ENG470: Engineering Honours Thesis

Protection in Low Voltage DC Microgrids

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Abstract

Protection is an important aspect when designing a microgrid system, as it ensures the network is able to run safely. As the debate between AC vs. DC protection schemes continue, there appear to be distinct advantages and disadvantages on each side with respect to reliability, efficiency, security, environmental and economic concerns. In this thesis, a low voltage DC microgrid protection scheme used in a data center is proposed. The final goal of this project is to develop a network and perform a fault analysis study while investigating different aspects of power protection schemes. Research is done on different protection devices which will be used to protect their respective components.

Three types of faults will be tested on the system for fault current observation purposes. In order to calculate the theoretical fault current of the battery and converter, Microsoft Excel will be used. ICAPS by Intusoft will be used to simulate three different faults in the network. Fault 1 will be on the positive and negative pole of the converter/battery and the load. Fault 2 is a double line to ground fault located on one of the feeders near the load. Fault 3 is a single line to ground impedance located on one of the positive pole of the feeder with a high impedance.

Results show that there are commercial devices available to protect components in such a system. Ultra hybrid DC circuit breakers are used to protect the converter, Molded Case Circuit Breakers are used for feeder protection, and lastly fuses or circuit breakers can be used for battery protection.

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Glossary

LVDC	**Low Voltage Direct Current**
DC	Direct Current
AC	Alternating Current
CERTS	Consortium for Electric Reliability Technology Solutions
PCC	Point of Common Coupling
LVAC	Low Voltage Alternating Current
HVDC	High Voltage Direct Current
MCCB	Molded-case Circuit Breakers
UPS	Uninterruptable Power Supply
IGBT	Insulated-Gate Bipolar Transistor
VSC	Voltage Source Converter
SMPS	Switched-Mode Power Supplies

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1. Introduction

For many decades, there has been an ongoing debate between AC and DC protection in microgrids. The idea of a protection scheme is concerned with protecting a system from transient faults during normal or islanding operations and also covering aspects faced by component protection used in microgrids such as converters, feeders, batteries and sources. DC microgrids are used in data centers, and has been gaining traction of late due to the system having less conversion which results in greater efficiency. However, as there are major advantages and disadvantages in both AC and DC systems, different types of protection strategies have been implemented throughout the years. The concept of DC microgrid protection was first introduced in the early 1990s and in Australia, there are a number of DC microgrids set up in remote areas for research and experimental purposes.

This thesis will compare the difference between AC and DC protection and ultimately focus on developing a protection scheme for a Low Voltage DC microgrid used in Data Centers. The goal of this thesis is to develop a protection scheme in order to perform different types of faults on the network. Early stages of this thesis will involve researching different types of protection schemes in order to model a network for a DC microgrid. Commonly used electrical components such as DC sources, batteries, converters and feeders will also be studied with respect to their behaviour during fault transients. The developed system will be based on a 2009 paper “Protection in LVDC Microgrids” [1]. Lastly, in order to have a reliable and safe DC protection scheme, technical challenges such as protection devices, coordination, fault detection and analysis will be addressed in this paper.

1.1 Thesis Schedule and Report Structure

This thesis was conducted over a period of seven months and separated into three categories of research, experimenting and report writing. In the first four months, heavy research was done on comparing AC vs. DC protection schemes and the concept of DC microgrid used in Data centers.

Subsequently, the following two months were spent on circuit modelling and fault analysis. Finally in the last month, information gathered from research and results was used in order to write this report.

This report has been broken down into a number of sections. Firstly, the project is introduced where the importance of this project is discussed along with aims, challenges and a brief literature review. The next section provides background information that is relevant to this project. This section comprises of background history and implementation of microgrids around the world, protection strategies in AC and DC microgrids, the concept of data centers and lastly the associated programs that are used in this project. Next, the methodology and result section consists of network modelling of the LVDC network and fault simulations. The second last section describes any future recommendations and improvements that can be done to the system. Finally, the last section summarizes the whole project and all outcomes are evaluated.

2. Literature Review

This section provides a review on the references which are important and relevant to this project. As many articles, websites and journal were used in this thesis, only key references will be discussed.

In terms of AC and DC distribution history, [2] presents the first DC distribution network was called the Pearl Street Generating Station, and describes the ongoing debate of AC vs. DC distribution. The first ever DC generating station was developed by Thomas Alva Edison on 4th of September 1882, it supplied power to customers within a 0.65km^2. In 2014, [3] reviews the different types of microgrid test beds used all over the world. Comparison was made between AC and DC microgrids with respect to control and protection strategies, system stability, efficiency and reliability of the both systems. Furthermore, advantages and disadvantages of both systems were realized while presenting technical challenges and opportunities faced in DC microgrids [4] [5].

The concept of a data center is introduced in [6] [7], it describes how DC microgrids are implemented in a data center and the reasons behind supporting the preference of using DC microgrids compared to AC. Technical challenges such as safety and reliability, protective devices and standards were also discussed. As results from the articles show that a DC network has higher efficiency and lower cost in the system, the LVDC microgrid for data center was chosen as a case study.

A low voltage DC microgrid for data centers has been presented in [1]. The protection scheme used in this thesis is derived from the network shown in this article. This article contains information regarding the different types of fault simulation that are tested on the system to observe the reaction of each component when experienced with fault transients. Key aspects such as grounding in a DC microgrid system and protection devices are also covered in this article.

As DC protection schemes being a fairly new concept, there are some uncertainties in some of the research papers used. This is due to some articles that appear to contradict each other and offering different outcomes based on the same concept.

3. Background

This section comprises relevant information and concepts implemented in this project based on research. This will allow readers to gain an understanding of the fundamental concepts used in this project.

3.1 History (DC and AC Distribution)

There has been a long relationship history between AC and DC Microgrids. Extensive research and experiments were done based on microgrids since the early 19th century. In 1882, it was Thomas Edison who successfully constructed his first power plant called the "Manhattan Pearl Street Station" [2]. Edison's plan was to supply incandescent lighting using a centralized power station. At the time, the concept of a centralized grid had not been introduced but Edison's power plant was essentially constructed as a Low Voltage DC Microgrid and it was the first of its kind. The initial Pearl Street Station project proved that there are huge benefits that lies in DC distributed generation and losses in terms of efficiency. It was not initially a financial success but was able to supply power to around 400 or more lamps that served fewer than 90 customers. Within a year, the power plant was further improved to be able to handle around 10,000 lamps serving up to 513 customers. For the next 10 years, the Manhattan Pearl Street Station Project served as a blueprint for LVDC microgrids and was licensed to be implemented in towns throughout Japan, Europe, North America and South America [8].

However in the 1980, the project was retired and later demolished due to major disadvantages in terms of system reliability. One of major issues experienced from the DC protection side of things were high losses in transmission lines, this was a key problem because DC systems could only be used in a relatively small area that has a high load density. So the longer the transmission lines, the higher the losses would be which will result in high cost maintenance [2].

Standards for proper protection were yet to be realized at that time so LVDC came to a halt. As a result, many other inventors such as William Stanley, Elihu Thomson and one of the most famous one, Nikola Tesla began to design an alternating current (AC) system to compete with Edison's design [2]. The concept presented by Tesla proved to solve the huge issue of large losses in long transmission lines by installing an AC transformer was more economical and efficient. By the end of the 19th century, AC systems became more popular while DC systems began to decline [2].

Back to the present day, AC systems are still the standard choice for commercial distribution since the 19th century. As the demand and supply of electricity grows exponentially each year, AC systems proved to be expensive to maintain. Factors such as global warming, increased number of DC loads and awareness that some energy resources can run out reveal that the conventional power system has to be redesigned. Today, DC distribution systems are used in industries such as avionics, marine, automotive and manufacturing. The types of loads that require DC power are computers, hospitals, commonly used electronic devices and data centers. This paper will focus on the main challenges associated with DC protection system used in a data center [4].

3.1.1 Microgrids around the World

Over the years, the microgrid has been of growing interest to researches and scientists around the world. This led to installation of microgrids all around the world. The objective of most of these experiments is related to the protection design, system reliability and islanding mode when the grid experiences a disturbance. A detailed summary of microgrid test beds used around the world is shown in the Appendix A [3].

In Japan, the focus of microgrid research over the years is optimization. The aim is to have optimal generation of renewable energy however; in making this decision, power quality is affected negatively. All the systems used in Japan run on AC and have centralized control. Wind and photovoltaic AC systems are most commonly used but they have an irregular nature which is susceptible to dangerous outages [3].

Global warming and climate change are both important factors in the European Union. Microgrids must meet certain requirements set by the European Parliament (2001/77/EC, 2003/30/EC and

2006/32/EC) [9] in decreasing the amount of carbon footprint emissions but at the same time increasing generation of renewable energy. Most of these microgrids are used in residential areas and uses a sophisticated storage unit system that is able to maintain power quality [3].

The most prominent United States microgrid is the Consortium for Electric Reliability Technology Solutions (CERTS). Aim of this project was to develop a concept so that it was easier to manage micro generators to feed the main grid [3]. Most of the microgrids used in North America appear to favour AC systems and the preferred control type is decentralized. Most of these systems are able to supply loads in residential and commercial areas [3].

There also have been a number of small microgrids set up in Asia, where they are commonly used in remote areas. The more favoured control method used in this region is centralized control [3].

There are a number of microgrid projects currently happening in Australia too. Most of them are located in Western Australia where the primary energy for distribution is wind power. These microgrids are located in very rural areas where there is a need during power outages. Some of these projects are in early development and for research purposes [3].

3.1.2 Data Centers

A data centre is essentially a physical facility housed with IT equipment which centralizes an organisation’s IT operations and equipment. They are crucial in housing a network’s most critical systems, which includes providing application service and management of different types of data processing, some of which include web hosting, intranet, internet, telecommunication, and information technology. As core systems are vital to ensuring the continuity of daily operations, it is therefore imperative for organizations to prioritise the security and reliability of their data centers and information. Furthermore, they should also be provided with redundant and uninterruptible power supply (UPS). This prevents the housing equipment from power transients and outages [10].

Ever since 2004, there has been ongoing investigation regarding the efficiency of a DC system used in a data center compared to an AC system. Results show that using a DC source has a lower lifetime cost is safer due to no harmonics, is more reliable and have a less up-front cost in production volume. The outline of the results can be found in [7] and it is concluded that efficiency can be improved by eliminating some of the AC/DC conversion by using a DC Source. In addition, results also show that using a DC system instead of AC can save up to 15% of the overall cost due to the simplification of a DC power distribution system [7] [6].

From 2014 to 2019, the growth rate of data center markets has been 9.3% annually [6]. By 2019, the data center markets are expected to be around US$22.73 billion [6]. Due to increasing demand for data centers to be installed around the world, newer grid infrastructures have to be explored. The cost of distributing power, cooling and energy consumption is approximately 31% of a data center’s overall monthly operating costs [6]. There are a few challenges in DC that has prevented researchers and engineers from adopting and implementing DC as part of a standard around the world [6]. These challenges will be expand in more detail in the section of Protection in Data Centers.

