Master Thesis

Design of a protection scheme for an off-grid microgrid with inverter-based power sources

MSc in Electrical Engineering at TU Delft

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A mi padre

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Abstract

The electrical infrastructure is evolving, shifting into a decentralized grid that allows the incorporation of renewable energies and mitigates the negative effects of power outages. It is predicted that this will lead to a substantial increase in the amount of microgrids deployed worldwide. Especially in locations with a less reliable grid, the microgrids are often in off-grid or islanded operation. If an electrical fault occurs when the microgrid is not connected to the grid and there are only inverter-based power sources, the fault current will not be high enough to be detected by traditional overcurrent protection schemes. This poses a challenge that can be addressed with different strategies. So far, the proposed solutions for protecting microgrids in islanded operation are highly theoretical and have limitations.

This research introduces a protection strategy for a small, low voltage off-grid microgrid with only inverter-based power sources. The microgrid has energy storage, solar energy production and generic loads. In this study, a Tesla Powerpack and Inverter are assumed as energy storage devices, since the research is conducted in collaboration with the company Tesla. The microgrid is modelled in the software PowerFactory from DIgSILENT to verify that the current and voltage magnitudes during fault will be detected properly and the protection devices will be triggered. Protection devices available in the market are proposed, and their settings specified taking into account the results of several simulations. A brief economic analysis is also included to provide a general overview of the cost of such a protection system.

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Chapter 1. **Introduction**

This chapter contains a general introduction to the project. The motivation for choosing this topic of research is explained, and the scope of work is defined. The goal and research questions are enunciated and the methodology and general layout of the document are presented as well.

1.1. Motivation

Microgrids are part of the solution for incorporating renewable energies and increasing reliability and resilience of power systems. Therefore, the number of microgrids deployed and in the pipeline is increasing rapidly, especially in areas with a weaker grid that traditionally depend in power generation based in diesel fuel. A number of issues arise from the incorporation of microgrids to the conventional, radial and unidirectional power grid. One of the main challenges is protecting the system under fault situations. The lack of suitable and affordable protection schemes for microgrid is delaying the implementation of renewable resources, and therefore further investigation in the area is required.

This research is conducted in collaboration with the company Tesla, specifically with Tesla Energy in the region of Europe, Middle-East and Africa (EMEA). Amongst other energy products, Tesla Energy manufactures industrial size batteries and the inverter required to connect them to an AC grid. The electrical engineers at Tesla Energy are also involved in the design and commissioning of microgrid projects with the Tesla BESS, and often receive requests from customers to support on the protection design of the microgrids. The purpose is then to analyze the issues that arise with a standard microgrid with Tesla BESS and propose a suitable protection scheme for it, to serve as base for future projects and recommendation to customers.

1.2. Scope of work

As thoroughly explained later in this document, further research is required in order to solve the protection issues that arise in the design process and deployment of microgrids. The size of microgrids varies from a couple of KWh to hundreds of MWh. The sources of power go from diesel generators to solar or wind energy. The operating voltage also varies from low-voltage to medium voltage including then transformer stations, and the protection issues are present in both grid-connected and islanding operation. These and many other factors make the microgrid protection a very extensive research topic that is being explored from several different approaches by engineers worldwide.

In order to narrow the scope of this particular research and align it with the microgrid market section in which Tesla participates, the focus will be placed on off-grid, low-voltage microgrids of small to medium size. The systems studied in this research have therefore no connection with the external grid, and the stationary storage inverter supplies power from 70kVA to 700kVA. Furthermore, the main issues regarding protection relate to the limited fault current coming from inverter-based sources, and for this reason simple microgrids with exclusively solar generation and stationary storage will be considered. Reality is that this type of microgrids usually include a diesel generator as backup, but these are traditional devices that provide enough fault current to be detected and have been in the market for decades. For several reasons, diesel generator will not be considered further in this research.

1.3. Goal & Research Questions

The goal of this research is to *design a suitable protection scheme for an off-grid microgrid of small to medium size with inverter-based sources.* The microgrid basic subsystems are stationary storage in the form of batteries (BESS), solar generation and the load.

The principal research question in this master thesis is ***what is a suitable protection scheme for a small off-grid microgrid with only inverter-based power sources?***

In order to find a suitable and complete answer to this, response to the following secondary questions is researched:

- What are the main issues regarding microgrid protection?
- What are the limitations of already proposed solutions?
- What is a practical implementation of the designed scheme?
- What are the economic implications of the proposed protection schemes?

1.4. Methodology

The methodology that has been followed to complete this project is given in the points below, in chronological order:

- Document general background in protection, microgrids and Tesla.
- Analyze already available solutions and their limitations.
- Create a model of the system, simulate fault conditions, compile and analyze results.
- Introduce a suitable protection philosophy.
- Propose available protection devices that suit the philosophy.
- Implement the protection devices in the model and verify protection philosophy.
- Perform a brief economic analysis.

1.5. Document outline

This document is divided into eleven chapters. A brief description of the purpose and contents of each chapter is as follows:

- **Chapter 1:** General introduction
- **Chapter 2:** Provide background in Microgrids, Tesla and Electrical Protection.
- **Chapter 3:** Establish the relevance of this research for the current microgrid market.
- **Chapter 4:** Document and analyze the already available solutions to the research question and their limitations.
- **Chapter 5:** Introduce the software utilized for simulations, and the basic model of the system.
- **Chapter 6:** Describe the protection system designed and argument the choices and compromises taken.
- **Chapter 7:** Propose a practical implementation of the system designed in Chapter 6.
- **Chapter 8:** Present the results of the simulations for different fault scenarios, and how the protection scheme would deal with these.
- **Chapter 9:** Analyze results of simulations and present the limitations of the scheme.
- **Chapter 10:** Economic analysis of the proposed scheme.
- **Chapter 11:** Final summary, conclusions and further research in the topic.

Chapter 2. **Background**

The aim of this chapter is to introduce the general concepts of microgrid and protection to ensure writer and reader are on the same page before going into further technical detail. An overview on the current state of the microgrid market globally is also included. Since this project is conducted in collaboration with Tesla, the company is introduced as well as general information on its role in the energy storage field globally and the impact in the microgrid market.

2.1. About Microgrids

2.1.1. Brief history of microgrids

The term *microgrid* still sounds for many people like a revolutionary concept that is changing the way that electrical power is generated and distributed to our homes. This might be a correct conception to some point, but the concept of microgrid actually dates back to 1882. Thomas Edison opened then the first commercial central power plant at Pearl Street Station based on localized generation, a limited distribution network and storage in batteries [4]. The Edison Illuminating Company went on installing DC microgrids in the following years until in 1886 it was challenged by a new technology developed by Nikola Tesla: the alternating current (AC). Using Tesla's technology, George Westinghouse's company made it possible to use AC for indoor lighting by stepping down the high voltage with the use of transformers, but still keeping high voltage for transmission over long distances to reduce losses. The use of AC spread quickly despite of Edison claiming that high voltages were hazardous and the design was inferior to his direct current system [5]. The use of AC current enabled long distance power transmission and provided a solution to interconnect generation sites. In the late 1880s, the three-phase AC power system that is used in the present grid was developed, which allowed the electrification of much greater areas during the 1890s. Also, the possibility to supply loads from distant generation resources reduced significantly the price of electricity and resulted in the electric market evolving into a state-regulated monopoly. By the end of the 1900s, AC was established as the main source of power worldwide [6]. With the loss of investment in DC distribution systems and the advances in AC based technologies, the interest in developing microgrids was also lost and did not come back until about a hundred years later [7].

Since the late 1990s, environmental awareness, reliability concerns and new technologies started driving the electrical grid to *decentralize, decarbonize and democratize*, a trend known as the *three Ds* [8]. Engineers worldwide have been looking for a flexible solution that can enable the inclusion of distributed energy resources (DERs), which allow respectively for a number of advantages such as improved power quality, ancillary services, reduction in losses, power backup and, of course, decrease in the use of fossil fuels. Microgrids are part of the answer for all these requirements. Hurricane Sandy in 2012 was a turning point in which the potential of microgrids to keep the lights on became clear to the wider public. About 8.5 million people were left without power, 1.3 million of which for longer than a week. It became evident that climate change is amplifying the effects of natural disasters. At the same time, most of our societies are dependent on a constant and reliable power supply, so we have become very vulnerable to the effects of power outages. Microgrids contribute at the same time to stop or reduce climate change by integrating renewables that reduce greenhouse gas emissions, and to mitigate the impact of natural disasters by increasing resilience and reliability of the power supply infrastructure [9].

As it will be later shown in **3.1**, it is clear that grid operators and energy customers have recognized the capability of microgrids to increase resilience, integrate renewables and reduce costs. The microgrid market is growing very rapidly and expanding worldwide, especially in areas with a weak grid or with usual natural disasters that cause power outages.

2.1.2. Definition

It is possible to find many definitions for the concept of microgrid. After Hurricane Sandy kick-started the discussion about microgrids, there were different conceptions on what being a microgrid entitled. In the past decade, it has become clearer what is expected from a microgrid and what intrinsic characteristics are required in order for a power installation to be considered a microgrid.

The US Department of Energy Microgrid Exchange Group describes a microgrid as *a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode*.

The CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap defines microgrids as "*electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed*" [10].

In any case, it is clear from the definitions that the main requirements for a microgrid are connecting loads and distributed energy resources in a controllable and safe way, with clear boundaries, allowing both on-grid and islanding operation. **Figure 2-1** shows a typical schematic representation of a microgrid.

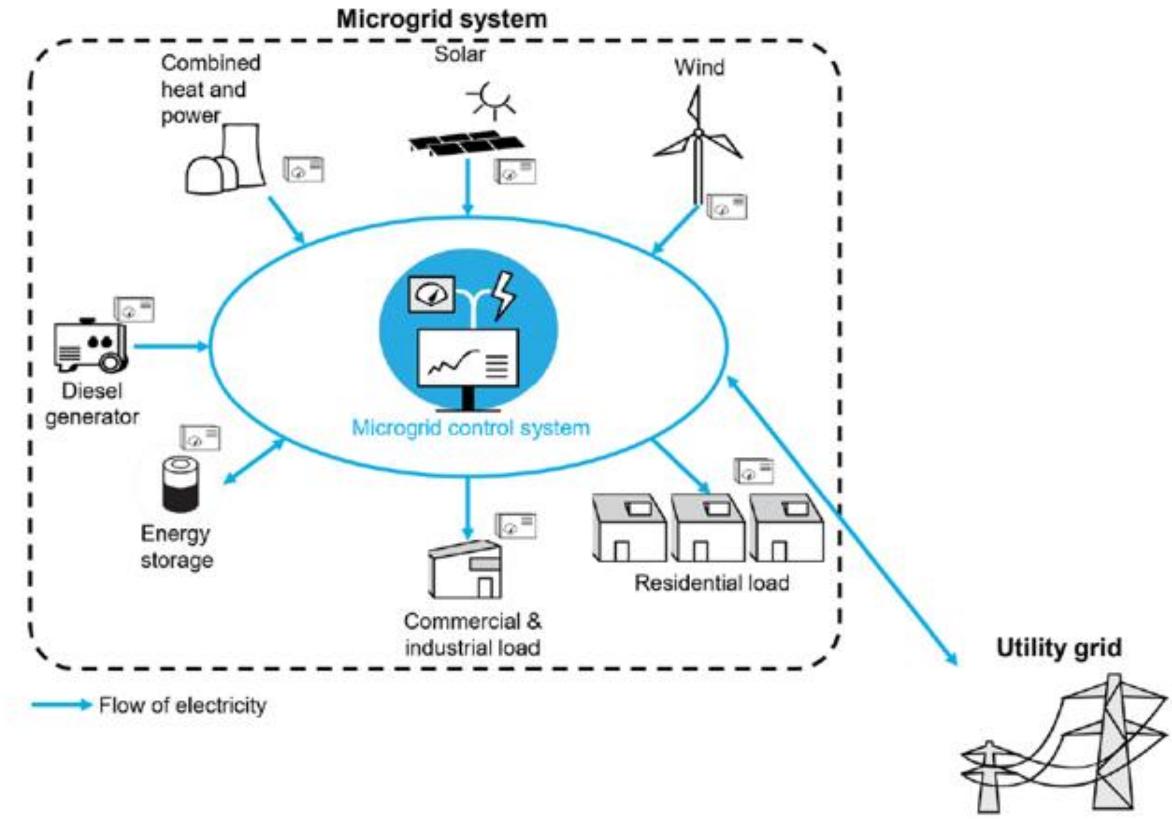

Figure *2-1*: Simplified scheme of a microgrid. **Source:** BloombergNEF, US DoE.

2.2. About Tesla

This section provides general background on the company Tesla Inc, with whom the research presented in this document is conducted. In order to do so, a short summary on the history of the company is presented and an introduction to Tesla Energy, which is generally less known that the car manufacturer side of the company, Tesla Motors.

2.2.1. Brief History of Tesla

Tesla Motors was founded in 2003 in California by two American entrepreneurs, Martin Eberhard and Marc Tarpenning, who wanted to make better, faster and fun to drive electric cars. Their idea was to design incredible vehicles that would have instant torque and a very large amount of available power combined with zero emissions by being full electrical. The famous Serbian electrical engineer Nikola Tesla inspired its name[2]. In 2004, Elon Musk contributed with $30 million funding from his company PayPal, and became chairman of Tesla Motors. On August 2, 2006, Musk published a document called *The Secret Tesla Motors Master Plan (just between you and me)* in which he explains that his master plan for the company is:

> *Build sports car*
> *Use that money to build an affordable car*
> *Use that money to build an even more affordable car*
> *While doing above, also provide zero emission electric power generation options* [11]

Under the mission to "accelerate the world's transition to sustainable energy", Tesla has been following closely the *Master Plan* published by Elon Musk. Tesla Motors released its first car in 2008, the Roadster. It had a range of 394km on one single charge and could reach 94km per hour in less than 4 seconds. In this same year, Elon Musk became CEO of the company. This was the first part of the *Master Plan*, a low volume car that would necessarily be expensive. In 2012, the Model S was released with three different battery size options, and Tesla started building Supercharger Stations designed to charge at high speed and free of cost for Tesla owners. The Model X was released in 2015, a bigger car with a range of 475km. This was the second point of the *Master Plan*, to use the money from the sales of the Roadster to develop a medium volume car at a lower price. The same year that the Model X was released, Tesla launched a line of energy storage products to store electric power from photovoltaic installations and acquired the company SolarCity.

In 2017, Tesla Motors changed its name to Tesla, Inc. to show that it was no longer just a car company, and the Model 3 started production, a more affordable vehicle with a range of 354km [12]. This would be the third point of the *Master Plan*, to create an affordable high volume car. **Figure 2-2** shows the three car models that Tesla has produced until now.

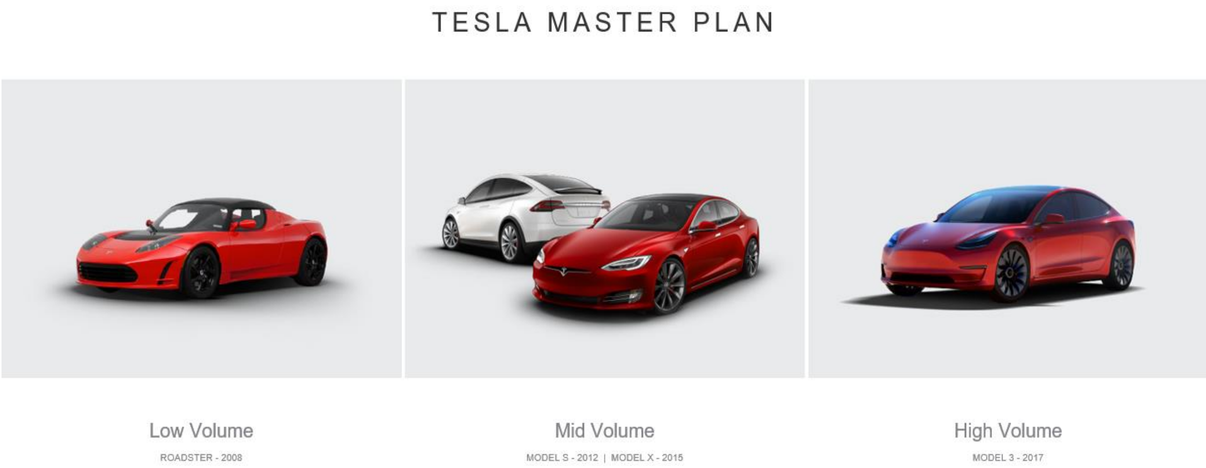

Figure *2-2*: Tesla Master Plan. **Source:** Tesla

[2] Ironically enough in the context of this project, it was Nikola Tesla's AC current technology that prevented Edison's microgrids to continue developing in the 1880's.

Ten years after publishing the first part of the *Master Plan*, Elon Musk released the *Master Plan, Part Deux*. In short, this second part of the Master Plan is as follows:

> *Create stunning solar roofs with seamlessly integrated battery storage*
> *Expand the electric vehicle product line to address all major segments*
> *Develop a self-driving capability that is 10X safer than manual via massive fleet learning*
> *Enable your car to make money for you when you aren't using it [13]*

The first point of the *Part Deux*, which is the same as the last point of the original *Master Plan*, confirms that Tesla is no longer (just) a car manufacturer. Tesla is actually a battery company that also happens to make the best electric cars in the world according to multiple official car reviews [14].

2.2.2. Tesla Energy

As mentioned before, Tesla Inc. expanded into the energy field with the launch of their division Tesla Energy. The development of energy products started in 2012. Since then, Tesla has brought three energy products to the market that provide an integral solution for both residential and industrial applications, as shown in **Figure 2-3**.

- **Solar Roof:** Tesla manufactures solar tiles made of tempered glass. They are more than three times stronger than standard roofing tiles and have a warranty of the lifetime of the house they are placed, or infinity, whichever comes first [15]. Tesla also manufactures non-solar tiles that look exactly the same as the solar tiles from floor level, in case the customer does not require the full roof of their house to produce solar energy.
- **Powerwall:** Rechargeable lithium-ion batteries intended for energy storage at a home level, for self-consumption, load shifting, and backup. In the case of a grid outage, the Powerwall disconnects from the grid and restores power seamlessly. The capacity of the latest version of the Powerwall is 5kW and 13.5 kWh.
- **Powerpack:** Based on the same battery cells as the Powerwall, the Powerpack is designed for commercial or electric utility grid use. It has multiple uses, varying from frequency regulation and voltage control to peak shaving, load shifting and of course power backup and microgrids. The capacity of the latest version of the Powerpack is 210 kWh, and its nominal power is 50 kW. Tesla also manufactures the inverter for AC connection and the site controller, providing an integrated solution.

Figure *2-3*: From left to right, Powerwall, Inverter and Powerpack (size not proportional). **Source:** Tesla

2.2.3. Introduction to Powerpack Systems

As mentioned earlier, one Tesla Powerpack has 50 kW nominal power and a nominal capacity of 210 kWh, and it is connected to the grid and other assets via the Tesla bi-directional inverter. The inverter power can be varied from 50 kVA to 700 kVA at 480V. The system is scalable, which means that the number of packs and inverters can be easily adjusted to meet the power demand of each site. The efficiency of the system (AC) is between 88% and 89% round-trip. The main uses of stationary battery storage systems are explained below.

