Residual Current Protection of a Meshed DC Distribution Grid with Multiple Grounding Points

E. M. Vandeventer
RESIDUAL CURRENT PROTECTION OF A MESHED DC DISTRIBUTION GRID WITH MULTIPLE GROUNDING POINTS

by

E. M. Vandeventer

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Student number: 4413709
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Supervisor: Prof. dr. ir. L. Ramirez Elizondo
Thesis committee: Prof. dr. eng. P. Bauer, TU Delft
Prof. dr. ir. L. Ramirez Elizondo, TU Delft
Dr. ir. J. Rueda Torres, TU Delft

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ABSTRACT

Due to the emergence of renewable sources of energy and the progress in sustainable technologies, it could become very interesting in terms of energy savings and cost efficiency to switch the consumer level of the electrical network from AC to DC. This way, less power conversion would be required, and the meshing of the grid would be possible, hence increasing the reliability and flexibility of the power supply.

Meshing the grid, however, is a challenge in itself. Indeed, it can be desirable to have several power sources connected to the same system, in order to provide for all the loads connected to the network when one of the sources fails. But having multiple sources in the network also means having several grounding points. Using the AC grounding methods, such as resistive grounding, proves problematic.

As a matter of fact, as there are several grounding points in the network, they form a loop in the ground where the current can flow. If the voltage across the grounding points is not null, then a current will be able to flow through the ground. In AC, this was not such a problem, but DC ground currents will corrode the infrastructure around the network, which will prove harmful over time. It is thus necessary to devise a new way of grounding the system.

The method proposed in this MSc thesis is capacitive grounding, which consists of using capacitors to ground the system, instead of resistors or inductors. This will ensure that no current flows through the ground in steady-state, and will consequently prevent corrosion. Grounding the grid through capacitors enables the use of the residual current measurement method to protect the meshed network against ground faults.

Coupled to a smart communication system that divides the network in protection zones, this method will ensure the selectivity of the protection scheme, and will also discriminate net currents circulating through the grid from actual ground fault currents. The protective relays will be able to determine where the ground fault is on the poles with the polarity of the residual current measurement, and will only disconnect that pole, leaving the other half of the network in operation. This selective disconnection will also help improve the reliability of the system, and the consumers will be able to use the network safely.
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E.M. Vandeventer, Rotterdam, August 2016
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<td>Current and voltage levels during a positive pole to ground fault</td>
</tr>
</tbody>
</table>
1

INTRODUCTION

1.1. MOTIVATION

The world of Electrical Engineering is full of discoveries and progress in the field of DC networks and applications. More and more, renewable energies interest individuals who see in them sustainable and profitable sources of electricity. In the mean time, with the advancement of electronics and their spread in the households, the demand of DC power increases. The decentralization of the energy production and the constantly rising demand of power transformation from AC to DC makes a perfect business case for DC networks.

To reduce the amount of losses due to power transformation, several groups of electrical engineers around the world have concluded that a Low Voltage DC grid, or LVDC grid, could be a good alternative to the existing AC network on a consumer level [1, 2]. This would allow the users to connect their sources of renewable energy, such as solar panels, to the network through a reduced amount of power transformation layers, thus increasing the overall efficiency of the transfer. From there, DC power would be readily available on a street level, allowing the users of electric cars to connect them to the network with greater ease, and hence possibly accelerating their spread in the society.

Something that cannot be avoided, however, is the necessity of power transformation. There will always be a need to raise or lower the voltage levels in the electrical network. Reduced losses in the distribution network through higher voltage levels is a fact that holds for DC as well as for AC. This yields that, for DC networks, converters will need to be used, whether they are step-up, step-down, or both. As for every electrical element, these converters have a maximum capacity of power transformation and transport.

With the current radial organization of the network, providing power from an LVDC microgrid to a neighbouring one would mean that the power would need to flow through the MVDC network first, as shown in the left part of Figure 1.1. During peak hours, the converters would already likely be at full capacity,
preventing this kind of power exchange.

If the network was meshed, as it is in the right part of Figure 1.1, there would be a possibility for the power to flow from one LVDC micro-grid to the other without transiting through the MVDC network, and thus avoiding two consecutive power transformations. This would greatly increase the flexibility and the reliability of this LVDC distribution grid in case of a fault on one of the converters, hence increasing the power reliability.

This improved reliability is one of the great strengths of the meshed LVDC distribution grid, but it also complexifies its implementation. Being the layer of the network closest to the end user, its protection is crucial, in particular that against indirect contact with a live part. Currents leaking through the insulation of the cables could very possibly occur in areas with high population density, thus endangering the consumers.

Careful grounding and tuning of the protection schemes would allow the consumers to use the network safely, but now that the latter is meshed, detection and isolation of the faults is more difficult. With different paths for the power to flow to one location, and several ground connections offering return paths for the current, the selectivity of the protection becomes a real challenge. In addition to that, were a person to come in contact with an energized part of the network, the current flow that would result of this contact would be far below the short-circuit current levels, thus indiscernible by these protecting relays, which impacts the sensitivity of the protection. This current could nevertheless be deadly, so it would have to be interrupted soon enough.

The challenge presented by the protection against leakage current, or more generally speaking, against ground faults in a multiple grounding points network, is then the following: faults have to be detected and cleared in a short amount of time to avoid, as much as possible, damage to the consumers. At the same time, supply must be maintained in the healthy parts of the network. These conditions require high levels of sensitivity and selectivity from the protection scheme, as well as a sufficient speed of operation and a careful design of the grounding scheme.

The design of such a protection scheme with the proper grounding configuration for a meshed LVDC distribution grid with multiple grounding points stands at the heart of this Master thesis.

1.2. Problem definition

The network under consideration is a bipolar, meshed low voltage DC distribution grid, which has to be grounded efficiently and has to be protected against ground faults and leakage currents. The following restrictions apply:

- The grid is meshed; it doesn’t follow the standard radial distribution
- The network is bipolar; the voltage levels are +350 V, 0 V (metallic return), -350 V
- The protection should trip in case of:
  - Pole-to-ground fault
  - Direct contact between a person and an energized component
  - Indirect contact between a person and an energized component
  - Current leaking through the insulation
- The protection should not trip in case of unbalanced load
- The protection should trip fast enough to avoid damage to the users of the network
- The network is grounded at multiple locations
- Islanding in case of a fault should be possible, each island with its own grounding point
- Corrosion due to leakage current should be reduced

All these requirements need to be met in order to ensure the safety of the end users of this LVDC distribution grid. They will also help define the characteristics of the grounding and protection schemes, as some might be ruled out because they do not comply to these rules or to the standards in effect in such a system. Short-circuits are out of the scope of this study, as is over-current protection.
1.3. RESEARCH QUESTIONS

Keeping the restrictions described in the previous section in mind, the research questions tackled by this thesis are the following:

- **How can a meshed bipolar LVDC distribution grid be grounded with multiple grounding points?**

  The focus points of this question will be: to devise a method to detect ground faults in a simple bipolar DC system, to find the grounding system that provides the highest level of safety for the network and its users, to determine the type of ground connection that allows the implementation of a multiple grounding point configuration and prevent corrosion, to determine the location of the grounding points, and allow the islanding of parts of the system without losing a connection to ground.

- **How can ground faults be located in a meshed bipolar LVDC distribution grid with multiple grounding points?**

  The focus points of this question will be: to identify phenomena occurring in a meshed bipolar DC grid with multiple grounding points that could tamper with the detection of a ground fault, to come up with a procedure that allows the protection scheme to differentiate these phenomena from actual ground faults (sensitivity), and to propose a method to make the protection scheme selective (ensure a proper localization of the ground faults).

- **How can a meshed bipolar LVDC distribution grid be protected against ground faults?**

  The focus points of this question will be: to determine a procedure to identify ground faults and prevent false tripping in case of transients in the system, to implement the ground fault localization method determined previously, to devise a fault clearing procedure that ensures the safety of the network users, and to build a protection scheme that meets these requirements and those of the standards in effect.

REPORT OUTLINE

Beginning the research that will allow to answer these questions requires a thorough understanding of the state of the art, which can be found in Chapter 2. The effects of voltage and current on the human body will be considered, underlining the importance of a strict monitoring of the system and operating protection scheme. A careful reading of the applicable standards will help establishing the allowable levels of touch voltages and leakage currents. An in-depth study of the possible grounding configurations, defined for radial AC networks, will be carried out to highlight their respective advantages and drawbacks, as well as their effects on the fault current levels.

In Chapter 3, a comparison between the several grounding configurations described in Chapter 2 will be carried out on a simple radial DC network to assess which of those configurations would suit the best to this kind of network. A decision concerning the grounding configuration satisfying safety and stability criteria will conclude this comparison.

From there on, the network under consideration will be expanded to a lightly meshed DC distribution grid with more than one grounding point, and the grounding performances will be studied anew in Chapter 4. The concept of capacitive grounding will be introduced and developed in this chapter to tackle the corrosion problem in such a network, and the possibility of islanding will be discussed.

The network will be extended even further, and several challenges that arise in a meshed DC distribution grid with multiple grounding points will be described, and methods to face them will be defined in Chapter 5. Methods to locate a fault in the meshed network will be discussed, in order to solve the selectivity problem. This chapter will be concluded by a list of requirements the protection scheme has to meet to satisfy safety criteria applicable in such a network.

A protection scheme meeting the requirements listed in Chapter 5 will be developed and explained in Chapter 6. Its performance on a meshed DC distribution grid will be studied, and conclusions will be drawn towards its adequacy in effectively protecting such a network and its users.

Chapter 7 will form a conclusion to this research report and make a summary of all the important results that were found along the research process, and will answer the questions listed above in a concise manner.
The low voltage network is the part of the electricity distribution system closest to the consumers. LVDC grids would thus spread throughout the cities, and households would be directly connected to them. As such, the safety of the users who surround the electric installations is of utmost importance. When currents flow through the human body, the person risks from a slight tingle, to a sharp shock, and eventually to death. The amplitude of the current and the time of exposure are two major factors in the severity of this contact, so limiting them both is crucial to ensure the consumers’ safety.

The first part of this chapter will give an overview of the consequences of a current flowing through the human body, both for alternate and direct currents. Although the network under consideration is in DC, it is still interesting to consider the effects of AC currents on the body in order to be able to compare the two, and draw conclusions about their level of safety.

Carefully grounding the network is a good way to keep the fault currents people could get in contact with under control. The second part of this chapter will hence be a discussion of the different grounding configurations that could possibly be used on a meshed LVDC grid. The grounding practices of HVDC grids will be studied, in order to get an idea of what has already been implemented on the field. The extent to which these grounding practices comply to the LVDC grid requirements will then be put under consideration, and their individual advantages and drawbacks will be compared.

These two parts will give a solid basis to start building the protection scheme that will be developed in the further chapters, and are consequently of importance.

2.1. THE EFFECTS OF CURRENT ON THE HUMAN BODY

If safety regulations are so strict when it comes to electrical equipment, then it is for a very good reason: current can hurt, burn, or even kill. And for that, high currents are not necessary. On the other hand, cases of people surviving a lightning stroke, where current can reach several thousands of amps, have also been recorded. The degree of hazardousness of the current is decided by a combination of current amplitude, contact duration, and the path taken by the current through the body.

Very high currents tend to burn their way through the body, in a phenomenon called "electroporation". Currents of such an amplitude will be detected by the over-current protection of the system, for which speed of operation is crucial [3]. Over-current protection is out of the scope of this study.

The main matter of this thesis concerns the low currents that result from a insulation failure, a high impedance fault, a contact between a person and a live part, for example. The following paragraphs will thus discuss the effects of low AC and DC currents on the human body. Afterwards, a brief explanation about why only the current seems important will be given. The limits drawn by the standard IEC 60479-1 will also be listed for the reader to know what is currently recommended in a low voltage network.
2.1.1. THE EFFECTS OF LOW FREQUENCY AC CURRENT

The present electrical network works in 50 Hz or 60 Hz alternating current, which is actually the worst frequency range for the human body. The tests done on human subjects in the 1940’s-50’s by Charles Dalziel, described in [4, 5], show as much.

These tests also revealed the presence of several body reactions to the current. The standard IEC 60479 [6] sorts these reactions in three categories, depending on the amplitude of the current for frequencies between 15 and 100 Hz. These categories are described in the following paragraphs.

THE PERCEPTION THRESHOLD

For currents below 0.5 mA, none of the test subjects felt anything when in contact with energized electrodes [4]. However, above this value, the volunteers started reporting tingling or prickling sensations. Currents of this magnitude are not dangerous for the human body; nevertheless, they are unpleasant and might provoke a startled reaction if unexpected.

The perception threshold varies depending on the kind of contact between the person and the energized element. If the skin is wet from sweat at the point of contact, then lower currents will be noticed than if the skin was dry. This has to do with the impedance of the skin that decreases when wet and/or salty.

THE LET-GO THRESHOLD

For the test subjects, the higher the current was above the perception threshold, the more painful the sensation was. The volunteers were experiencing more and more sharp and uncontrollable muscle contractions the further the current was increased. At one point, the subjects were actually unable to move the limbs that were in contact with the electrode. The value of the current for which people were not able to control their muscles any more is called the “let-go threshold”, because at this point, the hands that were holding the electrodes were cramped around them, thus incapable of letting them go.

This is due to the fact that, for a certain magnitude of the current, the signals coming from the neurotransmitters are overwhelmed by the current flowing through the muscles, making the brain lose control over them. In the case of the hand, the flexing muscles are stronger than the extending ones, so the hand will clutch on the energized object it got in contact with. The higher the current is, the faster this phenomenon occurs. Contrarily to the perception threshold, timing is of importance here. One can already deduce from this that the speed of operation of the protection scheme is crucial. Indeed, the longer the people cramp around the electrode, the higher the chances are that their body will sustain damage.

THE VENTRICULAR FIBRILLATION THRESHOLD

![Image: Normal cycle of the heart – Figure 17 of IEC 60479-1](image-url)
2.1 The Effects of Current on the Human Body

Figure 2.1 represents the cycle of a normally beating heart. For each cycle, a small electrical impulse is sent from the sinoatrial node (1), making the right and left atria (2) contract and send blood to the ventricles. The impulse is transmitted to the ventricles (3), which in turn send blood to the rest of the body (4 and 5). The first signal is depicted on the electrocardiogram (ECG) by the ‘P’ wave, while the contraction of the ventricles is represented by the spike at the ‘QS’ location. After this effort, the heart relaxes (wave ‘T’ on the ECG), and this part of the cycle is where it is at its most susceptible to shock, as depicted by the triangular wave.

Research has shown [7] that if a current flows through the heart when it is relaxing, and if that current has sufficient amplitude and the impulse lasts long enough, then it could tamper with the impulses sent by the sinoatrial node and shock the heart out of its normal beating cycle. When this occurs, the heart is said to be in “ventricular fibrillation”, and it undergoes erratic contractions, depriving the rest of the body from the normal blood flow, and eventually leading to death. The phenomenon is depicted by Figure 2.2.

The standard IEC 60479-1 states that a current of 40 mA flowing for 10 s through the body from left hand to feet is the lower threshold for ventricular fibrillation to occur. Below this current, the risk for ventricular fibrillation is almost non-existent. However, people with unhealthy hearts can still suffer from fibrillation at lower current levels. With a higher current, a shorter time is required to trigger fibrillation.

If this phenomenon is combined with the muscle paralysis described in the previous paragraph, then it is readily understandable that a prolonged contact with the electrodes greatly increases the risk of ventricular fibrillation. It is also very likely, as the let-go threshold is way below the fibrillation threshold, that a person getting in contact with an energized component will not be able to step away from it before his or her heart fails.

Figure 2.2: Electrocardiogram of a heart sent into ventricular fibrillation by an electric shock – Figure 18 of IEC 60479-1 [6]

**STANDARD VALUES**

The thresholds stated in the previous paragraphs are summarized in the figures 2.3 and 2.4 along with the time dependency described previously.

Figure 2.3: Time-current zones for an AC current (15-100Hz) for a path from hand to feet – Figure 20 of IEC 60479-1 [6]

The threshold value for the ventricular fibrillation depends greatly on the path the current takes through the body. In Figure 2.3 the path from the left hand to the feet is considered. For other paths, different
current levels apply, due to the body impedance and the amount of current that eventually flows through the heart. To account for the different possible paths and the repercussions on the dangerous current levels, a heart factor was implemented [6] (see appendix A.1).

There are worse cases than left hand to feet, namely that of a current flowing directly through the chest of the victim. In that case, less current is necessary to send the heart in fibrillation. However, one could consider that closing a current loop by touching a live component with one of the hands is more likely to occur than closing it with the chest. Additionally, the heart being placed on the left side of the body, the path from left hand to heart offers less resistivity than that from right hand to heart, thus lower currents are necessary to damage it. Therefore, using this path as a reference for the threshold values seems reasonable.

Residual current devices (RCDs), used to detect leakage currents in AC networks, usually trip at 30mA, which is below the lower threshold for fibrillation. By means of fast tripping, the users of the network are hence effectively protected. In areas where wet conditions arise, such as a bathroom, RCDs can be found for rated values as low as 10mA in order to provide even more security.

### 2.1.2. The Effects of DC Current

Without the polarity reversal that are distinctive of alternating current, direct current has a different impact on the human body, but it can just as well lead to death if someone were to get in contact with it.

Nevertheless, as it has been discovered by Charles Dalziel during his tests on human volunteers [4], the perception threshold is actually higher for direct current, with 2mA the lowest value that was felt by one of the subjects. When the current was gradually increased, then the subjects would feel a sensation of heat spreading through the limb in contact with the electrode, but no muscular contractions.

Muscular contractions were not completely absent of the tests, however. Involuntary movements and cramp-like sensations were experienced by the subjects when the current was changing sharply, such as during the breaking of the current. After a while, the pain felt while letting go of the electrode was too great for the subjects to handle, so from there on they refused to make the experiment with higher currents. The current levels they nonetheless endured without losing their capacity to let go of the electrode were higher than the let-go threshold that was experienced in AC.

Because of the fact that direct current only provokes muscular contractions during important variations, there is no real let-go threshold in this case. The sudden cramps occurring whilst removing the hand from the electrode would tend to make someone jerk away from it instead of paralysing him.

With increasing current, burning sensations would occur, along with pain at the contact location. If the current were to reach 300mA, then the person in contact with it would be very likely to faint [6]. But before that, the heart would suffer from damage. Although the behaviour of the heart is slightly different in DC, if the current reaches 200mA for 10s, then it can be lethal.
2.1. The Effects of Current on the Human Body

At such current levels, the heart would not start beating erratically like in AC, but would suddenly stop. Eventually, because the rest of the body would be deprived of oxygenated blood, death would occur if the current flows through the heart long enough. This phenomenon is used in modern defibrillators: when the heart beats frantically, the best way to save the person is to stall his or her heart temporarily for it to recover and come back to its normal cycle [8].

Overall, the thresholds for direct current are higher than for alternating current, making DC safer than AC. These thresholds, as well as their relation to time, are depicted in figures 2.5 and 2.6.

---

Figure 2.5: Time-current zones for an DC current for a path from hand to feet – Figure 22 of IEC 60479-1 [6]

<table>
<thead>
<tr>
<th>Zones</th>
<th>Boundaries</th>
<th>Physiological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-1</td>
<td>Up to 2 mA curve a</td>
<td>Slight prickling sensation possible when making, breaking or rapidly altering current flow</td>
</tr>
<tr>
<td>DC-2</td>
<td>2 mA up to curve b</td>
<td>Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects</td>
</tr>
<tr>
<td>DC-3</td>
<td>Curve b and above</td>
<td>Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected</td>
</tr>
<tr>
<td>DC-4</td>
<td>Above curve c1</td>
<td>Pathophysiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time</td>
</tr>
<tr>
<td></td>
<td>c1 &lt; c2 &lt; c3</td>
<td>DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %</td>
</tr>
<tr>
<td></td>
<td>c2 &lt; c3</td>
<td>DC-4.3 Probability of ventricular fibrillation up to about 50 %</td>
</tr>
<tr>
<td></td>
<td>Beyond curve c3</td>
<td>DC-4.3 Probability of ventricular fibrillation above 50 %</td>
</tr>
</tbody>
</table>

† For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.

---

Figure 2.6: Explanation of the time zones of figure 2.5 – Table 13 of IEC 60479-1 [6]

Once again, the threshold values are defined for one particular path, which is here left hand to feet for an upward current, which means that the current is actually flowing from feet to hand. After experiment on animals [6], it has been discovered that the direction of the current matters in the dangerousness of the contact. Indeed, an upward current is twice as dangerous as a downward current, which is reflected by the fact that the threshold for downward current is twice as high as the other one. Once again, a heart factor, the same as in AC, can be used to calculate the hazardous current levels in the body, depending on the path of the current (see appendix A.1).

The path used by the standard as reference, even though it does not yield the highest risk for the people, is the one that is the most likely to occur, as this is the path the current would take in case of indirect contact, for example1. Hence, considering the threshold values it yields is a good way to ensure the user’s safety.

---

1A person touches the case of his laundry machine, which has a faulty insulation; the current enters the body through the hand in contact, and leaves it through the feet, in contact with the ground.
2.1.3. CURRENT VS. VOLTAGE

From the beginning, only the current has been cited as a danger for the human body. It is indeed the amount of current flowing through the heart that is potentially lethal. However, as it is defined by Ohm’s law, the voltage and the current are closely related. They are linked together by the impedance, and in the case study of this thesis, the human body impedance $Z_{\text{body}}$.

The body impedance, however, is far from being constant. As a matter of fact, it depends on multiple things, such as, among others:

- The area of contact (size, humidity, presence of salt)
- The touch voltage
- The frequency
- The state of the skin

As such, the current flowing through the body does not vary linearly with the touch voltage, which is also an important criterion in designing a protection scheme. All of the above conditions and more have to be determined in order to calculate the maximum allowable voltage for one particular application.

Nevertheless, it is good to remember that the body resistance (DC) is higher than the body impedance (AC) due to the blocking effect of the human skin’s capacitance, which holds until approximately 200V. Above these values of the touch voltage, the skin tends to break down and the values of the body resistance and impedance converge.

Standards, such as the IEC 61201, give information about the physiological effects of voltage on the human body, but this information alone is not sufficient to ensure the safety of the users.

2.1.4. SUMMARY OF THE IMPORTANT VALUES FOR THE PROTECTION

The purpose of this section is to gather the different threshold values for the protection schemes. In order to lower the risks, and to imitate what is done in AC, the current threshold for the residual fault protection of the DC network is chosen to be the lowest ventricular fibrillation threshold, for an upward current flowing between hand and feet. The different threshold values can be found in Table 2.1.

<table>
<thead>
<tr>
<th>Threshold values [mA]</th>
<th>AC</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Let-go</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Fibrillaton</td>
<td>40</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of the different current thresholds

Nonetheless, it can be that the current flowing through a person, in the case of the network under consideration here, will be greater than this limit. To determine the operation requirements of the protection devices, such as speed for example, a few calculations have to be made. Depending on the touch voltage and the body impedance, the current flowing through the person in direct contact with the circuit can be calculated; from there, and with the time-current curve depicted in Figure 2.5, the maximum time of operation of the protection scheme can be determined.

Table 2.2 lists the calculated values. The values of the body resistance are the taken from IEC 60479-1 [6]: the asymptotic values are used to make conservative calculations. This table shows that all the calculated values are above the fibrillation threshold. Direct contact between a person and the network is thus extremely dangerous and the protection scheme needs to trip almost immediately (in less than 10 ms) to ensure the safety of the person.

In the case of indirect contact, e.g. when the insulation of a laundry machine is faulty, the hazard level is lower. Due to the high resistivity of the insulation, the current levels that someone could be subjected to are sensibly lower than in the previous case. Even in the case of a person being in direct contact with the neutral and the ground connector, if a neutral voltage deviation of 50V is considered, the current flowing
### 2.2. POSSIBLE GROUNDING PRACTICES FOR AN LVDC NETWORK

<table>
<thead>
<tr>
<th>Touch voltage</th>
<th>Body resistance</th>
<th>Current</th>
<th>Max. time of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>350V</td>
<td>575Ω</td>
<td>609mA</td>
<td>&lt;10ms</td>
</tr>
<tr>
<td>350V</td>
<td>775Ω</td>
<td>452mA</td>
<td>30ms</td>
</tr>
<tr>
<td>350V</td>
<td>1050Ω</td>
<td>333mA</td>
<td>50ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Touch voltage</th>
<th>Body resistance</th>
<th>Current</th>
<th>Max. time of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>700V</td>
<td>575Ω</td>
<td>1.22A</td>
<td>&lt;10ms</td>
</tr>
<tr>
<td>700V</td>
<td>775Ω</td>
<td>903mA</td>
<td>&lt;10ms</td>
</tr>
<tr>
<td>700V</td>
<td>1050Ω</td>
<td>666mA</td>
<td>&lt;10ms</td>
</tr>
</tbody>
</table>

Table 2.2: Speed of operation calculations for different touch voltages and body resistances

...through the body is below the fibrillation threshold (87 mA in the worst case). In those instances, the most people will experience is warmth in the hands and uncontrolled, possibly painful, muscular contractions when they break the current loop.

The highest touch voltage that will be allowed in the network can be calculated as follows:

$$V_{\text{touch}} = I_{\text{threshold}} \times R_{\text{body, min}} = 150.10^{-3} \times 575 = 86.25V$$

With low current levels, the hazard level is low, but the fault can also be harder to detect. However, if it is detected, the protection scheme of the whole network will have enough time to determine where the fault is located and if it is necessary to disconnect the faulted part, thus ensuring the selectivity. If the fault levels are higher, the fault will have to be cleared sooner, thus leaving less time for the protection scheme to be selective. Selectivity remains important in this case as disconnecting a healthy bus before the unhealthy one could mean irreversible damage to the people in contact with the network. The accurate determination of the fault location is hence of prime importance.

