sixth study case.

6th Case

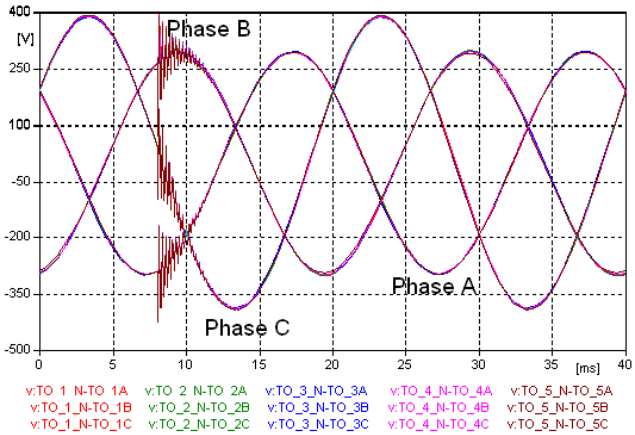


Figure 4.19.1: Phase to Neutral Voltages at various nodes of the circuit.

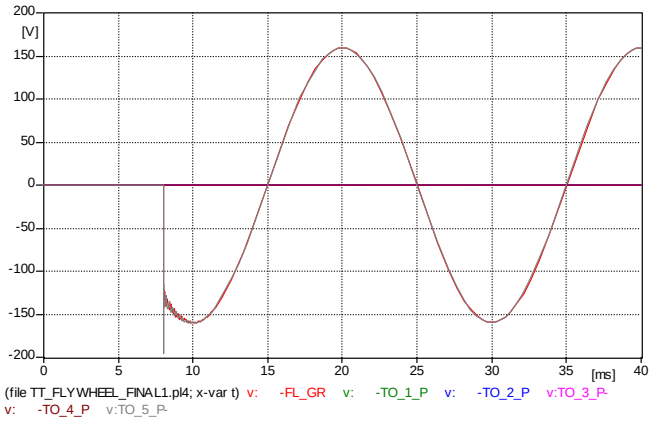


Figure 4.19.2: Touch voltages at various points of the circuit.

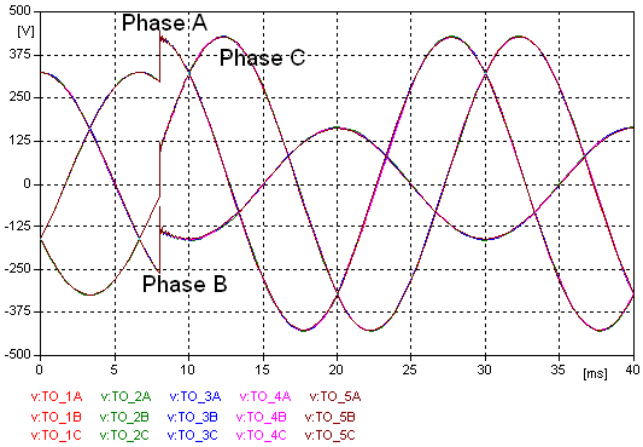


Figure 4.19.3: Phase voltages at various nodes of the circuit.

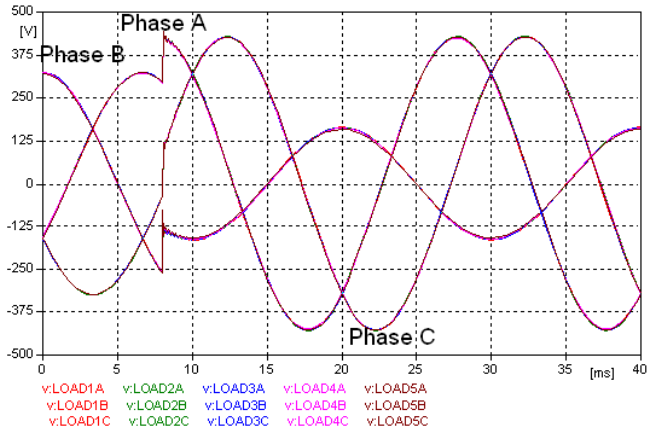


Figure 4.19.4: Phase voltages at load connection points.

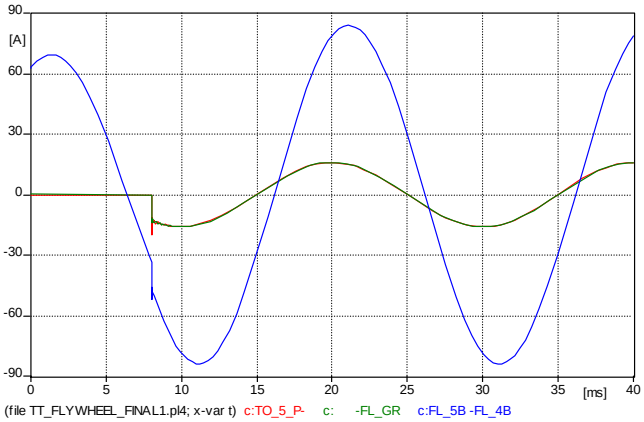


Figure 4.19.5: Fault currents.

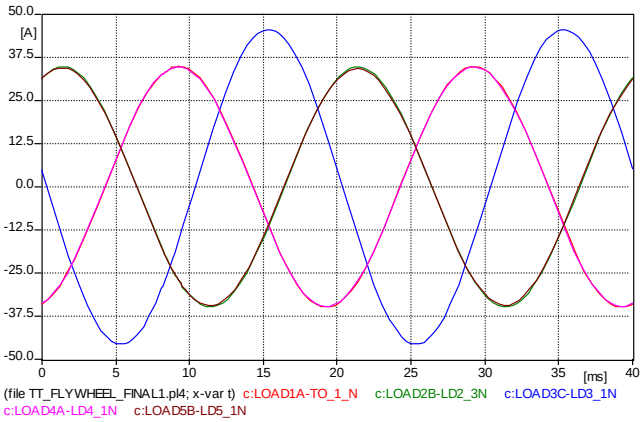


Figure 4.19.6.: Currents along the loads.

Figure 4.19: ATP calculation results for the circuit of fig. 4.18, considering fault at load 5.

4.3 Discussion and conclusions

Case 1

Phase A to neutral voltages are reduced, while the voltages of phases B and C are not influenced by the short-circuit. Voltages to earth of the neutral and PE conductors at all nodes of the network do not exceed 20 V and therefore do not present any threat. The short circuit current is of the order of 2 kA, ensuring thus the fast operation of the overcurrent protection.

Case 2

The voltages of the healthy phases are slightly increased, particularly near the end of the feeder. Voltages to earth of the neutral and PE conductors at all nodes of the network will rise to maximum values of the order of 140V, necessitating the fast operation of protections, which is possible, but not guaranteed with fault currents of approximately 400 A (a known issue in TN networks, when faults occur far from the source).

Case 3

The apparent reduction of the total earthing impedance of the network, due to the loss of the substation neutral earth, results in healthy phase voltages increased by 25-30%, which is quite significant. Voltages to earth of the neutral and PE conductors at all nodes of the network do not exceed 60V, while the fault current of 1.5 kA ensures fast operation of the overcurrent protection. However, it is questionable whether small distributed resources could supply fault currents of such a magnitude, corresponding to a fault power of about 1 MVA.

Case 4

The limitation of the inverter fault current contribution to approximately 200 A (three times its rated current) results in small over-voltages for the healthy phases, as well as between the N/PE conductors and earth, ensuring thus the safety of operation, even though the low resistance neutral earthing point at the MV/LV substation is now outside the circuit. However, the selective operation of over-current protection along the network is questionable with such low current values and has to be further examined. Nevertheless, the investigation of this case should be repeated with a

detailed inverter model, because the current limiting function was here realized in EMTP by simply increasing the series impedance of the inverter to a suitable value.

Case 5

It is observed that the application of the TT system results in very low fault currents, which would hardly lead to the operation of any overcurrent protection device. This is due to the non-negligible earthing resistances (primarily at the consumer premises and secondarily at the source), leading also to the appearance of high touch voltages. This is a well-known characteristic of the TT earthing system, which is recommended only with good earthing provisions. In addition, the use of Residual Current Breakers (RCBs) is always stipulated by the standards.

