# Msc Thesis

## Developing Protection Schemes for Offshore Wind Parks

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Challenge the future

# MSC THESIS

## DEVELOPING PROTECTION SCHEMES FOR OFFSHORE WIND PARKS

by

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Author
Devendra Moharkar

# Contents

# List of Abbreviations

**ANSI** American National Standard Institute

**CB** Circuit Breaker

**CT** Current Transformer

**KCL** Kirchhoff's Current Law

**PCC** Point of Common Coupling

**PSCAD** Power System Computer Aided Dynamics

**RMS** Root Mean Square

**sec** Second

**TSO** Transmission System Operator

**VT** Voltage Transformer

**WPO** Wind Park Owner

**WT** Wind Turbine

**WTG** Wind Turbine Generator

# LIST OF FIGURES

# List of Tables

# Abstract

The increasing demand for electricity and the need to decelerate the use of fossil fuels to prevent a dramatic climate change have urged the need for new sources of energy. Thus, electrical sustainable energy is an ever growing field. Investigations into performance improvements and extraction of maximum benefits from Renewable Energy Sources (RES) is the need of the hour. In particular, wind power contributes to a significant share of renewable electricity generation and has seen great leaps in terms of implemented technologies. The advancements in wind turbine technology have introduced converter based generation, thereby affecting the electrical grid's inertia and short circuit current contributions. These short circuit contributions have been of particular interest for protection engineers in the development of protection systems worldwide. TenneT, which is the TSO of the Netherlands, faces the challenge regarding the protection scheme implementation for their upcoming offshore wind farm connections involving Type 4 Wind Turbines (WT). The lower magnitudes of current flow, post fault and the presence of balanced currents irrespective of the type of fault are some of the major challenges.

The system starting from the busbar (where WTs are connected) is owned by the system operator and the WT along with the cable connecting to the busbar, or the Point of Common Coupling (PCC) is an asset of the Wind Park Operator (WPO). Non-technical issues such as the ownership of components at the point of common coupling between the wind park operators and the system operators together along with the technical challenges described earlier necessitates the development of a standard protection scheme that provides satisfactory performance. Implementation of end-to-end connection protection system for the individual component protection is also challenging considering the challenges associated with the ownership of the assets. Therefore , it is necessary to analyse the performance of conventional protection systems (single unit operation). The performance of definite time overcurrent, directional overcurrent, under voltage and distance protection have been studied for faults on PCC and the infeed WPO strings.

The study aims at finding the right choice of primary and back up protections that are independent of the type of short circuit currents available by the generation technologies. In addition, the research aims to develop a new busbar protection scheme that can detect and identify the fault location with the challenges explained before. Following the undesirable behaviour observed with overcurrent and directional overcurrent protection system the author then proposes two new schemes using conventional protection systems. The considerations regarding successful operation of under voltage protection and distance protection are further addressed. Finally, a new scheme involving fault generated travelling waves to detect fault on the network is extensively tested. All the protection systems are then compared to describe their merits and demerits to make a decision about the primary and backup protection implemented.

# 1

# INTRODUCTION

This thesis presents a comparison of protection systems for the Offshore Wind Farms of 66kV networks independent of the Wind Park Operator. This chapter brings to light the reasons that motivated the need to develop models and the new protection scheme. It describes the objectives of this research work and the methodology used to achieve them. The chapter also provides a report outline and emphasizes the original contribution of the research work.

## 1.1. OFFSHORE CONNECTIONS

Electricity generation field has been revolutionized with the advent of renewable generation to the network, namely, the Wind Farms (onshore and offshore) and the solar PV generation. Renewable sources of power generation as a sustainable alternative has risen several folds during the last decades with the increased capacity of individual wind turbines and solar panels. This integration of renewable sources of power generation into existing network has however, led to a drop in system inertia and lower contribution of the short circuit currents. The grid integration of large wind farms and solar panels have already started in many European countries with new Offshore Wind Farms coming up in the North Sea area [2].

The wind power plants have emerged as the fastest growing renewable power source with around 25.7 % of growth in the last 10 years [3]. Short-circuit studies; therefore, provide a basis for assessment of the impact of newly connected wind farms on the fault levels of the system. The increased levels of power penetration provided by the new advancements in the wind turbines technologies have caused many utility companies to revise their grid code. The wind turbines are now supposed to support the grid voltage in case of a fault. Therefore, a detailed study of these fault currents will help in making of a robust and efficient grid code. There is a potential to develop protection concept from these studies that will help in setting of the relays in the meshed network.

The low peaks of short circuit currents provided by these WT can highly influence the protection relay behaviour, demanding revised settings for the relay and change the response time to a fault. Also affecting the grid code if the changes are very severe during a disturbance period owing to this connection. These offshore wind farms are usually connected to a strong grid onshore, and cause a flow of high currents from the grid side during a fault condition.

## 1.2. PROBLEM DEFINITION

Protection is a critical part of the transmission network; hence, proper selection and working of the protection system is of utmost importance. The Asset Management Offshore team of Tennet who is a transmission system operator in The Netherlands (NL) and east of Germany (DE) had defined the first standard protection specification for the 380 kV grid up to 66 kV. The organisation now aspires to build a standard protection concept for the 66 kV network suitable for both the NL and DE, which is also the goal of the thesis.