Now that the dangerous currents levels are known, one can focus on the grounding configurations that could be applicable to a low voltage DC distribution grid.

### 2.2. POSSIBLE GROUNDING PRACTICES FOR AN LVDC NETWORK

In practice, even a cable without any voluntary connection to earth will be grounded through the capacitance of its insulation. This phenomenon holds for all the electrical equipment, and it cannot be avoided. Ideally, no current is exchanged between the cable and the ground, but the stray capacitance that connects the two is far from being ideal. The current leaking through the insulation will be really low, but there is a high level of uncertainty as far as where the current loops will close during faults to the ground.

For some configurations, these leakage currents are not problematic, and the degree of safety provided by an ungrounded network is desired. In some other cases, however, the floating voltages stress the insulation to the point of breakdown, which can be dangerous, whether it is for the equipment or for people. In these situations, the connections to earth need to be controlled, and the system is intentionally grounded.

LVDC grids are still in the concept phase, but HVDC connections have already been implemented, for example the NorNed HVDC Interconnector, that links the Netherlands to Norway. Although these systems only consist of radial connections for now, it can be informative to study their grounding schemes. From there, a grounding configuration for the LVDC grid can be imagined, with consideration given to the advantages and drawbacks of the different connections.

#### 2.2.1. STUDY OF HVDC GROUNDING CONNECTIONS

Bipolar HVDC connections provide a high level of reliability due to the possibility to redirect part of the power during a fault on one of the poles. These links allow the connection between the main land and remote wind farms located in the sea, for example. Power is then transferred over long distances with reduced losses.
In cases like that, undersea cables are used to transport the power, so they are very far from the end users.

This is advantageous in the sense that people risk close to nothing with this kind of cable during a fault. However, this also means that any fault on the cable will have a permanent character [9], and maintenance will be more difficult. Careful protection of such a connection is thus crucial. Limiting the fault currents and the overvoltages on the cables via a meticulous design of the grounding scheme is one way to do so.

HVDC links are usually grounded at one of the converters, if not both [10]. In bipolar configurations, the middle point is connected to ground through a low or high impedance, as it is depicted in Figure 2.7.

![Figure 2.7: Grounding configuration of a bipolar HVDC link](image.png)

If the system were to be left ungrounded, even though the steady-state pole-to-ground fault current would be zero, the voltage would reach as high as twice its nominal value on the healthy pole [11], putting the insulation under great strain. Such overvoltages are dangerous for the integrity of the system, and should be avoided in order to increase the life-time of the equipment.

Grounding the middle conductor allows the control of its voltage, and also of the maximum fault current. For such a configuration, three options are available:

- **Solid grounding**: the middle conductor is directly connected to the ground without the intentional addition of an impedance; during pole-to-ground faults, the middle voltage will remain at zero, but the fault currents will be very high. The voltage on the healthy pole will stay at its nominal value.

- **Low impedance grounding**: the middle conductor is connected to the ground through a small resistance or impedance; in this case, the resistance/impedance of the grounding connection will dominate that of the network, limiting the fault current levels. The voltage on the middle conductor remains close to zero during a fault, and the currents are still rather high, even though lower than in the solidly grounded case.

- **High impedance grounding**: the middle conductor is connected to the ground through a high resistance or impedance; the currents flowing through the ground during a fault will be greatly reduced by this resistance/impedance. The disadvantage is, however, that the voltage on the middle and healthy pole will shift to high values. An ungrounded system can be considered to be grounded through an infinitely high impedance, and thus represents the extreme case.

Due to the duality between voltage and current, no optimum can be found. If one were to ground the system through a medium impedance, trying to reduce both the fault current and voltage shifts, then the power dissipated during the fault would negate all these efforts and possibly be even more dangerous. A compromise has to be made between keeping the fault currents low or limiting the overvoltages.

The same grounding principles will be applied later in this research on a small-scale LVDC grid, and the response of the network to a fault in these conditions will be studied. It is probable that the same choice concerning voltage and current levels during a fault will have to be made.

Choosing the grounding connection and its location is crucial in designing the protection scheme. As the types of grounding connection have been discussed in this section, the following part will focus on their location on an LVDC grid.
2.2. Possible grounding practices for an LVDC network

2.2.2. Grounding configurations of an LVDC distribution network

The constraints of an LVDC grid protection are different from those of an HVDC grid, in the sense that many more branches exist, and that the distances are much smaller. The connection of the grid nodes and loads to the ground is essential. As a matter of fact, this connection will determine the return path of the current during a fault, and make the difference in the fault current levels. Indeed, providing a return path parallel to the normal operation path will transform a ground fault into a short-circuit, with very high currents flowing through the ground. This can be very dangerous for the users of the network, especially if they walk on a piece of land through which current flows in high quantities (see Section 2.1).

Inspired from the grounding configurations used in AC systems, four options have been selected to ground an LVDC network [12]:

- **TT-system**: both the system and the load dispose of their individual connections to the ground, with no intentional connection between the two. During a fault to ground, however, these two connections will allow the current to loop and thus its magnitude will be high.

- **TN-system**: the system has its own connection to ground, and the load is connected to it via the middle conductor (TN-C), or via a separate conductor used specifically for that, called protected earth (TN-S). The touch voltage during a fault can rise to unacceptable levels in case of a TN-C network, which makes it probably unfit for use in a residential network [12].

- **IT-system**: the system is left ungrounded, or grounded through a high impedance, and the load disposes of its own ground connection. Due to the high resistance of the fault loop, the fault current and touch voltages will be very low. However, the fault will be difficult to detect, and if left unattended, a second fault could occur and lead to very high current levels [13].

As a contribution to this thesis, the different grounding types, adapted to a bipolar DC system, are described by Figure 2.8.

Different grounding practices also yield the need for an adapted ground fault detection scheme. The simplest method used to detect a ground fault on a line is the residual current measurement method; if the sum of the currents flowing through the poles and the middle conductor is not null, then it means that some current is leaking through the ground, and hence that there is a fault somewhere on the line (see section 3.1). It is necessary to know where the fault current will return into the system, as the measurement devices need to be placed between the fault and the return path of the current to be able to detect the ground fault.

It can happen that ground faults go undetected in IT-systems, where there is no known return path for the current. Because of that, the residual current measurement (RCM) method as it is described in the previous paragraph cannot be used; the risk of not detecting a ground fault is too great. Instead, ground faults are detected by monitoring the insulation of the cables. If its resistance deviates too much from its normal value, then it means that the insulation is breached at one location, and thus that there is a fault somewhere on the line (see section 3.1). Insulation monitoring is an efficient but complicated way of discovering ground faults. One thing can be said about IT-systems in this perspective: even though they are virtually safer than the other systems, due to the fact that two simultaneous ground faults are required to reach dangerous current levels, their protection is made difficult by the fact that there is no known return path for the fault currents. Fault current levels will certainly be higher in other systems, but the faults will be easier to detect and thus protection will be simpler.

There is a compromise that has to be made between low fault current levels and straightforward protection. The following section makes a summarizing list of the different grounding scheme possibilities and the fault detection methods that would be applicable to an LVDC micro-grid, located on a residential level.

2.2.3. Review of the grounding scheme possibilities

Sections 2.2.1 and 2.2.2 gave an overview of the grounding schemes that could be implemented in the LVDC network under consideration. The former described the available earthing connections, with their impact
Figure 2.8: Grounding types for a bipolar DC network

Table 2.3 summarizes all these options and the different combinations that can be made to ground the system. The column “ground connection” only concerns the grounding point at the source, if applicable.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Ground connection</th>
<th>$I_{fault}$</th>
<th>$\Delta V_{gnd,fault}$</th>
<th>Measurement method</th>
<th>Threshold value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>High impedance</td>
<td>low</td>
<td>high</td>
<td>Current difference</td>
<td>150 mA</td>
</tr>
<tr>
<td></td>
<td>Low impedance</td>
<td>high</td>
<td>low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>very high</td>
<td>very low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN-C/S</td>
<td>High impedance</td>
<td>low</td>
<td>high</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low impedance</td>
<td>high</td>
<td>low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>very high</td>
<td>very low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT</td>
<td>-</td>
<td>very low</td>
<td>very high</td>
<td>Insulation monitoring</td>
<td>Clearance when first fault detected</td>
</tr>
</tbody>
</table>

These grounding practices were mostly developed for AC networks with a single grounding point, so a few adaptations are expected before the correct grounding scheme is found for an LVDC distribution grid with several grounding points. In addition, insulation monitoring can be used for all configurations but it complicates the protection scheme, so the residual current measurement is preferred to it. If the latter method proves insufficient to protect TT- and TN-systems, then insulation monitoring will be considered as well.
Multiplying the number of ground connections divides by almost as much the amount of current that will flow through each of them during a ground fault. On the other hand, it also means that a larger area will be affected by this ground fault. Additionally, it can also lead to current flowing through the ground in steady-state, because of an unbalance somewhere in the network. An AC current flowing through the ground is not a problem, but a DC current will provoke corrosion, due to its continuous nature [15]. The phenomenon will be explained in the following paragraph.

2.2.4. THE CORROSION PROBLEM

DC leakage currents flowing through the ground will provoke corrosion on the metallic elements they encounter [15]. The amount of metal that reacts to such currents is calculated in the following fashion:

\[
m_{\text{metal}} = kIt
\]  

With:

- \( m_{\text{metal}} \): the mass of metal that reacts (in grams)
- \( k \): the electrochemical equivalent, constant which value depends on the metal considered (in gram per coulomb)
- \( I \): the current (in amperes)
- \( t \): the duration of the current flow (in seconds)

An example: if the DC currents encountered a zinc pipe \((k=3.39 \times 10^{-4} \text{ g/C})\) and were flowing continuously for one year, then the pipe would lose:

- If \( I = 1 \text{ pico-amps} \): \( m_{\text{metal}} = 3.39 \times 10^{-4} \times 1 \times 10^{-12} \times (60 \times 60 \times 24 \times 365) = 10.7 \text{ ng} \)
- If \( I = 100 \text{ nano-amps} \): \( m_{\text{metal}} = 3.39 \times 10^{-4} \times 1 \times 10^{-7} \times (60 \times 60 \times 24 \times 365) = 1.07 \text{ mg} \)

Overtime, the pipe could rupture due to the corroding effect of the current through the ground. This could also occur with a metallic structure, which could be weakened by the corrosion, making it collapse when it cannot support its own weight anymore. If it occurs in a building, then the people in and around it are endangered. DC leakage currents through the ground can thus generate hazardous situations that can have very serious consequences. For this reason, it is important to carefully control the amount of current flowing through the ground, or more generally leaking from the electrical network, and to reduce it, or even prevent it from flowing.

2.3. CONCLUSION

The aim of this first chapter was to determine more precisely a starting point for the development of a protection scheme against ground faults. The first section described the diverse effects of the current on the human body, both for AC and DC currents. As the dangerous thresholds are higher for DC than for AC, it can be said that the former is safer than the latter. This study also yielded the fault current levels that have to trigger the protection scheme in order to protect effectively the users of the network.

The second section described the different grounding schemes that can be implemented on an LVDC distribution grid, as far as the grounding configuration and the connection to ground are concerned. The study of HVDC and LVDC systems showed that the grounding scheme has an important role to play in limiting the fault current levels, but it also raises the problem of worrisome voltage deviations in certain cases. Additionally, depending on the grounding configuration, different fault detection methods have to be used.

The goal of this research is to eventually implement a multiple grounding point configuration for a meshed bipolar LVDC grid. Before designing a protection scheme that would ensure the network and its users safety, one needs to carefully consider the way the system will be grounded, as the two are closely linked. The following chapters will tackle the grounding configuration of such a system, first on a small scale system, to assess which configuration (IT, TT, TN-C or TN-S) will provide a high level of safety for the users, and then the system will be extended and the multiple ground point configuration will be studied.
3

**Effect of the Grounding Configuration on the Behaviour of the System**

The way an electrical system is grounded will determine many things, such as its behaviour during a fault, as far as voltage deviations and fault currents are concerned. Section 2.2.3 shows a list of the different grounding configuration possibilities. In total, they amount to twelve different schemes: four systems (IT, TT, TN-C, TN-S), and three types of ground connection (high impedance, low impedance, solid). To simulate each and every one of them and assess the response of the system to a fault, a very simple radial network is modelled. This network is composed of a bipolar DC source connected to a bipolar load through a cable. The network will be subjected to different kinds of ground faults for all the possible grounding configurations, and its behaviour will be studied, as well as the results of the ground fault detection scheme, described in the first part of this chapter. Ultimately, conclusions will be drawn about the grounding schemes and one of them will be chosen for the rest of the study.

3.1. **Detection of a Ground Fault**

3.1.1. **Definition of a Ground Fault**

A ground fault corresponds to the current following another path to ground that the one intended for it when designing the circuit. In AC transmission and distribution systems, ground faults represent up to 80% of the total amount of faults, and in power plants, 95% of the faults originate from a ground fault [16]. Ground faults can be due to the ageing of the cables or insulation devices, or to human error, in the case the insulation of a cable is punctured while digging the ground around it.

A ground fault can occur in many ways. There is a ground fault when an unwanted connection appears between one of the conductors and the ground. The fault path can have a high resistance, in the case a human body makes the connection between a live part and the ground, or it can be bolted, in case the conductor is bare and in direct contact with the ground.

Direct connections between two conductors are not considered here, as they belong to the short-circuit group of faults, which is out of the scope of this study.

3.1.2. **The Residual Current Measurement Method**

Under normal conditions, the network can be represented by the equivalent circuit of Figure 3.1a. Applying Kirchhoff’s law at node A yields the following result:
\[
\begin{align*}
I_+ + I_m + I = I_{\text{gnd}} \\
I_{\text{gnd}} = 0
\end{align*}
\]  \tag{3.1}

If the load is balanced on the poles, then \( I_+ = -I \) and \( I_m = 0 \); when it is unbalanced, then \( I_+ \neq -I \) so \( I_m \neq 0 \).

![Figure 3.1: Kirchhoff law applied to the network under consideration](image)

When there is a ground fault in the system, then it can be represented by the equivalent circuit of Figure 3.1b. Applying Kirchhoff law at node \( A \) yields the following results:

\[
\begin{align*}
I_+ + I_m + I = I_{\text{gnd}} \\
I_{\text{gnd}} = \frac{V_{\text{pole}}}{R_{\text{sum}}} \\
\therefore I_+ + I_m + I = \frac{V_{\text{pole}}}{R_{\text{fault}}} 
\end{align*}
\]  \tag{3.2}

The current through the ground is superimposed to the current provided by the source, and the sum of all the currents flowing through the positive pole, middle and negative pole conductors is not null anymore. This relation holds whether the load is balanced on the poles or not. Using \( I_{\text{sum}} = I_+ + I_m + I \) as an indication of a ground fault is a good way to protect the system while removing the danger of triggering the protection when the load is simply unbalanced on the poles, but the system is free of faults. As \( I_{\text{sum}} \) is representative of the leakage currents in the network, also called residual currents, this method of detection is called “residual current measurement (RCM) method”.

One could argue that measuring the current through the ground connection would yield the same result. It could indeed indicate that there is a fault in the system, but it would remove all information about the location of the fault, making this information impossible to use efficiently. For the sake of consistency, the RCM method as a way to detect the fault will be used throughout this document.

### 3.2. Description of the Network Under Consideration

The network used in this survey consists of four main components: the bipolar source, the bipolar load, the cable that connects the two and the bipolar measurement devices. These elements are connected together in the way described by Figure 3.2. All these components are modelled as individual blocks in MatLab Simulink, which descriptions can be found in the coming paragraphs.

![Figure 3.2: Network used in the survey](image)

As the exact behaviours of the source and load are not the main focus of this thesis but that of the network as a whole, simple models are used for these two components in order to simplify the simulations. This first approximation of the network will allow one to determine some of the main challenges that will have to be tackled, and the models will need to be improved greatly before attempting a practical implementation of such a system.
3.2.1. THE SOURCE

The bipolar source is represented by two ideal DC voltage sources connected in series. The ports “Pole +” and “Pole -” give access to the positive and negative pole of the source respectively, while the port “Middle” gives access to the middle point of the voltage.

This block is parametrized with the absolute value of the middle to pole voltage, in the case of this thesis 350 V. The block’s outside appearance and its inside connections are represented in figures 3.3a and 3.3b.

![Figure 3.3: The source block](image)

3.2.2. THE LOAD

Each load is represented by a resistance. The bipolar load consists thus of two resistances connected in series, following the same principle as the source. The block’s outside appearance and its inside connections are represented in figures 3.4a and 3.4b.

Each individual load of the bipolar load can be parametrized separately. Each load is characterized by its rated voltage, in this case 350 V and rated power. As the load flow is not of importance here, and an average model is sufficient for this part of the study, and will hence be used in the simulations.

![Figure 3.4: The load block](image)

3.2.3. THE CABLE

In the undergoing survey, the voltage deviations in the system are of importance. For that reason, the cable needs a model that is substantially more developed than a simple connection between the components. The model chosen for this study comprehends the resistance and the inductance of the conductors.

A voltage drop, increasing with the length of the cable, is thus observable with this representation, drawing it nearer to what would be observed in practice. The inductance does not play a role in the steady-state simulations, but it will affect the transient behaviour of the system, thus it is important to include it in the model.

As it will be explained in Section 3.3 some grounding configurations require the use of a cable with three conductors, while some others necessitate a four-conductor cable. The four-conductor cable model is
thus simply an extension of the three-conductor cable model with the addition of another resistance and inductance. The fourth conductor, also called protected earth (PE) sometimes has different characteristics than the other three. For the sake of simplicity, it is here considered that all four conductors are identical.

The cable blocks are parametrized with the resistance ($\Omega$/km) and inductance (H/km) of the individual conductors and with the total length of that piece of cable in kilometres.

3.2.4. THE MEASUREMENT DEVICE

The last block used in this round of simulations is the measurement block. All the voltages and currents are monitored in the model to ensure a good understanding of the occurring phenomena. This block was created to simplify the connection of all the volt- and amp-meters on the poles. In one component, three (or four) volt-meters can thus be found, and an equal number of amp-meters. The current flowing through each conductor is measured, as well as the potential difference between the conductors and a reference point, chosen at the ground connection of the network.

This block gives as an output a vector containing the three (or four) voltage measurements, the three (or four) current measurements, and for the protection scheme, the sum of the currents flowing through the power carrying conductors, namely the positive pole, middle and negative pole conductors (refer to Section 3.1 for further explanation).

Figure 3.6 depicts the model of the measurement block used in the configurations where cables with three conductors are required. Another block is available for the four-conductor configuration of the network, however the sum only concerns once again the three power carrying conductors, as described previously.

A smaller version of this measurement device is also available to carry out the measurements at the grounding points. This block measures the current flowing through the ground and the potential difference across the grounding resistance.
3.3. Description of the Different Grounding Schemes Applied to the Network Under Consideration

The four blocks described in the previous section are connected together and then to one or several grounding points. The connection to the ground can be done:

- Solidly: the network and the ground point are connected directly without adding any element between the two;
- Low impedance: an impedance of low value is connected between the network and the ground point;
- High impedance: an impedance of high value is connected between the network and the ground point.

In the low and high impedance grounding cases, the grounding impedance is simply represented by a resistor. Low impedance corresponds to a resistance of 5$\Omega$, and a high impedance to a resistance of 100$\Omega$\(^1\). Additionally, the voltage reference for the measurements is taken at the ground point itself and not at the middle point of the source to avoid a voltage offset when current flows through the grounding resistors.

The four possible grounding configurations are described in the following paragraphs.

3.3.1. The TN-C Configuration

The source is connected to its own grounding point, and the load is connected to the same ground point via the middle conductor. For this reason, a three-conductor cable is used. The TN-C configuration is modelled in MatLab Simulink in the way depicted by Figure 3.7.

![Figure 3.7: The TN-C configuration](image)

3.3.2. The TN-S Configuration

The source is connected to its own grounding point, and the load is connected to the same ground point via the protected earth conductor. For this configuration, cables with four conductors need to be used to have the PE connection. TN-S systems are the only ones that require the use of a PE conductor.

The TN-S configuration is modelled in MatLab Simulink in the way depicted by Figure 3.8.

In this case, the load is grounded through its insulation, which is done to provide extra protection to the user against shocks due to indirect contact. The insulation is represented in this model by a resistance of very high value (10\(^{10}\)\(\Omega\)\(^2\)), connecting the middle conductor, which is the zero voltage point of the network in normal conditions, to the PE conductor.

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\(^1\)These values were inspired by a webinar given by John P. Nelson PE, FIEEE, NEI Electric Power [16]

\(^2\)Corresponds to the approximate resistance of a slab of polyethylene, insulation material used in cables.
3.3.3. The IT Configuration

The source is left ungrounded, and the load disposes of its own grounding point. As for the TN-S configuration, the load is grounded through its insulation. Its representation is identical to that of the TN-S configuration. The IT configuration is modelled in MatLab Simulink in the way depicted by Figure 3.9.

3.3.4. The TT Configuration

Both the source and the load have their own grounding points, which are not interconnected. Once again, the load is grounded through its insulation. The TT configuration is modelled in MatLab Simulink in the way depicted by Figure 3.10.
3.4. Effect of the Grounding Scheme on the System

3.4.1. Survey of the Effects of the Grounding Scheme on the Behaviour of the System During Ground Faults

Before running fault simulations, it is important to run simulations in which the system does not suffer from a fault to have some reference values for the second part of the survey. The twelve possible grounding schemes (four configurations and three connections) are simulated one after the other, and for each of them, the same values of the voltage and current are gathered:

- The voltages at the outputs of the source with reference to ground, and the currents flowing out of the source in all the conductors, including the protection signal $I_{sum}$;
- The voltages at the load inputs with reference to ground, and the currents flowing in the load through all the conductors, including the protection signal $I_{sum}$;
- The voltage across the grounding resistance(s) in low and high impedance grounding configurations, or the voltage between middle or protected earth and ground in solid grounding configuration, as well as the current flowing through the ground, at all grounding locations.

A summary of these measurements can be found in Appendix B. The conclusions derived from the multiple simulations will be described in the following paragraphs.

Balanced Load - Healthy System

When the load is balanced on the poles, no current flows through the ground connection, so there is no voltage deviation on the middle conductor. This holds for all the configurations.

Due to its resistance, there is a voltage drop along the cable in absolute values, a drop of 18.7 V is observed on both positive and negative poles for a cable of 300 m. The loads are thus not polarized with 350 V but with 331.3 V instead. This represents a voltage loss of 5.34% in this case. From this, one could infer that, depending on the power quality requirements, namely how low the voltage is allowed to be at the load, and on the load power consumption, there will be a maximum distance between the source and

---

3For the complete set of measurements, please ask the author.

4The cable used in the simulations is EO-YMeKaszh OV 0.6/1 kV from Draka, with: $R = 4.61 \Omega/km$ and $L = 0.36 \text{mH/km}$
the load. For the cable currently in use and a 5 kW load on each pole, a distance of 281 m represents a 5% voltage loss, and a distance of 580 m represents a voltage loss of 10%. These values, found empirically, can be used as a reference for the meshed grid that will be studied in the following chapters.

\[ I_{\text{sum}} \] is in all the cases null, as no current is flowing through the ground.

**Unbalanced Load - Healthy System**

Compared to the previous simulations, the load is now twice as large on the negative pole as it is on the positive. This yields that the negative pole carries more current than the positive one, enhancing the voltage deviation on one side. Indeed, at the load, the voltage on the positive pole is: \[ V_{\text{pos}} - V_{\text{mid}} = 345.07 \text{ V} \], while on the negative pole it is \[ V_{\text{neg}} - V_{\text{mid}} = -301.15 \text{ V} \], with a voltage on the middle conductor of \(-14.55 \text{ V}\) with reference to ground, in TN-C, TN-S and TT configurations. The voltage on the positive pole is still well between the boundaries, but on the negative pole it is too low. The same voltages are observed on the load poles in the IT configuration, except the voltage deviation on the middle conductor. This time, it is the middle point of the source voltage that shifts to 14.55 V with reference to ground, as the load is grounded and the source not. Additionally, for all the configurations, the middle conductor starts transporting current as well, namely 10.52 A, contrarily to the previous case when it was not. Once again, \[ I_{\text{sum}} \] is null.

**Conclusions Over the Normal Operation of the Network**

The voltage deviations along the cable in all the grounding schemes can be found in Figure 3.11. In this part of the study, it has been observed that the nature of the ground connection, whether it is solid, low or high impedance grounding, has little impact on the overall behaviour of the system in steady-state. Voltage deviations from the nominal values are the same for every ground connection, and there is no current flowing through the ground.

The voltage deviations depend on the load distribution on the poles and the grounding configuration. For all the configurations, when the load is balanced, the voltage drops symmetrically on both poles along the cable, and the middle voltage remains at ground level. The influence of the grounding configuration appears when the load is unbalanced. The voltage on the middle conductor will diverge from ground level, shifting the pole voltages by as much with reference to ground.

The difference between the different configurations can be found when looking at where this voltage deviation occurs: in the IT configuration, it occurs at the source, which is floating, while in all the other configurations, it occurs at the load (see Figure 3.11). The voltage differences between poles and middle are the same in all configurations, only their absolute values with regard to ground change. The maximum pole to ground voltage is an important quantity, as it stresses the cable insulation; a high value of the former will require a stronger insulation, and thus more losses and a more expensive cable.