Case 6

Remarks similar to those for Case 5 apply here as well. In the isolated mode of the TT grounded network, very low fault currents and high touch voltages are observed, along with large voltage increases in the healthy phases. Nevertheless, the operating and safety problems are not aggravated compared to the grid-tied mode. It is not that the inverter current limitation is irrelevant here, because very small fault currents are expected.

Hence, from the study cases presented in the previous sections it is deduced that EMTP can be easily applied to the study of the MicroGrid earthing systems. It can easily represent the complexity of actual networks with sufficient detail and accuracy, while the simulation times required are not prohibitive at all.

Regarding the earthing arrangements of the network, it appears that the TN system with a multi-grounded neutral is rather preferable to the TT system. Most significant though is the observation that the isolated operation of a MicroGrid does not pose any exceptional requirements on the earthing arrangements of microsources and consumer premises. Situations with potentially dangerous touch voltages may indeed appear, but the same would happen if the network operated in the grid-tied mode, i.e. the problem is not associated with the islanded operation and the microsources. Hence, the main issue remains the design of suitable protection systems, to effectively deal with the reduced fault level and the non-radial feed of faults in the islanded mode of operation.

5.0 STEP AND TOUCH VOLTAGES

One of the main concerns when designing a grounding system is to ensure that no electrical hazards exist outside or within the substation during normal and fault conditions. Potential gradients will be produced within and around a substation due to the flow of current into the earth during ground fault conditions. During steady state normal conditions, no current or a very small residual current flows in the neutral and grounding system. This residual current is usually less than 10% of the nominal load current and poses no threat to the safety of the system. Therefore safety is usually a concern only during phase to ground faults.

A safe grounding design has two main objectives

1. To provide a path for electric currents in to the earth under normal and fault conditions
2. To ensure the safety of a person in the locality

The primary objectives of this grounding analysis are to propose an earthing system for a typical MicroGrid and to evaluate the safety and adequacy of the proposed design. The safety criterions used are touch voltage, step voltage and ground potential rise.

ANSI/IEEE Standard 80-2000 [1] provides a methodology of determining maximum acceptable values for touch voltage and step voltage. The actual step and touch voltages in and around the substation (for prospective earth fault currents) are evaluated in order to ensure that they are within safe limits.

5.1 Safety in grounding [1]

Safety in grounding is achieved by controlling the interaction of the two grounding systems, 1) the intentional ground, consisting of ground electrodes buried below earth surface and 2) accidental ground, which is temporary and caused by a person exposed to a potential gradient in the locality of a grounded facility. The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energised.

Effects of an electric current passing through the vital parts of a human body depend on the duration, magnitude and frequency of this current. The most common physiological effects in order of severity are threshold of perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage and burning.

If shock currents can be kept below the fibrillation threshold, injury or death may be avoided. Non-fibrillating current is related to the energy absorbed by the body according to the following formula (for durations ranging from 0.03 – 3.0 seconds).

$$S_B = (I_B)^2 \times t_s \qquad \text{Equation (5.1)}$$

Where

S_B = Empirical constant related to the electric shock energy tolerated by a certain percentage of a given population

I_B = Current (rms) through the body (A)

t_s = Duration of the current exposure (s)

The circumstances that make electric shock accidents possible are:

1. Relatively high fault current to ground in relation to the area of grounding system and its resistance
2. Soil resistivity and distribution of ground currents such that high potential gradients may occur at the earth surface
3. A person bridging two points of high potential difference.
4. Absence of sufficient contact resistance or other series resistance to limit the current through the body
5. Duration of the fault and body contact

There are two advantages in high-speed clearance of ground faults.

i. Reduced probability of exposure to electric shock.
ii. Reduced chance of severe injury or death.

High ground gradients due to faults are rare and shocks resulting from high ground gradients are even more rare in reality. Further, such events are often of very short

duration. Therefore it is not practical to design a ground system against shocks that are only painful and do not cause serious injury, i.e. for currents below the fibrillation threshold.

5.1.1 Tolerable body current limit

To ensure safety, the magnitude and duration of the current conducted through a human body should be less than the value that can cause ventricular fibrillation of the heart. It is assumed that 99.5% of the population can safely endure a current with magnitude and duration determined by Equation (5.2), without causing ventricular fibrillation.

$$I_B = \frac{k}{\sqrt{t_s}} \qquad \text{Equation (5.2)}$$

Where

$k = \sqrt{S_B}$ From (5.1)

Fibrillation current is assumed to be a function of individual body weight. Shock energy that can be survived by 99.5% of persons weighing approximately 50 kg is $(S_B)_{50kg} = 0.0135$. Therefore $k_{50} = 0.116$.

Hence the tolerable body current limit for 50kg body weight is

$$(I_B)_{50kg} = \frac{0.116}{\sqrt{t_s}} \qquad \text{Equation (5.3)}$$

For persons weighing approximately 70kg, $(S_B)_{70kg} = 0.0246$ and $k_{70} = 0.157$

$$(I_B)_{70kg} = \frac{0.157}{\sqrt{t_s}} \qquad \text{Equation (5.4)}$$

It has to be kept in mind that the above equations (5.3) & (5.4) are based on tests limited to a range of time between 0.03- 3.0 seconds and are not applicable for very short or long durations.

5.1.2 Ground resistance of feet

The human foot can be represented as a conducting metallic disc when calculating its ground resistance while the contact resistance of shoes, socks, etc. is neglected.

The ground resistance of a metallic disc of radius b (m) on the surface of a homogeneous earth of resistivity ρ (Ω. m) is given by

$$R_f = \frac{\rho}{4b}$$

Usually, a circular plate with a radius of 0.08 m is used to represent the foot. Thus, the ground resistance of one foot (with presence of the substation grounding system ignored) is

$$R_f = \frac{\rho}{0.32} \qquad \text{Equation (5.5)}$$

The internal resistance of the human body is approximately equal to 300 Ω. However the body resistance including the skin could range from 500 – 3000 Ω. The resistance of a human body, R_B, is taken as 1000 Ω for this study. This resistance could be from hand-to-feet, hand-to-hand or from one foot to the other foot.

5.1.3 Ground Potential Rise (GPR)

GPR is defined as "*the maximum electrical potential that a substation grounding-grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR is equal to the maximum grid current times the grid resistance*" [1].

GPR differences can occur between remote parts of the grounding grid as a result of circulating currents in the substation grounding system. Significant potential differences between distant parts of the grounding system can give rise to local touch voltages or equipment stress voltages when low voltage insulated conductors connect equipment at two such locations [2]. Appropriate protection must be in place at such locations, rated for the GPR differentials that can arise. It is necessary to identify such locations.

The above issues related to GPR differences would be particularly true for grounding systems extending over a large area. However this study is based on a simple grounding system covering a small substation area. Thus GPR differences would not be a safety concern in this case.

5.1.4 Touch voltage

An accidental ground circuit is established when a person is exposed to a potential gradient in the vicinity of a grounded facility. The tolerable body current, I_B, defined by Equation (5.3) or (5.4), is used to define the tolerable total effective voltage of the accidental circuit (touch or step voltage).

ANSI/IEEE Standard 80-2000 defines the touch voltage as "*the potential difference between the GPR and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure*".

Figure 4.1 shows an accidental circuit where a person is exposed to a touch voltage. The fault current, I_f, is discharged to the ground by the substation grounding system and the human body. This person is touching a grounded metallic structure at Point H, which is at the same potential as the station grid. F is the small area on the surface of the earth that is in contact with the person's two feet. The current, I_b, flows through the body of the person to the ground.