- **Peak shaving and Load Shifting.** Installing a battery storage system makes it possible to lower the peak demand charges and reduce the grid connection costs. The load can be shifted from times of high electricity prices to the cheaper hours of the day.
- **Self-consumption and Backup**. The value of having a storage system installed locally is potentially increased by the use of solar energy on site to recharge the batteries during the day. The batteries also serve as backup in locations with weak grid connection.
- **Ancillary services and demand response.** Large storage installations contribute to the frequency regulation of the grid. When the frequency drops below the nominal, discharging the battery provides positive regulation power that brings the frequency up, and vice versa. The system can also provide frequency regulation services.
- **Microgrids.** Combining energy storage with a power source, preferably a renewable source, allows the creation of microgrids that provide steady power without the need of connection to the public electricity grid. The energy costs are reduced and so is the use of diesel for generation, since the generator run hours are kept as low as possible. The market for this solution is growing exponentially in remote locations that used to rely solely on diesel generators.

Tesla Energy has commissioned about 2GWh in energy storage, and this number is expected to increase exponentially in the coming years, especially since the release of Tesla's latest energy product, the Megapack[3]. Some examples of Powerpack sites with high impact or relevance are detailed below and shown in **Figure 2-4**, to help create a better idea on the influence of big battery energy storage systems in the energy market.

- In February 2017 there was a statewide blackout in South-Australia caused by several storms. In response to this, the Government started a tender to deploy grid-scale energy storage options and Tesla was awarded the entire energy storage system component of the project, which is 100MW and 129MWh. Tesla commissioned this project, which is the largest lithium-ion battery in the world in a time frame of 100 days. Just one year after the start of its operation, the system had prevented several blackouts in the region and already paid back for around 30% of the initial investment [16].

- The island of Ta'u is part of the Samoan Islands. It is powered by 1.4MW solar plant and a battery system of 750kW and 6MWh. This combination offers a more reliable source of electricity to the island, reduces diesel costs and increases reliability of the power sources. The island can stay powered for three days without sun just using energy from the Tesla batteries.

- In the Kauai Island, Hawaii, the Utility Cooperative installed a 13MW / 52 MWh system in 2017 to shave the power peak demanded in the evening. Before the installation of the batteries, the power demand was supplied by diesel generators. The island saves 1.6 million gallons of diesel fuel per year since the project was deployed.

[3] Data retrieved from the Tesla database on August 30, 2019

Figure *2-4*: From top to bottom, Hornsdale plant in South Australia, microgrid in Ta' u island and utility project in Kawai island. **Source:** Tesla.

2.3. About Protection

Electrical power systems aim to supply the energy demand in a safe, efficient and reliable way. Even when properly designed, power systems can be affected by faults that are not possible to control or predict. Between the most common causes of electrical fault are lightning discharge in exposed parts, premature ageing of the insulation due to permanent overload or bad ventilation, equipment failure and inappropriate manual system operation [17]. Faults can create situations that are dangerous for people in the surroundings and can produce severe damage to equipment. Besides, a power outage in a modern society can cause serious impact and disruption to the customer, especially if not handled properly and persisting during a long time. Therefore, any power system must be provided with equipment, mostly in the form of protective relays, that operates according to the protection scheme design parameters to reduce the negative consequences of a fault.

Protection schemes have different and several functionalities. For this research, the following three priorities are established as the main functions that a protection scheme must comply with. The first priority is to ensure that people are safe around the system when making proper use of it, and also when accidentally creating a hazardous situation due to human error. Secondly, the protection scheme needs to ensure that valuable equipment is not damaged. Finally, any fault should be cleared rapidly so that power supply to the customer is restored as fast as possible. The area affected must be kept as reduced as possible, isolating the fault and leaving the rest of the system undisturbed.

The purpose of this section is to compile the basic principles of protection schemes, the different features that a scheme can offer and the most common devices that can provide these features. It serves also as a general introduction to the following chapter, in which protection will be analyzed in much more depth and therefore it is important to have the basic concepts clarified beforehand.

2.3.1. Basic Principles

There are four basic principles that need to be taken into account during the design of a protection scheme [18]:

- **Reliability:** A reliable protection system has two attributes, *dependability* and *security* [19]. The design of the system must ensure that it operates under all required conditions (providing dependability) and refrains to operate when not required (providing security). The protection devices need to be programmed with the correct settings and correctly installed to operate within the system. Before operation of the system, the protection scheme must be tested thoroughly. Deterioration in service with time or external conditions also needs to be taken into account. It is common practice to achieve reliability with redundancy, for example, by duplicating equipment on critical parts of the system. It is also common to have a back-up protection that will operate in the event of failure of the main protection system, ensuring the fault is isolated.
- **Selectivity:** The protection scheme is expected to isolate the fault and only alter operation on the minimum section of the network possible. This is called selective tripping or discrimination. Usually, in order to minimize the negative impact of a fault, the system is divided into zones that can be independently protected and isolated from the rest of the system. An overlap between protection zones normally ensures that there is no part of the system is unprotected. If there is a fault in the overlap zone, the two sets of relays corresponding to both zones will operate. **Figure 2-5** shows a typical arrangement with zones that overlap.

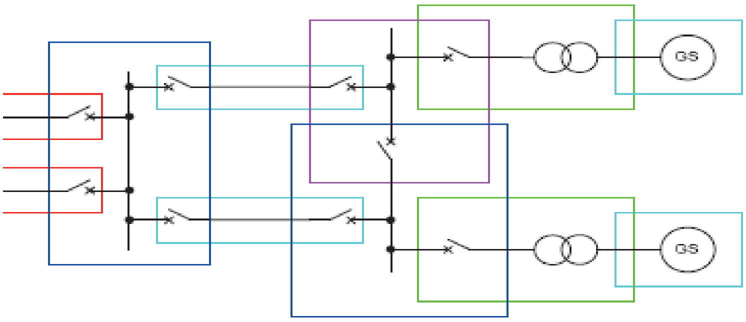

Figure *2-5***:** Protection system with overlapping zones. **Source:** [13].

Coordination also plays and important role in selectivity and is a fundamental characteristic of any protection scheme. This concept will be explained later when implemented in the proposed protection scheme, but it basically implies that the device closest to the fault should operate first.

- **Speed:** A fault within the protected area must be isolated by the protection devices as quickly as possible to prevent loss of synchronization, especially when the system is under a big load. In the case of fault, the damaging energy liberated is proportional to the time that the fault is present. Therefore, by clearing the fault as fast as possible, damages to equipment are also prevented or minimized.
- **Sensitivity:** The protection equipment must be able to detect and act on a minimum operating level, meaning, minimum values of current, voltage, power, etc. A relay is sensitive if its primary operating values are low [20]. This is usually not a problem for Low Impedance Faults, but can pose a challenge in High Impedance Faults in which the current is limited, as explained in section 2.3.2.

2.3.2. Electrical Faults

An electrical fault can be defined as an abnormal operating condition in a power system derived from environmental conditions, equipment failure or human interaction.

According to their nature, faults can be classified in:

- **Short-circuit faults** happen when two points of different potential are unintentionally connected by a conducting path. They are caused by insulation problems, overload of equipment or events like a tree branch falling on the transmission lines. A large current will flow through the conducting path, which could liberate large amounts of energy if not cleared quickly. This can be dangerous for people or animals around and severely damage equipment.

  Depending on the nature of the short-circuit, faults can either be of Low Impedance (LIF) or High Impedance (HIF):

  Low Impedance Faults (LIF) are mostly caused when the two points of different potential come directly in touch with each other. This brings the potential of the contact point to the same level liberating a large amount of current in the process, which makes them easy to detect by traditional protection devices. The resistance between the two points of contact becomes very low, between zero and two ohms at most [21]. The impedance of the fault will influence the level of current liberated, and the current fault at a specific point of the system will also be dependent on the distance to the fault. **Figure 2-6** shows the current dependency on distance for a fault of zero ohms (bolted) and a fault with two ohms between contact points.

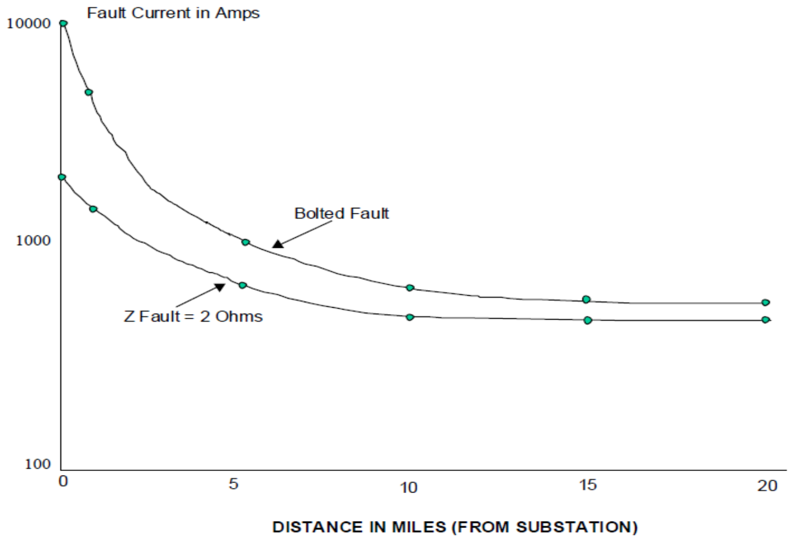

Figure *2-6*: Low Impedance Fault dependency on distance for the case of no resistance (bolted fault) and for the limit case of 2 Ohm resistance between the points of contact. **Source:** [37]

High Impedance Faults (HIF) are defined as faults that do not produce enough fault current to be detectable by traditional protection features due to a high resistance in the current path [22]. These faults are affected by many variables and usually lead to currents behaving in an unstable and random way, which makes their detection and clearing even more challenging. HIF are usually caused by a downed conductor on a high impedance surface, and this is more common in long distribution systems than in the small off-grid microgrids that are the scope of study in this research. **Figure 2-7** shows an average current level provided by a High Impedance Fault depending on the surface that comes in contact with the connectors. High Impedance Faults are usually not an immediate threat to power equipment, but they can be dangerous to people since they may create very high step and touch voltages [23]. Step and touch voltages are the high voltages than can occur between the two feet or a hand and a foot of a person in touch with points of different potential [21]. This voltages can be very dangerous to people, and the safety of people at all times is the priority in this research. This is why, even if they represent a small percentage of the total amount of faults in a system, High Impedance Faults need also to be considered when designing a protection scheme.

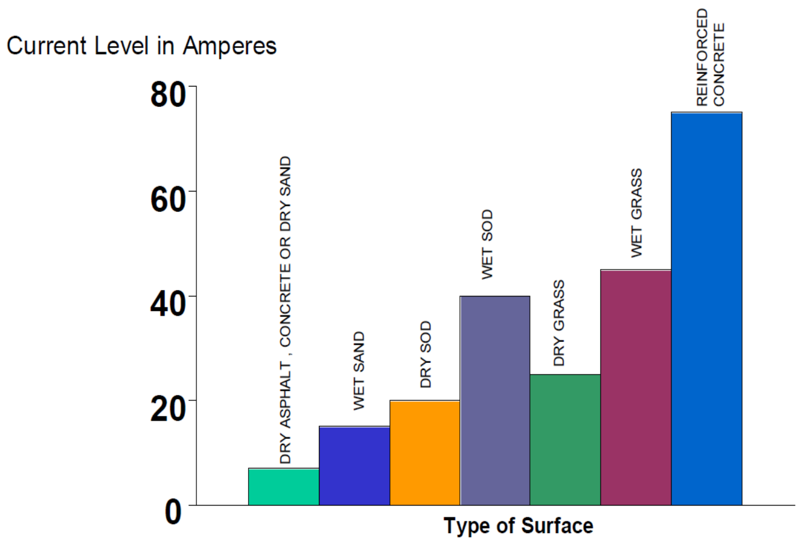

Figure *2-7*: High Impedance Fault dependency on surface of contact for conductors of different potential. The lower the current level, the more difficult it is to detect the fault. **Source:** [37]

In order to design a proper protection scheme, fault currents need to be calculated. There are several methods for this, nowadays incorporated in computational softwares like the one that will be used in this research, called DIgSILENT Power Factory and introduced later in section **5.1.**

- **Open-circuit faults** occur when the electrical path for the current is interrupted. This can be caused, for example, due to a fuse melting, a circuit breaker malfunctioning or deterioration of a conductor. This type of faults cause disruption in the power supply but are less dangerous to equipment or people than short-circuit faults since no current is flowing and therefore no power is dissipated. Further in this research, only short-circuit faults will be considered.

For the scope of this research, the power system will be considered a balanced, symmetrical, three-phase network. According to the effect on the balance, faults can be classified in:

- **Symmetrical faults,** also known as three-phase short-circuit. Symmetrical faults are Line to Line to Line (L-L-L) and Line to Line to Line to Ground (L-L-L-G), and lead to currents of different magnitude but with 120° phase angle displacement. This type of faults produce the largest short-circuit currents, but they occur luckily not very often. They are usually around the 2-5% of all the faults happening to a system. **Figure 2-8** shows an example representation of a Line to Line to Line short-circuit.

- **Unsymmetrical faults,** during which the balance between phases is altered and currents and voltages of different amplitude and phase shift appear in the network. Unsymmetrical faults are Line to Line (L-L), Line to Ground (L-G) and Line to Line to Ground (L-L-G). It is common that a Line to Line fault eventually becomes a Line to Line to Ground fault, for example, due to the installation collapsing. Line to Ground faults are the most common, between 70 and 80% of the faults that occur in a power system [24]. **Figure 2-9** shows an example representing a single phase to ground fault.

Finally, a fault situation can also be cause by an overload, which is the excess of the actual load over the full load. It is caused when the load requires more power than the nominal value, generating currents larger than the rating of the equipment. If the overload persists for a long time, it can damage the equipment or even become the cause of fire [25].

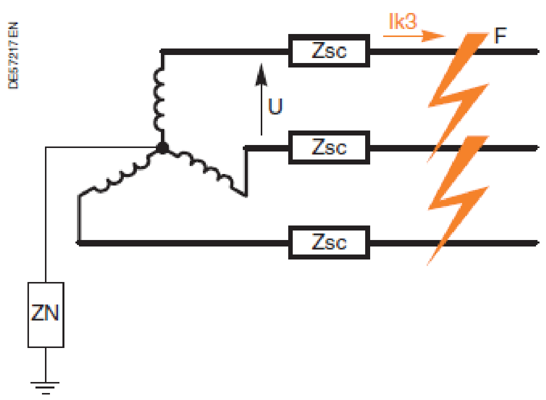

Figure ***2-8*****:** Three-phase short-circuit between the phase conductors. **Source:** [48]

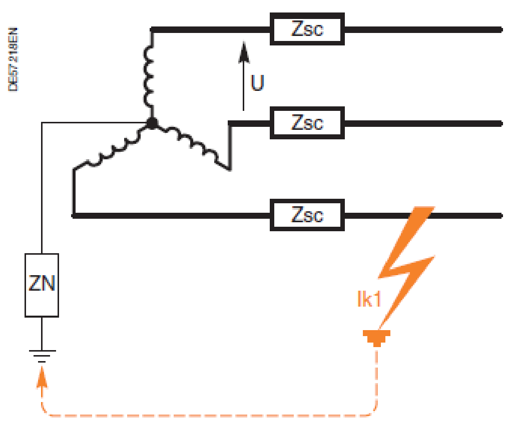

Figure ***2-9*****:** Single phase to ground short-circuit. **Source:** [48]

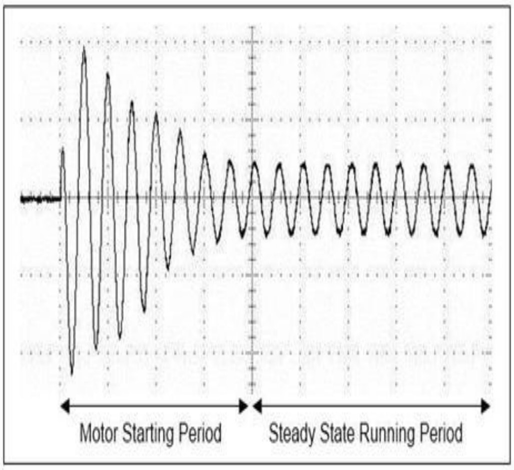

Figure *2-10*: In-Rush current demanded by a three-phase induction motor during starting and steady-state period. **Source:** [46].

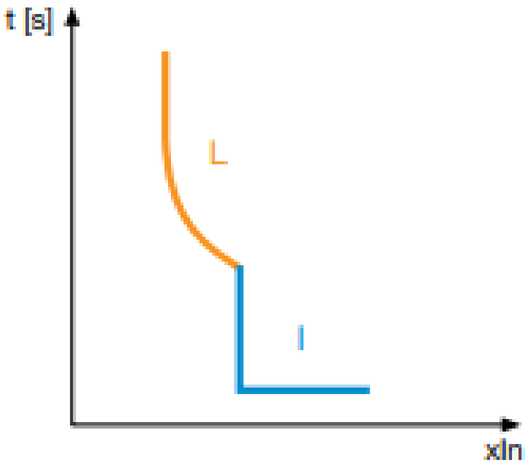

Figure *2-11*: Generic time-current tripping curve. The part marked with an L is the one corresponding to overload protection. **Source:** [49]

It is important to distinguish an overload fault from a momentary overload. An overload fault is caused by malfunctioning of a component or connecting more load than allowed to the circuit. Certain loads, like motors, cause a momentary overload during start-up that should not be considered as faults, so the protection devices should not trip immediately. For example, **Figure 2-10** shows the start-up current of a motor, during its acceleration to nominal speed after being connected to a power supply. The current during the starting period is higher than the nominal, which the circuit should be able to tolerate for a brief period of time without overheating. In order to discriminate a temporary overload from an overload fault, the tripping should have a delay. This time dependency is represented in the tripping curve by the section closer to the time axis, as shown in **Figure 2-11**. This curve is represented by the relation I^2t, which corresponds to the liberated energy. The higher the current, the smaller time that it will be allowed to flow before tripping.

2.3.3. Grounding

The concept of grounding, also known as earthing, is a common practice in power systems not only for protection but also for measurement purposes. The ground is the return path for electrical current or a physical connection to earth. When designing electrical systems or calculating magnitudes, the ground is also usually the point of reference for potentials. Depending on the size and characteristics of the system, one or more points of grounding can be installed. There are also some special systems that are left ungrounded.

Electrical systems are connected to ground for several reasons. Grounding reduces the electrocution risk for people touching accidentally a conducting part exposed with a high voltage compared to ground. The goal is to provide the current with a path of less resistance than the human body, in order to limit the amount of electrical current flowing through the person. This path would effectively be a short-circuit to ground, which would trip the protective devices. The earth providing the return path for the current will have a ground impedance, commonly represented as Z_s. This impedance will naturally have an effect on the ground current. In order to clear ground faults properly, it is necessary to know or at least have a good estimate of the value of Z_s.

Grounding also provides the high currents providing from a lightning discharge with a path to earth. Electro-Magnetic Interference (EMI) is also greatly reduced by applying proper grounding techniques, which improves power quality.