So far, there is no current flowing through the ground, whether the load is balanced on the poles or not. This is due to the fact that there is a maximum of one grounding point in direct contact with the electric parts of the network per configuration (in the TT and IT configurations, the grounding point is connected to the insulation of the load, so not directly to energized components), which prevents current loops from forming through the ground.
The table in appendix B.1 makes a summary of the steady-state values that will be used as a reference for the fault study.

### 3.4.2. System under fault conditions

#### Conditions of the simulations

In order to try and assess the behaviour of the network in all the possible fault configurations, eight scenarios were simulated per grounding scheme:

- Positive pole to ground faults, with high or low fault path resistance
- Negative pole to ground faults, with high or low fault path resistance
- Middle to ground faults, with high or low faults path resistance, with balanced load
- Middle to ground faults, with high or low faults path resistance, with unbalanced load

A balanced load means that each pole has to provide the same amount of power to the households at the end of the line. An unbalanced load means that the poles have to provide a different amount of power to the loads. The load distribution on the poles is made arbitrary to cover the general case.

All the faults are located after the cable, at the load location. They are simulated by connecting the conductors with a new ground point through a resistor. To simplify the model, a block was created for this purpose. The block’s appearance and internal configuration can be found in Figure 3.12.

![Figure 3.12: The fault block](image)

(a) Outside view of the fault block  
(b) Inside view of the fault block

The current is positive when it flows from the ‘+’ to the ‘-’ port, and the voltage is measured across the resistance. These values are of importance especially in the case of direct contact between a person and the network, as they will define the touch voltage and the current flowing across the body. In this case, the current path is chosen to be the one defined by the standard IEC 60479 (see Section 2.1), with the ‘+’ port representing the hand and the ‘-’ port the feet of the person.

To simulate the case of a direct contact, the resistance in the block is set to 1000 Ω: it is a high value of the body resistance, so it depicts a good case scenario for the person, but it also makes the fault harder to detect. In this sense, it is interesting to see how low the leakage current would be in such a configuration and to make sure that the fault is still detected. The term ‘high fault path resistance’ hence corresponds to 1000 Ω. To simulate a short-circuit between one of the conductors and the ground, the resistance is set to 1 Ω, which corresponds to the low fault path resistance.

The faults are treated in two groups: the positive pole to ground and negative pole to ground faults are treated together as the response of the system is similar in both cases, the quantities being of equal magnitude and opposite polarity. The second group is composed of the middle to ground faults with balanced and unbalanced load, as the behaviour of the system differs in these cases from the previous two. The IT-system will be studied separately, as its behaviour differs greatly from that of the other systems.
POLE TO GROUND FAULTS — TN-C, TN-S AND TT-SYSTEMS

The pole to ground faults are the most dangerous of the ground faults for the system or the person in contact with it, but they are also the easiest to detect. As a matter of fact, the fault currents are so high in these cases that even for a high fault path resistance and a high impedance grounding, where the fault currents are the lowest, they are still in average twice as high as the threshold value defined in Section 2.1.4.

The measured values of the current flowing through the body come really close to the predictions made in that same section. These predictions were made assuming that the body resistance was the only current limiting factor, corresponding to a solidly grounded system in the simulations. In this case, the measured current reached 330.8 mA against a predicted current of 333.3 mA for almost identical conditions (1000 Ω for 330.8 V in the simulations and 1050 Ω for 350 V in the predictions, see Table 2.2). The results of the simulations can thus be considered conclusive.

Additionally, the behaviour of the system varies with the change in grounding connection, as it has been described in Section 2.2.1: the higher the grounding resistance, the lower the fault current, but the higher the voltage deviations on the healthy poles. The three grounded systems behave almost like the ungrounded one when their grounding resistance is high. The fault currents and voltage levels, in the case of a positive pole to ground fault, are listed in the table in appendix B.2 as a function of the grounding connection. The response of the system in case of a negative pole to ground fault is symmetrical to that.

The grounding resistance has a relatively little effect on the body current in case of direct contact: 331 mA for solid connection against 301 mA for 100 Ω grounding resistance, the main current limiting factor being the body impedance (1000 Ω, see Figure 3.13a). On the other hand, the impact on the fault current during a low resistance fault is drastic: 143 A for a solid connection against 45.3 A for 5 Ω grounding resistance and 3.24 A for 100 Ω grounding resistance (see Figure 3.13b). This time, the current is limited by the grounding resistance, hence the increased effect.

For solid and low impedance grounding, the fault current is so high (several times the nominal current carried by the poles) that it will be picked up by the short-circuit protection, and be interrupted as such. This is preferable because the short-circuit protection is likely to be faster than the ground fault protection, and thus irreversible damage to the system could be avoided. For high impedance grounding, even though the current would be lethal for anyone getting in contact with it, it will go undetected by the short-circuit protection, so the ground fault protection will have to clear it.

Finally, something of great importance for the discrimination of the ground fault protection scheme has been noted. As explained in Section 3.1, the measurement $I_{sum}$ is equal to the current flowing through the fault. Depending on the pole where the fault is located, the current through the fault changes polarity, and so does $I_{sum}$, as it can be seen on Figure 3.14. As a result, for a positive pole to ground fault, $I_{sum}$ will be positive, and for a negative pole to ground fault, it will be negative. This fact can be used by the protection scheme to open the faulted pole and leave the healthy one closed.

MIDDLE TO GROUND FAULTS — TN-C, TN-S AND TT-SYSTEMS

When the load is balanced on the poles, the voltage on the middle conductor is null. Thus, if someone were to be in contact with the middle conductor, no current would flow through this person. Even if a fault with
3.4. Effect of the grounding scheme on the system

Figure 3.14: Effect of the fault location on the poles on the polarity of $I_{\text{sum}}$

On the contrary, if the load is unbalanced on the poles, then the middle voltage differs from the ground at the fault location. In this case, if a ground fault occurs on the middle conductor, current will flow through the fault. The bigger the unbalance, the further the middle voltage will deviate from the ground voltage, and the more fault current will flow. It is not necessarily dangerous to the users, however. In the simulations, the high resistance fault yielded a leakage current of 10 to 15 mA, which does not require immediate clearing, but is worth being noted; the low resistance fault yielded a fault current of 6.62 A, 2.02 A and 142 mA for the solid, low and high impedance grounding configurations respectively. The first two require immediate clearing from the protection, whereas the last one not, as just below the protection threshold. Theses results are displayed in figures [3.15a] and [3.15b] respectively.

Figure 3.15: Effect of the grounding resistance on the fault current - middle conductor to ground fault

In this case, the positive pole being more loaded than the negative pole, the measurement $I_{\text{sum}}$ is positive. When the load is reversed on the poles, then $I_{\text{sum}}$ becomes negative. This phenomenon is illustrated in Figure [3.16]. It follows the same logic as for the pole to ground faults, even though the current magnitudes are lower in this case. Due to that, it will be difficult to make the difference between a pole to ground fault and a middle to ground one. However, if the protection scheme disconnects one pole when it is actually the middle that is faulted, then the fault will remain, allowing the protection to open the other pole to clear the fault.

The network as it is defined in this chapter cannot function without a middle conductor, as the houses must be polarized with 350 V and not 700 V. It is thus impossible to only disconnect the middle conductor and leave the rest of the network working. If a fault on the middle conductor requires clearing, then the whole faulted cable must be disconnected to effectively isolate the fault without damaging the rest of the network.

It is, however, highly unlikely that a fault on the middle conductor would prove to be dangerous for a person. Considering the worst case scenario for the body impedance ($575 \Omega$) and the lowest current triggering the protection ($150 \text{ mA}$), the voltage deviation on the middle conductor would need to be $U_{\text{mg}} = 575 \times 150 \times 10^{-3} = 86.25 \text{ V}$ under normal operation, and such a middle to ground voltage could only be obtained by having a very heavily unbalanced load. It is expected that, for such a situation, the voltage at the
load would not be between acceptable limits, and thus part of this load would need to be disconnected, consequently reducing the unbalance and the middle voltage deviation at the same time.

**The IT-system**

As said earlier, the IT-system behaves differently than the other systems during a fault. The main reason for this is that the network will be grounded by the fault itself, regardless of the resistance of its path. Because of this, during a pole to ground fault, the faulted pole voltage will drop to 0V while the voltage on the two healthy conductors will shift by almost 331V, which comes close to the nominal voltage. This phenomenon has been described in Section 2.2.1, although applied to an HVDC system, and is represented here for the network under consideration in Figure 3.17. Because the system is now electrically grounded through the fault, there is no current flowing through the ground, and the fault will not be detected by the protection scheme.

The case of a middle to ground fault with balanced load was explained in the previous paragraph, so it will not be repeated here. That of a middle to ground fault with unbalanced load differs very little from the steady-state case. Indeed, the same voltage deviation is observed in the network, and no current flows through the fault, whether its path has a low or high resistance. This can be explained by the fact that, in this case, the fault will close a loop with the grounding point of the load, which is grounded through its insulation. The loop will thus have a very high resistance, effectively blocking the current. If a person were in contact with the network at this point, he or she would be protected by the load grounding point. The same would occur if the fault was located at the source; in this case, the source would be grounded by the fault just as explained above, and again no current would flow through it.

These observations could lead to the conclusion that the IT-system seems safer than the other systems, at least as far as the fault currents are concerned. For maintenance reasons, however, all the faults in the IT-system will go undetected. This could lead to second faults, which would have dire consequences for the network as they are in effect short-circuits through the ground.

**3.5. Selection of the Grounding Configuration**

In order to ensure the safety of both the network and its users, three elements need to be considered:
3.6. CONCLUSION

- Great voltage deviations on the cables are dangerous for the stability of the network, especially if the system is big; because of this, the IT grounding system will not be used;

- The size of the grounding resistor does not affect much the magnitude of the current in case of high resistance faults. It will play a role in limit the current in case of short-circuits, but not during ground faults;

- Having a TT-system would require the implementation of many grounding points, especially in a large scale system; this could make the localization of ground faults more difficult, as the fault current could form loops through the ground at any grounding point, and the RCM devices could be out of these loops; for this reason, it seems desirable to limit the amount of grounding points in the system, and the TT-system will not be used further in this research;

This leaves only the TN-C and TN-S systems to be used. The TN-S system, however, has multiple advantages over the TN-C system. First of all, the load has of a more stable grounding point; indeed, as the protected earth conductor, which is used to ground the load, is solidly connected to the ground and not through the grounding resistance, then the load ground voltage will not be affected by currents flowing through the grounding resistance. Secondly, in the case of indirect contact between a person and the network, the touch voltage will be 1.5 to 2 times lower with TN-S grounding than with TN-C [12], making it safer for the person, especially in case of a defect on the neutral conductor.

The TN-S configuration with a low resistance connection to ground is thus the grounding scheme that offers the best combination of both user and network safety. As such, it will be this configuration, or an adaptation of it, that will be used in the meshed grid in the coming chapters.

3.6. CONCLUSION

The detection of a ground fault in a bipolar DC network was described in the first part of this chapter. The residual current measurement (RCM) method allows the detection a ground faults occurring in the system, and it also informs about its location on the poles, as the simulations have shown. This information can be used to selectively disconnect the faulted pole and leave the healthy part of the network in operation.

This method, however, can only be used when the return path of the current is known, or in other words, when the system is grounded, as it is in all the configurations except the IT-system. This is due to the fact that the devices used to perform the RCM need to be included in the fault loop, otherwise the fault will not be detected. Having the network grounded at the source ensures that the devices will always be able to measure the ground fault current.

Simulations were run for every possible grounding scheme, which is the combination of a connection to ground (solid, low impedance, high impedance), and a grounding configuration (TT, TN-C, TN-S, IT). The system was put under several operating conditions, such as healthy and faulted situations, and the load followed different distributions on the poles. All these simulations led to conclusion that the TN-S configuration with low resistance grounding is the grounding scheme that yields the best combination of network and consumer’s safety.

It is thus the grounding scheme that will be used to ground the meshed grid in the following chapters, or at least an adaptation of it. As a matter of fact, meshing the grid brings up new challenges that will need to be carefully considered, and it is expected that the nature of the grounding connection itself will need to change in order to tackle these challenges. The grounding of a meshed grid will be the topic of the following chapter.
MULTIPLE GROUNDING POINTS

Grounding schemes for AC distribution grids and HVDC links are known, but the challenge of a meshed LVDC distribution grid with multiple grounding points has not been tackled yet. The goal of having such a grid is to increase the flexibility and the reliability of the grid while allowing the islanding of parts of the network. That way, when one grounding point needs to be disconnected from the network, the rest of the system is still safely grounded.

As the LVDC distribution grid is the closest part of the network to the consumers, its grounding needs to be carefully designed. It has already been concluded in Chapter 3 that the TN-S grounding configuration would be used in the rest of this paper. This study, however, was carried out on a single grounding point system, and the aim of this chapter is to consider the grounding possibilities of a network with multiple grounding point. One question arises from that: how can a DC distribution grid be grounded at multiple locations?

This challenge will require a careful consideration of the network elements that should be grounded, and what changes need to be made to the traditional AC grounding schemes to ensure a satisfactory level of safety in the LVDC distribution grid.

4.1. LOCATION OF THE GROUNDING POINTS

In 1982, the IEEE published a document [17] in which it recommends grounding practices for power systems. Even though this document was written for AC power systems, some safety principles can be used as well on a DC system. As far as the location of the grounding points in the AC network is concerned, the IEEE recommends the following:

1. Any generator or transformer used for grounding should, as far as possible, be one that is always connected to the system. Alternatively, a sufficient number of generators or transformers should be grounded to ensure at least one ground connection on the system at all times.

2. Ground at the Power Source and not at the Load. [...] Since power sources are fewer in number than loads and are less likely to be disconnected, they are preferred as grounding points.

From these two recommendations, it has been decided that all DC sources of the network will be grounded, to ensure that the whole network will be grounded at all times, even if two parts need to be isolated from one another. Doing so will allow islanded networks to also have a grounding point at all times, and thus be safer for the users of the network.

Islanding happens when a part of the network is detached from the main power grid, the way an island is detached from the main land. The islanded part of the network needs to be able to function on its own
and have its own safety ensured. The islanding of a part of the network can occur when, for example, a
neighbourhood, where solar panels are installed on some houses, needs to be disconnected from the rest of
the grid, because a ground fault occurred on the link between the two. The houses with solar panels could
then provide power for the rest of the neighbourhood, effectively acting as power sources, and making the
system a stand-alone one. To secure this smaller network, the houses with solar panels would need to be
electrically grounded.

Figure 4.1 depicts the two scenarios described above.

![Figure 4.1: Implementation of several grounding points in the meshed grid to ensure continuous grounding of the network](image)

4.2. IMPLEMENTATION OF MULTIPLE GROUNDING POINTS ON A NETWORK WITH TWO DC SOURCES

As explained in the previous paragraph, all the electrical sources of the network need to be grounded to
ensure that the elements connected to it will also be grounded at all times, even in the event of a source
being disconnected.

The grounding configuration chosen in Chapter 3 was TN-S, which means that the load is grounded
through its insulation at the source location via a dedicated conductor. As a first approximation, a rough
estimation of the load insulation was made in that chapter, but studying the exact effects of that type of
connection on the network would require a more detailed model. As the load insulation is not the main focus
of this thesis, and as the only interesting factors in the faults are the fault current levels and their location on
the network and not their nature (for the purpose of this thesis only), it has been decided that the insulation
part of the models would be removed from the simulations to improve the computation time. A more in
depth study of the load insulation would be required to assess its impact on faults when they occur due to
a defective insulation. The TN-S network will thus be modelled in the same fashion as the TN-C system in
the rest of this report.

4.2.1. RESISTIVE GROUNDING

That being said, the grounding point itself was chosen to be a resistance of low value (5Ω), to limit short-
circuit currents without suffering from unacceptable voltage deviations at the ground locations. A network
comprising two DC sources supplying the same load is modelled, and the ground currents flowing through
the resistors, when the system operates under normal conditions, are observed. The network configuration
is depicted in Figure 4.2 and represents one of the lowest levels of grid meshing.

When the load is perfectly symmetrical on the poles, no current flows through the grounding resistors.
However, it is highly unlikely that the load can be exactly balanced on the poles; it is expected that it will
always be slightly unbalanced. When such a situation is simulated, the behaviour of the system changes.
As a matter of fact, a load unbalance will provoke a small voltage deviation across the grounding points.
As these are resistors, it means that a current will start flowing. Figure 4.3 shows the voltage across the
grounding resistors, and the current that flows through the ground when the network supplies loads of 2 kW
on the positive pole and 2.2 kW on the negative pole.

Currents of about 4 mA, as in the case described above, although they are not directly dangerous for the
4.2. IMPLEMENTATION OF MULTIPLE GROUNDING POINTS ON A NETWORK WITH TWO DC SOURCES

Figure 4.2: Network configuration - two sources

Figure 4.3: Current through the ground when \( P_{\text{pos}} = 2\, \text{kW} \) and \( P_{\text{neg}} = 2.2\, \text{kW} \)

network users, will greatly damage the surrounding installations due to their corroding effect. Additionally, the bigger the difference between the two loads, the more current will flow through the ground, even though there is no fault. If no corrosion protection is installed in the network, then current will constantly leak into the ground and provoke great damage to the infrastructure.

On the other hand, for the same load unbalance, the bigger the grounding resistor, the less current will flow through the ground. Nevertheless, this phenomenon cannot be stopped, even with high resistance grounding, as current will flow through the resistor as soon as there is a voltage deviation on the middle conductor. What is more, increasing the size of the resistor to compensate for this current exiting the network will eventually lead to high voltage deviations on all the conductors during a fault, which is something that has been advised against in Chapter 3 to ensure the stability of the system; what is more, the benefits of low resistance grounding during a fault would be lost.

A purely resistive grounding point is thus not a sensible choice to ground a DC grid with multiple grounding points.

4.2.2. RESISTOR IN SERIES WITH A DIODE

One could argue that diodes in series with the grounding resistors, such as the configuration depicted by Figure 4.4, could help prevent current from flowing through the ground in steady-state.

The diodes effectively block the current that would flow through the ground connection otherwise. Nevertheless, the implementation of the diodes is problematic. As a matter of fact, depending on the orientation of the diodes, some pole to ground faults would go undetected. In the case of the network presented in Figure 4.4, positive pole to ground faults would occur without triggering the protection; if the diodes’ polarity is reversed, then it would be negative pole to ground faults. In both cases, the diodes would prevent the fault current from re-entering the network through the grounding points, so the fault loop
would close through the parasitic capacitance of the network, at a location that would likely exclude the measurement devices. Any person getting in contact with the faulted part of the network would thus be put at great risk, as the protective relays would not sense the fault. Grounding the system in such a way would almost be equivalent to using a high impedance grounding in some cases, which has been ruled out of the list of possibilities in Chapter 3.

The diodes would make the behaviour of the network completely asymmetrical (see Figure 4.5), so two different fault detection methods and protection schemes would need to be implemented for the same type of fault. The complexity of the network would increase greatly, which leads to the conclusion that this grounding configuration is not viable: resistive grounding, with or without diodes, is not a clever solution for a meshed DC grid.

![Figure 4.4: Resistive grounding with diodes](image1)

![Figure 4.5: Current through the fault when the same fault block (R_{fault} = 1050\Omega) is connected to the positive and then negative pole; the network displays an asymmetric behaviour](image2)

### 4.2.3. Capacitive Grounding

A simple solution to block steady-state currents from flowing through the ground when the load is unbalanced on the poles, while letting fault currents through to keep control of the fault current loop and thus enable the fault detection, is to make use of capacitors to ground the system. Basic circuit theory states that capacitors act as open-circuits when supplied in DC, and an short-circuit when supplied with AC current.

These characteristics are highly desirable for the network under consideration here. In steady-state, no matter the balance of the load on the poles, no current would flow through the ground as the grounding capacitors would isolate the network from the ground, and no corrosion would occur. On the other hand, during a fault, the capacitors would dominate the parasitic capacitance of the network (they are much bigger) and most of the fault current would flow back to the network through them, thus ensuring a good fault detection and increasing the safety level of the grid. Current flowing through the ground during a fault is a phenomenon that cannot be avoided, so the resulting corrosion neither. However, as it flows only for a very short amount of time, the corrosion it provokes is negligible.
It is easy to predict that the charge of the capacitor during a fault will be a problem to overcome, as it is important to keep the voltage variations in the network low. The concrete implementation of capacitive grounding will be described in the following sections.

4.3. **IMPLEMENTATION OF CAPACITIVE GROUNDING**

4.3.1. **STEADY-STATE CONSIDERATION**

The network described in the previous section is now grounded through capacitors, as it is shown in Figure 4.6.

![Figure 4.6: Two sources network grounded through capacitors](image)

The advantage of such a grounding configuration is immediately visible when steady-state simulations are run. Even if the load is unbalanced on the poles, there will be no current flowing through the ground in steady-state. Simulations with the same load balance as the resistive grounding case are run, and the results of the steady-state simulation is depicted in Figure 4.7.

![Figure 4.7: Steady-state simulation - unbalanced load - 2kW on positive pole and 2.2kW on negative pole, \( C_{\text{gnd}} = 1 \mu\text{F} \)](image)

The goal, which was preventing current from flowing through the ground while the meshed network with multiple grounding points is in steady-state, in order to avoid corrosion of the surrounding infrastructure, is thus achieved by the use of capacitive grounding. New challenges arise, however, when the dynamics of the network are considered.

Another advantage of the capacitive grounding is that, as no current flows through the ground due to the load unbalance, then the residual current measurement will not detect anything. In other words, the signal \( I_{\text{sum}} \) will remain at zero, so the protection will not disconnect the load from the network.

The combination of capacitive grounding and residual current measurement allows the continued supply of a load that is unbalanced on the pole by preventing its detection as a fault.
4.3.2. Network under faulted conditions

The occurrence of a fault on the network will cause the grounding capacitors to charge. For each capacitor, the situation in this case is similar to the one described in Figure 4.8.

At \( t = 0 \), the switch \( S \) closes, and it is considered that the capacitor \( C \) is initially discharged. The resistor \( R \) represents the fault itself. The charge of the capacitor is described by equations 4.1 and 4.2.

\[
v_c(t) = V(1 - e^{-t/\tau}) \quad \text{with} \quad \tau = RC
\]

\[
i_c(t) = C \frac{dv_c(t)}{dt} = \frac{V}{R} e^{-t/\tau}
\]

These equations represent well what happens with the grounding capacitors in the system. There is, however, some inductance present in the network, mainly in the cables and the protective relays (see Chapter 3 and Appendix E.1). This inductance will provoke some oscillations in the voltage and current of the grounding capacitors, which are depicted in Figure 4.9. It was not included in the calculations for the sake of simplicity, because the inductance of the fault loop depends entirely on the fault location. For the same reason, the cable resistance was not included; compared to the fault resistance, the cable resistance is negligible and can be omitted from the calculations without losing in accuracy.

As there are two grounding points in the network, the fault current splits between the two. A pitfall of the model can be found here while looking at the distribution of the fault current among the grounding points. Indeed, in this model, the distance between the fault and the grounding points is not taken into account, so the fault current splits equally among the capacitors, which then charge (or discharge) at the same rate. It is expected that, in reality, the resistivity of the ground between the fault location and the several grounding capacitors will not be the same over the whole network, and thus will the current flow in majority to the closest grounding point, as it offers the path with the least resistance.

When only capacitors are used to ground the network, during a fault, the current will stop flowing after a time without the action of protection, but it will only occur when the capacitors are charged to a value close to \( U_0 \) (350 V in this network). The charge of the capacitor will provoke a voltage shift of the whole network, as it can be seen in Figure 4.10. This voltage shift is highly undesirable, as it was described in Chapter 3.

To keep the steady-state characteristics of the capacitive grounding and prevent the complete charge of the capacitors, it is necessary to clamp the voltage across the capacitors. This is done in this project with
4.3. IMPLEMENTATION OF CAPACITIVE GROUNDING

Figure 4.10: Voltage deviations on the cables after a fault – fault on the negative pole, \( R_f = 1000\Omega \) and \( C_{gnd} = 1\mu F \)

the help of voltage clamps, as it will be described in the next section.

4.3.3. ADDITION OF THE VOLTAGE CLAMP

DESIGN OF THE GROUNDING POINT

A voltage clamp is now added in parallel with the grounding capacitor, as depicted in Figure 4.11. The voltage clamp can be made of two string of diodes connected in anti-parallel, or two Zener diodes in anti-series, etc.

The function of the voltage clamp is more important than its conception.

The idea behind the use of the voltage clamp in parallel with the grounding capacitors is the following. After the occurrence of a fault, and before it is isolated, the grounding capacitors will charge. If nothing is done, their voltage could reach the value of the voltage across the fault itself. By adding a voltage clamp, one can keep the voltage across the capacitors under control. Indeed, as soon as the capacitor voltage reaches the clamp voltage \( V_{\text{clamp}} \), the latter will start conducting the current, thus preventing the voltage from rising any further, all the while providing a path for the fault current, which simplifies the fault detection.

The important parameter of the clamp is its clamp voltage, because the capacitor voltages will be limited to this value. It has been shown that a load unbalance will provoke voltage deviations on the middle conductor. As long as the system is functioning in healthy conditions, these voltage deviations should not make the voltage clamp conducts, as the advantages of capacitive grounding would be lost otherwise. Indeed, having one of the clamp conducting would be equivalent to having a low resistance grounding scheme, and with load unbalance, current would flow through the ground.