3.2 The Microgrid Concept

In order to fully understand the concepts of a microgrid, the main grid has to be understood. The main grid operates by connecting residential, commercial or industrial areas to a central power source and allows consumers to use electrical appliances. In an event of a crisis such as storms or power outages on the main grid, this means that consumers will be affected and the faulty part of the grid needs to be repaired. Due to this reasons, implementing a microgrid can help in reducing this problem [11].

The structure of the microgrid is very similar with respect to the main grid but operates at a smaller scale. It is a power distribution system which consists of electrical components such as distributed energy resources and loads. The type of distributed resources can be generators, batteries, and renewable energy like solar panels. The loads used in a microgrid system are generally electronic but in some cases, rotating or resistive loads are used instead. These components operate within the microgrid and only when required to [11] [12].

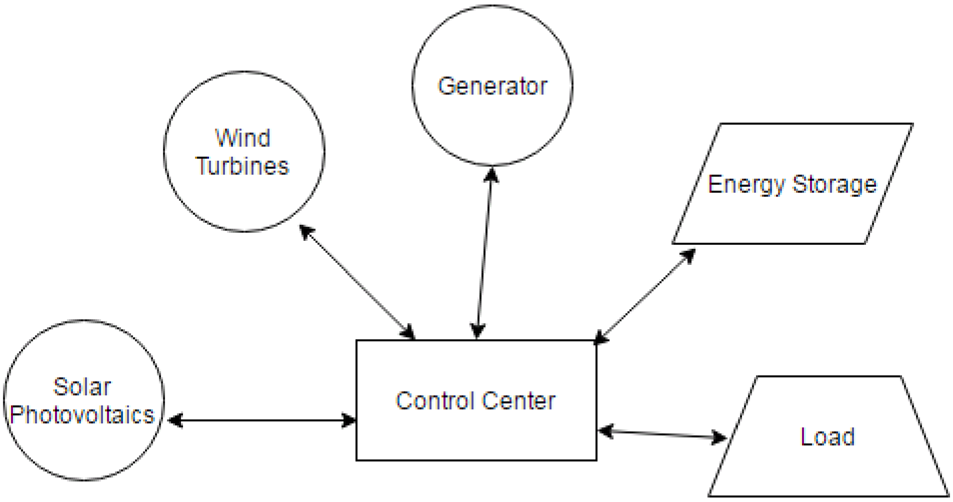

Figure 1 Structure of Microgrid [13]

Microgrids generally have two modes of operation, normal mode and islanding mode. During the normal operations, the main grid and microgrid are connected at a point of common coupling (PCC) in which the voltage from both grids are synchronized and maintained at the same magnitude.

Microgrids go into an islanding mode when there is a disturbance on the main grid. This disconnection and reconnection process happens at PCC and depends upon the controllers present in the microgrid. These controllers make sure that the transitions from normal operation to islanding operation occur seamlessly [11] [12]. During islanding operations, microgrids are capable of detecting faults in the main grid and then disconnecting itself from the main grid automatically or manually. In a sense, microgrids work as a backup for the main grid during emergencies and there are many distinct advantages of implementing microgrids, such as improved efficiency and cost reduction. Installing a microgrid can also improve reliability of the system during generation and consumption. The focus on this thesis is on low voltage DC microgrids while exploring the differences in both AC and DC systems. In the future, the goal is to have a smart grid capable of supplying a whole district in terms of producing the same magnitude of energy that it consumes [14].

3.2.1 Comparison of AC and DC Systems

Over the past few decades, there have been many debates on whether to implement DC or AC microgrids. This decision is based on influential issues such as reliability, efficiency, security, environmental and economic concerns. There are pros and cons in both systems and this section will discuss the difference between the two systems. More importantly, protection challenges and the technical aspects of both systems are also discussed [5].

As mentioned in the history section, since the feud between Tesla and Edison, AC distribution is more favoured than DC and has been used around the world since. AC systems use fossil fuel which is a non-renewable energy such as coal, petroleum and natural gas whereas recent DC systems typically use renewable energy such as wind, solar, hydro all of which occurs naturally. Using an AC system can leave carbon footprints which is the main contributing factor to the greenhouse effect. It is inevitable that fossil fuels will run out in the future and since there has been so much investment in low voltage AC (LVAC) systems, the challenge of enacting change is difficult. However change can have a positive impact on future smart grids [5].

As mentioned above, the type of system is based upon a number of influential issues. Since electric system resources in the recent years have become increasingly distributed, there is a need to have a more reliable and robust power electronic interface to accommodate the growing amount of renewable and other distributed generation resources. There also has been a growing interest in electric vehicle technology, hence it plays a big role in this debate, and this is because the batteries and energy storage in electric vehicles can provide improved grid reliability. When electrical vehicles are grid connected, power can be resupplied back into the power grid. The nature of loads has also changed in the recent years compared to the past. For example, in terms of lighting appliances at home, some consumers have selected other efficient alternatives to replace their lights. These alternatives require a DC source as their power supply [5].

3.2.2 LVAC Microgrid System

In this system, distributed generators supply AC power to the main system through power converters. The AC bus line is connected directly to the distributed generators such as tidal and wave turbines, wind turbines, biogas plants and low head hydros. The existing AC microgrid system is suitable for supplying power over long distance transmission lines with radial distribution system for consumers. The LVAC microgrid is connected via AC/DC/AC converters to the utility system at the PCC through a power transformer. These power converters make sure that there is stable connection between the utility grid and the AC microgrid. DC loads used in an AC microgrid requires AC/DC power converters whereas AC loads can be directly connected to the LVAC microgrid. Figure 2 shows the general structure of an AC Microgrid [15] [4].

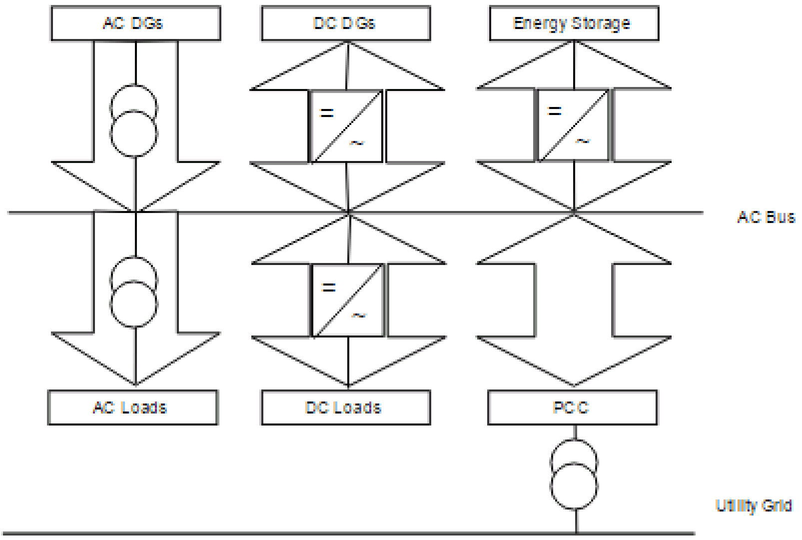

Figure 2 AC Microgrid Structure [16]

In terms of voltage transformation, the greatest benefit is the simplicity of adjusting the magnitude of the AC voltage compared to a DC system. Other than that, another advantage of an AC system is that it can independently control the voltage through management of reactive power since reactive power exists in an AC system. The AC voltage is controlled by injecting reactive power via managing the active power supplies located at their terminals. One disadvantage of using an AC system is that increasing level of penetration from renewable energy sources, which can deteriorate the stability of the system [5] [15].

3.3.3 LVDC Microgrid System

In the near future, the aim of implementing DC microgrids is to have DC power distributed to all electrical equipment at a more efficient rate with improved safety and security. With the concept of smart grid becoming a recent area of interest, there will be an increasing number of LVDC networks used for industrial or commercial purposes. The electrical components connected to the bus will be optimally controlled via an energy management system. DC based distribution generators and energy storage can be connected to the LVDC microgrid or DC bus line since it uses a central or string inverter. However AC generator units require an AC/DC converter to be able to connect to an LVDC network [4]. Figure 3 shows the general structure of a DC Microgrid.

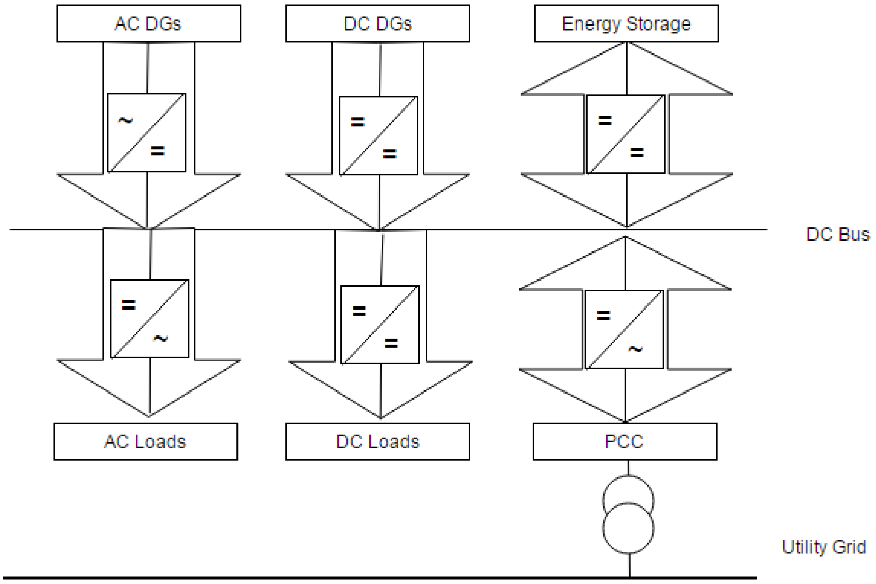

Figure 3 DC Microgrid Structure [16]

Voltage transformation for DC is slowly improving due to the complex nature of DC voltage conversion. At this time, DC systems have yet to reach the level where converters can compete with high voltage distribution transformers. This excludes High Voltage DC (HVDC) transmission, which is only used in remote substations capable of rectifying and inverting HVDC supplies. The biggest advantage of the DC system is the implementation of DC renewable energy resources, as it would eliminate the use of converters which proves to be more efficient. On the other hand, electrical components in a DC distribution system might have a negative effect on voltage stability and becomes a challenge when AC and DC systems are used together. In a DC system, voltage drops are resulted from real power flow over a conductor's length. As mentioned in the history section above, many consumers are moving away from incandescent lighting which is less efficient compared with lighting technologies such as compact fluorescent fixtures. This would at least eliminate the use of converters because compact fluorescent fixtures require DC distribution for power. Most home electronic devices nowadays require a DC power supply so a rectifier is needed to convert the AC power into DC. Another advantage of a DC distribution system is the use of variable speed drives which operates by matching the input and output power in both generation and loads. DC distribution systems can also reduce some potential health risks of human exposure to a 60 Hz distribution system [5].

3.3 Protection Strategies in AC and DC Microgrids

The concept of protection plays a big role in designing a proper strategy for microgrid operations. The goal of designing a protection scheme is to allow the microgrid to operate properly in both operation and islanding mode. As DC microgrids are rising to popularity, there are many new factors that have to be considered with respect to safety, selectivity, speed of response, security level, stability and fault analysis. Analysing these factors will show why DC microgrid protection is the preferred choice for a data center in this thesis.