Increasing wind power penetration in the grids is creating new challenges for protection engineers around the world. The short circuit behaviour of the WTs creates challenges for conventional protection systems. It is hence essential to study the fault behaviour of these variety of renewable generators to develop capable protection techniques that will serve to protect the system and ensure safe and secure operation. For faults near the wind turbine generator, the short circuit current provided is several times the rated full load current and is only limited by the generator impedances and the system [4]. Type 3 and Type 4 WT, on the other hand, have an unconventional behaviour of faults currents owing to the complex converter principles and characteristics employed by them. The WTs mainly of Type 4 (studied in this thesis) are unable to supply a large magnitude of short circuit currents due to limitations of the full converter that is used. The fault current contribution by this Type of WT is as a result limited to a maximum of 1.1 to 1.2 p.u. following any initial transients. This makes it extremely complicated to distinguish a fault from the normal behaviour of the WT, and exposing the system to the risk of damage.

It is also important to mention that for an existing offshore project of the organisation involving the connection of Type 4 wind turbines has a protection concept developed entirely with an assumption of short circuit current contributions of that of a Type 3 wind turbine. Owing to the difference between these two, it is crucial to revise the existing protection concept while highlighting the challenges involved. The 66 kV offshore network is studied in this thesis, and important consideration about the network being not easily accessible for any faults or maintenance activities is stressed upon. This consideration is based on the concept that high expenses are involved in making trips to the offshore network. The conventional protection systems located to clear the fault for high currents flowing from the strong grid (onshore) can be operated due to high current magnitude available. However, the protection relays at the 66 kV network located from the Wind Park Operators (WPO) side could not operate hence causing damage to the assets. Most of the time and in this case the TSO is responsible for the system starting from the busbar on the offshore substation. The cables that connect the Wind Parks to the offshore substation (also referred in the document as connection cable) are responsibility of the WPO. The Wind Park Operator is not bound by the contract to provide any protection for the cables. The transmission system operator has to make sure that the protection applied as a back up for the busbar protection, has to operate with a suitable time delay, to protect the assets on the offshore platform and avoiding any fatalities. This thesis therefore makes efforts towards solving these problems by contributing a detailed study of protection systems.

## 1.3. OBJECTIVE AND METHODOLOGY

### 1.3.1. OBJECTIVE

After the consideration of the new technologies of WT employed by the Wind Park Owners and also co-ordinating with the protection systems installed by every individual party (different wind park owners) the TSO now has to develop or install a protection system on the 66 kV part of the network, more precisely, around the 66 kV busbar which is also the Point of Common Coupling (PCC), that can effectively provide the following functions;
1. To protect the busbar in case the primary busbar protection fails by identifying a fault and opening the Circuit Breakers from the Wind Park side.
2. To disconnect the faulty string while maintaining the supply from healthy strings in case of cable fault on the connection cable.
3. To selectively operate for busbar fault and faults on connection cable.

In this thesis, modelling of the different protection function is realised by applying PSCAD models. Thereafter, by applying a test network, the models are used to simulate fault currents and to investigate the performance of the protection systems mentioned in table 1.1. The operational behaviour and feasibility to operate will also be elaborated. The main objective of the study is to develop a protection scheme that can be a standard for all the Offshore networks that will be developed in the future by the organisation (TSO of the Netherlands and some parts of Germany). The study provides early steps in the direction of a scheme that helps the transmission system operator to operate protection systems independent of the type of generation connected. Hence, steps towards the development of an independent and selective protection scheme are studied.

### 1.3.2. METHODOLOGY

To study the behaviour of the relays during a fault for the wind turbine technology of Type 4 an existing project at the organisation is used as a study case for this work. The project of Borselle that is under development offshore connection and is yet to be live by September 2019, uses a Type 4 WT technology employed by the WPO. This connection will be consisting of total connected generating capacity of 1400 MW, which has been divided into four parts, namely, Borselle Alpha (A1 and A2) and Borselle Beta (B1 and B2). All the four parts are very similar, except for the Wind Park Owners, hence in this model only one part is modelled in detail. The developments and findings with this part can be easily extended to the other parts of the network. For the study, therefore, a detailed model on Borselle Alpha A1 is developed on PSCAD where the main area of interest as described earlier is the 66 kV network. The model attempts to depict a real life scenario by using accurate modelling and behaviour in terms of current contributions from the WT.

| | Protection Type |
|---|---|
| 1. | Instantaneous Overcurrent Protection (50) |
| 2. | Directional Overcurrent Protection (67) |
| 3. | Undervoltage Protection (27) |
| 4. | Distance Protection (21) |
| 5. | Travelling wave based Protection |

Table 1.1: Protection relays studied in thesis

The relay models that have been provided by PSCAD are used for studying their behaviour during a fault. Hence the following mentioned type of protections in table 1.1 are tested for their response during a fault. Owing to the model limitations, only symmetrical faults will be studied. In addition, a travelling wave based protection scheme will be implemented to alleviate the unexpected relay behaviour. Finally, a detailed comparison will be made to elaborate on every tested protection system for its suitability to be used with the WT Type 4 technology and offshore connections.

## 1.4. THESIS LAYOUT

The document is structure is in the following way:

- Chapter 2 Background; deals with the review of the existing literature for low infeed situations.
- Chapter 3 Modelling and Network Configuration; deals with the developed model in PSCAD and the Offshore connection considerations/details.
- Chapter 4 identifies the challenges associated with the Instantaneous overcurrent protection system.
- Chapter 5 tests the working of directional overcurrent protection on the grid.
- Chapter 6 is related to the response of under-voltage protection during a fault.
- Chapter 7 refers to the application of distance protection.
- Chapter 8 tests the fault generated travelling wave based protection system.

- Chapter 9 provides a detailed comparison between the protection systems that are tested during this thesis and providing conclusions regarding the same.