It has been assumed in this project that the biggest allowable voltage deviation on the poles would be 10% of the nominal source voltage, or in other words 10% of 350 V, which is \( \pm 35\text{V} \)\(^1\). Half of this voltage deviation must then be allowed on the middle conductor, so it corresponds to a \( \pm 17.5\text{V} \) deviation with reference to ground. The clamp voltage must then be at least 17.5 V. As the voltage deviations on the middle conductor have to be as small as possible, this is thus the value of the breakdown voltage that will be kept for the rest of this project: \( V_{\text{clamp}} = 17.5\text{V} \).

\(^1\)There is, at the time of the completion of this MSc thesis, no standard defining the allowable voltage levels in the network; this value of 35 V as been taken as it seems to be a sensible one
Tests on the network

When the capacitor and voltage clamp configuration is used to ground the network, its behaviour during a fault meets the following expectations: no current flows through the ground in steady-state, and during a fault, the fault current has a defined and controlled return path, while the voltage of the network remains between acceptable boundaries. Figure 4.12 shows the results of a simulation in which a positive pole to ground fault occurs at the load location. In this example, the fault is represented by $R_f = 1000\Omega$, and the grounding capacitors have a value of $C_{gnd} = 1\mu F$, while the clamp voltage is, as described previously, $V_{clamp} = 17.5\, V$.

(a) Voltage and current through the grounding capacitors – start: $V_{gnd1} = -0.46\, V$, $I_{gnd1} = 0\, A$, $V_{gnd2} = 0.23\, V$, $I_{gnd2} = 0\, A$; end: $V_{gnd1} = -17.5\, V$, $I_{gnd1} = -0.33\, A$, $V_{gnd2} = -16.97\, V$, $I_{gnd2} = 0\, A$

(b) Details about the charge of the capacitors

What can be observed on the graphs from Figure 4.12 is that the average rate of charge of the two grounding capacitors is the same. This is a direct consequence of the fact that the resistance of the path through the ground is not accounted for here, so both capacitors receive the same amount of fault current. The capacitors are subjected to small current and voltage oscillations that are due to the inductance of the network. However, as soon as one of the capacitors is charged and its voltage reaches 17.5 V, the voltage clamp takes the current over and prevents the voltage from rising any further. At this point, the grounding capacitor voltages is clamped, and the source is grounded through the diode. All the fault current flows through this clamp, and the other grounding capacitor stops charging.
Ideally, this situation should be avoided: if several voltage clamp conducts, they can form a current loop through the ground with low resistivity, which could lead to high currents flowing through the ground in steady-state, and consequently to corrosion (see Appendix C.1 for further explanation). This can be achieved by carefully sizing the grounding capacitors, as shown in the following section.

### 4.3.4. Sizing of the Capacitors

As explained previously, it is advantageous to keep the capacitive grounding as long as possible in the network, meaning that the capacitors should be sized in such a way that the protection would have time to isolate the fault before the capacitors are charged to clamp voltage. If the capacitors are not properly sized, then the voltage clamp would conduct at one point during the occurrence of the fault. After the isolation of the fault, the network will be heavily unbalanced, which would lead to current flowing through the ground in steady-state if the clamp conduct. This current would provoke, as stated previously, corrosion of the surrounding infrastructure. This phenomenon can only be avoided with the help of capacitive grounding, hence the importance to keep it effective as long as possible.

For now, the minimum size of the grounding capacitors has to be determined, thanks to the restrictions described above. For each value of the fault current, the protection needs to operate below a certain time limit, defined with the help of the standard IEC 60479-1, and more precisely Figure 2.5. Several values were extracted from this picture and are listed in Table 4.1. For more explanations over the choice of these values, please refer to Chapter 6.

<table>
<thead>
<tr>
<th>Current amplitude [mA]</th>
<th>Time of operation [ms]</th>
<th>Detection threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>185</td>
<td>500</td>
<td></td>
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<tr>
<td>200</td>
<td>400</td>
<td></td>
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<tr>
<td>300</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>375</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>425</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>500 and above</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Current thresholds and their corresponding time of operation

The total grounding capacitance of the network will be calculated as follows. For each value of the fault current, corresponds a maximum time of operation for the protection scheme. During this time and for that current, to ensure that the capacitive grounding is kept even after the occurrence of the fault, the total capacitance will be allowed to see its voltage increase to the clamp voltage at most. From there, the total grounding capacitance of the network can be calculated. The value of the individual grounding capacitors will then depend on the number of grounding points in the network, as the fault current is expected to split among them.

Before starting these calculations, several assumptions need to be made:

- The resistance of the fault path, that will determine the fault current flowing through the ground and ultimately through the grounding capacitors, is much bigger than the ground resistance or that of the cables; consequently, the latter two are judged negligible and will not be included in the calculations;

- The inductance of the cables and protective relays will reduce the \( \frac{di}{dt} \) of the fault current. In addition, the total inductance value of the fault loop greatly depends on the location of the fault; in order to have conservative values that cover the general case, and also to simplify the calculations, the total inductance of the fault loop is not taken into account in the calculations;

- The initial voltage of the individual capacitors greatly depends on the load balance of the network. Additionally, calculations are made here for the total grounding capacitance of the network, so including

\(^2\)In Chapter 6 it will be shown that the protection never waits until the very last moment to operate, so this restriction will still ensure the continuation of the capacitive grounding
a realistic value of the capacitor voltage before the fault is close to impossible; for that reason, the initial voltage of the total grounding capacitance of the network is considered to be null;

- The voltage across the fault depends also on the load connected to the faulted pole, as well as the overall load balance in the network; to cover the general case and thus get conservative value, the nominal pole voltage is considered;

Using equation 4.1 and considering that $V = V_f = R_f I_f = V_{nom}$, $V_{c,max} = 0.5 V_{clamp}$, and the boundary condition stating that for $t = t_{max,op}$, $V_c(t) = V_{c,max} = V_{clamp}$, then the total grounding capacitance can be calculated for each time-current couple with the following equation:

$$C_{gnd,tot} = -\frac{t_{max,op}}{R_f} \frac{1}{\ln\left(1 - \frac{V_{clamp}}{V_f}\right)}$$ (4.3)

The derivation can be found in Appendix C.2.

The final value of the total grounding capacitance is the highest value yielded by the calculations for each time-current couple, while keeping in mind realistic values for the fault resistance when a person gets in contact with the network (575-1050Ω). The results of the calculations carried out for the time-current values listed in Table 4.1 can be found in Table 4.2.

<table>
<thead>
<tr>
<th>$V_f$ [V]</th>
<th>$I_f$ [A]</th>
<th>$R_f$ [$\Omega$]</th>
<th>$t_{max,op}$ [s]</th>
<th>$V_{clamp}$ [V]</th>
<th>$C_{gnd,tot}$ [F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>350.00</td>
<td>0.150</td>
<td>2333.33</td>
<td>2</td>
<td>17.5</td>
<td>0.0167</td>
</tr>
<tr>
<td>350.00</td>
<td>0.170</td>
<td>2058.82</td>
<td>1</td>
<td>17.5</td>
<td>0.0095</td>
</tr>
<tr>
<td>350.00</td>
<td>0.185</td>
<td>1891.89</td>
<td>0.5</td>
<td>17.5</td>
<td>0.0052</td>
</tr>
<tr>
<td>350.00</td>
<td>0.200</td>
<td>1750.00</td>
<td>0.4</td>
<td>17.5</td>
<td>0.0045</td>
</tr>
<tr>
<td>350.00</td>
<td>0.300</td>
<td>1166.67</td>
<td>0.2</td>
<td>17.5</td>
<td>0.003342</td>
</tr>
<tr>
<td>350.00</td>
<td>0.375</td>
<td>933.33</td>
<td>0.1</td>
<td>17.5</td>
<td>0.0021</td>
</tr>
<tr>
<td>350.00</td>
<td>0.425</td>
<td>823.53</td>
<td>0.05</td>
<td>17.5</td>
<td>0.0012</td>
</tr>
<tr>
<td>350.00</td>
<td>0.500</td>
<td>700.00</td>
<td>0.01</td>
<td>17.5</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Table 4.2: Total grounding capacitance: results of the calculations

One can see from this table that, the lower the fault current, the longer it can take for the protection scheme to operate, but the bigger the grounding capacitance is required to sustain capacitive grounding. Low fault currents, however, require a very high fault path resistance, and do not correspond to the case of a person touching the network. Using the upper value of the body impedance (1050Ω) as a maximum for the fault path resistance, yields a total grounding capacitance of around 3.34 mF for the whole network. During the calculations, the fault current was assumed constant, but it will not be so in the simulations. For safety measures, and to ensure that the capacitors will not be completely charged before the fault isolation, an additional 5% of this value is taken for the total grounding capacitance: $C_{gnd,tot} = 3.51 \text{ mF}$

It has been observed in the simulations that the current splits equally among the grounding capacitors during a fault. It is expected that in reality, the distribution of the current will depend on the distance between the fault and the grounding points. However, the distance will vary with the location of the fault, which is highly unpredictable, especially in the case of a person touching the network. For this reason, the current distribution amongst the capacitors is neglected, and the capacitance of each individual grounding capacitor will be calculated as follows:

$$C_{gnd,indiv} = C_{gnd,tot} \frac{1}{N} \quad \text{with} \quad N = \text{number of grounding points in the system}$$ (4.4)

When applied to the system under consideration in this chapter, it yields grounding capacitors of $C_{gnd,indiv} = \frac{3.51 \times 10^{-3}}{2} = 1.75 \text{ mF}$. The behaviour of the network in that case, for example for a fault ($R_f = 1050\Omega$) on the positive pole, is shown in Figure 4.13c. When $R_f = 1050\Omega$, it yields a fault current $I_f = 310.2 \text{ mA}$. 

in steady-state, and such a current needs to be interrupted within $t_{\text{max,op}} = 186.4 \text{ ms}$\footnote{This time was obtained by using a look-up table in Simulink with the values of Table 4.1 as breakpoints; Simulink interpolated the values between those given in the table}. It can be seen on Figure 4.13b that the voltage clamp only start conducting at $t = 292.1 \text{ ms}$, which is $192.1 \text{ ms}$ after the occurrence of the fault, and thus after the latest possible operation of the protection scheme. The capacitors have thus been properly sized, confirming our previous assumptions.

Figure 4.13: Positive pole to ground fault

This results yields a \textit{minimum size} of the individual capacitors; the bigger the capacitors, the more stable the system will be and the more faults can occur before the loss of capacitive grounding. It is expected, however, that the capacitors cannot be infinitely big. First of all, big capacitors are expensive, and secondly, bigger capacitors will need more current to adapt to a new load balance on the poles, which can be dangerous for the elements in the network.

\section*{4.4. Conclusion}

This chapter started with an important question: how can a meshed DC distribution grid be grounded? A study of IEEE recommendations on power system grounding indicated that it is desirable to ground every power source, leading, in the case of the meshed DC grid, to a multiple grounding point system.

Upon considering the standard AC grounding schemes, it has been discovered that the TN-S configuration was a good proposition, as far as touch voltage is concerned, but not with resistive grounding. Indeed, as soon as the load is unbalanced on the poles, a voltage deviation will occur on the neutral conductor, and consequently across the grounding resistors. Due to the very nature of the resistors, this will lead to a current flowing through the ground, when the network is simply unbalanced and otherwise healthy. Such a leak is actually picked up by the residual current measurement device, and the resulting signal, at a certain point
of unbalance, could be considered by the protection scheme as a fault in the network.

Additionally, and this is one of the important themes of this thesis, such a current flowing through the ground continuously will cause corrosion of the surrounding infrastructure. This phenomenon was not such a problem in AC, as the systematic current polarity reversal was cancelling its corroding effects. In DC, it becomes truly important to consider countering this effect at the source. This is why the principle of grounding the system through capacitors was used in this project.

In steady-state DC, capacitors act as open-circuits, and they isolate the network from the ground; even in the worst situations of load unbalance on the poles, no current will flow through the ground. During transients, however, capacitors act as short-circuits, thus offering a privileged return path for the fault current, and enabling the protection of the circuit. The important voltage deviations on the network, occurring during the charge and discharge of the capacitors, are circumvented by the addition of voltage clamps in parallel with the grounding points, effectively keeping the voltage on the middle conductors between allowable boundaries.

The requirement that is to keep the network grounded through the capacitors without letting the voltage clamps conduct, and such as long as possible, led to the calculation of the minimum size of the individual grounding capacitors. If the capacitors were smaller, then one who take the risk to see the voltage clamps start conducting before the protection had time to isolate the fault, the worst case being when the fault current is low. It is thus important to respect this lower limit of the grounding capacitance size.

DC grids with multiple grounding points are more challenging to implement than they would suggest, in particular when they are grounded through capacitors. The challenges such a network presents will be described in the following chapter, as well as their impact on the protection of the distribution grid.
Locating ground faults in a meshed DC distribution grid with multiple grounding points

Meshed grids are a topic that is seldom covered in literature, in particular when DC distribution grids are concerned. With several path for the power to flow to one destination, ensuring the selectivity of the protection scheme becomes challenging. The fact that the network under consideration here is grounded through capacitors, and not through resistances like in AC systems, adds another layer of difficulty to the localization of the faults.

Now that the more general aspects of the DC distribution grid with multiple grounding points have been covered, it is time to focus on the technical challenges such a network represents. Having a meshed grid can lead to seeing net currents flowing through it, without actually corresponding to a fault. The first part of this chapter will describe the phenomena that cause such net currents to flow, in order to understand them better, and highlight the fact that no action is required from the protection scheme in these cases. After that, the consequences of these net currents on the localization of a ground fault in the meshed network will be studied, and the requirements for the protecting elements will be derived. Finally, the way to ensure the selectivity of the protection scheme will be described.

5.1. Balancing currents flowing in a capacitively grounded DC grid with multiple grounding points

5.1.1. Voltage across the grounding points in steady-state

The voltage on the middle conductor will not be the same everywhere in the network when the load is unbalanced on the poles. The bigger the unbalance, the worse the voltage deviation will be. If there is only one grounding point, then the voltage on the middle conductor at the grounding point will be null with reference to ground, and all the voltage deviations will occur further on in the cables. An example of that phenomenon is depicted in Figure 5.1 for which an extreme case of load unbalance has been simulated to make the voltage deviations on the conductors more obvious.

If, however, there is a second grounding point, like in the network described in Figure 5.2a, and the load is not exactly located at equal distance from both sources, then the voltage deviation will be distributed over the grounding points: in the case of a network with two grounding points, the voltage across the grounding capacitors will be of equal magnitude and opposite polarity, as shown in Figure 5.2.

The voltage across the grounding capacitors is depending on two things: the location of the load with respect to the grounding points, and the difference between the load connected to the positive pole and the one connected to the negative pole. For a voltage to appear across the grounding capacitors, the load has
5. LOCATING GROUND FAULTS IN A MESHED DC GRID

(a) Network with one grounding point under consideration

(b) Voltage deviations along the cable when $P_{pos} = 10\,\text{kW}$ and $P_{neg} = 1\,\text{kW}$

Figure 5.1: Voltage deviations in network with one grounding point

(c) Network with two grounding points

(d) Load at equal distance from the sources

(c) Load at 200 m from S1 and 400 m from S2

(d) Load at 100 m from S1 and 500 m from S2

Figure 5.2: Voltage deviations across the grounding points for a cable of 600 m and a load ($P_{pos} = 10\,\text{kW}$ and $P_{neg} = 1\,\text{kW}$) at different locations

to be closer to one grounding point than to the other, and the loads connected on the poles have to be different. If one of these conditions is not true, then there will be no voltage across the grounding points.

The further away the load is from the middle point between the ground points, or the bigger the difference between the positive and negative pole loads, the higher the voltage will be across the grounding points. Figure 5.3 is a representation of this phenomenon. Each line corresponds to a different location of the load on the cable: the load is $n \times L$ metres away from the grounding point $C_{\text{gnd}}$, $L$ representing the total length of the cable (fixed). The load balance on the pole is then varied: the x-axis represents the ratio of the loads on the poles $P_{pos}/P_{neg}$; $P_{neg}$ (the power consumed by the load connected to the negative pole) stays constant while $P_{pos}$ (the power consumed by the load connected to the positive pole) increases.

The simulations were run only for the load located on the first half of the cable, and for $P_{pos}$ varying,
5.1. BALANCING CURRENTS FLOWING IN A CAPACITIVELY GROUNDED DC GRID WITH MULTIPLE GROUNDING POINTS

5.1.1. Absolute Currents Flowing in the Overhead Line

The load distribution on the network is subjected to transient effects due to the changing load. During load changes, all the capacitances of the network need to adapt to the new load distribution, and their voltage changes. The effect on the grounding capacitors is of importance in the design of a good protection system. Indeed, as the grounding capacitors’ voltage changes, current will flow through the grounding points to account for the new load balance on the network (hence the name balancing current), and this current will thus be detected by the protection scheme. An example of the phenomenon is displayed on Figure 5.4.

![Grounding capacitor voltage as a function of load distribution](image)

**Figure 5.3:** Voltage across the grounding capacitors for different combinations of load location on the cable and load balance on the poles

and the behaviour of the system has been found to be symmetrical. If the load is located on the second half of the cable, then there is a symmetry in the resulting graph with regard to the x-axis. If $P_{\text{neg}} > P_{\text{pos}}$, then there is an axial symmetry with regard to the line $x = 1$. It is expected that, in practice, there will always be a voltage drop on the capacitors, as the network’s configuration will never be perfectly symmetrical.

These voltages across the grounding points are due to the load balance and its location on the network. These values are, in this case, steady-state values. In a network, loads get connected and disconnected during the course of a day. This means that the load distribution on the network will be subjected to change, and these changes will force the capacitors to adapt to different voltage levels every time. Of course, the voltage changing across a capacitor will cause this capacitor to charge or discharge, so a current will flow. The impact of such a current on the meshed DC distribution grid will be described in the following section.

5.1.2. Impact of Load Changes on the Grounding Points

During load changes, the network is subjected to transients: all the capacitances of the network need to adapt to the new load distribution, and their voltage changes. The effect on the grounding capacitors is of importance in the design of a good protection system. Indeed, as the grounding capacitors’ voltage changes, current will flow through the grounding points to account for the new load balance on the network (hence the name balancing current), and this current will thus be detected by the protection scheme. An example of the phenomenon is displayed on Figure 5.4.

![Voltage drop across grounding points](image)

![Protection cable 1](image)

(a) Volatages and currents at the grounding points

(b) Protection signals and $I_{\text{sum}}$ measurement

**Figure 5.4:** Load change in the network: $P_{\text{pos},0} = 2$ kW, $P_{\text{neg},0} = 3$ kW, $d_{\text{LS}_1} = 200$ m, $C_{\text{grid,ind}} = 1.75$ mF, and at $t = 0.05$ s, $P_{\text{pos}} = 4$ kW
The voltages and currents across and through the grounding points can be seen on Figure 5.4a after the load change, a current wave flows through the grounding points due to their voltage change. This wave, as it can be seen on the figure, has a maximum value above the threshold of the protection scheme (150 mA); the protection scheme might consider it as a fault. Additionally, the bigger the load change, the higher the peak of the balancing current wave, and hence the sooner the protection might react (see chapter 6 for more explanations).

The phenomenon, however, is very fast, and the balancing current goes below the protection threshold again very soon in this case, so the protection does not have time to react to it (see Figure 5.4b). As a matter of fact, the duration of the current wave is determined mostly by the size of the grounding capacitors: the bigger the capacitors, the more current will be needed to charge them to the required voltage level, and thus the longer the current will flow through the ground.

So far, no communication was required in the system. If the grounding capacitors are sized in such a way that important load changes will not be perceived as ground faults due to the balancing current wave, then the network can still function without communication. This criteria can be used as a upper size limiter for the grounding capacitors. The determination of this maximum size, however, would require an in-depth study of the possible load on the network (load that does not cause more than 10% of $V_{pole, nom}$ voltage drop along the cables), and it would have to be done for every network configuration under consideration. This value is too specific and too dependant on the network configuration for a general value to be given here. As of now, the grounding capacitors will be sized with the minimum value calculated in Section 4.3.4, as it represents a boundary condition for system stability and will ensure that load changes are not seen as faults by the protection scheme.

5.2. NET CURRENTS CIRCULATING IN A MESHED GRID

5.2.1. INTRODUCTION TO CIRCULATING NET CURRENTS

So far, the resistance in the network was assumed to be perfect: all the conductors have the same resistance, there is no contact resistance between the elements, among others. It is obvious that it will not be so in practice; there will always be a slight difference in resistance between the conductors in one cable, and this has consequences on the detection of a ground fault. Significant cases of resistance asymmetry in the network are when a pole has been disconnected to isolate a fault, or when one of the conductors in a cable has overheated. In both cases, one pole has a resistance that is different from that of its counterpart (infinite resistance in the case of an open pole), and a net current starts flowing.

The circulating net current phenomenon has been demonstrated mathematically for the general case of a ring configuration, such as the one described in Figure 5.5. In Appendix D.1, it has been shown that:

\[
\begin{align*}
I_{sum,S1,cable1} &= -I_{sum,S2,cable1} \\
I_{sum,S1,cable2} &= -I_{sum,S2,cable2}
\end{align*}
\]

under the condition that at least one of them is not null and that there is no ground fault.

If, for example, $I_{sum,S1,cable1}$ is chosen positive (entering the cable), then the net current would flow as described in Figure 5.6. This shows that the net current is indeed circulating in the network, hence the name. Additionally, it does not participate to the load supply nor does it correspond to a fault. It is thus important that the protection detects such a net current and does not open the poles wrongly. The two coming sections will describe cases in which circulating net currents occur, and more importantly, the magnitude of these net currents and what they depend on.
5.2. Net Currents Circulating in a Meshed Grid

5.2.2. Case of a Disconnected Pole

The case of a simple loop network, represented in Figure 5.7, has been chosen to explain what happens in the network after a pole has been disconnected. The mathematical expressions that describe the phenomenon are derived in Appendix D.2, and only the most significant results will be discussed here.

After a pole has been disconnected from the network, the RCM (residual current measurement, see Section 3.1.2) devices on each cable pick up a signal, that can have the magnitude corresponding to a fault, but that is not actually a fault. The magnitude of the signal mainly depends on the voltage difference between the grounding points, as described by Equation 5.3:

\[
I_{\text{sum}} = \frac{1}{2} \left( \Delta V_C \frac{3R_2 - 2R_1}{R_1 R_2} + \Delta V_S \frac{R_2 - R_1}{R_1 R_2} - \frac{\Delta V_S'}{R_1} \right) \quad (5.3)
\]

Several factors can be seen in this formula:

- The difference in capacitor voltages \(\Delta V_C\)
- The cable resistances \(R_1\) and \(R_2\)
- The difference in pole voltages, measured at the sources, \(\Delta V_S\) and \(\Delta V'_S\), for the positive and negative pole respectively
The differences in pole voltages $\Delta V_S$ and $\Delta V'_S$ play a role in the magnitude of the circulating net current, but because they are usually very small, their influence can be neglected. If one particular network configuration is considered, then $R_1$ and $R_2$ are constant, and the circulating net current is thus only proportional to the difference in ground voltages (see Section 5.1.1 for explanations on the grounding capacitors voltage distribution). For a chosen configuration ($R_1 = 2.766\, \Omega$, $R_2 = 3.688\, \Omega$, $\Delta V_S = 0$ and $\Delta V'_S = 0$), the circulating net current as a function of the difference in grounding capacitor voltages is depicted in Figure 5.8.

![Figure 5.8: Circulating current as a function of the difference in grounding capacitor voltages](image)

Because of the voltage clamps, the voltage difference between two grounding points cannot be higher than $2 \times 17.5 = 35\, \text{V}$. Consequently, in the chosen configuration, the maximum amplitude of the circulating net current in case of an open pole is of about $\pm 9.5\, \text{A}$, which is fairly high. With a different configuration, the circulating net current can be higher, especially for a shorter cable on the side where both poles are still connected. It is expected, however, that the voltage difference between two grounding points on either side of the loop will stay rather small. Indeed, a high value of $\Delta V_C$ means that the network is highly unbalanced, and it is likely that the voltage at the loads will be close to its allowed minimum. In the rest of this paper, the maximum circulating net current flowing due to an open pole is thus estimated to be of about $\pm 10\, \text{A}$, to remain conservative.

### 5.2.3. CASE OF OVERHEAT

When a conductor needs to carry a high current for a long time, its temperature can increase. An increase in temperature will mean that the resistance of this conductor will also increase, while the resistance of the other conductors in the same cable will not change. This causes a circulating net current to flow in the network, but only if the overheated cable is part of a ring. The network configuration used to derive the equations for the circulating net current flowing in case of overheat is depicted in Figure 5.9. The whole derivation can be found in Appendix D.3, and only the most significant results will be displayed here.

![Figure 5.9: Ring network with one conductor overheating in cable 1](image)

The magnitude of the circulating net current flowing in case of an overheated conductor can be determined
with the help of Equation 5.4

\[ I_{\text{sum}} = \frac{\Delta V_S - \Delta V'_S + 3\Delta V_C}{2R_2} + \frac{1}{2R_1} \left( 2\Delta V_S + \Delta V'_S + \frac{d_{21} R_k R_{10} I_{L1}}{R_1 + R_{10}} \right) - \left[ \frac{(\Delta V_S + \Delta V'_C)[3R_1 + 2R_{10}]}{R_1 + R_{10}} \right] \] (5.4)

The equation is more elaborate than the one for the open pole case, but several common factors can be seen. The overheat induced circulating net current depends on:

- The differences in poles voltages \( \Delta V_S \) and \( \Delta V'_S \), but once again, these values tend to be small
- The difference in grounding capacitors voltages \( \Delta V_C \), which, as described in Section 5.2.2, can be as high as \( \pm 35\text{V} \)
- The network configuration, in the form of \( R_1 \) and \( R_2 \), representing the total resistances of the two cables without overheat

For one given configuration, the factor that will have the most impact on the circulating net current is the current flowing through the overheated conductor to supply the load connected to it, represented in Equation 5.4 by:

\[ I_{L1} = \frac{d_{21} R_k R_{10}}{2R_1(R_1 + R_{10})} \] (5.5)

This equation clearly shows that the higher the load current, the higher the circulating net current. This statement is illustrated by Figure 5.10, which corresponds to the results of a series of simulations.