The most important factor mentioned above relates to safety. The level of confidence in a protection scheme is determined by how safe the model is. The role of a protection scheme is to identify faults and isolate them accordingly. In an event of a disturbance, fault identification is based on the direction of the power and the change in current and voltage magnitude. For protective relays used in the protection scheme, speed of response is an important factor because it is required that protective relays must respond in the least amount of time to avoid permanent damage to the equipment and also maintain stability in the system. Lastly, security is also an important factor so that the protection system will only operate when needed to and reject non-fault transients and abnormal conditions [4].

3.3.1 AC Microgrid Protection Strategy

There are several methods for protecting an LVAC microgrid and [17] shows some of the proposed protection schemes that are used in LVAC distribution networks such as the adaptive scheme, distance protection scheme, harmonic content-based scheme and so on. The protection devices mainly used in a LVAC protection scheme are overcurrent relays, sectionalizers, miniature circuit breakers, reclosers and fuses [4].

The control of a LVAC microgrid can be distinguished as two different type, centralized and decentralized mode. In a centralized mode, phase voltages are converted into DQ coordinates which is then compared with a reference voltage. When the voltage magnitude exceeds the allowable threshold value, it will then activate the tripping device which in turn sends a signal to an appropriate switching device or protection relays as mentioned above. On the other hand, in a decentralized mode, each distribution generator is designed to have its own protection relay which operates accordingly in an event of a disturbance. This method is much more efficient in calculating single line to ground faults or line to line faults but is only limited by low impedance faults [4].

3.3.2 DC Microgrid Protection Strategy

Since protection schemes for LVDC microgrids are fairly new, aspects for the standard of electrical safety (SFS 6000) must be fulfilled. The technical challenges of LVDC protection scheme lies within the customer-end inverter such as double fault between AC and DC networks or inverter switching transients. LVDC microgrids usually include protective relays, measurement equipment, grounding systems and current interrupting devices. These devices are used in different grounding and fault detection methods, and these methods will be discussed later in more detail. LVDC can be protected from devices which are commercially available such as power circuit breakers, fast static switches, isolated case CBs, molded case circuit breakers (MCCBs) and fuses [4].

LVDC microgrid systems can also be grounded or ungrounded. Both systems are widely used in real life applications with certain companies preferring one system over another. In a DC grounded system, a conductor or point is purposely grounded whereas DC ungrounded systems do not have any grounded points unless it is through current measuring or high impedance devices. To compare the pros and cons of both systems, DC grounded systems provide fault currents a low impedance path to flow through and hence protective devices are able to operate with speed to isolate the faulted areas so no further damage can be done on the components [18]. Whereas the benefit of using a DC ungrounded system lies in cases where ground faults occur on the feeder close to the DC loads and thus a ground fault detection system can be created for fault identification and isolation. In choosing between DC grounded and ungrounded systems, codes and standards must be considered and applied [18].

The DC microgrid protection scheme can be divided into five different categories: distributed generator protection, utility protection, converter protection, feeder protection and bus protection. The operation of a LVDC protection scheme is similar to the case of a LVAC protection scheme which operates in a centralized or decentralized system [4] . In the Protection in Data Centers section, a more detailed explanation will be given on technical challenges and some key issues that need to be addressed in a LVDC protection system for Data Centers.

3.4 Protection in Data Centers

As the trend toward data centers is ever increasing, there are some technical challenges that prevent engineers from implementing DC systems as a standard. Some of the key issues lie in the protection design of data centers, and in order for DC to take over, each challenge needs to be evaluated and addressed [6].

Since the beginning of power distribution, there has been a popular misconception that using a DC system is more dangerous than an AC system. Another misconception is that losses in DC systems are higher than AC systems; this is technically true because DC system is normally used at low voltage levels, but at the same time, it is more efficient than the AC system [6]. In order to model a data center system, research was done on the safety and reliability of the system and a few data center standards were studied.

3.4.1 Data Center Protection Scheme

The layout of this protection scheme used in this paper is based on [1] which show a DC microgrid connected to an AC source at PCC. This system will be utilized for a number of fault tests to determine the suitable types of protection devices that can be used to protect different types of components present in a DC microgrid. A protection scheme will be laid out to investigate how current in the components react when a different types of faults occur on the system. The protection devices used in a DC microgrid will be also compared with each other according to the suitability of the protection location. The layout of the overall system is shown in Figure 4

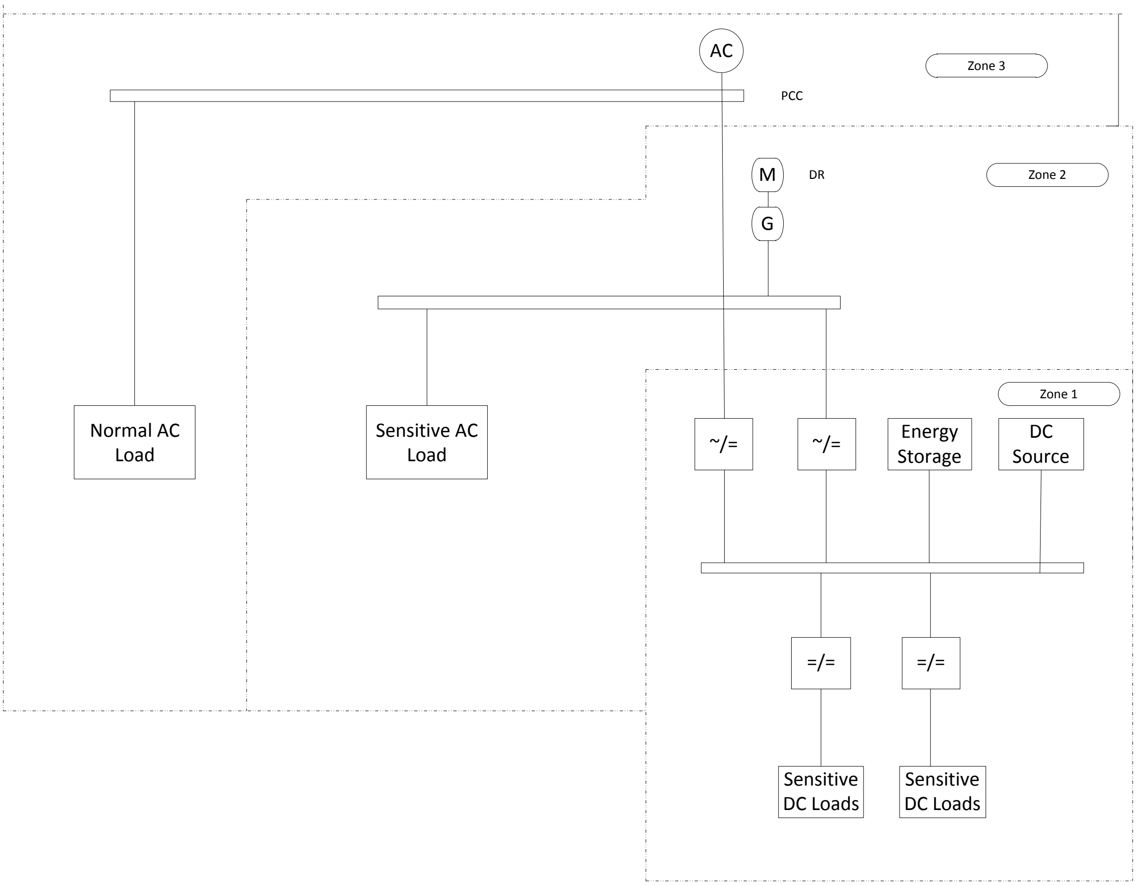

Figure 4 DC Microgrid Used in Data Centers

The overall system can be divided into three zones of Zone 1(DC microgrid), Zone 2(AC microgrid) and Zone 3(AC Grid). Zone 1 is the area in which this paper will focus and represent a DC microgrid in which power can be fed to sensitive DC loads. Zone 2 represents an AC microgrid with a consumer and utility connection and diesel generation. Zone 3 is the connection to the main AC grid [1].

This DC microgrid scheme for data centers consists of the following main components such as sources, converters, energy storage and loads.

3.4.1.1 Sources

DC sources utilize renewable energy such as wind, solar and hydro, in order to produce of a DC voltage with a frequency and magnitude that is suitable to connect to a DC bus via DC/DC converters. Whereas, AC sources such as combustion engines or diesel engines which run on fossil fuels are much more suitable for an AC power system [1].

3.4.1.2 Converters

There are two types of converters that can be used in a microgrid, DC/DC and AC/DC converters. DC/DC converter are used to connect loads and sources to a DC bus, and are easier to construct compared with AC/DC converters, therefore they are more cost effective and also results in less power loss. AC/DC converters are used for interconnecting a DC microgrid to an AC microgrid. It is used in this system is used to convert an AC current from AC microgrid into a DC current that is suitable for the DC microgrid [1].

As power conversion is needed for components that require a DC supply, the AC/DC converter is capable of transforming an AC source's frequency and amplitude into a DC level that can be fed into the loads. [1] shows the AC/DC converter used in this paper which is a voltage source converter (VSC) with a DC-link capacitor and six controllable Insulated Gate Bipolar Transistors (IGBT). With implementation of Pulse Width Modulation (PWM), the output voltage across the VSC can be controlled. In turn, the regulated power flow from the VSC can be controlled by the current through the grid filter and can also be bidirectional while individually controlling active and reactive power. The DC-link voltage produced from the converter will be of constant voltage. IGBTs are more advantageous than Bipolar Junction Transistors (BJT) and Power MOSFETs because they are a combination of the two elements and are easier to control during high voltage and current applications. In real life applications, IGBTs can be used in UPS systems, Switched-Mode Power Supplies (SMPS), and power systems that require high switching frequencies [19] [20].

3.4.1.3 Energy Storage

Energy storage can come from devices such as batteries, supercapacitors and flywheels. Batteries and capacitors can be directly connected to a DC bus without any conversion whereas flywheels must be connected through a converter and a machine. Energy storages are used to supply loads when there is a disturbance in the system [1].

3.4.1.4 Loads

As loads used in a data center are generally electronic, these computing devices naturally require a DC supply without any modifications, thus conversions can be omitted. These types of loads are usually found in data communication systems, lighting systems, control systems and safety system. Nowadays, electronic loads can be operated from a voltage range of 100-240V and a frequency range of 50-60Hz due to SMPS capabilities [21] [1].

3.4.2 Safety and Reliability in Data Centers

Data centers are expected to run 24 hours a day, 7 days a week without interruption, so continuity is an important factor to consider and is dependent upon the safety and reliability of a DC data center. There are two main issues there are worth focusing on related to the safety of data centers, grounding and no zero current crossing on DC system.

A DC system produces a constant DC voltage in which current does not cross to zero unlike in AC systems which produces sinusoidal waveforms. This tends to be a problem because there are no zero current intervals for the arc to cool, this means that current wavelength does not cross zero at any time. Zero crossing detection is a fairly new concept for measuring the period or frequency of a periodic signal. A few measurement techniques have been introduced in [22]. The grounding of an equipment is also complex issue and there are several methods in designing a ground for a DC system. If a single line to ground fault happens on a HVDC application, there can be large impedance which gives a small fault ground current that is hard to detect, this could result in equipment being permanently damaged. [23].

