Study on Faults and Protection in AC Grids Connected with HVDC Offshore Wind Farm

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DECLARATION

We hereby confirm that this thesis is our own original work. It has not been submitted, either partially or in its entirety, to any other institution. We have provided proper attribution for all sources used in this project.

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APPROVAL

The following students have submitted their thesis, "Study on Faults and Protection in AC Grids Connected with HVDC Offshore Wind Farm," to the following esteemed member of the engineering faculty in partial fulfilment of the requirements for the degree of Bachelor of Electrical and Electronic Engineering on……………The thesis has been approved as satisfactory.

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Abstract

In this paper, a study and observation were done of the faults associated with HVDC and AC system of a windfarm connected to AC grid through HVDC link. Moreover, reliable protection was given to the AC system. Simulation tool DIgSILENT PowerFactory was used for the observation. Wind power is a form of renewable energy and isone of the fastest growing energy sources in the world because of its vast advantages. But it is a complex system and can cause various problems to the power system if the impact or response of fault is not analyzed properly and proper protection is not given according to it. So, researchers are focusing on these challenges and find safe reliable solutions. This thesis can contribute to the advancement of the reliability of wind power system connected to AC grid connected through HVDC link. various unique information was evaluated in this study. This information can be very useful in the future researches to ensure a safe and ecofriendly power system future.

CHAPTER 1
INTRODUCTION

1.1 Introduction

In recent years, there has been a notable shift towards renewable energy sources in the global energy landscape, with offshore wind energy emerging as a key player in the generation of sustainable electricity. As energy demands rise and environmental awareness grows, numerous countries have set ambitious targets to enhance the incorporation of renewable energy, including offshore wind power. Offshore wind farms are gaining traction due to their access to stronger wind resources compared to onshore locations, which are becoming increasingly limited. To connect the electricity generated offshore to the grid, submarine cables are essential. Utilizing AC cables for this purpose leads to elevated capacitive currents and energy wastage. AC transmission presents notable disadvantages, particularly magnified as the distances from the offshore wind park to the shore lengthen. Consequently, high-voltage direct current (HVDC) is favoured [1] and plays a vital role in offshore wind projects. HVDC cables are a more feasible option for transmitting offshore wind energy over distances surpassing 100 km. In an offshore wind HVDC network, the primary function of the HVDC link is to gather offshore wind power and transfer it to the AC grid. Two HVDC technologies are currently accessible: LCC-based HVDC and VSC-based HVDC. LCC employs thyristors, known as line-commutating devices, while VSC utilizes insulated gate bipolar transistors (IGBT), which are self-commutating devices. LCC stands out for its minimal power losses and cost-effectiveness compared to other converters used in HVDC systems. Additionally, LCC-based HVDC is well-suited for transmitting large-scale power loads, with its reliability and consistent availability having been proven over an extended period [2]. Furthermore, advancements in IGBT technology and control methodologies for Voltage Source Converter (VSC) stations have enhanced the efficiency of HVDC transmission systems. VSC-based HVDC systems have the capability to independently control both active and reactive power at each converter station, and they can facilitate the connection of asynchronous systems. This adaptability renders them well-suited for integrating offshore wind farms into the grid, even in systems with weak or passive AC networks. In the event of faults in HVDC cables, the current can rapidly surge due to the lower inductance of DC cables compared to AC lines. It is imperative to promptly isolate faulty cables to prevent significant damage. Swift fault detection and localization algorithms are essential for upholding power system stability and minimizing economic losses resulting from supply interruptions in VSC-based HVDC transmission [3].

The integration of offshore wind farms into the existing electrical grid infrastructure presents both opportunities and challenges, particularly concerning fault detection, analysis, and protection strategies. This thesis conducts a thorough examination of the fault behaviour and protective mechanisms of alternating current (AC) grids that are linked to offshore wind farms that use high-voltage direct current (HVDC). This research seeks to improve the reliability, resilience, and efficiency of offshore wind energy integration by analysing the interconnections between these complex systems while ensuring grid stability and operational safety.

Fig 1.1: Technologies of OWF integration[4]

1.2 Background

A major technical achievement in the field of renewable energy is the integration of offshore wind farms with high-voltage direct current (HVDC) systems. This is especially noteworthy in light of the difficulties involved in transporting electricity across vast distances. The development of fault and protection mechanisms in these arrangements, together with their historical context, are deeply embedded in the growth of offshore wind technology and HVDC systems.

1.2.1 Early Advances in Offshore Windfarm and HVDC Technology

In the latter half of the 20th century, offshore wind farms gained popularity as an alternative to onshore wind farms, which frequently had visual and space limitations. In 1991, the first offshore wind farm was established on the Danish coast. These farms originally used standard alternating current (AC) systems for power transmission, and they were situated rather near to the coast. But as technology developed and the need to use wind resources farther from the coast grew, it became clear that AC transmission had drawbacks, including significant transmission losses and big cable diameters.

The evolution of HVDC systems happened with the development of offshore wind technologies. HVDC transmission, first successfully implemented in the 1950s, became a preferred method for long-distance power transfer due to its lower transmission losses and superior performance in underwater applications. HVDC was especially well-suited for offshore wind applications because of its efficiency across long distances and its capacity to link asynchronous power systems.

1.2.2 Challenges in AC HVDC Systems

There were several challenges with integrating HVDC systems with the current AC grids. Key among them was the management of faults across systems that operate fundamentally differently. Because the inherent zero crossing points in AC waveforms aid in interrupting the flow of current during faults, AC systems naturally facilitate simpler fault identification and clearance. On the other hand, HVDC systems, using earlier technologies lacked natural current zero points, which made it more difficult to quickly identify and interrupt faults.

Moreover, offshore wind farms add complexity such as shifting generation levels due to changing wind speeds and the harsh sea environment, which can increase the likelihood of equipment failure and system failures. The need for robust protection methods became clear in order to avoid these errors from propagating through the system and impacting the onshore AC grid stability.

1.2.3 Evolution Of Protection Strategies

The progress of protection strategies for AC grids linked to offshore wind farms through HVDC connections has been profoundly influenced by advancements in control and converter technologies. A pivotal development occurred with the transition from line-commutated converters (LCC) to voltage source converters (VSC). VSC technology offers enhanced controllability, swifter response times, and the capability to regulate voltage and power flow autonomously, all essential elements for effective fault management.

By efficiently managing voltage levels and power flow at the point of connection to the AC grid, modern VSC-HVDC systems can isolate faults quickly. These systems improve the detection and response strategies for different fault conditions by utilising digital controls, real-time monitoring, and complex protection algorithms.

1.2.4 Integrated Protection Mechanism

Nowadays incorporating offshore wind farms with HVDC systems into AC grids usually requires complex protection schemes involving both software and hardware components.

These schemes are intended to handle errors in both the AC and DC segments quickly. For example, the use of DC circuit breakers, which was once considered a huge technological barrier, has begun to see practical uses, allowing for speedier isolation of defective areas in the HVDC link while maintaining the overall integrity of the associated AC grid.

1.2.5 Current Challenges and Research Directions

The ongoing research in this field is focusing on enhancing the interoperability of AC and HVDC systems, developing more resilient protection technologies, and improving predictive maintenance capabilities to address potential faults before they occur. The goal is to build a grid infrastructure that is seamless, efficient, and highly reliable, capable of supporting the increasing share of renewable energy generated by offshore wind farms. This could increase interconnection capacity and support the integration of offshore wind and other renewable energy technologies on a larger scale [5].

1.3 Objectives

- Fault Analysis of Both HVDC and AC System.
- Developing Index of Fault Severity
- Develop fault detection and protection strategies for AC grids connected to HVDC offshore wind farms.

1.4 Structure Of This Thesis:

The thesis is organized into seven chapters-

Chapter 1: The article presents readers with the concept of the forthcoming theory, providing background information on the topic. Additionally, it identifies the objectives of this study.

Chapter 2: Introduces offshore wind energy systems. The history, foundations, economic aspects, future trends all are discussed.

Chapter 3: Gives an overview of HVDC transmission system including the background, technology, key components and advantages.

Chapter 4: Shows the methodology, test system and simulation tool.

Chapter 5: Describes all the case studies along with simulation results, related to fault occurrence and severity indexing with respect to various parameters.

Chapter 6: Describes all the simulations and the outcomes related to protective devices such as overcurrent and distance relays. Discusses Optimizing protection strategies that was followed.

Chapter 7: The paper concludes with a summary, key findings, and potential avenues for future research.

CHAPTER 2
A GUIDE TO OFFSHORE WINDFARM

2.1 Introduction to Offshore Windfarm

Growing attempts have been made in the past few decades to lower CO2 emissions and other pollutants that worsen the consequences of global warming. In an effort to lessen the negative effects of climate change, regional and international agreements like the European 2030 climate and energy framework and the Kyoto or Paris Agreement have been implemented. By 2030, these objectives call for a 40% decrease in CO2 emissions, a mandatory 27% increase in renewable energy, and a 27% improvement in energy efficiency. Thanks to the recent technology advancements and industrial growth, the offshore wind sector appears to be a crucial component for several nations in achieving the set quota in renewable energy. These days, both short- and long-term international energy strategy heavily rely on the offshore wind energy sector [6].

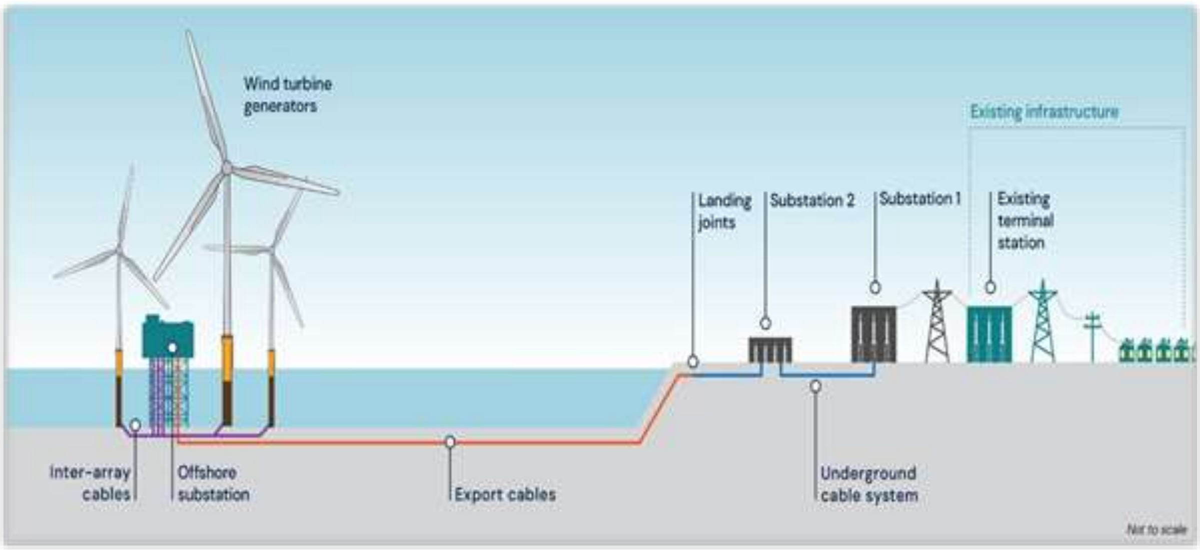

Fig 2.1: Offshore Wind Turbine Integrated System [7]

Arrays of wind turbines moored to the seabed make up offshore wind farms, which are usually found in open oceans or coastal areas. Compared to their onshore counterparts, offshore wind turbines have the advantages of stronger and more constant wind speeds, which increases their capacity for producing electricity. This natural advantage has accelerated the global growth of offshore wind energy capacity, especially when paired with technological advancements in turbine design and installation methods. A variety of factors contribute to the development of offshore wind farms, including environmental imperatives, energy security concerns, and economic incentives. By tapping into the vast energy resources available offshore, countries can diversify their energy mix, reduce greenhouse gas emissions, and create new opportunities for job growth and economic development in coastal regions.

Fig 2.2: The anticipated size and capacity of wind turbines, both offshore and onshore, in 2035 in comparison to 2019 [8]

Offshore wind farms are situated across multiple countries globally, primarily in Europe, with Asia and America following suit. Now, let's look at the global offshore wind energy capacity from 2009 to 2023

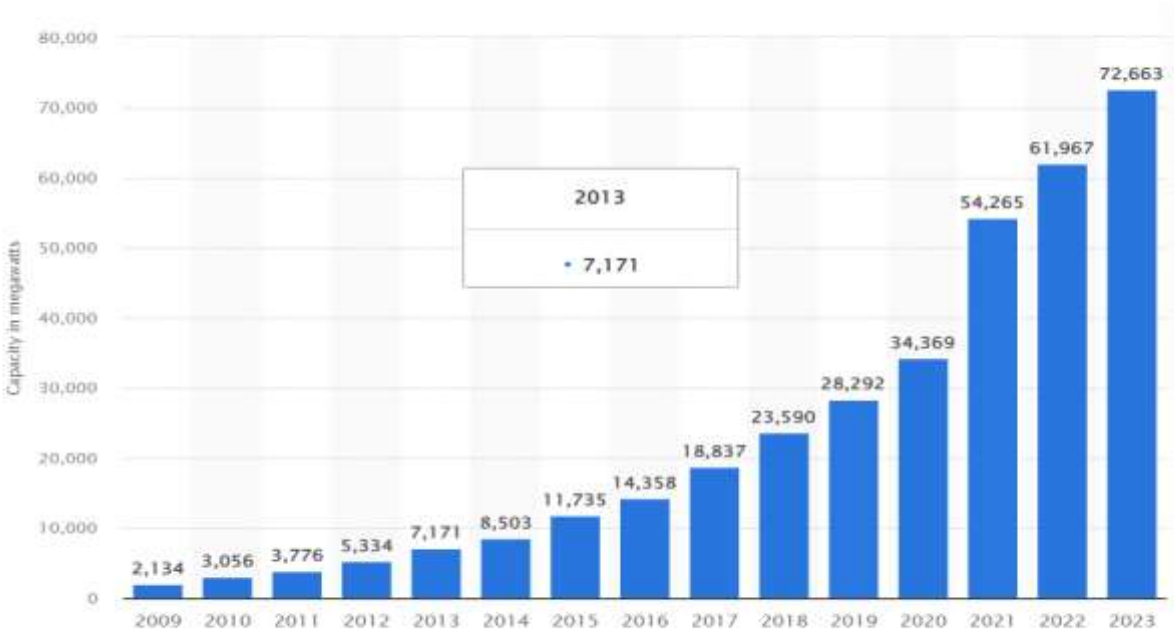

Fig 2.3: Offshore wind energy capacity worldwide from 2009 to 2023 [9]

2.2 Offshore Windfarm History

Elkraft, a former subsidiary of DONG Energy that was formerly known as Orsted, started looking at offshore turbines in 1987 and evaluated the seas around Lolland in 1989. Built by SEAS and Elkraft, the wind farm started operations in 1991 at an estimated cost of €10 million. In 11 days, the 11 turbines were constructed. Because offshore turbines must operate in saline conditions and have a far lesser output than central power plants, the electrical industry at the time saw them as absurd. Six years later, the skeptics' perspective had evolved when offshore winds surpassed onshore ones in driving energy output. Six years later, the skeptics' perspective had evolved when offshore winds surpassed onshore ones in driving energy output. Although there had previously been one wind turbine installed in Swedish seas, Vindeby was the first offshore wind farm to consist of many turbines. The comparable-sized Tuno Knob wind farm was constructed four years later. To find out what to do and what not to do, tests were conducted. The knowledge gained at Vindeby helped to create more affordable methods of harnessing offshore wind energy.

Fig 2.4: The world's first offshore windfarm in Denmark[41]

The initial 25-year government concession ran from 1991 to 2016. DONG Energy first thought about closing the wind farm in 2016 as it had long since outlived its intended use and had grown unprofitable. Vindeby was the first of several prosperous wind farms that spearheaded a trend toward declining costs. Dong Energy completed the decommissioning of Vindeby, the first wind farm, in September 2017. Vindeby has generated 243 GWh in 25 years [10], [11].

2.3 Structures of Offshore Wind Turbine

The most widely used designs for wind offshore structures include gravity-based foundations, tripods, jackets, and monopiles.

- **Monopile:** The installation involves driving the monopiles, which are generally 50–60 m long, 5–6 m in diameter, and 500–800 tones in weight, into the seafloor using a hydraulic hammer. Locations where the water is between 0 and 30 meters deep, These constructions work well. Most offshore wind use the monopile foundation for a number of reasons. One of them is the North Sea soil, which is easier to drill piles in. The vast majority of wind farms have been set up in regions with shallow water, typically not deeper than thirty meters.

- **Jacket Structure:** Typical jacket support structures are four-legged piles with interconnected cross braces having a diameter of about 2 m. The base piles are nailed inside the seabed to the adequate water depth with the support of pile sleeves. These offshore structures are suitable for locations having a water depth between 25 m and 50 m. Currently, there are 220 wind turbines supported by this foundation type.

- **Gravity Base:** The GBS is often a concrete structure with a central concrete or steel shaft connecting the transition piece to the turbine tower, and inside spaces filled with sand, rock, and iron ore. Water depths over 20 meters are appropriate for the GBS. Since larger offshore wind power projects are expected to be built in deeper waters, the GBS may be considered an alternative to the other support structures [12].

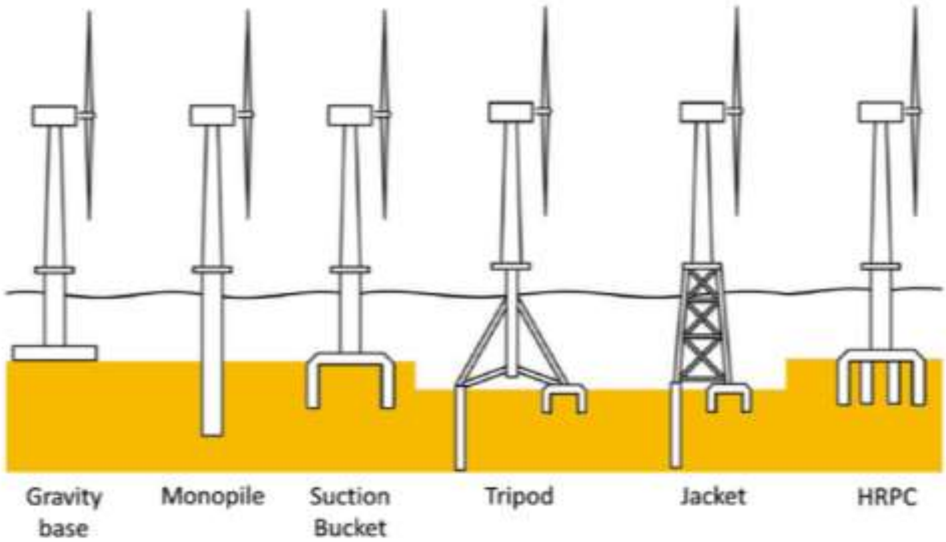

Fig 2.5: Offshore wind turbine foundations [13]

- **Tripod:** Compared to a typical lattice construction, the tripod structure is believed to be a lighter three-legged steel jacket. Forces from the tower are transferred to the three steel piles via a steel frame located beneath the central steel column, which is below the turbines. To assist in anchoring the tripod to the seabed, piles are positioned at each leg location. In three different places, the seafloor is pushed between ten and twenty meters down. The tripod is deployed at transitional water depths in projects like The Global Tech I, BARD Offshore 1, and Trianel Windpark Borkum. A tripod may be a more useful tool than a monopile. The monopolies need larger suction caissons or longer piles in the case of major weather occurrences like hurricanes or typhoons.

- **High Rise Pile Cap (HRPC):** The HRPC structure is ideal for sea areas with water depths from 0 to 20 meters and is compatible with soft soil foundations. It offers robust resistance to seawater corrosion while being cost-effective, reliable, and easy to construct. The design features an elevated concrete bearing platform supported by a cluster of steel pipe piles, with the lower ends of these piles angled slightly outward. Predominantly used on the Asian continent, the HRPC structure constitutes 40% of all installed foundations in the region. Notably, all offshore wind farms in Vietnam utilize this type of turbine support structure. [14].

- **Suction Bucket:** When used to anchor offshore constructions, this technology might be thought of as upside-down buckets that are lowered into the seabed. By pumping the water out of the bucket, the pressure inside the bucket skirt is decreased. The offshore foundation can sink farther into the bottom thanks to the creation of this negative pressure and its weight. The installation of the suction bucket may be readily reversed in the event that the offshore foundation has to be removed. Large wind turbines and deep oceans are the ideal applications for this technology, which doesn't require bottom preparation. Furthermore, the quick and simple installation process makes this kind of construction more economically viable. As of right now, only China's XiangShui offshore wind farm has these kinds of support structures constructed [13], [15].

2.4 Economic Aspects of Offshore Wind Farms

Offshore wind farms represent a significant investment opportunity in the renewable energy sector, with various economic considerations influencing their development, operation, and impact. Understanding these economic aspects is crucial for policymakers, investors, and stakeholders to assess the viability and potential benefits of offshore wind projects.

- **Investment and Financing:** Infrastructure, equipment, and project planning must be invested in up front in large amounts for the establishment of offshore wind farms. Utility companies, institutional investors, private equity firms, and government agencies are examples of potential investors. Typically, financing alternatives combine debt, equity, and government subsidies. For projects to be financially viable and to secure funding, it is critical to evaluate the financial risks and rewards connected with offshore wind investments.

- **Cost-Benefit Analysis:** Conducting a comprehensive cost-benefit analysis is essential for evaluating the economic feasibility of offshore wind projects. This analysis considers factors such as capital expenditures (CAPEX), operational expenses (OPEX), revenue streams from electricity sales, renewable energy credits, and other incentives. Assessing the levelized cost of energy (LCOE) helps determine the competitiveness of offshore wind power relative to other energy sources, such as fossil fuels and onshore wind.

- **Market Dynamics:** Offshore wind farms operate within dynamic energy markets influenced by factors such as government policies, technological advancements, energy demand, and fossil fuel prices. Understanding market trends and regulatory frameworks is crucial for project developers and investors to make informed decisions. Long-term power purchase agreements (PPAs) with utilities and corporate buyers provide revenue stability and mitigate market risks.

- **Supply Chain and Job Creation:** The development and operation of offshore wind farms create opportunities across the supply chain, including manufacturing, construction, installation, and maintenance services. Investing in local supply chains and workforce development can enhance economic benefits and support job creation in coastal communities. Government incentives and procurement policies may encourage domestic manufacturing and job growth in the offshore wind industry [16].

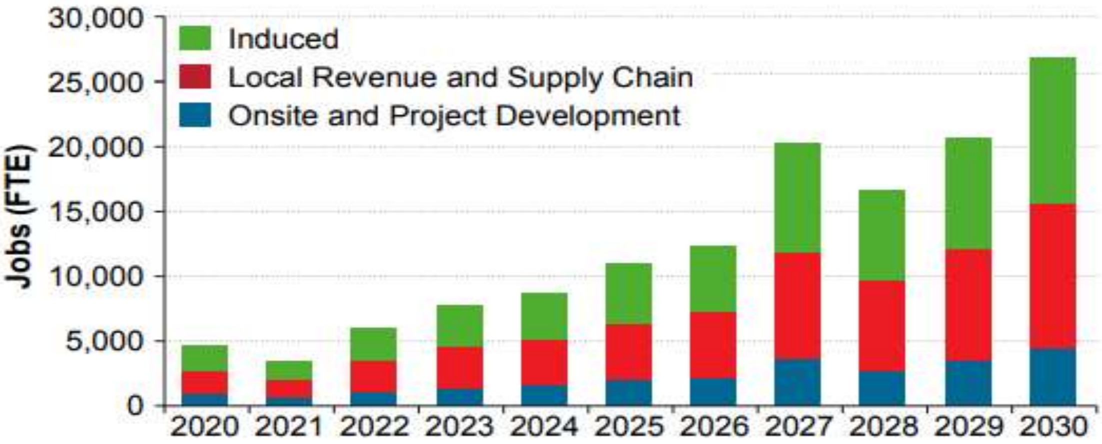

Fig 2.6: Projected number of jobs generated by offshore wind development from 2020 to 2030[16]

- ❖ **Socio-Economic Impacts:** Offshore wind farms can have significant socio-economic impacts on local communities, ranging from job creation and economic development to environmental conservation and tourism. Stakeholder engagement and community benefits agreements are essential for addressing concerns, maximizing local benefits, and fostering positive relationships between project developers and host communities.
- ❖ **Return on Investment and Financial Performance:** For investors and project developers, evaluating the offshore wind projects' financial performance and return on investment (ROI) is essential. Project expenses, income sources, operational effectiveness, market conditions, and regulatory risks are some of the variables that affect financial performance. Stakeholders may maximise project outcomes and make well-informed decisions by assessing the financial indicators and risks related to offshore wind projects.

2.5 Upcoming Developments in Offshore Wind Farms

The offshore wind industry's drive toward larger turbines are not expected to abate in the upcoming years. Global wind turbine ratings are predicted to average 6 MW, which is 37% more than the present average. The European market, led by Germany and the UK, will account for the majority of this growth rise. Turbine height and rotor diameter increases are also anticipated to continue unabatedly. Table 1 illustrates a 23% and 19% global growth in turbine diameter and installation height, respectively Even if the European market is driving these gains, the Asian homonym will be close behind. In Europe and Asia, the turbines' average diameters will be 156 and 134 meters, respectively. This increase in diameter will have an effect on the turbine height, which will be 155 meters for offshore wind farms in Asia and 184 meters for installations in Europe. In addition, the planned offshore wind farms will have turbines with an average capacity of 6 MW instead of 4 M[15].

Table 1

Trends of offshore wind turbines [17].

	Parameters	Project Status	Europe	Asia	World
Average	Turbine capacity (MW)	Operative	7	4	6
		Pre/under construction	4	3	4
		Trend (%)	+47	+27	+37
		Uncertainty			30%
	Turbine diameter (m)	Operative	156	134	145
		Pre/under construction	112	107	111
		Trend (%)	+28	+23	+23
		Uncertainty			30%
	Turbine height (m)	Operative	184	155	171
		Pre/under construction	139	135	138
		Trend (%)	+25	+13	+19
		Uncertainty			66%

In the coming years, offshore wind turbines are expected to undergo significant advancements, spurred by continuous technological progress aimed at optimizing energy production, cutting expenses, and mitigating environmental effects. These advancements will encompass various notable trends:

First of all, the ongoing trend towards larger turbine sizes is expected to persist, as bigger turbines promise enhanced efficiency and cost-efficiency by harnessing more wind energy.

Secondly, the rise of floating offshore wind technology is broadening the scope of offshore wind expansion, enabling access to deeper waters and minimizing visual impact on coastlines.

Thirdly, innovations in materials science and turbine design, including lightweight materials and aerodynamic improvements, promise enhanced energy capture and reliability.

Moreover, the integration of advanced control systems and predictive maintenance algorithms is enabling turbines to operate more efficiently and reliably, reducing downtime and maintenance costs.

Furthermore, the future may see the integration of offshore wind with other renewable energy sources, such as solar and energy storage, to create hybrid energy systems that enhance grid stability and support a more sustainable energy mix.

Finally, as offshore wind development expands, there is a growing emphasis on mitigating environmental impact, with turbines incorporating features such as bird-friendly blade designs and noise reduction measures.

In summary, the future of offshore wind turbines embodies innovation, efficiency, and sustainability, fuelling the ongoing expansion of the offshore wind sector and opening up fresh avenues for global-scale clean, renewable energy production.

2.6 Summary

This chapter provides a comprehensive introduction to offshore wind farms, exploring their significance within the context of global efforts to combat climate change and transition to renewable energy sources. The initial segment of the introduction underscores the critical role of offshore wind energy in fulfilling renewable energy targets, driven by industrial advancements and technological innovations. The evolution of offshore wind technology and its increasing economic viability are illustrated through the historical progression of offshore wind farms, commencing with the pioneering Vindeby project.

The chapter also delves into the various types of offshore wind foundations, including monopiles, jackets, and suction buckets, detailing their suitability for different water depths and soil conditions. Economic aspects such as investment, financing, cost-benefit analysis, market dynamics, supply chain, job creation, and socio-economic impacts are thoroughly examined, highlighting the multifaceted nature of offshore wind projects.

Additionally, the chapter delves into forthcoming developments in offshore wind turbines, highlighting the persistent push towards larger turbine sizes, the emergence of floating offshore wind technology, progress in materials and design, intelligent turbine control systems, hybrid energy systems, and environmental concerns. These trends underscore the ongoing innovation, effectiveness, and sustainability of offshore wind energy, cementing its pivotal role in the worldwide shift towards clean and renewable energy sources.

CHAPTER 3
INTRODUCTION TO HVDC SYSTEM

3.1 Principles Of HVDC Transmission

HVDC systems work by converting alternating current (AC) into direct current (DC) at the transmitting end for the transmission of electricity over long distances and then converting it back into AC at the receiving end. This technology offers several advantages over traditional AC transmission, particularly for long-distance and underwater cable applications, such as those used for offshore wind farms.

The conversion process involves two primary components: the rectifier, which transforms AC to DC, and the inverter, which converts DC back to AC. The HVDC converter, a bidirectional device, simplifies the system by performing both functions. In unidirectional power transmission, a converter functions as either a rectifier or an inverter. In contrast, bidirectional systems, such as cross-border power trading, utilize a single converter that alternates between rectification and inversion depending on the power flow direction. Similar to AC transmission substations, HVDC converter stations contain all the equipment required for AC-to-DC and DC-to-AC conversion. The power capacity of an HVDC system is determined by the capability of its converters. HVDC converters minimize harmonics, boost reliability, and enhance fault tolerance in the transmission system. There are two main types of converters: Line Commutated Converters (LCC) or Current Source Converters (CSC), and Voltage Source Converters (VSC). These converters leverage advancements in power electronic devices like thyristors and transistors. A control system manages the flow of active power and the operation of converters within an HVDC network, ensuring system stability regardless of variations in AC voltage magnitude, phase angle, and frequency. [18].

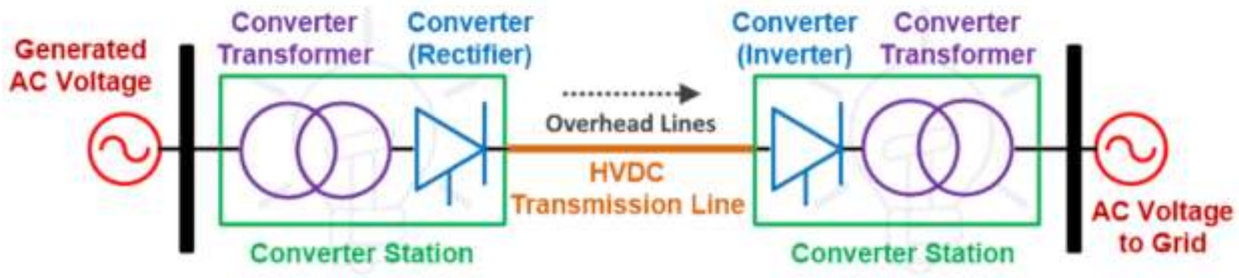

Fig 3.1: Block diagram of HVDC Transmission Line[19]

3.2 The Background of HVDC Transmission

HVAC and HVDC systems may both be used for bulk energy transfer. Due to early developments in AC transformers, which allowed for long-distance transmission at high voltages with lower losses, HVAC has historically been the most often used technique. The "War of Currents" between Edison and Tesla was successfully settled in favor of Tesla by this advancement in technology. But by the 1930s, mercury arc valves had become widely available, which was a major turning point that allowed DC to become more popular again in the energy transmission industry by allowing greater DC voltages to be used.