![Figure 5.10: \( I_{\text{sum}} \) varying with the load current carried by the overheated cable for a fixed load position](image)

However, it is not the only factor that plays a role: the length of the overheated conductor also determines the final amplitude of the circulating current. Expression 5.5 can be re-written to be depending on the relative location of the load on the cable, and thus on the length of overheated conductor in the following fashion:

\[ I_{L1} = \frac{R_0}{2R_k + R_0} \cdot \frac{x(1-x)}{R_k R_{10}} \] (5.6)

which has a maximum, located at:

\[ x_{\text{max}} = \frac{-2R_k + 2\sqrt{R_k(R_k + R_0)}}{2R_0} \]

with \( R_k \) representing the resistance of the cable per unit of length at nominal temperature (20°C), while \( R_0 \) represents the additional resistance due to overheat per unit of length for the current cable temperature (see Appendix D.4 for the derivation). This phenomenon can be observed in Figure 5.11, which depicts a simulation for a fixed load, moving along the cable which overheats in part.

---

1Simulation parameters: \( R_k = 4.61\Omega/\text{km} \), \( R_0 = 1.1177\Omega/\text{km} \) (additional resistance when cable at maximum allowable temperature), \( d_{11} = 0.06\text{km} \), \( d_{21} = 0.54\text{km} \), \( d_{12} = d_{22} = 0.4\text{km} \), \( P_{L1,\text{neg}} = P_{L2,\text{pos}} = P_{L2,\text{neg}} = 2\text{kW} \)
The circulating net current induced by the overheating of a conductor is significantly smaller than when it is caused by an open pole. The phenomenon, however, cannot be disregarded, as the circulating net current amplitude reaches the ground fault current level. As such, the protection scheme could detect it as a false positive, and disconnect properly operating parts of the network.

The overheat of the cable was emulated by adding a resistor on the conductor, thus provoking a resistance asymmetry between the conductors. It is expected that such resistance asymmetry will be a more frequent occurrence in the network, due to the multiple phenomena that can cause it: overheat, as described here, or contact resistance between the different components of the network, but also simply due to the fact that two components can never be perfectly equal in practice. However small, it is likely that a net current will circulate consistently in ring configurations, even without fault to ground. Consequently, it is very important to consider this carefully while designing the protection scheme.

5.3. CONSEQUENCES ON THE PROTECTING ELEMENTS

5.3.1. THE MEASUREMENT DEVICE

When located in a loop

An accurate measurement of the net current flowing into a cable ($I_{\text{sum}}$) is necessary to ensure the safety of the network users. If 0.1% error on the measurement is allowed, and as the protection threshold is of 150 mA, one can consider that the measurement device needs to be accurate in the range of 0.1 mA. Additionally, it has been shown that circulating currents could reach $\pm 10$ A in amplitude. These two requirements are very constraining for the measurement devices that will be placed on cables that are part of a loop, as they will need to be very accurate over a large range of values.

At first, a Hall effect sensor was considered to measure the net current $I_{\text{sum}}$; an iron core would be placed around the cable, and the sum of the currents flowing through the conductors would be made without any external intervention. This method would also have the benefit of providing galvanic isolation between the network and the protective system, which is desirable at such power levels.

The problem with such a measurement method is that the iron core will need to be chosen in such a way that it will not saturate over the whole expected range of current values ($\pm 10$ A), which means a big iron core is required. Additionally, to make sure that the measurement is accurate in the small values, the Hall effect sensor, consisting of a semi-conductor slab, also needs to be quite big. This would result in a big and expensive measurement device, that needs to be placed next to each relay to ensure a high level of safety, so the implementation would be expensive.

Another method would be to use shunt resistors to measure the current in each conductor. Accurate values of the current are obtained with bigger resistors, which in turns provoke more losses in the network. Each measurement would then need to be summed externally and the data processed, which increases the likelihood of introducing errors in the measurements, and thus reducing its accuracy. The galvanic isolation provided by the Hall effect sensor would also be lost.

It derives that choosing the appropriate measurement device that would measure the fault currents
5.3. CONSEQUENCES ON THE PROTECTING ELEMENTS

accurately, especially when circulating currents are superposed to it, is a more complicated task than one
would think. The development of such a measurement device could be a MSc thesis in itself, so for the
rest of this research, it will be considered that the device is available and the measurement is satisfactory in
terms of accuracy and range.

When located on a string

If the measurement device is placed on a cable that does not belong to a loop, then no circulating will
flow through that part of the network. If that cable is located between two grounding points, then it
will see balancing currents flowing. However, if the grounding capacitors are sized in the way described
in Section 5.1.2 then the exact value of the balancing current does not need to be measured, so the
measurement device only needs to be accurate over the range used in the protection scheme. As every
current above 500 mA triggers an protection operation of equal speed, it is not necessary to measure these
values accurately either. A current transducer able to measure from 0.1 up to 600 mA (safety margin)
would thus be enough to protect these parts of the network, and would consequently be much cheaper than
the devices used in loop configurations. It would also allow a cheaper protection of individual houses, for
example, and the implementation of a high level of protection on street level would then be facilitated.

5.3.2. NEED FOR COMMUNICATION

In the previous sections, it has been shown that in the case of a net current flowing around the network,
whether it is balancing or circulating, so without being caused by a fault, its magnitude could still correspond
to a ground fault current, and would be picked up by the protection scheme. Actions could be taken, such
as the disconnection of a pole which is actually healthy. This is extremely undesirable, as it would disrupt
what can be considered as the normal operation of the system, and it would reduce the availability of the
power and reliability of the supply. Something needs to be done to ensure that the protection will be able
to discriminate such net currents from actual fault currents.

One interesting result that has been obtained in those sections is that, when there is no fault, all the net
current coming into a cable from one side, comes out at the other side. In other terms: if a load is located
between two nodes, and each cable leaving a node has its own protective relay, then both relays will measure
a net current of same amplitude and opposite polarity:

\[ I_{\text{sum, relay1, apparent}} = -I_{\text{sum, relay2, apparent}} \] (5.7)

On the other hand, if there is a fault on the cable connecting the two nodes, as it is supplied from both
sides, then the total fault current will be:

\[ I_{\text{fault}} = I_{\text{sum, relay1, fault}} + I_{\text{sum, relay2, fault}} \] (5.8)

A combination of the two can occur, and then each relay will measure the following current:

\[ I_{\text{sum, relay i}} = I_{\text{sum, relay i, apparent}} + I_{\text{sum, relay i, fault}} \] (5.9)

If one were to sum the measurements made by the two relays, it would yield:

\[
I_{\text{sum,tot}} = I_{\text{sum, relay1}} + I_{\text{sum, relay2}} \\
= I_{\text{sum, relay1, apparent}} + I_{\text{sum, relay1, fault}} + I_{\text{sum, relay2, apparent}} + I_{\text{sum, relay2, fault}} \\
= I_{\text{sum, relay1, fault}} + I_{\text{sum, relay2, fault}} \\
= I_{\text{fault}}
\] (5.10)

which can be used both to make the difference between a fault and a net current flowing around the network,
and also ensure the selectivity of the protection scheme by enabling it to locate the exit point of the current.
Indeed, if a fault occurs elsewhere in the network and the fault current has to transit through several other
cables, then on these cables, the fault current would also be detected as a travelling current and the protection would not be triggered. Figure 5.12 presents an illustration of these findings.

One has to note, however, that if a load is connected to a source only from one side, as in the configuration depicted in Figure 5.13, then no communication is required as the fault current can only come from one side, and neither the balancing or circulating current phenomena occur in such a configuration.

![Figure 5.12: Illustration of the net current direction in case of fault or travelling currents](image)

### 5.3.3. COMMUNICATION SPEED

Summing the measurements of two relays requires them to communicate, and communication takes time. However, as human life can be threatened when a fault occurs, the protection needs to act fast, so the communication needs to be even faster. Time is strictly limited.

As it has been described in [6], for currents of 500 mA and above going through the body, about 10 ms are sufficient for the heart to enter fibrillation. As a matter of facts, above 500 mA, the current is strong enough to cause fibrillation if a whole heart cycle is covered: the time matters then more than the magnitude of the current. A heart cycle lasts for about 10 ms, so it can be considered to be the fastest reaction time required from the protection scheme to ensure human safety.

In those 10 ms, the individual relays need to communicate to locate the fault, and the protection scheme needs to isolate it. It has been decided that the protective switches used for short-circuit protection (MOSFETs, see the works of Dimitris Petropoulos and Nikos Gouvalas) would also be used to isolate the ground faults; as short-circuits need to be interrupted in the range of $\mu$s, the switches are chosen in part for their fast opening times, and thus for the isolation of a ground fault, they are more than fast enough. Consequently, the opening time of the switches can be neglected here. Additionally, if the data is processed numerically by the relays, it can be considered that the computation time will not be problematic for the protection scheme to operate before damage is caused. The limiting factor is the operation time of the protection is then, by default, the communication.

If one considers that the maximum amplitude of the net currents is $\pm 10 A$ (see Section 5.2.2), and by considering an accuracy of the measurement devices in the range of 0.1 mA, then

$$N = \frac{2 \times 10}{0.1 \times 10^{-3}} = 200000$$

different values would be required to represent the whole span of the current measurement. As $2^{18} = 262144$, then 19 bits would be needed to encode the signal into binary. Checksums can be added to the signal to reduce the likelihood of communication errors, and the conservative number of 32 bits, or 4 bytes, is reached.

For measure of safety, it can be considered that these 32 bits should be transmitted within a tenth of the smallest operation time of the protection, which in this case would yield a transmission time of 1 ms. The
required transmission rate for such a short communication time would then be:

\[ T_r = \frac{32 \text{ bits}}{0.001s} = 32 \text{kbps} \]

It is expected that in such a network as the one described in this research paper, communication would be done over Power Line Communication (PLC) in medium frequencies. Narrowband PLC, mostly used for Smart Grid applications, has typical transmission rates in the range of hundreds of kilobits per second (100s kbps) [18], which is significantly higher than the value calculated previously. Communication over PLC will thus be fast enough for the protection relays to be able to ensure the selectivity and discrimination necessary for a reliable and accurate protection of the system.

5.4. PROTECTION ZONE DEFINITION

Ideally, relays would be placed on every cable leaving a node, to ensure the highest level of selectivity. In heavily meshed grids, this would require a high number of relays and measurement devices, which, as it was explained in Section 5.3.1, could turn out to be quite expensive. Protecting the grid in such a way could thus represent a significant investment, that could possibly be overwhelming for the network owner. In this case, it might be interesting to define ‘protection zones’.

A protection zone would be delimited by the protective relays: if a zone is connected to \( n \) nodes, then \( n \) relays would need to communicate to ensure the safety of the zone. To make sure that the relays disconnect the right poles during a pole-to-ground fault, they need to be polarized; as such, currents flowing from the node to the load are considered positive. Two examples are given in Figure 5.13, with the white arrows indicating the polarization of the relay (current flowing in that direction will be measured positive).

![Figure 5.13: Definition of protection zones](image)

In the network configuration of Figure 5.13a relays \( R_1 \) and \( R_2 \) communicate together to assess if there is a fault in the part of the network that is located between them two. In Figure 5.13b \( R_1, R_2 \) and \( R_3 \) do the same thing. The more entry points there are to a protection zone, the more relays need to communicate together to ensure the selectivity of the protection scheme.

One needs to consider, however, that the bigger the zone, the more elements will be disconnected when a fault occurs in the zone. There is a balance to be found between the reliability of the supply, which would require the protection zones to be small to disconnect as few loads as possible after a fault, and the expenses involved in protecting these zones, due to the expected high costs of the measurement devices.

5.4.1. NODE PROTECTION

So far, only the parts of the network between nodes were protected. However, it can happen that a ground fault occurs at the nodes themselves, or even at the sources. To avoid using relays dedicated to protecting the nodes or the sources, one can reuse the relays already in place by making them communicate differently.
For example, to protect a node, all the relays located on the cables that leave that node need to communicate together. The difference with the protection of a zone between nodes is that the polarity of the trigger signals is reversed. The node is, by definition, on the other side of the relay, so if current is leaking through the ground there, it will be seen as ‘exiting the zone’ by each relay on the cables connected to that node. The polarity of the current will thus need to be reversed to treat the fault correctly: for a positive pole-to-ground fault at the node, the net current will be negative, and for a negative pole-to-ground fault at the node, it will be positive. Figure 5.14 illustrates the phenomenon.

![Figure 5.14: Fault current direction (in red) in case of a fault at the node](image)

5.4.2. SOURCE PROTECTION

The protection of the source requires an additional relay, or at least a residual current measurement (RCM) inside the source itself. Indeed, if a ground fault occurs at the source, all the fault current will be supplied by the source itself, and the relays located on the cables will not notice it. On the other hand, whenever a fault occurs on the rest of the network, the ground fault protection of the source will detect it. Just like for the node protection, the protection device of the source needs to communicate with all the relays located on the cables leaving that source to make sure it only opens when there is a fault at the source and not in the rest of the network. A difference of all the measurements needs to be made:

- If the difference is null, then it means that the fault current is travelling to another part of the network.
- If the difference is not null, then it means that the fault is located at the source and the normal fault isolation procedure needs to take place.

5.4.3. SUMMARY OF THE COMMUNICATION PROCEDURE

The communication pattern of the relays throughout the network can be found in Figure 5.15.

The communication procedure among the relays is the following:

- Source protection: the triggering signal is obtained by subtracting the $I_{\text{sum}}$ measurements made by the relays on the cables leaving the source to the $I_{\text{sum}}$ measurements of the source itself (green relays in the example).

$$I_{\text{trig, source}} = I_{\text{sum, source}} - \sum_{n=1}^{N} I_{\text{sum, cable } n}$$

- Zone protection: the triggering signal is obtained by summing the measurements from the relays located at each entrance of the zone (blue relays for zone 1, orange relays for zone 2).

$$I_{\text{trig, zone } j} = \sum_{n=1}^{N} I_{\text{sum, zone } j, \text{ relay } n}$$

- Node protection (node without direct connection to a source): the triggering signal is obtained by summing the $I_{\text{sum}}$ measurements of all the relays located on the cables leaving that node, and by reversing its polarity to ensure a good isolation of the fault (plain red relays for node B in the example).

$$I_{\text{trig, node } j} = -\sum_{n=1}^{N} I_{\text{sum, relay } n, \text{ node } j}$$
5.5. CONCLUSION

This chapter has shown, in essence, the necessity of having a communication system between the protective relays in the meshed grid configuration.

Indeed, every time a load is connected or disconnected, balancing current waves will flow through the network and the ground to allow the grounding capacitors to adapt themselves to the new voltage distribution over the network. This is due to the fact that no network can be perfectly symmetrical, and as such, there will always be a voltage drop across the capacitors, that changes with the load distribution in the network. Moreover, when there is a resistance unbalance between the poles, such as in the case of an open pole, or when a conductor overheats, a steady-state circulating current starts flowing in the network. For both balancing and circulating currents, the current levels can reach fault levels, and the protection would be triggered if there was no communication.

With communication, one can ensure that only the ground faults will be detected by the protection scheme. Combining the measurements of the relays in a clever way allows one to protect sources, nodes and zones with a minimum amount of relays, thus reducing the overall price of the protection equipment, and making the difference between an actual fault and a current that only travels through the network.

However, such net currents (balancing or circulating) take their toll on the protection equipment. It has been shown that travelling currents can reach values in the order of tens of amps, while fault currents need to be detected as soon as they reach 150 mA. As such, the measurement devices that perform the RCM need to be accurate over a wide range of values, and such demanding requirements might make their production expensive.

On the other hand, due to the time sensitivity of the protection scheme, as human lives could be in danger, the communication that is required to ensure the selectivity and discrimination of the protection scheme needs to be fast; at the very least, it needs to be faster than the fastest reaction time of the protection scheme. This, again, requires a performing communication protocol, with a level of error reduced as much as possible.

All this, combined with results discovered in the previous chapters, leads the following list of requirements that the protection scheme and protection devices need to comply to:

![Figure 5.15: Relays that need to communicate together to ensure protection selectivity](image)
The device performing the RCM needs to be accurate over a range of ±10 A with an accuracy of about 0.1 mA to ensure a good fault detection in case fault currents and travelling currents are superposed.

Communication is required between the relays:

1. The communication procedure needs to be much faster than the fastest protection operation (10 ms in this case, so a maximum of 1 ms spent on communication); at least 32 bits are required to encode the signal, which yields a minimum transmission rate of 32 kbits/sec.

2. Different types of ground fault protection (source, node, zone) can be performed by making the relays communicate in a clever way; each relay must be able to respond to two independent triggering signals.

The protection scheme must be able to differentiate a fault located on the positive pole from one located on the negative pole; for this, the polarity of $I_{\text{sum}}$ can be used (see chapter 3).

Ground faults on the poles are much more likely to be dangerous than when located on the middle conductor; additionally, it is important that the faults are interrupted in a timely fashion, to ensure the safety of the users; Figure 2.5 is used as reference for the correlation between current amplitude and maximum operating time of the protection scheme.

The relays performing the isolation of the faults use the switches designed for the short-circuit protection, as they provide very short opening times and good current breaking capability.

This list of requirements, combined to all the knowledge gathered in the previous chapters, will help define a protection scheme that can effectively locate faults on the network, and interrupt them on time to prevent damage to the network users. The following chapter is the writer’s proposition for such a protections scheme, with the proof on a test network that it is reliable, selective, standard-compliant and adaptive.

\[\text{See the MSc theses of Nikos Gouvalas and Dimitris Petropoulos on short-circuit protection of a DC grid}\]
6

THE GROUND FAULT PROTECTION SCHEME

In Chapter 2, the current levels that are dangerous for the human body have been defined. In Chapter 3, a way to differentiate positive pole from negative pole-to-ground faults has been found. In Chapter 4, a grounding configuration that should be implemented in a meshed DC distribution grid has been defined. In Chapter 5, a way to localize a ground fault on the network has been demonstrated, and that chapter also yielded a list of requirements the protection scheme needs to comply to. The goal of the current chapter is to combine all these elements to define a protection scheme that is adaptive, dynamic, reliable, selective and compliant to the standards.

A solution is proposed here. The basic operation of the protection scheme will be described in the first part of this chapter, and then its concrete implementation in MatLab Simulink will be explained. The third part of this chapter will relate the results of the simulations in which the protection scheme was tested. Finally, conclusions will be drawn about the ability of this protection scheme to adapt to the situations to come and possible additions will be discussed.

6.1. REQUIREMENTS

6.1.1. Threshold values

Protecting the network against ground faults also includes protecting its users, who could get in contact with the fault currents that are leaking through the ground. For that, it is necessary to choose thresholds that will satisfy the safety requirements stated in the standards, such as the Low Voltage Directive [19], which is applicable in Europe. This standard states:

Measures of a technical nature should be prescribed [...] in order to ensure: that persons and domestic animals are adequately protected against the danger of physical injury or other harm which might be caused by direct or indirect contact.

In that perspective, the values that can be chosen as thresholds for the protection scheme are those found in the standard IEC 60479-1 [6], using curve \( c_1 \) in Figure 2.5 as a reference, as it is done in AC systems. Below this curve, there is no risk of fibrillation for the average person; keeping the current and time combination below these values is thus a way to ensure safety of the network users. Table 6.1 makes a summary of these values.

The standard states that these values are “probably conservative for all humans”, so they will be used in the protection schemes described in this document, which will in turn be considered compliant to the Low Voltage Directive. However, if further research proves these to be unsatisfactory on a safety point of view, then they will have to be re-evaluated. Fault currents originating from a pole to ground faults, being significantly higher than the currents stated in Table 6.1 will thus be effectively detected and interrupted by the protection scheme.
Table 6.1: Current thresholds and their corresponding time of operation

<table>
<thead>
<tr>
<th>Current amplitude [mA]</th>
<th>Time of operation [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2000</td>
</tr>
<tr>
<td>170</td>
<td>1000</td>
</tr>
<tr>
<td>185</td>
<td>500</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>375</td>
<td>100</td>
</tr>
<tr>
<td>425</td>
<td>50</td>
</tr>
<tr>
<td>500 and above</td>
<td>10</td>
</tr>
</tbody>
</table>

The input signal $I_{\text{trig}}$ will be compared to the values of Table 6.1 and the required actions will be taken to isolate the fault. The isolation of the fault is explained in the following paragraph.

6.1.2. ISOLATION OF THE FAULT

To properly isolate a ground fault, the faulted cable or piece of equipment must be disconnected from the parts of the network that feed its fault current. The fault must be properly localized and the healthy parts of the system identified. Indeed, as it was stated in Chapter 3, it is desirable to leave the whole network in operation as long as possible to maintain a high power quality, which means only the faulted elements should be disconnected, until the network reaches again a satisfactory level of safety.

The network is protected in zones, each zone being demarcated by the protective relays (see Appendix E.1). The same relays are used to protect the sources and the nodes themselves (see Chapter 5 for further explanations). Each part of the network is protected with the help of the signal $I_{\text{trig}}$, defined as follows:

$$I_{\text{trig}} = \begin{cases} I_{\text{sum, source}} - \sum_{n=1}^{N} I_{\text{sum, cable } n} & \text{in the case of a source} \\ \sum_{n=1}^{N} I_{\text{sum, zone } j, \text{ relay } n} & \text{in the case of a zone} \\ -\sum_{n=1}^{N} I_{\text{sum, relay } n, \text{ node } j} & \text{in the case of a node} \end{cases}$$

$I_{\text{trig}}$ corresponds to the amount of residual current flowing into the protected area, as measured by the relays. Most relays will be involved in the protection of several areas, for example a zone and a source, or a zone and a node. In this case, the protection scheme needs to react to either of these signals, without distinction. For every possible combination, the trigger signal has been defined in such a way that the pole-opening procedure is identical, and it is defined as follows:

- If the magnitude of $I_{\text{trig}}$ is greater than the detection threshold (see Table 6.1), then there is a ground fault on the cable, and it needs to be treated;
- If $I_{\text{trig}}$ is positive, then it means that the fault is located on the positive pole, or on the middle conductor if the positive pole is more loaded than the negative one;
- If $I_{\text{trig}}$ is negative, then the fault is located on the negative pole, or on the middle conductor if the negative pole is more loaded than the positive one;

The polarity of $I_{\text{trig}}$ gives precious information, but there will always be an uncertainty over the exact location of the fault, whether it is on one pole or on the middle conductor. As half the bipolar network can still function when one of its poles is damaged, the first action to be taken when the threshold is exceeded is to disconnect one pole. If $I_{\text{trig}}$ goes below the threshold again, then it means that the fault was indeed on the pole, and it is now isolated. If $I_{\text{trig}}$ remains above the threshold, then it means that the fault is located on the middle conductor; the other two conductors will thus be opened, and the fault will be isolated.

It has to be kept in mind, however, that ground faults in a DC-system tend to have a permanent character (see Chapter 2). The fault will be isolated, but will not necessarily be cleared. An automatic reclosing could
verify if the fault is cleared by attempting to reconnect the faulted parts of the network. If the fault lingers, then maintenance will be required. Additionally, to effectively isolate the fault, the loads connected to the faulted part of the network also need to be disconnected to remove any possible path for the current to keep flowing through the fault.

Finally, the protection should not be triggered for spikes or transient states in $I_{\text{trig}}$, but only for faults that persist in time. These could occur during load switching, or the (dis)connection of other parts of the network for example, and do not actually correspond to a ground fault. To avoid unintentional disconnection of healthy parts of the network, it is necessary to insert a time delay in the procedure. For that, the maximum operation times listed in Table 6.1 will be used as limiting factors. The magnitude of $I_{\text{trig}}$ will be monitored during this time delay, and if it remains higher than the threshold long enough, the protecting elements will be opened.

6.2. Operation of the Ground Fault Protection Scheme

Now that what is required from the protection scheme has been described, the protection algorithm can be written. The corresponding flowchart can be found in Figure 6.1.

Signals and parameters  The important signals and parameters of the protection scheme are:

Inputs  the signal $I_{\text{trig}}$
Parameters  the ground fault detection threshold $I_{\text{thresh}}$
            the equivalence table $T_{\text{eq}}$ giving $t_{\text{max}} = f(I_{\text{trig}})$ (see Table 6.1 for an example)
Outputs  the trigger signals for the protection switches

The parameters listed above will have to be tuned to fulfil the safety requirements for a given network configuration.