In terms of reliability, when the system experiences a fault, the DC protection scheme must have the ability to isolate and repair a fault without compromising the other components in the load. Since DC systems are equipped with a rectifier that has the capability of sourcing finite current, fast responding fuses or circuit must be used to achieve the required fault clearing time. A good protection coordination control system is needed to ensure that only the appropriate protection device will trip according to the type of fault that has appeared [23].

3.4.3 Data Center Standards

In the meantime protection in LVDC data centers is a fairly new concept, so there are only a few DC standards that can be used when designing a protection system. Some of the standards have been put in practice over the last several years but in some cases, these standards does not give sufficient confidence for engineers to design standard DC distribution networks in homes, businesses and industries [6].

Currently, there are few standards that have been put into practice in the last few years. These standards are essentially guidelines and codes that are applicable to different types of data centers. In all cases, these guidelines must be followed when designing, constructing and operating a data center with upmost respect to life safety and energy efficiency [24]. The following are some of the standards that is related to data centers

3.4.3.1 ANSI/BICSI 002-2014

This standard is a guide for planning, designing, constructing and also covers all issues in major systems located within a data center. It is written by credited engineers and professionals from a wide range of disciplines, and provides recommendations on best practice methods of implementing a data center that will fulfil a user’s need [25].

3.4.3.2 EN50600: An International Standard

This is a standard that is still in continuous development, it is a worldwide series for data center implementation that includes aspects such as power distribution, environmental control, building construction, security systems, management and operational information systems, and so on [26].

3.4.3.3 Battery Standard

A guide for the Protection of Battery system has been introduced by the IEEE. As DC microgrid systems and battery sources are different from AC microgrids, the functionality of a DC battery must be understood. Batteries are usually used as an emergency and backup power source but occasionally required to supply power to the microgrid during transient operations. When designing a battery protection scheme, it is desired that the battery will operate with reliability and efficiency in order to minimize risk in damaging components and limit the number of service interruptions that resulted from a transient fault condition. IEEE presents standards for two different types of batteries: Lead acid batteries and Nickel cadmium batteries [18].

3.5 Computer Simulation Packages

For this thesis project, two main types of computer simulation packages have been used for fault testing of a LVDC microgrid used in a data center. These simulation programs provide a diverse range of tools with the capability of modelling, designing, controlling and monitoring. The two types of software packages used in this paper are Microsoft Excel, and Intusoft ICAP/4.

3.5.1 Intusoft ICAP/4

The first IsSpice simulator was introduced by Intusoft in 1985 [27], and several decades later, the 4th edition has been introduced. This program offers a wide range of parts that can be found in industrial or commercial applications. It specializes in circuit modelling and provides simulations with instantaneous monitoring capabilities. This simulation package also contains different types of simulation analysis such as DC, AC, transient, Fourier, operating points and so on [27]. This program is ideal to be used within an industry but also for educational purposes. For this project, iCaps has been used for simulating fault currents in a protection scheme of a LVDC microgrid used in a data center.

3.5.2 Microsoft Excel

This is diverse and powerful computer software developed by Microsoft [28]. It is suitable for storing and organizing data in a spread sheet format and capable of performing complex analysis. Complex calculations in Excel can be done by entering formulas and equations into cells. It also allows user to present their data in many formats such as different types of charts and graphs. This program has been used in this project mainly used for fault calculation purposes [28].

4. Methodology

This section will deal in the fault testing of a LVDC microgrid for a data center and implementing the proper protection devices in their appropriate location. The steps taken to complete this project is as follows:

- DC microgrid system is modelled with ICAPS based on the system shown in [1].
- Three types of faults will be tested on the system with the assumption that faults happen at separate times. The fault locations are shown in Figure 9.
- Implementation of protective devices on each component.

Results will be presented in each fault cases, while improvements and further expansions to the system will be treated in the next section.

4.1 Development of a LVDC Microgrid for Data Centers

The first phase of this experiment involved developing a DC microgrid for fault testing purposes. At the end, a simple test network will be created along with results that show protective devices used in the appropriate location n. This network system was modelled after a system shown in "Protection of Low Voltage DC Microgrids [1]", which was a simple protection scheme for data center purposes. Figure 5 shows the layout of Zone 1 of the utility grid which is the DC microgrid used in a data center. The system was modelled in a way that the AC side can be omitted and therefore only the DC side is considered. The types of DC electronic devices will be discussed along with their specifications.

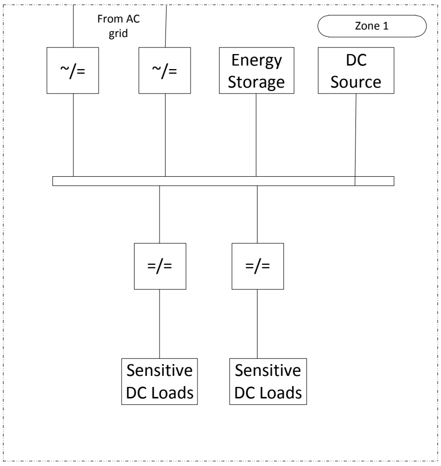

Figure 5 Zone 1 of DC Microgrid

The modelled network will consist of a converter, a battery and two feeders which represent the components found in Zone 1 such as AC/DC converter connected to the AC grid, energy storage and sensitive DC loads respectively. DC sources will be omitted in this investigation but can be added on in the future. Zone 2 and Zone 3 is not considered because the interest lies in investigation of the Zone 1 DC microgrid.

It is important to note that in ICAPS, for example resistors used in the converter, some of the resistors components are labelled as R_C and R_{CX}. These two are the same components but labelled differently due to ICAPS inability to reuse the same components.

4.1.1 Converter

As Zone 1 is connected to PCC which is supplied with an AC power, an AC/DC converter is used for power conversion. Figure 6 shows that the left part is the AC side and right part is the DC side. A constant voltage is required coming out of the converter from the DC side, this can be done via controlling the power flow on the AC side of the VSC to equal the magnitude and frequency needed to maintain charge of the DC-link capacitor and supply electronic loads connected to the DC side of the VSC.

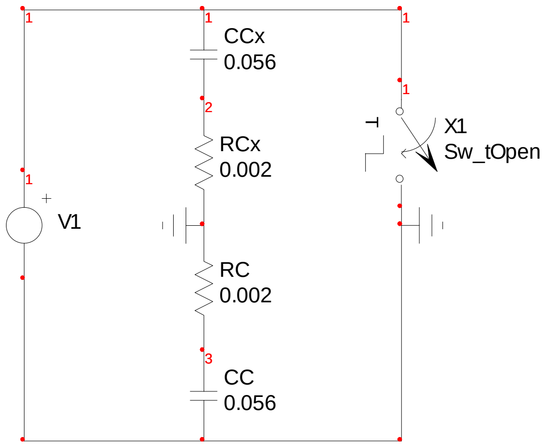

Figure 6 Schematic Diagram of Converter

The schematic diagram of the converter used in this project is shown in figure 6. Since voltage is constant, the AC/DC converter can be represented and modelled as a constant 400V DC source and labelled as VI on Figure 6. The converter consists of two capacitors and two resistors and a DC voltage source and their parameters can be found in Table 1.

Converter System Parameters				
	U_{dc}(V)	R_C(Ω)	C_C(F)	S_C(kVA)
Converter(DC)	400	0.002	0.056	320

Table 1

4.1.2 Battery

During normal operation, the two feeders in the system will be supplied with power at PCC from the AC grid. In an event of a disturbance such as voltage dips occurring on Zone 2 or Zone 3, Zone 1 DC microgrid will go into transient operations mode, in which case power will be fed to the feeders from the battery instead of coming from the converter. The main function of the battery is to act as an emergency and back-up power supply for the feeders when there is a disturbance.

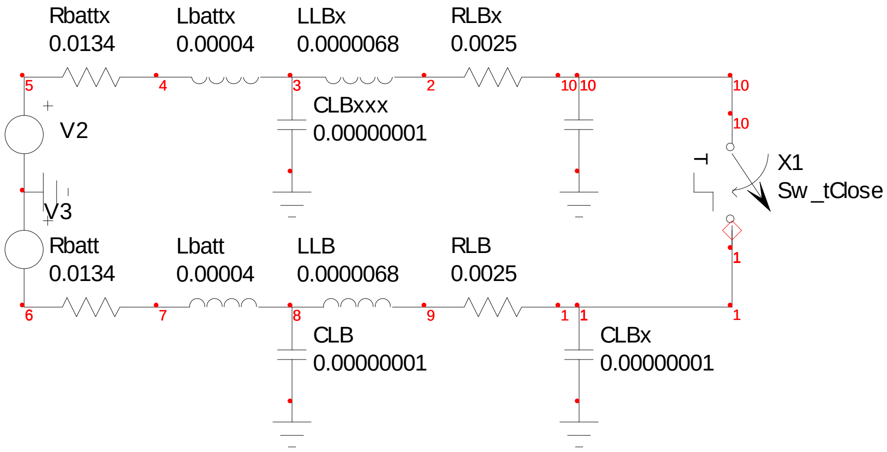

Figure 7 Schematic Diagram of Battery

Figure 7 shows the schematic diagram of the battery used for this project and it mainly consist of two batteries, two resistors, two capacitors and two inductors with a battery cable length of 20m. Battery specifications and battery cable parameters are shown in Table 2.

Battery System Parameters					
	U_{batt}(V)		R(Ω)	L(H)	C(F)
Battery	400		0.0134	0.00004	
		Length(m)	R_{LB}(Ω/km)	L_{LB}(H/km)	C_{LB}(F/km)
Cable(Battery)		20	0.125	0.00034	0.00005

Table 2

4.1.3 Feeder

There are two feeders connected to the positive pole and negative pole of the battery and the converter. These two feeders are also connected to their own DC electronic load separately. Both of the loads consist of one capacitor, one resistor and two inductors. The system parameters for the load resistance, capacitance and inductance are the same in both loads but they have different cable lengths. They also share the same cable characteristics with a cable length of 30m and 70m for feeder 1 and feeder 2 respectively. The schematic diagram and parameters for the load is shown in Figure 8 and Table 3 respectively.

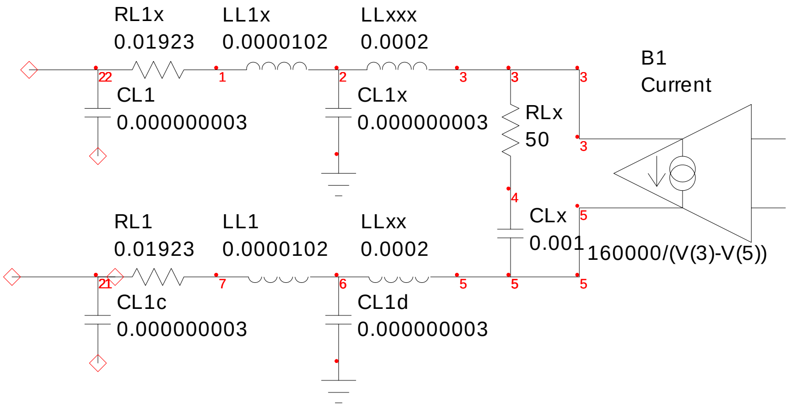

Figure 8 Schematic Diagram of Feeders 1 (Or Feeder 2)

Note that Figure 8 shows the schematic diagram of feeder 1 but can also be referred to as feeder 2 because both feeders have the same layout and almost the same parameters, the difference being the length of the cables.