ABB created the first commercial HVDC link in Sweden by 1954, following years of testing. With a 98 km stretch and 20 MW at 100 kV, the Gotland 1 connection was operational [20]. With the invention of thyristor valves in the 1960s, the use of HVDC transmission advanced and overcame the shortcomings of its forerunners. The primary advantages included decreased thyristor weight and space constraints, together with enhanced control flexibility, power density, and efficiency. Thyristor-based lines thus swiftly took over the HVDC market. An intriguing overview of the early HVDC market shift from mercury-arc to thyristor switching valves is provided by Reference. IGBT valves were developed in the 1980s [20], [21] as a result of further invention, and by the late 1990s [21], they had been brought to the HVDC market. Technically speaking, IGBT valves are superior to earlier solutions because they provide enhanced power quality management and extra grid-support ancillary services (such reactive-power support) for linked AC networks.

3.3 Main Components of HVDC Converter Substation

1) AC switchyard
2) AC harmonic filters
3) High frequency filters.
4) DC filter
5) Converter
6) Converter transformer
7) DC smoothing reactor
8) DC switchgear
9) DC transducers [22]

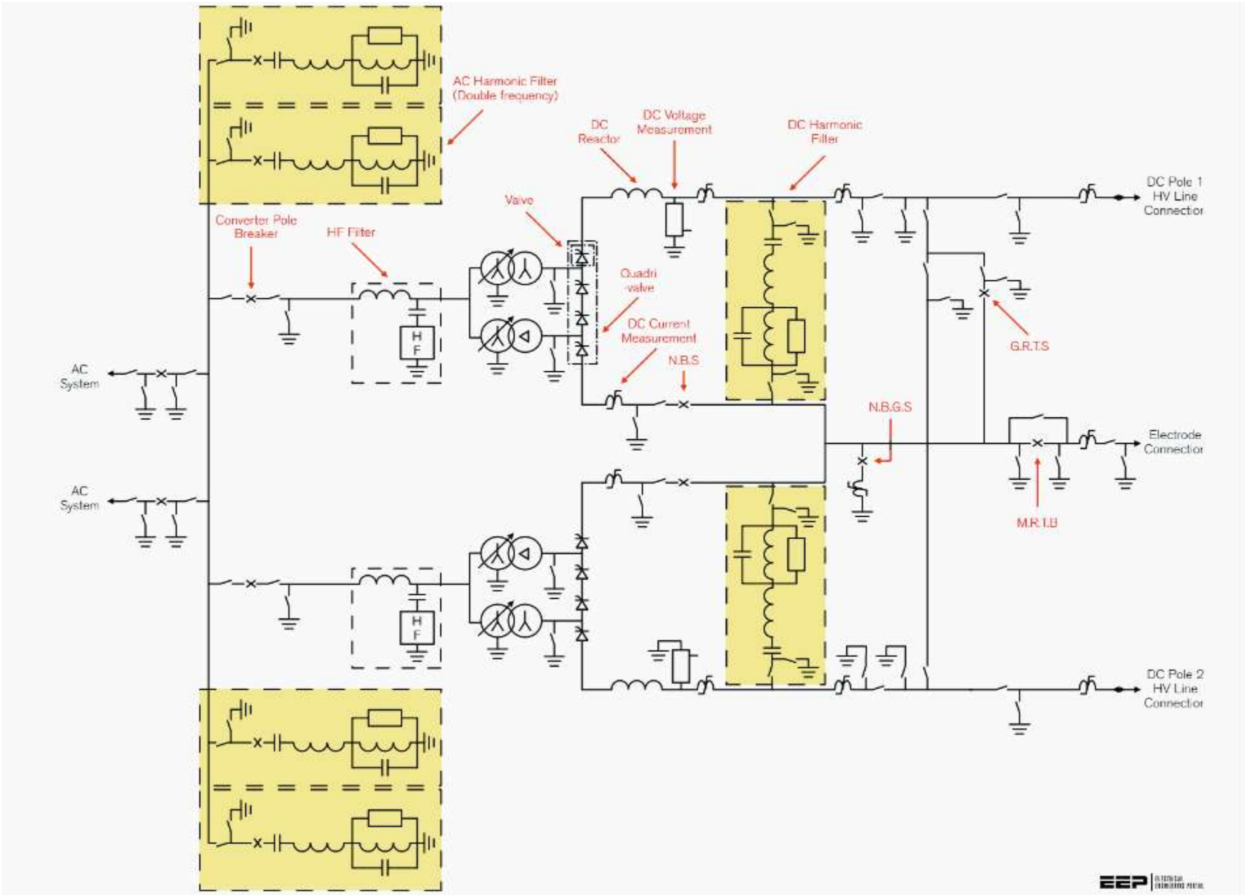

Fig 3.2: A standard diagram representing a bipolar HVDC converter [22]

3.4 HVDC Transmission Technology Overview

For more than 50 years, high-voltage direct current (HVDC) technology has been a crucial component of power transmission. It is mostly used to connect nonsynchronous networks, make long-distance energy transfer easier, and permit the transmission of cables under the sea and underground. The traditional systems use thyristor-type valves and either a current source converter (CSC) or a line commutated converter (LCC) HVDC. On the other hand, the introduction of voltage source converter (VSC)-HVDC, which makes use of quicker power electronic switches, is a noteworthy development that is expected to completely transform DC grids in the future. An overview of HVDC technology is given in this section [23].

There are two main types of HVDC transmission technology.

1. Line Commutated Converter (LCC)

- ❖ LCC HVDC systems use thyristor-based converters for the conversion of AC to DC and DC to AC.
- ❖ Thyristors are semiconductor devices which can handle high voltage and current levels. So, it is suitable for high-power transmission.

❖ LCC HVDC systems are well-established and have been widely used for a long time.

❖ They are generally used for long-distance transmission of bulk power, interconnecting asynchronous AC grids, and connecting remote power generation sources to the main grid [24].

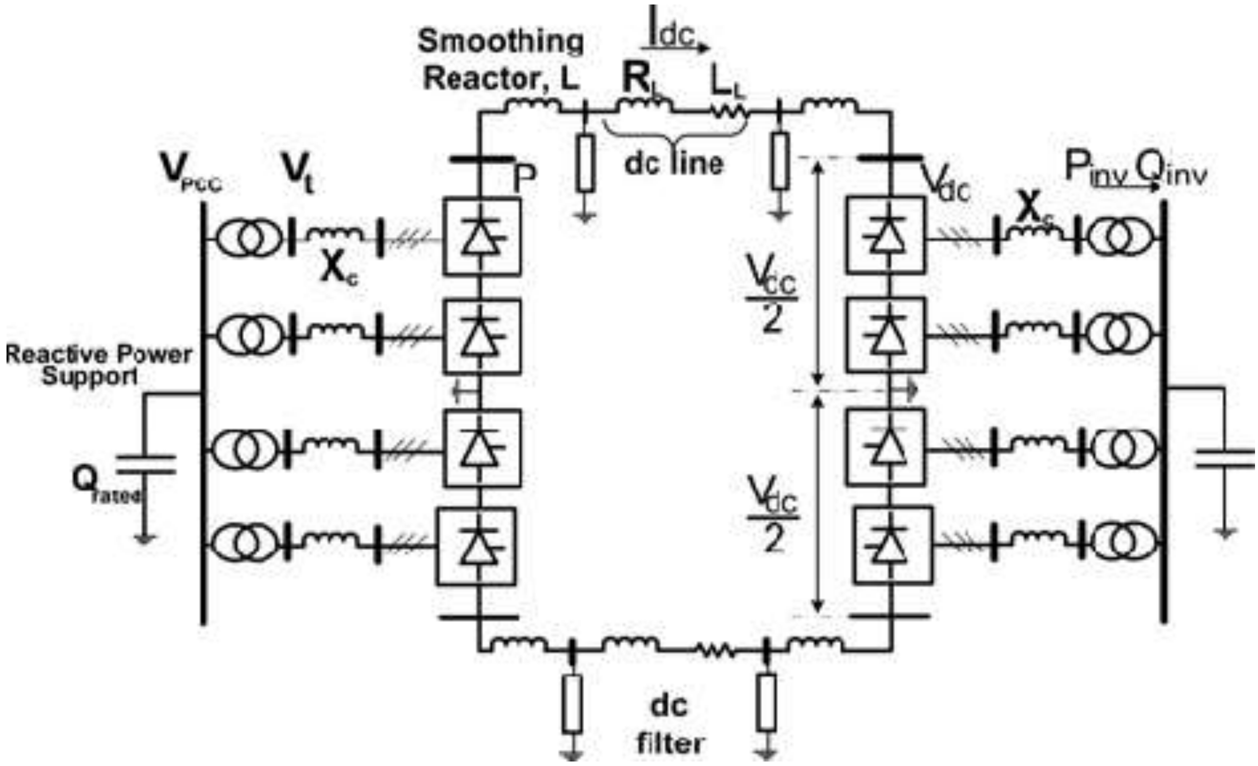

Fig 3.3: One-line depiction of the LCC HVDC system

2. Voltage Source Converter (VSC)

❖ To convert AC to DC and DC to AC, VSC HVDC systems use semiconductors such insulated-gate bipolar transistors (IGBTs).

❖ Compared to LCC HVDC, VSC technology offers more control over voltage and frequency and permits bidirectional power flow.

❖ VSC HVDC systems are appropriate for applications which need quick reaction times, such as, offshore wind farm connectivity, grid stabilisation, and the integration of renewable energy sources.

❖ Because they can reduce harmonic distortion and voltage swings, they are also the technology of choice for transmitting cables below and under submarines [26].

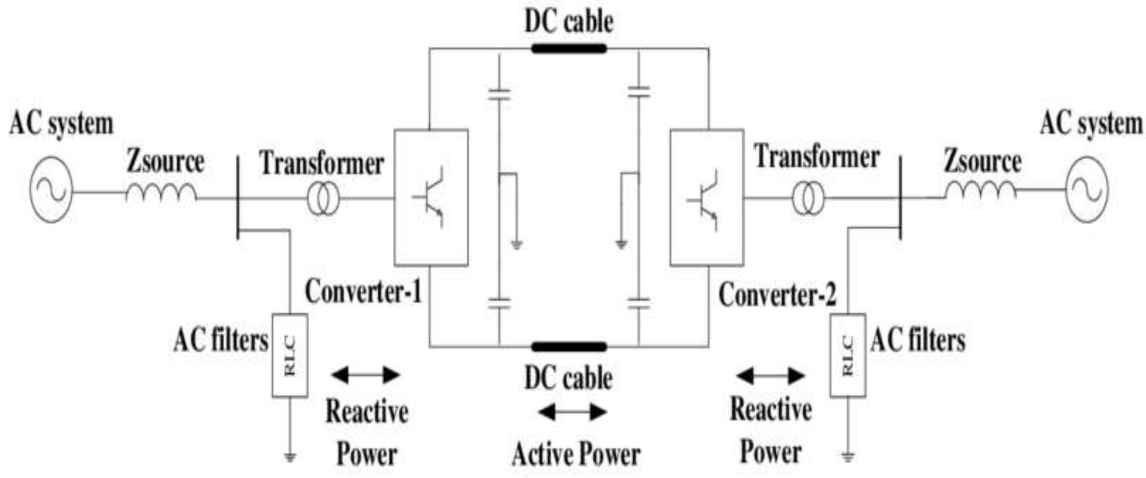

Fig 3.4: One line depiction of the VSC-HVDC System [27]

3.4.1 Comparison between LCC & VSC

LCC HVDC has previously dominated the HVDC industry by using thyristor-based converters. With its intrinsic VAR usage, decreased station power loss, and proven fault management capabilities on the AC side, it provides dependable performance. Nevertheless, it is constrained by the fact that it requires more reactive/filtering equipment, especially in weak grids, and that it depends on line frequency for commutation, resulting in a bigger footprint for the converter station. For high-power, long-distance transmission projects, LCC HVDC is frequently utilised.

On the other hand, VSC HVDC, which uses IGBT-based converters, is a more recent and important development in the HVDC field. Fast power-flow reversal, a reduced footprint for the converter station, lower intrinsic VAR consumption, inherent VAR management, and grid support are only a few of its benefits. Multi-terminal HVDC systems and offshore and cable-based projects are especially well-suited for VSC HVDC. In contrast to LCC HVDC, it may have fewer viable rating combinations and has more upfront expenditures, particularly at higher ratings.

Table 2

Comparison between HVDC transmission technology options [28].

Feature	VSC (Voltage Source Converter)	LCC (Line Commutated Converter)
Switching Device	IGBT (1990s - Present)	Mercury Arc (1950s-1970s), Thyristor (1970s - Present)
Commutation (Frequency Range)	Self-Commutated (up to several kHz)	Line-Frequency Dependent (50-60 Hz)
Station Power Loss	Approximately 1%	Between 0.6% and 0.8%
Power-Flow Reversal Mechanism	Current Direction Reversal (Fast, increases reliability)	Voltage Polarity Reversal (Slow, adds current stress)
Network Strength Dependency	Mostly Independent	Dependent (requires expensive equipment for weak grids)
Converter Station Footprint	Smaller by 40-50%	Larger
Inherent VAR Consumption	None, can support reactive power to AC grid	50-60% of rated power
Reactive/Filtering Equipment Requirements	Low	High (Costly)
Inherent VAR control and Grid Support	Yes	No
Inherent AC Grid Black-Start Capability	Yes	No
Fault Handling Capability - AC Side	Higher (Supports MVAR/Black Start)	Lower (Dependent on line frequency)
Fault Handling Capability - DC Side	Lower (High rate of current change)	Higher (DC Reactor/SC failure protection)
AC & DC Side Harmonics Level	Lower	Higher
Market Share (# of Projects)	(1954-2018) 19%, (2010-2018) 30%	(1954-2018) 81%, (2010-2018) 70%

Available Rating Combinations	Max: 2000 MW / +500 kV	Max: 12,000 MW / +1100 kV
	Avg: 2000 MW / +400 kV	Avg: 580 MW / +220 kV
Common Applications	Ideal for offshore and cable-based projects	Suitable for high-power, long-distance transmission
Multi-Terminal HVDC Suitability	Very Suitable	Limited Suitability
Station Costs (at High Ratings)	Higher	Lower

3.5 Different Types Of HVDC Links

Various types of HVDC links are used to connect two networks or systems. Discussed below:

1. **Monopolar**: A monopolar link returns current through a single negative-polarity conductor and either the sea or the ground; a metallic return is occasionally utilised. Each pole ends with two converters. Pole earthing is accomplished using earth electrodes positioned between 15 and 55 km from the relevant terminal stations. However, the Monopolar connection has some drawbacks because it relies on the earth for current return. Currently, less of these links are used.

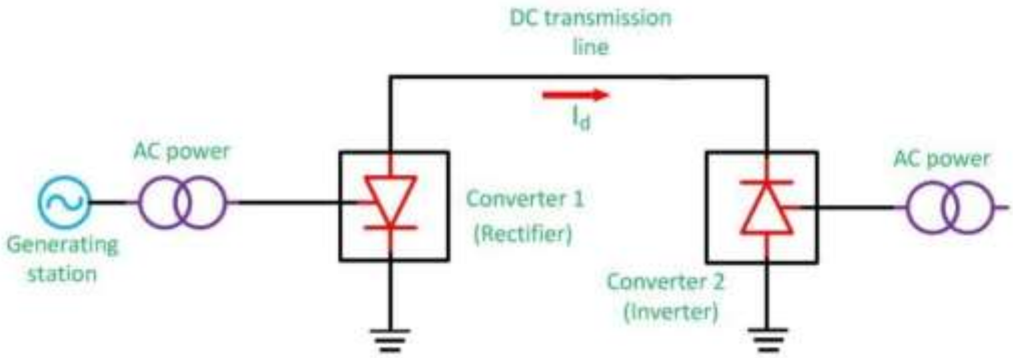

Fig 3.5: Monopolar HVDC link [29]

2. **Bipolar**: Two conductors, one positively charged and the other negatively charged in relation to the earth, make up the bipolar connection. There is a converter station on either end of the connection. Using electrodes, the midway between the converter stations is grounded. Precisely half of the voltage used in the transmission line for HVDC transmission is applied to the grounded electrodes.

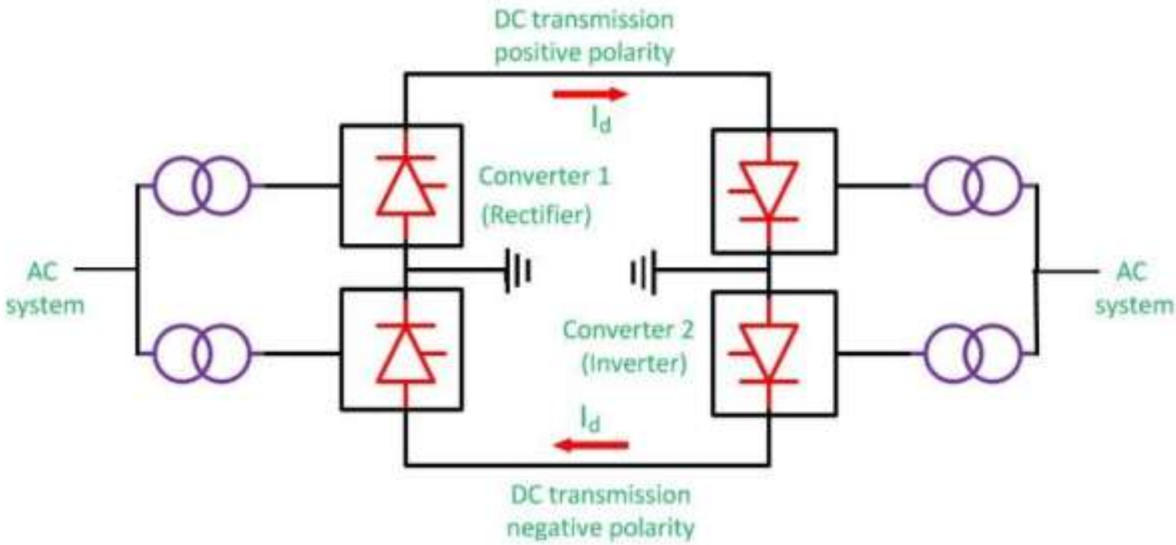

Fig 3.6: Bipolar link [29]

3. **Homopolar:** A homopolar link always functions with an earth or metallic return and consists of two conductors with the same polarity, often negative. Because the poles in the

homopolar connection are operated in parallel, the cost of insulation is decreased. It is not used nowadays

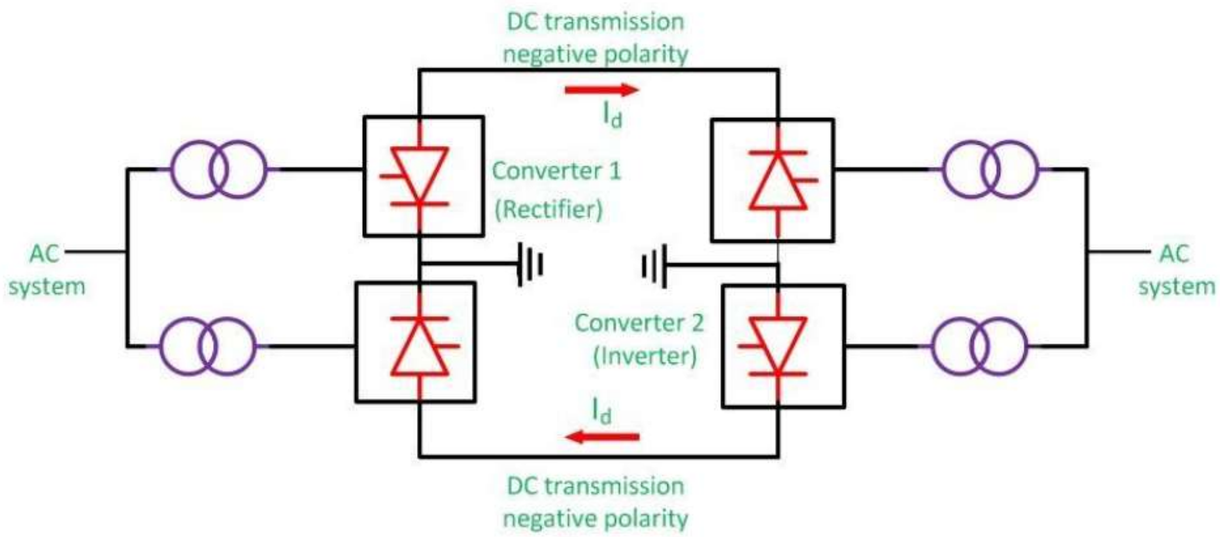

Fig 3.7: Homopolar link [29]

3.6 Advantages of HVDC transmission

HVDC transmission has the following primary benefits over High Voltage Alternating Current (HVAC) transmission:

1. Asynchronous connections, capable of linking two AC systems with differing frequencies.
2. Overcoming technical challenges involves utilizing HVDC for lengthy cable systems when AC systems are insufficient. In AC transmission, the high cable capacitance induces considerable capacitive current (reactive power flow), limiting the available current capacity for actual power transfer.
3. There is no need for upgrading protective devices due to the absence of an increase in short-circuit capacity in the link.
4. Losses are low.
5. Higher power transfer.
6. There are no limitations on stability distance.
7. The absence of reactive voltage drops leads to improved voltage regulation under both heavy and light loading conditions, eliminating the Ferranti effect.
8. Enhanced control capabilities can bolster AC system stability and serve as a rapid generation reserve. [30].

3.7 The Use of HVDC Transmission for Offshore Wind Projects

As wind farms are constructed farther offshore, utilizing conventional AC power lines becomes increasingly challenging due to technical constraints. This is where high-voltage direct current (HVDC) technology becomes valuable. HVDC, a well-established method for transmitting power over long distances on land, is now being employed to link offshore wind farms to the mainland in Europe. However, employing HVDC for offshore wind farms presents several novel challenges, such as managing the distinct offshore power grid. But HVDC also has many benefits. Such as, it reduces power losses and gives more control over the electricity flow. Moreover, it opens up opportunities to connect multiple wind farms to different countries and also transmit electricity from the turbines to the mainland using DC all the way. A lot of research and development is going on to make this possible, including creating new components like DC circuit breakers and converters [31].

3.8 Summary

This chapter dives into the fundamental concepts, historical context and technological components of HVDC transmission systems. HVDC systems convert alternating current (AC) to direct current (DC) for efficient long-distance transmission, making them ideal for undersea cable applications such as offshore wind farms. The chapter delves into the history of HVDC technology, beginning with mercury arc valves and on to current thyristor and insulated-gate bipolar transistor (IGBT) converters. Moving on, it discusses the key components of HVDC converter substations, including AC and DC equipment, and gives an overview of LCC and VSC HVDC technology. The topic also includes other types of HVDC links, such as monopolar, bipolar, and homopolar connections, as well as the advantages of HVDC transmission over standard alternating current. In the end it focuses on the use of HVDC in offshore windfarm.

CHAPTER 4
METHODOLOGY

4.1 Introduction

The operation of AC grids in conjunction with HVDC systems requires intricate protection mechanisms to safeguard the integrity and reliability of the overall power network. Fault occurrences can propagate swiftly and disrupt power flow, potentially leading to widespread outages and costly downtime. Hence, an in-depth study of fault characteristics and effective protection strategies is imperative to ensure the seamless and secure operation of these complex energy systems.

In this context, simulation tools play a pivotal role in comprehensively analysing fault scenarios and evaluating protection schemes. Utilizing advanced software platforms like DIgSILENT PowerFactory enables detailed modelling and simulation of fault events, facilitating a nuanced understanding of system behaviour and response dynamics. Furthermore, severity indexing methodologies applied through case studies offer useful insights into the criticality of different fault types and guide the prioritization of protection measures.

This literature review endeavours to delve into the intricacies of fault analysis and protection strategies within AC grids connected to HVDC offshore wind farms. By examining existing research and advancements in this field, it aims to elucidate the methodologies employed, evaluate the efficacy of current protection systems, and propose potential modifications to enhance system resilience and reliability (if possible).

4.2 Flowchart Of Proposed Methodology

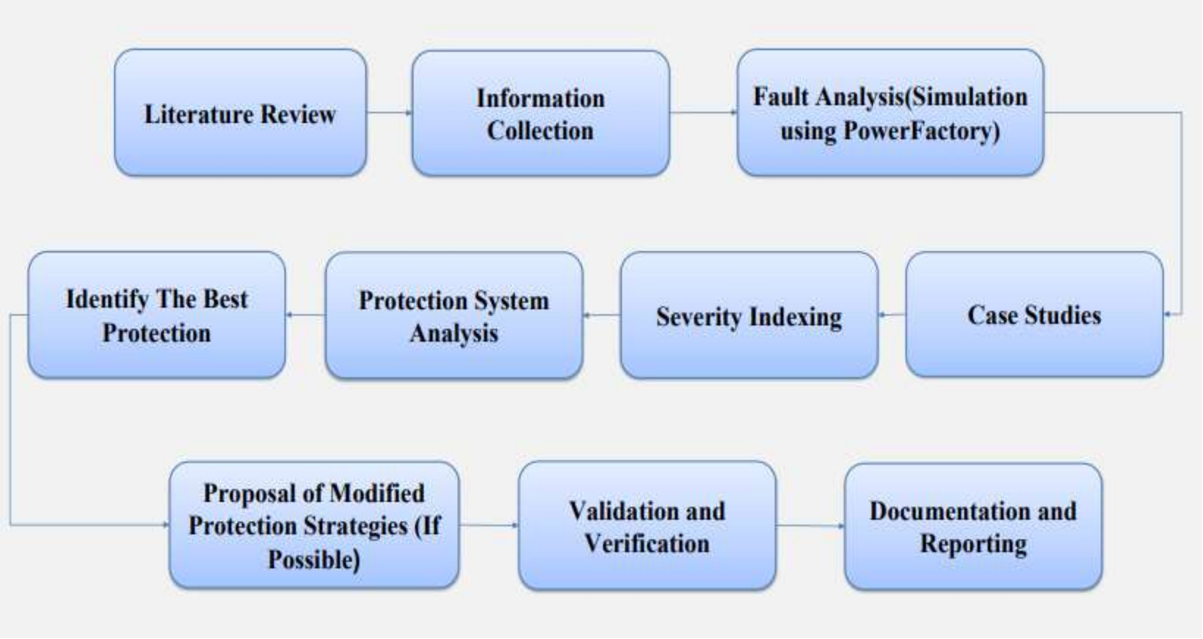

Fig 4.1: Methodology flowchart

Let's Discuss some main points of the methodology that was followed:

1. Information Collection:

This literature review focuses on the fault analysis and protection systems of AC grids connected to HVDC offshore wind farms. The scope encompasses studies published within the past decade, prioritizing peer-reviewed articles in English. Searches will be conducted in databases like IEEE Xplore and ScienceDirect using keywords such as "AC grid," "HVDC offshore wind farm," "fault analysis," and "protection systems." Inclusion criteria emphasize relevance and quality, filtering out studies lacking empirical data or theoretical rigor. This approach ensures a thorough compilation of scholarly works contributing to the understanding of fault analysis and protection systems in this specific context.

2. Fault Analysis (Simulation using DIgSILENT PowerFactory):

This section focuses on simulating various fault scenarios within AC grids connected to HVDC offshore wind farms using PowerFactory software. A build in HVDC model is used in this study. A 9 bus AC system is also used. Various fault (symmetric & asymmetric) scenarios were simulated in all the buses of both ac system as well as HVDC system [32]. Various analysis was done according to different parameters. Specific data extracted from these simulations include fault response times, voltage dips, magnitude of fault current, impact on electrical output, and system stability. Analysing this data provides insights into the effectiveness of existing protection mechanisms and highlights areas for improvement in fault detection and response strategies.

3. Severity Indexing:

Severity of faults were analysed by various case studies both in wind connected and disconnected systems. Firstly, indexes of fault severity were found with respect to the magnitude of fault current. Secondly a cooperative analysis of voltage dips due to various fault locations were evaluated both for wind connected and disconnected systems. These indexes can be very useful to give proper relay coordination and eventually give better protection [33].

4. Protection System Analysis:

Both distance and overcurrent relays were tested in simulation to compere which one is better in the 9-bus system. Firstly, the case studies were done in a radial system. Afterwards analysis was done in the 9 bus AC system.

5. Identify the Best Protection:

After various case studies it was found that in the AC system, overcurrent relays give better and reliable protection than distance relay. Though no protection was given in the HVDC side but after various studies it was found that distance protection is better in case of HVDC system due to long transmission line and other valid reasons.

4.3 Simulation Tool

Simulation tool used in this study was DIgSILENT PowerFactory.

- The calculation program PowerFactory, as written by DIgSILENT.
- It is a computer aided engineering tool for the analysis of industrial, utility, and commercial electrical power systems.
- It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.
- DIgSILENT power system calculation package was designed as an integrated engineering tool.
- It provides a complete “walk-around” technique through all available functions, rather than a collection of different software modules.
- PowerFactory Version 14, DIgSILENT represents a further step towards seamless integration of functionality and data management within a multi-user environment [34].

4.3.1 Key Features

1. Core functionalities of PowerFactory include defining, modifying, and organizing cases; executing key numerical routines; and managing output and documentation processes.

2. It features an integrated interactive single-line diagram for graphical representation and handling of data cases.

3. A comprehensive database for power system elements and base cases is provided.

4. Integrated calculation capabilities, such as determining line and machine parameters based on geometric data or nameplate information, are available.

5.Power system network configuration can be performed interactively or with online SCADA access.

6. A generic interface is available for integration with computer-based mapping systems

[35].