# 2

# BACKGROUND

## 2.1. GOAL OF PROTECTION STUDIES

The protection studies are associated to the short circuit level of the power system to gain a thorough understanding to ensure safe and reliable operation. The results of these studies help in the selection of the type of relay scheme and determining the settings of the relay. A short circuit and coordination study is critical for the safe, efficient, and economical operation of all electrical distribution system. A short circuit study will help to ensure that personnel and equipment remain protected by establishing proper interrupting rating [5]. Connecting additional power generating capacity to an existing power system also demands revision of the protection studies. Major power failures can have a severe impact on the economy, critical infrastructure, businesses, and the end-consumer. So successfully protecting the power systems and related high voltage equipment against such failures is critical [6].

Although a 3 phase to ground fault rarely occurs, it is considered as the most severe type of fault. Under the symmetrical short circuit, the fault current is balanced between the three phases and hence sometimes referred to as balanced fault [1]. To simplify the analysis, steady-state AC circuit theory is exploited to calculate a worst-case (i.e., initial) root-mean-square (RMS) the magnitude of the symmetrical AC component to characterize a particular time interval of the fault-ON time period. During a fault there are three periods of interest as can be seen on Fig. 2.1: "the sub-transient period, lasting only for the first few cycles (at 50 Hz) during which the current decrement. The transient period, covering a relatively long time (i.e., beyond six cycles) during which the current decrement is more moderate. Finally, the steady-state period (i.e., beyond thirty cycles) [7]. Using the above information, short circuit capacity or fault MVA is calculated. The calculation uses nominal system voltages with the assumption that the power system operates at no-load immediately after fault occurrence. Further minimum and maximum short circuit current levels on the system has to be determined.

After gathering all the essential information related to protection such as short circuit currents, fault MVA, system configuration, and components involved, all the protection devices need to be selected accordingly. The selection of protection devices does not depend

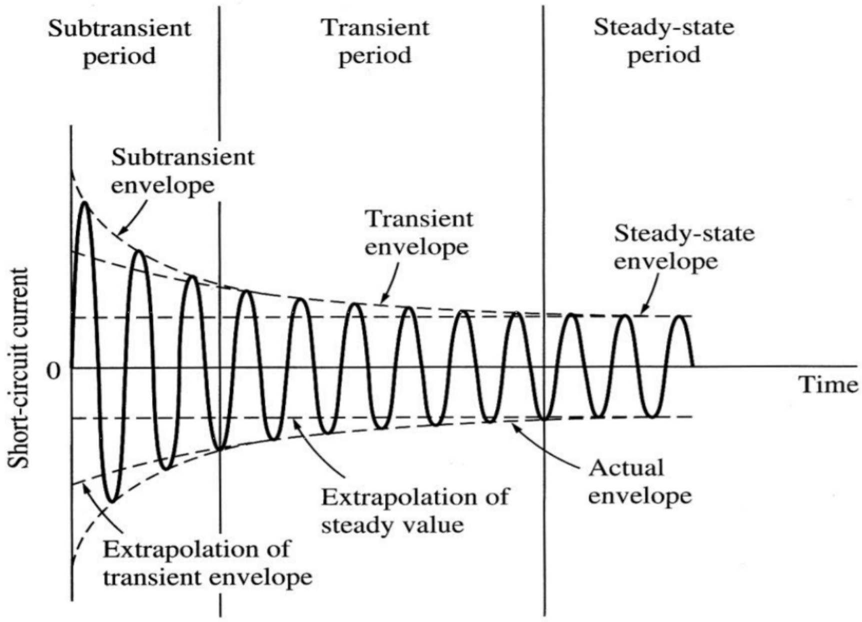


Figure 2.1: Periods after a fault [1]

only on the mentioned parameters and is also affected by other non-technical parameters. The best device selection does not guarantee secured operation and hence to achieve the desired accuracy and selectivity in the network, proper coordination of these devices is needed. This reason then gives rise to the protection concept, which is specific to every individual network and describes the operation of the power system and the protection devices during a fault with additional scenarios possible on the specific grid. The protection concept also underlays the specifications of protection devices and has to be followed when setting up the protection relays in the substation.

Moreover, with increased penetration of renewable in the grid and interconnection of power systems have created challenges for protection engineers. Interconnected power grids enable faults to be feed by more than one source, which can have different magnitudes of fault currents. Strength of the electric power system can be defined as the ability of the system to maintain its voltage during the injection of reactive power [8]. Earlier the wind farms could be disconnected in the event of a fault. Evolving technologies within the wind power generation and their increased penetration have now forced many system operators to revise their grid codes. In other words demanding voltage support for a specified period by the wind farms. Although WTs remain connected to the grid, the amount of short circuit current to be injected by the wind turbine generator during fault ride through is not standardized yet and remains specific to each country [9]. These conditions make an impact on the short circuit current contributions from these wind turbines during a fault on the grid.

The short circuit current parameters necessary for calculations are mentioned in IEC60909 [10]. Safe and reliable operation of the power system requires detailed tests with various power system simulation software such as PSCAD, RSCAD, EMTP-RV to provide accurate settings for the protection systems. Which enable studying the power system short circuit phenomenon by accurate modelling of the components involved. [10], however, does not provide any regulations or guide to the contribution of converter based generations. Integration of such fast acting renewable requires a comprehensive study to evaluate the possible risks and instability involved. Hence, it is necessary to study their behaviour with changing grid scenarios to understand their dependencies for providing short circuit currents.