According to the International Standard IEC 60364, the grounding scheme can be TN, TT and IT. The first letter refers to the connection between the earth and the power supply equipment, and it can either be "T" if directly connected or "I" if isolated or only connected via a high impedance path. The second letter refers to the connection between the earth and the device that is being supplied. It can either be a "T" if it is the device is locally connected to earth or an "N" if the neutral is provided by the supply network, either combined with the earth (PEN) or separately (PE). This is well illustrated in **Figure 2-12**. TN systems can be TN-S, in which the Neutral (N) and Protective Earth (PE) are only connected together close to the power source, TN-C, in which the Neutral (N) and Protective Earth (PE) are combined in one conductor, or TN-C-S, in which the Neutral (N) and Protective Earth (PE) are one conductor when leaving the power source and split into two at some point [26].

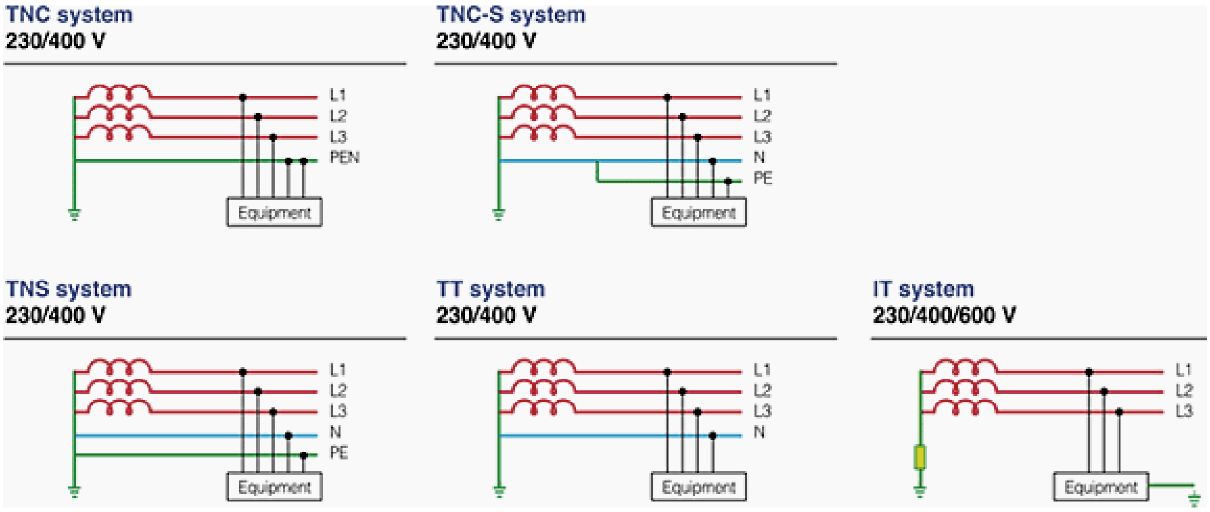

Figure ***2-12***: Schematic representation of the different types of grounding according to IEC 60364. **Source:** [51]

2.3.4. Protection Devices

Protection devices are part of the protection scheme in charge of detecting a fault situation and consequently interrupting the power flow in a circuit within acceptable time limits. Some devices can detect and interrupt the fault themselves, and some need an external relay to detect the fault and make them operate. In order to minimize negative effects of a fault, the process of detecting and interrupting the power flow should be automatic, it cannot rely on human interaction. Some devices can also be operated manually to open the circuit, for example, for maintenance purposes. There are numerous protection devices available in the market that protect against different kinds of faults and suitable for different types of equipment. The ones relevant for the purpose of this research and briefly explained below [27] [28]:

- **Fuses** are protection devices that react to an overcurrent situation, either caused by a short-circuit or an overload. They have a wire of fusible metal that melts when the current exceeds the rating of the fuse, interrupting the power flow. Fuses have the advantage of being simple, cheap and reliable components, and they do not need an extra device for fault detection. They operate in a range of time around the 0.002 seconds. Main disadvantages is that they need to be manually replaced when blown, they are only available as one-pole devices and their breaking capacity is quite lower than in circuit breakers.

- **Circuit Breakers** are switches that automatically interrupt currents over the rated value, based on electromagnetic principles. They protect against overcurrent created by overload or short-circuit faults. They can usually not detect a faulted situation directly, so they need a relay that indicates when to operate and to be provided with auxiliary contacts. Some circuit breakers have built-in protective functions and do not require a relay for correct operation. The operating

time is around 10 times slower than in fuses, between the 20ms and 50ms. They are available for single or multi-phase. As mentioned, they are normally operated by a relay automatically, but they can also be switched on and off manually, for example, for security purposes during maintenance in the system.
Reclosers are a special type of circuit breakers normally installed at the top of distribution poles on long distribution lines, or at the Point of Common Coupling between the grid and a microgrid. Their function is to isolate a feeder with overload or fault conditions to leave the rest of the system unaffected, and have normally a coordinated action with a fuse. The difference with regular circuit breakers is that the recloser will interrupt the circuit and restore the power almost immediately, measuring again the operating conditions when it does. If the fault situation is still present, the recloser will open the circuit again and this time wait for a preset time of normally a couple of seconds. After this preset time, the recloser will restore the power flow and measure again. At this point, if the fault is still present the fuses will probably blow clearing the fault. If this is not the case and the recloser measures still fault conditions, it will open again and interrupt the circuit until manually reclosed. This operation allows a faster power supply restore after temporary faults, which is the case in about 80-90% of the cases on high voltage lines, for example, with a branch falling on the distribution lines or a bird creating a line to line short-circuit [29].

- **Residual Current Devices (RCD)**, also known as Residual Current Circuit Breakers (RCCB), are devices that trip the circuit when the current flowing through the phases is not equal to the current through the neutral, a situation that is caused when there is an earth fault. This type of current is generally induced by a person touching live terminals, so RCDs main function is to protect people from an electric shock. They are connected between a phase and the neutral, or all three phases and the neutral. The current flowing through the phases should return through the neutral. If this condition is not satisfied, it means there is a leak and the current is flowing somewhere else, so the RCD trips the circuit in a time of around 30ms. In TT systems, higher value RDCs (300mA – 500mA) are also usually installed for fire protection.

  Surge Protection Devices (SPDs) limit the overvoltage derived from atmospheric conditions, like a lightning discharge, from internal faults in the power supply system or from switching power sources. Strictly speaking, they cannot be considered protective devices since they are not able to interrupt the power flow, but they are mentioned here because they will be included in the protection schemes later in this research. SPDs are connected in parallel with sensitive loads, bypassing them in case of fault causing overvoltage and directing the transient current to the ground.

2.3.4.1. Protection relays

The basic difference between protection relays and the devices mentioned previously is that relays do not act directly on the circuit. Relays monitor a signal or set of signals, usually current or voltage. When the magnitude of any of these signals is outside an allowed margin, the relay opens internal electrical contacts to stimulate another device to interrupt the power flow, usually a circuit breaker. The relay could be seen as the brain of the protection system, in the sense that the parameters for the scheme will be programmed via the relay’s software and it will be in charge of making the rest of controllable devices actuate when needed.

Relays can be classified in a number of different ways. For example, according to their construction, relays are classified in thermal, electromechanical, solid state, microprocessor, digital and numerical. Thermal and electromechanical relays are being replaced by digital and numerical relays that offer improved reliability and functionality together with a smaller size. Numerical relays offer the functionality that previously required several different relays, all in one device. This could lead to reliability problems. If one numerical relay includes all the protection features, then they would all be lost in case of failure of that one device. However, advances in software and alarm systems for failure prevent most of the reliability issues that could arise [20].

Another common classification for relays is according to their function. One relay can also integrate several functions. Relays are commonly described according to their function by the standard device numbers assigned by the ANSI/IEEE as shown in Table 2. The most relevant functions for the purpose of this research are highlighted in bold in Table 2 and briefly described below [30].

- **Distance (21).** Responds to a ratio of the current and voltage at a specific location, with the dimensions of an impedance. The impedance between the location of the relay and the location of a fault is proportional to the distance of the fault, and it is independent of the direction of the current [19]. This is a very valuable characteristic in modern systems with stationary storage that allow current in both directions. The distance relay is capable of measuring the impedance of a line up to the reach point. The basic principle of distance protection is to divide the voltage at a point by the measured current at that same point and compare it to the impedance at the reach point. If the measured impedance is less than the reach point impedance, the relay assumes that there is a fault between the relay and the reach point, and therefore it opens the circuit [20].
- **Synchronizing or Synchronism-check (25).** Produces an output that causes closure of a circuit breaker between two circuits whose voltages are within limits of magnitude, phase angle, and frequency.
- **Undervoltage (27).** Operates when the input voltage is less than the minimum established value. A time delay is normally associated to this function to allow momentary sag of the voltage due, for example, to inrush currents during the start-up of motors.
- **Directional Power (32).** Operates on a predetermined value of power flow in a given direction.
- **Instantaneous Overcurrent (50).** Operates with no intentional time delay when the current exceeds a preset value. In order to avoid nuisance tripping, this preset value needs to take into account inrush currents associated, for example, with the start of a motor. Depending on the level of current that will instantaneously trip, curves are divided commonly in type B, C and D. Curve B is meant for resistive circuits, and will trip instantaneously for 3-5 times the nominal current. Curve C is meant for medium inductive loads and will trip instantaneously for 5-10 times the nominal current. Curve D is meant for highly inductive circuits and capacitive loads, and will trip on 10-20 times the nominal current. For very specific applications, other curves can be found. An example of curves B, C and D is shown in **Figure 2-13**. The exact tripping point is dependent on factors such as temperature and age of the equipment, so the area shown represents the maximum and minimum margins between which the tripping will happen for a specific current [31].
- **AC Inverse Time Overcurrent (51).** Functions when the magnitude of the current exceeds the preset value, known as the pickup setting for a determinate amount of time. The higher the current, the faster the relay will close its output contact to trip the circuit breaker. The pickup current must be higher than the maximum load current under normal operating conditions, normally with a margin of 2-3 times to avoid nuisance tripping [19]. The IEC 60255 defines traditionally three standard characteristics for inverse-current tripping, as shown in **Figure 2-14**.
- **Overvoltage (59).** Operates when the input voltage exceeds a maximum established value.
- **AC Directional Overcurrent (67).** Functions at a desired value of AC overcurrent flowing in a predetermined direction. This function is necessary when the fault current can circulate in both directions, like in the case of microgrids with multiple sources of power.

- **Frequency (81).** Responds to the frequency of an electrical quantity, usually voltage or current, operating when the frequency or rate of change of frequency exceeds or is less than a predetermined value.
- **Differential (87).** Operates on a percentage, phase angle, or other quantitative difference of two or more currents or other electrical quantities.

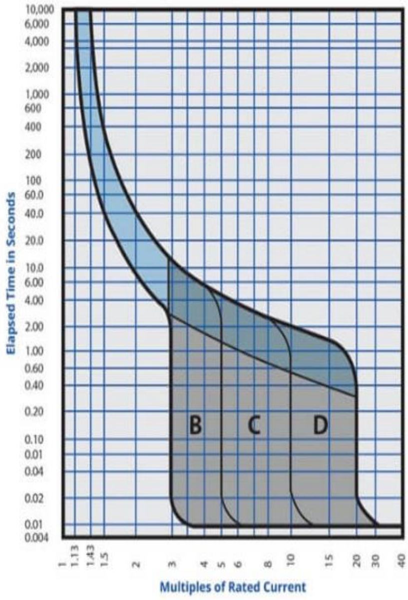

Figure 2-13: Example trip B, C and D curves. **Source:** [26]

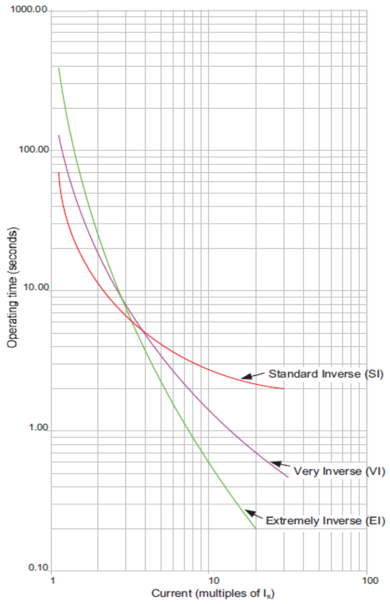

Figure 2-14: Standard curves defined by IEC 60255 for inverse time trip curves. **Source:** [20]

Table *1*: Standard device/function number according to IEEE C372.2008.

1 - Master Element
2 - Time Delay Starting or Closing
3 - Checking or Interlocking
4 - Master Contactor
5 - Stopping Device
6 - Starting Circuit Breaker
7 - Rate of Change
8 - Control Power Disconnecting Device
9 - Reversing Device
10 - Unit Sequence Switch
11 – Multifunction Device
12 - Overspeed Device
13 - Synchronous-speed Device
14 - Underspeed Device
15 - Speed or Frequency-Matching Device
16 - Data Communications Device
20 - Elect. operated valve (solenoid valve)
21 - Distance
23 - Temperature Control Device
24 – Volts per Hertz
25 - Synchronism-Check Device
26 - Apparatus Thermal Device
27 - Undervoltage
30 - Annunciator
32 - Directional Power
36 - Polarity or Polarizing Voltage Devices
37 - Undercurrent or Underpower
38 - Bearing Protective Device
39 - Mechanical Condition Monitor
40 –Field (over/under excitation)
41 - Field Circuit Breaker
42 - Running Circuit Breaker
43 - Manual Transfer or Selector Device
46 - Rev. phase or Phase-Bal. Current
47 - Phase-Seq. or Phase-Bal. Voltage
48 - Incomplete-Sequence
49 - Machine or Transformer Thermal
50 - Instantaneous Overcurrent
51 - AC Inverse Time Overcurrent
52 - AC Circuit Breaker
53 - Field Excitation
55 - Power Factor
56 - Field Application
59 - Overvoltage
60 - Voltage or Current Balance
62 - Time-Delay Stopping or Opening
63 - Pressure Switch
64 - Ground Detector
65 - Governor
66 - Notching or jogging device
67 - AC Directional Overcurrent
68 - Blocking or "out of step"
69 - Permissive Control Device
74 - Alarm
75 - Position Changing Mechanism
76 - DC Overcurrent
78 - Phase-Angle Measuring
79 - AC-Reclosing
81 - Frequency
83 - Automatic Selective Control / Transfer
84 - Operating Mechanism
85 - Pilot Communications
86 - Lockout Relay
87 - Differential Protective
89 - Line Switch
90 - Regulating Device
91 - Voltage Directional
92 - Voltage and Power Directional
94 - Tripping or Trip-Free

Chapter 3. **Relevance of Research**

In this chapter, an overview of the current status and predictions in the near future for the microgrid market is presented utilizing data published by Navigant Research, a research market group. It is followed by a summary of the common issues regarding microgrid protection. The purpose of combining this two topics in one chapter is to show the relevance of this project based on the exponential growth in power installed in microgrids worldwide and the need of further research in the topic of microgrid protection.

3.1. Microgrid Market

Navigant Research provides its own definition for microgrid to guide its collection of data, stating that *a microgrid is a distribution network that incorporates a variety of possible DER that is optimized and aggregated into single system balancing loads and generation with or without energy storage and is capable of islanding whether connected or not connected to a traditional utility power grid.* In 2018, they published a report about the status of the microgrid market and the forecast for the coming 10 years. The results presented here speak for themselves, and show clearly the growth in relevance of microgrid projects worldwide.

The global installed power in microgrids was 2.694MW in 2018, and is expected to grow to 15805.5MW in 2027, which implies an annual growth of 21.7%. This means that the microgrid market should grow from $6.3 billion in 2018 to $30.9 billion in 2027. **Figure 3-1** shows the predicted growth per region and the investment required. The region with a faster growing market is Middle East & Africa, which is expected to increase the microgrid market at a rate of 27% per year. The largest market is Asia Pacific, which had 1110.3MW installed in 2018 and is expected to grow to 6870.2MW in 2027, with a growth rate of 22.4% per year [32].

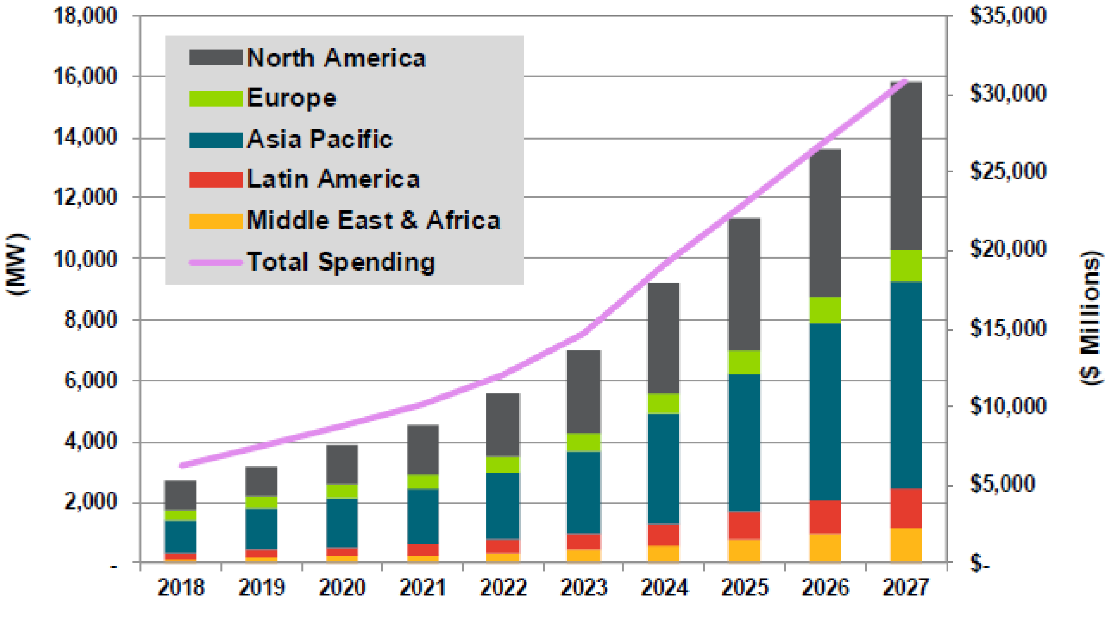

Figure ***3-1*****:** Annual microgrid capacity installation forecast per region. **Source:** [32]

Navigant Research also makes a classification in their report regarding the type of microgrid. They consider six different market segments, namely Campus/Institutional, C&I, Community, Stationary Military Base, Utility Distribution and Remote Microgrids. The main interest for this research is with the segment of the remote microgrids. A microgrid is considered remote if it has no connection to the grid whatsoever, so it operates always in islanding mode. The purpose of many of these microgrids is to reduce diesel consumption by integrating renewable DERs such as solar or wind. Microgrids without a renewable source are not considered in this report. **Figure 3-2** shows the forecast for growth in the remote microgrid market by region. It shows also that Asia Pacific is by far the top global market for remote microgrids, followed by North America and Latin America. Middle East and Africa is the fastest growing market, at a rate of 24.6% per year [32].

These numbers are a forecast based in different business models and extensive research in the topic. However, it is still a prediction, the future of the microgrid market is uncertain. The base case scenario presented by Navigant Research forecasts a $30.9 billion annual microgrid investment by 2027, but they most conservative assumptions lead to a forecast of only $13 billion. The most optimistic case leads however to a $46.6 billion spent per year implementing microgrids. In any case, all assumptions lead to a growth in the microgrid market, at a faster or slower pace, which fundaments the relevance for the electrical market of research in the topic of microgrids.