4.3.2 DIgSILENT PowerFactory Advantages for Simulation and Analysis.

PowerFactory has become the preferred choice for industry professionals due to its affordability, intuitive interface, and precise results. DIgSILENT offers numerous benefits for power system simulations and analyses, enhancing users' understanding of system behavior while significantly reducing the costs tied to manual analysis. Its user-friendly design ensures that even those new to power system simulations and analyses can use it effectively. With DIgSILENT, users are assured of obtaining accurate results, empowering them to make well-informed decisions about their power systems.[35]

4.4 Test system

The work of this study is based on 2 test systems. One is an offshore windfarm connected HVDC system and the other is a 9 bus AC system. The systems are given below:

4.4.1 HVDC System:

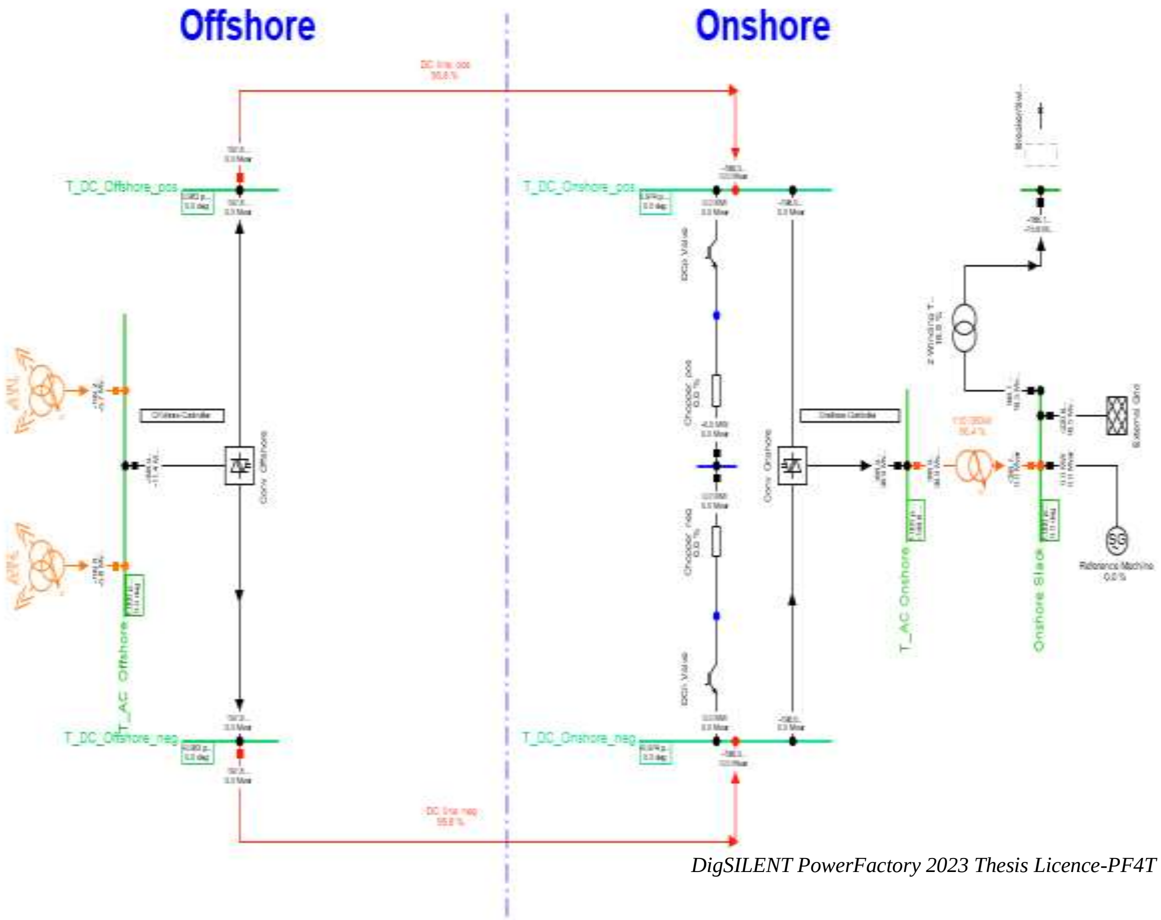

Fig 4.2: Schematic diagram of HVDC system

Here in this system, we can see that in the left side the power from wind is coming to the HVDC system from offshore windfarm. Which is around 389MW. Then this AC power of wind turbine in converted to high voltage DC by the offshore converters. The HVDC transmission line is 100km long here. Power is transmitted from offshore to the onshore converter station by this long HVDC transmission line. In the onshore converter station, the high voltage DC supply is converted to AC again. Then in the schematic we can see the power is consumed by the external grid as well as the reference machine. Which is around 220MW. The rest of the power goes to another test system (nine bus ac system). Which is around 169MW.

4.4.2 Nine bus AC system

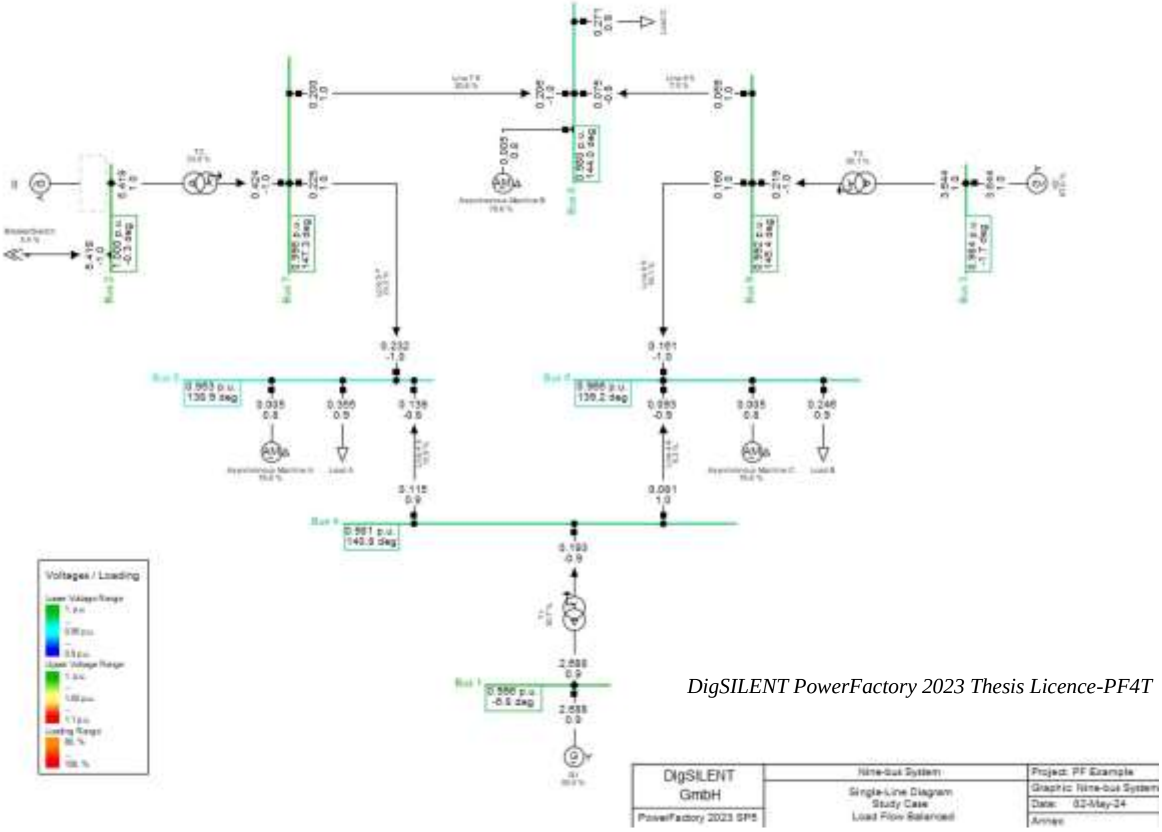

Fig 4.3: Schematic diagram of nine bus AC system

Here in the schematic diagram total 9 buses and 3 generators were used. Wind power line is connected in bus 2. Generator 2 operates when wind is disconnected from the AC system. Otherwise remains out of operation. Generator 1 is the slack bus here.

4.5 Summary

This chapter gives a good overview of a study conducted on fault analysis and protection systems in AC grids connected to HVDC offshore wind farms. It begins by highlighting the critical need for intricate protection mechanisms to ensure the reliability and integrity of power networks, given the potential for fault occurrences to disrupt power flow and cause widespread outages. Simulation tools, particularly DIgSILENT PowerFactory, play a pivotal role in analysing fault scenarios and evaluating protection schemes, providing valuable insights into system behaviour and response dynamics.

The methodology employed in the study is outlined, including information collection, fault analysis using PowerFactory simulation, severity indexing, protection system analysis, and identification of optimal protection strategies. Key findings indicate that overcurrent relays offer more reliable protection in AC systems, while distance protection is preferable for HVDC systems due to long transmission lines. The article also discusses the simulation tool DIgSILENT PowerFactory, its core features, popular applications, and advantages for power system simulation and analysis.

The study is based on two test systems: an HVDC system connecting offshore wind farms and a nine-bus AC system. Detailed schematics illustrate the setup of these systems, highlighting the flow of power from offshore wind generation to onshore converter stations and external grids. Through rigorous simulation and analysis, the study aims to enhance understanding of fault characteristics and effective protection strategies, contributing to the seamless and secure operation of complex energy systems.

CHAPTER 5
FAULT ANALYSIS AND SEVERITY INDEXING

5.1 Introduction

The incorporation of renewable energy sources has created new challenges for power management and grid stability in the rapidly evolving world of electrical power networks. Fault analysis and severity indexing are two of these issues that need to be taken very seriously, especially when it comes to systems that use HVDC and sustainable energy sources like offshore wind farms. Fault currents and voltage dips are two serious problems that can result from power system faults, which are defined by unintentional electrical disconnections brought on by equipment failure or disturbances. These disturbances have the potential to compromise the grid's safety and dependability and to result in widespread operational failures.

As the thesis is on the study on fault and protection of ac grid connected to HVDC offshore windfarm, the response of fault scenarios in both AC system as well as HVDC system must be evaluated. By observing the changes in the system due to fault, many decisions can be made. With respect to various parameters, the severe conditions of various fault locations can achieve. The parameters may include magnitude of fault current, voltage dip and tripping time etc. From that analysis, the index of fault severity can be evaluated. Besides, a comparative observation between wind connected and wind disconnected scenarios can also be done. Two indexes can be achieved from this observation. Moreover, by changing the fault resistance, the response of fault parameters as well as the severity indexes can also be analysed.

5.2 Fault Locations

During fault analysis, fault was simulated in all the buses of both HVDC and AC nine bus system. No fault was done in the line. Let’s see the fault locations of both the systems:

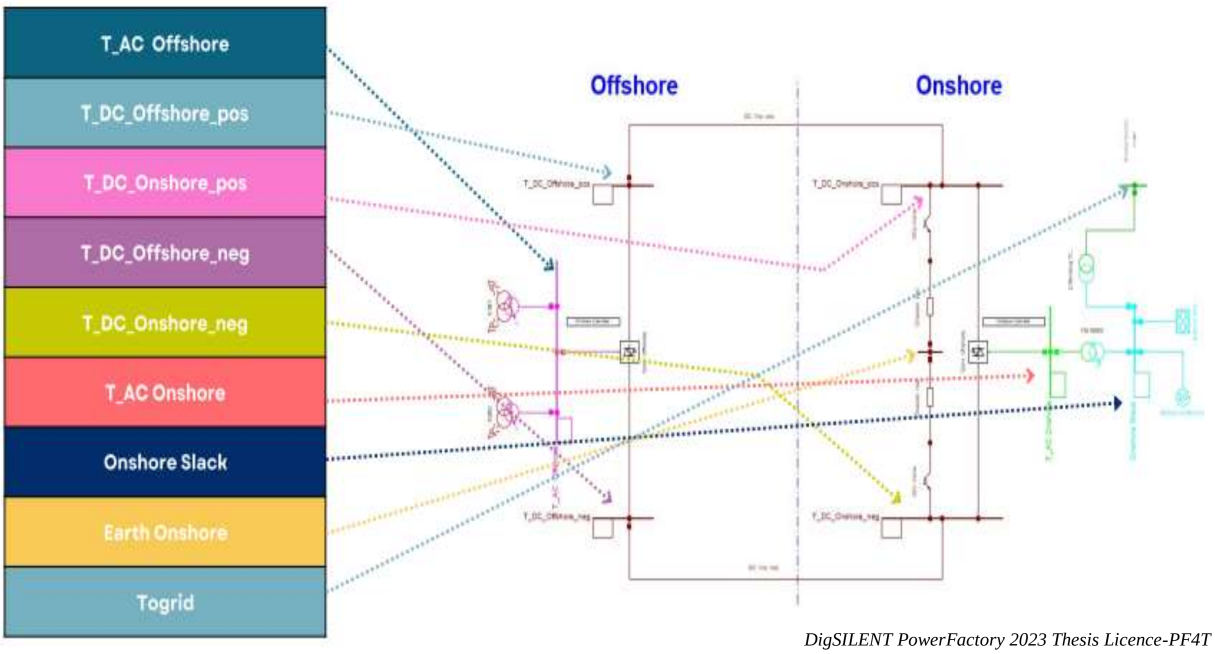

Fig 5.1: Fault locations of HVDC system

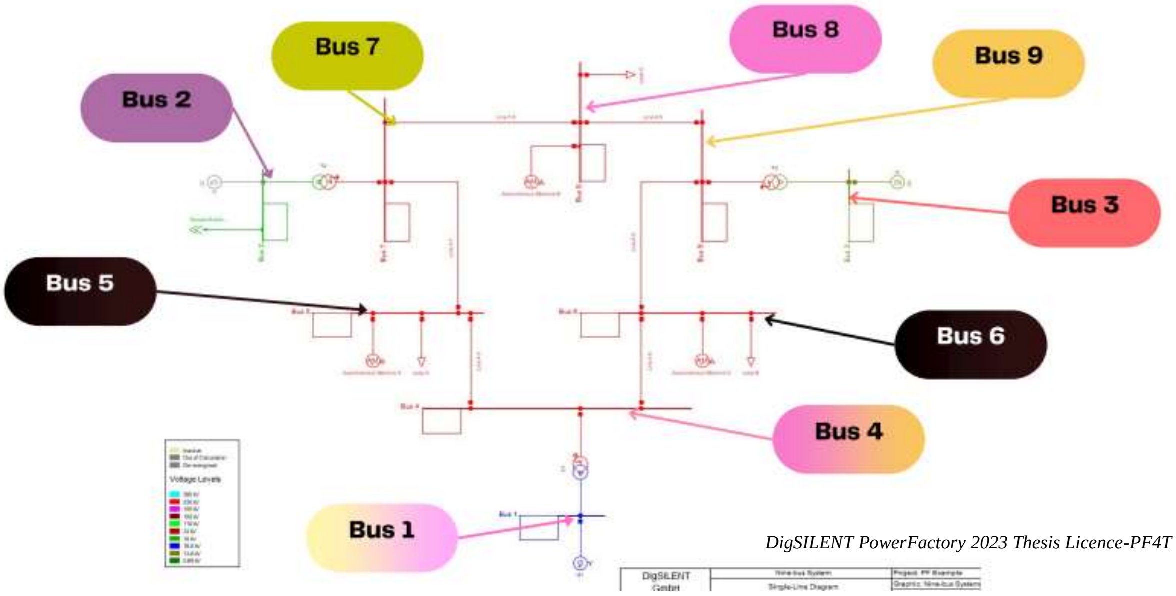

Fig 5.2: Fault locations of HVDC system

5.3 Case Studies and Simulation Results

Short circuit as well as phase to ground fault was done in both the system. The response of fault in each bus is different. Here in this study the response of fault was observed with respect to two parameters. They are magnitude of fault current and voltage dip. The fault was done in 1 second of the time period and the fault was cleared after 0.2 second.

5.3.1 Fault Response with Respect to Magnitude of Fault Current

The response to faults in electrical systems varies depending on the magnitude of the fault current. Fault currents occur when an abnormal path is created in the electrical system, typically due to a short circuit or ground fault. The magnitude of the fault current is influenced by factors such as the impedance of the faulted circuit, the available power source, and the system configuration. When the wind system is not connected to the AC nine bus system, the generator of bus 2 operates. Now, let’s see the response of fault with respect to fault current magnitude in each bus of the AC system, when the wind system is disconnected:

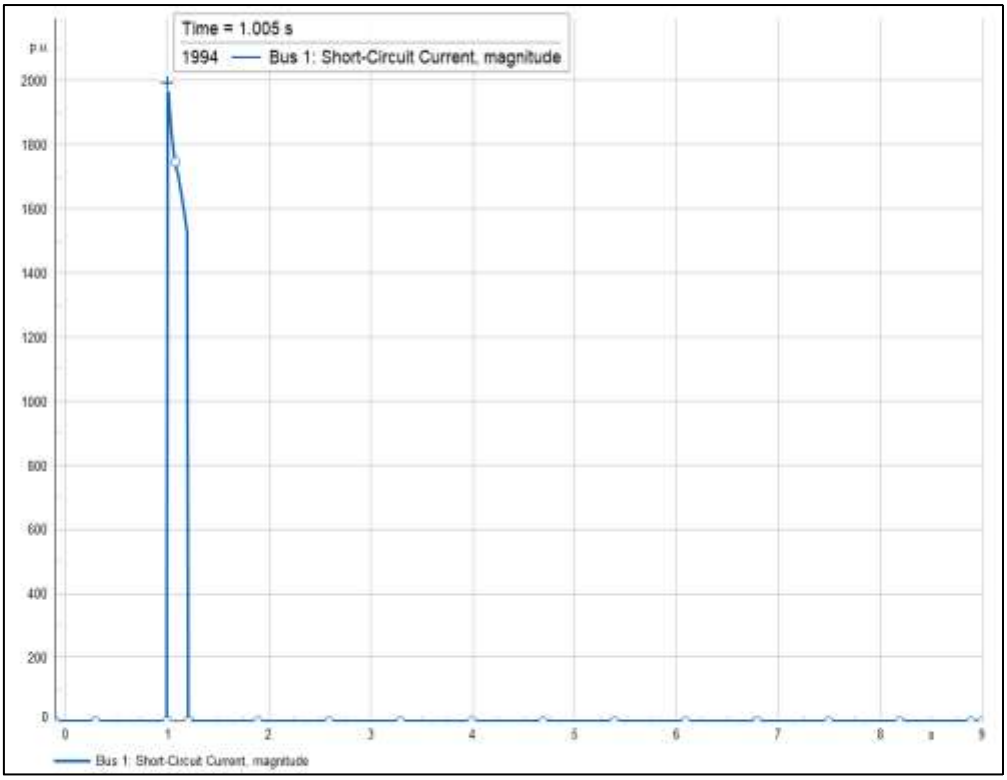

Fig 5.3: Fault current of bus 1

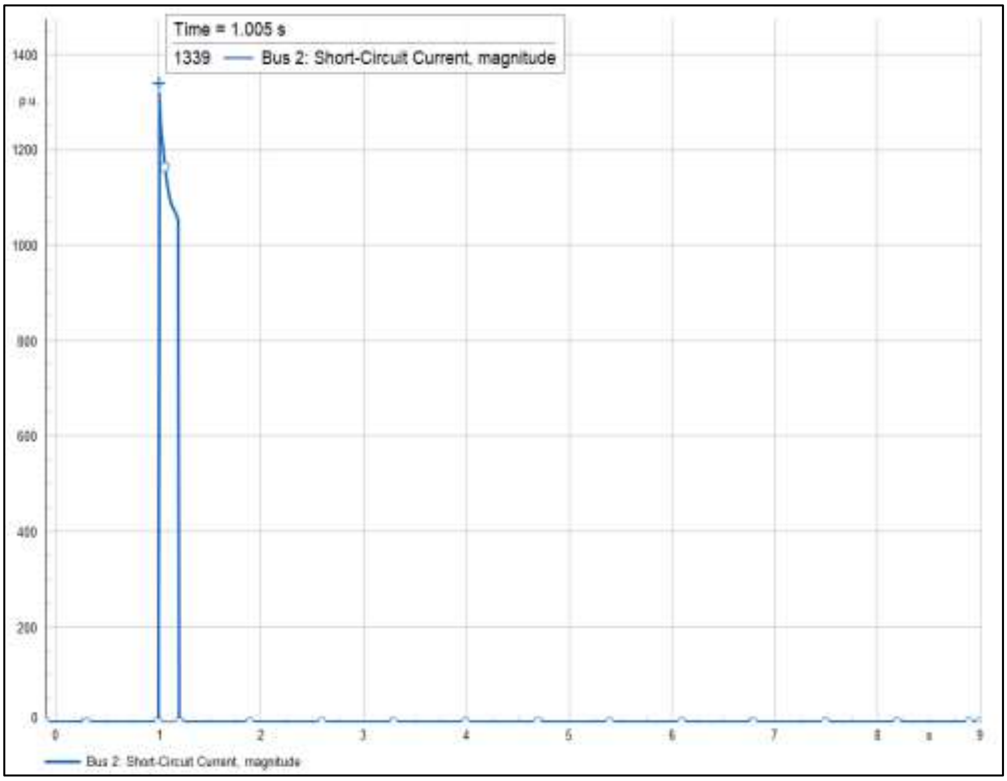

Fig 5.4: Fault current of bus 2

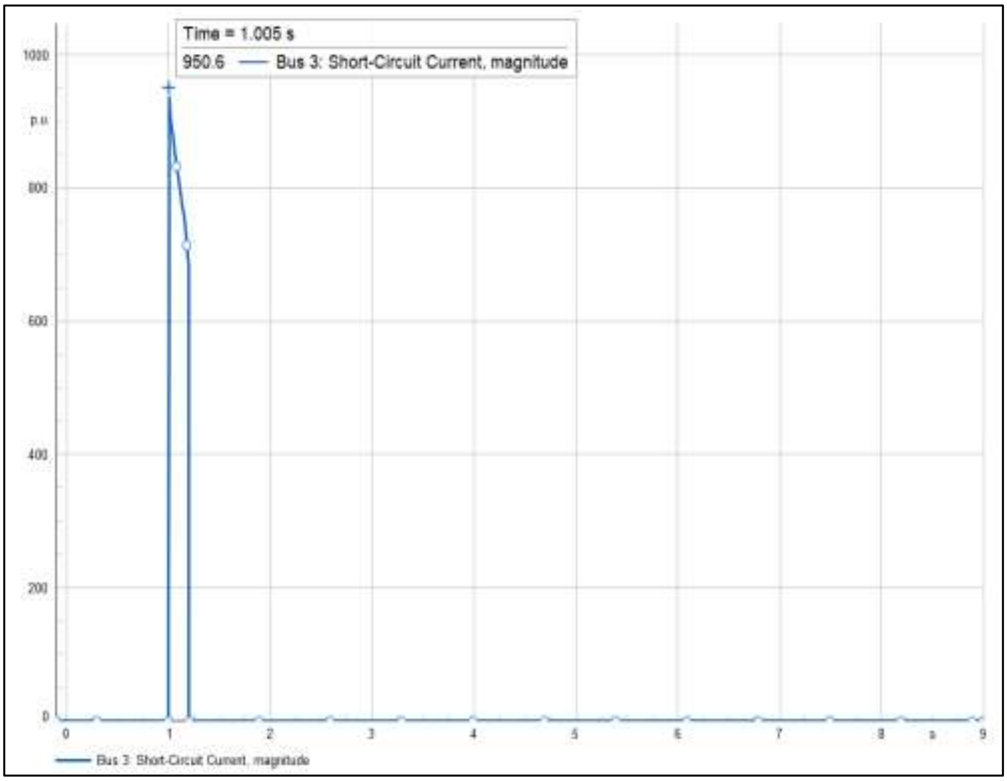

Fig 5.5: Fault current of bus 3

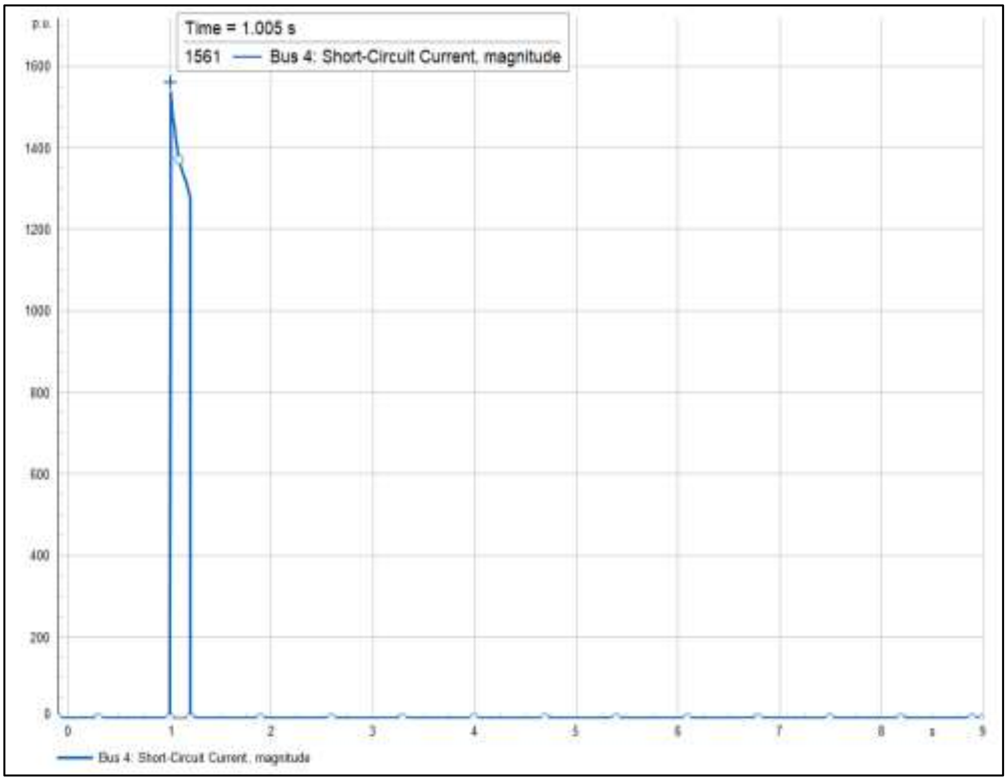

Fig 5.6: Fault current of bus 4

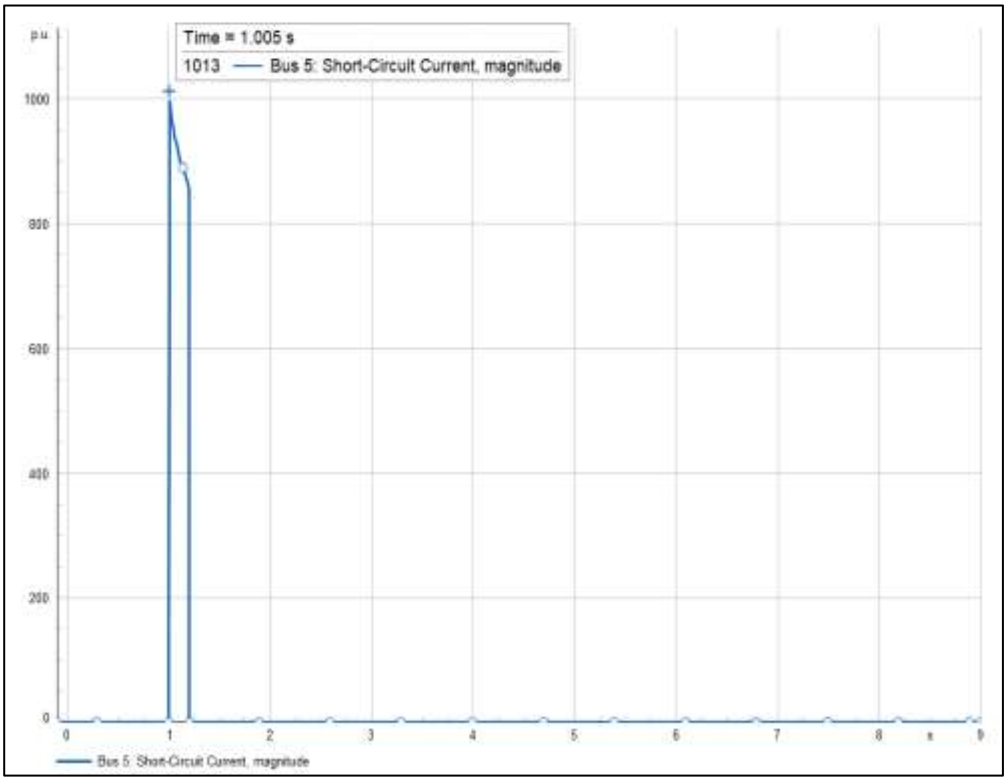

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Fig 5.7: Fault current of bus 5

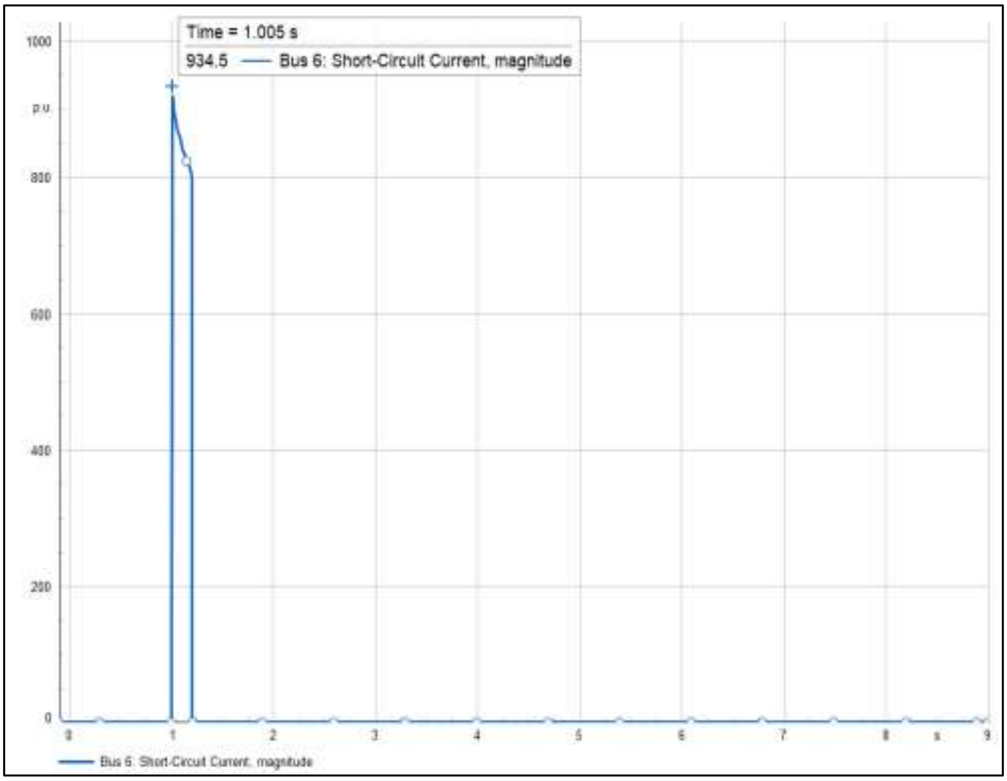

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Fig 5.8: Fault current of bus 6