Loads used in feeder 1 and 2 will be modelled as an arbitrary current controller [29]. As loads are required to have 160kW fed to them, a simple power equation can be implemented into the controller to be used to calculate the current across the load.

$$i_{load} = \frac{P_{load}}{V}$$

Where V is the voltage at the both nodes closest to the load, i_{load} is load current.

Load System Parameters					
	Power(W)		R(Ω)	L(H)	C(F)
Load	160000		50	0.0002	0.001
		Length(m)	R(Ω/km)	L_L(H/km)	C_L(F/km)
Cable (Feeder 1)		30	0.641	0.00034	0.00001
Cable (Feeder 2)		70	0.641	0.00034	0.00001

Table 3

4.1.4Protection Devices

Protection devices suitable for the LVDC microgrid protection scheme are fuses, ultra-fast hybrid DC circuit breakers and MCCBs. Most of these devices can be implemented for AC applications but some of them are designed for DC systems specifically. Due to the different current and voltage ratings between DC and AC operations, this must be considered when designing a microgrid protection scheme.

4.1.4.1 Fuses

In modern applications, fuses are made up of a fuse link and ceramic cartridge that contains silica sand [1]. The silica sand is a heat absorbing material used to quench transient arcs. Depending upon the voltage and current ratings of the system, the fuse link can be either copper or silver. Time constant of the system is an important factor to consider when fuses are used in a DC protection system because it determines the current transient rise time which will affect the fuses from interrupting the current. A small time constant means that current transient can be cooled through the ceramic cartridge, however a long time constant will result in fuses not able to quench the arc due the rise in temperature. Fuses are also required to handle overcurrents to run smoothly [1]. Commercially available fuses are shown in the Table 4.

Protection Device	Manufacturer	I_{SC}(kA)	I_n(A)	U_n(V)
Fuses	Ferraz Shawmut	100	1-600	500-1000
	IFO Electric	120	2-630	250-550

Table 4 [1]

4.1.4.2 Circuit Breakers

The structure of a circuit breaker typically consists of a contactor, a tripping device and a quenching chamber. A circuit breaker has two main functions. Firstly it is able to switch the rated current based on the rated voltage in the system. Secondly, a circuit breaker provides overcurrent protection by sensing fault conditions and also has the ability to open the circuit automatically. When the overcurrent has been cleared, it is able to relatch itself into a state in which it can be turned on again [1] [18].

MCCBs are normally installed with a thermal magnetic tripping device, which can be used to sense heat energy. It is more commonly used in low voltage systems and can either have a fixed or adjustable current-time characteristic depending on the system used. Examples of commercially available circuit breakers and MCCBs are shown in Table 5 [1].

Protection Device	Manufacturer	I_{SC}(kA)	I_n(A)	U_n(V)
MCCB	Eaton	10-42	15-630	250-750
	ABB	16-70	25-800	250-750
	Siemens	20-32	26-630	250-600
Circuit Breakers	Secheron	80	1000-6000	900-3600

Table 5 [1]

4.2 Case Study and Assumptions

The overall system with converter, battery and the two feeders connected together is shown in Figure 9. Y1, Y2, IV6, IV7, IV8, IV9, IV10 and IV11 are the locations of the protective devices used in this system. Figure 9 also shows the fault location of F1, F2 and F3.

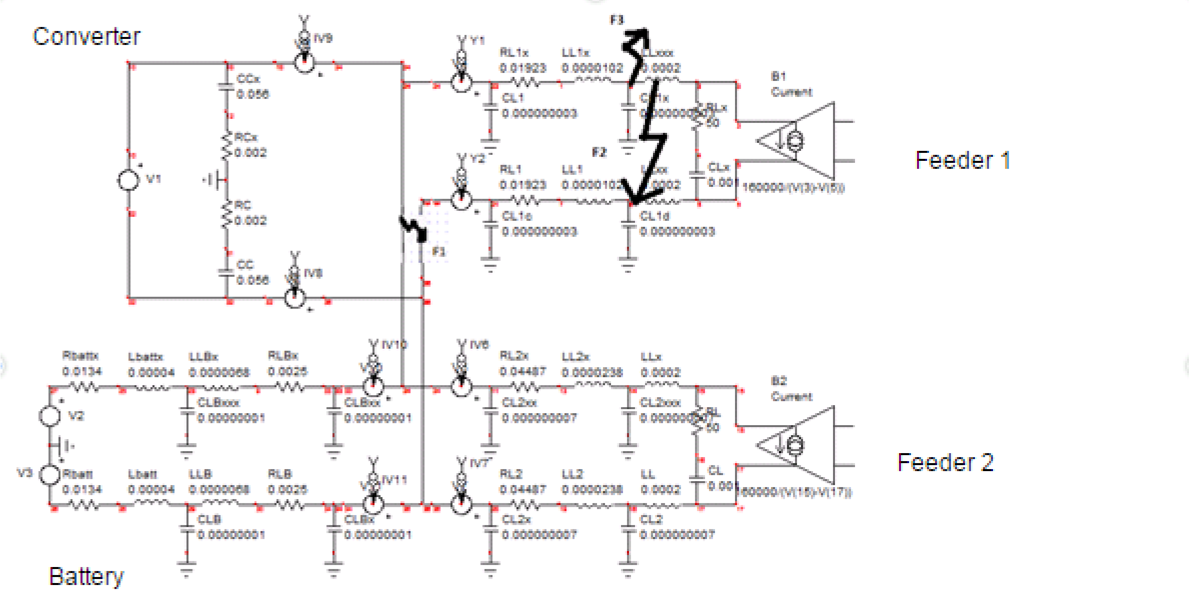

Figure 9 Overall Schematic Diagram with Fault Locations

The three types of fault that will be investigated in this project as follows:

- Fault 1 – Positive and negative pole of converter/battery and sensitive DC loads
- Fault 2 – Pole to Pole fault on Feeder 1
- Fault 3 – Single line to ground fault on Feeder 1

A few assumptions have been made prior to conducting this experiment. The protection scheme is assumed to be an ideal system. It is also assumed that F1, F2 and F3 occurs at different times and are already detected by fault detection device so each fault can be simulated separately. Fault detection time can be calculated with the formula below by using DC-link voltage and the derivative of the converter current [1].

$$\frac{di_C(t)}{dt} = -\frac{u_{dc}}{R^2C}e^{-\frac{t}{RC}}$$

This equation is important as it gives the minimum time required for fault detection where i_C is the converter current, R and C are the values of the converter's resistance and capacitance respectively. U_{dc} represents the value of DC-link voltage. Protection relays on the AC side of the converter are assumed to have the following settings.

- Battery overcurrent – 80% of max battery fault current
- DC-link undervoltage level – 40%

These settings are important as they need to be considered when calculating the maximum fault current of the battery and the capacitor current discharge of the converter [1].

5. Result

5.1 Fault 1 – Positive and Negative Pole of Converter/Battery and Feeders

Fault 1 can be simulated as a short circuit between the positive and negative poles. When fault 1 occurs, the battery and converter can be investigated separately. This reason is that the positive and negative pole of the converter/battery are connected to the loads in parallel and power has not reached the loads. The simulated result of the converter and the battery should reflect the battery overcurrent and DC-link undervoltage set in the assumptions.

5.1.1 Converter

5.1.1.1 Simulations of Excel and ICAPS

The converter has low impedance due to connection to the bus where L_C can be disregarded in calculating the converter fault current. Fault 1 will cause discharging of the capacitors in the converter and can be calculated using the following formula

$$i_C(t) = \frac{u_{dc}}{2R_C} e^{\frac{-t}{\tau_C}}$$

Where $\tau_C = R_C C_C$. U_{DC} in this case is 400 x 0.4 = 160V due to undervoltage level of 40% setting on the AC side. R_C and C_C represents the converter's resistance and capacitance respectively. As it is assumed that fault detection has already occurred, t=0 for converter current to discharge. Refer to Appendix B for converter current discharge calculation and the Excel spreadsheet data. Plotting the equation in excel gives the graph shown in Figure 10.

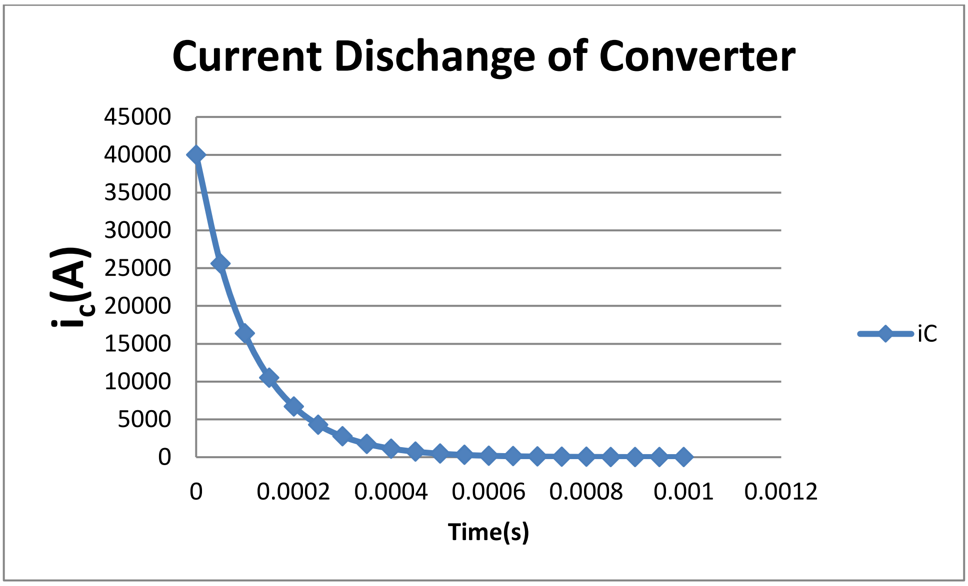

Figure 10 Current Discharge of Converter

The Excel plot shows that the converter current discharges from 40kA to 0A at approximately 0.5ms.

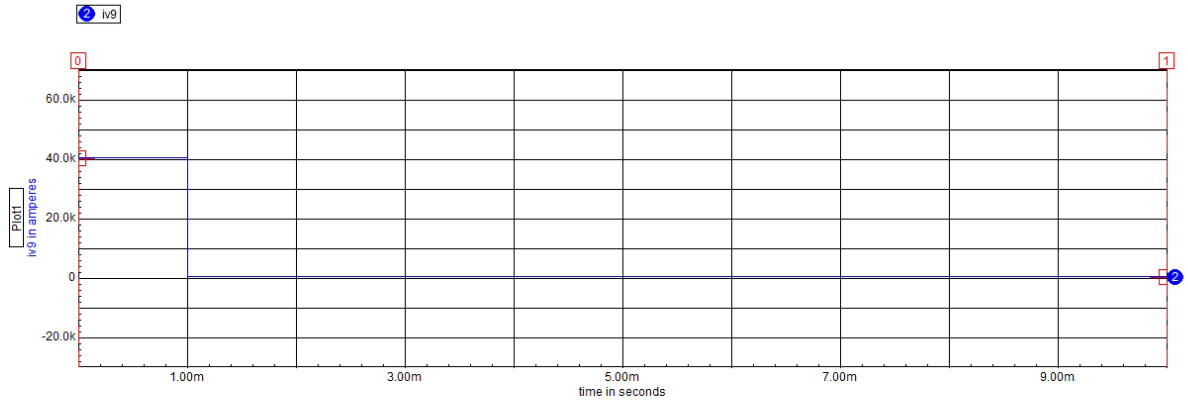

Figure 11 Fault 1 Simulation of Converter

Simulating the converter in ICAPS and measuring the current across IV9 shows that the current discharges from 40kA to 0A in 0s. Current across IV8 has the same magnitude but reversed in direction. The current flowing through IV9 test point is shown in Figure 11.