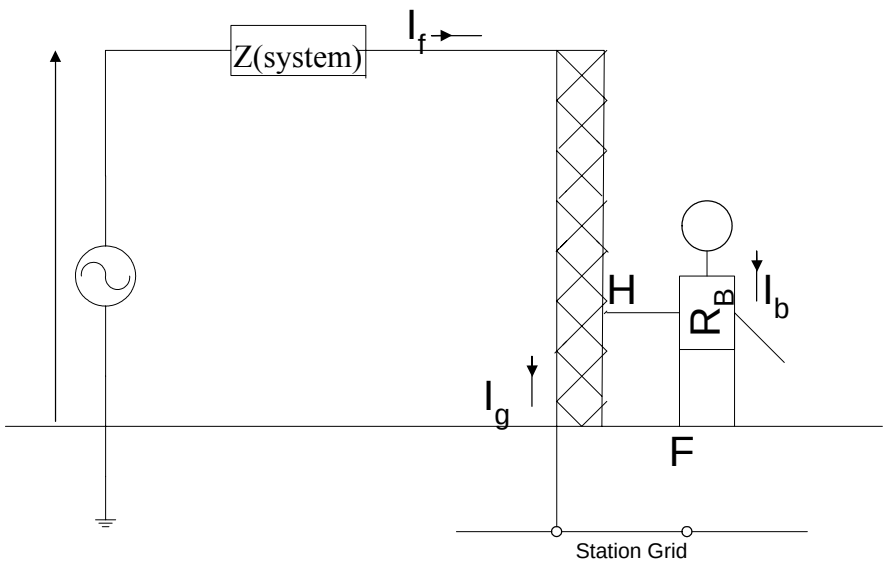


Figure 5.1: Exposure to touch voltage [1]

Using the Thevenin theorem, we can represent the above network by the circuit in Figure 5.2. The Thevenin voltage V_{TH} is the voltage between terminals H and F when the person is not present. The Thevenin impedance Z_{TH} is the impedance of the system as seen from points H and F with voltage sources of the system short-circuited. R_B is the resistance of the human body.

A conservative value for the Thevenin impedance of this circuit is given by $Z_{TH} = \frac{R_f}{2}$. A detailed derivation of this value can be found in the report "MicroGrid Grounding system Analysis" presented in Appendix VIII of this report.

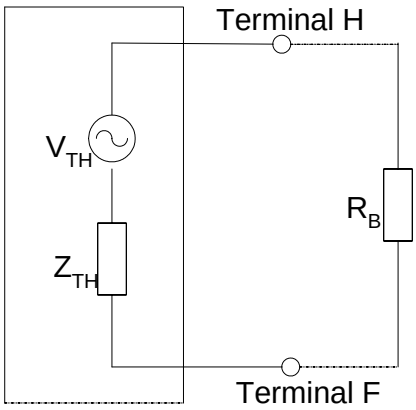


Figure 5.2: Touch voltage circuit [1]

Hence, the Thevenin impedance for touch voltage accidental circuit with uniform soil resistivity,

$$Z_{TH} = \frac{R_f}{2} \Rightarrow Z_{TH} = 1.5 * \rho \qquad \text{From Equation (5.5)}$$

The current through the body of the person, I_b, is given by

$$I_b = \frac{V_{TH}}{Z_{TH} + R_B} \qquad \text{Equation (5.6)}$$

The tolerable touch voltage in V

$$E_{touch} = I_B \times (R_B + 1.5\rho) \qquad \text{Equation (5.7)}$$

For body weight of 50kg, from (5.3) and for $R_B = 1000\Omega$

$$E_{touch,50} = (1000 + 1.5\rho) * \frac{0.116}{\sqrt{t_s}} \qquad \text{Equation (5.8)}$$

For body weight of 70kg, from (5.4) and for $R_B = 1000\Omega$

$$E_{touch,70} = (1000 + 1.5\rho) * \frac{0.157}{\sqrt{t_s}} \qquad \text{Equation (5.9)}$$

5.1.5 Step voltage

Step Voltage is defined as "*the difference in surface potential experienced by a person bridging a distance of 1m with the feet without contacting any grounded object*" [1].

Figure 4.3 shows an incident where a person is exposed to a step voltage. F1 and F2 are the areas on the surface of the earth that are in contact with the two feet. The fault current, I_f, is discharged to the ground by the substation grounding system. The current, I_b, flows from one foot F1 through the body of the person to the other foot F2.

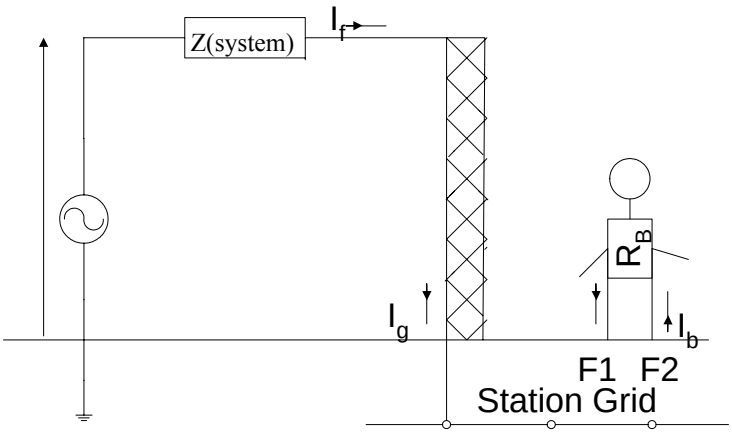


Figure 5.3: Exposure to step voltage [1]

Using the Thevenin theorem, we can represent the above network by the circuit in Figure 5.4. The Thevenin voltage V_{TH} is the voltage between terminals F1 and F2 when the person is not present. The Thevenin impedance Z_{TH} is the impedance of the system as seen from points F1 and F2 with voltage sources of the system short-circuited. R_B is the resistance of the human body.

The current through the body of the person, I_b, is given by Equation (5.6) in touch voltage section.

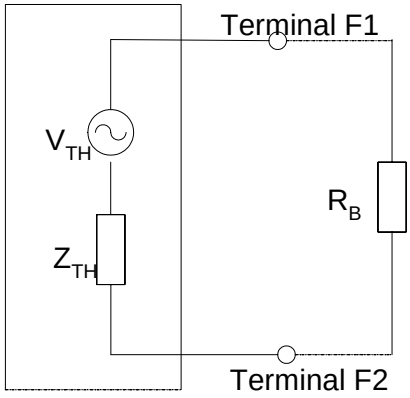


Figure 5.4: Step voltage circuit [1]

For step voltage accidental circuit, with uniform soil resistivity

$$Z_{TH} = 2 * R_f \Rightarrow Z_{TH} = 6 * \rho \qquad \text{From Equation (5.5)}$$

The tolerable step voltage in V

$$E_{step} = I_B \times (R_B + 6\rho) \qquad \text{Equation (5.10)}$$

For body weight of 50kg, from (5.3) and for $R_B = 1000\Omega$

$$E_{step,50} = (1000 + 6\rho) * \frac{0.116}{\sqrt{t_s}} \qquad \text{Equation (5.11)}$$

For body weight of 70kg, from (5.4) and for $R_B = 1000\Omega$

$$E_{step,70} = (1000 + 6\rho) * \frac{0.157}{\sqrt{t_s}} \qquad \text{Equation (5.12)}$$

5.2 Safety Criterion

MicroGrid ground system safety analysis is based on the step and touch voltage criterion. The maximum driving voltage of any accidental circuit (step or touch voltage) should not exceed the limits defined in the above sections (Equations 5.8, 5.9, 5.11 and 5.12).

It has to be noted that the above equations have been derived on the assumption of uniform soil resistivity. However a 3-6 inch layer of high resistivity material such as gravel is often spread on the earth surface above the ground grid. This is carried out to increase the contact resistance between the soil and the feet of persons in the substation vicinity. In turn, the current through the body of a person is lowered considerably.

The expression for the ground resistance of the foot on a thin layer of surface material is different from Equation (5.5), which was derived for a homogeneous soil. Our study is based on the assumption of uniform soil resistivity in the substation ground. Therefore we are not considering the effects of a layer of surface material. However, these effects and the resulting equations are presented in Appendix VIII.

The maximum allowable voltage limits have to be calculated and then the touch and step voltages in and around the substation need to be examined. The safety of the substation ground was determined by ensuring that the step and touch voltages did not exceed the above-mentioned safe limits.

5.3 Simulation study

This study is based on the simplified MicroGrid model of the study case network proposed by NTUA, which is shown in Figure 5.5. The 20/0.4 kV distribution transformer secondary is earthed and this earth resistance is equal to 3Ω.

The earthing system to be used in the MicroGrid had been proposed as TN-C-S or TT [3]. The fault current distribution in the MicroGrid for a phase to ground fault had been determined [4]. The electrical protection schemes for the MicroGrid had been defined and the highest fault clearing time is 0.7 seconds [5]. The system frequency is 50 Hz and the system X/R ratio is taken as equal to unity. The soil resistivity is assumed to be uniform and is equal to 100Ωm.