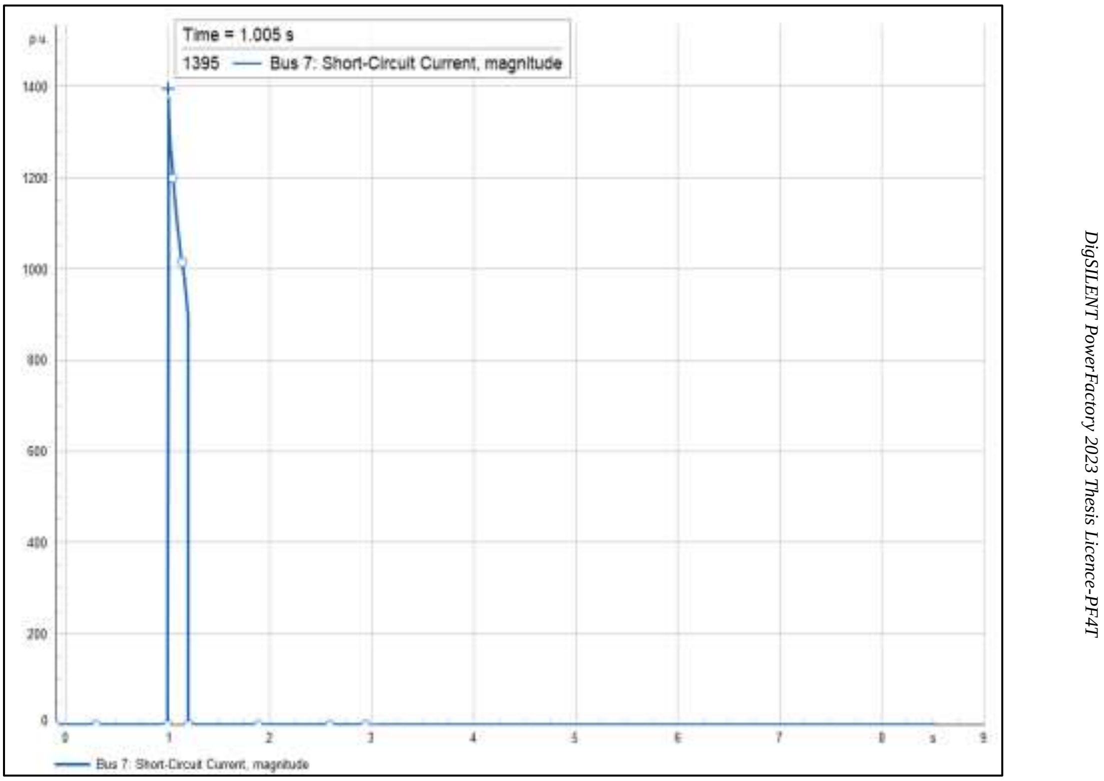

Fig 5.9: Fault current of bus 7

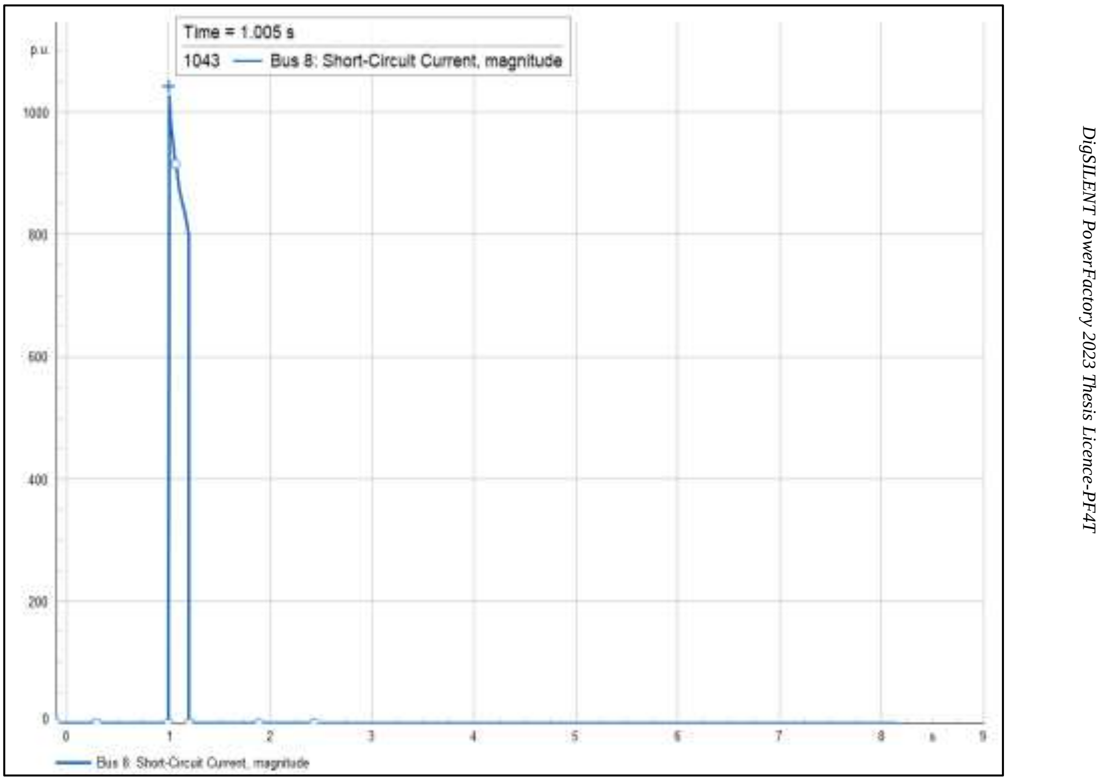

Fig 5.10: Fault current of bus 8

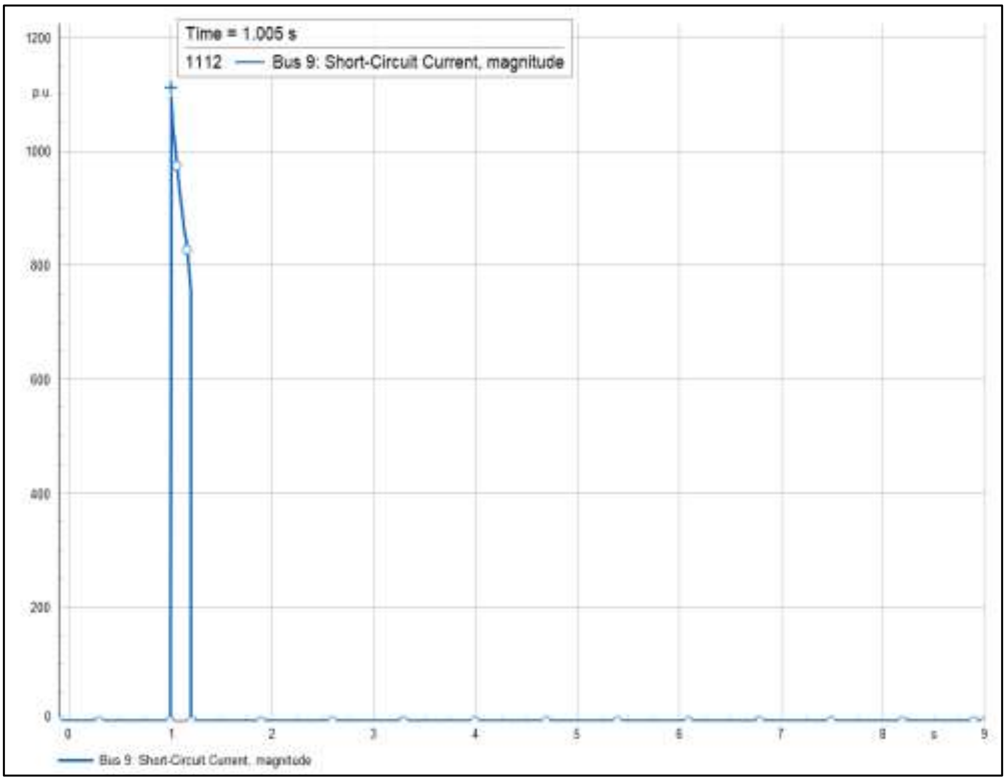

Fig 5.11: Fault current of bus 9

When the wind system is connected with the AC nine bus system, the response is quite different. The magnitude of fault currents become higher in this case. Also, the buses of the HVDC system have to be considered here. Now, let's see the response of fault current in each bus of the AC system as well as HVDC system, when the wind system is connected:

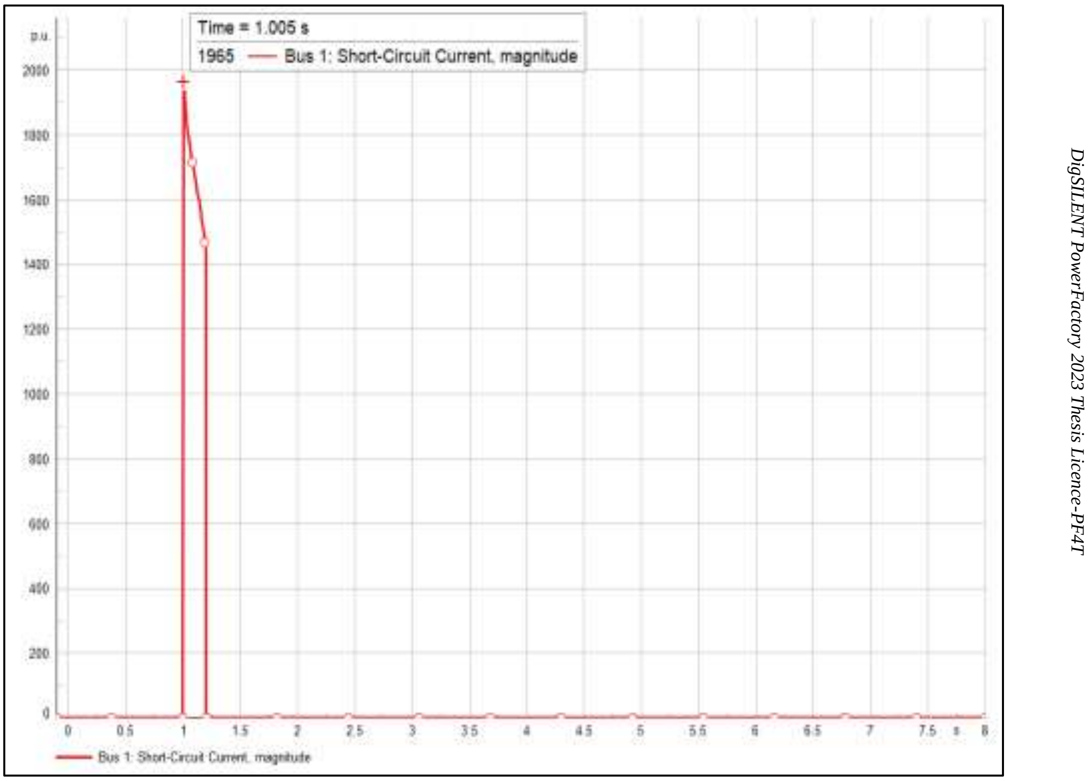

Fig5.12: Fault current of bus 1

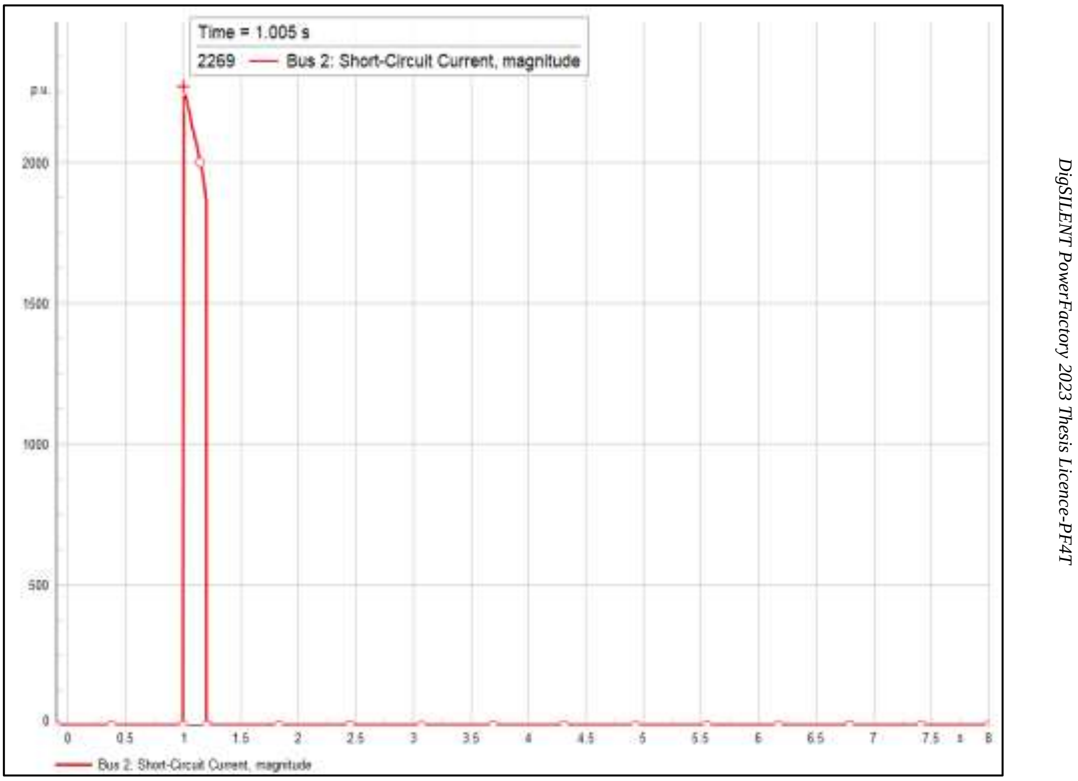

Fig 5.13: Fault current of bus 2

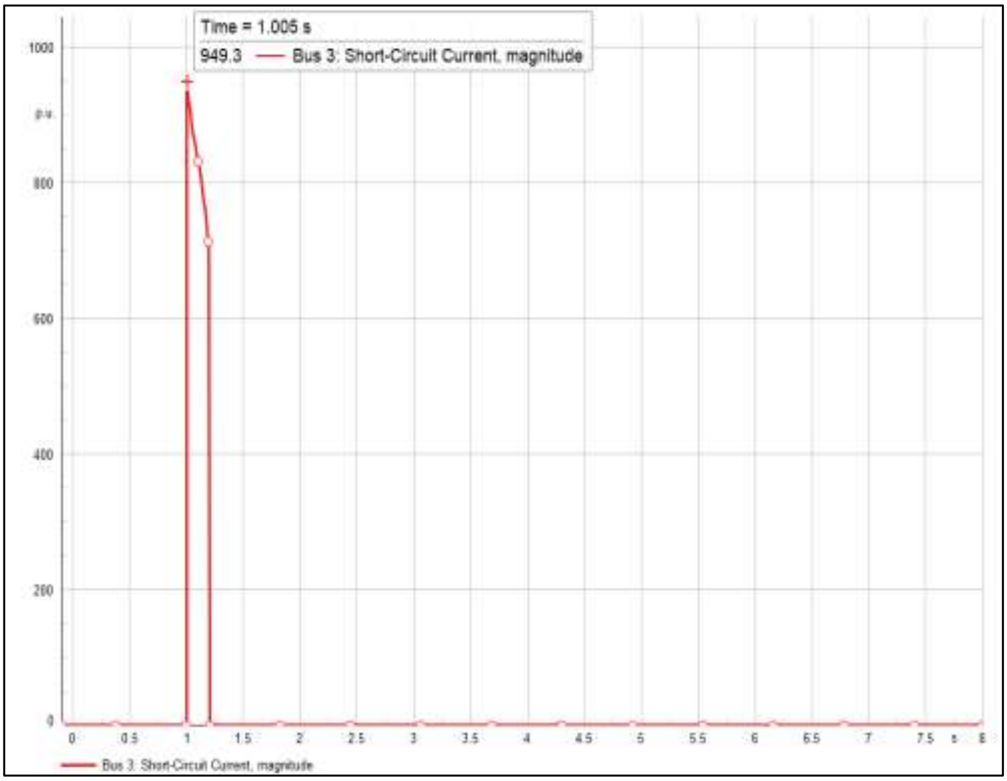

Fig 5.14: Fault current of bus 3

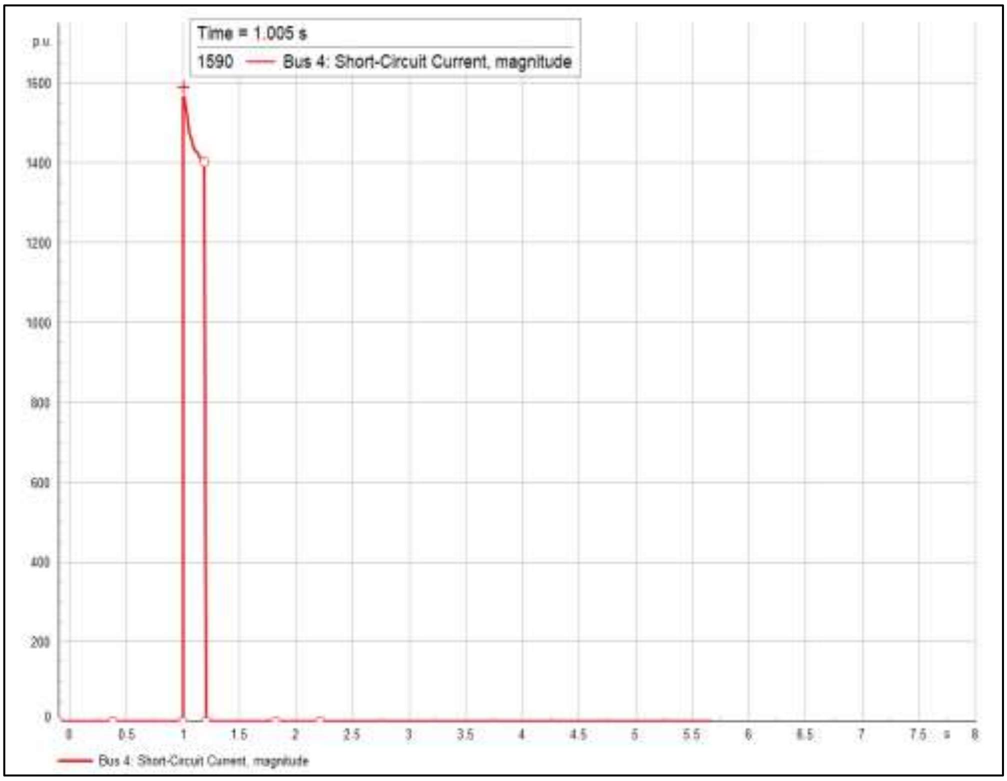

Fig5.15: Fault current of bus 4

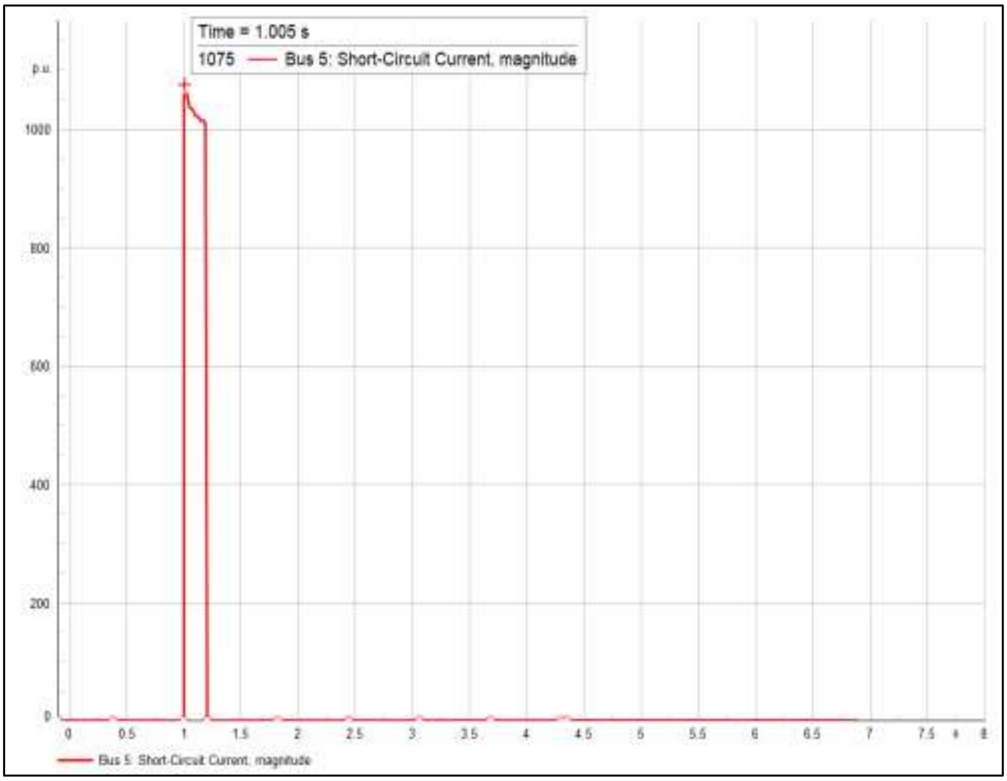

Fig 5.16: Fault current of bus 5

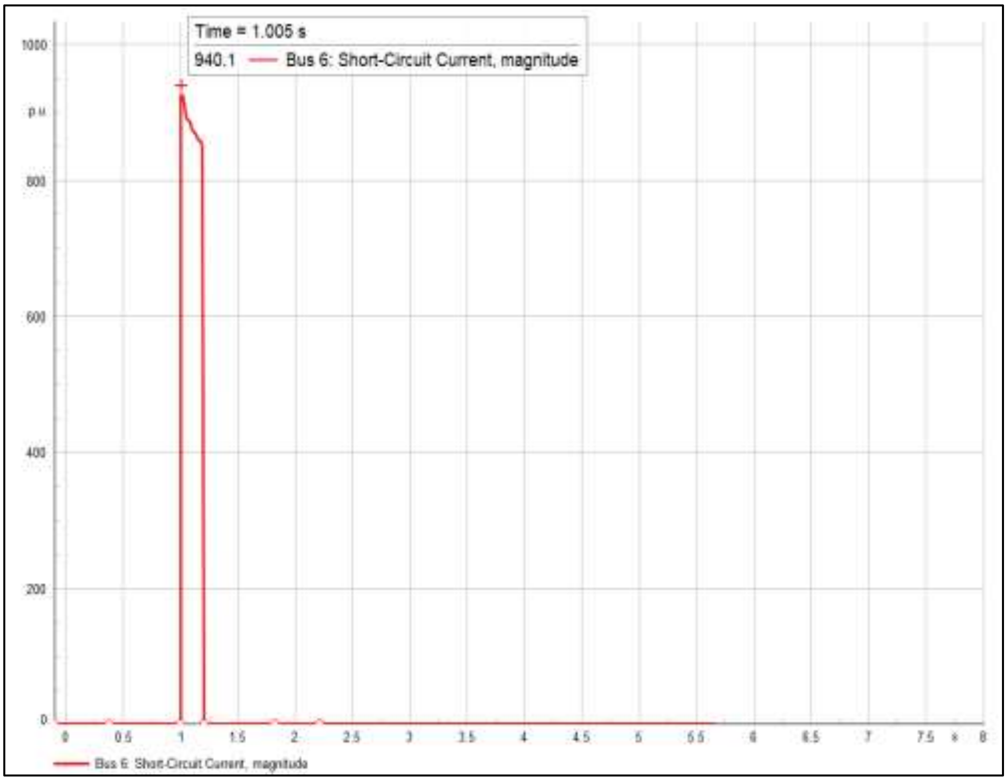

Fig 5.17: Fault current of bus 6

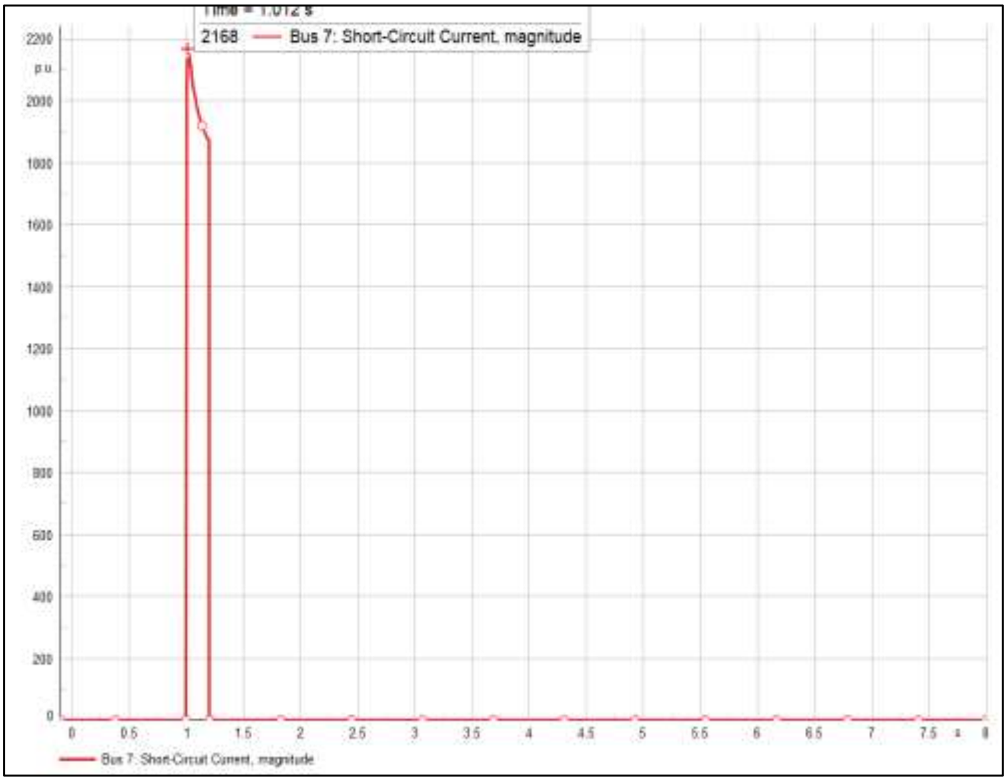

Fig 5.18: Fault current of bus 7

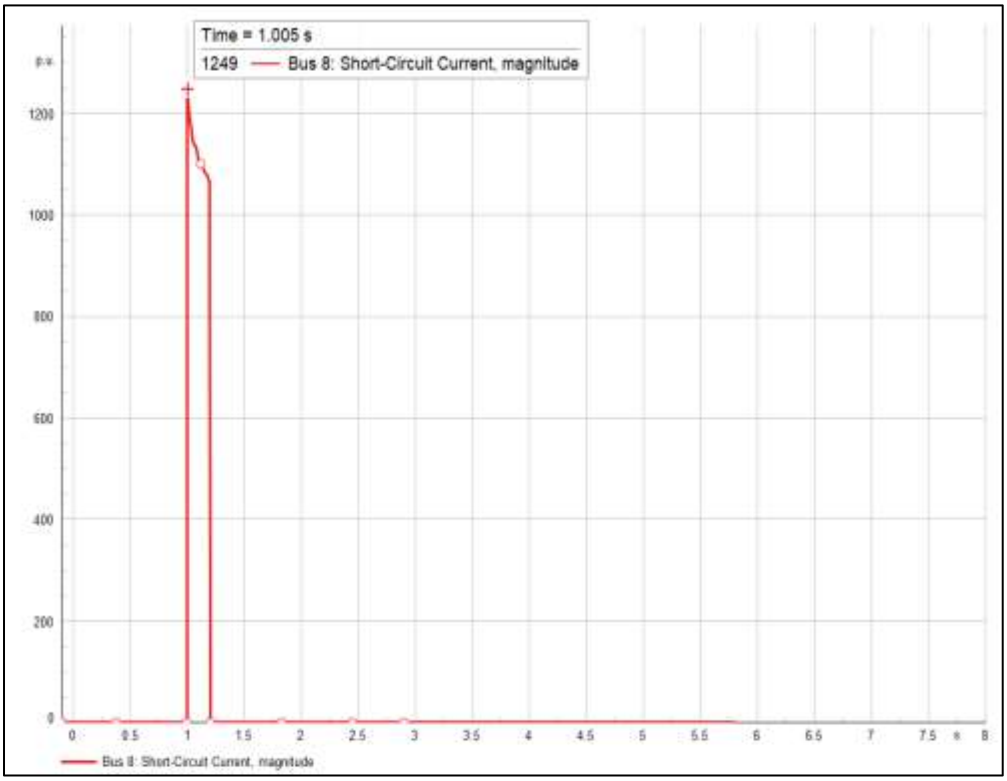

Fig 5.19: Fault current of bus 8

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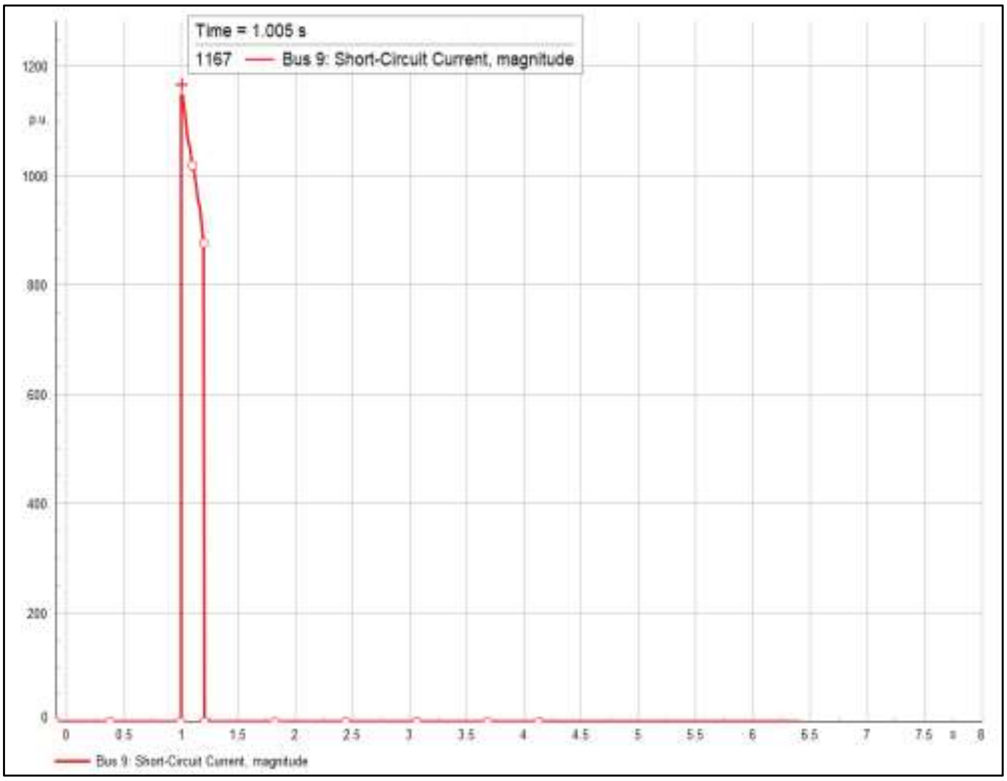