As comparison, both Excel and ICAPS simulation show that the peak magnitude of converter fault current is approximately 40kA. However, the time of converter current discharge for the ICAPS simulation falls to zero immediately when Fault 1 occurs compared to the excel graph which shows a discharging time of 0.5ms. Even with a small time step for the simulation, the simulated current still decreased immediately instead of exponentially. This error could be due to not considering AC side of the converter, as the converter is supplied with a constant DC source of 400V.

When fault 1 occurs, DC-link voltage will fall to around zero, the direction of the current will be reversed with the converter acting as a diode rectifier. On the AC side, the current controller will also lose its control capability and fault current will start to flow through IGBTs but limited by a grid filter [1].

5.1.1.2 Protection Devices for Converter

Due to current discharging time of 0.5ms of the converter, it results in a short transient hence a fast clearing time is needed for location IV8 and IV9. A longer interruption time on the system could damage the DC-link capacitor on the DC side and reverse diodes on the AC side. The chosen method for converter protection in this case is using power electronic switches or ultra-fast hybrid DC circuit breakers.

Protection Devices for Converter	
Location	Protection Devices
IV8	Power Electronic Switches or Ultra-Fast Hybrid DC Circuit Breakers
IV9	

Table 6 Converter Protection Devices

These protection devices have a very short fault clearing time up to 10ms and able to handle high but short transient current which will give the converter maximum fault clearing time to clear the fault current. Most of these devices are still in research and development stages and also suitable for HVDC applications [1]. Some power electronic switches have been developed by ABB, Secheron, with implementation of Integrated Gate Commutated Thyristors (IGCT) which is a fairly new concept. IGCT has been optimized to handle low losses in conduction with an on/off switching frequency in the range of 500Hz. Since communication between the device and IGCTs are connected via optical fibre, this enables a short on-off burst with switching frequencies which can go up to 40kHz [30].

5.1.2 Battery

5.1.2.1 Simulations of Excel and ICAPS

The backup battery used in this system is connected to a DC bus via a cable. As fault 1 occurs, the total fault impedance is the sum of cable impedance (R_{LB} and L_{LB}) and the internal impedance of the battery (R_{Batt} and L_{Batt}). The battery fault current during Fault 1 can be calculated by using the following formula [1]:

$$i_{batt}(t) = \frac{u_{batt}}{R_{batt} + R_{LB}}(1 - e^{\frac{-t}{\tau_{batt}}})$$

Where $\tau_{batt} = \frac{L_{batt}+L_{LB}}{R_{batt}+R_{LB}}$. For calculations in Excel, U_{batt} has been set at U_{batt}=400 x 0.8 based on the battery overcurrent level of 80% assumed on the AC side of the converter. Due to fault 1 being a pole to pole fault, cable capacitance does not need to be considered in the battery fault current calculation. Design of the battery will determine how long it is able to supply the short circuit fault current without causing damage to the components. The calculation of the battery fault current is found in Appendix C with the Excel spreadsheet data. Figure 12 shows the maximum rise battery fault current plotted in Excel.

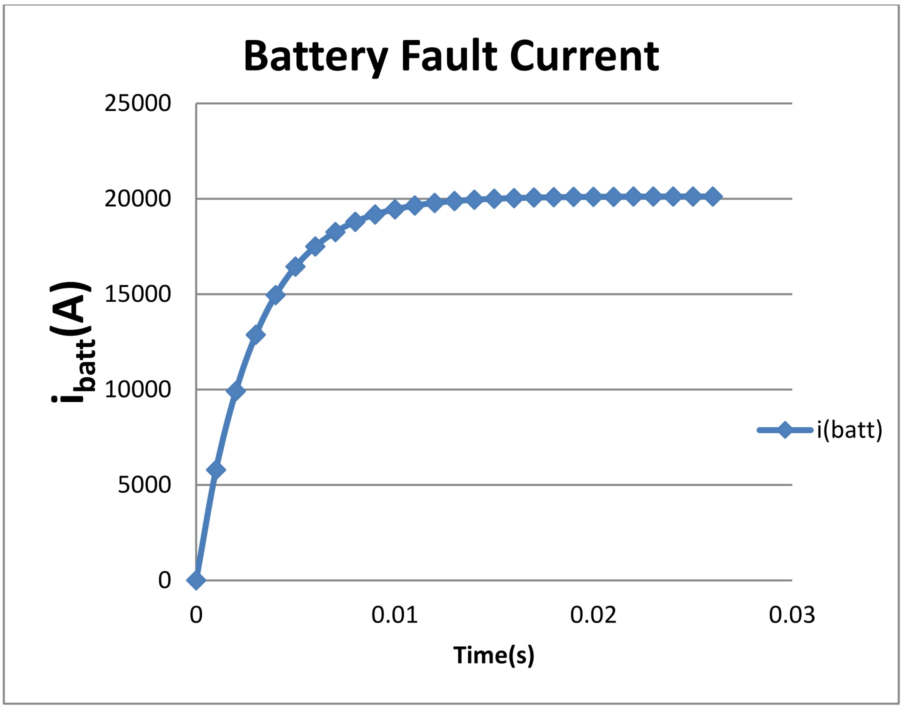

Figure 12 Current Discharge of the Battery

With an overcurrent level setting of 80%, it can be seen that Figure 13 shows the maximum battery fault current reaching up to 20.122kA in a time of 0.02s.

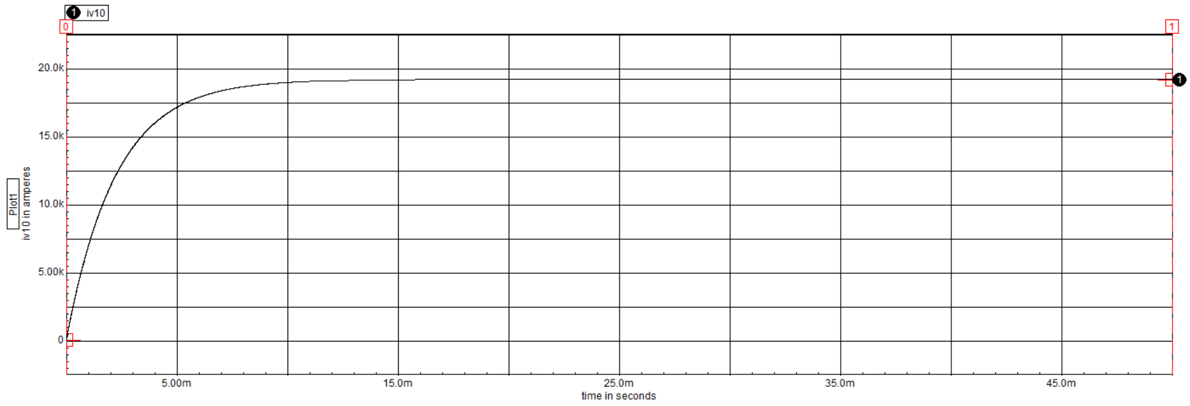

Figure 13 Fault 1 Simulation of Battery

IV10 and IV11 are represented as protection devices which will be used in this location, however in ICAPS they are used for measuring current through the battery. Current flowing through test point IV10 is simulated in figure 13. The ICAPS simulation shows that battery fault current reaches a maximum of 19.133kA within approximately 0.02s. This fault current needs to be cleared before reaching maximum point.

5.1.2.2 Protection Devices for Battery

When fault 1 occurs, it is desired that the battery is able to disconnect itself to clear the fault and then reconnecting itself back to the system which can be achieved by using circuit breakers as they possesses switching capabilities. The protection devices chosen for location IV10 and IV11 are shown in the table 7.

Protection Devices for Battery		
Location	Protection Device	Rated I_{SC}(kA)
IV10	Circuit Breaker(Secheron)	80
	Fuses (Ferraz Shawmut)	100
IV11	Circuit Breaker(Secheron)	80
	Fuses (Ferraz Shawmut)	100

Table 7 [1]

As battery fault current can reach up to 20kA, circuit breakers by Secheron are chosen for battery protection based on its rated short circuit current of 80kA. Another method to clear faults in the battery is to use a fuse in series with a switch. Fuses are required to operate through a control system in which, if fault current exceeds an allowable threshold, the controller will send a signal to the switch prompting it to open. Figure 14 shows the fault current cleared within 0.02s before it reaches the maximum fault current. In this case, fuses and circuit breakers are both suitable choices for battery protection, however the decision on implementing either device is affected by their size, robustness, responsiveness and cost. Future improvements and expansion can be done on the system in considering the proper protection device for the battery. For example, fuses tend to be cheaper than circuit breakers but on the other hand, circuit breakers are more robust compared to fuses. Fuses also have a shorter response time and must be replaced when they overheat and melt, whereas circuit breakers have an internal switch mechanism that allows it to reset.

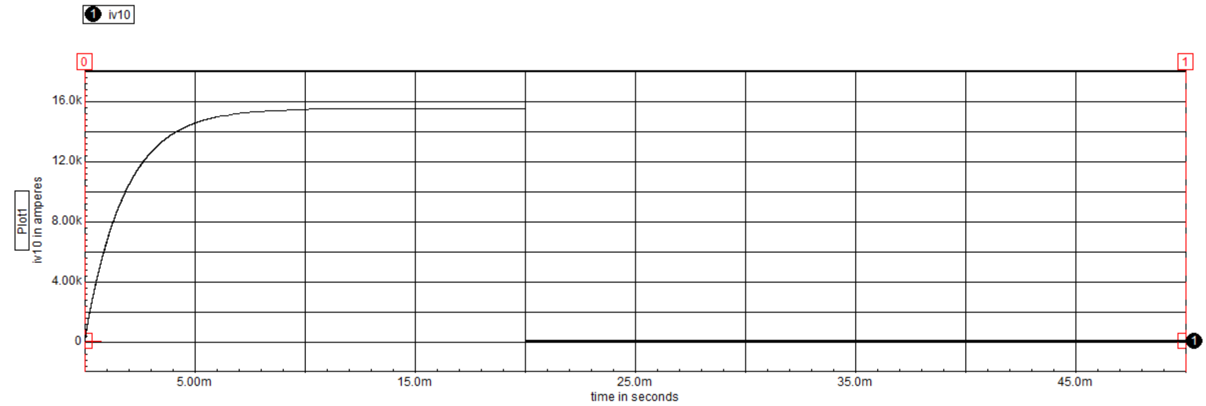

Figure 14 Fault 1 Being Cleared

5.2 Fault 2 Pole to Pole fault on feeder 1

5.2.1 Fault simulation in ICAPS

Fault 2 is located on feeder 1 after the protection devices of Y1 and Y2, therefore will only affect the loads connected to this feeder, feeder 2 will continue to supply power to the loads connected to it. The feeder will be modelled along with the battery and converter in this case. Fault 2 is pole to pole fault which will be simulated as a short circuit second order RLC system shown in Figure 15.