## 2.2. LITERATURE REVIEW

With the above section discussing the purpose of short circuit studies and the increased penetration of full converter based renewable, it is essential to consider the fault current contribution of Wind Turbine Generators. As this thesis deals with Type 4 full converter based generation, this section discusses the difference between the WTs Type 3 and Type 4. Secondly, the issues associated with the WTs Type 4 is discussed and later on, the developments in protection systems for these conditions will be covered.

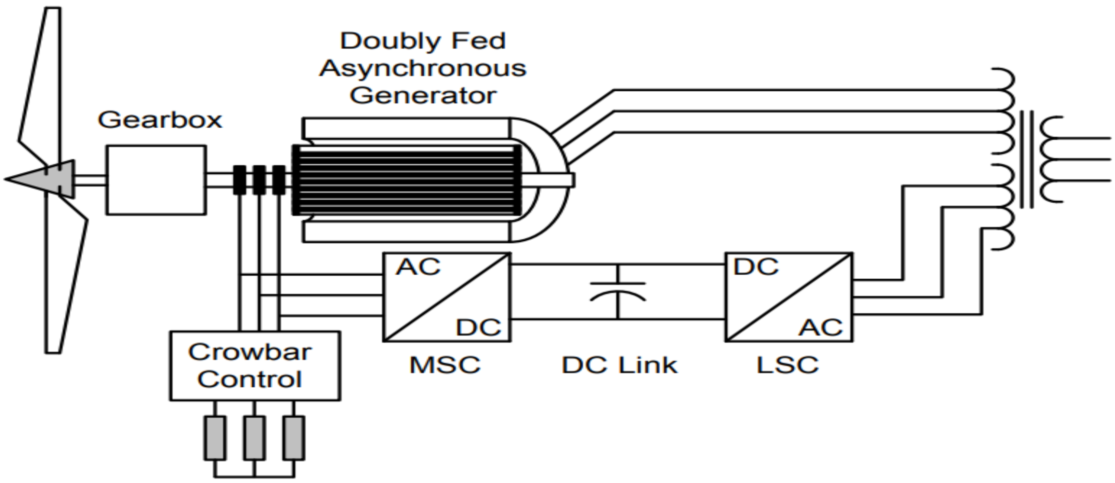


Figure 2.2: Type 3 WT representation

As described in the problem statement section, the existing protection concept developed includes an assumption of a WT Type 3 connection at the Offshore network. The turbine usually implements a Doubly Fed Induction Generator (DFIG), which in concept is like a variable speed synchronous generator with bus fed excitation. Although there is a word Induction used the behaviour of Type 3 WT is very different from that of Induction generators. Type 4 WT uses a permanent magnet or an induction machine. Both the Type 3 and Type 4 WT implement an AC-DC-AC conversion block, and this makes the generator to be isolated from the main grid. A schematic illustration of WT Type 3 and Type 4 with its primary components is described in fig. 2.2 and 2.3 respectively. Both WTs Types 3 and 4 generators control the real power to manage wind turbine speed and mechanical loads, the reactive power is used

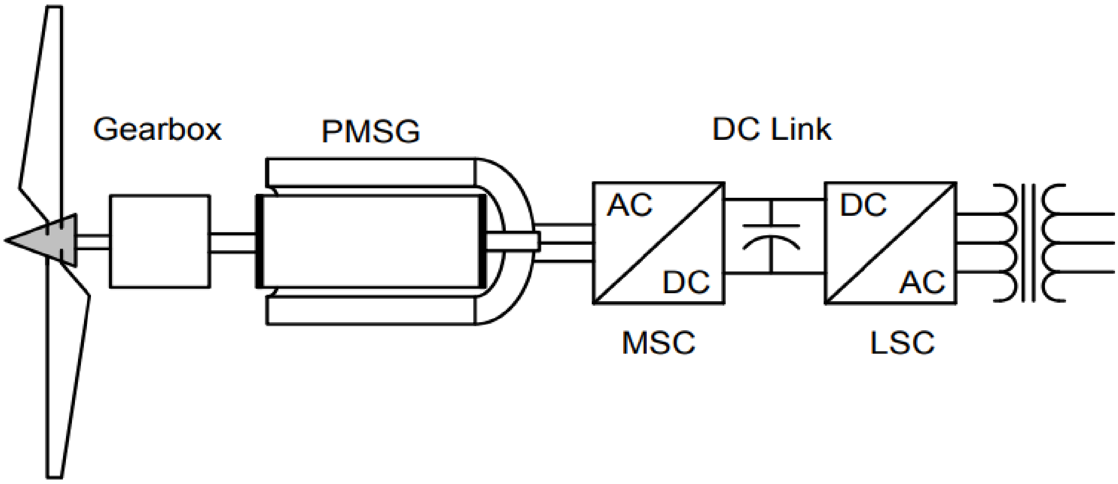


Figure 2.3: Type 4 WT representation

to achieve STATCOM-like control of voltage [11]. The short circuit contribution of these two WT, however, is different and has to be considered during short circuit calculations. The conventional synchronous or induction generator has their fault behaviour described by general physics and subjects to changes owing to the impedance magnitudes involved. The introduction of converters between the generation and grids change the fault behaviour controlling it to full fill the requirements by changing the converter algorithms and is limited with the physical constraints of the converters. Also, because performance is so dependent on the particular control strategies, these machines cannot be readily characterized by generic models [11]. The most crucial component of Type 3 WT that diverges its performance from Type 4 is the inclusion of crowbar. A crowbar is a tool used by the WT to switch between a constant current source generation and induction generator depending on the severity of the fault. The severity of fault is a measure of an excessive drop of voltage and extremely high currents i.e., typically a 3 phase to ground faults. Hence, the fault currents with crowbar in operation can be substantially higher compared to without a crowbar or controlled operation.