The specialist grounding software, CDEGS, was used for the computer modelling. One of its subsystems, MALZ, was used as the simulation tool in this particular study. MALZ calculations are based on IEEE standard 80.

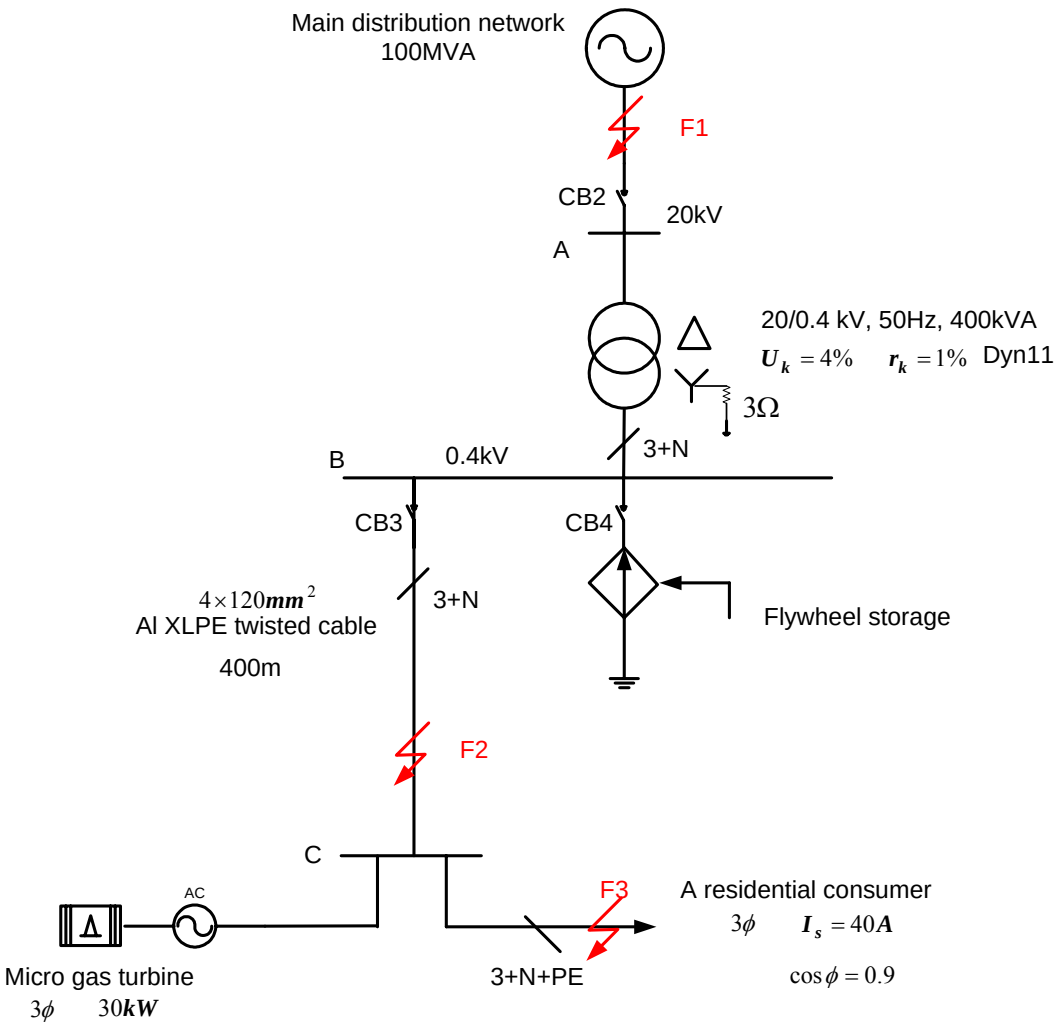


Figure 5.5: A simple MicroGrid model derived from NTUA study case network

5.4 The substation grounding system design

A grounding system is installed to ensure the safety of people or equipment under normal or fault conditions. The system should also ensure continuity of service.

The grounding design analysis is normally carried out in six major steps [6]

1. An equivalent soil model to the real earth structure is determined.
2. A preliminary economical grounding system configuration is developed. Its performance is analysed based on an assumed fault current magnitude discharged by the grid.
3. The actual fault current discharged by the substation grounding system is determined.

4. The results are analysed to determine whether all the design requirements are met. In particular, the safe step and touch voltage thresholds are determined based on the applicable standards and regulations and those are compared with the computed actual voltages.
5. If all design requirements are not met the initial design is modified and design analysis is restarted at Step 2
6. If seasonal soil resistivity variations must be accounted for then the entire analysis is repeated for every realistic soil scenario and the worst-case scenario is used to develop the final design.

5.4.1 Soil model

A uniform soil model with a soil resistivity of 100 Ωm was assumed in this MicroGrid grounding system design.

5.4.2 Initial design of the grounding system

According to the step 2 of the design methodology, a preliminary system has to be configured. A grounding grid is a system of horizontal ground electrodes buried in the earth. A typical grid usually is supplemented by a number of vertical ground rods and may be further connected to auxiliary ground electrodes to lower its resistance with respect to remote earth. The common practice of most utilities is to use a combined system of vertical rods and horizontal conductors.

A system that combines a horizontal grid and a number of vertical ground rods penetrating lower soils was selected as the initial design. Such a design has the following advantages [1]

a) Horizontal conductors of a grid buried in a shallow depth (usually 0.3 – 0.5 m below earth surface) help to reduce high step and touch voltages on the earth's surface while sufficiently long ground rods help to stabilize the performance of such a combined system.
b) For a two-layer or multilayer soil with a higher earth resistivity in the upper soil layer, rods penetrating the lower resistivity soil are far more effective in dissipating fault currents.

c) If the rods are installed predominately along the grid perimeter, they will help to control the steep increase of the surface gradient near the peripheral meshes.

The initial design of the grounding system is as illustrated in Figure 5.6. This system consists of a 5m * 5m grid of four horizontal conductors along with four vertical ground rods at each corner of grid. Each vertical rod is 5m long and the grid is buried at 0.5 m depth.

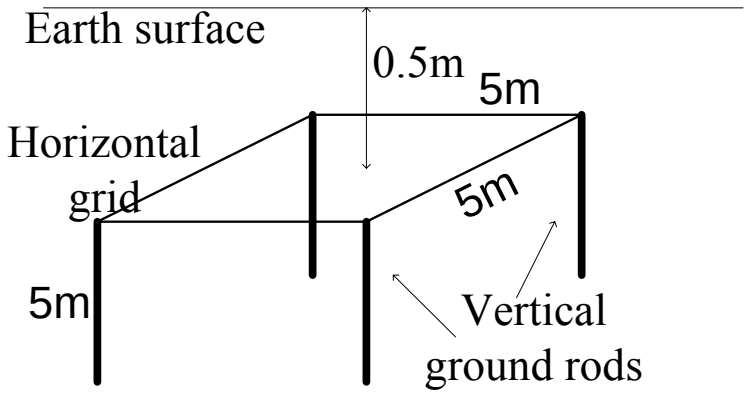


Figure 5.6: Preliminary design of the grounding system (not to scale)

5.4.3 Fault current calculation

The fault current distribution in the study case MicroGrid was determined in Chapter 3 of this report. Therefore the Step 3 of the design had already been completed.

Faults had been applied at the main distribution network (F1), MicroGrid network (F2) and at a load end (F3) during grid connected operation and islanded operation. The currents injected to the earth due to the faults F2 and F3 only influence the performance of the substation ground system. Therefore only the earth currents due to F2 and F3 are considered. The fault current distribution in a MicroGrid for TN and TT systems is as given in Table 5.1.

According to this table, the maximum possible earth fault current in a MicroGrid for a TT system or a TN system is in the order of 18 A. Therefore 20A was chosen as the earth fault current being discharged to the ground and this value is used to analyse the performance of the preliminary grounding design.