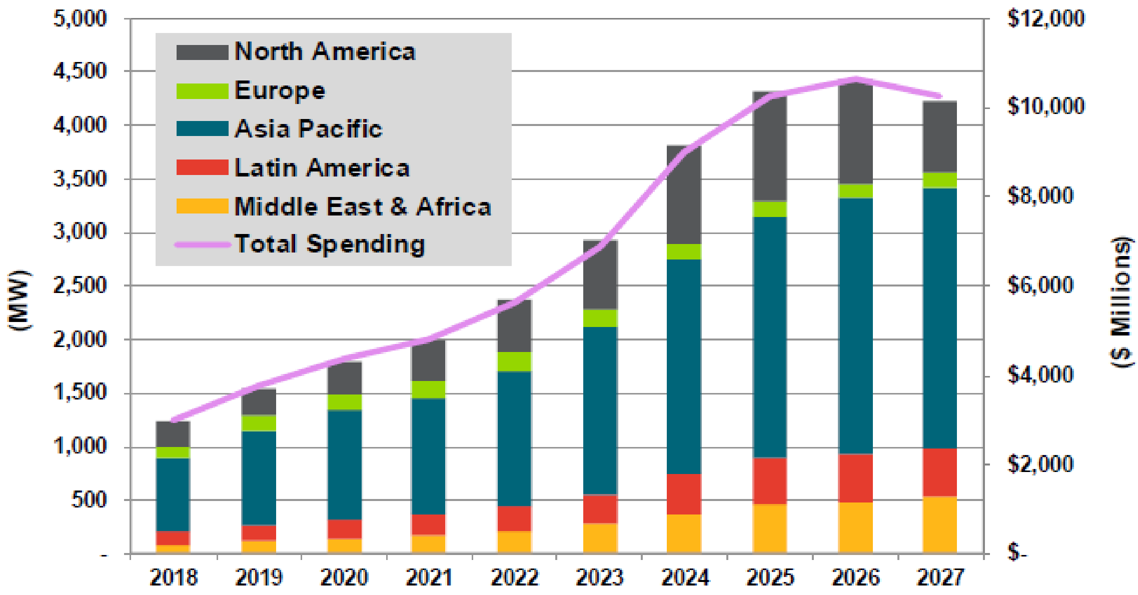

Figure *3-2*: Annual remote microgrid installation forecast per region. **Source:** [32]

3.2. Protection Issues in Microgrids

One of the fundamental characteristics of microgrids is that they can operate in grid-connected and off-grid or islanded mode. The protection scheme needs to be suitable for both modes of operation and during the transition from one to another. In traditional systems, protection schemes operate based in fault current magnitudes and unidirectional power flow. The most common devices are therefore overcurrent and directional relays, fuses and reclosers. This is no longer valid in supply networks with microgrids integrating Distributed Energy Resources (DERs).

The main protection issues that arise are listed below and explained briefly. It should be noted that depending on their nature, the issues can be related to a specific mode of operation or happening in both modes [33]:

Bidirectional Power Flow. Conventional power systems have a single power source, and have a radial configuration. This means that the current flows always in the same direction under normal operating conditions, bringing the power from the transformer substation to the loads. The protection scheme for this type of systems is normally equipped with unidirectional relays that are not valid to detect faults when power flow is reversed, which is a normal operating condition in systems with multiple power sources.

Limited Fault Current. When a fault happens during grid-connected operation, the grid supplies a fault current of 10-50 times the nominal load current, which is easily detected by the protection devices causing tripping [34]. Fault currents provided by inverter based power sources are much lower than regular fault currents provided by the grid, normally just above the peak current of the inverter. This current is not high enough to trip the traditional overcurrent protective devices, but lowering the settings of these devices will cause nuisance tripping.

Protection Blinding. The microgrid is connected to the main distribution network at the Point of Common Coupling (PCC) via a switch that should trip in the case of fault either downstream or upstream. When a fault occurs during grid-connected operation at a point that is supplied both via the distribution network and one or more DERs, the relay that measures the current at the PCC will see less than the real current value, since the grid and the DERs contribute to the fault with currents in opposite direction. This can lead to the relay not operating or with an unacceptably long delay. **Figure 3-3** shows an example schematic of this issue.

Sympathetic False Tripping. Relays from non-faulted feeders might trip when a fault occurs in an adjacent feeder. This happens especially during islanded operation, since the healthy feeder might be the one providing the fault current, depending on the location of the fault. If the wrong breaker operates, the fault is not isolated and the reliability of the system is compromised. **Figure 3-3** shows an example schematic of this issue.

Device Discrimination. In the radial distribution for conventional networks, the magnitude of the fault is inversely related to the distance from the point of fault to the power supply. This means, the longer the distance to the fault, the smaller the fault current. This principle is used for selectivity purposes by distance protection devices. The distance between power sources and loads is usually much smaller in microgrids, being one of their intrinsic characteristics the allowance for local generation. This combined with the fault current magnitude limitation in inverter based sources leads to fault current having almost the same magnitude in all parts of the feeder, so traditional distance protection is no longer valid.

Single Phase Connection. Depending mainly on their size, DERs are sometimes connected only to one phase of the distribution network. Generation peaks can disturb the balance of the system and induce currents in the neutral wire that can be dangerous if not handled properly, which increases complexity of the protection scheme.

Recloser issues. The operation of reclosers is coordinated with fuses in radial distribution networks. This coordination will be affected by the bidirectional power flow introduced by DERs. The fault current magnitude measured by the recloser will also be affected by the inclusion of DERs, due to the same principle that causes protection blinding explained previously in this chapter. Protection schemes including reclosers need therefore to be redesigned when microgrids are included in the network.

Islanding. When the microgrid goes into islanding mode, the frequency and voltage are no longer dictated by the grid, and one of the DERs needs to act in grid-forming mode to establish the voltage and frequency for all loads supplied by this microgrid. When reconnecting to the grid, an islanding device is needed to ensure the voltage and frequency are similar enough to the grid conditions, to avoid unbalance issues that would trip other protection devices upstream.

Variation in the Reach Capability of Distance Relays. A distance or impedance relay is able to detect faults in a maximum distance, known as the reach capability of the relay. Distance relays calculate the impedance to the point of fault based on measured current and voltage values. When a fault happens downstream of a feeder with DER the measured impedance will he higher than it actually corresponds to that fault current, due to the increase in voltage caused by both the grid and the DER feeding the fault. This might cause the relay to have a delay in operation or not even operate.

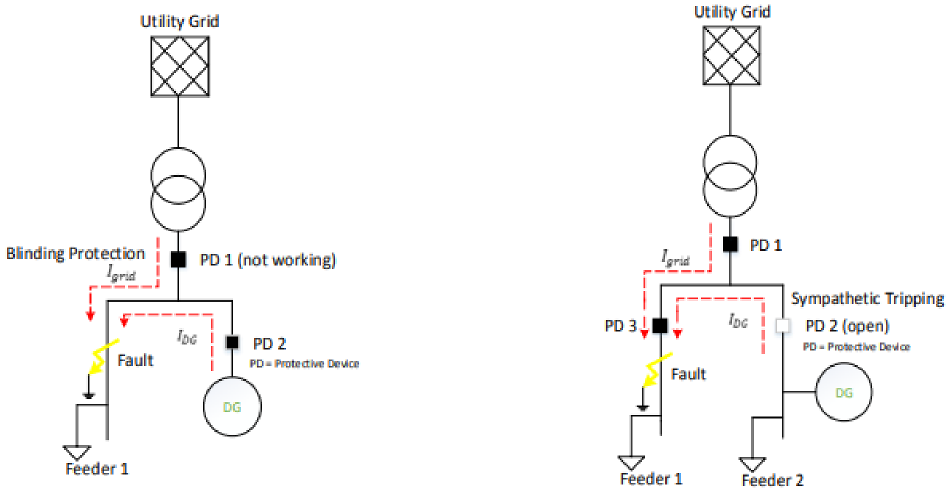

Figure 3-3: Left schematic shows a blinding protection example. Right schematic shows a sympathetic false tripping example. **Source:** [29].

Chapter 4. **Available solutions and limitations**

This chapter includes a summary of the most popular available solutions and proposals for the protection of microgrids and a highlight of their limitations. Many other alternatives that are not mentioned here can be found in the literature, but they either have more limitations than the options presented here or they are not suitable for the low voltage off-grid microgrid in the scope of work of this research. Even the ones presented here have several limitations, mainly regarding detection of High Impedance Faults (HIF) and the dependence on communication links.

The purpose of this chapter is to introduce the protection schemes that have already been proposed and analyze what are their limitations and what could be of interest for the design of a new and improved scheme.

4.1. Residual Current and Symmetrical Components Measurement

One of the first approaches to solving the protection issues in microgrids was presented by Lasseter in [35]. This method aims to have the same protection scheme for on-grid and islanded operation. The microgrid is connected to the main grid by a Static Switch (SS), that should open for all kinds of faults. In the case of islanded operation, the switch is already open and therefore faults need to be cleared with techniques not depending on high fault currents, since the grid is not able to provide these anymore. In the example given by Lasseter, the system is divided in zones, each of them with one independent Inverter-Based Distributed Energy Resource (IB-DER). The main distribution line is also a zone in itself, as shown in **Figure 4-1**.

The idea is to protect the system from Single Line-to-Ground (SLG) faults based on differential current (Id). The differential current (Id), which is nowadays also commonly known as residual current, is the sum of currents in all three phases and the neutral, and should be zero. A Single Line-to-Ground fault in zone 4, for example, generates an Id that is not equal to zero in zones 2, 3 and 4. This would cause Relay 2 to open the Static Switch (if not already open) and Relay 4 to isolate Zone 4 and switch down the inverter source in this area. Relay 3 has a delay, and therefore Zone 3 should not be disconnected

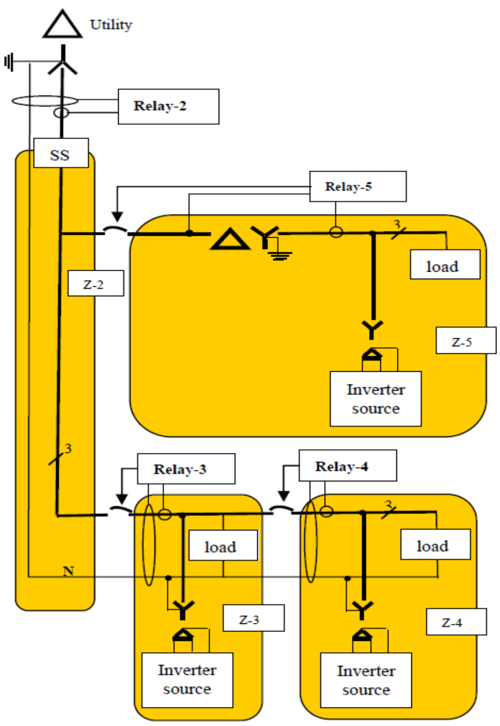

Figure 4-1: Basic microgrid representation with one protection zone per inverter source (Zones 3,4,5), and one zone for the distribution line itself (Zone 2). **Source:** [32]

from Zone 2. This concept would also work for a fault in Zone 5, but the problem arises when the fault is in Zone 3. In this case, Relay 2 and Relay 3 would measure a differential current and open the Static Switch and the circuit breaker between zones 2 and 3, but the fault ground current does not circulate through Zone 4, and therefore Relay 4 is unable to detect the fault. Generalizing, this is true for any subsystems downstream from the fault location. In this particular case, Zone 4 would remain connected and feeding current fault to Zone 3. In conclusion, this solution protects only completely in case of Single Line-to-Ground fault in the furthest subsystem from the Static Switch.

The proposal for high impedance Line-to-Line (LL) faults is to detect them via the negative sequence current. When a balanced system is in normal operating conditions and not faulted, the currents in each phase are equal and displaced 120°. A fault causes an unbalanced situation that leads to negative and zero sequence currents to appear, as shown in **Figure 4-2** [36].

Lasseter also proposes I^2t protection as backup, which is based in the heat dissipated. In many cases, during islanded operation the current will not be large enough to activate this protection, but it still ensure no major damage happens to the equipment in case of larger currents. Undervoltage is also suggested as backup, but this will only actuate for low-impedance faults, since the voltage will not drop enough in high impedance faults to activate it. Three-Phase faults are not considered in this method.

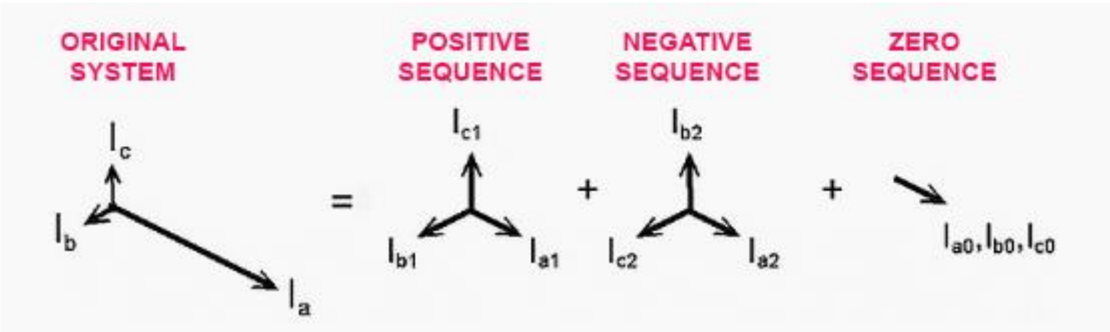

Figure 4-2: Symmetrical components, positive, negative and zero sequence. **Source:** [33]

4.2. Voltage Based Protection

This method requires monitoring the output AC voltages of the power sources (*abc*), and transforming them into DC quantities represented in the *dq* reference frame [37]. This is done in two steps, with Clark and Park transformation matrices, as shown in **Equation 4-1** and **Equation 4-2.**

$$\begin{bmatrix} Vds \\ Vqs \\ 0 \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad \text{Equation 4-1}$$

$$\begin{bmatrix} Vdr \\ Vqr \end{bmatrix} = \begin{bmatrix} \cos(wt) & -\sin(wt) \\ \sin(wt) & \cos(wt) \end{bmatrix} \begin{bmatrix} Vds \\ Vqs \end{bmatrix} \quad \text{Equation 4-2}$$

The three phase AC voltages (V_a, V_b and V_c) are easily measured by the use of Voltage Transformers (VTs), and the data is converted to DC quantities (V_{dr}, V_{qr}) as explained before. This is performed under normal operating conditions, obtaining a reference vector V_{ref}, with components V_{d_ref} and V_{q_ref}. A disturbance in any of the three phase voltages will cause measured V_d and V_q to differ from the reference values. It is possible to discern what kind of fault is happening by analyzing the disturbance signal (V_{DIS}), which is the difference between the reference and the measured values at a point of time. If the fault is a single-phase disturbance, V_{DIS} is an oscillating signal. If the fault affects two phases, V_{DIS} is a DC voltage with an AC ripple, and V_{DIS} is a pure DC voltage is the fault is three-phase.

When the system is divided in several zones, the protection relays in both zones need to communicate the measured values with each other. The fault can then be located by comparing the different V_{DIS} provided by every relay, since V_{DIS} will be larger when closer to the fault location. This makes it possible to only disconnect the faulted zone, and the method works for both Line to Line to Line (LLL), Line to Line (LL) and Single-Line to Ground (SLG) faults.

The main limitation of this protection strategy is the dependence on the communication link for the device trip and location of faults. Also, HIF will not be detected in most of the cases, since the voltage variation will not be significant enough [38].

4.3. Harmonics Content Based Protection Scheme

This method is based in the measurement and interpretation of the Total Harmonic Distortion (THD) at the terminals of the inverters. THD is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. A pure sine wave only has a component in the fundamental frequency and the THD is close to zero. When there is a disturbance in the wave, harmonic components appear at other frequencies. The relays are configured to trip the breaker in case the THD reaches a threshold [39].

This method can identify the type of fault as well as the location of it, provided there is communication between the relays at different zones. Monitoring the fundamental frequency provides information about the type of fault, since the amplitude will drop significantly in a faulted phase compared to the non-faulted phases. The calculation of the THD gives information on the location of the fault, since it will be larger in the faulted phase than in the non-faulted phases. The communication between the two relays allows the discrimination to trip the right breaker based on the THD measurements. **Table 2** shows an example of the variation in the THD measured per phase, in the case of L-L fault between phases *b* and *c*.

As explained in [39], the harmonics content based method is not valid if one of the sources in the microgrid has pure voltage output, since it would then always have zero THD. Otherwise, inverter-based sources can provide quite accurate feedback for detecting faults. Other limitations are the dependency on the communication link between the relays for the location of the fault, and the possible failure if very dynamic loads are present in the system.

Table *2*: Comparison between THD values for un-faulted system and L-L fault in phases b and c.

	Un-Faulted	**Faulted**
THD_a (%)	2.4946	2.4255
THD_b (%)	2.0656	**3.9321**
THD_c (%)	2.4977	**9.0644**

Chapter 5. **Software and Model Description**

This chapter provides a general overview on the calculation software utilized for the design of the protection scheme and the simulation of load flow and fault conditions. A description of the model created for this purpose is included as well.

5.1. Software description

DIgSILENT *PowerFactory* is the calculation software utilized in this research. *PowerFactory* is an engineering tool for the analysis of electrical power systems. Within this software, there is an interface for the automation of tasks that is controlled via the DIgSILENT Programming Language (DPL) or via Python. The two *PowerFactory* most used basic functions for this research are Load Flow and Short-Circuit calculations, explained below [17]:

Load Flow Calculations are used to analyze the system under steady-state, normal operating conditions. Variables and parameters are assumed to be constant during the period of analysis, reflecting the behavior of the system at a specific point of time. The Load Flow Calculation provides the active and reactive power flow in all branches and the current and voltage in all nodes of the system. This feature is useful to ensure the correct design of the system and prevent any elements such as busbars or nodes to be overloaded. Power Factory utilizes the Newton-Raphson method to solve the non-linear equations required to determine the load flow.

Short-Circuit Calculations are used to analyze the system under fault conditions. PowerFactory allows several current calculation methods, with different levels of complexity. For less detailed calculations that do not require specific load data, there are multiple calculations methods that apply extreme-case estimations, such as *IEC 60909/VDE 0102*, *ANSI*, *IEC 61363* and *IEC 61660*. When more precise information is needed, for example to find out the cause of a relay malfunctioning or detailed protection studies, more complex methods should be used, such as the *Complete Method*. For the purpose of this research, since the system is not very complex, it is possible to use the *Complete Method* without increasing significantly the computational time, and therefore this will be the method used for the short-circuit calculations.