Fig 5.20: Fault current of bus 9

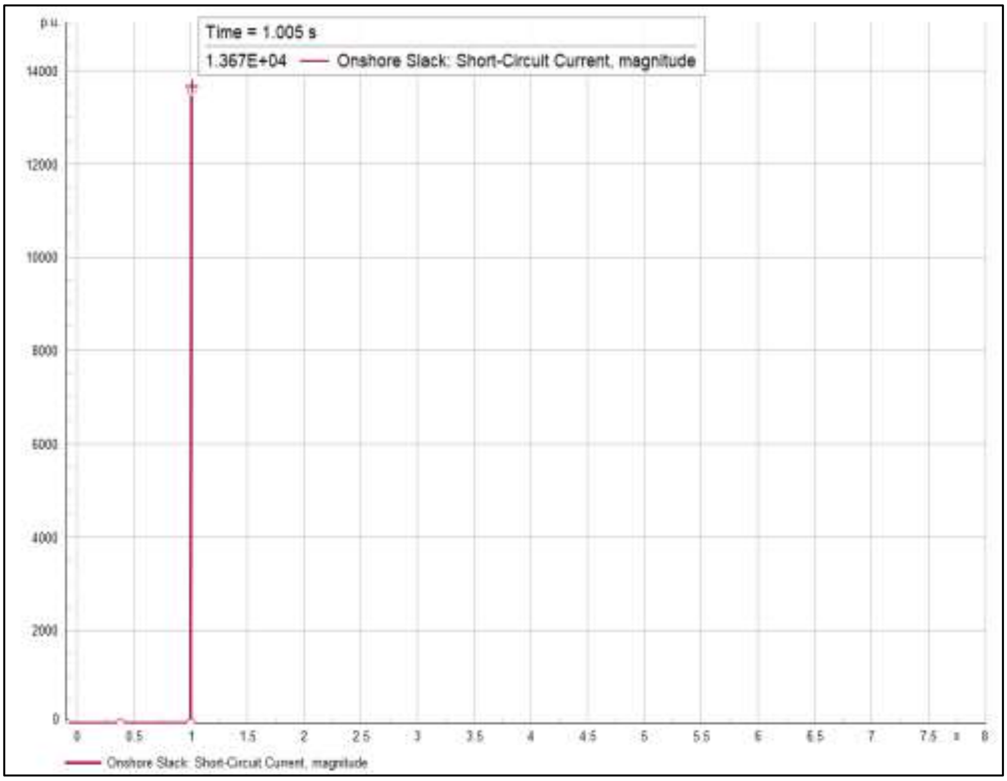

Fig 5.21: Fault current of Onshore slack bus

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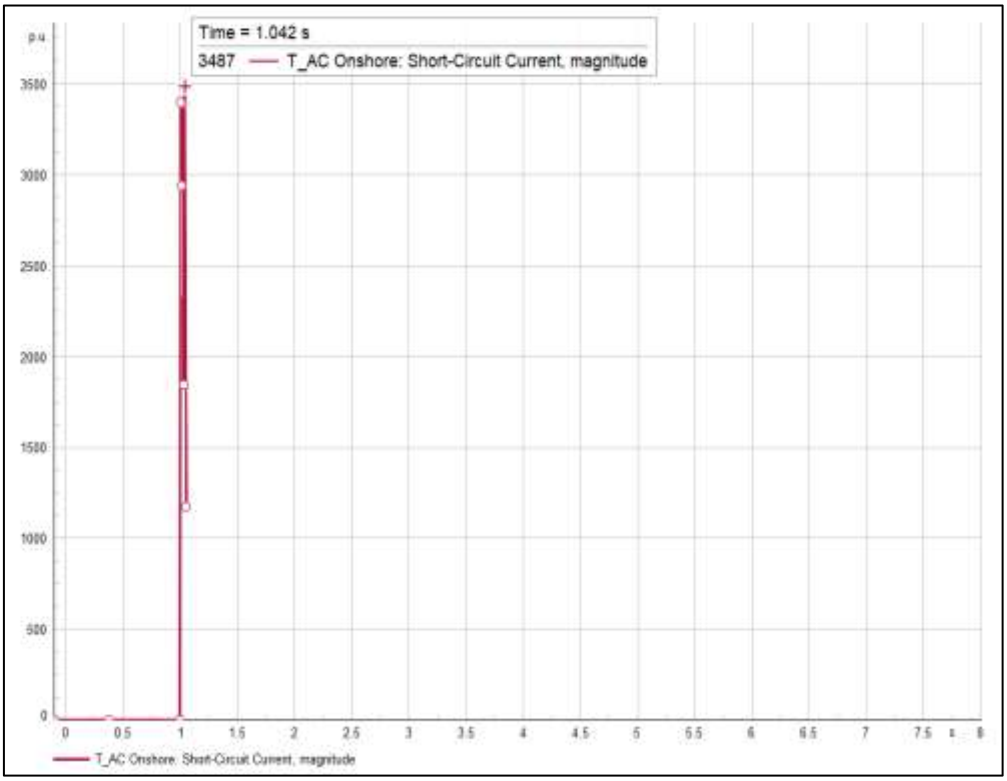

Fig 5.22: Fault current of T AC Onshore bus

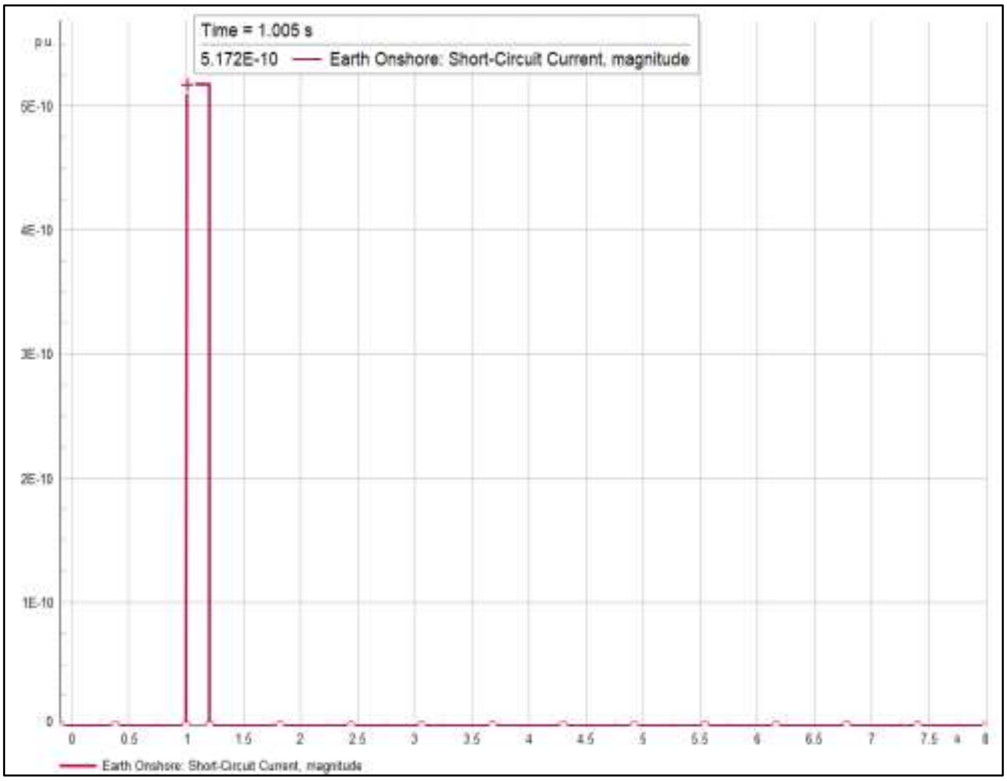

Fig 5.23: Fault current of earth onshore bus

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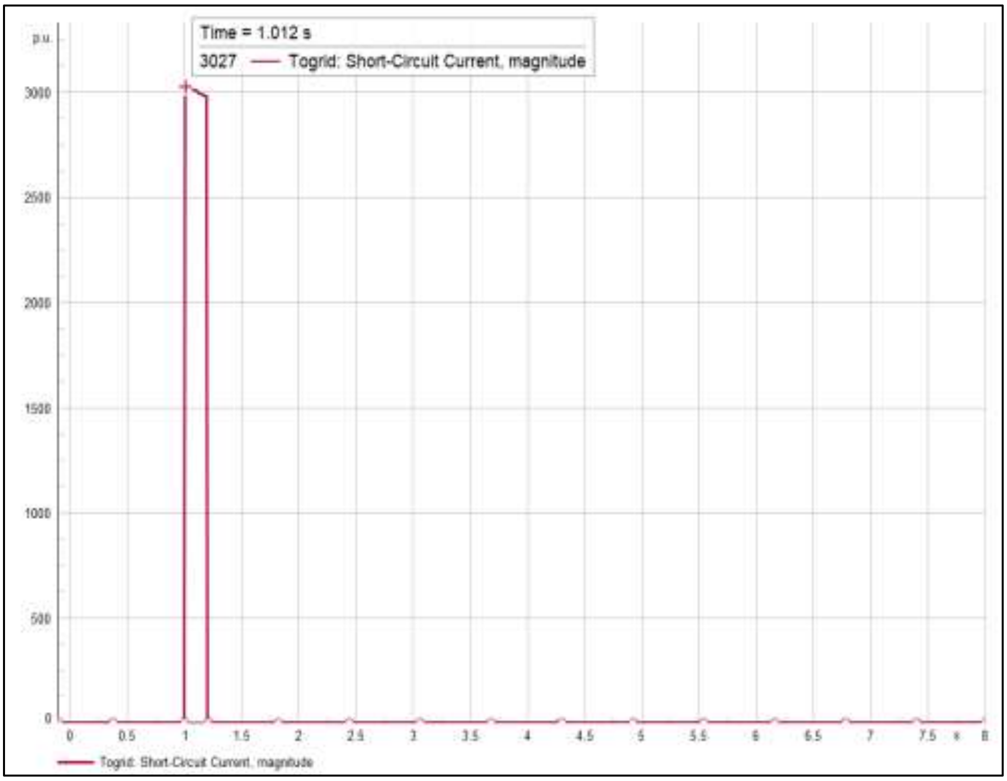

Fig 5.24: Fault current of to grid bus

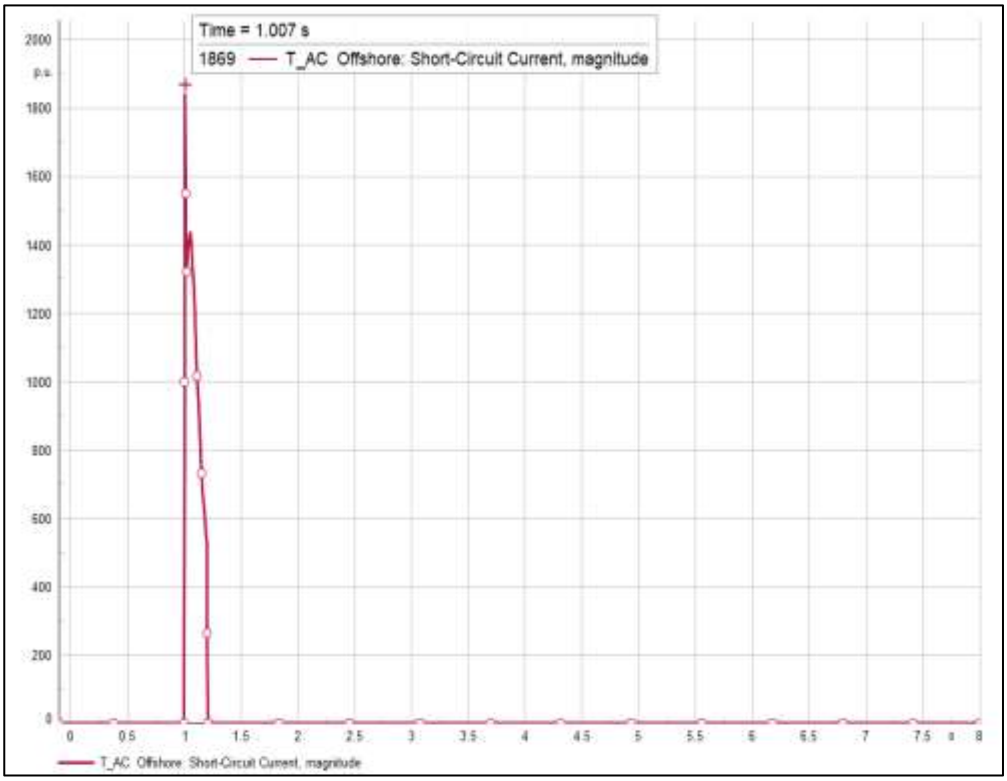

Fig 5.25: Fault current of T AC offshore bus

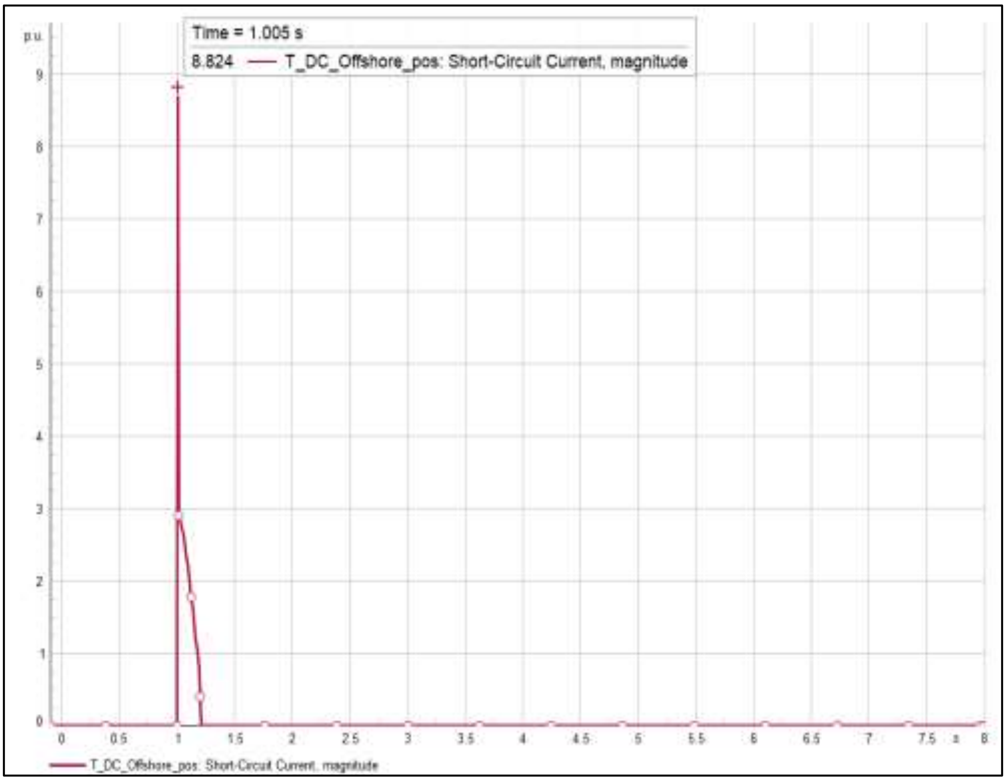

Fig 5.26: Fault current of T DC offshore pos bus

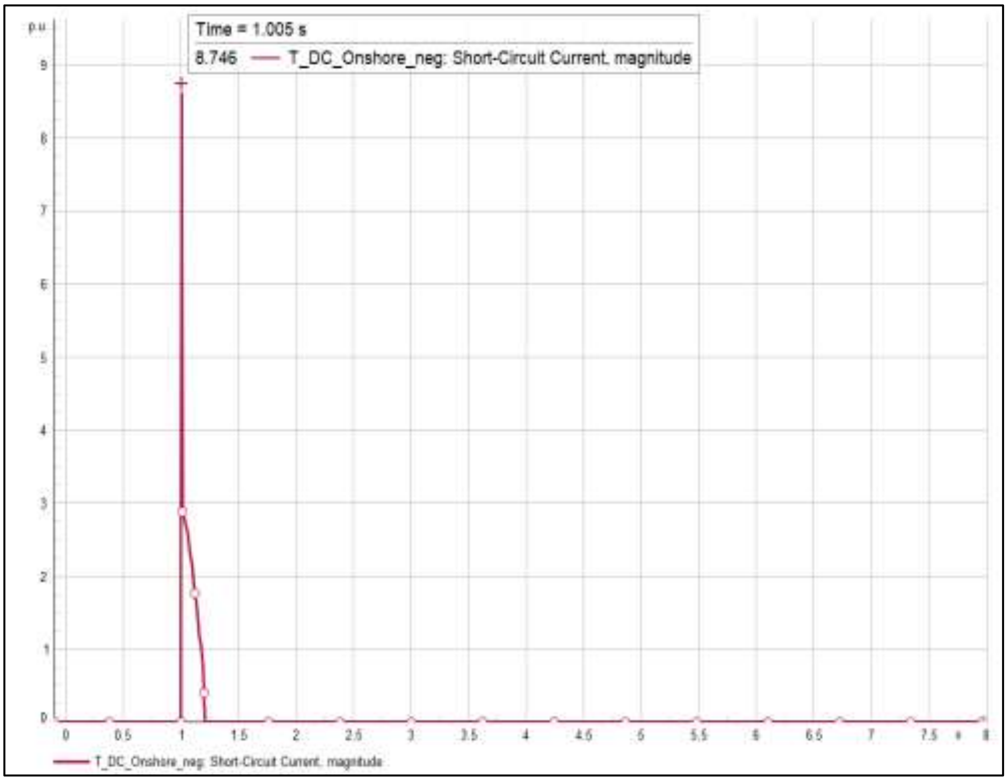

Fig 5.27: Fault current of T DC onshore neg bus

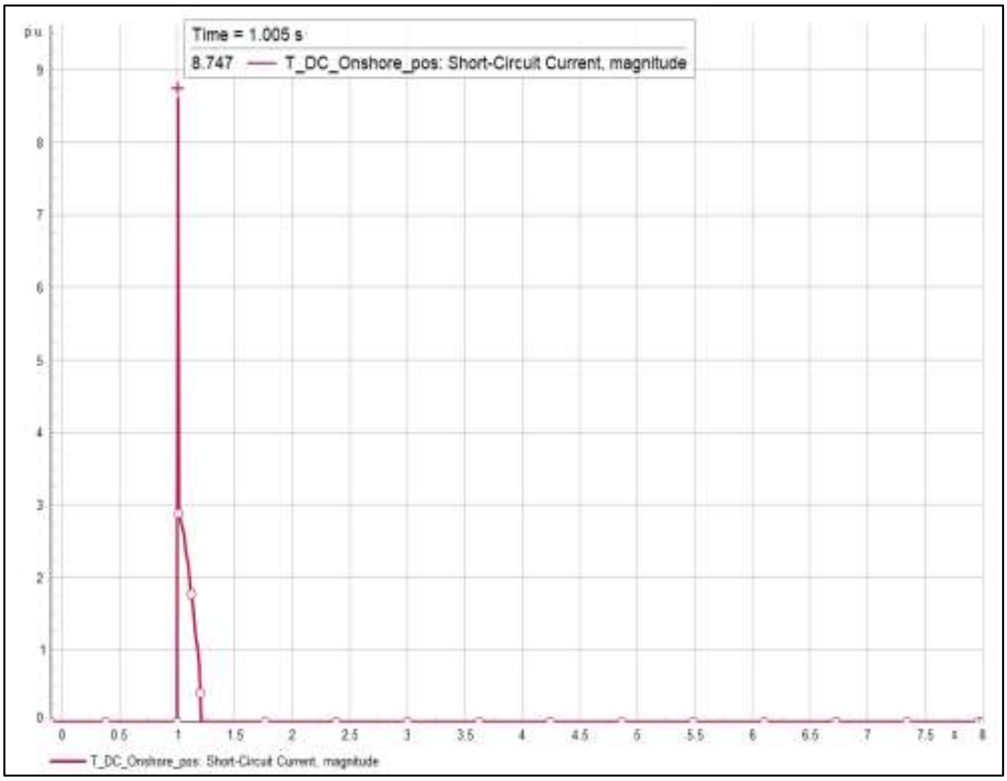

Fig 5.28: Fault current of T DC onshore pos bus

5.3.2 Fault Response with Respect to Voltage Dip

When it comes to electrical systems, fault response with respect to voltage dips is crucial for maintaining system stability and protecting equipment. Voltage dips, also known as sags, are temporary reductions in voltage levels caused by various factors such as sudden changes in load, faults on the network, or starting large motors.

Now, let's see the response of fault with respect to voltage dip in each bus of the AC system, when the wind system is disconnected:

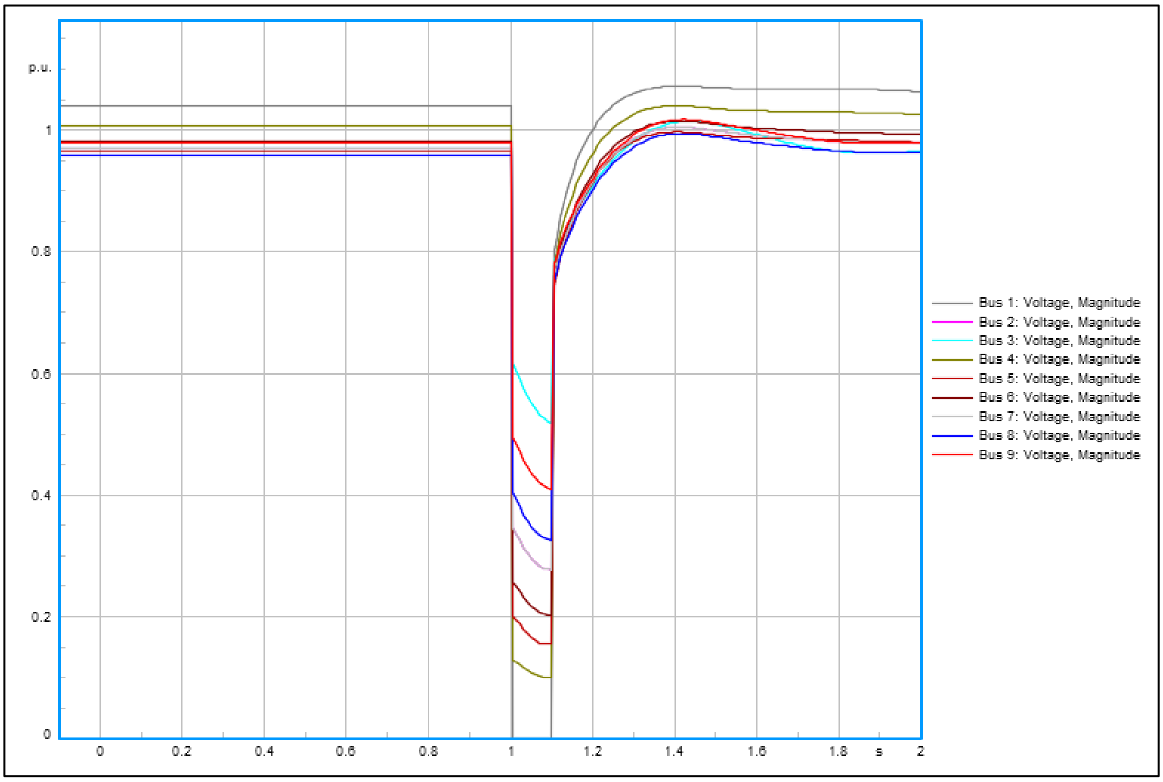

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Fig 5.29: Voltage dip of the buses when fault is in bus 1

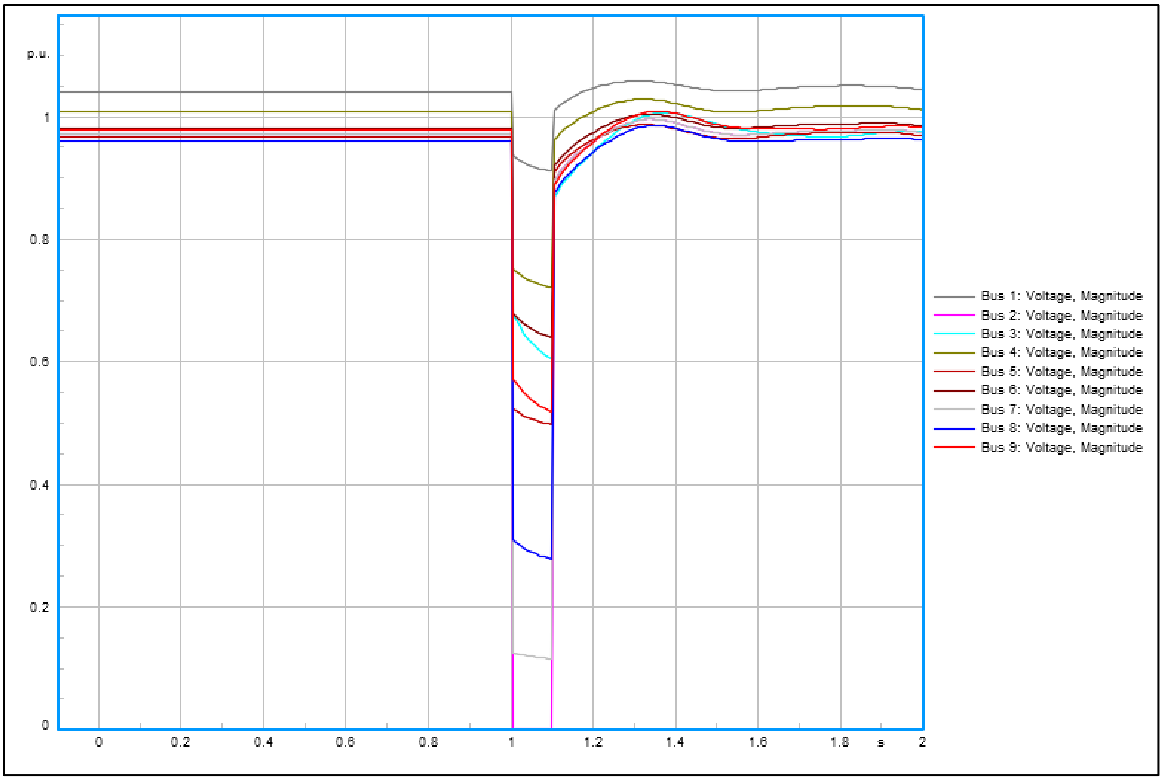

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Fig 5.30: Voltage dip of the buses when fault is in bus 2

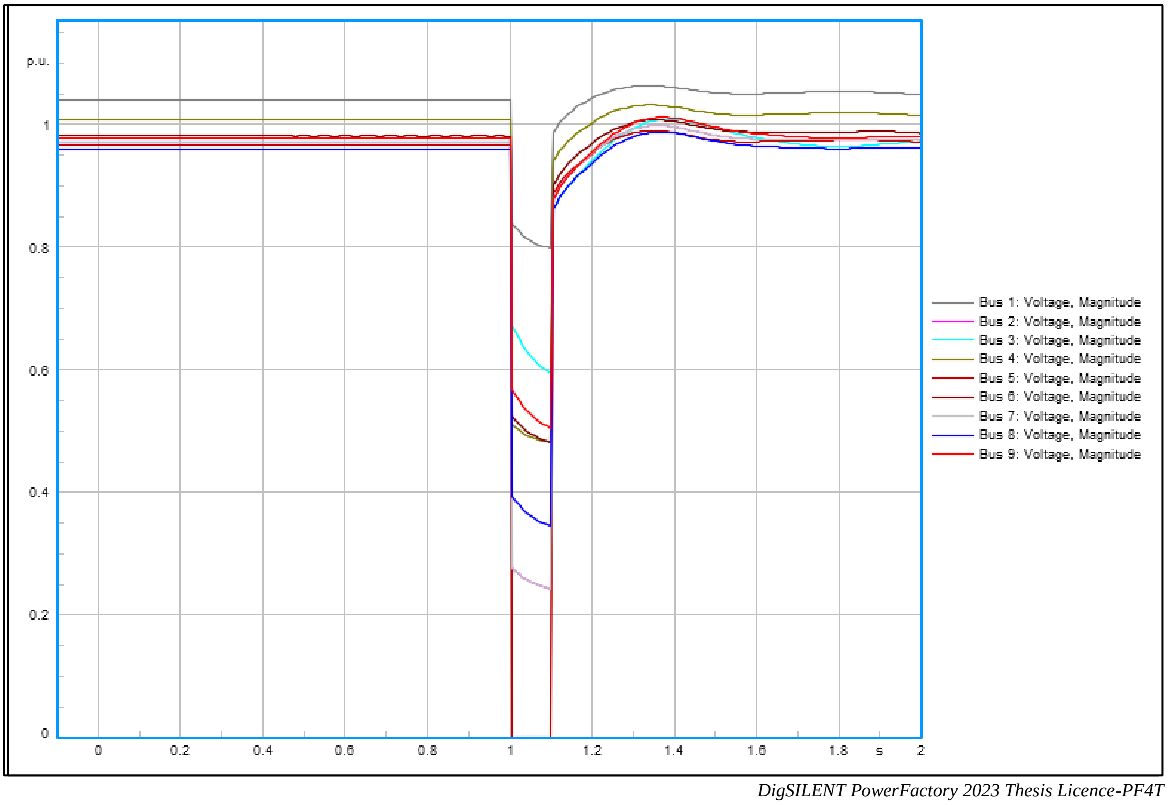

Fig 5.31: Voltage dip of the buses when fault is in bus 3

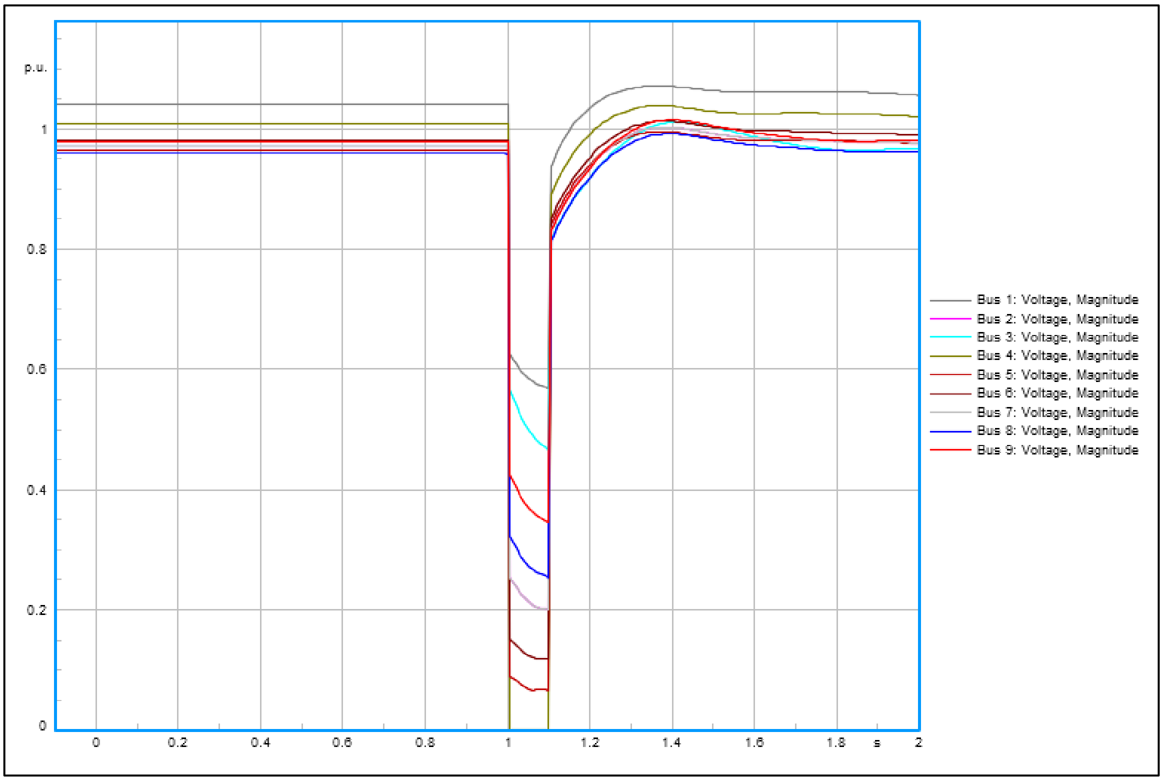

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Fig 5.32: Voltage dip of the buses when fault is in bus 4