Grid connected operation			
Fault type	Earthing system	Total Fault current (A)	Total earth current (A)
F2	TN	14,828	0
	TT	17.8	17.8
F3	TN	858	8.7
	TT	17.6	17.6
Islanded operation			
Fault type	Earthing system	Total Fault current (A)	Total earth current (A)
F2	TN	1462	0
	TT	17.5	17.5
F3	TN	558	5.7
	TT	17.4	17.4

Table 5.1: Fault current distribution in a MicroGrid [4]

5.4.4 Performance analysis of the initial design

The ground grid performance including its ground impedance needs to be determined in this stage. In the analysis of the grounding system performance, step and touch voltages were used as the main safety requirements. First, the safe step and touch voltage thresholds need to be estimated.

5.4.4.1 Safe limits for step and touch voltages

The safety threshold values for step and touch voltages need to be calculated first. These parameters would vary in the presence of a layer of surface material on the earth above the grounding system. The safe step and touch voltage limits for different surface layer resistivities are given in Table 4.2 for three different fault clearing times (0.25s, 0.5s and 0.7s). This safety calculation table had been generated using MALZ, for a body weight of 50 kg.

Safety Calculations Table

```
System Frequency.............................(Hertz).:  50.000
 System X/R.........................................:  1.0000
 Surface Layer Thickness....................(  in ).:  6.0000
 Number of Surface Layer Resistivities...............:   10
 Starting Surface Layer Resistivity..........(ohm-m).:   NONE
 Incremental Surface Layer Resistivity.......(ohm-m).:  500.00
 Equivalent Sub-Surface Layer Resistivity....(ohm-m).:  100.00

 Body Resistance Calculation..........: IEEE 80
 Fibrillation Current Calculation.....: IEEE 80 (50kg)
 Foot Resistance Calculation..........: IEEE (Std.80)  Series Expansion Cs
    User Defined Extra Foot Resistance:   0.0000     ohms
```

Fault Clearing Time (sec)	0.250	0.500	0.700
Decrement Factor	1.006	1.000	1.000
Fibrillation Current (amps)	0.231	0.164	0.139
Body Resistance (ohms)	1000.00	1000.00	1000.00

SURFACE LAYER RESIST-IVITY (OHM-M)	FAULT CLEARING TIME 0.250 sec. STEP VOLTAGE (VOLTS)	0.250 sec. TOUCH VOLTAGE (VOLTS)	0.500 sec. STEP VOLTAGE (VOLTS)	0.500 sec. TOUCH VOLTAGE (VOLTS)	0.700 sec. STEP VOLTAGE (VOLTS)	0.700 sec. TOUCH VOLTAGE (VOLTS)	FOOT RESIST-ANCE: 1 FOOT (OHMS)
NONE	**374.6**	**266.6**	**266.6**	**189.7**	**225.3**	**160.3**	**312.5**
500.0	765.4	364.3	544.7	259.2	460.3	219.1	1160.1
1000.0	1237.7	482.3	880.8	343.2	744.4	290.1	2184.5
1500.0	1708.2	600.0	1215.5	426.9	1027.3	360.8	3204.8
2000.0	2178.1	717.4	1550.0	510.5	1310.0	431.5	4224.1
2500.0	2647.9	834.9	1884.2	594.1	1592.5	502.1	5242.9
3000.0	3117.5	952.3	2218.4	677.6	1874.9	572.7	6261.5
3500.0	3587.1	1069.7	2552.6	761.2	2157.3	643.3	7280.0
4000.0	4056.7	1187.1	2886.8	844.7	2439.8	713.9	8298.5
4500.0	4526.4	1304.5	3220.9	928.3	2722.2	784.5	9317.0

*** NOTE * Listed values account for short duration asymmetric waveform decrement factor listed at the top of each column.**

Table 5.2: Safety calculation Table generated by MALZ

According to the above table, the safe limits for touch and step voltages for a homogeneous soil (the case with no surface layer) are 266.6V and 374.6V respectively (for a fault clearing time of 0.25 seconds). The safe voltage limits are increased for higher surface layer resistivities and faster fault clearing times. The safety calculation table above demonstrates this fact clearly.

These same limits for a homogeneous soil could be determined using Equations (5.8) and (5.11), for a body weight of 50 kg and a fault clearing time of 0.25 seconds.

From (5.8), $E_{touch50,0.25s} = (1000 + 1.5 * 100) * \frac{0.116}{\sqrt{0.25}} = 266.8$ V Equation (5.13)

From (5.11), $E_{step50,0.25s} = (1000 + 6 * 100) * \frac{0.116}{\sqrt{0.25}} = 371.2$ V Equation (5.14)

However, the worst-case scenario was selected to determine the maximum step and touch voltage, i.e. where the fault clearing time is 0.7 seconds according to the proposed protection schemes for the MicroGrid [5]. Therefore 160.3 V and 225.3 V were taken as the safety thresholds for touch voltage and step voltage respectively.

5.4.4.2 Observation profile

In order to determine whether this design is safe, the actual step and touch voltages need to be compared against the above safety limits. The examination of touch voltages could be restricted to the substation. However the step voltages are of interest not just in the substation, but also in the immediate surrounding area of the substation. Therefore in order to examine the step and touch voltages in and around the substation, the observation points were defined to cover an area extending 2m outside the substation. A profile containing observation points spaced 1m apart at the surface of the earth above the grounding system was defined and this profile was replicated every 1m along the grid. Thus eight profiles (P1- P8) were created for the analysis. These profiles are shown in Figure 5.7.

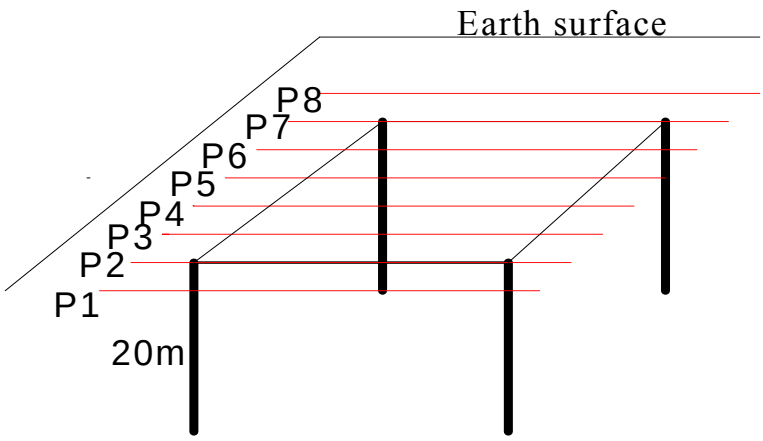


Figure 5.7: Observation profiles (not to scale)

5.4.4.3 Step and touch voltage of the initial design

The touch voltages are shown in Figure 5.8 while the step voltages are shown in Figure 5.9. We have only shown the 2D view for this initial analysis. Profiles 1 and 8 are outside the substation ground area. Profiles 2 - 7 consist of the observation points that fall within the substation ground area. In the profiles 2 –7, within 2m – 7m distance from the origin, lays the substation ground system area. All the other points lie outside of the substation and have been included for further analysis of the immediate area surrounding the substation.

It could be seen that the following profiles are coincident with each other due to the symmetry of the ground design.

Profile 1 with Profile 8
Profile 2 with Profile 7
Profile 3 with Profile 6
Profile 4 with Profile 5

As could be observed from these two graphs, the maximum touch voltage is less than 33 V and the maximum step voltage is approximately 21 V within the substation area. These actual values are well below the previously calculated safety limits (touch voltage limit =160.3 V and step voltage limit = 225.3 V). Therefore this grounding system satisfies the safety criterion.