5.2. Model description

The model of the islanding microgrid created in PowerFactory is shown in **Figure 5-1**. The main subsystems are:

- The **Tesla BESS** is composed by the battery and the Tesla inverter. The battery is simulated by a DC – Voltage Source with nominal voltage 400V. The inverter is simulated by converters with rated AC voltage 400V and rated DC voltage 1kV. More converters can be connected in parallel in one same inverter to increase the available power, up to a maximum of 10. The rated power per parallel converter is approximated to 70kVA at 400V and the current output at nominal operating conditions is 80A. The Tesla Inverter operates in grid-forming mode in the absence of external grid, so it is the subsystem in charge of determining the voltage and frequency of the microgrid. In an overload scenario, the Tesla Inverter supplies 1.2 pu current for 10 seconds, sagging the voltage as necessary to maintain this limit. If the voltage reaches a limit, tripping is triggered.
- The **Solar Generation** is simulated by the subsystem named PV_System. PowerFactory provides directly the option to simulate a solar inverter and modify the active power provided and other parameters. In this case, an active power of 50kW is chosen as a reasonable value according to the battery system and load size.

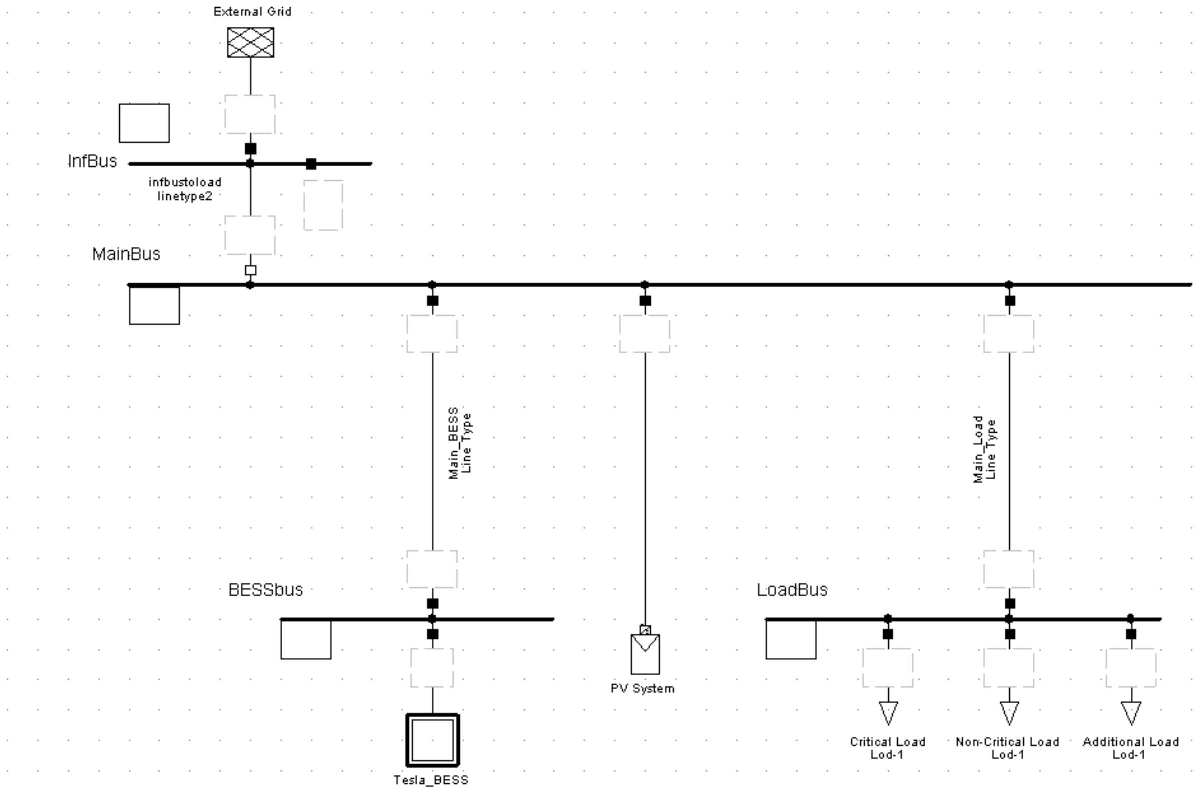

Figure ***5-1*****:** Model created in PowerFactory representing an off-grid microgrid (the External Grid is always disconnected so it has no influence in the rest of the system).

- **Three loads** connected to a common load busbar that is supplied from the main busbar via one load circuit breaker. The loads are called here Critical, Non-critical and Additional respectively, to show a typical example of load distribution, and have a nominal power requirement of 30 kW each. This means that the maximum total load seen by the rest of the system is 90kW.

Note that the model also shows an external grid, even when this research is narrowed to islanding operation only. The external grid is always disconnected during the calculations performed. The reason to include it is double, to avoid malfunction of the software and to allow a future expansion of the research to include on-grid operation simulations.

5.3. Load Flow Analysis

As mentioned before, the purpose of running a Load Flow analysis is to analyze the system under normal, steady-state operating conditions. For the purpose of testing the model created and determining nominal characteristics of protection devices, several Load Flow calculations under different operating conditions have been run. The *PowerFactory* option used is *AC Load Flow, balanced, positive sequence*. This runs calculations for a single phase, assuming a balanced and symmetrical system. **Figure 5-2** and **Figure 5-3** show the results of running the load-flow for two different operating conditions. **Figure 5-2** shows the calculations for equal power requirement of 20 kW in all three loads, meaning a total load of 60 kW and a solar generation of 10 kW. In this case, the battery would need to provide the rest of the power to the load, so it discharges with 50 kW. **Figure 5-3** shows the calculations for equal power requirement of 10 kW in all three loads, meaning a total load of 30 kW and a solar generation of 50 kW. In this case, the battery would charge with the rest of the power available from the solar generation, 20 kW.

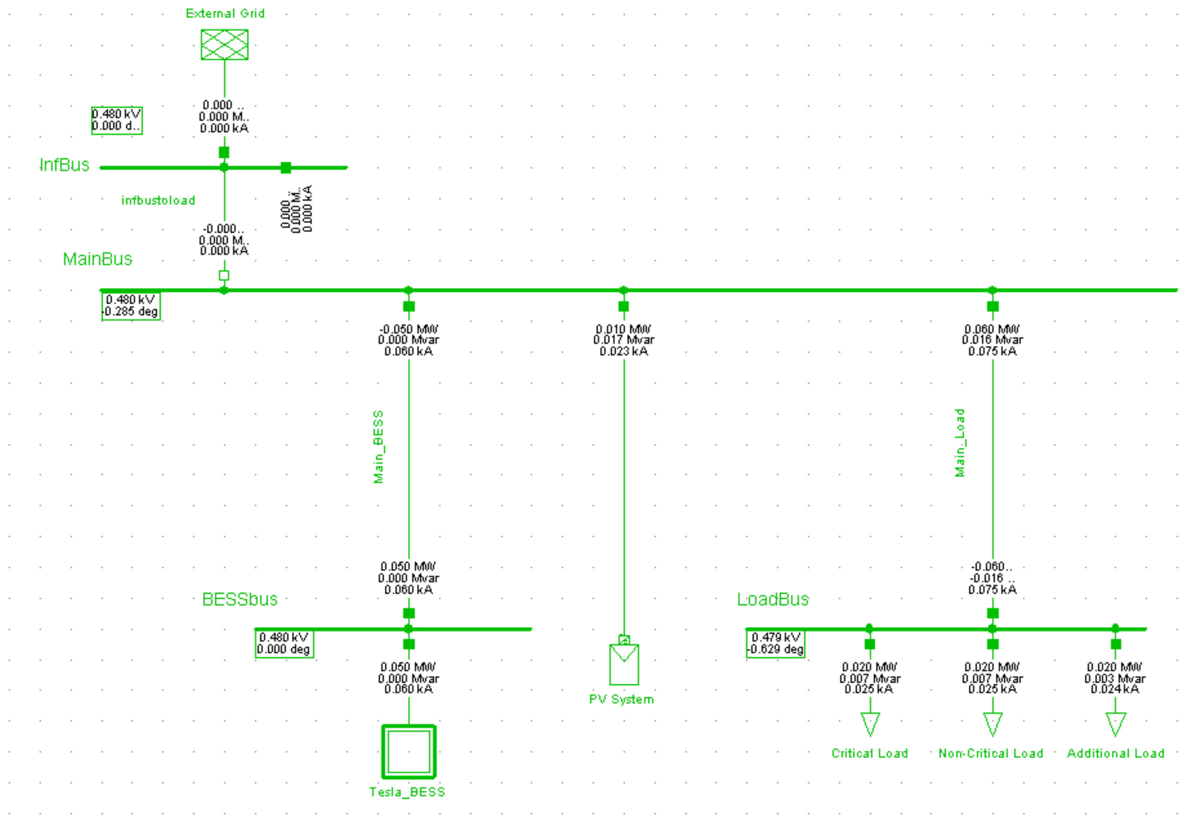

Figure *5-2*: Load Flow calculations for basic case, with 60kW total load and 10kW solar generation. Battery discharges with 50kW. The color green reflects a voltage and power in the elements within the limits for normal operation.

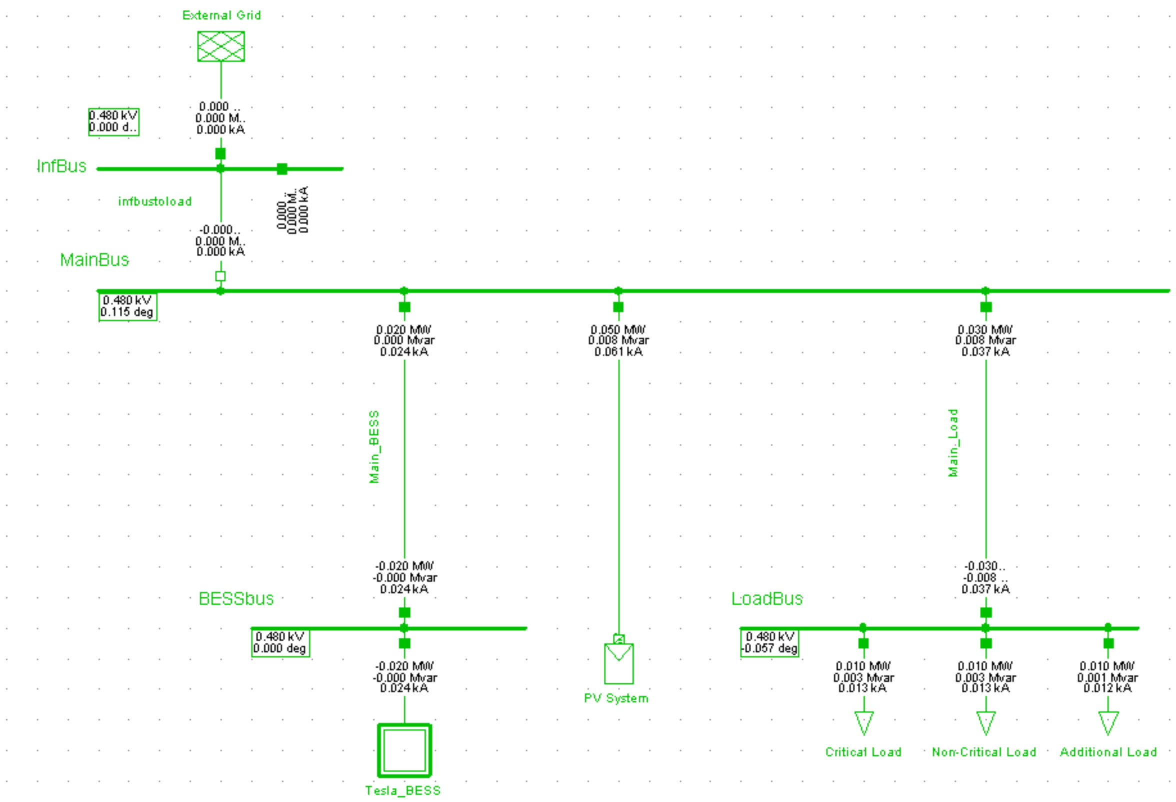

Figure *5-3*: Load Flow calculations for basic case, with 30kW total load and 50kW solar generation. Battery charges with 20kW. The color green reflects a voltage and power in the elements within the limits for normal operation.

5.4. Short-Circuit Analysis

PowerFactory allows the calculation of maximum and minimum short-circuit currents, which is needed to choose the protection devices properly and to ensure that the settings of the equipment have the right sensibility. Running the simple short-circuit command provides the levels of short-circuit current that would flow if no protection devices would act. Further options are available to examine tripping times of devices included, show time-overcurrent plots, run coordination studies, etc. **Figure 5-4** shows the short-circuit currents for a simple calculation for a single-phase to ground fault at the main busbar (MainBus) in phase *a*. The BESS provides all the short-circuit current, 96A, since the PV is disconnected at the moment of the fault. There are no protection devices included for this example so all the fault current is absorbed at the load.

The results for numerous short-circuit calculations for different fault conditions will be performed in the coming chapters, after the protection scheme designed during this research is introduced. This scheme is implemented into the microgrid model presented here, since *PowerFactory* allows the incorporation of relays, current and voltage transformers, switches, fuses and other protective devices. Simulations are made for different scenarios, to examine the currents and determinate if the protection devices would actuate accordingly and predict any situations that would cause malfunctioning of the equipment.

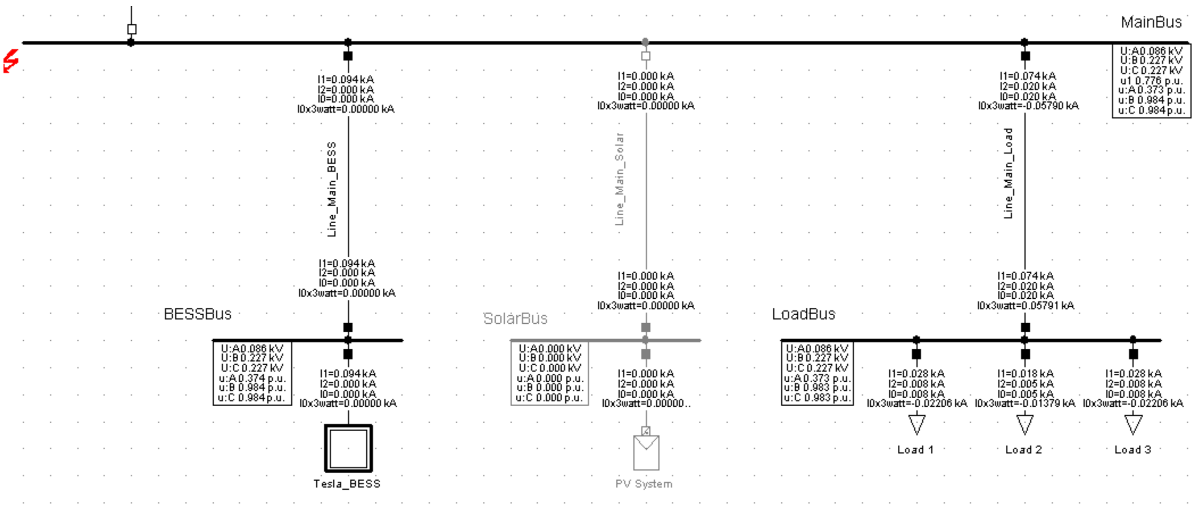

Figure *5-4*: Short-circuit currents for a simple calculation for a single-phase to ground fault at the main busbar (MainBus) in phase a.

Chapter 6. **Protection System Design**

In the previous sections, the protection challenges for an off-grid microgrid with inverter-based sources have been explained, as well as the available solutions for particular fault scenarios and their limitations. This chapter describes the approach to the different aspects of the protection scheme that has been chosen, as a prelude for **Chapter 7** in which the detailed scheme is presented.

The chapter begins by defining the protection zones in which the system is divided and naming the main protection devices for easier identification during the rest of the design process. The following sections explain how different fault situations will be handled, what breakers should be tripped and in what order depending on the location and nature of the fault. Finally, the proposed grounding scheme is introduced.

6.1. Protection Zones

The practice of dividing power systems in protection zones was explained in **2.3.1**. This will be applied here as well, for selectivity and coordination reasons. In addition, two main areas are identified , the *AC Distribution Area* and the *Customer Area.* It is assumed that only trained personnel with appropriate Personal Protective Equipment has access to the main AC distribution panel. On the contrary, it is assumed that any person could have access to the loads in the Customer Area, and therefore it has different protection requirements. In the AC Distribution Area, there are four protection zones. Faults in each zone will be handled differently, as explained in the upcoming sections of this Chapter. The Customer area is in this case divided in three different zones, just to create an example of how the distribution might be done. Faults downstream of any load breakers will be handled on the same way, so the strategy will be explained once in **6.3.** The division of zones for the chosen system is shown in **Figure 6-1**.

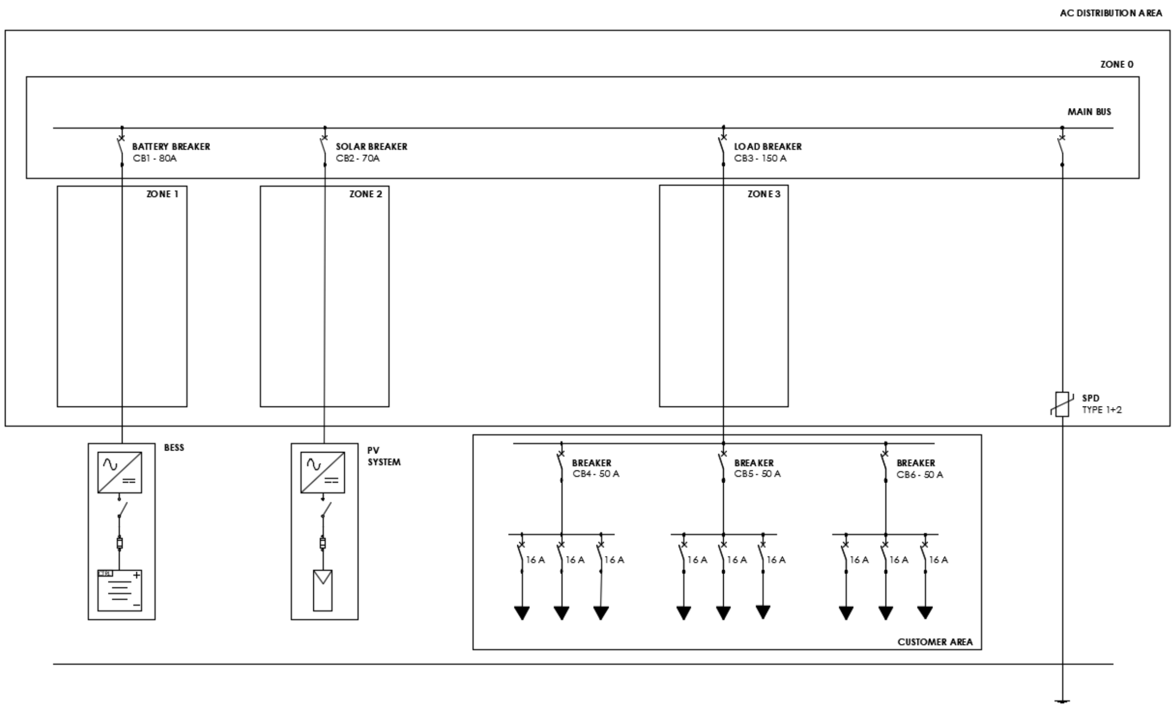

Figure *6-1*: Division of the system in protection zones.