The Type 4 WT, has no crowbar and as seen in Fig. 2.3, the isolation using a converter does not allow high fault currents to flow to the grid. Therefore causing short circuit current as low as 1.1 ~ 1.2 p.u. with severe low voltages creating difficulty for protection systems. The contribution to unbalance faults is also very low and highly discriminating from the conventional sources of generation. In conclusion, the Type 3 WT can be modelled as a voltage source behind the reactance and that Type 4 as a current limited source. The Type 3 and Type 4 wind turbine during unbalanced faults inject negative sequence currents into the grid. Absence of the negative sequence controller results in opposition of negative sequence currents created by the negative sequence voltages resulting from the control characteristics of the converter based generations. In addition, an unbalanced fault would create a significant ripple on the DC link and require a large capacitor [4]. The wind turbine manufacturers avoid using this large capacitor, and forcing balanced currents even during an unbalanced fault. This strategy helps to maintain the DC bus voltage. [4], [9], [11] discuss in detail about the modelling of

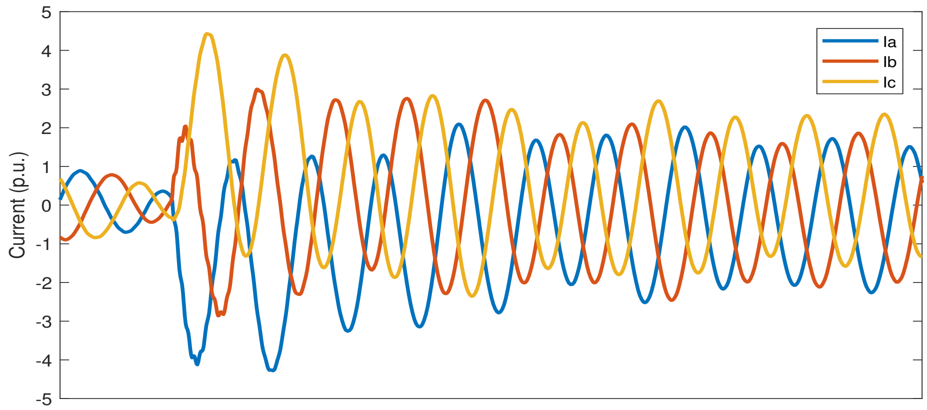


Figure 2.4: Short circuit currents with Type 3 wind turbine (crowbar activated)- 3 phase to ground faut

Type 4 Wind Turbine for accurate representation to study the transients, short circuits, and time domain simulations. This large capacitors or batteries, in addition to the reasons above, would also have a positive effect by introducing synthetic inertia in the system. Therefore, supporting the grid during a fault and provide a solution to the problem of low inertia with increasing renewable in the grid. However, this is an interesting topic of research but not a part of this study.

After understanding the short circuit currents from the Type 4 WT, it is essential to design the protection systems/schemes for reliable operation. Presently, there has been no significant additions or any standard scheme for protection against fault currents from the Type 4 WT. For faults occurring in the grid, the converter adjusts itself to maintain the current magnitude between the limits specified (low currents), but the protection system observes a low voltage and may mal-operate. [4] proposes a protection concept based on DC link voltage; however, it is essential to mention that the wind parks consisting of many wind turbines are connected through a short cable to the substation busbar of the TSO. Consequently, the PCC has two possible locations the point of cable at the wind turbine that is connected to the busbar or the substation busbar, depending on the contracts mentioning the ownership of the cable. In this study, the cable is an asset of the Wind Park Owner. Hence creating non-technical issues and the transmission system operator may at all times not have access to the DC link voltage at the wind turbines. As mentioned, the cable is an asset of the WPO, and the Wind Park Owner can choose the protection system implemented or leave it unprotected. This gives rise to critical fault locations that require thorough consideration,

- Faults at the Busbar (point of common coupling)
- Faults at the connection cable

The connection cable is the short section of cable that connects the last WT of the Wind Turbine String in the Wind Park to the busbar or point of common coupling as referred here. The TSO now has to implement protection systems on the busbar section both primary and

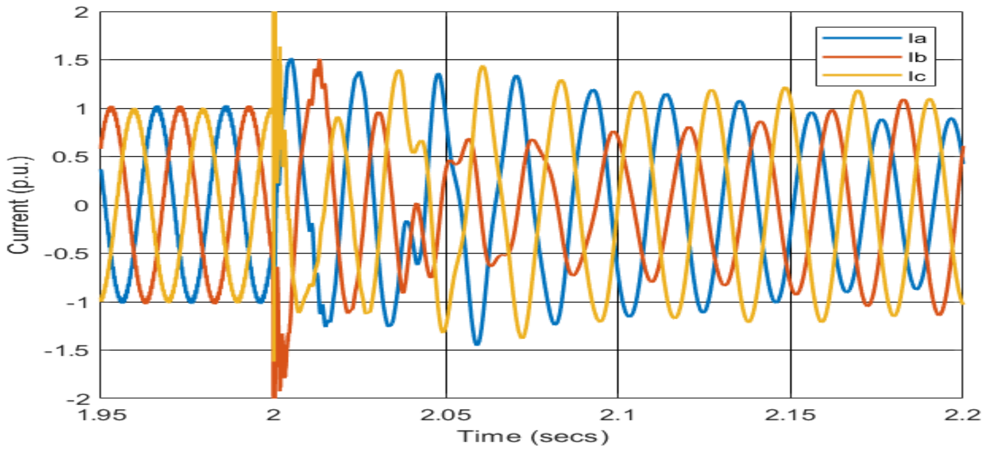


Figure 2.5: Short circuit currents provided with Type 4 Wind turbine - 3 phase to ground fault