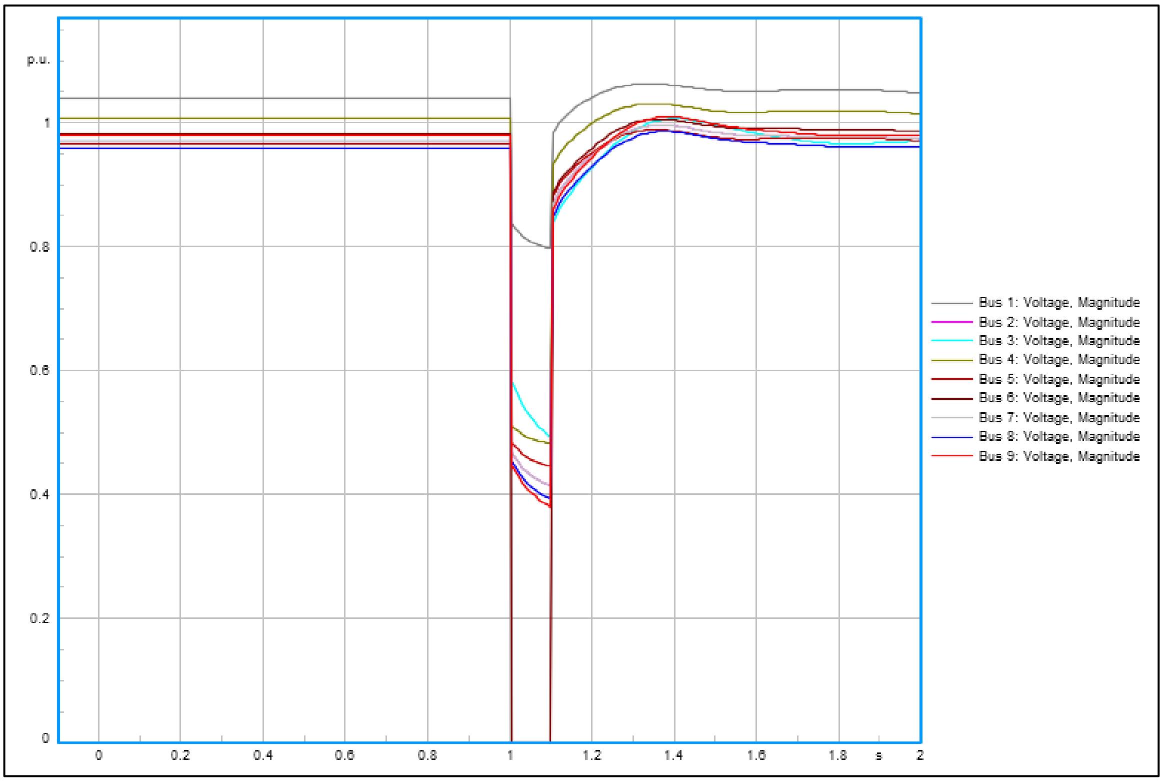

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Fig 5.33: Voltage dip of the buses when fault is in bus 5

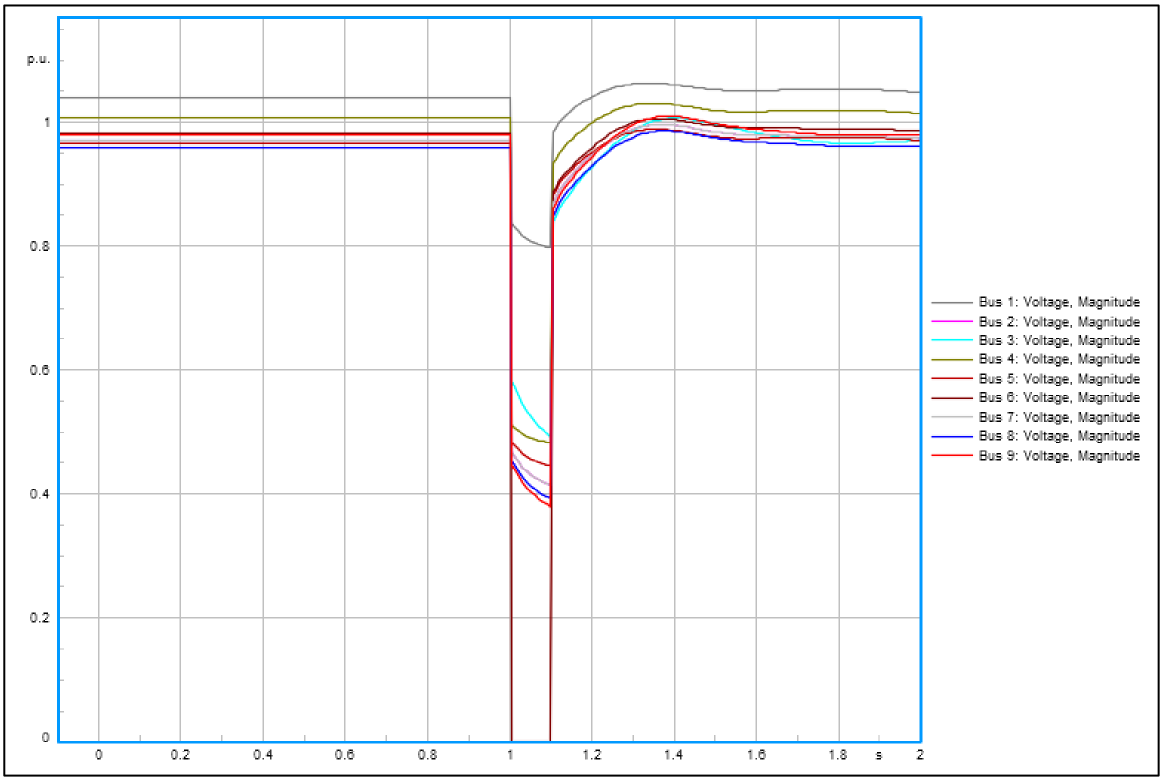

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Fig 5.34: Voltage dip of the buses when fault is in bus 5

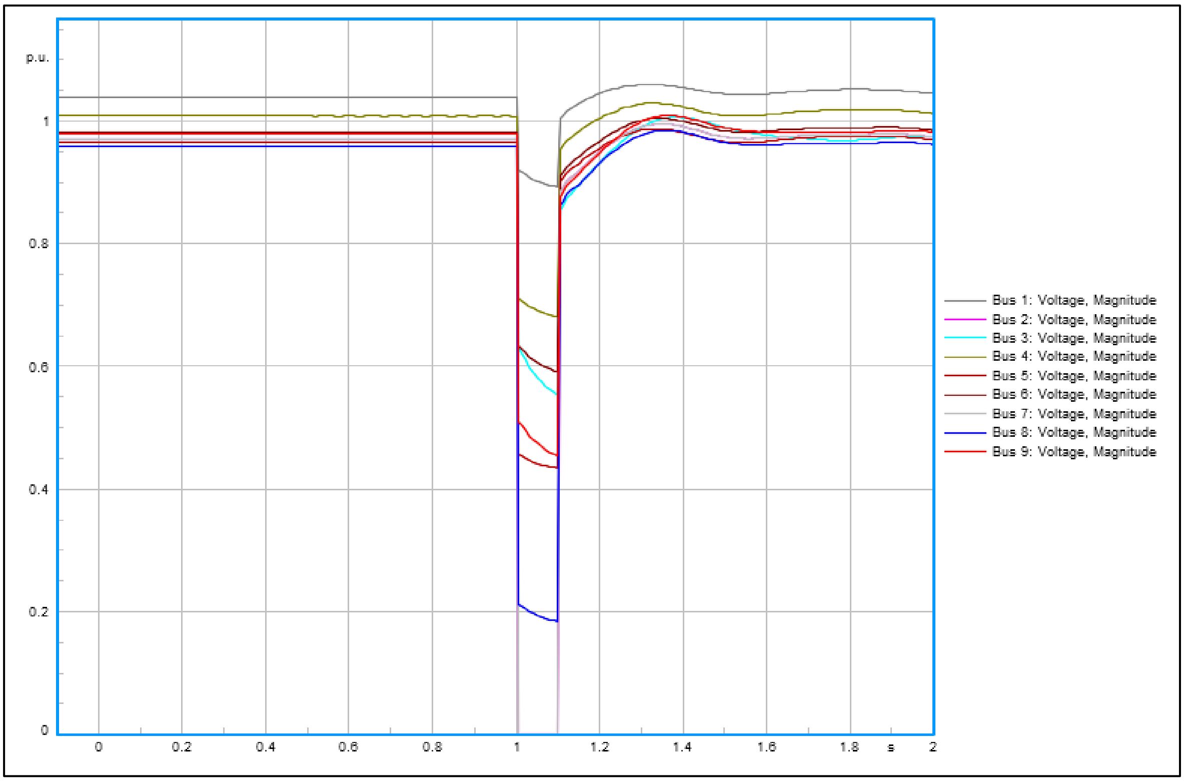

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Fig 5.35: Voltage dip of the buses when fault is in bus 7

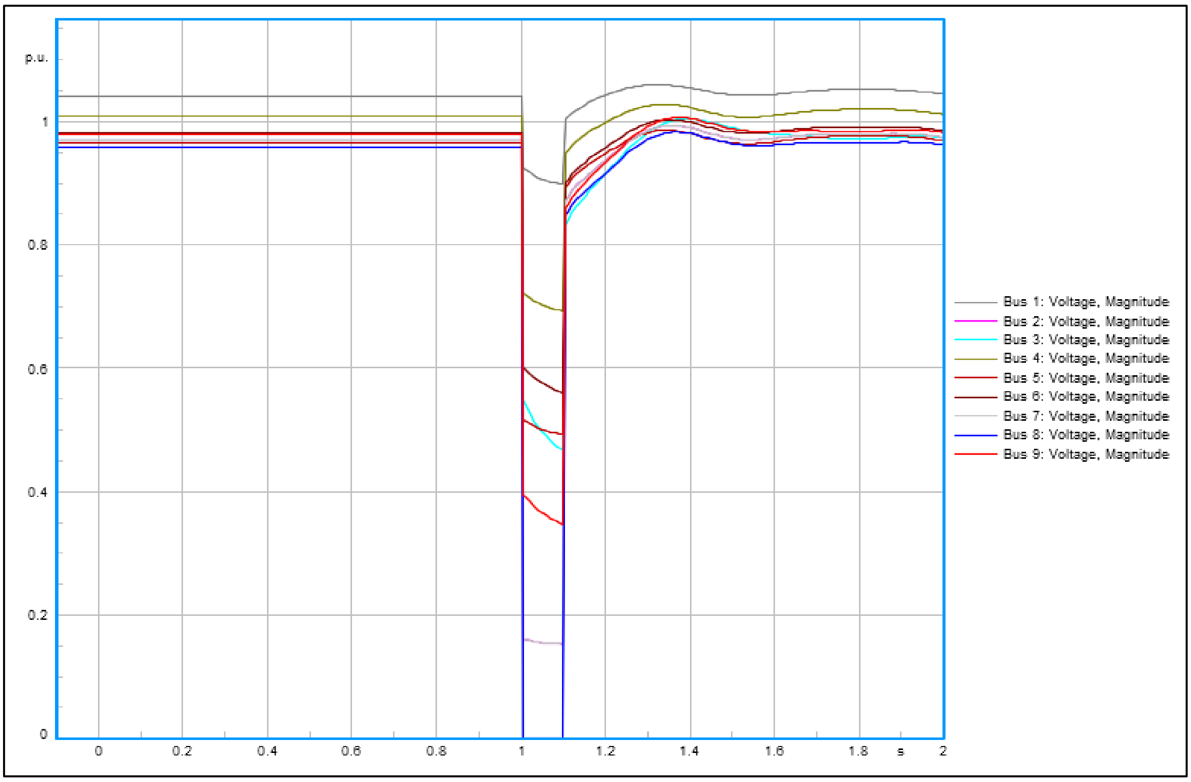

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Fig 5.36: Voltage dip of the buses when fault is in bus 8

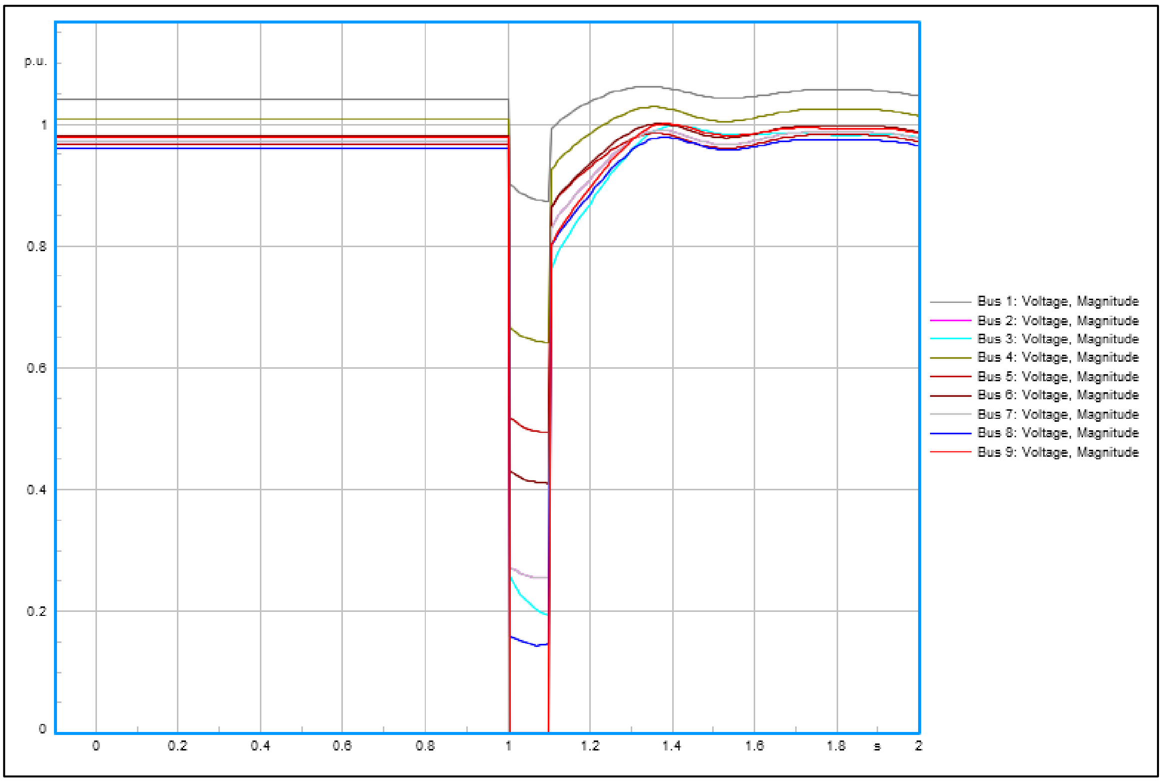

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Fig 5.37: Voltage dip of the buses when fault is in bus 9

When the wind system is connected with the AC nine bus system, the response is quite different. Let’s see the response of fault current in each bus of the AC system as well as HVDC system, when the wind system is connected:

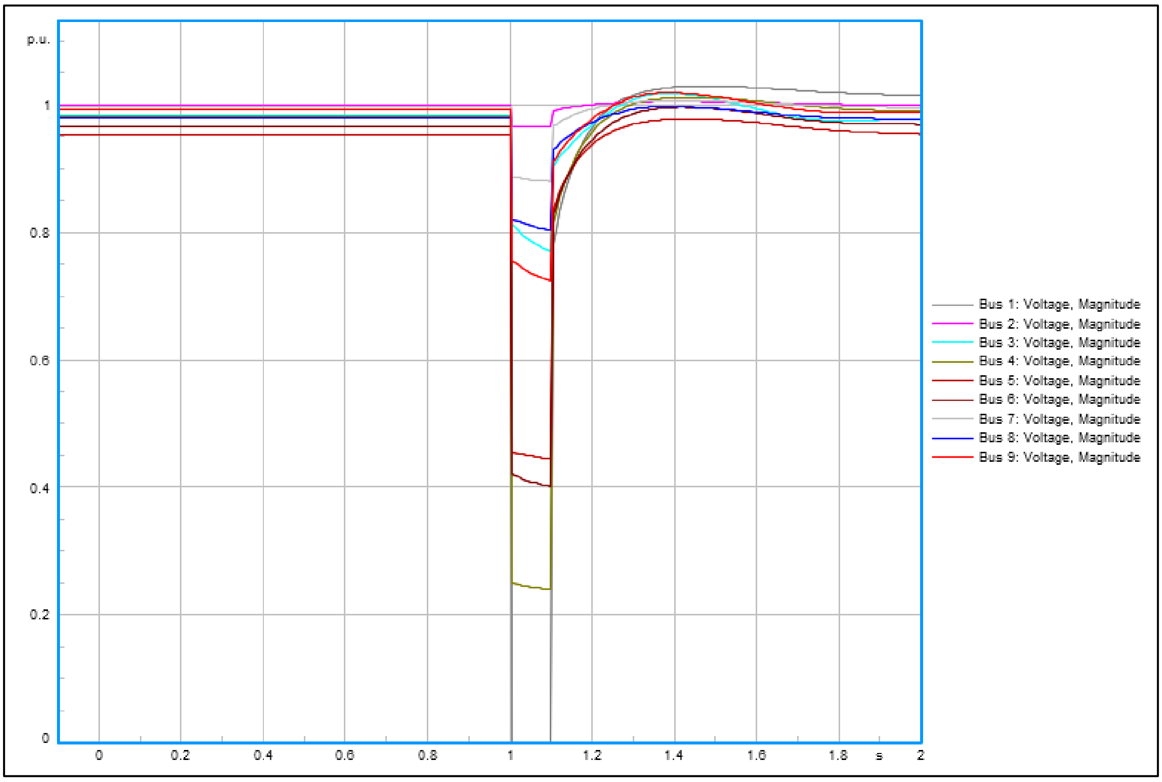

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Fig5.38: Voltage dip of the buses when fault is in bus 1

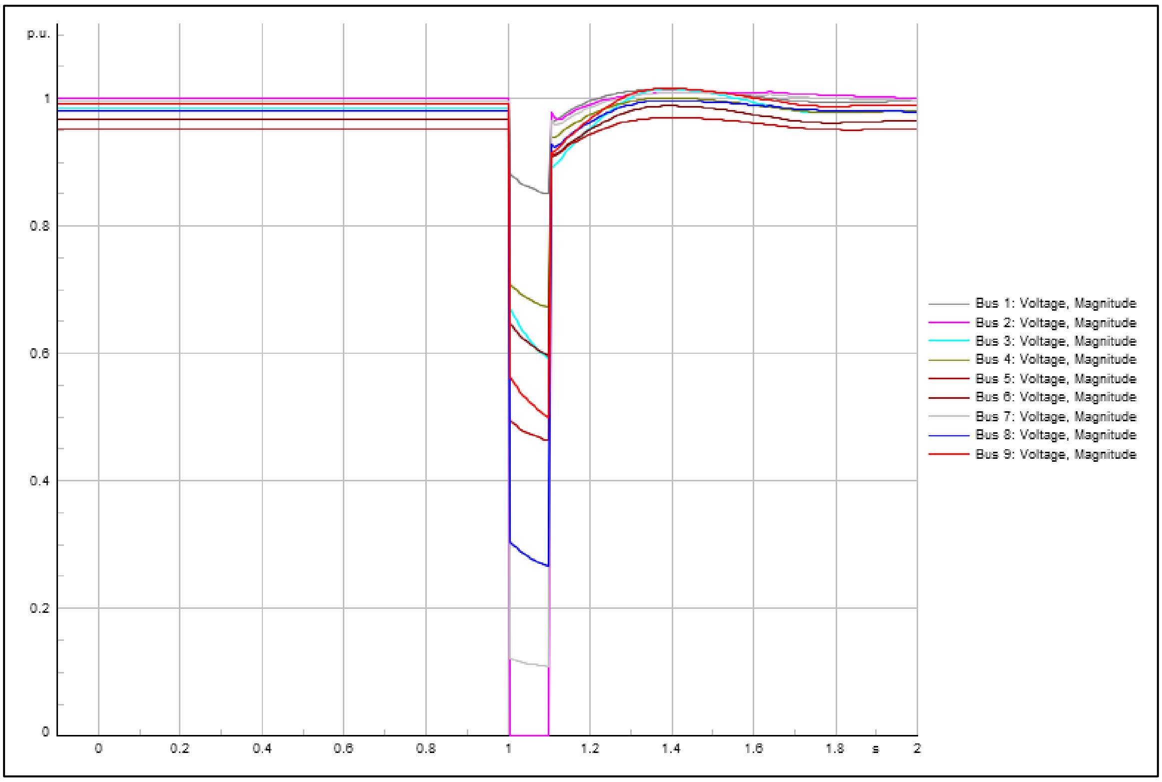

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Fig5.39: Voltage dip of the buses when fault is in bus 2

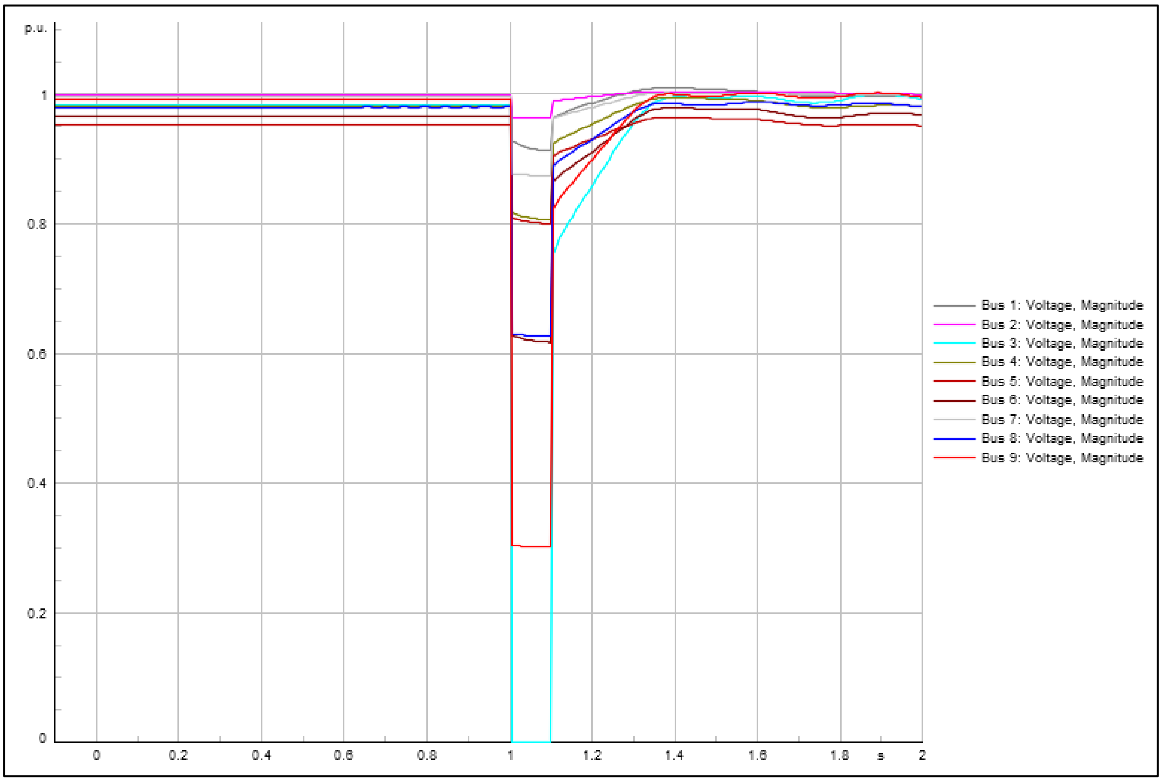

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Fig 5.40: Voltage dip of the buses when fault is in bus 3

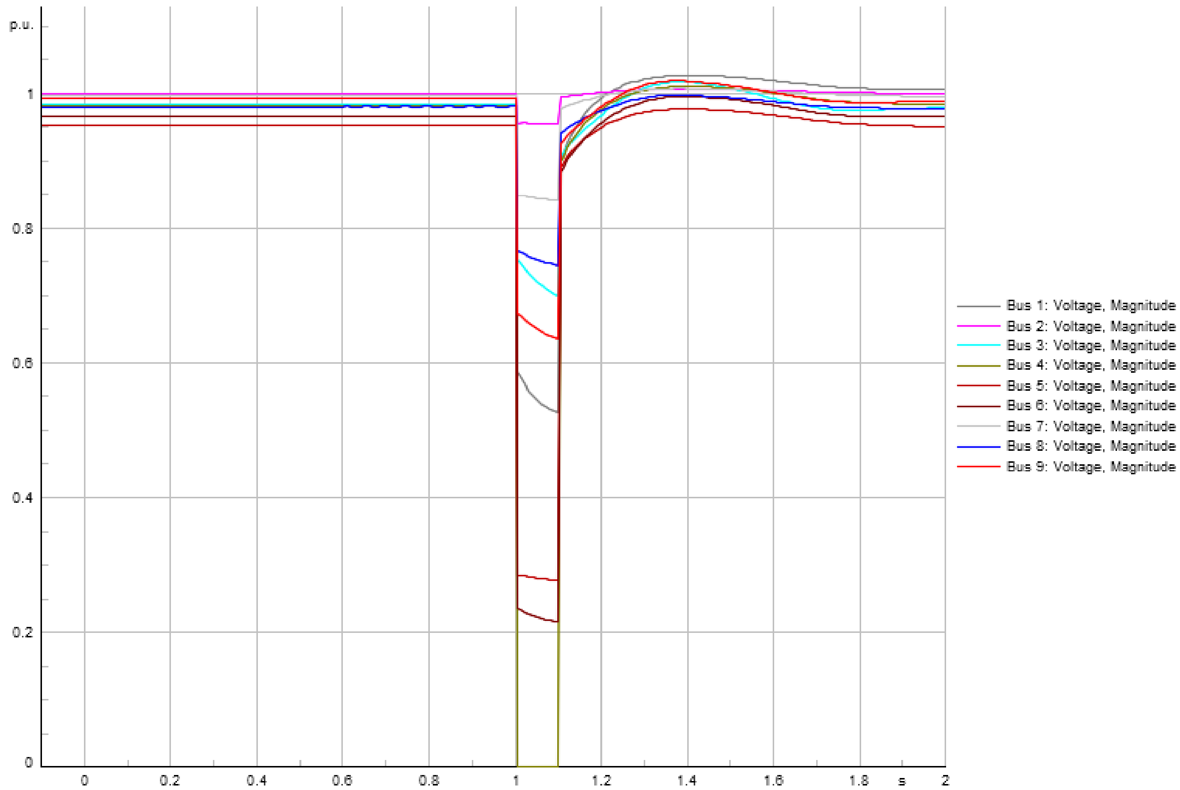

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Fig 5.41: Voltage dip of the buses when fault is in bus 4

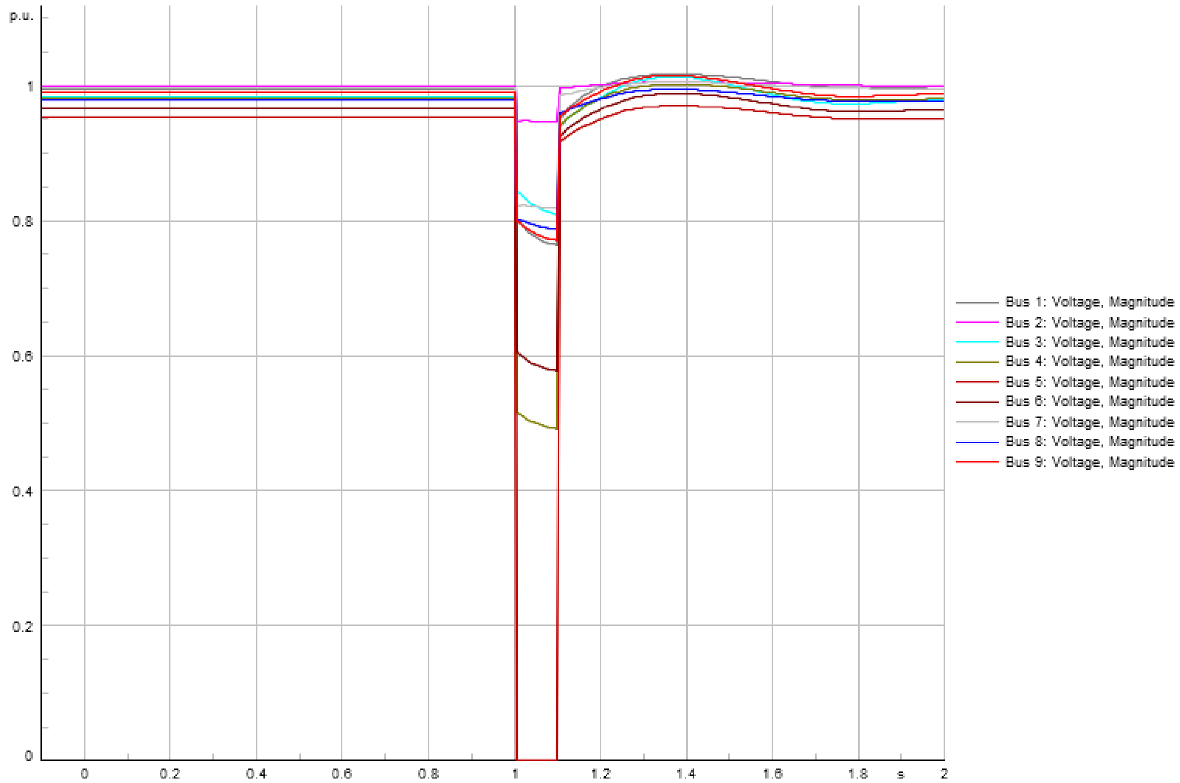

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Fig 5.42: Voltage dip of the buses when fault is in bus 5