Protocol of operation  The protection protocol is the following:

1. The magnitude of $I_{\text{trig}}$ is monitored. If it exceeds the parameter $I_{\text{thresh}}$, then a ground fault has probably occurred on the protected element and may have to be treated; proceed to Step 2
2. The maximum value of the operation time $t_{\text{max}}$ is deduced from the equivalence table $T_{\text{eq}}$; proceed to Step 3
3. To avoid triggering for a momentary increase in $I_{\text{trig}}$, a time delay of half $t_{\text{max}}$ is introduced; proceed to Step 4
4. The magnitude of $I_{\text{trig}}$ is monitored carefully during the delay. If it is still above $I_{\text{thresh}}$ at the end, then it is considered that there really is a ground fault on the protected zone, and actions have to be taken; proceed to Step 5
5. The polarity of $I_{\text{trig}}$ is checked: if it is positive, then the fault is possibly on the positive pole (Step 6a); if it is negative, then the fault is possibly on the negative pole (Step 6b); proceed to Step 6
6. The relevant pole is disconnected:
   (a) $I_{\text{trig}} > 0$: the positive pole is disconnected; proceed to Step 7
   (b) $I_{\text{trig}} < 0$: the negative pole is disconnected; proceed to Step 7
7. To make sure that the fault has indeed been isolated, a second time delay of half $t_{\text{max}}$ is introduced; proceed to Step 8
8. The magnitude of $I_{\text{trig}}$ is monitored during the delay once again. If the fault was indeed on one of the poles, it will have decreased and gone below $I_{\text{thresh}}$ (Step 9b). If not, it means that the fault was actually located on the middle conductor, and the fault is not isolated yet (Step 9a); proceed to Step 9
9. The relevant action is taken on the other pole:

(a) The fault is not isolated yet: the second pole and the middle conductor are disconnected; end of the procedure

(b) The fault has been isolated: the healthy pole is left to function; end of the procedure

END

Figure 6.1: Flowchart of the protection algorithm
**Clarifications**  In Steps 3 and 7, time delays of $t_{\text{max}}/2$ are used to ensure that a fault occurring on the middle conductor will be isolated within a total operation time of $t_{\text{max}}$, as it requires a sequential disconnection of the two poles. This also yields that pole to ground faults will be isolated in half the maximum operation time, which increases the level of safety.

**Additional considerations** It has been shown in the previous chapter that fault currents would remain relatively low in the case of a middle to ground fault, as the voltage on the middle conductor will be limited. This yields that more time could be taken before opening the first pole, and less before opening the rest of the conductors. The time delays could be $0.7t_{\text{max}}$ and $0.3t_{\text{max}}$ respectively, for example. One has to keep in mind, however, that communication can only go so fast; it has been considered that 1 ms was the maximum allowable communication delay. This yields that, to make sure the signals are correctly communicated over the network before any action is taken, the second opening cannot take place before 3 ms, so $0.3t_{\text{max}}$ is actually the lower limit for the second opening action. On the other hand, waiting longer before opening the first pole decreases the level of safety in the network in the case a pole-to-ground fault is occurring. Additionally, a shorter time delay for the second opening would increase the risk that a spike in the input signal would be considered as a fault (as in the case of a load change, see Section 5.1.2); for these reasons, it has been decided that the time delays used in the protection scheme would remain as they are described in the protocol.

### 6.3. IMPLEMENTATION OF THE PROTECTION SCHEME IN MatLab Simulink

The protection scheme is implemented in MatLab Simulink with a combination of coded functions and simple blocks. The overview of the whole protection scheme can be found in Appendix E.2. To simplify its explanation, it will be broken down into several parts, starting with the input signal, continuing with the steps described in Section 6.2, and ending with the automatic reclosure procedure.

#### 6.3.1. The input signal

In case one relay is only protecting one area, then the $I_{\text{trig}}$ signal measured by the relevant RCM device can be sent directly to the input of the protection scheme block. However, as it has been explained in Section 5.4 when the relay needs to protect more than one area, it has to be able to react to any combination of the two input signals it will receive. Pre-processing the signal can be done to prioritize the signals and filter out the noise.

The idea is the following. The relay receives two signals on which it might need to operate, $I_{\text{trig,area1}}$ and $I_{\text{trig,area2}}$. A detection level is defined as the minimum significant amplitude of the net current measurement, or in other words the lowest value of the RCM that can safely be considered above noise level.

If both signals are below the detection level, then no signal will be sent to the first step of the protection scheme, as it means that both signals correspond to noise in the measurements. If one of the signals is above the detection level, then it is sent to the first step of the protection scheme, as the latter might need to react on it.

If both signals are above the detection level, then both signals are compared to one another and only the signal of bigger amplitude is sent to the first step of the protection scheme, as it would need to react on it sooner than for the other one.

The implementation of this signal pre-processing in MatLab Simulink is displayed in Figure 6.2. The output of the pre-processing block is sent to the protection scheme block, described in the following sections.

#### 6.3.2. Steps 1 to 4: fault detection

Figure 6.3 shows how the four first steps of the protection scheme are modelled in Simulink.

**Step 1** The signal $I_{\text{trig}}$ enters the protection block at this point. Its magnitude is obtained by feeding it through an ‘absolute value’ block. The output of this block is then sent to a comparator; if $I_{\text{trig}}$ is superior to $I_{\text{thresh}}$, the comparator outputs a ‘1’, otherwise it outputs ‘0’. This signal is used to activate the rest of
the protection scheme. If it falls back to '0' before the time delay of Step 3 is over, then nothing will be sent to the protective elements, as it was only a transient in \( I_{\text{trig}} \). The value of \( I_{\text{thresh}} \) is taken from the MatLab workspace; as such, it can be defined in a script outside of the model.

**Step 2** The equivalence table \( T_{\text{eq}} \) is given as a parameter to a 'look-up table' block. This block associates every value of \( I_{\text{trig}} \) to a operation time \( t_{\max} \). It is very important to define carefully every \( I_{\text{trig}} - t_{\max} \) pair for \( I_{\text{trig}} \) above the detection threshold to comply to the safety requirements.

**Step 3** This step consists of waiting for half of \( t_{\max} \), defined in Step 2, once the detection threshold is exceeded. This is done via a user-coded function that carries out a variable time delay, in case the value of \( I_{\text{trig}} \) changes. Indeed, if \( I_{\text{trig}} \) increases after exceeding the threshold, it is important that the time delay takes a new value for the whole protection scheme to never last longer than \( t_{\max} \).

The function’s signals are the following:

<table>
<thead>
<tr>
<th>Inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>clk</td>
<td>gives the actual time step of the simulation</td>
</tr>
<tr>
<td>trig1</td>
<td>is the direct input of the comparator</td>
</tr>
<tr>
<td>trig2</td>
<td>is the input of the comparator delayed by one time step</td>
</tr>
<tr>
<td>deltat</td>
<td>is the operation time obtained from ( T_{\text{eq}} )</td>
</tr>
<tr>
<td>told</td>
<td>receives the output ttrig; works as feedback</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>trigout</td>
<td>gives the confirmation that there is indeed a fault on the protected element and actions need to be taken</td>
</tr>
<tr>
<td>ttrig</td>
<td>gives the information about the exact moment the threshold has been exceeded</td>
</tr>
</tbody>
</table>

The function’s algorithm works as follows. The exact moment the threshold is exceeded is detected by comparing 'trig1' and 'trig2', 'trig2' being 'trig1' delayed by one time step: if they are different, then it means that the output of the comparator changed. The value of 'clk' is stored at this point in 'ttrig', which stands for 'time of trigger'. If 'trig1' is in high state, the function will measure the time elapsed since 'ttrig' by comparing it to the sum of 'clk' and half of 'deltat'; if it exceeds it, then the time delay has passed, and the output 'trigout' changes from '0' to '1'. Were 'trig1' to fall back to '0' before the end of the delay, then
6.3. IMPLEMENTATION OF THE PROTECTION SCHEME IN MatLab Simulink

'\textit{trigout}' would remain at '0', and the rest of the scheme would not be activated.

The code of this function can be found in Appendix [E.3] as a reference.

\textbf{Step 4} \quad I_{\text{trig}} \text{ has stayed above the threshold value long enough for the time delay to be elapsed, so action has to be taken. If the trigger signal was sent directly to the switches, and their opening was actually isolating the fault, then the switches would close again as soon as } I_{\text{trig}} \text{ goes below the threshold again. This would lead } I_{\text{trig}} \text{ to exceed the threshold once again, and the switches to open, etc. This would provoke important oscillations in the network due to successive opening and closing of the protective elements.}

\text{To avoid this phenomenon, the output of the delay block is fed to the 'Set' input of an 'R-S flip-flop', and its 'Reset' input is held at '0' by the automatic reclosure function. This way, once the trigger signal has been sent, what happens before the flip-flop will not have an effect on its output, and the switches will remain open.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Diagram1.png}
\caption{Model of the protection scheme —steps 1 to 4}
\end{figure}

6.3.3. \textbf{STEPS 5 AND 6: POLE SELECTION}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Diagram2.png}
\caption{Model of the protection scheme —steps 5 and 6}
\end{figure}

A triggered system is used to perform Step 5, as shown in Figure [6.4], to avoid the oscillation problem, as the output of Step 6 is sent to the protective switches. The system will trigger for a rising edge in the signal ‘\textit{trig}’, which corresponds to the output of the flip-flop described in Step 4.

\textbf{Step 5} \quad The polarity of the signal } I_{\text{trig}} \text{, input to the triggered system, is determined with the 'sign' block. This block will output a '1' if } I_{\text{trig}} \text{ is positive, a '-1' if it is negative, and a '0' if it is null. This output will be used by the switch in Step 6 to send the trigger signal to the relevant protecting element.}

\textbf{Step 6} \quad The first input of the switch contains the vector } v_{\text{trig,p}} = [\text{trig};0;0] \text{, used to open the positive pole, while its third output contains the vector } v_{\text{trig,n}} = [0;0;\text{trig}] \text{, used to open the negative pole. If the output
of the sign block is positive, then the switch will propagate the vector $v_{\text{trig,p}}$ to the protecting elements; otherwise, it will propagate $v_{\text{trig,n}}$. This is how the relevant pole is disconnected and the rest left in service.

**Note** So far, the logic used in the program was positive, with ‘0’ used for false/no action and ‘1’ used for true/action. However, the switch blocks used to disconnect the poles require a ‘0’ to open, and a ‘1’ to close; the logic is reversed, so a logic ‘NOT’ block is inserted between the output of Step 6 and the protecting elements to solve this problem.

### 6.3.4. STEPS 7 TO 9: CLEARANCE VERIFICATION

Time has come to verify that opening one of the poles was enough to actually isolate the faulted element from the rest of the network, which is done in Steps 7 to 9, as depicted in Figure 6.5.

**Figure 6.5: Model of the protection scheme — steps 7 to 9**

**Step 7** The delay function is implemented once again, with a small twist. It receives the continuously updating value of ‘deltat’, but this time it triggers on the signal ‘trig’, which is the output of the previous delay function filtered through the first flip-flop. This way, it will detect the first order to disconnect one of the poles, and start measuring the time from there. The signal ‘threshold’ is used to activate the block. As soon as it goes back to ‘0’, the block will reset. If it stays high until the end of the delay, then the function will output a ‘1’.

**Step 8** If the second delay function outputs a ‘1’, then it means that the fault was not cleared by the first opening of the pole, so action has be taken anew. The signal is sent to a new flip-flop, to avoid oscillations, and this flip-flop will trigger the final protection action. The flip-flop will be reset by the automatic reclosure function.

**Step 9** The ‘Q’ output of the flip-flop is sent to a switch. If the switch receives a ‘0’ as input, then it keeps on sending the trigger signal that was determined at the end of step 6. If it receives a ‘1’, then it will send trigger signals to open the remaining poles, and finally isolate the fault.

### 6.3.5. AUTOMATIC RECLOSURE

Even though it is expected that most of the faults occurring in the DC micro-grid would have a permanent character (e.g. insulation failure), it can also happen that the fault was due to a person in contact with a live part and that the person has moved away from it after being shocked. Additionally, in the case of a false tripping, it would be interesting to reclose the switches to resume the operation of the system.

In any case, because of the human factor and the fact that cables are not self-repairing, the number of attempts at reclosing the protective switches has to be limited to avoid further damage. The limit in this project has been set to one attempt. This value, set as a input parameter to the automatic reclosure
6.4. VERIFICATION OF THE PROTECTION SCHEME ON A TEST CONFIGURATION

Now that the protection scheme has been devised, it is time to test it on a network. The network that has been chosen for the purpose of these tests contains several configurations: a ring, a load fed by two feeders, and a string to represent the radial configuration. This will allow one to visualize the several phenomenon that were mentioned earlier, such as the load change, the overheated cable, and the open pole configuration after a fault has been isolated. On the radial part of the network, a time discrimination will be used to isolate the faults; this yields that fewer relays are needed to protect the string, and no communication is needed in this part of the network (communication is only required when the fault can be fed by more than one source, see Chapter 5). The node and source protection can also be tested on the test configuration.

The network configuration chosen to test the protection scheme is depicted in Figure 6.7; each source is grounded, and the nodes are named A to D. A more detailed description of the test configuration, including the protection areas, can be found in Appendix E.5.

6.4.1. BALANCING CURRENTS

After many simulations, two situations were chosen as being the most representative of the network behaviour. The situations are: first, an additional load is connected to the positive pole of Cable 1 (between nodes A and B). Secondly, an additional load is connected to the negative pole of Cable 4 (leaving node A). The simulations yield interesting results.

The behaviour of the network in the first case is not surprising. When a load of about 3 kW is added on the positive pole of Cable 1, then all the cables connected between two grounding points see a current wave flowing, which corresponds to the different grounding capacitors charging or discharging, to adapt to the...
new voltage distribution in the network. The currents and voltages of the grounding capacitors are depicted in Figure 6.8.

In these simulations, the communication between the relays is assumed to be instantaneous. Nevertheless, as it can be seen in Appendix E.6, the balancing current wave of highest amplitude occurs on cable 5, with a peak at 487 mA. It lasts 9.3 ms, and spends 2.2 ms above the protection threshold of 150 mA. These results show clearly that even if there were no communication between the relays, the balancing current wave would be too short for the protection to react, and would only be seen as a spike that does not require immediate attention.

A very interesting fact is observable when the same load is connected to Cable 4 instead. Just like in the first case, the relays on Cable 4 do not pick up any balancing current wave (refer to Appendix E.7), as Cable 4 is only connected to a grounding point on one side. On the rest of the network, however, the relays will see the wave. This clearly shows that only the relays on parts of the network connected between two grounding points are impacted by the balancing currents, whereas those on zones connected to only one grounding point will not measure it. This is valid for any load change in the network, wherever it occurs. The voltage and current levels of the grounding capacitors in this second case are visible in Figure 6.9; the final voltage distribution over the grounding capacitors is different than in the previous case, but this is due to the fact that the final load distribution in the network is also different. This was thus to be expected, and it correlates to what has been stated in Section 5.1.

Conclusions: The multiple simulations have shown that the grounding capacitors have been sized in
6.4. Verification of the Protection Scheme on a Test Configuration

such a way that the load changes occurring in the network will not be detected as faults, even if there were no communication between the protective relays. Additionally, all the network elements located between two grounding points will be affected by a load change, wherever it occurs. In that sense, the behaviour of the system is satisfactory and meets the requirements.

6.4.2. Circulating Net Currents

Two examples of the network with an overheated conductor will be described here, while the open pole case will be treated together with the fault simulations. These examples were chosen among many others as the most representative of the phenomenon.

As expected, when part of the positive pole conductor of Cable 2 overheats, then a net current starts circulating in Cables 1, 2 and 3 (see Appendix E.8 for the results). The net current is equal in all these cables, and its amplitude is of about 168 mA, as it can be seen in Figure 6.10. However, thanks to the communication implemented between the relays, even though the circulating net current amplitude is above the protection threshold, no relay will mistake it for a fault and they will all remain close to continue the operation of the network.

When part of Cable 5 overheats, no net current circulates in the network. This was expected, as Cable 5 is not part of the loop formed by Cables 1, 2 and 3. The results of this simulation can be seen in Appendix E.9.

Conclusions: The simulations have shown that, thanks to the communication implemented between the relays, the circulating net currents will not be considered as faults, even though their amplitude can be greater than the protection threshold. The communication in this case allows a good discrimination between
travelling net currents and fault currents, and thus meets the requirements. Additionally, these simulations prove that net currents start circulating in the network when there is a resistance asymmetry, only in the case of a loop configuration.

6.4.3. Pole to Ground Faults

Zone Protection

A positive pole to ground fault is simulated in the area ZC1 (see Appendix E.5), close to the load. The goal of this paragraph is to show that the protection scheme is able to locate the fault correctly and that it interrupts it within the limits specified in Section 6.1.

As Figure 6.11a shows, the fault occurs at \( t = 0.1 \) s, the fault current is positive (which reflects the fact that it is located on the positive pole), and its magnitude reaches 332.3 mA at its peak (before interruption). The relays defining area ZC1 pick up a signal that corresponds to the fault, as depicted in Figure 6.11b, while the other zone relays only see a travelling current (see Appendix E.10).

![Figure 6.11: Fault in Zone 1](image)

(a) Fault current - positive pole to ground fault ZC1  
(b) Protection signals - positive pole to ground fault ZC1

The fact that only the relays located at each end of ZC1 open their positive poles is a sign that the selectivity is ensured in the system. Moreover, the fault is interrupted after 88.4 ms, which is far below the maximum operation time for 300 mA as listed in Table 6.1, and even below the time listed for 375 mA; the safety of the user is thus insured.

While the current flows through the fault, it flows back to the grounding points and charges the grounding capacitors, as shown in Figure 6.12. Even though the distance the current has to travel through the ground is not taken into account in this model, and hence all the capacitors receive the same amount of current, one can see that the capacitors have been sized such that the way that the protection scheme has time to interrupt the fault before the voltage clamps start conducting, which was one requirement stated in Chapter 4. The sizing of the grounding capacitors is satisfactory in this regard.

Another phenomenon that can be observed after the interruption of the fault is the circulating current; indeed, after the interruption of the fault, a pole is left open in area ZC1, and as it is part of the loop formed by Cables 1, 2 and 3, a net current starts circulating in this loop. However, as already stated in Section 6.4.2, the relays communicate amongst themselves, so this net current is not considered to be a fault current, even though its amplitude reaches above 1 A. The discrimination is consequently effective.

Conclusions: In this section, it has been shown that the protection scheme was able to interrupt the fault in a timely fashion, which ensures the network users’ safety. Additionally, as the capacitors are not charged at 17.5 V before the fault is interrupted, one can derive from this that the grounding capacitors are sized adequately, in correlation with the speed of operation of the protection scheme. The protection scheme, thanks to the communication between the relays, was able to correctly pinpoint the location of the fault and only disconnect the unhealthy part of the network, without consequences on the rest. Finally, after the isolation of the fault (pole opening), the communication between the relays allowed them to detect the net current flowing around the network as a circulating net current, and thus stay closed, as it was required of them. This test yielded many important results in the assessment of the protection scheme’s performance, which is meeting all the requirements so far.
6.4. Verification of the Protection Scheme on a Test Configuration

Figure 6.12: Voltage and current at the grounding points

Node and source protection

Now that the effectiveness of the protection scheme has been demonstrated, it is time to show the consequences of ground faults on the network when they occur at the nodes or at the sources, as the impact is somewhat heavier than when it occurs in a zone.

Fault on Node C  A positive pole to ground fault is simulated at Node C at $t = 0.1 \text{s}$. The required relays open, and several phenomenon are observable. First of all, since parts of the positive poles on Cable 2 and Cable 3 are now open, a current starts to circulate in the loop formed by Cables 1, 2 and 3, as shown in Figure 6.13a for the relays protecting area ZC1. This was expected. Secondly, the voltages on the cables connected to Node C collapse, as shown in Figure 6.13b for Cable 5.

Figure 6.13: Fault on Node C - first results

The voltage across the loads remain at good levels, and so do the currents. The impact of the disconnection of Node C is mostly visible on the current delivered by the sources. Indeed, part of the current that was provided by the positive pole of the sources is now flowing through the middle conductor, as the network is heavily unbalanced by the node disconnection. In the case of Source 3, there is no more current flowing through the positive pole, and it has been almost completely transferred to the middle conductor, as it can be seen in Figure 6.14.

Figure 6.14: Voltage at Cable SC
Fault on Source 1  A negative pole to ground fault is simulated on Source 1 at $t = 0.1 \text{s}$. The required relays open.

As this fault is located at the source, not only does the unhealthy pole of the source need to be disconnected, but also all the conductors that should have be connected to that pole. If not, then the fault current will be fed by the other sources, and as it will travel through all the cables, no relay will try to interrupt it. Doing this is necessary to effectively isolate the fault, although it has the disadvantage that it also interrupts the supply to the loads connected on the negative pole of Cable 4, as it can be seen in Figure 6.15. This was to be expected however, since Cable 4 and the loads connected to it are only fed by Source 1.

This problem could be solved by adding a protective relay between Source 1 and Node A, which would then open when a fault is detected on Source 1 instead of the relays located on the other side of the node, which in turn are used to protect the zones ZC1, 2 and 4. This would also require additional communication between the relays to ensure the protection of the node itself. The remaining sources, however, would need to provide for a much heavier load, as they lost the support of half of Source 1. The strain on these sources might be unacceptable. Consequently, one might need to decide whether it is wise to place this additional relay or not, as far as the quality of the supply and the sources performance are concerned.
6.5. CONCLUSION

The first part of this chapter showed how the protection scheme could be made compliant to the standards: by carefully setting the equivalence table, that is used by the protection scheme to determine the maximum time of operation as a function of the fault current, one can ensure that the fault will be isolated fast enough to avoid damage to the users of the network, as it is required by the Low Voltage Directive [19].

The second part of this chapter demonstrated that the protection scheme was dynamic and adaptive. It is made dynamic by its concrete implementation itself: the value of the fault current is monitored continuously, and every change in it results in a new value of the maximum operation time, which is in turn fed at every time step to the variable time delay functions. This way, the protection scheme makes sure at all times that, no matter the variations in the fault current, it will never flow so long that it will become dangerous for the users. It is made adaptive by the fact that the threshold values and equivalence tables can be tuned to fit every situation, and also because additional modules, such as an automatic reclosure function, can be easily implemented on the already existing protection block.

The tests performed at the end of this chapter proved how reliable the protection scheme was. The simulations showed that, for every scenario, the faults were isolated on time, and the network was made safe again before irreversible damage was done. Wherever the fault was, the communication between the relays ensured that it was found and that only the unhealthy parts of the network were disconnected, leaving the rest functioning: the selectivity of the protection scheme is hence ensured. The opening of the protecting switches, although it provoked temporary spikes in current and voltage, did not generate oscillations that could have threatened the stability of the network, which can then keep operating with a high power quality.

The protection scheme fulfils all that was required of it. It can thus be declared fit for use in the network, as it delivers a satisfactory level of safety.
7

CONCLUSION

The goal of this research was to determine a way to ground a meshed bipolar DC distribution grid, and to protect it against ground faults and leakage currents, in order to prevent corrosion. Thanks to extensive research and countless simulations, a solution has been found to this problem, and the questions listed in the introduction, used as guidance to determine the most critical aspects of this investigation, can finally receive an answer.

The meshed bipolar DC distribution grid should be grounded at each power source, with the TN-S configuration to limit touch voltage levels, and through the use of capacitors with voltage clamps. This type of connection to ground should prevent current from leaking to the ground in steady-state situations and limit the voltage level at the middle conductor to keep it between acceptable boundaries. The network would thus have multiple grounding points, which would also allow islanding in parts of the network connected to a local source.

The system should be protected against ground faults with the help of a network of relays that communicate in a pre-defined pattern to ensure selectivity and fault discrimination. The protection scheme should be designed in such a way that all the current exiting the network through an unexpected connection to ground would be detected, via the residual current measurement method, and the fault would be isolated if the current magnitude is high enough to be a threat to the users’ safety. Time being an important factor in the danger presented by current flowing through the human body, each value of the fault current is paired with a maximum operating time for the protection; to ensure the reaction of the protection scheme is fast enough to ensure user safety (combination of communication, fault detection and fault isolation by opening the relays), the protection scheme should only use a fraction of this maximum operating time between the fault detection and the opening of the relevant protective relays. The relays would make use of the switches designed for short-circuit protection to carry out the ground fault isolation, because of their robustness and speed of operation.

The combination of RCM detection and capacitive grounding should prevent the protection scheme from false tripping in case of an unbalanced load.

7.1. RESULTS DISCUSSION

One of the pitfalls of the models used in this research was the fact that all the grounding points were connected to a virtual grounding plane, so the ground resistivity was not taken into consideration. This yielded that, during a fault, all the grounding capacitors were carrying the same amount of current, regardless of the distance to the fault location. It is expected that, in reality, the grounding capacitors closer to the fault will carry more fault current than those further away. The rate of charge of the capacitors would thus differ, depending on their location with respect to the fault, in opposition to the simulations carried out for this research, in which the capacitors were all charging at the same rate.

1See the MSc theses of Nikos Gouvalas and Dimitris Petropoulos on the short-circuit protection of a DC grid.
In addition, the insulation of the components has been ignored in the simulations, to simplify the models and gain computation time. The load casings will be grounded through a separate conductor, called Protected Earth, which in turn will be connected between the grounding capacitor and the rod to the ground itself, to ensure the case of the loads will always be at minimum voltage and increase the level of safety for the users. It is expected that some current will escape the network through the insulation of the load, as no insulation is ever perfect. This could yield very slow voltage changes across the grounding capacitors, which has been ignored here. However, this could also lead to current leaking through the ground in steady-state, however small it may be. Using the capacitors as a way to ground the network would hence prevent the worst of the steady-state current from flowing through the ground, but it wouldn’t suppress it entirely. Additionally, the parasitic capacitance between the cables and the ground has been dismissed, as it was considered that the grounding capacitance would override it.

The source and loads models were also very basic, and it is obvious that such ideal behaviour will never be observable in practice. More detailed models and careful analysis of the simulation results are thus required before actually building such a network. The results displayed here must not be seen as covering the whole topic, but more as a starting point for further research, and eventually a stepping stone leading to the implementation of such a network.