backup considering the Type 4 fault contribution. In case of failure of the primary protection, the backup protection has to isolate the busbar in case of busbar faults. This back up protection for busbar also acts as backup for protecting the connection cable and hence has to identify and disconnect the faulted string during a fault on the connection cable. The TSO and WPO may at all times not have access to the other end of this connection cable and hence makes it difficult to implement a communication based or an end to end solution to protect this cable. In this thesis, therefore, conventional protection system performance is analysed, and new schemes are proposed to tackle the challenges mentioned before successfully.

# 3

# Modelling and Network Configuration

The grid and models used in this work have developed in the electromagnetic transient software (EMT) PSCAD. The software is mature, widely used around power systems engineers and has a friendly user design, hence allowing the user to investigate complex phenomenon and analyse results with ease.

## 3.1. Network overview

In the appendix, Fig. A.5 shows a Single Line Diagram of the modelled network used throughout this thesis. The grid is building offshore substations connecting 1400 MW of power generated by WTs to the Dutch grid. The 1400 MW wind farm is divided into four offshore stations Alpha 1, Alpha 2, Beta 1 and Beta 2 each of capacity 350 MW. One such section of 350 MW is represented in Fig. A.5. Every 66 kV busbar connects 175 MW of generation, so two busbars every section. Eight busbars accounting for 175 * 8 = 1400 MW. The scope of TSO starts at the offshore substation at the 66 kV busbar; the cable that flows from the last wind turbine to the busbar is also managed and is an asset of Wind Park Operator (WPO). The 66 kV network is grounded using an earthing transformer connected through the busbar. After the busbar, an offshore transformer connects two buses from alternate sections (bus A1 and bus A2) to provide redundancy. After stepping up the voltage from 66 kV to 220 kV using the power transformer, the power is transported to the shore with 60 km of undersea cable section. The cable section is compensated for its high capacitance on both sides using appropriate values of reactor banks. At the shore, the voltage is further stepped up to 380 kV to the level of the main grid of Maasvlakte. The step up is done using an autotransformer that has an MVAR controller to control the reactive power compensation. In the thesis, only one section has been modelled and studied, but given that the other sections have a similar configuration, the results shown can be easily extended to the remaining sections.

The Fig. 3.1 shows a close up image of a single 66 kV offshore busbar, which will be focused in the thesis. The figure also explains the terms that will be frequently encountered in the document. There are several numbers of wind turbines connected in parallel that further connect to the busbar on offshore substation. This arrangement is known as a string, and three such strings are connected to every busbar. In the string sea cable that connects the last wind turbine to the busbar is referred as connection cable. The term string fault and connection cable fault have been used interchangeably throughout the document, whereas both refer to the faults occurring on the cable section that connects the last wind turbine to the busbar (66 kV). The CT and VT measurements for all the relays are executed at the busbar end of the connection cable for individual string in the thesis. In the existing grid however, there is only CT measurement at individual strings and the voltage is measured at the busbar as a common point.

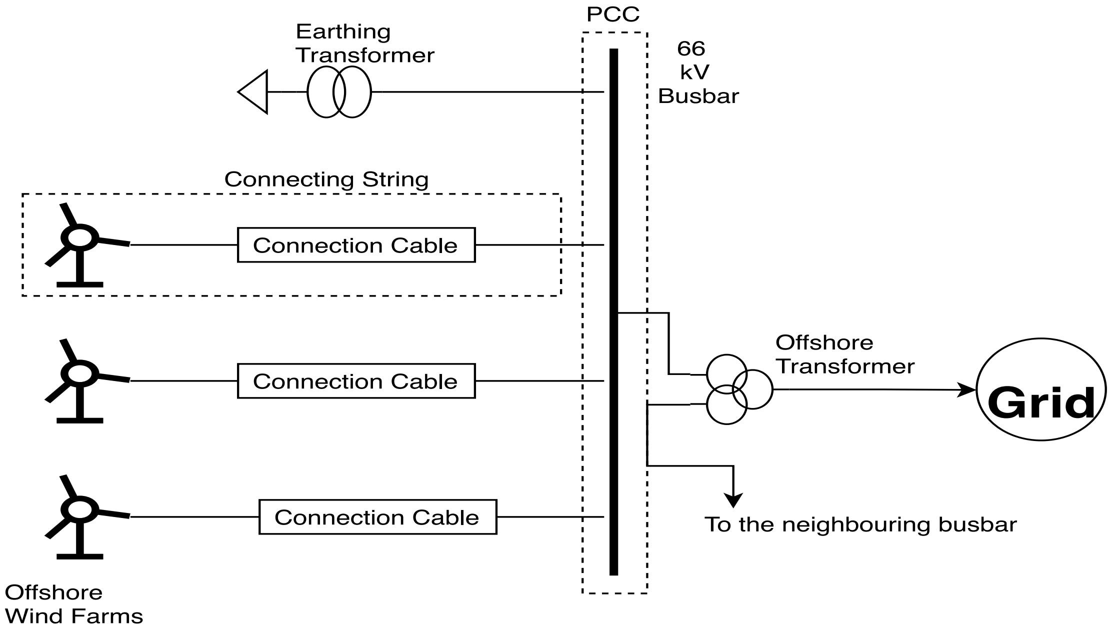


Figure 3.1: Simple representation of 66 kV network under study.