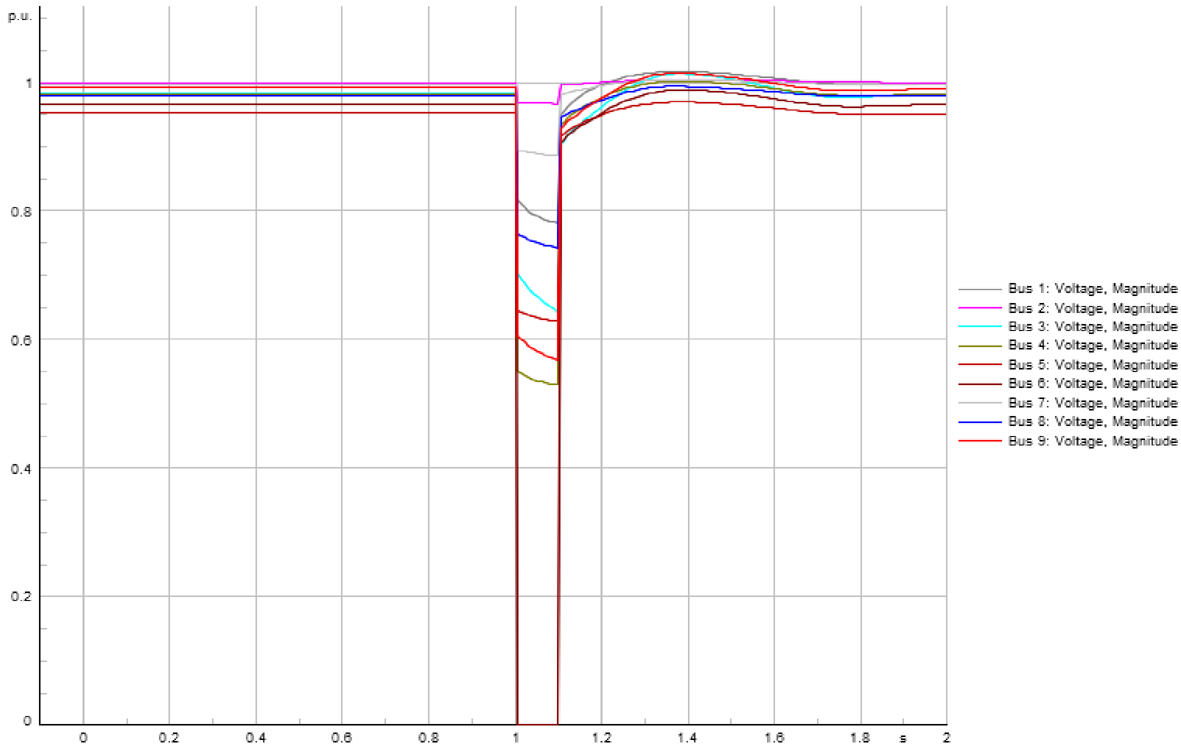

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Fig 5.43: Voltage dip of the buses when fault is in bus 6

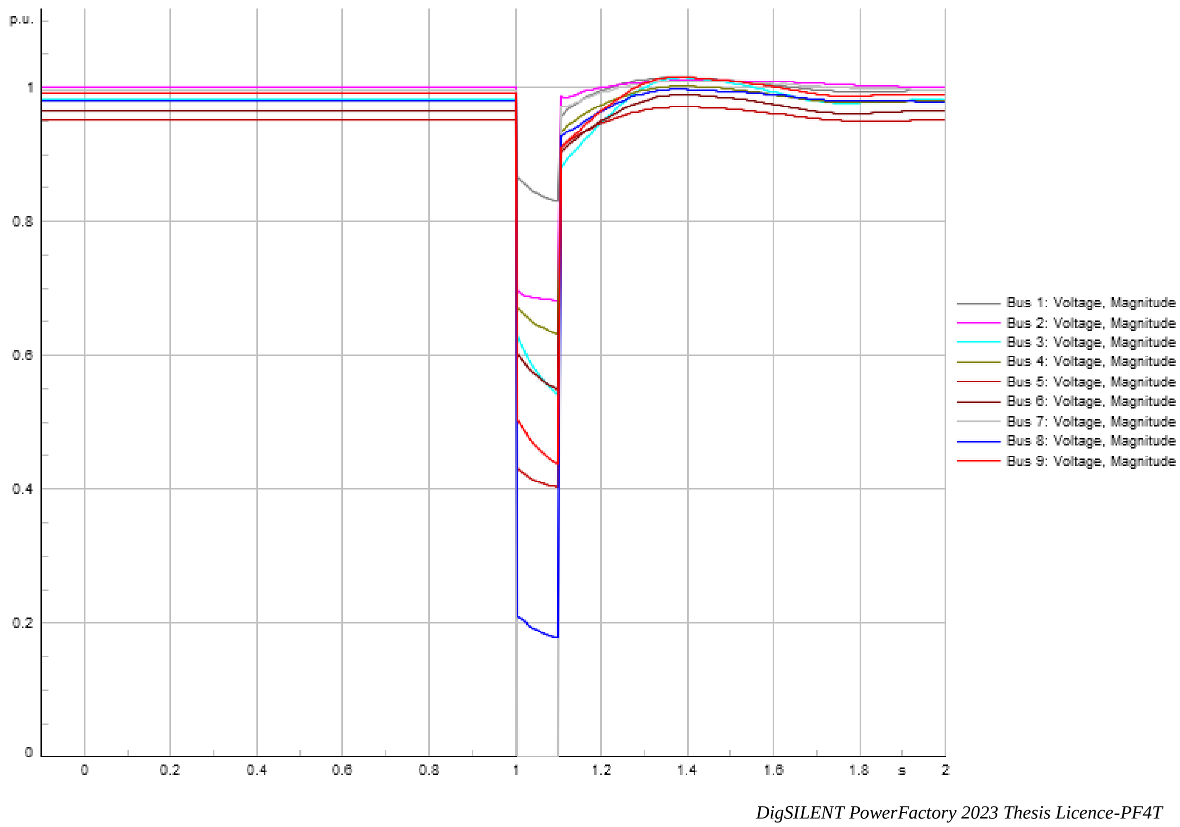

Fig 5.44: Voltage dip of the buses when fault is in bus 7

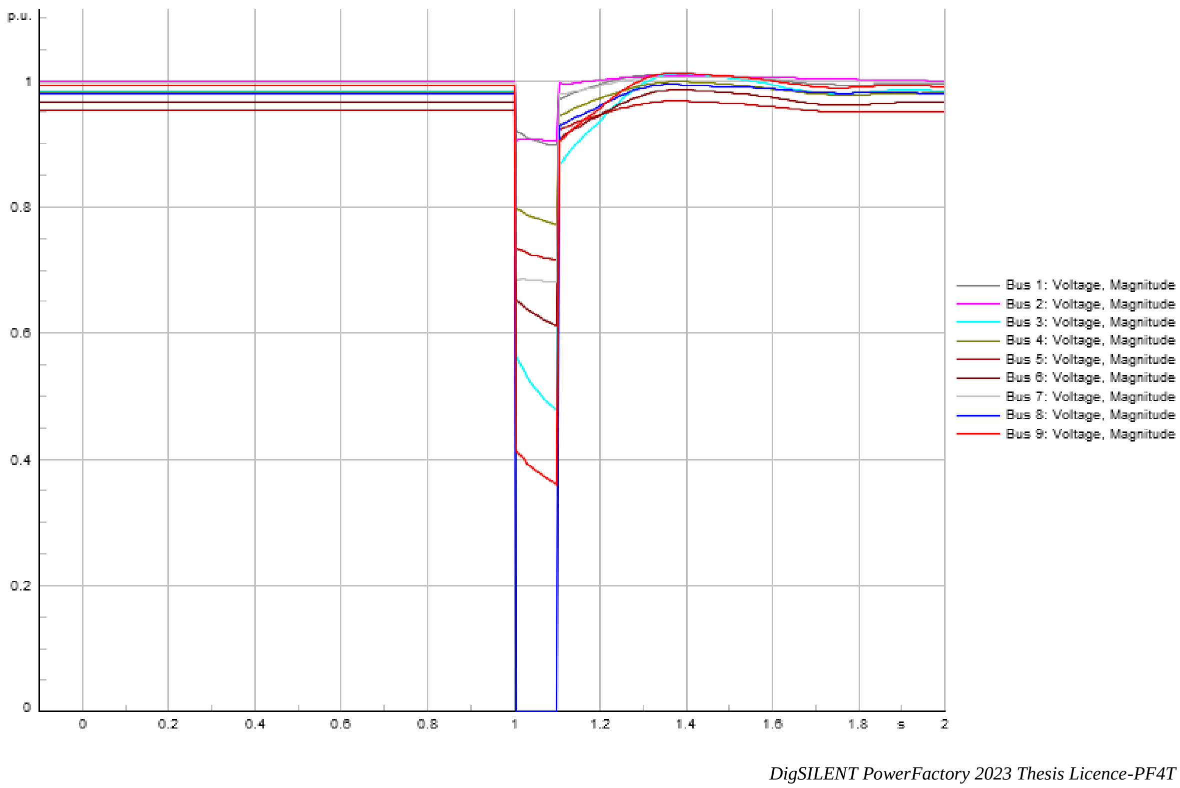

Fig 5.45: Voltage dip of the buses when fault is in bus 8

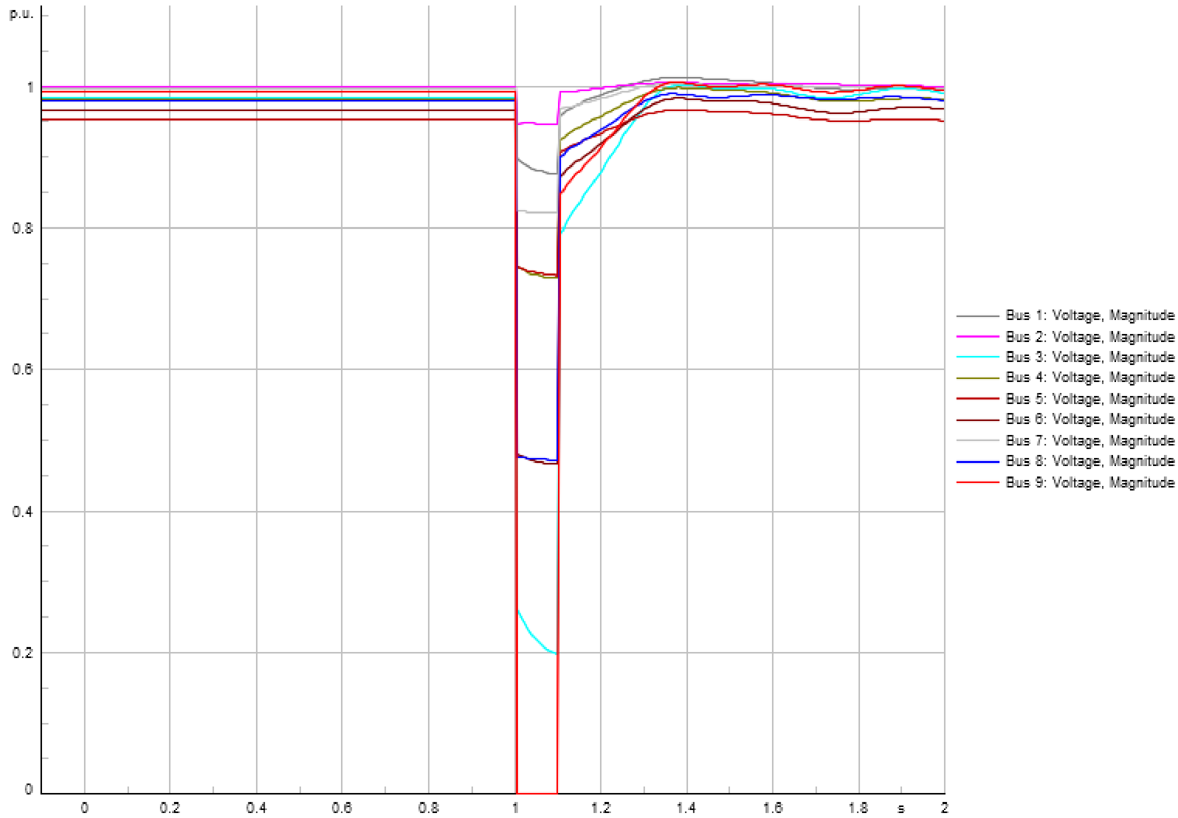

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Fig 5.46: Voltage dip of the buses when fault is in bus9

5.4 Severity Indexing with Respect to Short Circuit Current

Wind Disconnected

BUS Name	Fault Current (pu)
BUS 1	1994pu
BUS 4	1561pu
BUS 7	1395pu
BUS 2	1339pu
BUS 9	1112pu
BUS 8	1043pu
BUS 5	1013pu
BUS 3	950.5pu
BUS 6	934.5pu

Wind Connected

BUS Name	Fault Current (pu)
Onshore Slack	13670pu
T AC Onshore	3487pu
To Grid	3027pu
BUS 2	2269pu
BUS 7	2168pu
BUS 1	1965pu
T AC Offshore	1869pu
BUS 4	1590pu
BUS 8	1249pu
BUS 9	1167pu
BUS 5	1075pu
BUS 3	949.3pu
BUS 6	940pu
Earth Onshore	$5.172*10^{-10}$ pu

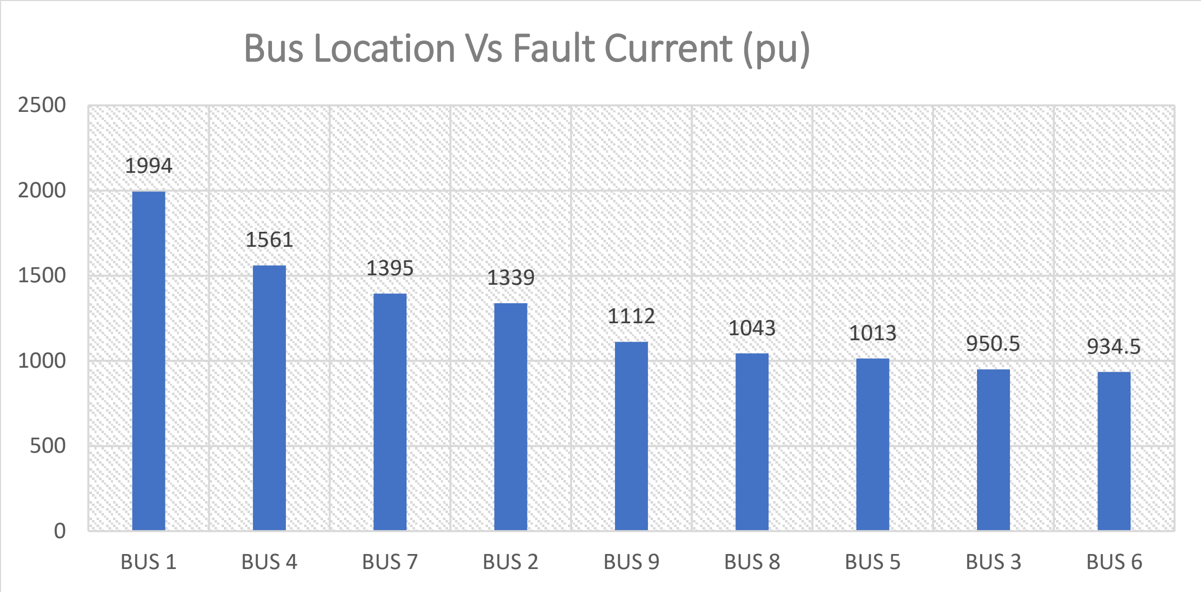

Fig 5.48: Bar diagram of fault severity index when the wind is disconnected

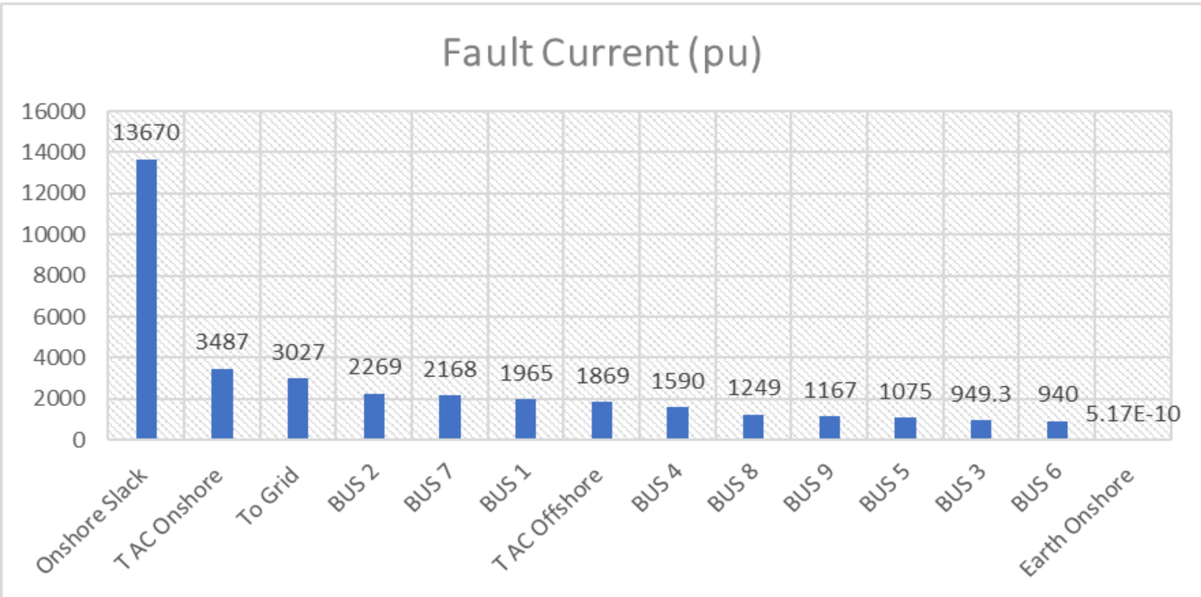

Fig 5.49: Bar diagram of fault severity index when the wind is connected

5.4.1 Result Analysis

For wind disconnected system, we can see that bus 1 has the highest magnitude of fault current when fault is in this bus. Then, bus 4, 7, 2, 9, 8, 5, 3, 6 has the highest fault current magnitude respectively. On the other hand, we can see that, buses of HVDC system have the higher value than the AC system, when the wind is connected. In case of AC system, bus 2 has the highest fault current magnitude compared to other buses of AC system.

From the above severity indexes, the comparison of wind connected and disconnected system can be achieved. Through this, better protection mechanisms can be designed for each case. As we know that, for IDMT relays the tripping time gets shorter when the fault current increases.

So, this index can be used to give proper relay settings. Eventually, reliability and safety can be ensued by this analysis.

5.5 Severity Analysis with Respect to Voltage Dip

By the difference between the voltages before and after the fault, the voltage dips can be analysed. The tables below include the data of voltage of each bus of the AC system before and after the fault and their difference for both wind connected and disconnected system.

Table 3: Voltage dip analysis at Bus 1 fault with wind connected:

	BUS 1		
	With Wind Connection		
Bus Name	**Before Fault (V)**	**After Fault (V)**	**Voltage Difference**
BUS 1	0.9962	0	0.996
BUS 4	0.9814	0.2354	0.746
BUS 6	0.9663	0.391	0.575
BUS 5	0.9528	0.44	0.513
BUS 9	0.9915	0.7097	0.282
BUS 3	0.9838	0.7548	0.229
BUS 8	0.9802	0.794	0.186
BUS 7	0.9965	0.8775	0.119
BUS 2	1	0.9652	0.035

Table 4: Voltage dip analysis at Bus 1 fault with wind disconnected:

	BUS 1		
	Without Wind Connection		
Bus Name	**Before Fault (V)**	**After Fault (V)**	**Voltage Difference**
BUS 1	1.04	0	1.04
BUS 4	1.033	0.1989	0.834
BUS 6	1.024	0.3476	0.676
BUS 5	1.009	0.3537	0.655
BUS 9	1.051	0.646	0.405
BUS 8	1.038	0.6605	0.378
BUS 7	1.05	0.6847	0.365
BUS 3	1.044	0.7238	0.32
BUS 2	1.051	0.7378	0.313

Table 5: Voltage dip analysis at Bus 2 fault with wind connected:

	BUS 2		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 2	1	0	1
BUS 7	0.9965	0.036	0.961
BUS 8	0.9802	0.024	0.956
BUS 9	0.9915	0.103	0.889
BUS 3	0.9838	0.3	0.684
BUS 6	0.9663	0.3455	0.621
BUS 5	0.9528	0.3844	0.568
BUS 4	0.9814	0.5894	0.392
BUS 1	0.9962	0.845	0.151

Table 6: Voltage dip analysis at Bus 2 fault with wind disconnected:

	BUS 2		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 2	1.051	0	1.051
BUS 7	1.05	0.09817	0.952
BUS 8	1.038	0.2394	0.799
BUS 9	1.051	0.4518	0.599
BUS 5	1.009	0.4593	0.55
BUS 3	1.044	0.5538	0.49
BUS 6	1.024	0.5556	0.468
BUS 4	1.033	0.6742	0.359
BUS 1	1.04	0.882	0.158

Table 7: Voltage dip analysis at Bus 3 fault with wind connected:

	BUS 3		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 3	0.9838	0	0.984
BUS 9	0.9915	0.3021	0.689
BUS 8	0.9802	0.6265	0.354
BUS 6	0.9663	0.6171	0.349
BUS 4	0.9814	0.8054	0.176
BUS 5	0.9528	0.8	0.153
BUS 7	0.9965	0.8745	0.122
BUS 1	0.9962	0.9129	0.083
BUS 2	1	0.9632	0.037

Table 8: Voltage dip analysis at Bus 3 fault with wind disconnected:

	BUS 3		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 3	1.044	0	1.044
BUS 9	1.051	0.2323	0.819
BUS 8	1.038	0.4562	0.582
BUS 6	1.024	0.55	0.474
BUS 7	1.05	0.6312	0.419
BUS 2	1.051	0.6889	0.362
BUS 5	1.009	0.6543	0.355
BUS 4	1.033	0.7433	0.29
BUS 1	1.04	0.9147	0.125

Table 9: Voltage dip analysis at Bus 4 fault with wind connected:

	BUS 4		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 4	0.9814	0	0.981
BUS 6	0.9663	0.2066	0.76
BUS 5	0.9528	0.2771	0.676
BUS 1	0.9962	0.5229	0.473
BUS 9	0.9915	0.6061	0.385
BUS 3	0.9838	0.6659	0.318
BUS 8	0.9802	0.7262	0.254
BUS 7	0.9965	0.8382	0.158
BUS 2	1	0.9537	0.046

Table 9: Voltage dip analysis at Bus 4 fault with wind disconnected:

	BUS 4		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 4	1.033	0	1.033
BUS 6	1.024	0.1872	0.837
BUS 5	1.009	0.1972	0.812
BUS 9	1.051	0.547	0.504
BUS 1	1.04	0.5435	0.497
BUS 8	1.038	0.5675	0.471
BUS 7	1.05	0.5946	0.455
BUS 3	1.044	0.644	0.4
BUS 2	1.051	0.6595	0.392

Table 10: Voltage dip analysis at Bus 5 fault with wind connected:

	BUS 5		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 5	0.9528	0	0.953
BUS 4	0.9814	0.4908	0.491
BUS 6	0.9663	0.5747	0.392
BUS 1	0.9962	0.7631	0.233
BUS 9	0.9915	0.7663	0.225
BUS 8	0.9802	0.7853	0.195
BUS 3	0.9838	0.8024	0.181
BUS 7	0.9965	0.8186	0.178
BUS 2	1	0.9468	0.053

Table 11: Voltage dip analysis at Bus 5 fault with wind disconnected:

	BUS 5		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 5	1.009	0	1.009
BUS 6	1.024	0.07954	0.944
BUS 4	1.033	0.3618	0.671
BUS 9	1.051	0.4481	0.603
BUS 8	1.038	0.4484	0.59
BUS 7	1.05	0.4982	0.552
BUS 2	1.051	0.5933	0.458
BUS 3	1.044	0.5947	0.449
BUS 1	1.04	0.77	0.27

Table 12: Voltage dip analysis at Bus 6 fault with wind connected:

	BUS 6		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 6	0.9663	0	0.966
BUS 9	0.9915	0.5261	0.465
BUS 4	0.9814	0.5295	0.452
BUS 3	0.9838	0.5935	0.39
BUS 5	0.9528	0.6276	0.325
BUS 8	0.9802	0.7172	0.263
BUS 1	0.9962	0.7809	0.215
BUS 7	0.9965	0.8813	0.115
BUS 2	1	0.9668	0.033

Table 13: Voltage dip analysis at Bus 6 fault with wind disconnected:

	BUS 6		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 6	1.024	0	1.024
BUS 9	1.051	0.065	0.986
BUS 5	1.009	0.06884	0.94
BUS 3	1.044	0.3088	0.735
BUS 8	1.038	0.3029	0.735
BUS 4	1.033	0.3644	0.669
BUS 7	1.05	0.4726	0.577
BUS 2	1.051	0.5933	0.458
BUS 1	1.04	0.7826	0.257

Table 14: Voltage dip analysis at Bus 7 fault with wind connected:

	BUS 7		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 7	0.9965	0	0.997
BUS 8	0.9802	0.04851	0.932
BUS 9	0.9915	0.1186	0.873
BUS 3	0.9838	0.3	0.684
BUS 6	0.9663	0.3068	0.66
BUS 5	0.9528	0.3463	0.607
BUS 4	0.9814	0.5455	0.436
BUS 2	1	0.6821	0.318
BUS 1	0.9962	0.8181	0.178

Table 15: Voltage dip analysis at Bus 7 fault with wind disconnected:

	BUS 7		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 7	1.05	0	1.05
BUS 8	1.038	0.05551	0.982
BUS 2	1.051	0.1267	0.924
BUS 9	1.051	0.1345	0.917
BUS 3	1.044	0.3288	0.715
BUS 6	1.024	0.3233	0.701
BUS 5	1.009	0.3666	0.642
BUS 4	1.033	0.5749	0.458
BUS 1	1.04	0.86	0.18

Table 16: Voltage dip analysis at Bus 8 fault with wind connected:

	BUS 8		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 8	0.9802	0	0.98
BUS 9	0.9915	0.05186	0.94
BUS 3	0.9838	0.2404	0.743
BUS 6	0.9663	0.434	0.532
BUS 7	0.9965	0.6821	0.314
BUS 5	0.9528	0.6783	0.275
BUS 4	0.9814	0.7075	0.274
BUS 1	0.9962	0.8841	0.112
BUS 2	1	0.9058	0.094

Table 17: Voltage dip analysis at Bus 8 fault with wind disconnected:

	BUS 8		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 8	1.038	0	1.038
BUS 9	1.051	0.1091	0.942
BUS 7	1.05	0.1738	0.876
BUS 2	1.051	0.3	0.751
BUS 3	1.044	0.304	0.74
BUS 5	1.009	0.2816	0.727
BUS 6	1.024	0.3037	0.72
BUS 4	1.033	0.5294	0.504
BUS 1	1.04	0.827	0.213

Table 18: Voltage dip analysis at Bus 9 fault with wind connected:

	BUS 9		
	With Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 9	0.9915	0	0.992
BUS 3	0.9838	0.1866	0.797
BUS 8	0.9802	0.472	0.508
BUS 6	0.9663	0.465	0.501
BUS 4	0.9814	0.7283	0.253
BUS 5	0.9528	0.7326	0.22
BUS 7	0.9965	0.8212	0.175
BUS 1	0.9962	0.8758	0.12
BUS 2	1	0.9473	0.053

Table 19: Voltage dip analysis at Bus 9 fault with wind disconnected:

	BUS 9		
	Without Wind Connection		
Bus Name	Before Fault (V)	After Fault (V)	Voltage Difference
BUS 9	1.051	0	1.051
BUS 8	1.038	0.1569	0.881
BUS 3	1.044	0.2055	0.839
BUS 7	1.05	0.2724	0.778
BUS 5	1.009	0.2632	0.746
BUS 6	1.024	0.3513	0.673
BUS 2	1.051	0.3913	0.66
BUS 4	1.033	0.5503	0.483
BUS 1	1.04	0.857	0.183

5.5.1 Result Analysis

From the above data tables, the difference between voltages of buses is evaluated for each bus fault. The calculation is done for both wind connected and disconnected system. This analysis can be useful to distinguish between the protection mechanisms of wind connected and disconnected system as the voltage dips are different in these two scenarios. Let's take the example of bus 7. For wind disconnected system, after bus 7&8, bus 2 has higher voltage dip than the other buses. On the other hand, for wind connected system, the voltage dip of bus 9 is higher after bus 7& 8. Similarly, the rest of the index is not same for both the cases.

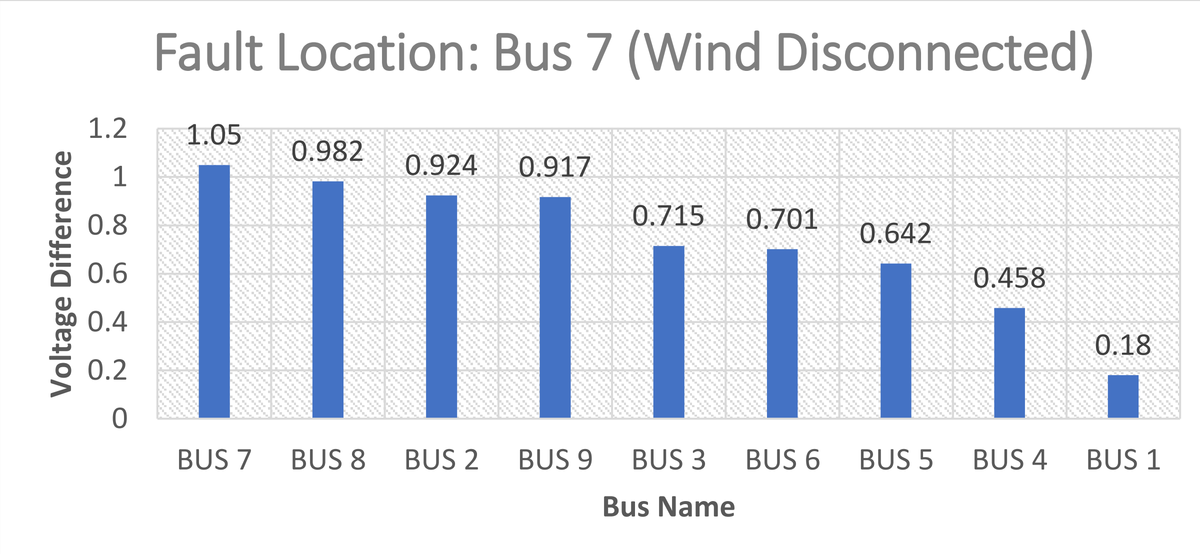

Fig 5.50: The Response of All the Buses According to Voltage Dip When Fault is in Bus 7 (Wind Connected)

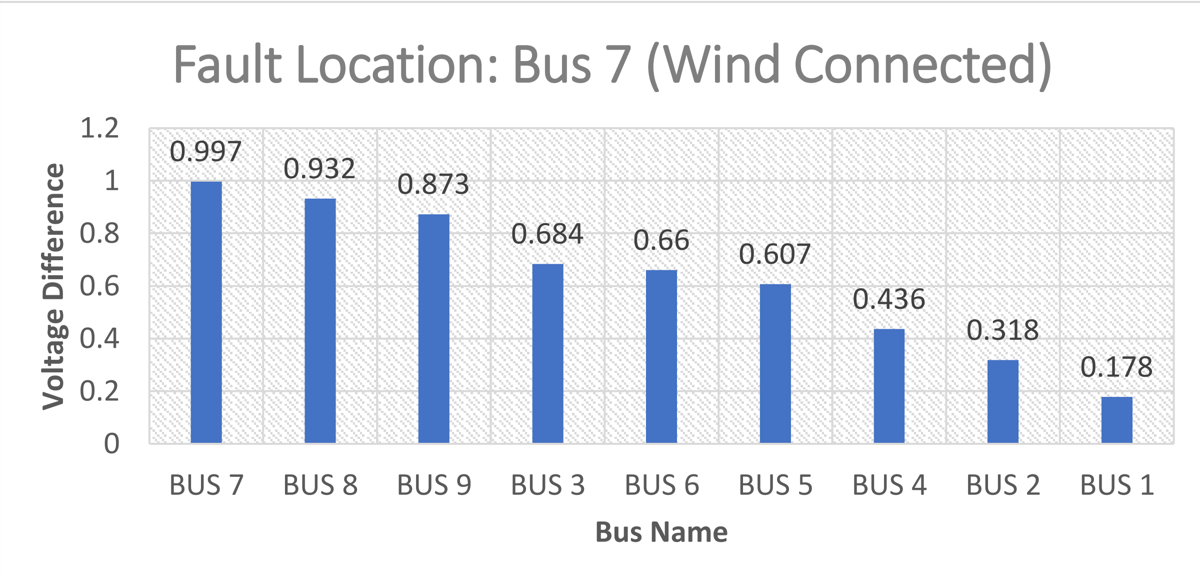

Fig 5.51: The Response of All the Buses According to Voltage Dip When Fault is in Bus 7(Wind disconnected)

These data can be helpful to identify proper relay coordination of the AC system as well.