7.2. FUTURE DEVELOPMENTS

7.2.1. CENTRALIZED GROUNDING POINTS VOLTAGE CONTROL

In this paper, only the detection and isolation of ground faults was considered, but not the actions that should be taken after the network has regained stability. It has been demonstrated that the voltages across the grounding points had changed because of the fault. The grounding capacitors have been sized in such a way that they could sustain the current corresponding to one fault without reaching the clamp voltage. However, if the capacitors are not discharged again after the system regained stability, the chances that the voltage clamps will start conducting when another fault occurs are very high. For this reason, it could be interesting to implement a centralized voltage control system over the grounding points.

The idea would be to discharge the grounding capacitors slowly through variable resistors, for example, to lower the voltage levels over the whole network, and bring them back as close to the nominal values as possible (close to 0V on the middle conductors). Because of the load distribution on the network, it can be expected that after completely discharging the capacitors, balancing current waves would flow for a short time to let the capacitors adapt to the new voltage distribution.

What could be interesting to look into would be the implementation of such a centralized grounding point voltage control: when would it be considered safe to discharge the grounding capacitors after the isolation of a fault? What kind of components could be used to perform such a task? How would the coordination between the several bleeders of the network be carried out? Would there be a maximum rate of change in the grounding points voltage levels? These questions, among others, could form an attractive follow up to the research described in this paper.

7.2.2. THE RESIDUAL CURRENT MEASUREMENT DEVICE

As it has been described in Chapter 5, the performance required from the measurement devices protecting loops is difficult to achieve. First of all, they need to be accurate, with a step of 0.1 mA, as assumed in this paper. Secondly, they need to cover an important range, that could reach ±10 A, especially in the case of an open pole. The combination of the two make it difficult to choose a measurement method, as usually a compromise between the two needs to be made.

Having a RCM device performing both in terms of accuracy and range of measurements could lead to an expensive implementation of the protection scheme, as the RCM device needs to be present at each relay. One could thus wonder how such a measurement could be performed for a reduced price, so that the protection areas could be reduced, and the reliability of the power supply increased. This topic is a combination of technical and financial aspect, possibly combined with a risk assessment, that could be worth looking into.
7.2.**Future developments**

7.2.3. **Protection of a Street Network**

In this research, only the higher levels of the distribution grid have been studied; in other words, the loads were all agglomerated at one location on the different cables, to simplify the simulations. The case of a street network configuration would be very interesting to investigate, especially if one considers that several houses have solar panels on their roofs and are able to operate independently from the main grid. This would yield that these houses need to be grounded individually, to ensure the possibility of islanding.

Such a network configuration is represented in Figure 7.1. The challenge would then be to locate a ground fault and isolate it properly, when so many ground points are connected in the same system. One advantage of such a network is that all the houses would have their own RCM device, which would be quite cheap as no circulating current would flow in such a configuration. Another aspect to look into would be the sizing of the capacitors in such a network. What would be the ideal sizing that complies with what has been stated earlier? Would this ensure the safety of the users? This topic could require an extensive investigation before a satisfactory answer is found.

![Figure 7.1: Example of a street network](image)

**7.2.4. Inclusion of the Insulation Parameters**

In this research, the insulation of the loads and cables has been neglected to improve the computation time. The loads, however, should be all grounded at the load location through the use of a protected earth conductor, as required by the TN-S configuration (see Chapter 3). It is known that no insulation is perfect, and in the case of a meshed DC distribution grid, it would certainly lead to leakage currents. The questions are thus: would the current leaking from the cable insulation be measurable and what impact would it have on the grounding capacitors, in terms of voltage and current? Additionally, the protected earth conductor would be connected between the grounding capacitors and the earth rod (see Figure 7.2), to keep the load casing voltage as low as possible to reduce the risk of shock by indirect contact. This yields that the current leaking through the load insulation would either flow through the grounding capacitor and back to the network, or through the ground directly. What impact would that have on the grounding capacitors and on the corrosion of the surrounding infrastructure? This investigation would require models with a greater level of detail than those used in this research, and a good overview of the possible leakage currents that can flow in such a network.

![Figure 7.2: Connection of the load’s insulation to the grounding point at the source - TN-S configuration](image)
A.1. **Heart factor**

Table 12 – Heart-current factor $F$ for different current paths

<table>
<thead>
<tr>
<th>Current path</th>
<th>Heart-current factor $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left hand to left foot, right foot or both feet</td>
<td>1,0</td>
</tr>
<tr>
<td>Both hands to both feet</td>
<td>1,0</td>
</tr>
<tr>
<td>Left hand to right hand</td>
<td>0,4</td>
</tr>
<tr>
<td>Right hand to left foot, right foot or both feet</td>
<td>0,8</td>
</tr>
<tr>
<td>Back to right hand</td>
<td>0,3</td>
</tr>
<tr>
<td>Back to left hand</td>
<td>0,7</td>
</tr>
<tr>
<td>Chest to right hand</td>
<td>1,3</td>
</tr>
<tr>
<td>Chest to left hand</td>
<td>1,5</td>
</tr>
<tr>
<td>Seat to left hand, right hand or to both hands</td>
<td>0,7</td>
</tr>
<tr>
<td>Left foot to right foot</td>
<td>0,04</td>
</tr>
</tbody>
</table>

For a different path than from hands to feet, the heart factor is used to calculate the fibrillation current at 10s in the following fashion: $I_h = \frac{I_{ref}}{F}$

With:
- $I_h$ the body current for a certain path
- $I_{ref}$ the body current for the hand to feet path
- $F$ the heart factor for the chosen path

For example, for the back to right hand path, the fibrillation current at 10s would be:

$$I_h = \frac{40 \text{ mA}}{0.3} \quad \text{(10 s)} = 133 \text{ mA} \quad \text{(10 s)}$$
APPENDIX B

B.1. RADIAL SYSTEM: MEASUREMENTS UNDER NORMAL CONDITIONS

<table>
<thead>
<tr>
<th>Balanced load</th>
<th>Unbalanced load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TN-C</td>
</tr>
<tr>
<td>$V_{p-g}$</td>
<td>Source 350 V</td>
</tr>
<tr>
<td>$V_{m-g}$</td>
<td>Source 0 V</td>
</tr>
<tr>
<td>$V_{n-g}$</td>
<td>Source -350 V</td>
</tr>
<tr>
<td>$I_{pos}$</td>
<td>13.5 A</td>
</tr>
<tr>
<td>$I_{mid}$</td>
<td>0 A</td>
</tr>
<tr>
<td>$I_{neg}$</td>
<td>-13.5 A</td>
</tr>
<tr>
<td>$I_{sum}$</td>
<td>0 A</td>
</tr>
<tr>
<td>$I_{gnd}$</td>
<td>$10^{-12}$-$10^{-13}$ A</td>
</tr>
</tbody>
</table>

Table B.1: Summary of the steady-state values

|               | TN-C | TN-S | TT | IT |
|---------------|-----------------|
| $V_{p-g}$     | Source 350 V | Load 364.5 V |
| $V_{m-g}$     | Source 0 V | Load 14.5 V |
| $V_{n-g}$     | Source -350 V | Load -335.5 V |
| $I_{pos}$     | 14.1 A |
| $I_{mid}$     | 10.5 A |
| $I_{neg}$     | -24.6 A |
| $I_{sum}$     | 0 A |
| $I_{gnd}$     | $10^{-12}$-$10^{-13}$ A | $10^7$ A | 0 A |

B.2. RADIAL SYSTEM: MEASUREMENTS DURING A POSITIVE POLE TO GROUND FAULT

<table>
<thead>
<tr>
<th>$R_{fault}$</th>
<th>1000 Ω</th>
<th>1 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{gnd}$</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-1.65</td>
</tr>
<tr>
<td>Voltage levels (source)</td>
<td>350.00</td>
<td>348.35</td>
</tr>
<tr>
<td>$V_{pos}$</td>
<td>0</td>
<td>-1.65</td>
</tr>
<tr>
<td>$V_{mid}$</td>
<td>350.00</td>
<td>-351.65</td>
</tr>
<tr>
<td>$V_{neg}$</td>
<td>-350.00</td>
<td>-335.5 V</td>
</tr>
<tr>
<td>Voltage levels (load)</td>
<td>330.86</td>
<td>329.22</td>
</tr>
<tr>
<td>$V_{pos}$</td>
<td>330.86</td>
<td>329.22</td>
</tr>
<tr>
<td>$V_{mid}$</td>
<td>-0.02</td>
<td>-1.67</td>
</tr>
<tr>
<td>$V_{neg}$</td>
<td>-331.30</td>
<td>-332.95</td>
</tr>
<tr>
<td>Touch voltage</td>
<td>330.86</td>
<td>329.22</td>
</tr>
<tr>
<td>$V_{touch}$</td>
<td>330.86</td>
<td>329.22</td>
</tr>
<tr>
<td>Fault current</td>
<td>$I_{fault}$</td>
<td>0.331</td>
</tr>
<tr>
<td>$I_{fault}$</td>
<td>0.331</td>
<td>0.329</td>
</tr>
<tr>
<td>Ground point current</td>
<td>$I_{gnd}$</td>
<td>-0.331</td>
</tr>
<tr>
<td>$I_{gnd}$</td>
<td>-0.331</td>
<td>-0.329</td>
</tr>
</tbody>
</table>

Table B.2: Current and voltage levels during a positive pole to ground fault
C.1. SYSTEM BEHAVIOUR WHEN ONE OR MORE GROUNDING CAPACITORS ARE CAPPED

Two distinct sets of conditions can lead the grounding capacitors to be capped by the voltage clamps. The first possibility is that a fault occurred somewhere in the system, where the sizing of the capacitors has not been done carefully; in this case, the grounding capacitors will be charged to ±17.5 V (all with the same polarity) before the protection isolates the fault and prevents more current from flowing through the ground. The second possibility is when, in a very large network, the load unbalance is such that two grounding capacitors will be capped, one because it is charged at 17.5 V, the other at -17.5 V. This appendix aims at explaining the two phenomena for the reader to understand why it is undesirable to have capped grounding capacitors, and thus why the capacitors are sized in the way described in Chapter 4.

C.1.1. FAULT IN THE SYSTEM WITH TOO SMALL CAPACITORS

To understand this section, it is advised to read Chapters 5 and 6 first in order to understand the behaviour of the current during a fault interruption.

When a fault occurs in the network, the fault current splits among the capacitors, and their voltages start changing, all in the same direction, as it can be seen on Figure C.1. If the capacitors are not sized as described in Chapter 4, then one will charge to 17.5 V before the fault is isolated and the ground current interrupted.

As soon as one grounding capacitor is capped, it starts carrying all the fault current, and the voltage across the other grounding points will stop varying, as shown in Figure C.1. The only way for several grounding capacitors to be capped at the same time, with the same voltage, is that they all conduct exactly the same current, which makes their voltages vary at the same rate, and that their initial voltages are equal.

Disclaimer: in the simulations used for the purposes of this research, it is indeed the case, as the distance through the ground
To meet these requirements, the load distribution over the network needs to be perfectly symmetrical, and the fault needs to be located at equal distance between the grounding points; having one of these conditions, or a combination of the two, is highly unlikely.

The disconnection of the fault will cause balancing current waves to flow through the network, adapting the grounding capacitor voltages to the new load distribution in the network. The voltage across the grounding capacitors will thus change, with different values for each of them. Because of this, only one capacitor at a time can be capped, and as such, no current will flow through the ground afterwards. The capacitor that was capped during the fault will not necessarily remain capped after the disconnection of the unhealthy part of the system, even though it is likely it will. As a matter of fact, each grounding capacitor will receive a different balancing current wave. For an uncapped capacitor, the current wave can charge it further, to the point it would be capped, or discharge it, and reduce its voltage level. For the capacitor that was capped, if the current wave has the right polarity, it will discharge the capacitor, which will resume its isolating function. If the current wave has the opposite polarity, then it will be carried by the voltage clamp. This phenomenon is shown in Figure C.2.

The disconnection of the fault will always provoke a balancing current wave to flow, even in the case of a perfectly balanced system. Additionally, every load change will also change the grounding capacitors’ voltages. It is thus expected that the voltage across the grounding capacitors will always be able to vary within the boundaries set by the voltage clamp. It can be considered that having one grounding capacitor capped is not a threat to the network’s stability, and no external action is required to keep the system healthy. It is, on the other hand, advised to avoid such high voltage deviations on the middle conductor, simply to ensure a high quality of the power supply to the load at all times.

C.1.2. HEAVY LOAD UNBALANCE ON THE NETWORK

A simple network configuration, shown in Figure C.3, is used here to illustrate the problem posed by a heavy load unbalance on the system. When the load is heavier on one pole than on the other, and when the load is not located at an equal distance between the two sources, then a voltage deviation occurs across the grounding capacitors; because there are only two here, it will be of equal magnitude but opposite polarity (see Chapter 5 for more detailed explanations).

between the fault and the grounding capacitors is not emulated. It is, however, one of the known pitfalls of the models used here, and it is expected that in reality, all the grounding points will carry a different amount of current, thus making the capacitors charge at a different rate.
C.1. System behaviour when one or more grounding capacitors are capped

It is expected that, over a large network, the load balance could be such that one grounding capacitor would be capped at 17.5 V at one location, while another grounding capacitor would be capped at -17.5 V. In this case, the voltage clamps would close a loop through the ground, and some current would be able to flow. In the case of the network of Figure C.3 it would yield the waveforms obtained in Figure C.4. The protection has been disabled in this simulation to make the phenomenon easier to observe.

Due to the communication system described in Chapter 6 this current flowing through the ground will only be seen as a travelling current, and no action will be taken. Such current would, however, cause a very important corrosion to the surrounding infrastructure if left untreated. To avoid that, it would be necessary to switch some loads from one pole to the other to reduce the unbalance, and hence lower the capacitor voltages. Monitoring the grounding capacitor voltages at all times would give a good indication of how unbalanced the system is, and tell if loads have to be connected to the other pole to avoid the problem described here.

C.1.3. Conclusion

This part has shown that it is not a problem in itself if one grounding capacitor is capped in the network, due to a fault that changed the grounding capacitors’ voltage over the whole network, for example. Having two grounding capacitors capped with a different polarity is, however, an issue, as an important current could flow through the ground and would provoke an important corrosion of the surrounding infrastructure. This current would be seen by the protection scheme as a travelling current, and as such it would not interrupt it.
It is thus essential to monitor the voltages of the grounding capacitors over the whole network to make sure that none of them is capped. This way, the situation described in this appendix will be avoided. Additionally, sizing the capacitors properly would also greatly reduce the risk of having them capped during a fault, and would also increase the stability of the system, as the voltage across the whole network would vary more slowly during a fault or a load change.

C.2. **Derivation of the Equation Used in Sizing the Grounding Capacitors**

The goal of these calculations is to find the value of the capacitance that will limit the voltage deviation across the capacitor to the clamp voltage during the fault.

The capacitor voltage is described by the following equation:

\[ v_c(t) = V(1 - e^{-t/\tau}) \quad \text{with} \quad \tau = RC \]

By considering that \( v_c(t_{\text{max,op}}) = V_{\text{clamp}} \), and that during a fault \( V = V_{\text{fault}} \), then:

\[ V_{\text{clamp}} = V_{\text{fault}}(1 - e^{-t_{\text{max,op}}/R_{\text{fault}}C}) \]

\[ \Rightarrow \frac{V_{\text{clamp}}}{V_{\text{fault}}} = 1 - e^{-t_{\text{max,op}}/R_{\text{fault}}C} \]

\[ \Rightarrow e^{-t_{\text{max,op}}/R_{\text{fault}}C} = 1 - \frac{V_{\text{clamp}}}{V_{\text{fault}}} \]

\[ \Rightarrow -\frac{t_{\text{max,op}}}{R_{\text{fault}}C} = \ln \left( 1 - \frac{V_{\text{clamp}}}{V_{\text{fault}}} \right) \]

\[ \Rightarrow \frac{1}{C} = -\frac{R_{\text{fault}}}{t_{\text{max,op}}} \ln \left( 1 - \frac{V_{\text{clamp}}}{V_{\text{fault}}} \right) \]

\[ \Rightarrow C = -\frac{t_{\text{max,op}}}{R_{\text{fault}}} \ln \left( 1 - \frac{V_{\text{clamp}}}{V_{\text{fault}}} \right) \]

The goal has been reached, and this equation can be used to derive the required value of the capacitance for each \((R_{\text{fault}}, t_{\text{max,op}})\) pair.
**APPENDIX D**

**D.1. CIRCULATING CURRENT EXPLANATION**

Figure D.1: Ring configuration

Considering the network configuration described by Figure D.1, Kirchhoff’s current law yields:

\[
\begin{align*}
I_{11p} + I_{21p} &= I_{L1} \\
I_{L1} &+ I_{11m} + I_{21m} = I_{L2} \\
I_{L2} &+ I_{11n} + I_{21n} = 0 \\
I_{12p} &+ I_{22p} = I_{L3} \\
I_{L3} &+ I_{12m} + I_{22m} = I_{L4} \\
I_{L4} &+ I_{12n} + I_{22n} = 0
\end{align*}
\]  

(D.1a)  
(D.1b)  
(D.1c)  
(D.1d)  
(D.1e)  
(D.1f)

By definition:

\[
\begin{align*}
I_{\text{sum,11}} &= I_{11p} + I_{11m} + I_{11n} \\
I_{\text{sum,12}} &= I_{12p} + I_{12m} + I_{12n} \\
I_{\text{sum,21}} &= I_{21p} + I_{21m} + I_{21n} \\
I_{\text{sum,22}} &= I_{22p} + I_{22m} + I_{22n}
\end{align*}
\]  

(D.2a)  
(D.2b)  
(D.2c)  
(D.2d)  

By combining the sets of Equations (D.1) and (D.2), and assuming \( I_{\text{sum,11}} \neq 0 \), one can derive:

\[
I_{\text{sum,11}} = I_{11p} + I_{11m} + I_{11n} \\
= (I_{L1} - I_{21p}) + (I_{L2} - I_{L1} - I_{21m}) + (-I_{L2} - I_{21n}) \\
= -I_{21p} + I_{21m} + I_{21n} \\
= -I_{\text{sum,21}}
\]

(D.3)

Similarly, if \( I_{\text{sum,12}} \neq 0 \):
\[ I_{\text{sum},12} = - I_{\text{sum},22} \]  

(D.4)

Additionally, as the system is in steady-state, no current flows through the ground, so:

\[ I_{\text{sum},S1} = I_{C1} = I_{\text{sum},11} + I_{\text{sum},12} = 0 \]  

(D.5)

thus:

\[ I_{\text{sum},11} = - I_{\text{sum},12} \]  

(D.6)

Similarly,

\[ I_{\text{sum},21} = - I_{\text{sum},22} \]  

(D.7)

All this yields:

\[ I_{\text{sum},12} = - I_{\text{sum},22} = I_{\text{sum},21} = - I_{\text{sum},11} \]  

(D.8)

which corresponds to a net current flowing around the network, as depicted by the following figure:

---

**D.2. Equations describing the circulating current after a pole was disconnected from the network**

The goal of these calculations is to find an equation that describes the magnitude of the circulating current that flows when one pole has been disconnected from the rest of the network. The network under consideration is presented in Figure D.2.

The nomenclature is the following:

- Source voltages: \( V_{Sj}, V'_{Sj}, V_{Sj,\text{gnd}} \) and \( V'_{Sj,\text{gnd}} \) indicate the positive pole voltage, the negative pole voltage, the positive pole to ground voltage and the negative pole to ground voltage of source \( j \) respectively; \( j \in \{1;2\} \) (see figure).

- Cable currents: \( I_{jkl} \) stands for the current flowing from source \( j \) to the load on cable \( k \) in conductor \( l \); \( k \in \{1;2\} \), and \( l \) is ‘\( p \)’ for positive pole, ‘\( m \)’ for middle conductor, and ‘\( n \)’ for negative pole (see figure).

- Load quantities: \( V_{Lq} \) and \( I_{Lq} \) represent the voltage and current of load \( q \); \( q \in \{1;3\} \) (see figure).

The network is considered to be in steady-state; the inductance and capacitance of the network are thus ignored. Additionally, it is considered that the on-state resistance of the protective relays is negligible compared to the resistance of the cables; it is thus omitted. The conductors resistance \( R_k \) is given in ohms
D.2. Equations Describing the Circulating Current After a Pole Was Disconnected from the Network

Figure D.2: Open pole ring configuration

per unit of length and is considered to be the same for all the conductors in the cables. Kirchhoff’s voltage and current laws yield the following set of equations:

\[
V_{S1} = V_{L1} + R_k d_{11} (I_{11p} - I_{11m}) \quad \text{(D.9a)}
\]
\[
V'_{S1} = V_{L2} + R_k d_{11} (I_{11m} - I_{11n}) \quad \text{(D.9b)}
\]
\[
V_{S2} = V_{L1} + R_k d_{21} (I_{21p} - I_{21m}) \quad \text{(D.9c)}
\]
\[
V'_{S2} = V_{L2} + R_k d_{21} (I_{21m} - I_{21n}) \quad \text{(D.9d)}
\]
\[
V_{S1} = V_{L3} + R_k d_{12} (I_{12p} - I_{12m}) \quad \text{(D.9e)}
\]
\[
V_{S2} = V_{L3} + R_k d_{22} (I_{22p} - I_{22m}) \quad \text{(D.9f)}
\]
\[
I_{11p} + I_{21p} = I_{L1} \quad \text{(D.9g)}
\]
\[
I_{L1} + I_{11m} + I_{21m} = I_{L2} \quad \text{(D.9h)}
\]
\[
I_{L2} + I_{11n} + I_{21n} = 0 \quad \text{(D.9i)}
\]
\[
I_{12p} + I_{22p} = I_{L3} \quad \text{(D.9j)}
\]
\[
I_{L3} + I_{12m} + I_{22m} = 0 \quad \text{(D.9k)}
\]

Rearranging (D.9a) and (D.9c) and equating them yields:

\[
V_{S1} - R_k d_{11} (I_{11p} - I_{11m}) = V_{S2} - R_k d_{21} (I_{21p} - I_{21m}) \quad \text{(D.10)}
\]

Rearranging (D.9g) and (D.9h) and inserting them into (D.10) in order to remove \( I_{11p} \) and \( I_{11m} \) yields:

\[
V_{S1} - R_k d_{11} (I_{L1} - I_{21p} - I_{L2} + I_{11m} + I_{21m}) = V_{S2} - R_k d_{21} (I_{21p} - I_{21m}) \quad \text{(D.11)}
\]

From there, one can rearrange (D.11) to obtain an equation giving \( I_{21m} = f(I_{21p}) \):

\[
I_{21m} = I_{21p} + \frac{AV_S - R_k d_{11} (2I_{L1} - I_{L2})}{R_k (d_{11} + d_{21})} \quad \text{(D.12)}
\]
where $\Delta V_S = V_{S1} - V_{S2}$.

A similar operation can be done to obtain $I_{21n} = f(I_{21p})$ by adding (D.9) and (D.9b), and (D.9c) and (D.9d) respectively, while using (D.9g) and (D.9i) to remove $I_{11p}$ and $I_{11n}$ from the result. It yields:

$$I_{21n} = I_{21p} + \frac{\Delta V_S + \Delta V_S' - R_k d_{11} (I_{L1} + I_{L2})}{R_k (d_{11} + d_{21})}$$  \text{(D.13)}

with $\Delta V_S' = V_{S1}' - V_{S2}'$.