6.2. AC Distribution Area

This section focuses on faults happening within the AC Distribution Area. As mentioned before, only properly trained personnel is assumed to have access to this area, with the appropriate Personal Protective Equipment (PPE). Also, the AC distribution system is expected to be contained in an adequate enclosure that protects it from animals and environmental conditions, so the probability of faults happening here is significantly reduced. The main risk of fault is during installation or maintenance of the system, which would most probably lead it to being a Low Impedance Fault created by points of different potential getting in contact. A High Impedance Fault could also happen but it would then most likely be noticed by the trained personnel working on the AC Distribution Panel and be cleared before posing a hazardous situation. Taking all this into consideration, the proposal for handling faults in the AC Distribution Area is explained below. Different breakers are required to trip depending on the location of the fault. This section explains what breakers should trip and in which order, depending on which zone is faulted, and the techniques applied to make this happen.

6.2.1. Low Impedance Faults

This section considers faults created by two or more points at different potential coming in touch with each other via a path of zero or very small resistance, known as Low Impedance Faults. The case of a person getting in contact simultaneously with two points of different potential is not considered here, but later in **6.6.1.** The traditional way of dealing with Low Impedance Faults is by means of overcurrent features in protection devices. As explained thoroughly in previous sections of this document, this might not be enough to detect fault currents in systems that only contain inverter-based sources, since these currents are limited to around 120% of the nominal (1.2pu). In order to solve this, the fault detection will be done via Undervoltage (27), Negative-Sequence and Ground Overcurrent (50) and Directional (67) functions in the protective devices.

Low Impedance Fault in Zone 0

Zone 0 is the main AC distribution busbar, to which all main breakers are connected. There will be no distinction made in different fault locations within this zone, all faults happening here should be cleared by opening CB1. This breaks the connection between the Tesla Inverter and the rest of the system.

The Tesla Inverter forms the grid and supplies the AC voltage and frequency to the loads and solar inverters. If the Tesla Inverter is disconnected, the solar inverters detect the “loss of grid” and enter the anti-islanding mode, in which they stop producing power. This is true in most of the cases for commercially available inverters, since regulation IEEE1547 requires Distributed Energy Resources to disconnect within 2 seconds when detecting loss of grid for security reasons in case of a fault upstream. It would be possible to open CB2 as well when detecting a fault in zone 0, if the relay that orders the trip has enough outputs. Due to the anti-islanding function in solar inverters, this is not seen as necessary and therefore the opening of CB2 for faults in zone 0 will not be implemented further in this research.

Low Impedance Fault in Zone 1

Zone 1 is the area downstream from CB1 and connects the Tesla Inverter with the main distribution busbar. A fault here should be cleared by opening CB1. The Tesla Inverter monitors constantly the currents and voltages at the exit of its power converters. If a substantial change in this values is detected exceeding a determinate threshold, the Inverter itself will trigger an internal contactor that interrupts the power flow. Once the Tesla Inverter is shut down, since it was the device creating the grid, the Solar Inverters will also stop producing power due to their anti-islanding capabilities. However, this might be not fast enough, and there could be a small time period in which the solar inverters keep feeding current fault.

The Solar Inverters will go into anti-islanding mode eventually when the Tesla Inverter stops forming the grid and stop producing power, so a fault in Zone 1 implies loss of power supply to the loads. Since the current and voltage magnitudes are already monitored in the Tesla Inverter, no further sensing is required to clear faults in Zone 1.

Low Impedance Fault in Zone 2

Zone 2 is the area downstream from CB2, and a fault here should be cleared therefore by opening CB2. Any fault in Zone 2 is theoretically easy to handle. Since this area comprehends the connection between the Solar Inverter(s) and the main distribution busbar, the power should always flow in the direction of the busbar. If reverse power is detected through CB2, the breaker should trip immediately since this would mean that there is a fault downstream from CB2. This can be implemented either by installing Current Transformers close to CB2 that communicate the current direction to a relay, or by including reverse power detection capabilities in the circuit breaker on position CB2.

Note that by tripping CB2 the loads can still be powered from the battery system, so it does not create a blackout situation for the customer. The directional protection is enough to clear faults in Zone 2. Therefore, no further current and voltage sensing is required in this area.

Low Impedance Fault in Zone 3

Zone 3 is the area between CB3 and the load breakers downstream in the customer area. In this small system, it would be enough to trip CB1 to clear any fault, no matter the location, since this will cause the power flow to stop as explained before. However, it is desired to isolate the fault as much as possible and eventually to keep charging the battery with the PV system in case there was a fault downstream from CB3. This will only be possible if the PV and battery are sized accordingly, which will be an assumption for this research.

It is then established that a fault in Zone 3 should be cleared by opening CB3. Since a Low Impedance Fault might not create current enough to trip the breakers, current measurement will be combined with voltage measurement to determine fault conditions. The breaker will be opened when the voltage coils measure an Undervoltage of 0.75pu or less, combined with Phase, Negative-Sequence and Ground Overcurrent. A delay should be included as well to prevent nuisance tripping during temporary overloads due to motor startup at the load side, and to ensure the smaller load breakers trip faster than CB3 for faults downstream.

6.2.2. High Impedance Faults

The detection and handling of High Impedance Faults is still an issue in the protection field, as explained in 2.3.2. The proposal chosen here is inspired by the research in [38] and summarized in section 4.3 of this document. The basic concept from this research is based on the fact that the Total Harmonic Distortion at the exit of an inverter source will be increased when a Phase to Phase fault happens. The Tesla Inverter has been tested and guarantees that the output current harmonics are less than 3%. According to the research in [39], the harmonic distortion increases to a value between 3.4% and 9%. The proposal is to force the Tesla Inverter to trip when the harmonic distortion is higher than 3.1%.

Note that this is a theoretical recommendation, and it will not be implemented in the simulations presented later, since it is out of the scope of this research.

6.3. Customer Area

The customer area is downstream from CB4, CB5 and CB6, as shown in **Figure 6-1**. It is assumed that everyone can access this area, even people without proper electrical training or without wearing Personal Protective Equipment. The handling of faults is therefore different than in the AC Distribution Area.

6.3.1. Low Impedance Faults

The issues with reduced fault current coming from the inverter based sources are less significant here. This can be easily understood by looking at **Figure 6-2**, that shows an example of a load distribution downstream from CB4. The rating of the circuit breakers will be lower as they are placed downstream of the main load breaker. This ensures they will trip on overcurrent protection whenever there is a fault, since the 1.2pu fault current coming from the sources is above their rating. In the example, the current of the battery system under normal operating conditions is 80Afor maximum load, which means the fault current would be around 96A. This would trip the 16A breaker at fault location in a very short period of time, and the 50A breaker would also trip with a small delay compared to the 16A breaker if the fault current persists

Note that the most common faults in areas with general access are single phase to ground. This type of faults create a ground current, which will cause CB3 to trip under 50G condition in case the smaller breakers are unable to detect the fault. It is desired always to clear a fault with the breaker closer to it that isolates the rest of the system. In order to do this, the tripping of CB3 will be set with a higher time delay than the smaller breakers downstream.

Issues with low fault current arise when the fault happens close to the main load breaker, which is part of the AC Distribution Area and therefore is handled as explained in **6.2.1.** The inclusion of Residual Current Devices is also highly recommended in this area, as explained later in **6.5.**

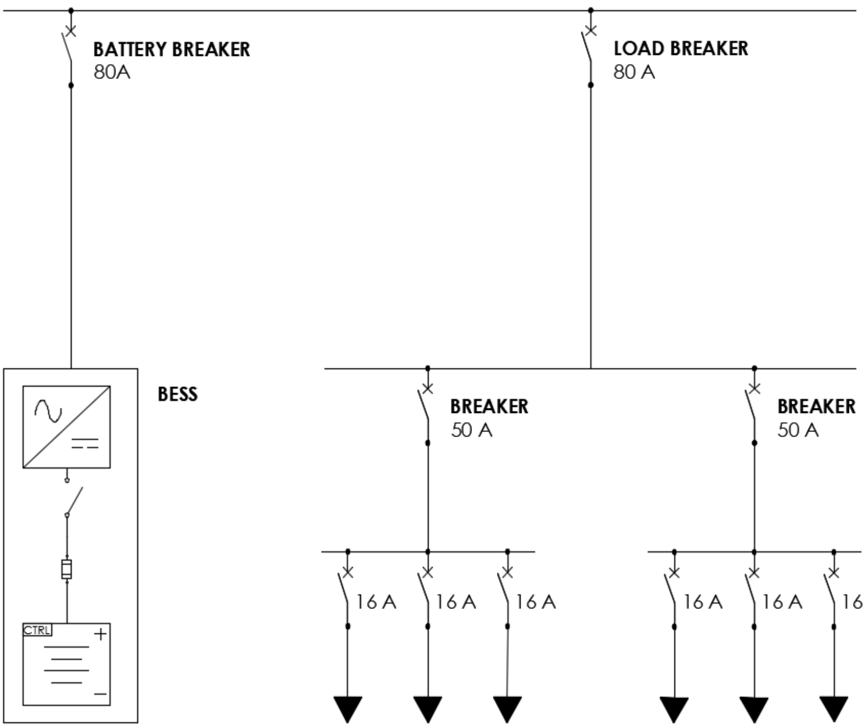

Figure *6-2*: Schematics of an example for load distribution with standard sizing of circuit breakers.

6.3.2. High Impedance Faults

Relay manufacturers have started including High Impedance Fault detection as a feature in their products, and nowadays it is available in some advanced protection devices, in some cases under the name of Arc Sense Technology [42]. The most common cause of High Impedance faults is a downed conductor in an overhead distribution line. The system analyzed here is of small size, and it is common in this type of microgrids to have the power generation and the loads close together and connected through underground cables. This reduces considerably the chance of High Impedance Faults, however, a possible solution is proposed since they could still be hazardous to people and equipment if they persist for a long time undetected.

This protection scheme suggests to deal with High Impedance Faults in the Customer Area by including a relay with this capability, like the SEL-751 from Schweitzer Engineering Laboratories. The SEL-751 High Impedance Fault detection is based on odd-harmonics and inter-harmonics [43], and implements logical functions to differentiate between High Impedance Fault conditions and other system operation such as switching and noisy loads that could also cause harmonic contents to be increased. Their method is explained in detail in [44].

6.3.3. Overload

The concept of overload is explained in **2.3.2**. An overload is caused when the load exceeds the nominal value for a period of time. It can either be temporary due to inrush currents during the start-up of devices or an electrical fault if it persists for a longer time. A temporary overload is not considered a fault, and it is therefore important to discriminate between those two situations. The protection systems should not trip when there is a temporary overload, since the electrical devices are sized with some margin to allow some current over the nominal for a short period of time, but it should trip under overload fault, since allowing it to continue is dangerous for equipment or people.

According to its datasheet, the Tesla Inverter has an overload capability of 120% nameplate power for 10 seconds. This means, that it will produce a current of 1.2pu for a maximum time of 10 seconds before shutting down. The inrush currents during devices start-up do not usually exceed a duration of 1 second, as shown in **Figure 6-3**. This makes the discrimination between inrush currents and overload fault relatively easy. It will be assumed when measuring a stable current of 1.2pu for longer than 3 seconds that there is an overload fault, and CB3 should be opened to clear it.

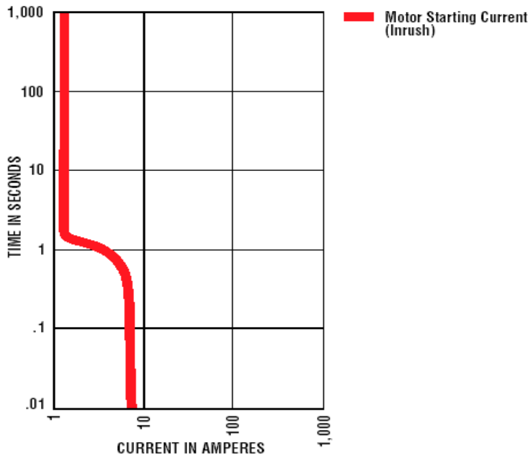

Figure *6-3*: Inrush current of an AC motor depending on time since start-up. **Source:** [19]

6.4. Measurement position

Relays have usually a limited number of current and voltage inputs. In order to increase discrimination and ensure only the smallest part of the system is isolated in the case of fault, it has been carefully considered where the best place is to place the current and voltage measurement points, trying to keep it to a minimum to reduce cost and number of required devices.

Given the small size of the system and that there is only one voltage level, it is possible to achieve discrimination with just one point of current measurement and one point of voltage measurement. It is decided to place the current transformers directly downstream from CB3, and the voltage measurement at the main distribution busbar, between CB2 and CB3. This allows fault discrimination by implementing simple logical conditions into the relay, as explained later in **Chapter 7**. The position of the current and voltage measurement is shown in **Figure 6-4**. Note that by measuring current and voltage at different points of the system there will be some deviation the accuracy of the power measured. This is not a concern in this scope of research, since the priority is protection and not the analysis of the power quality.

6.5. Grounding Scheme

The theory of grounding is explained in **2.3.3**, as well as the different standard grounding schemes according to IEC 60364. Basically, the purpose of grounding is to provide a low resistance path for the current to flow back to the source through the earth instead of it flowing through someone that would touch an energized surface. This is achieved by ensuring there is a continuous connection to the ground busbar (PE). Due to the small size of the system and the fact that it is a low-voltage network, the grounding strategy is significantly simplified compared to complex medium voltage microgrids.

The system is grounded according to a TN-S scheme. The solar inverter and the battery inverter are grounded directly via one or more rods in the earth. Tesla also requires all enclosure parts, wireway and support platforms for its equipment to be directly grounded. The loads could also be grounded independently, if positioned far from the BESS. There is only one Neutral-Earth bond, which is made directly at the AC Distribution panelboard. This is shown in **Figure 6-4**. This figure can also be found in the **Appendix** with better resolution.

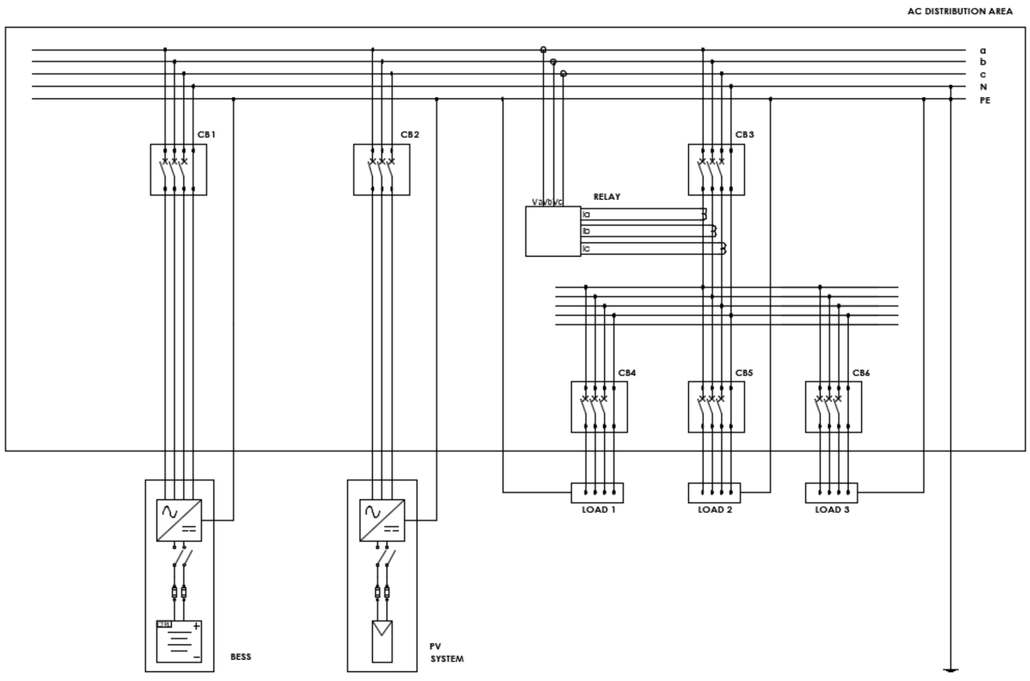

Figure *6-4*: Detailed diagram showing grounding and measurement positions.

6.6. Additional Protection Devices

In addition to the protection strategies explained in the previous sections, there are some extra devices that need to be installed in order to complete the scheme.

6.6.1. Residual Current Devices

Residual Current Devices, known commonly as RCDs, are introduced in **2.3.4**. They are connected between the phases and neutral, and trip the circuit if the current flowing through the phases is not equal to the current in the neutral. They protect people that accidentally come in contact with something at a different potential than the ground from getting an electrical shock.

The proposal is to install RCDs downstream from the three small load breakers, where it is most probable that someone could come in contact with an energized piece of the system. Note that CB4, CB5 and CB6 should trip anyway if there was a fault downstream from them, but the RCDs add an extra layer of protection for people and redundancy to the system. It would also be possible to install a bigger RCD at the main busbar to protect technicians performing maintenance on the AC Panelboard.

6.6.2. Surge Protection Device

Surge Protection Devices (SPD), as explained in **2.3.4**, protect electrical equipment against transient overvoltages originated by a lightning discharge, equipment malfunction or simply by switching power sources. They do not interrupt the power supply, but they provide an alternative path to excessive currents to limit their damaging effect. SPDs can be classified in Type 1, Type 2 and Type 3, or a combination of those, depending on the characteristics of the system. Type 1 devices protect against direct lightning discharge. Type 2 prevents the spread of overvoltages. Type 3 has a lower discharge capability and is usually installed as a supplement to Type 2 for specially sensitive loads [45].

In this case of small off-grid system, it is recommended to include a Type 1 and 2 Surge Protection Device connected in parallel at the main distribution busbar in the AC Panelboard, as shown in Error! Reference source not found.. Depending on the location of the microgrid and the nature of the loads, an extra SPD Type 2 and 3 could be installed close to the loads, if deemed necessary after analysis of the system. This last addition will not be considered in this research.

Chapter 7. **Practical Implementation Proposal**

This chapter presents a detailed protection scheme based on the protection philosophy introduced in **Chapter 6.** A single line diagram is included, in order to illustrate the way devices are interconnected between them and within the system. Specific devices available in the market are chosen and their settings are specified as well. Note that there are other available options in the market that would be equally valid but are out of the scope of this research.

For standardization purposes, the current sizing shown in the Single Line Diagram of **Figure 7-1** is considered. The nominal operating voltage is 400V. This can be scaled to higher current ratings depending on the load requirements.

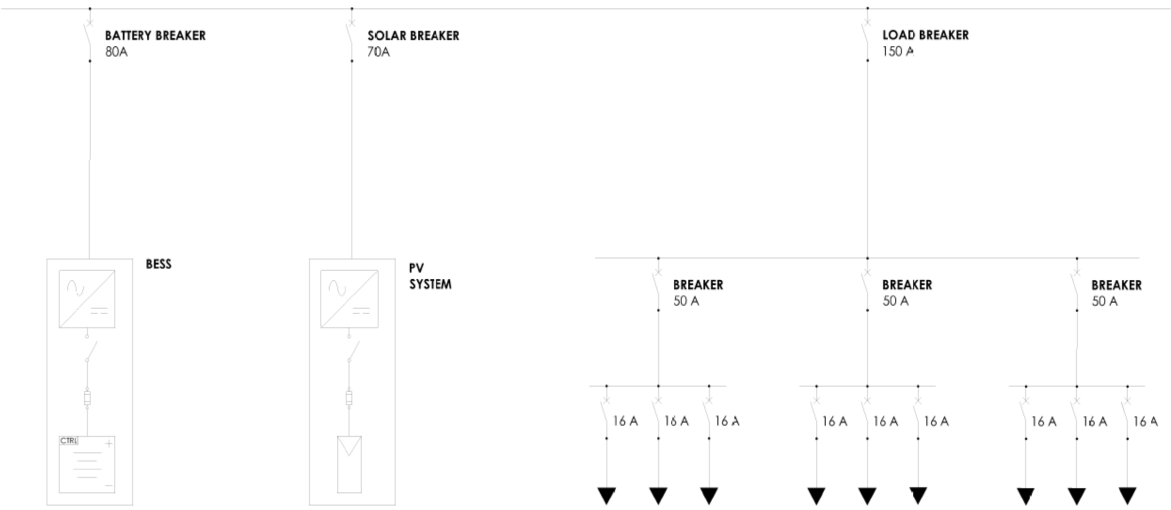

Figure *7-1*: Standard case of current rating for protection devices.