## 3.2. TYPE 4 WIND TURBINE

For studying the proper behaviour of the wind turbines during a fault, a Type 4 wind turbine model available with PSCAD is implemented. As the primary focus is on the 66 kV network of the grid where the connection of wind turbines also exists, it is essential to model their accurate representation concerning various aspects, such as current contribution, reactive current injections as the Wind Park Operators are entirely responsible for the number, capacity, installation and maintenance of the Wind turbines.

External parties already developed the model for an internal project concerning the organisation, and hence, its confidentiality is respected. The model represents a single wind turbine of capacity 6 MW (the original wind turbines connected to the grid are 8 MW). The scaling component is also provided to step up the power output; the scale-up component is a black box model delivered to step the active power and current output as a multiple of the mentioned value. The model uses a Permanent Magnet Synchronous Generator machine, which is further connected to the grid using AC-DC and DC-AC converter. The converter system is further classified as, generator side converter and grid side converter, which have their individual control systems. This configuration isolates the grid from the generation, hence causing the system to lose inertia. The output of the converter is now passed on to the step-up transformer. The transformer is installed inside every wind turbine and raises the voltage level to the required voltage at the point of common coupling. Although the model is highly detailed, the focus is protection studies and analysing the behaviour of conventional protection systems and therefore the detailed dynamic modelling and studying the accurate dynamic response of the wind generator is not addressed in this thesis.

It is also once again essential to mention that these WTs are not installed or owned by the system operator, making it difficult to adjust the control strategy, its contribution during steady state and fault conditions. An important aspect concerning the behaviour of WT is the missing negative sequence controller. The negative sequence controller is an essential component that injects negative sequence currents during an asymmetrical fault, making the currents unbalanced. No inclusion of this type of converter results in balanced 3 phase currents even during unbalanced faults, making it challenging to identify the type of fault. The model response is also adjusted to deliver 1 p.u. of reactive current in cases when the voltage drops to 0 during a fault until the grid code reacts to the fault. As studying the protection systems in this research, the model is customised to deliver 1 p.u. of reactive current for the entire range of fault.

## 3.3. CONNECTION CABLE

The Wind Park Operator owns the cable connecting the last WT of every string to the offshore substation busbar. However, the WPO is not legally obliged to provide any protection equipment on this cable section. Since the cable is terminated at the system operator owned substation, and the protection system are required to coordinate accordingly, the parameters of this cable are available with the system operator. The length of cable for every string is different but is no more than 5 km for any individual string. The cable parameters are not shared owing to the confidentiality of the data of the organisation. However, to understand the behaviour of this cable and to obtain outputs similar to the real situation, the cable in PSCAD is modelled as a frequency dependent model. Frequency dependent model is considered as one of the best models when studying the transients or dynamics of the system. Although power system protection studies do not demand such highly advanced, multiple frequency models, it is needed to analyse the travelling wave phenomenon, which is an important part of the thesis. Owing to the model limitations and considering the simulation time steps and the computational burden, only one string with a detailed frequency dependent connection cable section was modelled. The other strings had the connection cable represented using a $\pi$-section. All the analysis concerning the faults on this cable section and also on the busbar have been executed on this detail modelled string and the results can be extended to other strings.

## 3.4. OFFSHORE TRANSFORMER

The power transformer installed at the Offshore substation is also modelled in PSCAD. It is a three winding transformer with voltage rating of 220 / 66 / 66 kV, (Y / Δ / Δ) and 400 MVA. The 66 kV part can operate with only one winding in operation in cases of maintenance or fault on the other part of the network, maintaining the continuity of supply. However, this involves the modelling of the tap changer and adjusting the reactive power compensations accordingly, hence is not modelled in this thesis. The assumption considered for conducting the study is that the offshore connection section is delivering the full power of 350 MW per section. The measurements and test data of the actual transformers used on the grid were used. The model further considers the core saturation routines and the hysteresis modelling of the transformer is neglected for the thesis. The transformer response is not studied in the thesis, but it is an essential component of the offshore section and has been modelled with the generic three winding transformer model available with PSCAD.

## 3.5. SEACABLE, ONSHORE TRANSFORMER AND MAIN GRID

The power from Offshore transformer at 220 kV is carried by a 60 km length sea cable. This sub-sea cable forms a link between the offshore and onshore substation. The model of this cable was assumed from another project that involved modelling of the 220 kV subsea cable. The model is also a frequency dependent model and yields a very good behaviour. Owing to the higher length of cable they are compensated with appropriate reactor banks; the compensation is provided using two reactance banks at offshore and onshore respectively. The transport capacity becomes limited due to the high reactive power cable loading current. These onshore shunt reactors although is controller based are blocked during any fault on the grid, hence modelled as steady-state reactors of value assumed by the nominal tap of the reactor banks.

An Onshore transformer of 400 MVA is used to step-up the voltage to the main grid level. It is an autotransformer with a voltage rating of 220 / 380 / 33 kV ( Y / Y / Δ) The auxiliary delta winding comprises of reactive compensation using capacitor and reactor banks alongside a grounding transformer.

The 380 kV cable carries the output to the main grid of Maasvlakte( this is also referred to as the main grid in the document). The modelling of the main grid is represented by Thevenin equivalent. The voltage level and the short circuit reactance values are adjusted for the thesis.