The net current $I_{\text{sum},21}$ is the current entering cable 1 from the source 2 side and is defined as follows:

$$I_{\text{sum},21} = I_{21p} + I_{21m} + I_{21n}$$  \text{(D.14)}

By combining (D.12), (D.13) and (D.14), one can express $I_{\text{sum},21}$ as a function of $I_{21p}$ only:

$$I_{\text{sum},21} = 3I_{21p} - 3I_{L1} d_{11} (d_{11} + d_{21}) + \frac{2\Delta V_S + \Delta V_S'}{R_k (d_{11} + d_{21})}$$  \text{(D.15)}

The same procedure is applied to derive $I_{\text{sum},22} = f(I_{22p})$, and the following equation is obtained:

$$I_{\text{sum},22} = 2I_{22p} + \frac{\Delta V_S - 2R_k d_{12} I_{L3}}{R_k (d_{12} + d_{22})}$$  \text{(D.16)}

Assuming the load current $I_{L1}$ is a known measurement, one can use this quantity to replace $I_{21p}$ in (D.15) by applying Kirchoff laws to the circuit described in Figure D.3 as follows:

![Figure D.3: Network equivalent used to obtain $I_{21p} = f(I_{L1})$](image)

$$I_{11p} = \frac{V_{S1,gnd} - V_{L1,gnd}}{R_k d_{11}}$$  \text{(D.17a)}

$$I_{21p} = \frac{V_{S2,gnd} - V_{L1,gnd}}{R_k d_{21}}$$  \text{(D.17b)}

$$I_{L1} = I_{11p} + I_{21p}$$  \text{(D.17c)}

Replacing $I_{11p}$ and $I_{21p}$ in (D.17c) with (D.17a) and (D.17b) yields:

$$I_{L1} = \frac{V_{S1,gnd} - V_{L1,gnd}}{R_k d_{11}} + \frac{V_{S2,gnd} - V_{L1,gnd}}{R_k d_{21}}$$  \text{(D.18)}

Rearranging (D.18) to obtain an expression of $V_{L1,gnd}$ yields:

$$V_{L1,gnd} = \frac{V_{S1,gnd} d_{21} + V_{S2,gnd} d_{11}}{d_{11} + d_{21}} - I_{L1} \frac{R_k d_{11} d_{21}}{d_{11} + d_{21}}$$  \text{(D.19)}

Rearranging (D.17c) and replacing $V_{L1,gnd}$ by the expression calculated in (D.19) yields the following expression of $I_{21p}$.
\[ I_{21p} = \frac{d_{11}}{d_{11} + d_{21}} \left( l_{L1} - \frac{V_{S1,\text{gnd}}}{R_k d_{11}} \right) + \frac{V_{S2,\text{gnd}}}{R_k (d_{11} + d_{21})} \]  

(D.20)

Performing the same actions to determine \( I_{22p} \) as a function of \( I_{L3} \) yields:

\[ I_{22p} = \frac{d_{12}}{d_{12} + d_{22}} \left( l_{L3} - \frac{V_{S1,\text{gnd}}}{R_k d_{12}} \right) + \frac{V_{S2,\text{gnd}}}{R_k (d_{12} + d_{22})} \]  

(D.21)

Replacing \( I_{21p} \) in the expression of \( I_{\text{sum,21}} \), described by (D.15), by the value calculated in (D.20), yields:

\[ I_{\text{sum,21}} = \frac{2\Delta V_S + \Delta V'_S - 3\Delta V_{S,\text{gnd}}}{R_k (d_{11} + d_{21})} \]  

(D.22)

with \( \Delta V_{S,\text{gnd}} = V_{S1,\text{gnd}} - V_{S2,\text{gnd}} \). Similarly, replacing \( I_{22p} \) in the expression of \( I_{\text{sum,22}} \), described by (D.16), by the value calculated in (D.21), yields:

\[ I_{\text{sum,22}} = \frac{\Delta V_S - 2\Delta V_{S,\text{gnd}}}{R_k (d_{12} + d_{22})} \]  

(D.23)

Now, to see how to combine these values to give the final magnitude of the circulating current, one needs to look at the total net current seen by the sources. To account for both sides of the network, and thanks to (D.8), one can write:

\[ I_{\text{sum}} = \frac{1}{2} (I_{\text{sum,11}} + I_{\text{sum,22}}) = \frac{1}{2} (I_{\text{sum,22}} - I_{\text{sum,21}}) \]  

(D.24)

which translates into:

\[ I_{\text{sum}} = \frac{1}{2} \left( \frac{\Delta V_S - 2\Delta V_{S,\text{gnd}}}{R_k (d_{11} + d_{22})} - \frac{2\Delta V_S + \Delta V'_S - 3\Delta V_{S,\text{gnd}}}{R_k (d_{11} + d_{21})} \right) \]  

(D.25)

By using the fact that:

\[ V_{S1} = V_{S1,\text{gnd}} - V_{C1,\text{gnd}} \Rightarrow V_{S1,\text{gnd}} = V_{S1} + V_{C1,\text{gnd}} \]  

(D.26a)
\[ V_{S2} = V_{S2,\text{gnd}} - V_{C2,\text{gnd}} \Rightarrow V_{S2,\text{gnd}} = V_{S2} + V_{C2,\text{gnd}} \]  

(D.26b)

then it yields:

\[ \Delta V_{S,\text{gnd}} = V_{S1,\text{gnd}} - V_{S2,\text{gnd}} \]
\[ = (V_{S1} + V_{C1,\text{gnd}}) - (V_{S2} + V_{C2,\text{gnd}}) \]
\[ = \Delta V_S + \Delta V_C \]  

(D.27)

When \( \Delta V_{S,\text{gnd}} \) is replaced in (D.25) by the value of (D.27), and by considering that \( R_1 = R_k (d_{11} + d_{21}) \) and \( R_2 = R_k (d_{12} + d_{22}) \), then it yields:

\[ I_{\text{sum}} = \frac{1}{2} \left( \Delta V_C - \frac{3R_2 - 2R_1}{R_1 R_2} + \frac{R_2 - R_1}{R_1 R_2} \right) \]  

(D.28)

The final value of \( I_{\text{sum}} \) has been obtained, so the goal has been reached. One can see that the value of \( I_{\text{sum}} \) depends on the voltage differences between the poles on each side, but also greatly on the difference in capacitor voltage, which depends directly on the load balance in the system: the load balance on the poles, and where the load is located in the network will thus play an important role in how much current will circulate after a pole has been opened in the network.
D.3. EQUATIONS DESCRIBING THE CIRCULATING CURRENT WHEN A CONDUCTOR IS OVERHEATING

The goal of these calculations is to find a mathematical expression that gives the magnitude of the circulating current flowing in the ring network when a conductor is overheating. The network under consideration is depicted in Figure D.4 with an additional resistor on one conductor of cable 1 to account for its increased temperature.

Figure D.4: Ring network with overheated conductor in cable 1

The nomenclature is the following:

- Source voltages: $V_{S_j}$, $V'_{S_j}$, $V_{S_j,\text{gnd}}$ and $V'_{S_j,\text{gnd}}$ indicate the positive pole voltage, the negative pole voltage, the positive pole to ground voltage and the negative pole to ground voltage of source $j$ respectively; $j \in \{1; 2\}$ (see figure).

- Cable currents: $I_{jkl}$ stands for the current flowing from source $j$ to the load on cable $k$ in conductor $l$; $k \in \{1; 2\}$, and $l$ is $p$ for positive pole, $m$ for middle conductor, and $n$ for negative pole (see figure).

- Load quantities: $V_{Lq}$ and $I_{Lq}$ represent the voltage and current of load $q$; $q \in \{1; 4\}$ (see figure).

The network is considered to be in steady-state; the inductance and capacitance of the network are thus ignored. Additionally, it is considered that the on-state resistance of the protective relays is negligible compared to the resistance of the cables; it is thus omitted. The conductors resistance $R_k$ is given in ohms per unit of length and is considered to be the same for all the conductors in the cables. The overheat is represented by an additional resistance located on the positive pole conductor of Cable 1 on Source 1 side; the value of this additional resistance $R_o$ is given in ohms per unit of length and corresponds to the resistance increase that would occur when the cable reaches its maximum allowable temperature. Kirchhoff’s voltage...
and current laws yield the following set of equations:

\[ V_{S1} = V_{L1} + R_k d_{11} (I_{11p} - I_{11m}) + R_o d_{11} I_{11p} \]  
\[ V'_{S1} = V_{L2} + R_k d_{11} (I_{11m} - I_{11n}) \]  
\[ V_{S2} = V_{L1} + R_k d_{21} (I_{21p} - I_{21m}) \]  
\[ V'_{S2} = V_{L2} + R_k d_{21} (I_{21m} - I_{21n}) \]  
\[ V_{S1} = V_{L3} + R_k d_{12} (I_{12p} - I_{12m}) \]  
\[ V'_{S1} = V_{L4} + R_k d_{12} (I_{12m} - I_{12n}) \]  
\[ V_{S2} = V_{L3} + R_k d_{22} (I_{22p} - I_{22m}) \]  
\[ V'_{S2} = V_{L4} + R_k d_{22} (I_{22m} - I_{22n}) \]  
\[ I_{11p} + I_{21p} = I_{L1} \]  
\[ I_{L1} + I_{11m} + I_{21m} = I_{L2} \]  
\[ I_{L2} + I_{11n} + I_{21n} = 0 \]  
\[ I_{12p} + I_{22p} = I_{L3} \]  
\[ I_{L3} + I_{12m} + I_{22m} = I_{L4} \]  
\[ I_{L4} + I_{12n} + I_{22n} = 0 \]  

Rearranging (D.29b) and (D.29c) and equating them yields:

\[ V_{S1} + R_k d_{11} I_{11m} - I_{11p} d_{11} (R_k + R_o) = V_{S2} + R_k d_{21} (I_{21m} - I_{21p}) \]  

(D.30)

Rearranging (D.29j) and (D.29k) and inserting them into (D.30) in order to remove \( I_{11p} \) and \( I_{11m} \) yields:

\[ V_{S1} + R_k d_{11} (I_{L2} - I_{L1} - I_{21m}) - (I_{L1} - I_{21p}) d_{11} (R_k + R_o) = V_{S2} + R_k d_{21} (I_{21m} - I_{21p}) \]  

(D.31)

From there, one can rearrange (D.31) to obtain an equation giving \( I_{21m} = f(I_{21p}) \):

\[ I_{21m} = I_{21p} \frac{(R_k + R_o) d_{11} + R_k d_{21}}{R_k (d_{11} + d_{21})} + \frac{\Delta V_S + I_{L2} R_k d_{11} - I_{L1} d_{11} (2R_k + R_o)}{R_k (d_{11} + d_{21})} \]  

(D.32)

where \( \Delta V_S = V_{S1} - V_{S2} \).

A similar operation can be done to obtain \( I_{21n} = f(I_{21p}) \) by adding (D.29a) and (D.29b), and (D.29d) and (D.29e) respectively, while using (D.29f) and (D.29g) to remove \( I_{11p} \) and \( I_{11n} \) from the result. It yields:

\[ I_{21n} = I_{21p} \frac{(R_k + R_o) d_{11} + R_k d_{21}}{R_k (d_{11} + d_{21})} + \frac{\Delta V_S + \Delta V'_S + h_{L2} R_k d_{11} - h_{L1} d_{11} (R_k + R_o)}{R_k (d_{11} + d_{21})} \]  

(D.33)

with \( \Delta V'_S = V'_{S1} - V'_{S2} \).

The net current \( I_{sum,21} \) is the current entering cable 1 from the source 2 side and is defined as follows:

\[ I_{sum,21} = I_{21p} + I_{21m} + I_{21n} \]  

(D.34)

By combining (D.32), (D.33) and (D.34), one can express \( I_{sum,21} \) as a function of \( I_{21p} \) and \( I_{L1} \):

\[ I_{sum,21} = I_{21p} \left( 3 + \frac{2R_o d_{11}}{R_k (d_{11} + d_{21})} \right) - I_{L1} \left( \frac{3d_{11}}{R_k (d_{11} + d_{21})} + \frac{2R_o d_{11}}{R_k (d_{11} + d_{21})} + \frac{2\Delta V_S + \Delta V'_S}{R_k (d_{11} + d_{21})} \right) \]  

(D.35)

The same procedure is applied to derive \( I_{sum,12} = f(I_{12p}, I_{L3}) \), and the following equation is obtained:

\[ I_{sum,12} = 3I_{12p} - I_{L3} \frac{3d_{22}}{R_k (d_{12} + d_{22})} + \frac{2\Delta V_S + \Delta V'_S}{R_k (d_{12} + d_{22})} \]  

(D.36)
Assuming the load current $I_{L1}$ is a known measurement, one can use this quantity to replace $I_{21p}$ in (D.35) by applying Kirchhoff laws to the circuit described in Figure D.5 as follows:

![Network equivalent used to obtain $I_{21p}$](image)

Figure D.5: Network equivalent used to obtain $I_{21p} = f(I_{L1})$

\[
I_{11p} = \frac{V_{S1,gnd} - V_{L1,gnd}}{(R_k + R_o)d_{11}} \quad (D.37a) \\
I_{21p} = \frac{V_{S2,gnd} - V_{L1,gnd}}{R_kd_{21}} \quad (D.37b) \\
I_{L1} = I_{11p} + I_{21p} \quad (D.37c)
\]

Replacing $I_{11p}$ and $I_{21p}$ in (D.37c) with (D.37a) and (D.37b) yields:

\[
I_{L1} = \frac{V_{S1,gnd} - V_{L1,gnd}}{(R_k + R_o)d_{11}} + \frac{V_{S2,gnd} - V_{L1,gnd}}{R_kd_{21}} \quad (D.38)
\]

Rearranging (D.38) to obtain an expression of $V_{L1,gnd}$ yields:

\[
V_{L1,gnd} = \frac{R_kd_{21}V_{S1,gnd} + (R_k + R_o)d_{11}V_{S2,gnd} - I_{L1}(R_k + R_o)d_{11}d_{21}}{R_kd_{21} + (R_k + R_o)d_{11}} \quad (D.39)
\]

Rearranging (D.37c) and replacing $V_{L1,gnd}$ by the expression calculated in (D.39) yields the following expression of $I_{21p}$:

\[
I_{21p} = \frac{I_{L1}(R_k + R_o)d_{11} - \Delta V_{S,gnd}}{R_kd_{21} + (R_k + R_o)d_{11}} \quad (D.40)
\]

with $\Delta V_{S,gnd} = V_{S1,gnd} - V_{S2,gnd}$.

Performing the same actions to determine $I_{12p}$ as a function of $I_{L3}$ yields:

\[
I_{12p} = I_{L3} \frac{d_{22}}{d_{12} + d_{22}} + \frac{\Delta V_{S,gnd}}{R_k(d_{12} + d_{22})} \quad (D.41)
\]

Replacing $I_{21p}$ in the expression of $I_{sum,21}$, described by (D.35), by the value calculated in (D.40), yields:

\[
I_{sum,21} = \frac{1}{R_k(d_{11} + d_{21})} \left(2\Delta V_{S} + \Delta V_{S}' + \frac{d_{11}d_{21}R_kR_oI_{L1} - \Delta V_{S,gnd}(3R_k + 2R_o) + 3d_{21}R_k}{R_kd_{21} + (R_k + R_o)d_{11}} \right) \quad (D.42)
\]

Similarly, replacing $I_{12p}$ in the expression of $I_{sum,12}$, described by (D.36), by the value calculated in (D.41), yields:

\[
I_{sum,12} = \frac{3\Delta V_{S,gnd} - (2\Delta V_{S} + \Delta V_{S}')}{R_k(d_{12} + d_{22})} \quad (D.43)
\]
Now, to see how to combine these values to give the final magnitude of the circulating current, one needs to look at the total net current seen by the sources. To account for both sides of the network, and thanks to (D.8), one can write:

\[ I_{\text{sum}} = \frac{1}{2} \left( I_{\text{sum},12} + I_{\text{sum},21} \right) \] (D.44)

which translates into:

\[
I_{\text{sum}} = \frac{3\Delta V_S.gnd - \left( 2\Delta V_S + \Delta V'_S \right)}{2R_k(d_{12} + d_{22})} + \frac{1}{2R_k(d_{11} + d_{21})} \left( 2\Delta V_S + \Delta V'_S + \frac{d_{11}d_{21}R_kR_oI_{L1} - \Delta V_S.gnd \left[ d_{11}(3R_k + 2R_o) + 3d_{21}R_k \right]}{R_kd_{21} + (R_k + R_o)d_{11}} \right)

\] (D.45)

By replacing \( \Delta V_S.gnd \) by the value calculated in (D.27) and considering that \( R_1 = R_k(d_{11} + d_{21}) \), \( R_2 = R_k(d_{12} + d_{22}) \) and \( R_{1o} = R_o d_{11} \), (D.45) becomes:

\[
I_{\text{sum}} = \frac{\Delta V_S - \Delta V'_S + 3\Delta V_C}{2R_2} + \frac{1}{2R_1} \left( 2\Delta V_S + \Delta V'_S + \frac{d_{21}R_kR_{1o}I_{L1} - \left( \Delta V_S + \Delta V_C \right)[3R_1 + 2R_{1o}]}{R_1 + R_{1o}} \right)

\] (D.46)

The final value of \( I_{\text{sum}} \) has been obtained, so the goal has been reached. One can see that the value of \( I_{\text{sum}} \) depends on the differences in source voltages and grounding points voltages, but also on the length of the overheated conductor and how much current flows through it. The higher this current, the more the overheated conductor will have to carry current, and thus the higher the circulating current. The overall length of the cable also plays a role: the shorter the cables, the higher the circulating current. In case of overheat, the magnitude of the circulating current depends thus mainly on the network configuration itself, and on the load connected to the overheated conductor.

**D.4. Determination of the maximum participation of \( I_{L1} \) in \( I_{\text{sum}} \) in case of overheat**

The determining factor in the amplitude of \( I_{\text{sum}} \) in case of overheat is:

\[
A = I_{L1} \frac{d_{21}R_kR_{1o}}{2R_1(R_1 + R_{1o})}
\] (D.47)

The factors in this expression can be replaced by the following set:

\[
\begin{align*}
    d_1 &= d_{11} + d_{21} \\
    d_{11} &= xd_1 \\
    R_{1o} &= d_{11}R_o = xd_1R_o \\
    R_1 &= d_1R_k
\end{align*}
\] (D.48)

with \( x \) the relative length of the cable containing the overheated conductor with respect to the total length of the cable; \( x \in [0;1] \).

This yields:

\[
A(x) = I_{L1} \left( R_o \frac{x(1-x)}{R_k + R_o x} \right)
\] (D.49)

To obtain the maximum of \( A(x) \), one needs to derive it. The derived function is the following:
\[
\frac{dA}{dx} = I_{L1} \frac{R_o R_o x^2 + 2R_k x - R_k}{(R_k + R_o x)^2}
\]  
(D.50)

The maximum is found when:
\[
\frac{dA}{dx} = 0 \Leftrightarrow R_o x^2 + 2R_k x - R_k = 0
\]  
(D.51)

The only possible solution to the previous equation is:
\[
x = \frac{-2R_k + 2\sqrt{R_k(R_k + R_o)}}{2R_o}
\]  
(D.52)

which then yields the maximum of \(A(x)\), and consequently the maximum participation of \(I_{L1}\) in \(I_{sum}\).
E.1. THE PROTECTIVE RELAYS

The protective relays used in the isolation of ground faults are those used in the short-circuit protection of the network. These relays provide fast opening times and strong blocking capabilities, and are as such perfectly suited to isolate ground faults.

The relays are based on Solid-State Circuit Breakers (SSCB). As they are suited to the short-circuit protection of the system, short-circuit limiting inductances of 50 mH are placed in series with the SSCBs (here, MOSFETs are used) to limit the rate of rise of the current. Free-wheeling diodes are placed between the conductors to prevent the discharge of these inductors into the faults. The configuration used in this research is the following:

![Figure E.1: Protective relays](image)

See the works of Nikos Gouvalas and Dimitris Petropoulos on the topic.
E.2. **Overview of the Protection Scheme Implemented in MATLAB Simulink**

![Simulink Diagram](image)

*Figure E.2: Overview of the protection scheme as implemented in Simulink*
E.3. CODE OF THE DYNAMIC TIME DELAY FUNCTION

function [ trigout, ttrig ] = fcn(clk, trig1, trig2, deltat, told)

% told is the previous value of ttrig, they are linked together outside the function

if trig1 ~= trig2 % change in the state of the trigger signal
    ttrig = clk; % we capture the time of this change, which is then sent to told by the external loop
    trigout = 0;
else % there is no change in the trigger signal
    if trig1 == 1 % if it triggered -> need to check the time
        ttrig = told; % we propagate the value captured in the previous stage
        if clk >= told + deltat/2
            trigout = trig1; % the time is elapsed, we propagate the trigger signal
        else
            trigout = 0;
        end
    else % it hasn’t triggered, no need for action
        ttrig = 0;
        trigout = 0;
    end
end
end
E.4. CODE OF THE AUTOMATIC RECLOSEURE PULSE GENERATOR

function [reset, ttrig, bufreset] = fcn(time, tdelay, thresh1, thresh2, nbautoreclo, counter, told, prereset)

% told is the previous value of ttrig, they are linked together outside the function
% same thing for bufreset and prereset

length = 1e−1; % duration of the pulse

if (thresh1 < thresh2) % detection of falling edge in ‘threshold’
    if (nbautoreclo >= counter) % falling edge detected, time value is saved, and enabling signal is raised to 1
        ttrig = time;
        bufreset = 1;
    else
        ttrig = 0;
        bufreset = 0;
    end
    reset = 0;
else
    ttrig = told;
    if prereset == 1 % enabling signal is 1, so proceed with automatic reclosure
        if (time >= told + tdelay) && (time <= told + tdelay + length) % sending the pulse
            reset = 1;
            bufreset = prereset;
        elseif (time >= told + tdelay + length) % ending the pulse
            reset = 0;
            bufreset = 0;
        else % delay between falling edge and automatic reclosure attempt is not elapsed yet
            reset = 0;
            bufreset = prereset;
        end
    else
        reset = 0;
        bufreset = prereset;
    end
end
end
Figure E.3: Test network configuration
The different areas listed on the figure are protected by the following combinations of relays:

- ZS1 (protection of Source1): RelayS1 (included in Source1), Relay1a, Relay2a, Relay4a
- ZS2 (protection of Source2): RelayS2 (included in Source2), Relay1b, Relay3b
- ZS3 (protection of Source3): RelayS3 (included in Source3), Relay5d
- ZC1 (protection of zone between nodes A and B): Relay1a, Relay1b
- ZC2 (protection of zone between nodes A and C): Relay2a, Relay2c
- ZC3 (protection of zone between nodes B and C): Relay1a, Relay1b
- ZC4a (protection of the first part of cable 4): Relay4a
- ZC4b (protection of the second part of cable 4): Relay4b
- ZC5 (protection of zone between nodes C and D): Relay5c, Relay5d
- ZNC (protection of node C): Relay2c, Relay3c, Relay5c

As explained in chapter 5, each relay is listed a maximum of two times. The relays will need to operate for each protection area they are listed under.

The parameters of the network are the following:

<table>
<thead>
<tr>
<th>Cable #</th>
<th>Length [m]</th>
<th>Load #</th>
<th>$P_{nom}$ [kW]</th>
<th>Grounding points</th>
<th>Grounding points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>200</td>
<td>1 pos</td>
<td>2</td>
<td>$C_{gnd}$ 1.2 mF</td>
<td>$V_{Zener}$ 17.5 V</td>
</tr>
<tr>
<td>1B</td>
<td>400</td>
<td>1 neg</td>
<td>3</td>
<td>$R_{on,Z}$ 0.001 Ω</td>
<td>$R_{snub,Z}$ 500 Ω</td>
</tr>
<tr>
<td>2A</td>
<td>300</td>
<td>2 pos</td>
<td>2.1</td>
<td>$R_{on,Z}$ 0.001 Ω</td>
<td>$R_{snub,Z}$ 500 Ω</td>
</tr>
<tr>
<td>2B</td>
<td>200</td>
<td>2 neg</td>
<td>2</td>
<td>$R_{snub,Z}$ 250 nF</td>
<td>$R_{snub,Z}$ 250 nF</td>
</tr>
<tr>
<td>3B</td>
<td>300</td>
<td>3 pos</td>
<td>2</td>
<td>$R_{snub,Z}$ 250 nF</td>
<td>$R_{snub,Z}$ 250 nF</td>
</tr>
<tr>
<td>3C</td>
<td>300</td>
<td>3 neg</td>
<td>2.2</td>
<td>$R_{snub,Z}$ 250 nF</td>
<td>$R_{snub,Z}$ 250 nF</td>
</tr>
<tr>
<td>4A</td>
<td>300</td>
<td>4a pos</td>
<td>2</td>
<td>$R_{on,Z}$ 0.001 Ω</td>
<td>$R_{on,Z}$ 0.001 Ω</td>
</tr>
<tr>
<td>4B</td>
<td>300</td>
<td>4a neg</td>
<td>1.5</td>
<td>$R_{snub}$ 10 Ω</td>
<td>$R_{snub}$ 10 Ω</td>
</tr>
<tr>
<td>5C</td>
<td>300</td>
<td>4b pos</td>
<td>1.8</td>
<td>$C_{snub}$ 100 nF</td>
<td>$C_{snub}$ 100 nF</td>
</tr>
<tr>
<td>5D</td>
<td>500</td>
<td>4b neg</td>
<td>2</td>
<td>$L_{limit}$ 50 μH</td>
<td>$L_{limit}$ 50 μH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 pos</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 neg</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure E.4: \( I_{\text{sum}} \) signals throughout the network when 3 kW additional are connected on cable 1 at \( t = 0.1 \text{s} \)
E.7. **ADDITIONAL LOAD ON CABLE 4 - RESULTS**

Figure E.5: $I_{\text{sum}}$ signals throughout the network when 3 kW additional are connected on cable 4 at $t = 0.1$ s
Figure E.6: $I_{sum}$ signals throughout the network when the positive pole conductor on cable 2A overheats
E.9. OVERHEAT ON CABLE 5 - RESULTS

Figure E.7: $I_{sum}$ signals throughout the network when the positive pole conductor on cable 5C overheats
E.10. **Positive pole to ground fault ZC1 - results**

![Graphs showing net current flowing into ZC1-ZC5](image)

Figure E.8: Net current flowing into the protection zones
Figure E.9: Protective switches trigger signals
**LIST OF ACRONYMS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AC</strong></td>
<td>Alternating Current</td>
</tr>
<tr>
<td><strong>DC</strong></td>
<td>Direct Current</td>
</tr>
<tr>
<td><strong>ECG</strong></td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td><strong>HVDC</strong></td>
<td>High Voltage DC</td>
</tr>
<tr>
<td><strong>IEC</strong></td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td><strong>IT</strong></td>
<td>Ungrounded - grounded (Isolé - terre)</td>
</tr>
<tr>
<td><strong>LVDC</strong></td>
<td>Low Voltage Direct Current</td>
</tr>
<tr>
<td><strong>MVDC</strong></td>
<td>Medium Voltage Direct Current</td>
</tr>
<tr>
<td><strong>PE</strong></td>
<td>Protected Earth (conductor)</td>
</tr>
<tr>
<td><strong>RCD</strong></td>
<td>Residual Current Device</td>
</tr>
<tr>
<td><strong>RCM</strong></td>
<td>Residual Current Measurement</td>
</tr>
<tr>
<td><strong>TN-C</strong></td>
<td>Grounded - grounded through neutral, common conductor (Terre - neutre, commun)</td>
</tr>
<tr>
<td><strong>TN-S</strong></td>
<td>Grounded - grounded through neutral, separate conductor (Terre - neutre, séparé)</td>
</tr>
<tr>
<td><strong>TT</strong></td>
<td>Grounded - grounded (Terre - terre)</td>
</tr>
</tbody>
</table>


[18] Wikipedia, Power-line communication,