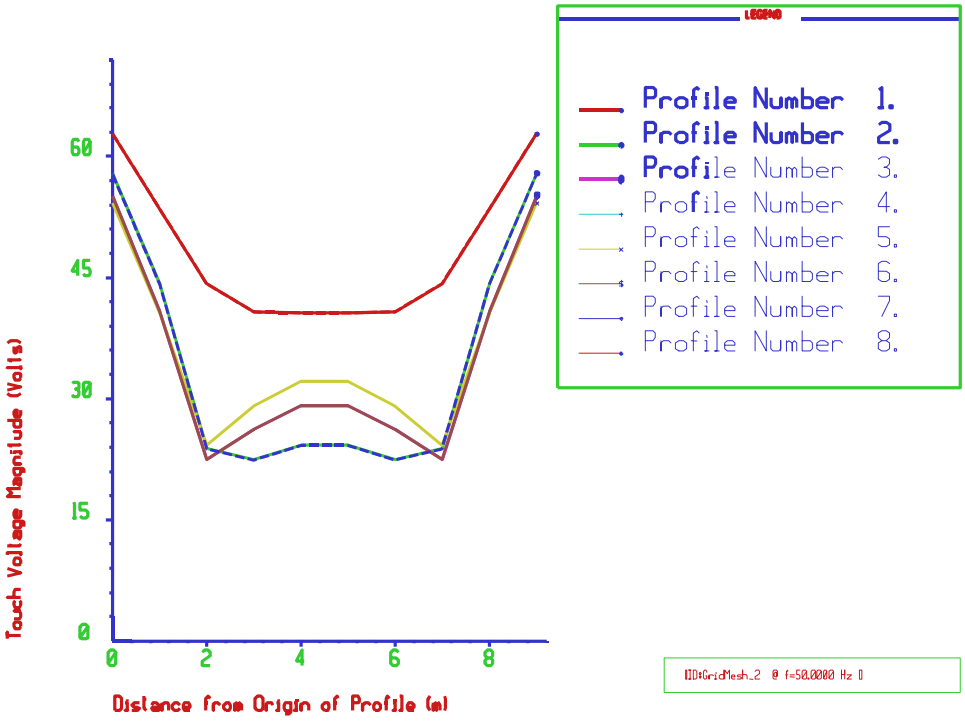


Figure 5.8: Touch voltages for the initial design

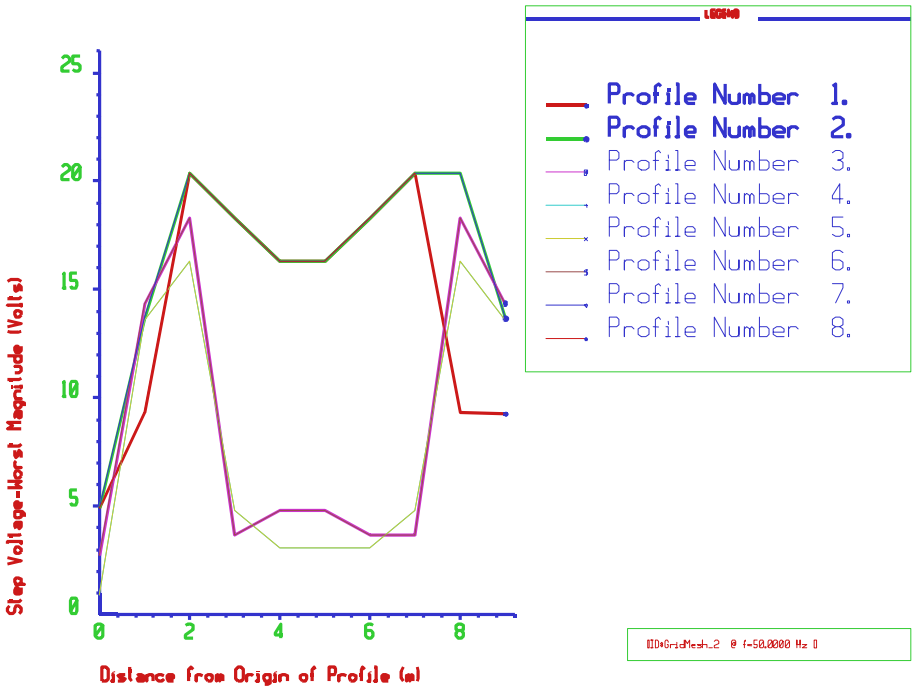


Figure 5.9: Step voltages for the initial design

5.4.4.4 Ground impedance of the initial design

We need to calculate the ground impedance next.

The Ground Potential Rise (GPR)	= 118.27 V
Injected current	= 20 A
Ground impedance	= 118.27 / 20
	= 5.9Ω.

The desired substation ground impedance according to the proposed study case network is 3Ω. Therefore this initial design needs to be modified in order to derive a system of 3 ohms ground impedance.

5.4.5 Modifying the initial design

Some of the parameters affecting the performance of the grounding system are given below.

a. Soil resistivity parameters

Whether the soil is homogeneous or multi layered affects the behaviour of the grounding system. However a homogeneous soil model had been assumed for this study. Therefore the rest of the parameters affecting the grounding system performance are discussed under the assumption of uniform soil resistivity.

b. Grid conductor spacing and arrangement

A larger proportion of the current is discharged from the outer grid conductors than ones at or near the centre of the grid. This is true for ground rods too. Current density is greater in the rods near the periphery of the grounding system than for those in the centre. Thus touch voltage and step voltages are higher near the outer ground rods.

Current density can be made more uniform by employing non-uniform conductor spacing, with conductor spacing larger at the centre of the grid and smaller towards the perimeter.

c. Number of meshes in a grid or number of ground rods

For a given area to be grounded, increasing the number of meshes decreases the resistance of the grid. However this decrease in resistance quickly becomes

negligible for large number of meshes. Increasing the number of ground rods reduces the resistance until the grounded area is saturated.

In addition to the lower resistance and lower GPR, the spacing between the horizontal conductors or rods is reduced. Thus earth surface potential is made more uniform and step and touch voltages are reduced too.

d. Grid burial depth or top-of-the-rod depth

Grid resistance shows a gradual decrease with burial depth until it approaches one half of its resistance value at the surface as the depth increases to infinity. But for typical variations of burial depths (approximately 0.5m –1.5m), this change in resistance with depth is negligible for uniform soil.

e. Length of rods

Increasing the length of the rods is effective in reducing the resistance of the system.

After considering the above factors, two modified designs are proposed for further consideration. The proposed modifications were based on the sole design requirement of reducing the resistance of the initial system to 3Ω. As the earlier design with higher ground resistance satisfied the safety criterion, no further safety evaluation is really required as a system with lower resistance would yield lower step and touch voltages.

5.4.5.1 Modified Ground System A

The number of ground rods and their length is increased. The grid area remains constant at 5m * 5m with four horizontal conductors. Twenty rods are installed along the perimeter of the grid with a spacing of 1m. The length of the rods is 20m. Grid burial depth is 0.5 m. This system is shown in Figure 4.10.

Calculating the ground impedance of the system

The Ground Potential Rise (GPR)	= 58.89 V
Injected current	= 20 A
Ground impedance	= 58.89 / 20 = 2.95Ω.

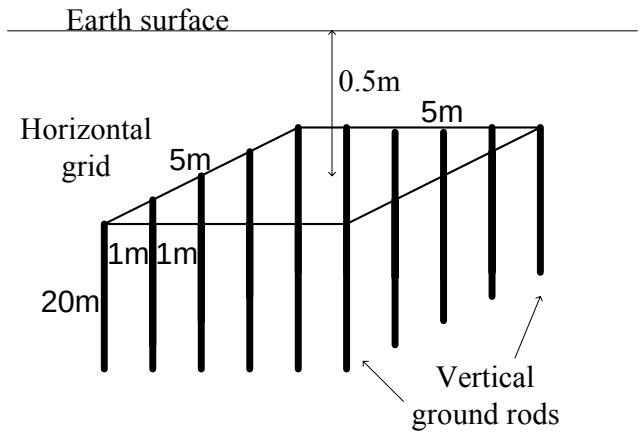


Figure 5.10: Modified ground system A (not to scale)

The total length of conductors in the system = 220 m

5.4.5.2 Modified Ground System B

The initial design is kept the same, i.e. a 5m * 5m grid buried at 0.5 m depth with four 5m long ground rods at the corners. Two horizontal conductors are added to the system as a means of increasing the ground system area because the ground impedance is dependent mainly on the area covered by the grounding grid and is relatively insensitive to the conductor density of the ground. Each of these conductors is 25 m long. This system is illustrated in Figure 5.11.