7.1. Proposed Scheme – Relay Based

The basic scheme proposed is based on a programmable relay with multiple protection features. This relay controls the circuit breakers CB1 and CB3 placed at the battery and load positions respectively. The load breakers downstream from CB3, the main load breaker of 150A, are regular thermal-magnetic circuit breakers in which the thermal trip protects against overload and the magnetic trip protects against short-circuit. It is considered that controlling CB1 and CB3 allows for enough selectivity and discrimination. The strategy for opening the solar breaker CB2 will be addressed at the end of the coming section.

7.1.1. Device Selection

This section proposes concrete protection devices for every position. These devices are commercially available and would be adequate for the requirements of the protection scheme. **Table 3** shows the specific devices proposed for the system size shown in **Figure 7-1**.

The programmable relay that has all functions required and has been chosen as the best fit for the system in this research is the SEL-751 Feeder Protection Relay manufactured by Schweitzer Engineering Laboratories [46]. **Figure 7-2** shows the different input configurations available for the SEL-751. Since both current and voltage measurements are needed, the first option (Base SEL-751 AC Currents Only) would not be suitable. LEA stands here for Low-Energy Analog Voltage Inputs up to 8V, which is insufficient for this system since the nominal voltage measurements are 400V, so the third and fifth options are also discarded. The choice lays therefore between the second and fourth option. The difference between them is the capability of High Impedance Faults detection. It is recommended to include this capability, therefore the recommended option is the fourth one in **Figure 7-2**.

Model Description	Slot Z Card Option (MOT String Digital Number 14, 15)	Slot Z Inputs	Slot E Card Option (MOT String Digits Number 12, 13)	Slot E Inputs
Base SEL-751 AC Currents Only	4 ACI (A1, A2, A3, A5, A6, A7)	IA, IB, IC, IN	None (0X)	None
SEL-751 With AC Voltages (300 Vac)	4 ACI/3 AVI (81, 82, 83, 85, 86, 87)	IA, IB, IC, IN, VA, VB, VC	None (0X)	None
SEL-751 With LEA AC Voltages (8 Vac)	4 ACI/3 AVI (L1, L2, L3, L5, L6, L7)	IA, IB, IC, IN, VA, VB, VC	None (0X)	None
SEL-751 With AC Phase Voltages (300 Vac), Vsync (300 Vac), Vbat (300 V) Input, and 4 Arc-Flash Detections Inputs	4 ACI/3 AVI (81, 82, 83, 85, 86, 87)	IA, IB, IC, IN, VA, VB, VC	2 AVI/4 AFDI (70)	VS, VBAT, AF1, AF2, AF3, AF4
SEL-751 With LEA AC Phase Voltages (8 Vac), LEA Vsync (8 Vac), Vbat (300 V) Input, and 4 Arc-Flash Detection Inputs	4 ACI/3 AVI (L1, L2, L3, L5, L6, L7)	IA, IB, IC, IN, VA, VB, VC	2 AVI/4 AFDI (L0)	VS, VBAT, AF1, AF2, AF3, AF4

Figure *7-2***:** Current (ACI) and Voltage (AVI) input options for SEL-751 models. **Source:** [46]

The proposed circuit breakers for the battery and load positions are manufactured by Schneider Electric. CB1 and CB3 are controlled by the SEL-751 relay, and will be tripped via simple trip shunt coils. The proposed circuit breakers for the downstream part of the load distribution (CB4, CB5 and CB6) are also manufactured by Schneider Electric. The proposed device for CB2 is manufactured by ABB and the choice for it is explained later in this section. The protection scheme includes as well a Type 1+2 SPD, in accordance with **6.6.2**, also manufactured by Schneider Electric.

Table 3: Device selection for the relay-based protection scheme.

Device Number	Description	Model	Manufacturer
Relay	Programmable Relay	SEL-751	*Schweitzer Engineering Laboratories*
CB1	Battery Breaker	NSX100	*Schneider Electric*
CB2	Solar Breaker	SACE Emax	*ABB*
CB3	Main Load Breaker	NSX160	*Schneider Electric*
CB4	Load 1 Breaker	NSX80	*Schneider Electric*
CB5	Load 2 Breaker	NSX80	*Schneider Electric*
CB6	Load 3 Breaker	NSX80	*Schneider Electric*
SPD	Surge Protection Device	PRD1 25r	*Schneider Electric*

Note on the strategy for the Solar Breaker

Two different options were addressed in 6.2.1 for operating the Solar Breaker, CB2, when there is a fault in Zone 2. The majority of solar inverters will detect current flowing in reverse direction and stop producing power anyway. However, the Tesla BESS would continue to feed fault current if Zone 2 is not isolated, therefore the need of tripping CB2.

The protection philosophy for tripping this breaker is quite straightforward. It should be tripped whenever a current is detected flowing to the solar inverters instead of to the load, since this would mean that there is a fault in Zone 2. There are two options for achieving this, either it can be detected by a relay or by the circuit breaker itself.

Option 1 – Relay

There are a number of relays available in the market that include protection function 67, directional power. The SEL-751 also includes this function, but doesn't have enough current inputs to allow current measurement in Zone 2. This means an extra relay would need to be included just for this directional function. In this case, it is not needed to have such an advanced relay as the SEL-751, but a simpler option including function 32 would be sufficient. An example of this is the MiCOM series 20 P127, manufactured by Schneider Electric. Other example is the SPAS348CAA361 from ABB or the DFP100 from General Electric.

Option 2 – Circuit Breaker

There are also some circuit breakers that can trip on directional overcurrent by adding an electronic trip unit to them. This way, no external relay would be needed. One example of this is the SACE Emax line of Low Voltage Circuit Breakers from ABB with electronic trip unit PR123 [47]. This will be the option recommended since it is a more compact solution that only requires once device and no external current measurement.

7.1.2. Single Line Diagram

The single line diagram showing the connection of the protective devices within the AC Panelboard is shown in **Figure 7-3**. The relay has inputs from the current and voltage transformers, and controls via digital outputs the opening via shunt trip of breakers CB1 and CB3.

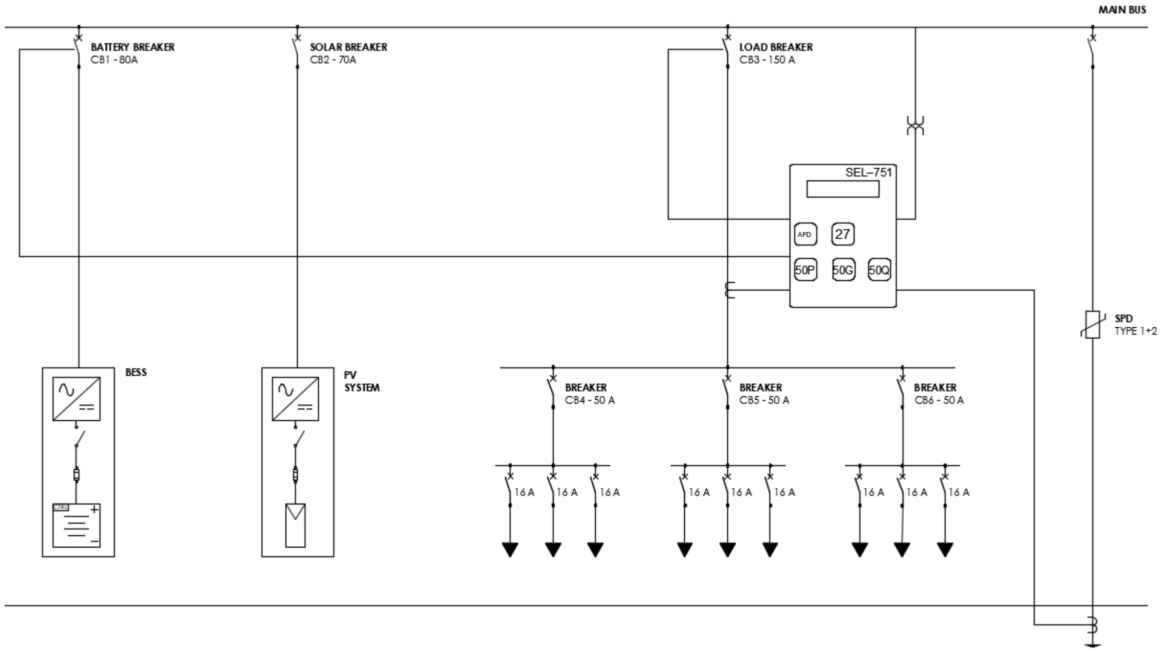

Figure *7-3*: Single Line Diagram including protection devices.

7.1.3. Relay Logic

The relay will open CB1 or CB3 according to the logical conditions presented in Equations 3 and 4. These can be programmed in the Software from the SEL-751. The relay functions available in the SEL-751 that consist the base of the protection philosophy for this case are Undervoltage (27), Instantaneous Overcurrent (50) and Arc-Flash Detection. In the equations below, 50Q refers to Negative-Sequence Overcurrent, 50G refers to Ground Overcurrent and 50P refers to Phase Overcurrent. The settings for each function will be specified later, based on the simulations results.

$$\text{IF } [(27) \text{ AND } (50P)] \rightarrow \text{OPEN } (CB3) \qquad \text{Equation 7-1}$$

$$\text{IF } [((27) \text{ AND } [(50G) \text{ OR } (50Q)]] \rightarrow \text{OPEN } (CB1) \qquad \text{Equation 7-2}$$

This logic functions add selectivity to the protection scheme. When there is a fault in Zone 3, the conditions in **Equation 7-1** are satisfied and CB3 is opened, which allows the battery to still be charged by the solar system until the fault is cleared. When there is a fault in the main distribution busbar, the conditions in **Equation 7-2** are satisfied and CB1 will he opened. The reason for also opening CB2 is to ensure the solar system does not continue to feed fault current. The solar inverters would detect loss of grid when CB1 is opened and switch off with their anti-islanding option anyway, but CB2 is opened as a backup protection measure.

Chapter 8. Simulations

The software utilized, *PowerFactory*, allows not only load-flow and short-circuit calculations as explained in Chapter 5, but also the integration of protective devices into the system to define the protection scheme. The relay based scheme proposed in **Chapter 7** has been implemented in the Network Model created, and the results of the simulations are explained in this chapter. These results are also used to establish the tripping settings for the SEL-751 relay.

8.1. Normal Operating Conditions

The operating point of the system under nominal conditions is obtained via the Load Flow simulations. The values shown by this calculation are used to determine the settings for the protection devices. The results for the Load Flow simulation in *PowerFactory* are shown in **Figure 8-1**, for the case of maximum load power requirement, 90kW.

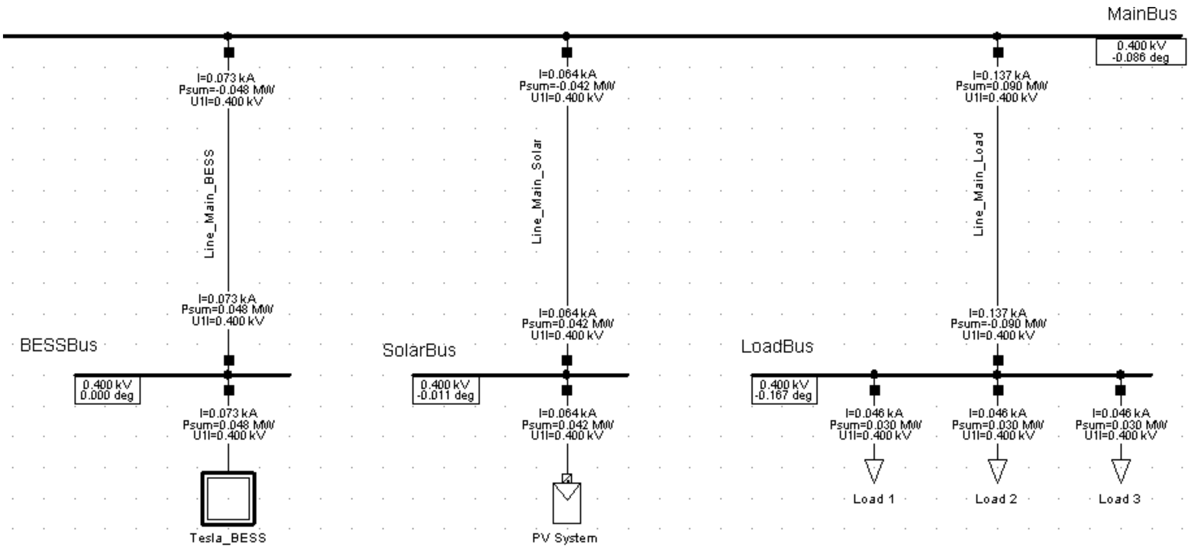

Figure *8-1*: Load Flow simulation for maximum load case.

The current and power values obtained from the Load Flow simulations at maximum load and 80% load are summarized in **Table 4** for the relevant elements in the system.

Table 4: Summary of results for load flow simulations at two different operating conditions.

Element	*Total Load 90kW*		*Total Load 72kW*	
	I [A]	**P [kW]**	**I [A]**	**P [kW]**
BESS Bus	73	48	49	32
Solar Bus	64	42	60	40
Load Bus	137	90	109	72
Load 1	46	30	36	24
Load 2	46	30	36	24
Load 3	46	30	36	24

8.2. Fault Conditions

Several fault types at different locations of the system have been simulated in order to determine the adequate logic and settings of the protection relay. The following assumptions and conditions have been implemented in order to reduce the amount of displayed data but keep a good overview on how the system reacts to fault conditions:

- Only the cases that represent realistic and relevant faults have results shown in **Table 5**[4].
- The color code on the fault column corresponds to a rough estimation on the likelihood of the fault happening taking into account the type of system being analyzed. Red is the most likely to happen, followed by yellow. Faults marked in green are less likely to happen.
- The faults considered in the table below are only in the AC Distribution area, since the coordination with the customer area downstream is based on time delays and not on the logical functions from the relay.
- Within the distribution area, faults in zone 2 are not considered because they will be directly cleared by a directional element in CB2.
- The method used for the simulations in *PowerFactory* is the complete short-circuit.

The zone division is the same as defined in **Figure 6-1**. The current is measured directly downstream of CB3, and the voltage is measured at the main busbar. The results presented here show that the combination of undervoltage and negative sequence current measurement should be a valid method for detecting faults, as explained in **Chapter 6.** The total load is expressed in percentage from the maximum load, which is 90kW.

Note that the results presented in this section correspond to the fault levels if no protective devices would be installed. The solar branch is disconnected for these simulation results, since that provides the worst case scenario in terms of low current provided by the inverter sources. This means the available fault current is 1.2pu of the Tesla BESS nominal output current.

[4] I_1, I_2 and I_0 are the positive, negative and zero-sequence currents respectively. I_G is the ground current. U_A, U_B, U_C are the phase to ground voltages. u_1 is the positive sequence voltage in values per-unit.

Table 5: Fault magnitudes for different simulation scenarios.

Fault Zone	Fault Type	Resistance [Ω]	Load %	I [A]			U [pu][5]		
				I_1	I_2	I_G	u_A	u_B	u_C
0	Ph_A – GND	0	100	96	27	77	0.5	1.05	1.05
0	**Ph_A – GND**	**0**	**80**	**96**	**25**	**70**	**0.45**	**1.1**	**1.1**
0	Ph_A – GND	0	50	96	20	53	0.36	1.2	1.2
1	Ph_A – GND	0	100	96	27	77	0.5	1.05	1.05
1	**Ph_A – GND**	**0**	**80**	**96**	**25**	**70**	**0.45**	**1.1**	**1.1**
3	Ph_A – GND	0	100	96	0	0	0.5	1.05	1.05
3	**Ph_A – GND**	**0**	**80**	**96**	**0**	**0**	**0.45**	**1**	**1**
3	Ph_A – GND	0	50	96	0	0	0.36	1.2	1.2
0	$Ph_{A,B}$ – GND	0	80	96	27	76	1.2	0.45	0.45
3	$Ph_{A,B}$ – GND	0	80	96	0	0	1.2	0.5	0.5
0	$Ph_{A,B,C}$ – N – GND	0	100	96	0	0	0.53	0.53	0.53
0	$Ph_{A,B,C}$ – N – GND	0	80	96	0	0	0.53	0.53	0.53
3	$Ph_{A,B,C}$ – N – GND	0	100	96	0	0	0.53	0.53	0.53
3	$Ph_{A,B,C}$ – N – GND	0	80	96	0	0	0.53	0.53	0.53
0	$Ph_{A,B,C}$	0	80	96	0	0	0.53	0.53	0.53
3	$Ph_{A,B,C}$	0	80	96	0	0	0.53	0.53	0.53
0	Ph_A – N – GND	0	80	96	27	76	0.50	1.05	1.05
3	Ph_A – N – GND	0	80	96	0	0	0.50	1.05	1.05
0	$Ph_{A,B}$	0	100	96	51	0	1.21	0.57	0.74
0	$Ph_{A,B}$	0	80	96	56	0	1.12	0.54	0.72
1	$Ph_{A,B}$	0	80	96	56	0	1.12	0.54	0.72
3	$Ph_{A,B}$	0	80	96	0	0	1.12	0.54	0.72
0	Ph_A – GND	500	100	96	0	0	1	1	1
0	Ph_A – GND	1000	80	96	0	4.4	1	1	1
3	Ph_A – GND	1000	80	96	0	4.4	1	1	1
3	Ph_A – GND	2000	80	96	0	4.4	1	1	1

[5] The base for voltage magnitudes is 230/400V. The voltage is shown in pu because the small size of the system makes it quite constant at all locations under nominal conditions
The currents are shown in A instead of pu to provide a better understanding on current levels during fault.

8.3. Relay Settings

The SEL-751 relay is programmed in PowerFactory with the logical functions explained in **Chapter 7,** and with specific settings for every protection function based on the results from **Table 5.**

8.3.1. Relay Current Settings

The SEL-751 current and time delay settings are shown in **Table 6**. The current values are based on the results introduced in **Table 5.** The time setting is set to the minimal for the functions affecting the opening of CB1, since there is no reason to delay the opening of this breaker for faults in Zone 0 and Zone 1. The time delay for 50P is slightly delayed. The reason for this is to allow smaller breakers downstream of CB3 to open faster than CB3 if there would be a fault in their protected area. This delay also provides discrimination between CB1 and CB3 for fault situations satisfying all trip conditions. In this case, according to the simulations, the fault will most probably be located at Zone 0 or Zone 1 so opening CB1 faster is desired.