5.6 Response Of Fault Impedance

Table 20: Fault current analysis with varying impedance when wind connected:

Wind Connected					
Bus Name	Fault Current				
	R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8
Bus 1	2868	1207	653.8	443.7	335
Bus 2	9265	1581	803.5	537.1	403.4
Bus 3	1122	701.3	424.4	296.8	226.8
Bus 4	1599	1598	1596	1595	1593
Bus 5	1108	1107	1106	1105	1103
Bus 6	941.3	940.4	939.6	938.7	937.8
Bus 7	3337	3334	3331	3327	3323
Bus 8	1360	1359	1358	1356	1355
Bus 9	1187	1186	1185	1185	1184

Table 21: Fault current analysis with varying impedance when wind disconnected:

Wind Disconnected					
Bus Name	Fault Current				
	R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8
Bus 1	2928	1254	681.4	462.8	349.6
Bus 2	1510	1087	717.1	517.5	401.2
Bus 3	1119	722.4	444.5	312.6	239.5
Bus 4	1562	1560	1559	1558	1557
Bus 5	1014	1013	1012	1011	1010
Bus 6	934.9	934.1	933.6	932.5	931.7
Bus 7	1395	1394	1393	1392	1391
Bus 8	1043	1043	1042	1041	1040
Bus 9	1113	1112	1111	1111	1110

Here we can see, with the increase of fault impedance the magnitude of fault current decreases for both wind connected and disconnected system.

The response of fault impedance changes with respect to voltage dip for bus 1 is given below:

Table 22: Voltage difference analysis with varying impedance when wind connected.

Wind Connected		Faulty Bus = 1									
Bus Name	Before Fault(pu)	After Fault					Voltage Difference				
		R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8	R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8
Bus 1	0.9962	0	0.7596	0.9057	0.9472	0.9643	0.9962	0.2366	0.0905	0.049	0.0319
Bus 2	0.9995	0.9653	0.9637	0.9816	0.989	0.9925	0.0342	0.0358	0.0179	0.0105	0.007
Bus 3	0.9838	0.7609	0.8184	0.9146	0.9465	0.9598	0.2229	0.1654	0.0692	0.0373	0.024
Bus 4	0.9814	0.2379	0.6097	0.8316	0.899	0.9273	0.7435	0.3717	0.1498	0.0824	0.0541
Bus 5	0.9528	0.4425	0.5678	0.789	0.861	0.8917	0.5103	0.385	0.1638	0.0918	0.0611
Bus 6	0.9663	0.396	0.5953	0.8157	0.8836	0.912	0.5703	0.371	0.1506	0.0827	0.0543
Bus 7	0.9965	0.8783	0.8853	0.9449	0.9676	0.9776	0.1182	0.1112	0.0516	0.0289	0.0189
Bus 8	0.9802	0.7984	0.8218	0.9093	0.9411	0.9547	0.1818	0.1584	0.0709	0.0391	0.0255
Bus 9	0.9915	0.7161	0.7777	0.9018	0.943	0.9603	0.2754	0.2138	0.0897	0.0485	0.0312

Table 23: Voltage difference analysis with varying impedance when wind disconnected.

Wind Disconnected		Faulty Bus = 1									
Bus Name	Before Fault	After Fault					Voltage Difference				
		R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8	R = 0	R = 0.2	R = 0.4	R = 0.6	R = 0.8
Bus 1	1.04	0	0.8156	0.9592	0.9961	1.011	1.04	0.2244	0.0808	0.0439	0.029
Bus 2	1.051	0.7386	0.8369	0.9723	1.009	1.025	0.3124	0.2141	0.0787	0.042	0.026
Bus 3	1.044	0.7244	0.8486	0.9753	1.008	1.022	0.3196	0.1954	0.0687	0.036	0.022
Bus 4	1.033	0.1993	0.7108	0.9155	0.969	0.9914	0.8337	0.3222	0.1175	0.064	0.0416
Bus 5	1.009	0.3545	0.661	0.8806	0.9389	0.9635	0.6545	0.348	0.1284	0.0701	0.0455
Bus 6	1.024	0.3483	0.6905	0.9038	0.9589	0.9819	0.6757	0.3335	0.1202	0.0651	0.0421
Bus 7	1.05	0.6857	0.8079	0.9623	1.004	1.021	0.3643	0.2421	0.0877	0.046	0.029
Bus 8	1.038	0.6614	0.7969	0.9518	0.9926	1.01	0.3766	0.2411	0.0862	0.0454	0.028
Bus 9	1.051	0.6467	0.8077	0.9659	1.007	1.023	0.4043	0.2433	0.0851	0.044	0.028

5.7 Summary

The chapter focuses on offshore wind farms connected by HVDC and explores the outcome of fault analysis in electrical power networks integrating renewable energy sources. It discusses the results of fault simulation. It draws attention to the serious problems that fault currents and voltage dips present and how they may endanger the stability and dependability of the grid. The chapter investigates fault responses in AC and HVDC systems through simulation studies. It takes into account both scenarios with and without wind system connections. To compare the effects of faults and direct the creation of protective measures, severity indexes are computed. All things considered; the chapter offers insightful advice for improving the robustness of contemporary power networks in the face of changing renewable energy integration conditions.

CHAPTER 6
PROTECTION OF AC SYSTEM

6.1 Introduction

The generation of renewable energy experienced a revolution with the integration of offshore wind farms with HVDC technologies.SO, The protection of the AC grid linked to these HVDC offshore wind farms is getting more attention as offshore wind farms are growing in numbers continuously. Ensuring energy security, promoting the shift to a sustainable energy future, and preserving grid stability all depend on smooth a reliable operation of the system. As the systems are complex, the protection mechanism should be designed after deep analysis of the system response. Reliable backup protection should be present. Moreover, the settings of the relays should be precise.

6.2 Type Of Protection

2 types of relays were used during protection analysis of AC system. These are distance relays and overcurrent relays. The relays were tested or analysed in a radial system first. Then after checking for all the settings, they were used and tested in the test system (AC 9 bus system).

6.2.1 Distance Protection

Distance relays are primarily employed to safeguard transmission lines from power system faults. These relays operate based on their unique resistance (R) and reactance (X) characteristics. [36]. Several distance relays must work together in order for the circuit breaker to operate quickly.

The three-zone protection of distance relays serves as a backup in instances where primary protection fails, particularly on the longest transmission line adjacent to the line requiring protection. To ensure precise fault detection, the relay's reach setting is adjusted to cover 100% of the primary line plus an additional 100% of the neighbouring longest line [37].

Let’s see the working simulation of distance relay using DIgSILENT PowerFactory: [38]

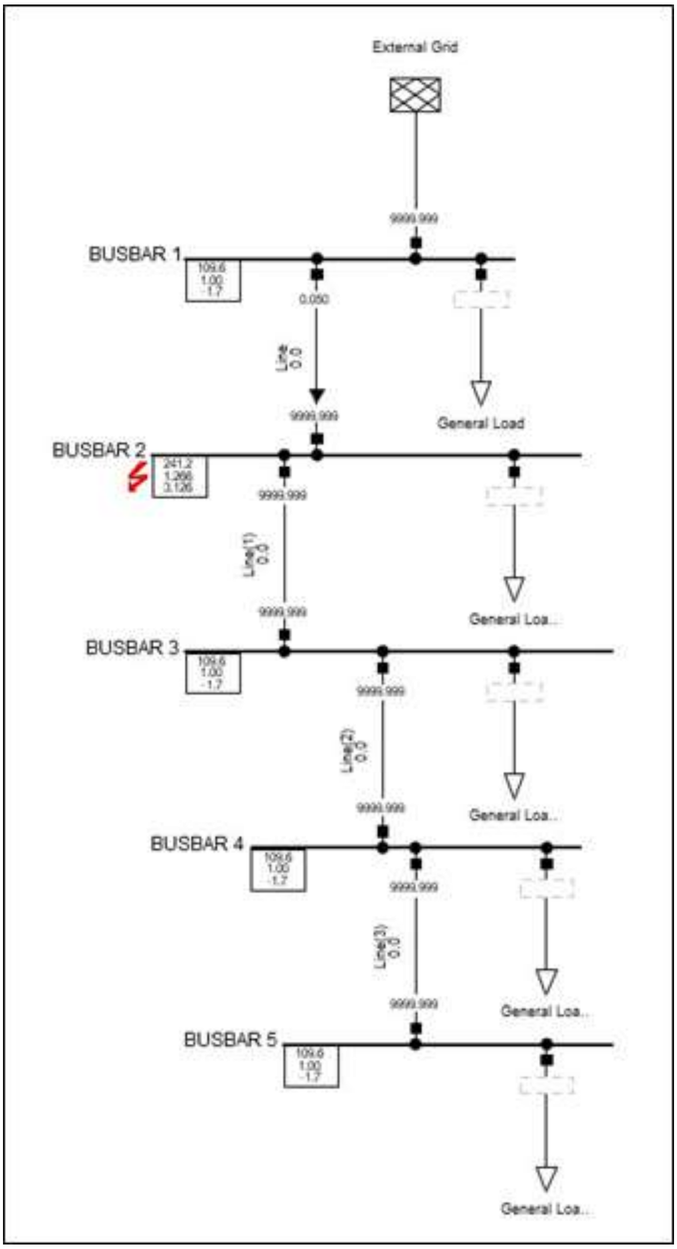

Fig 6.1: Single line diagram of a radial system

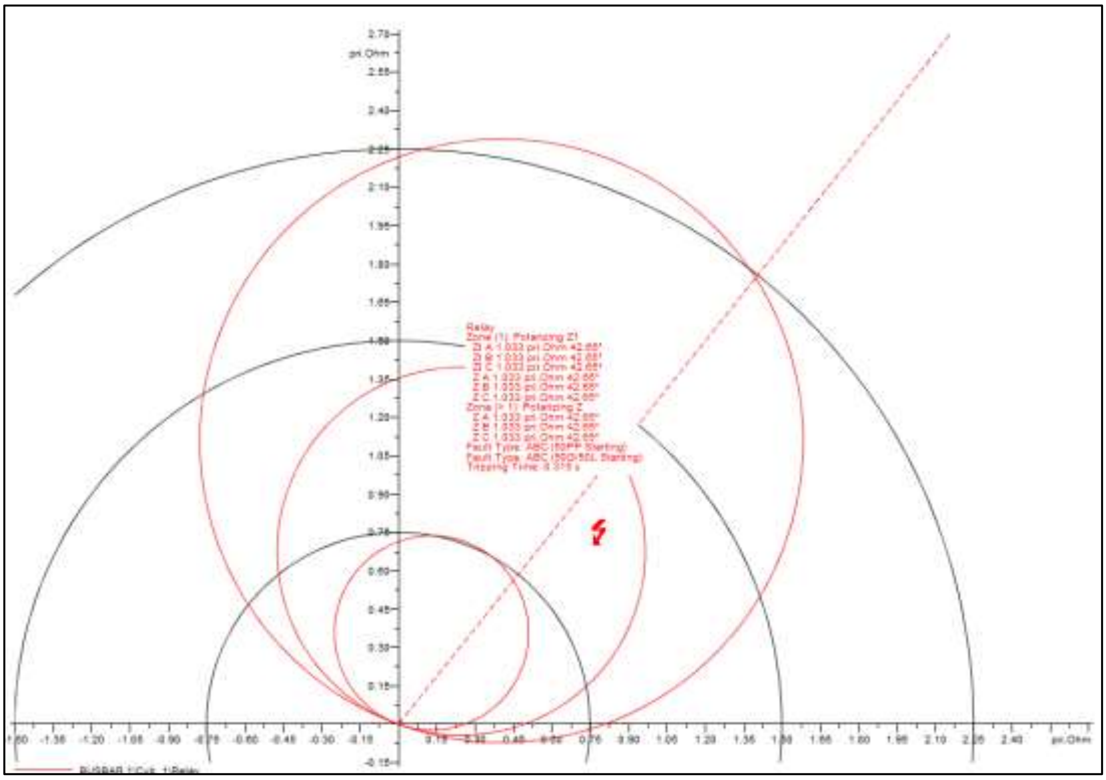

Fig 6.2: Characteristics curve of distance relay for 3 zone protection

Here in the radial system, the fault is in busbar 2. So, the relay senses the fault and trips as zone 2, which can be seen in the characteristics curve.

6.2.2 Overcurrent Protection

An overcurrent relay is a protective device that activates when the load current surpasses a pre-set threshold. There are two main types: the instantaneous overcurrent (IOC) relay and the definite time overcurrent (DTOC) relay[39]. The time settings of the relay can be changed according to the magnitude of fault current. As, there is no 3-zone concept here, proper coordination is necessary for backup protection.

Let's see the working simulation of distance relay using DIgSILENT PowerFactory [40]:

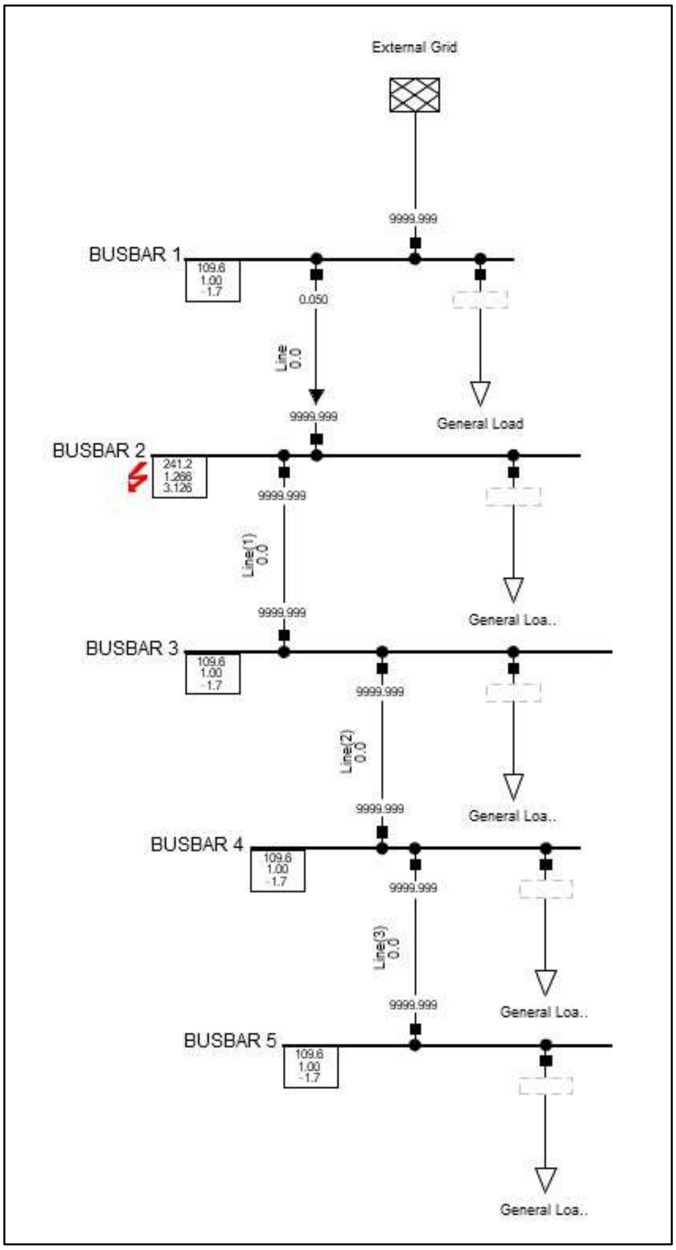

Fig 6.3: Single line diagram of a radial system

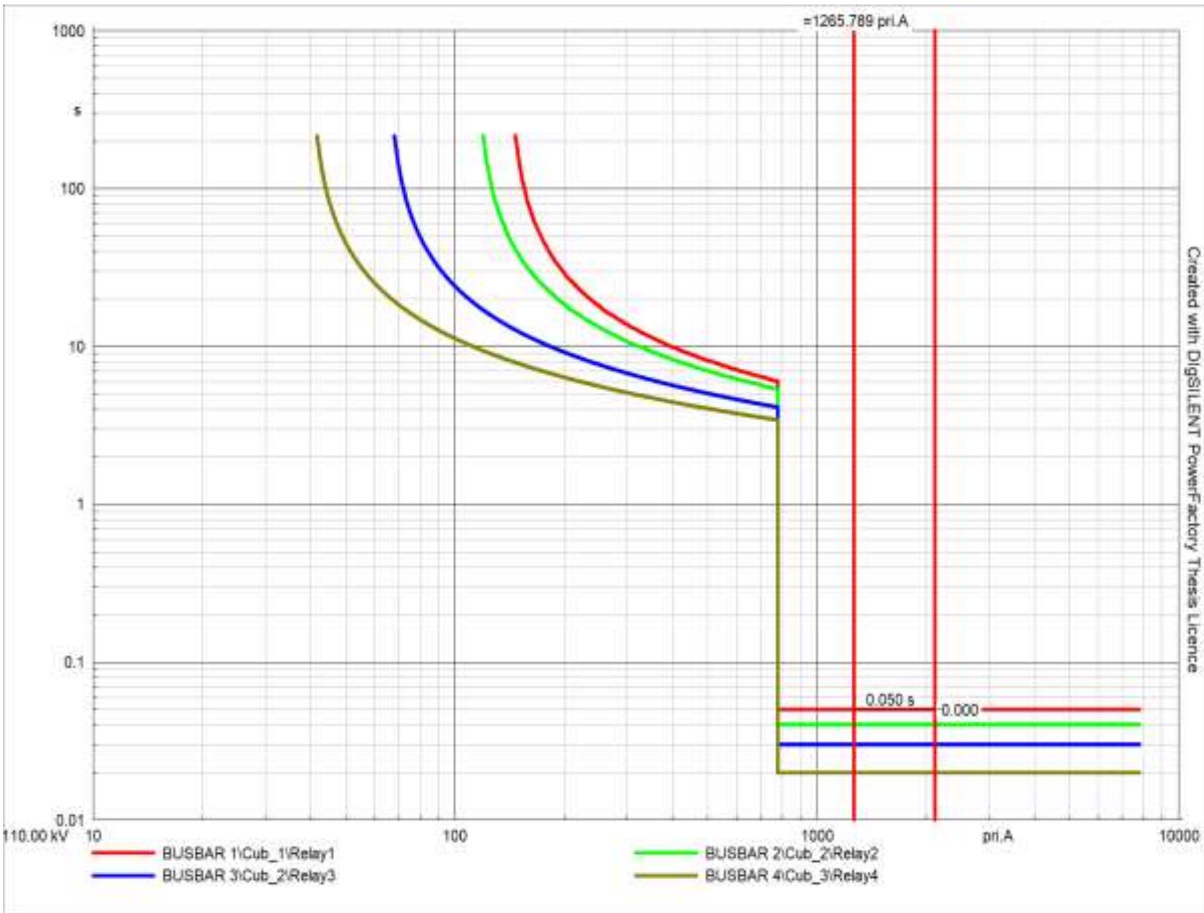

Fig 6.4: Characteristics curves of overcurrent relays

Here in the above diagrams, the fault is in busbar 5. As we can see there are multiple relay curves, there should be a coordination of relays for backup protection. The pickup settings were set according to it. In the characteristics curve we can observe both times delaying as well as instantaneous curves of relays. When the fault current is not that high, time delaying operation can be an option here. On the other hand, when the fault current is very high such as short circuit fault current, then instantaneous operation will be done. The settings are done after calculation the pick-up current.

6.3 Appropriate Protection Mechanism of AC System

After testing both distance and overcurrent relays for the nine-bus system, it was found that overcurrent relays give better coordination. As a result, proper backup protection as well as reliable protection can be ensured. On the other hand, in case of distance protection, zone overlapping cause the relays to be tripped unnecessarily. Handling the backup protection is quite difficult in case of distance protection. So, using overcurrent relays, a reliable protection mechanism was designed. Where a total of 17 relays [SEL 421 1A] were used. Let’s see the response of the protection mechanism:

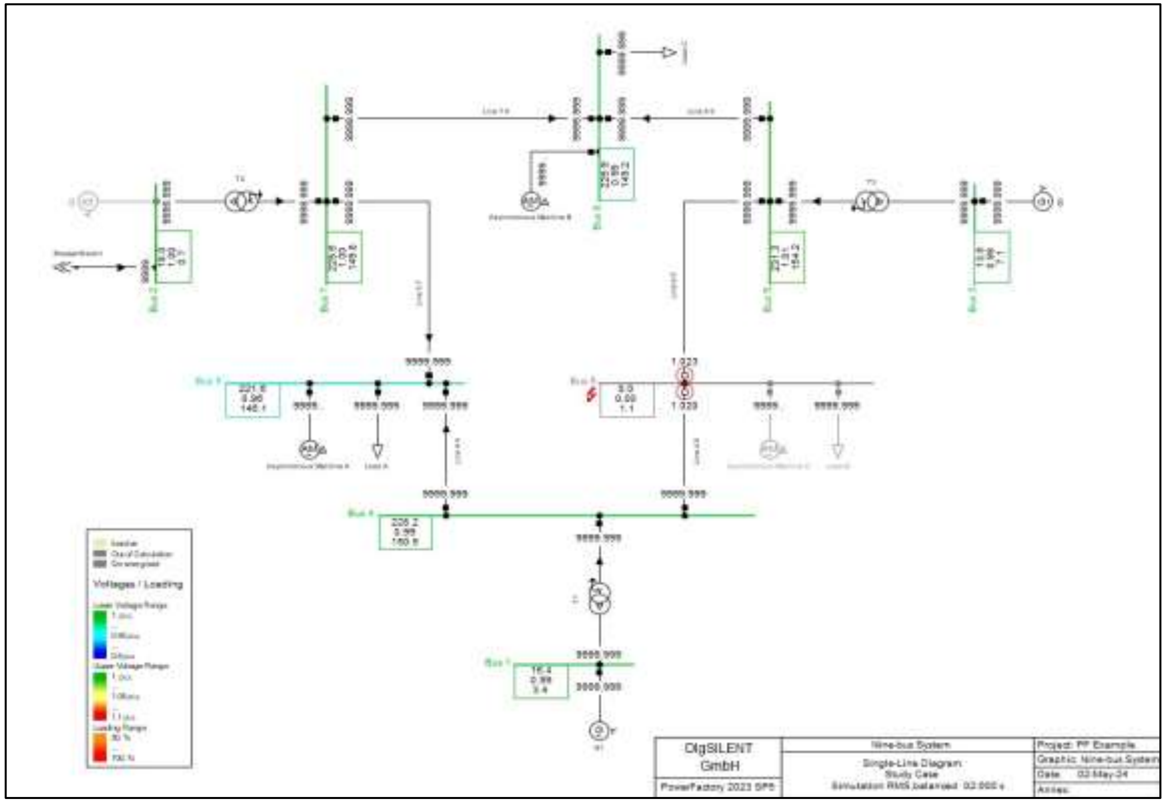

Fig 6.5: AC System's relay tripping when the fault is in bus 6

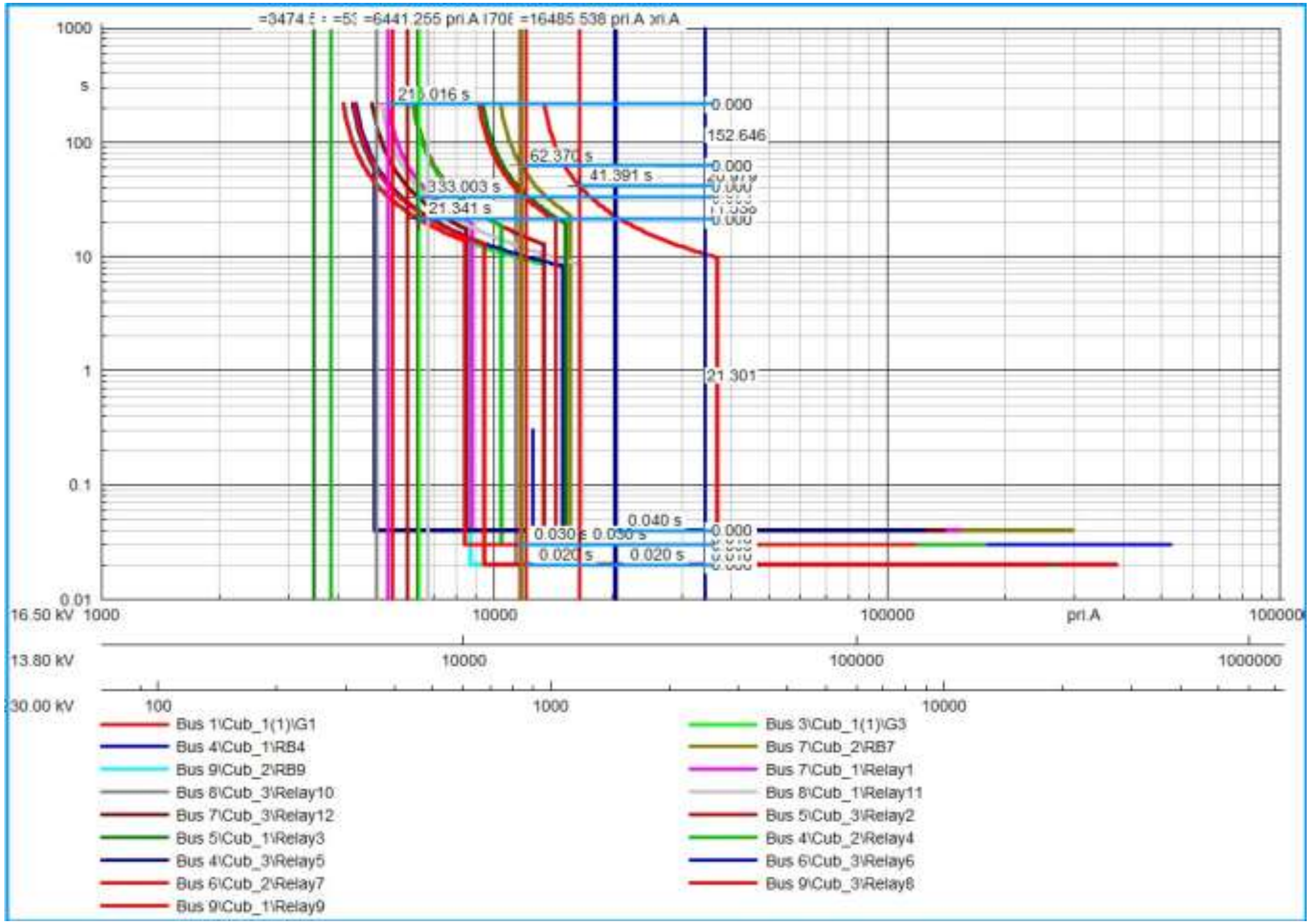

Fig 6.6: Characteristics curves of all the relays of 9 bus system

Here in the above diagrams, it can be seen that, when the fault is in bus 6, the relays of the 2 side of the bus gets tripped and selective operation is done. The relay settings were set after observing the fault currents during fault. Coordination was done and different tripping time for backup protection were set.

CHAPTER 7
CONCLUSION

7.1 Discussion

this study has highlighted how important it is to spot and shield against faults in AC grids connected to offshore wind farms using HVDC. Good protection plans are crucial for keeping the system stable and dependable. Although there are difficulties, improvements in protection tech show hope for solutions. This research sets the stage for future work to make integrating offshore wind power into grids better, creating a strong and eco-friendly energy setup

7.2 Findings

1. The response of fault with respect to magnitude of fault current.
2. The response of fault with respect to voltage dip.
3. Severity index of fault with respect to the magnitude of fault current
4. The comparison of voltage dips of each bus due to fault.
5. The fault response comparison of wind connected and wind disconnected system.
6. The impact of fault parameters when the fault impedance is varied.
7. Identification of better protection (Overcurrent) for the AC system.
8. Giving reliable protection to the AC system after analysis.

7.3 Future Works

The capacity of offshore wind farms is projected to grow substantially over the next decade. The International Energy Agency (IEA) anticipates that global offshore wind capacity could reach 234 GW by 2030.[42] So, to achieve this goal, researchers are focusing on enhancing the efficiency and reliability of the wind farm systems. The advancement of floating turbine technology and HVDC transmission opens up enormous new possibilities for offshore wind farm construction by enabling the harvesting of wind energy in deeper oceans. Power transmission from these isolated places to onshore networks is made more efficient with the use of HVDC. In case of HVDC transmission, integration of digitalization and smart functionality into DC circuit breakers will enable enhanced monitoring, diagnostics, and condition-based maintenance. Future DC circuit breakers may incorporate built-in sensors, communication interfaces, and self-diagnostic capabilities to provide real-time status monitoring and predictive maintenance insights which will eventually improve the overall system reliability and availability.

Wide-area monitoring systems (WAMS) and synchro phasors are two technology that may be used to enhance fault localization and detection accuracy, minimise downtime, and reduce the impact on grid stability. In the future, protection systems could have a distributed architecture, in which different grid infrastructure components perform different protective functions in a decentralised manner. Decentralised protection solutions have the potential to provide enhanced scalability and flexibility to suit the dynamic nature of offshore wind power generation, along with speedier fault isolation and restoration.

The outcome of this thesis can help the future research as well. From the severity indexes and comparative analysis, selective and efficient relay coordination can be done to enhance reliability. Moreover, wind can be disconnected for some severe conditions. As a result, separate protection for wind disconnected system can be developed.

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