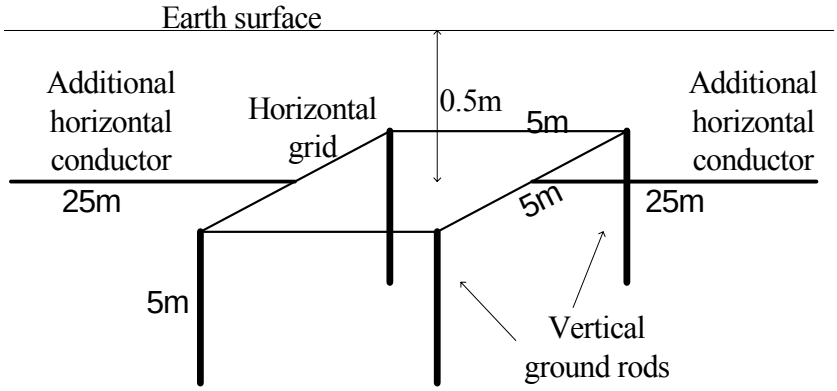


Figure 5.11: Modified ground system B (not to scale)

Calculating the ground impedance of the system

The Ground Potential Rise (GPR)	= 59.83 V	
Injected current	= 20 A	
Ground impedance	= 59.83 / 20	= 2.99Ω.

The total length of conductors in the system = 90 m

5.4.6 Final ground system design

Both the above designs (A and B) have a ground resistance approximately equal to 3Ω, satisfying our design requirement. However, the 'design B' is superior to 'design A' when practicality and cost of implementation are considered. Ground rods in 'design A' are 20m long and that would not be acceptable at a 20/0.4 kV substation ground. The two additional horizontal conductors in 'design B' could be laid along the cable trenches, which are already in place. Thus 'design B' would not incur too many extra costs when applying the design. Therefore we have selected the modified design B as our finalised ground system.

5.5 Performance evaluation of MicroGrid ground system

Now that the ground system is finalised, the safety and the adequacy of the proposed design need to be evaluated. The safety objectives were identified along with the safety criterion previously. The GPR of the system for an injected fault current of 20A is 59.83 V.

Actual step and touch voltages in and around the substation have to be computed. Figures 5.12 – 5.15 show the computed step and touch voltages for profiles 1 to 8, which were discussed in section 5.4.2 (Refer to figure 7). These profiles were taken inside and 2m outside the substation. Profiles 2 - 7 consist of the observation points that fall within the substation ground area. In the profiles 2 –7, within 2m – 7m distance from the origin, lays the substation ground system area. All the other points lie outside of the substation and have been included for further analysis of immediate area surrounding the substation.

5.5.1 Touch Voltages in the MicroGrid

Figure 5.12 shows the two-dimensional view of the touch voltages. Although the observation points had been defined to cover an area larger than the area covered by the substation (mainly to examine the step voltages), the voltages in the substation are the only safety concern with respect to touch voltage. The coincidence of the

following profiles with each other can be observed again. Profile 1 coincides with 8, 2 with 7, 3 with 6 and 4 with 5. This equivalence of profiles is due to the symmetry of the grid design.

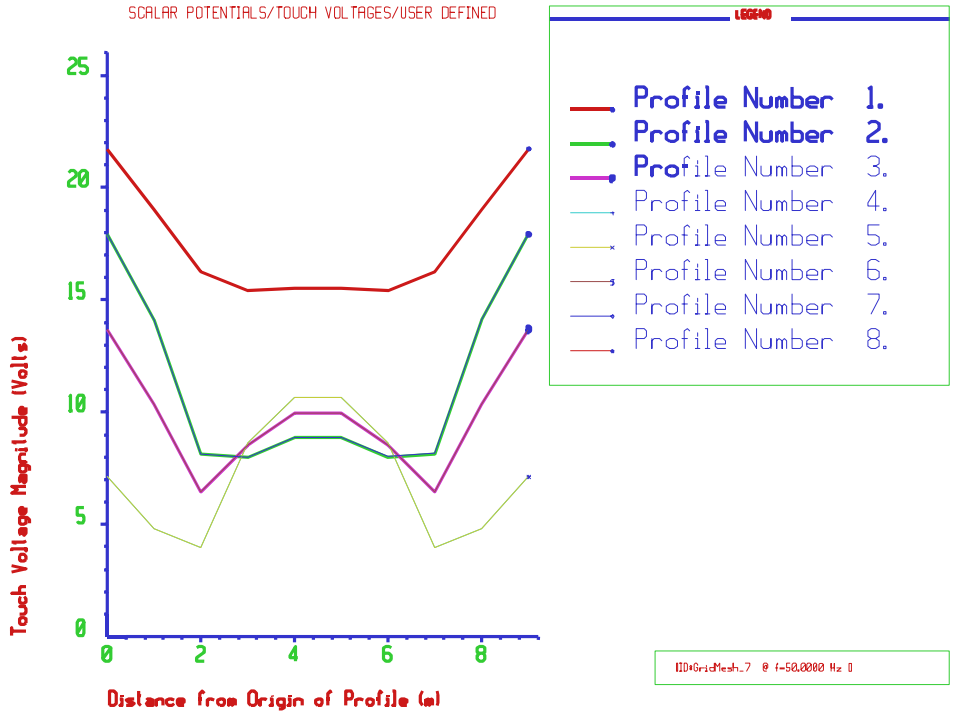


Figure 5.12: Touch voltages of the final design – 2D view

From figure 5.12, it is clear that the maximum touch voltage within the substation occurs towards its centre and is approximately 11V. This is well below the maximum acceptable touch voltage of 160.3V. The touch voltages range from 3V to 11V within the substation and show a considerable increase outside of it.

Figure 5.13 presents the touch voltages over the same area as a 2D spot colour view. The grid configuration is also superposed on for more clarity. It is evident that the touch voltages within the substation area do not exceed 40% of the maximum value of 21.72V, which occurs at 2m outside the substation perimeter.

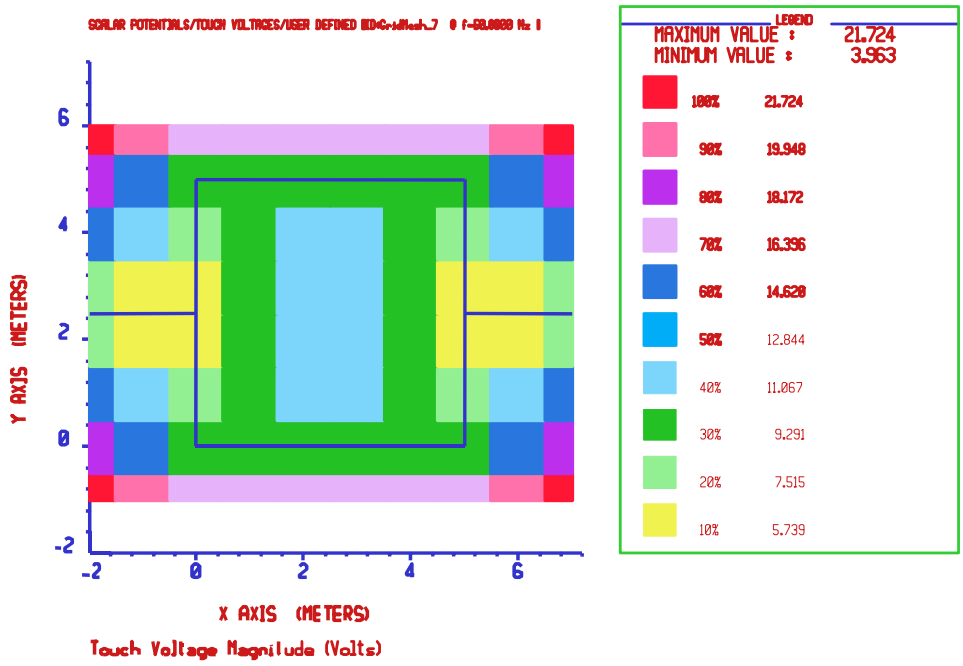


Figure 5.13: Touch voltages of the final design – spot view

5.5.2 Step Voltages in the MicroGrid

Within a substation and within 1m outside the perimeter fence, step voltages are lower than touch voltages. Furthermore, the safety limits for step voltages are higher than for touch voltages. Consequently, satisfying the touch voltage safety criteria for the substation automatically ensures satisfaction of the step voltage safety criteria. However step voltages also have been calculated and are shown in Figures 5.14 and 5.15.

These figures show that the maximum step voltage is approximately 8 V and this voltage occurs at the corners of the grid. The maximum acceptable step voltage is 225 V for the worst-case scenario of 0.7 seconds fault clearing time. It is obvious that there are no safety concerns regarding step voltages in and around this substation at all.