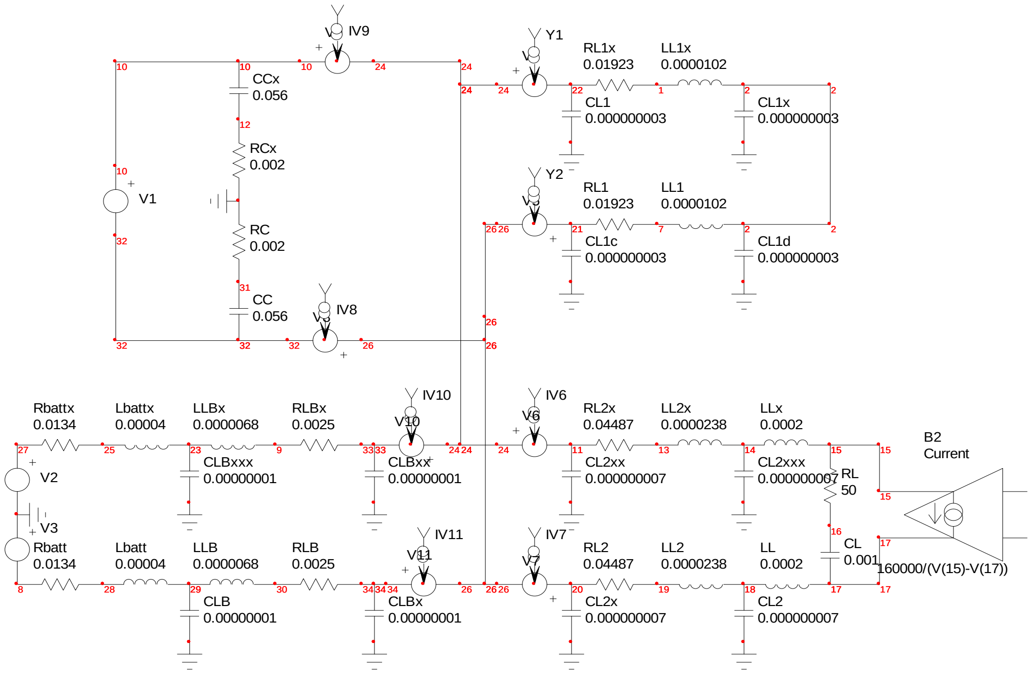

Figure 15 Fault 2 Simulated as a Second Order RLC

Figure 16 shows the simulation taken from the current passing through test point Y1. When Fault 2 occurs, it can be seen that the transient current starts to oscillate before reaching a steady state within approximately 0.03s. Power from the converter/battery to the load can reach a current transient of 10.4kA.

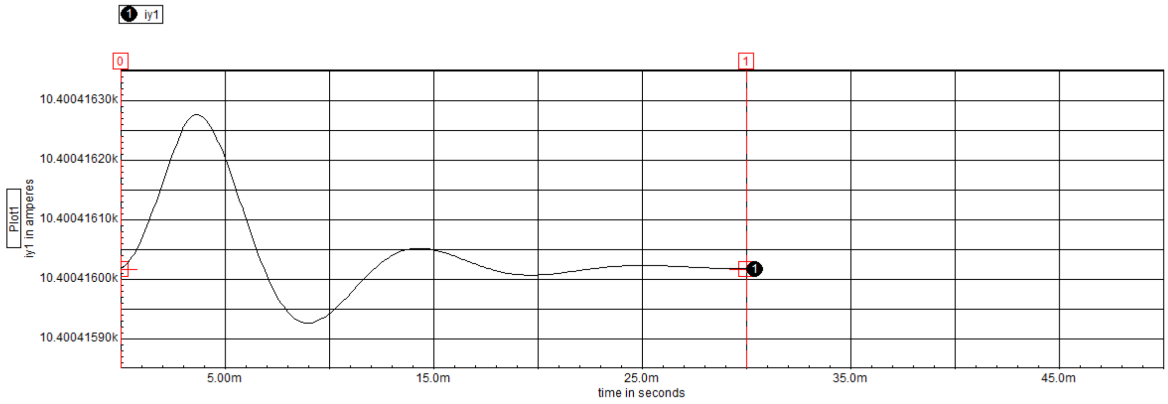

Figure 16 Fault 3 Current Simulation

5.2.2 Protection Devices for Feeders

As loads have the tendency to produce heat energy, this energy must be dissipated before it damages the loads in the feeder. Fuses or MCCBs can be used for loads as they protect the components from overloading or short circuits. The advantage of using MCCBs compared to fuses is the ability to open both poles in an event of a fault. Also, since MCCBs are equipped with thermal magnetic tripping device, heat energy from the loads can be quenched. Therefore, the type of protection device suitable for feeder 1 is MCCBs. For this case, MCCBs by Eaton were chosen due to Fault 2 current transient of 10.4kA falls within range of the rated short circuit current. These protection devices are controlled via a protection control system to operate when a fault has been detected.

Protection Devices for Feeder 1		
Location	Protection Devices	Rated I_{SC}(kA)
Y1	MCCB(Eaton)	10-42
Y2	MCCB(Eaton)	10-42

Table 8 Protection Devices for Feeder 1 [1]

5.3 Fault 3 – Single Line to Ground Fault on Feeder 1

Fault 3 is a case where single line to ground fault occurs on the positive pole of feeder 1. In this case only the positive pole is affected. This fault can be simulated with a 5kΩ impedance to ground as shown in Figure 17. Furthermore, C_{LB}, C_{L1} and C_{L2} are required to be considered in high impedance ground faults.

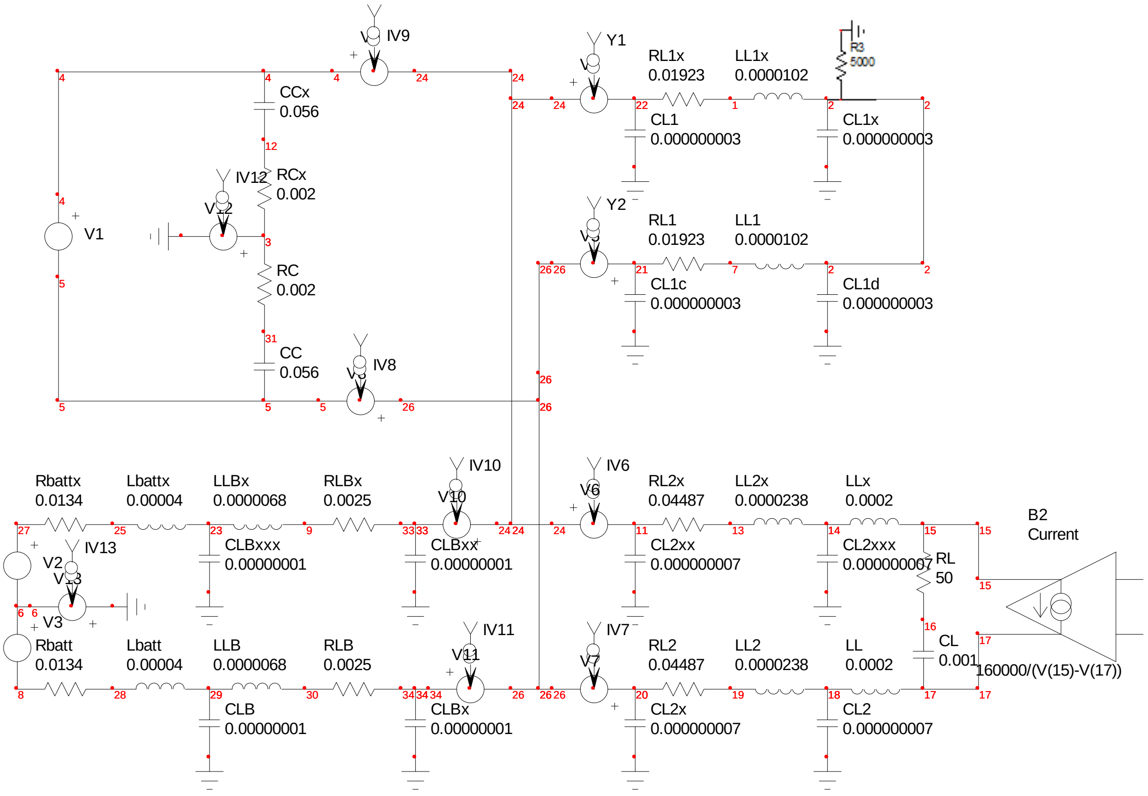

Figure 17 Fault 3 Simulated as a 5kΩ Impedance to Ground

Test points IY12 and IY13 were added to the system and used to measure the converter and battery ground current. With a fault impedance of 5kΩ, simulation of current passing through test point IY12 and IY13 are shown in Figure 18 and Figure 19.

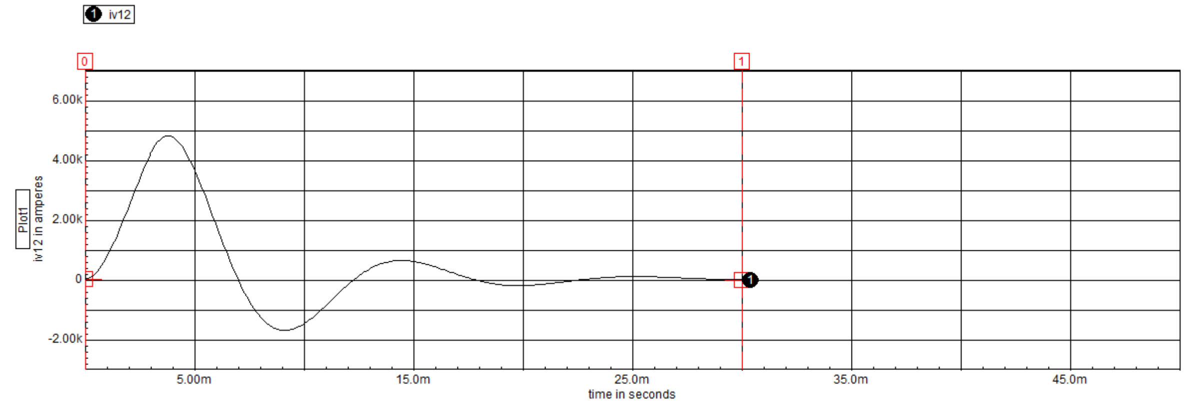

Figure 18 Fault 3 Simulation of Converter Ground Current

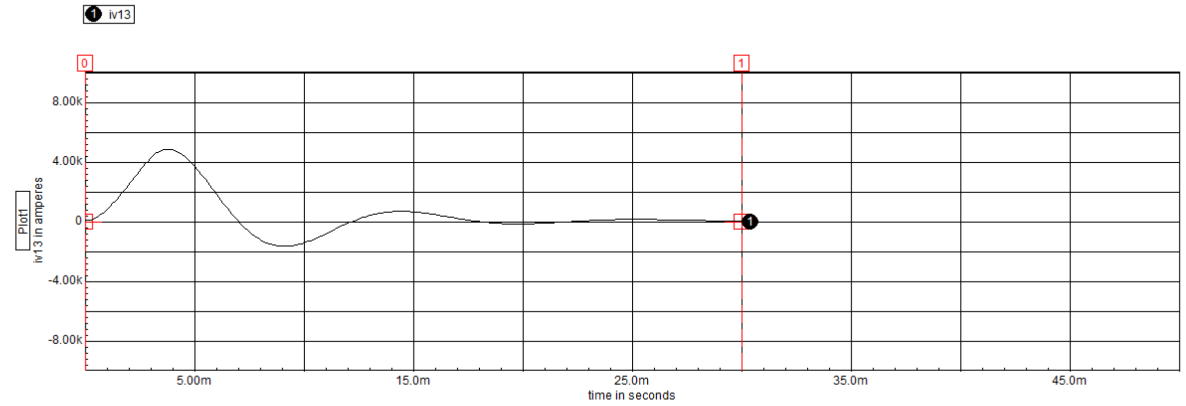

Figure 19 Fault 3 Simulation of Battery Ground Current

During normal operations, converter and battery ground currents should be zero however, as fault 3 is likely to occur after an isolation failure in the system, both figures shows that the transient current starts to oscillate from 0A up to 5kA before reaching a steady state of 0A in approximately 0.03s. The simulated ground fault current of the battery and converter shows a smaller fault current compared to Fault 1 and Fault 2.