Table 6: Trip setting and time delay for relay functions.

Function	Description	Trip Setting	Time delay
50P	Phase Overcurrent	90A	0.003s
50G	Earth Overcurrent	0.8A	0.001s
50Q	Negative-Sequence Overcurrent	12A	0.001s
27P	Phase Undervoltage	0.75pu	0.001s

The trip curves of the relay are shown in **Figure 8-2**, with the Nominal Phase Current, Earth and Negative-sequence currents obtained via the Load Flow simulations for maximum load. Note that by looking at this graph, one might be under the impression that the phase current will cause nuisance tripping. To prevent this, the Undervoltage condition is implemented with an AND in the logical functions. This ensures that both conditions need to be present to trip CB3, which is not the case during normal operating conditions since the voltage is then around 1pu.

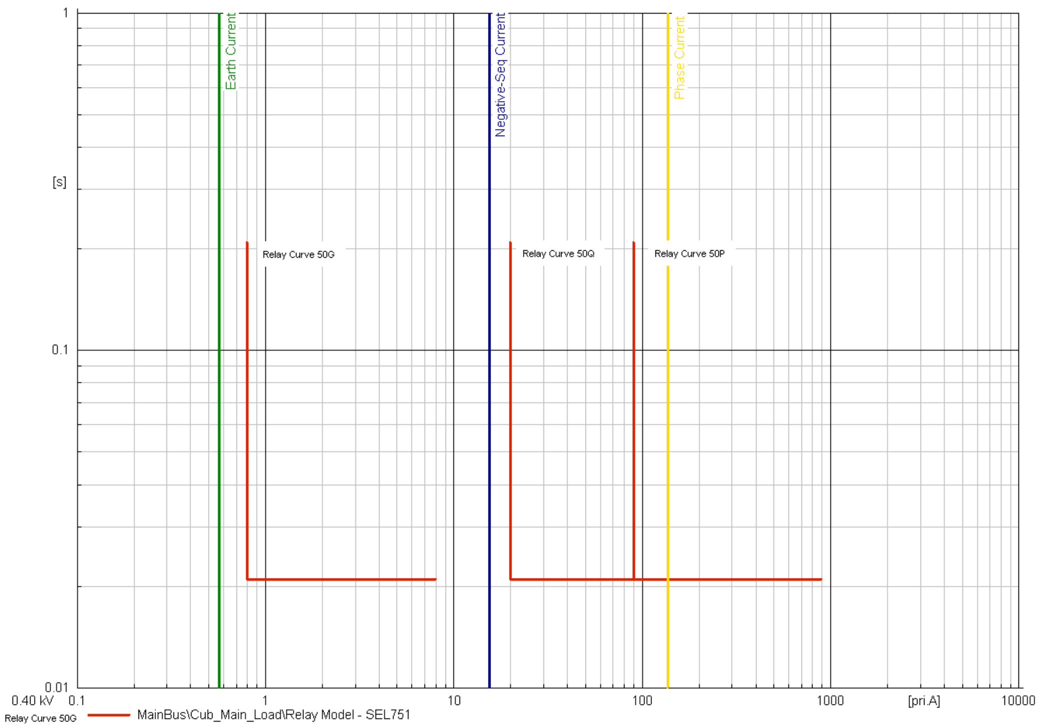

Figure *8-2*: Trip curves and Load Flow simulations.

8.3.2. Relay Logic Implementation

The logical conditions are implemented in *PowerFactory* as shown in **Table 7**. The discrimination for opening CB1 or CB3 is based on function 50P1, which corresponds to phase overcurrent. The setting for this function is 90A, which corresponds to 1.2pu of the Tesla BESS nominal output as shown in **Table 6**. If there is current of 1.2pu measured by the CTs, the fault must be downstream from CB3. If there is undercurrent measured by the CTs, the fault must be upstream, as explained in **Chapter 6.**

Table 7: Logical functions implemented in PowerFactory

Breaker	Logical Function	Equation in PowerFactory
CB1	$IF\ \left[\left((27)\ AND\ [(50G)\ OR\ (50Q)]\right]\right] \rightarrow OPEN\ (CB1)$	*yout = _27P1.and.(_50Q1.or._50G1)*
CB3	$IF\ [(27)\ AND\ (50P)] \rightarrow OPEN\ (CB3)$	*yout = _27P1.and._50P1*

An example of how the logic implementation looks like for CB3 in the simulation software can be seen below in **Figure 8-3**.

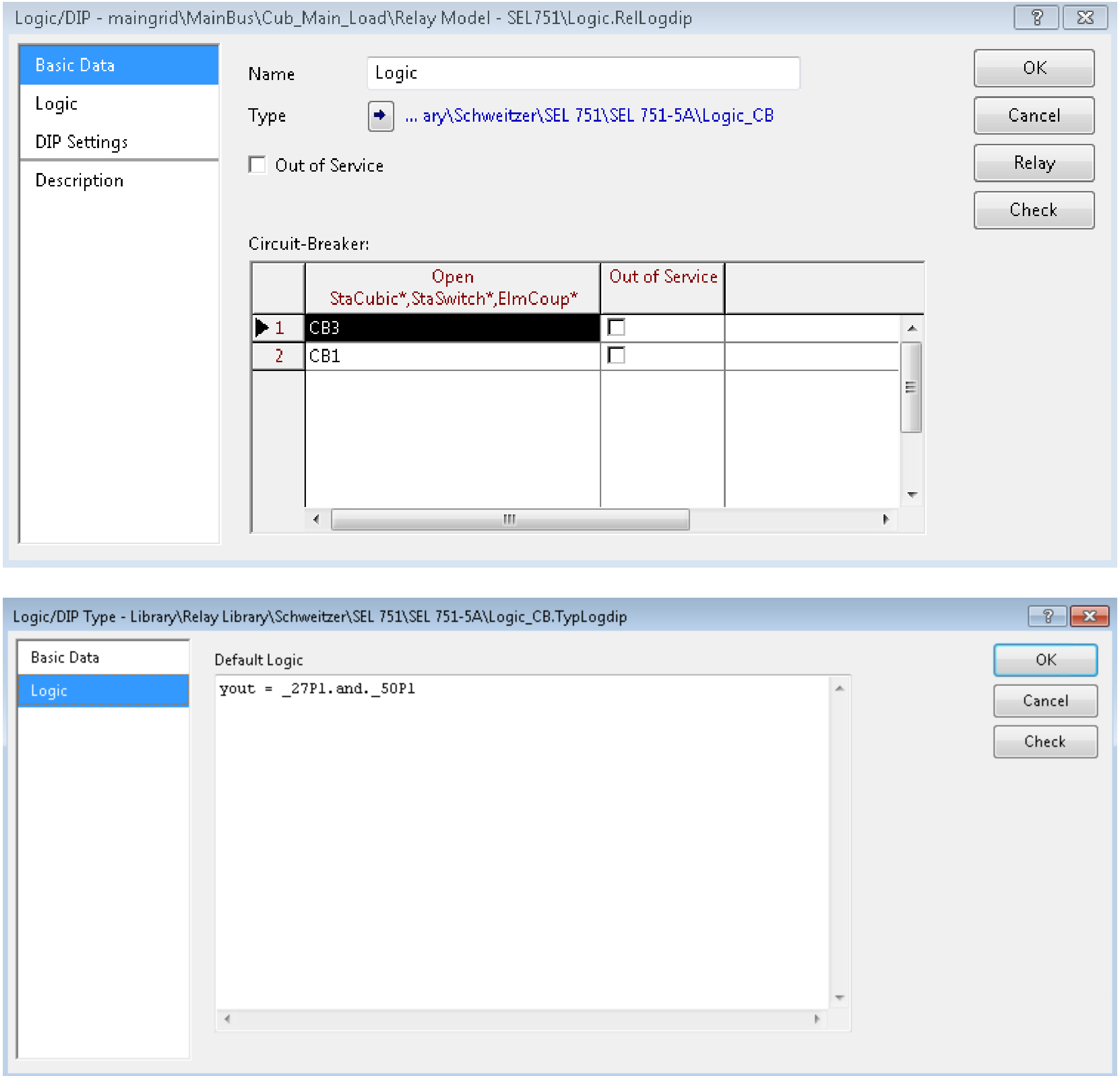

Figure 8-3: Logic implementation in PowerFactory for the main load breaker.

8.4. Tripping Analysis

The summary of which breaker will be tripped by the relay depending on the satisfied conditions is presented in **Table 8** for the same fault scenarios as presented in **Table 5**.

Two simulation results under no fault conditions are included as well for visibility. In order to show mostly relevant data, only the lowest voltage per phase is shown, since it will be the one causing the tripping on undervoltage. The results are satisfying for all Low Impedance Faults, since in all cases the desired breaker trips according to the logical functions.

The issue would appear, predictably, with High Impedance Faults. These will not be detected by the relay just by implementing the logical functions. It can be seen in the results that there will be a very small negative-sequence current created by these faults, so it would seem like a possible solution would be to lower the tripping current of function 50Q. This is not considered, since the negative-sequence current obtained is too low and setting the tripping limit to such a value would most probably cause nuisance tripping whenever the load is slightly unbalanced, which is not uncommon in this type of system. The SEL-751 has however High Impedance Fault detection features that are recommended to use to complement the protection scheme proposed in this research, in combination with harmonic detection at the Tesla inverter, as explained in previous sections.

Note that the results presented here are limited to faults happening in the AC Distribution area, since the focus of the logical functions is to discriminate the location of the fault and open the right breaker to isolate the smallest faulted area possible.

Table 8: Tripping analysis for different fault scenarios

Fault Zone	Fault Type	Resistance [Ω]	Load %	I [A]			Umin [pu]	Conditions satisfied	Breaker trip
				I_1	I_2	I_G			
-	No Fault	-	100	80	0	0	1	None	None
-	No Fault	-	80	64	0	0	1	None	None
0	Ph_A – GND	0	100	96	27	77	0.5	27, 50G, 50Q	CB1
0	Ph_A – GND	0	80	96	25	70	0.45	27, 50G, 50Q	CB1
0	Ph_A – GND	0	50	96	20	53	0.36	27, 50G, 50Q	CB1
1	Ph_A – GND	0	100	96	27	77	0.5	27, 50G, 50Q	CB1
1	Ph_A – GND	0	80	96	25	70	0.45	27, 50G, 50Q	CB1
3	Ph_A – GND	0	100	96	0	0	0.5	27, 50P	CB3
3	Ph_A – GND	0	80	96	0	0	0.45	27, 50P	CB3
3	Ph_A – GND	0	50	96	0	0	0.36	27, 50P	CB3
0	$Ph_{A,B}$ – GND	0	80	96	27	76	0.45	27, 50G, 50Q	CB1
3	$Ph_{A,B}$ – GND	0	80	96	0	0	0.5	27, 50P	CB3
0	$Ph_{A,B,C}$ – N – GND	0	100	96	0	0	0.53	27, 50P	CB3
0	$Ph_{A,B,C}$ – N – GND	0	80	96	0	0	0.53	27, 50P	CB3
3	$Ph_{A,B,C}$ – N – GND	0	100	96	0	0	0.53	27, 50P	CB3
3	$Ph_{A,B,C}$ – N – GND	0	80	96	0	0	0.53	27, 50P	CB3
0	$Ph_{A,B,C}$	0	80	96	0	0	0.53	27, 50P	CB3
3	$Ph_{A,B,C}$	0	80	96	0	0	0.53	27, 50P	CB3
0	Ph_A – N – GND	0	80	96	27	76	0.50	27, 50G, 50Q	CB1
3	Ph_A – N – GND	0	80	96	0	0	0.50	27, 50P	CB3
0	$Ph_{A,B}$	0	100	96	51	0	0.57	27, 50Q	CB1
0	$Ph_{A,B}$	0	80	96	56	0	0.54	27, 50Q	CB1
1	$Ph_{A,B}$	0	80	96	56	0	0.54	27, 50Q	CB1
3	$Ph_{A,B}$	0	80	96	0	0	0.54	27, 50P	CB3
0	Ph_A – GND	500	100	80	0	0	1	None	None
0	Ph_A – GND	1000	80	80	0	4.4	1	None	None
3	Ph_A – GND	1000	80	80	0	4.4	1	None	None
3	Ph_A – GND	2000	80	80	0	4.4	1	None	None

Chapter 9. Model Limitations and Future Research

The simulations performed show satisfactory results. The system behaves as expected during fault conditions and the relay is expected to trip accordingly. The simulations provide as well valid criteria for selecting the tripping settings of the relay. These settings are chosen accounting for the requirements of the network in terms of current and voltage levels. There are, however, some limitations in the model and the proposed solution that need to be acknowledged.

First, the content of this research is highly theoretical, no real life testing has been performed to validate the behavior of the relay. This is mainly due to the limited resources and scope of work for this project. In order to properly test the relay, an off-grid microgrid setup would be needed in which it is possible and safe to create real fault conditions. However, there is some validation of the model thanks to the simulations in PowerFactory, which gives grounds to recommend building this test set-up for further research.

Second, the logic proposed is not valid for detecting High Impedance Faults. There are two solutions proposed for this, depending on the location of the fault, either implement harmonic detection at the Tesla Inverter level or rely in the High Impedance Fault detection capability of the SEL-751. This capability of the relay has not been simulated due to license limitations with PowerFactory, so the recommendation to include it is based solely on the datasheet from the product provided by Schweitzer Engineering Laboratories. With grounds on the research performed, further investigation on the harmonic detection at inverter level has been proposed to Tesla as a new feature for their product.

Third, the simulations are based on a grid-forming model of the Tesla Inverter, which is the generation device in charge of forming the grid. This model of the Tesla Inverter has not been created by the author of this research, but developed internally by Tesla resources due to time limitations. The model is quite complex and is still under validation with real data from the Tesla Inverter, even if it is considered reliable enough for the purpose of this research. This might lead to some inconsistencies between the behavior of the real product and the results obtained in the simulations. The author is confident that any deviances would not make a difference in the behavior of the relay under fault conditions.

Finally, only one proposal has been reflected in this document, but there could be other valid solutions. Concretely, the author believes that a protection scheme based in LSIG tripping units at the circuit breakers might also work when adjusting the settings properly. This direction was explored at the beginning of research. It was concluded that a protection scheme based on circuit breakers with LSIG tripping units should still be enforced with undervoltage detection for reliability reasons. This can either be done by an undervoltage relay, or at inverter level. The solution proposed is believed to be more advanced and complete, and still includes the LSIG features at the programmable relay.

Chapter 10. Economic Analysis

The results presented are purely theoretical, however, this research is conducted in collaboration with Tesla with the purpose of finding a solution for actual protection issues that are affecting the deployment of real microgrid projects. Therefore, a brief economic analysis is included as well to provide an rough estimation on the cost of the protection scheme. Note that all prices included in Table 9 are an estimation and should in no case be considered as a real quote from the manufacturer or Tesla.

Table 9: Estimated price for different protection devices

Device	Model	Description	Price
Programmable Relay	SEL-751	*Programmable relay manufactured by SEL, with current and voltage inputs*	2500€
Programmable Relay	SEL-751	*Programmable relay manufactured by SEL, with current and voltage inputs, high impedance fault detection*	3200€
Directional Relay	DFP100	*Directional relay manufactured by General Electric*	2000€
Circuit Breaker (100A)	SACE Emax	*Circuit breaker from ABB with electronic trip unit for directional overcurrent function.*	8000€
Circuit Breaker (160A)	NSX160	*Circuit breaker from Schneider with incorporated RCBO, 160A rating.*	2000€
Circuit Breaker (100A)	NSX100	*Circuit breaker from Schneider, 100A rating.*	400€
Circuit Breaker (80A)	NSX80	*Circuit breaker from Schneider, 100A rating.*	300€
Circuit Breaker (16A)	NSXm E16	*Molded Case Circuit Breaker (MCCB), 16A rating*	100€
Current Transformer	AcuCT-200:5	*Rogowski coils, split core CTs, ratio 200:5A, maximum current 200A.*	50€
Surge Protection Device	PRD1 25r	*Type 1+2 Surge Protection Device*	400€

Guided by the price estimation in Table 9, it is possible to make a sensible decision depending on the requirements of the microgrid and the budget available. For example, if High Impedance Faults are frequent then it is recommended to choose the most expensive option for the SEL-751 and have the feature for detecting them. If this type of faults is not expected, or the final customer does not want to incur in extra costs to prevent them, then the cheaper option would be the chosen one. Regarding the solar breaker, it will be more cost effective to choose for the relay option, even with the added cost of a simple circuit breaker and the current transformers.

Chapter 11. Summary and Final Conclusions

Microgrids are electricity distribution systems interconnecting loads and distributed energy resources that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded [1]. Due to the capacity of operating in islanded operation, microgrids are a powerful resource to mitigate the consequences of power outages. They also contribute on the integration of renewable sources.

Microgrids are therefore an attractive complement to the electrical infrastructure that is already being implemented worldwide. However, they present a number of challenges in their design, especially regarding control and protection strategies. The traditional grid was conceived for a unidirectional flow of power and was not designed to integrate intermittent energy sources like renewable energies. The generation of active power downstream creates a challenge for the existing infrastructure. Moreover, the protection scheme of the microgrid itself needs to respond to faults both in grid-connected and islanded mode, which are highly dependent on the DERs connected and operating at the moment the fault occurs. Inverter based power sources feed limited fault current, which leads to traditional overcurrent protection devices not protecting the microgrid accordingly. Therefore there is a need to investigate different solutions that could deal with this challenge [2].

One of the key contributors to the energy market in the past years is the company Tesla, founded in 2003 in California by a group of engineers who wanted to make better, faster and fun to drive electric cars [3]. Pursuing the mission to *accelerate the world's transition to sustainable energy*, the company has grown in the last years into the energy field. Currently, Tesla has solar products and three different stationary battery storage solutions in the market. In the past year alone, Tesla has deployed more than 1GWh of global storage capacity in Powerwall and Powerpack products, bringing the total of energy storage installed to more than 2GWh. This is expected to grow exponentially in the coming years, especially since the introduction of their new energy product, the Megapack [3].

The purpose of this report is to compile the research performed as a final thesis for the Master in Electrical Power Engineering of the Delft University of Technology on the topic Microgrid Protection. The research is conducted in collaboration with Tesla and applied to their industrial stationary storage product. Since the main challenges in protection appear in islanded operation with only inverter-based sources, this is the scope of work of this research. The final goal is to design a protection scheme that is compatible with any operation of the microgrid and ensures that both people and equipment are protected from faults, regardless of the location and nature of these. The protection system must be reliable, selective and cost-effective.

The protection scheme designed is based on a programmable relay, the SEL-751, incorporating logical functions for undervoltage and negative-sequence current detection. By placing current and voltage transformers at a predefined location in the system, discrimination and selectivity is achieved. The system is modelled in the software Power Factory from DIgSILENT, and several fault scenarios are simulated to show the correct tripping of the devices.

The analysis of the results obtained shows that the protection scheme is theoretically valid for a small off-grid microgrid with only inverter-based generation sources. Further research in implementing the protection logic to real sites and evaluating the response to fault conditions is necessary to validate the scheme.

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Appendix

The figure below shows the detailed schematics for the interconnection of the measurement devices and the connections to the ground busbar.