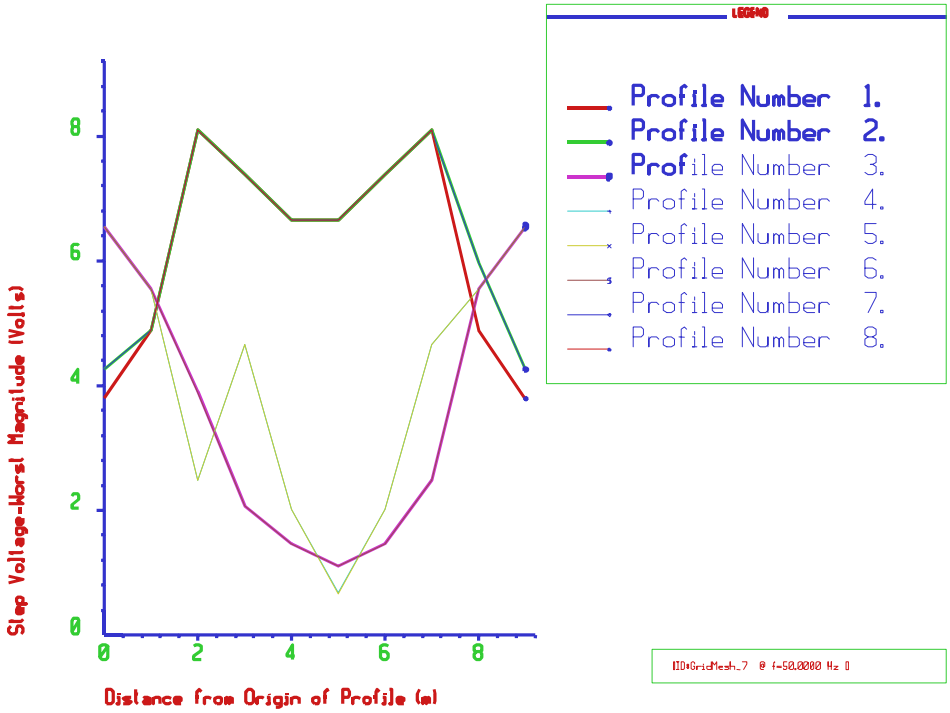


Figure 5.14: Step voltages of the final design – 2D view

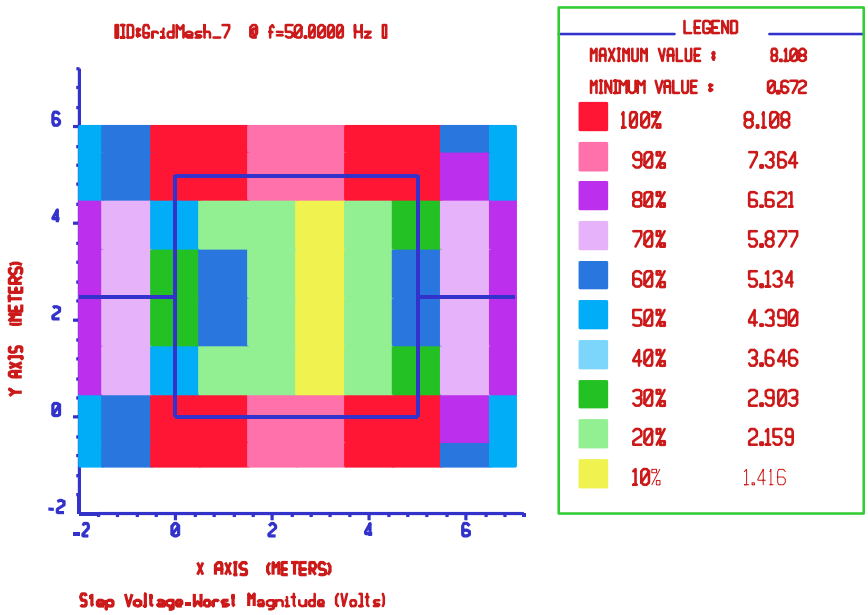


Figure 5.15: Step voltages of the final design – spot view

5.6 Conclusions

A grounding system design for the MicroGrid has been proposed. Its adequacy during fault conditions was studied from an electrical safety point of view. The safety criterion used was the touch voltage and the step voltage.

Step and touch voltages were calculated for several profiles covering the area within and around the substation. The worst-case fault conditions were assumed and the maximum touch voltage within the substation was approximately 11 V, while the maximum step voltage was around 8 V at the corners of the grid. The touch and step voltages were considerably higher outside the substation, but still well below the maximum allowable voltages. The safety limits for touch and step voltages are 160.3 V and 225.3 V respectively. Therefore the proposed ground system complies with the safety requirements.

5.7 References

1. IEEE Standard 80-2000 (Revision of IEEE Standard 80 – 1986), "IEEE Guide for Safety in AC Substation Grounding", 2000

2. "Large Suburban Substation Grounding System Analysis: Measurements and Computer Modelling", Version 8, January 2000, Safe Engineering Services & technologies Ltd., Montreal, Canada

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6. "A Simple Substation Grounding Analysis", Version 8, January 2000, Safe Engineering Services & technologies Ltd., Montreal, Canada

6.0 Conclusions

An extensive literature review was carried out on Low Voltage neutral earthing systems. According to this analysis, the most suitable earthing systems for a MicroGrid have been identified as follows in the order of their suitability.

1. TN-C-S
2. TT
3. IT

The protection guidelines for a MicroGrid propose that the MicroGrid should be disconnected from the main grid only by opening the circuit breaker upstream from the transformer. Therefore the micro-sources could be operated safely without earthing their neutral points locally as the source earth at the distribution transformer would be present after any event. Protective earthing of the micro-sources should be achieved by connecting the generator frame and all conductive parts to a main earthing terminal.

A study was carried out to determine the fault current contributions from various converter designs. According to the findings of this study, the only way to achieve this performance is to increase the rating of the power module. If a fault current in the order of 3 p.u is required, the rating of the module has to be increased by three times its load rating. This option implies incurring greater cost.

The fault current distribution in a MicroGrid for a single-phase-to-earth fault at different locations in grid-connected operation and islanded operation was studied. The major fault current contributor in grid-connected operation was the main distribution network and the micro-source provided only a small fraction of the fault current. The flywheel played a very important role in islanded operation as the main source of fault currents.

This study has re-confirmed the following about the performance of each earthing system. The fault currents in a TN system are high due to the low impedance of the fault loop impedance and the return path for these fault currents is the neutral

conductor and only a small current is directed in to the earth. The fault current values in a TT system are very low compared to TN systems, due to the high earthing impedance in the fault loop. The return path for the fault currents in a TT system is the earth and the total fault current flows in to the ground.

A grounding system design for the MicroGrid was proposed and its adequacy during fault conditions was studied from an electrical safety point of view. The safety criterion used was the touch voltage and the step voltage.

Step and touch voltages were calculated for several profiles covering the area within and around the substation. The worst-case fault conditions were assumed. The maximum touch voltage within the substation was approximately 11 V, while the maximum step voltage was around 8 V at the corners of the grid. The touch and step voltages were considerably higher outside the substation, but still well below the maximum allowable voltages. The safety limits for touch and step voltages are 160.3 V and 225.3 V respectively. Therefore the proposed ground system complies with the safety requirements.

Appendix I: List of reports contributing to DE1

Title of the Report	Authors	
Review of earthing practices in LV networks and installations	M.Lorentzou S.Papathanassiou N.Hatziargyriou (ICCS)	DE1_Appendix II
Low Voltage grounding in the UK Draft 2	N Jayawarna N Jenkins (UMIST)	DE1_Appendix III
Review of Earthing in a MicroGrid	N Jayawarna (UMIST) M.Lorentzou/ S.Papathanassiou (ICCS)	DE1_Appendix IV
Fault Current Contribution from Converters - Draft 1	N Jayawarna N Jenkins (UMIST)	DE1_Appendix V
Application of EMTP for investigating the performance of LV earthing systems	M.Lorentzou (ICCS)	DE1_Appendix VI
Fault current distribution in a MicroGrid	N Jayawarna N Jenkins (UMIST)	DE1_Appendix VII
MicroGrid grounding system analysis	N Jayawarna N Jenkins (UMIST)	DE1_Appendix VIII