It is safe to say that when Fault 3 occurs, the larger the ground fault impedance, the smaller the battery/converter ground current. This could cause a problem in detecting the fault as the fault current appears too small. In this case, instead of tripping the converter supply circuit during a fault, it is more recommended to measure the ground current of converter and battery. For example, if the current measurement reaches a certain threshold, a signal will be sent to notify the system that a high impedance ground fault has occurred.

6. Future Work and Recommendations

It is important to note that work done in this project is still inconclusive and can be used as a guide for future improvements that can be done to the system. A number of suggestions will be made in this section and could be implemented on this project based on a few aspects that was ignored or not focused on earlier.

This section also highlights the importance of conducting further experiments and the following aspects which will be discussed are protection coordination, fault detection system for single line to ground faults and implementation of the AC side of the converter. ICAPS has been the main program for this project but it has limitations in conducting fault analysis and implementation of the fairly new DC protection devices. In order to move forward in terms of expansions and improvements, a more versatile or powerful program should be used in the future, particularly for implementation of power relays or control systems. PowerFactory by DigSilent is an example of a program that can be used [31].

6.1 Fault Detection System (Ground Fault)

As it can be seen with Fault 3 appearing on the system, this ground fault can sometimes be hard to detect. The larger the fault impedance on the system, the harder it is to detect the small fault current. To tackle this problem, a fault detection system can be implemented.

The detection system has the ability of using information from measured currents or voltage and in some cases, communication information based with other components. It will then send a signal to protective relays in order to trip the appropriate protective devices. It is also important to note that the detection system is required to be able to differentiate Fault 1 and fault 3 as they both appear on feeder 1 [1].

6.2 Protection Coordination

Future implementation of protection coordination in this system is also an important aspect to investigate. In order to achieve high reliability in the system, it is very important that only dedicated protection devices will operate with respect to the type of fault that can occur. There are times that protection devices protecting a component may fail to clear the fault, therefore an emergency backup protection is required to operate and clear the fault.

For example the network shown in Figure 9, if fault 1 occurs, only the converter protection (IV8, IV9) and battery protection (IV10, IV11) should operate to clear the fault. In an event of fault 2, feeder 1 protection (Y1, Y2) is required to act, however if feeder protection fails to clear the fault, it is important that the converter and battery protection must operate and clear the faults [1].

6.3 Implementation of AC Side of Converter

The AC side of the converter was not considered due to limitations in ICAPS; hence the converter was modelled as a constant DC source. In order to implement the AC side of the converter, a centralized control method is required and requires a more sophisticated simulation package such as PowerFactory by DIGsilent [31]. A centralized control system is capable of sending signals to the appropriate protection device to act accordingly when an electrical surge is detected. It is of great importance to investigate the AC side of protection as some data centers require an AC and DC microgrid for protection. Further expansion can be done on the system by implementing Zone 2 and Zone 3 onto the existing scheme as shown in Figure 4.

7. Conclusion

One of the main challenges that an utility grid face is in the aspect of DC microgrid protection schemes. Since majority of the systems nowadays uses AC, the act of enacting change is challenging, but can however have a positive impact on future microgrids, one of the advantages being that DC systems have fewer conversions which results in less losses. In order to achieve this, protection in a DC microgrid must be highly prioritized. The goal in the future is to have DC smart grids implemented in utility grids for back up and emergency purposes.

This report has presented a case in which DC microgrids are used in data centers. Due to most loads in data centers being electronic loads and naturally require DC power, it was chosen as an experiment for this thesis. The aim of this thesis was to conduct a fault simulation of the system to see how components react to different faults and to investigate the types of protection devices required to protect the components.

The aim was achieved in this thesis with the exception of Fault 3 as further work needs to be done on the system. Result shows that the suitable protection device for batteries are circuit breakers or fuses, whereas loads are recommended to use molded-case circuit breakers with heat quenching abilities. The converter requires fast protection and therefore ultra-fast hybrid DC circuit breakers can be used. Furthermore, improvements and further expansions were also discussed based on protection coordination, fault detection and implementation of AC side of the converter. To conclude, this research is still in early stages and can be used as a foundation in developing a protection scheme suitable for a hybrid AC/DC microgrid protection in the future.

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Appendix A: Summary of Microgrid used all around the World

Region	Project Name	Power System	Control	Load
Japan				
	Aichi Microgrid	AC	Centralized	Commercial/Industrial
	Kyoto Eco-energy Microgrid	AC	Centralized	Residential
	Sendai Microgrid	AC	Centralized	Commercial/ Industrial
	CRIEPI Microgrid	AC	Centralized	Static
	Hachinohe Microgrid	AC	Centralized	Residential, Commercial , Industrial
European Union				
	Bronsbergen Park Microgrid	AC	Centralized	Residential
	Am Steinweg Microgrid	AC	Agent Based	Residential
	CESI RICERCA DER Testbed	DC	Centralized	Residential
	Kythnos Island Microgrid	AC	Centralized	Residential
	NTUA Microgrid	AC	Agent Based	Static
	DeMoTec Testbed	AC	Agent Based	Residential, commercial, industrial
	University of Manchester Testbed	AC	Centralized, Agent Based	Static
	Benchmark Low Voltage Microgrid	AC	Centralized	Residential
	Nimbus Microgrid Testbed	AC	Centralized	Residential
	Genoa University	AC	Decentralized	Residential
	University of Nottingham Testbed	DC	Decentralized	Residential

	UT Comiegne Testbed	DC	Decentralized	Motor
	University of Seville Spain Testbed	DC	Decentralized	Residential, Motor
	FEUP Microgrid Testbed	AC	Centralized	Static
North America				
	CERTS Testbed	AC	Decentralized	Residential
	UW Madison Testbed	AC	Decentralized	Static
	University of Miami Testbed	DC	Decentralized	Residential
	Sandia National Lab Testbed	DC	Decentralized	Residential, Static
	UT Arlington Testbed	DC	Decentralized	Residential, Static
	FIU Testbed	DC	Centralized, Agent Based	Residential
	Laboratory Scale Microgrid Testbed	AC	Centralized	Residential,
	UT Austin	AC	Decentralized	Static, Motor
	Microgrid testbed at Albuquerque	AC	Decentralized	Residential, Commercial
	Utility Microgrid at Los Alamos	AC	Decentralized	Residential
	RIT Microgrid	AC	Decentralized	Residential, Static
	Mad River Park Microgrid	AC	Decentralized	Residential, Commercial
	Palmade Microgrid	AC	Decentralized	Residential, Static, Commercial
	Hawaii Hydrogen Power Park	DC	Centralized	Residential, Static
	Boston Bar-BC Hydro	AC	Decentralized	Residential

	Boralex Plant	AC	Decentralized	Residential
	VSC Feeded Microgrid	AC	Decentralized	Residential, Static, Electronics
	Ramea wind-diesel Microgrid	AC	Decentralized	Residential
	Fortis-Alberta Microgrid	AC	Centralized	Industrial
China				
	HFUT Microgrid	AC	Agent Based	Static, Motor
	Tianjin University Testbed	AC	Centralized	Static
	NUAA Testbed	AC	Centralized	Static
Taiwan				
	INER Microgrid Testbed	AC	Decentralized	Static, Motor
India				
	MSEDCL at Wani Area Microgrid	AC	Decentralized	Residential
Australia				
	QUT Microgrid Testbed	DC	Decentralized	Residential, Motor

Appendix B Converter Calculations and Graph Data

$$i_C(t) = \frac{u_{dc}}{2R_C} e^{\frac{-t}{\tau_C}}$$

$$\tau_C = R_C C_C$$

$$\tau_C = 0.002 \times 0.056$$

$$=1.12 \text{ x } 10^{-4}\text{s}$$

$$i_C(t) = \frac{400 \times 0.4}{2(0.002)} e^{\frac{-t}{0.000112}}$$

Time (s)	iconverter(A)
0	40000
0.00005	25596.37865
0.0001	16379.36501
0.00015	10481.31072
0.0002	6707.08995
0.00025	4291.930351
0.0003	2746.446861
0.00035	1757.477345
0.0004	1124.62639
0.00045	719.6590731
0.0005	460.5166534
0.00055	294.6889659
0.0006	188.5742589
0.00065	120.6704534
0.0007	77.21816545
0.00075	49.41263505
0.0008	31.61961292
0.00085	20.23368963
0.0009	12.94772954
0.00095	8.285374698
0.001	5.301889702

Appendix C Battery Calculation and Graph Data

$$i_{batt}(t) = \frac{u_{batt}}{R_{batt} + R_{LB}}(1 - e^{\frac{-t}{\tau_{batt}}})$$

$$\tau_{batt} = \frac{L_{batt} + L_{LB}}{R_{batt} + R_{LB}}$$

$$\tau_{batt} = \frac{(40 \times 10^{-6}) + (6.8 \times 10^{-6})}{0.0134 + 0.0025}$$

=0.002943s or 2.943ms

$$i_{batt}(t) = \frac{400 \times 0.8}{0.0134 + 0.0025}(1 - e^{\frac{-t}{0.002943}})$$

Time(s)	ibatt(A)
0	0
0.001	5797.830706
0.002	9925.424006
0.003	12863.94141
0.004	14955.93156
0.005	16445.26179
0.006	17505.5462
0.007	18260.38418
0.008	18797.76865
0.009	19180.34355
0.01	19452.70639
0.011	19646.60702
0.012	19784.64881
0.013	19882.92356
0.014	19952.88735
0.015	20002.69599
0.016	20038.15577
0.017	20063.40031
0.018	20081.37241
0.019	20094.16711
0.02	20103.27592
0.021	20109.76066
0.022	20114.37728
0.023	20117.66395
0.024	20120.0038
0.025	20121.66958
0.026	20122.85548