## 3.6. RELAY MODELS

All the protection systems that have been tested throughout the thesis are available with PSCAD. These models are a part of the protection library of PSCAD. However, not yet released officially PSCAD these models were provided as a beta version. The models are delivered as black box models and are modelled to represent the behaviour of actual relays. The internal algorithms for pick up and trip logics cannot be altered, and the nominal settings possible with an actual relay can be edited. The current and voltage transformers are modelled as ideal for the study.

The fault studied in this thesis is modelled with fault resistance of 0.001 Ω. Owing to the limitations explained earlier, only a 3 phase to ground fault is executed on the network. The fault has been executed as a permanent fault to check the relay model operations and analyse it accordingly. All relay models have been tested for a location near the busbar with CT and VT measurements on each individual strings except for undervoltage protection, and the reason is discussed in the concerned chapter.

# 4

# Overcurrent Protection (ANSI 50)

Overcurrent protection is a basic protection system that uses the system current signals to detect a fault. This chapter first discusses the functions and provide an overview of the overcurrent protection. The existing setting is checked, and the working setting is tested. In addition, a new proposed scheme is discussed.

## 4.1. Overview and function

ANSI 50/51 is American national standard for over current protection. Overcurrent relays are a very commonly used protection relay type in the power system. Overcurrent relays use a basic principle, which transmits a trip signal when the measured/monitored current has reached the defined threshold. Fig. 4.1 shows the circuit for overcurrent protection relays. In case of fault the CT will measure high currents and the relay coil is energised. The switch closes and the relay circuit is completed and causing the trip coil to be energised which further provides a trip command to the CB. The instantaneous operation (ANSI 50) of this relay have no inherent time delay and can provide fast operations during a short circuit. This relay are also available with time delay characteristics (ANSI 51), this makes it possible to be coordinated with other protection devices, and providing selectivity. A common practice is to use overcurrent relays as backup protection for the feeders on busbar, as demonstrated in this case in the following sections. As discussed in the previous chapters, with the use of full converter based renewable generation technologies, the machine/generator is isolated from the grid by an AC-DC and DC-AC converter. The fault currents are limited to a maximum of $1.1 \sim 1.2$ p.u. following any initial transients. This also makes it troublesome to identify a fault situation from a temporary overload condition and could further lead to unwanted trips. The wind parks, in this case, fail to provide a higher fault current for the successful operation of the overcurrent relays.

The overcurrent relay model used for this test has been developed by PSCAD and has two setting groups with multiple phases and ground overcurrent elements, which can be used for single phase, two phase, and three phase applications. Both definite and inverse time over-current characteristics are available and can be used simultaneously. Each setting

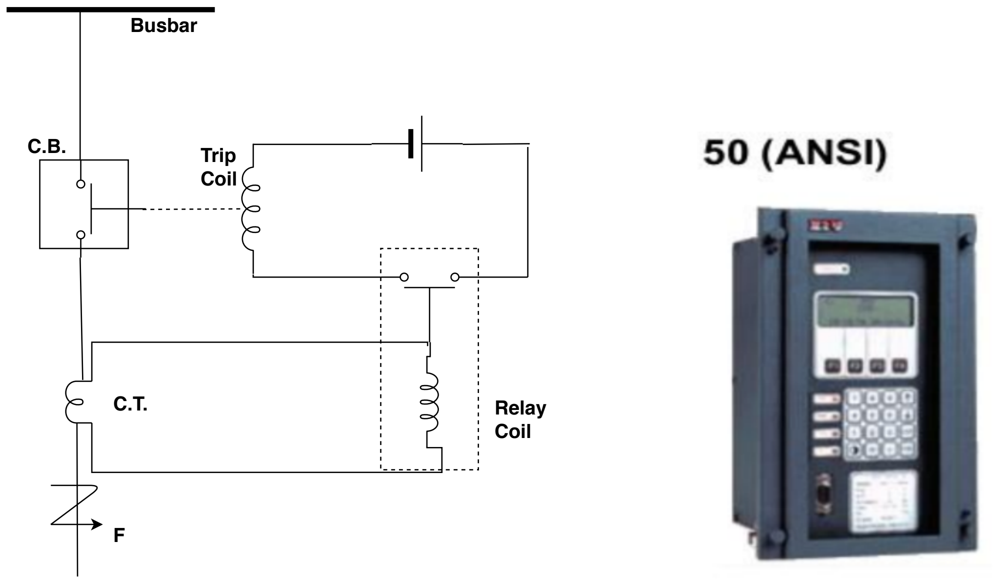


Figure 4.1: Conventional Overcurrent relays

groups has three definite time overcurrent functions (50) and three inverse time over-current functions (51). The inputs to the relay from the CTs are first processed using a signal processing block, this block then extracts the sequence components and fundamental phasor information from the analog input currents. The block makes use of Discrete Fourier Transform (DFT) along with anti-aliasing filter, DC removal filter, frequency tracking algorithm to perform the mentioned tasks. The output of the signal processing block is further fed to the various setting groups that are available for definite time and inverse time over-current elements. These setting groups serve as a base signals for the trip logic, which then creates one three-phase trip signal and three single phase trip signals for each phase, and outputs via external port "T". Several intermediate signals available as the internal outputs allow the user to troubleshoot further, monitor, and apply external algorithms.

## 4.2. EXISTING SETTING AND FEASIBILITY

The protection concept document provided by Siemens proposes an overcurrent relay function as a backup for the busbar protection. The existing proposed document, has been studied with a Type 3 WT model and proposes a concept that suggests setting the over-current relay with three times the nominal current and time delayed for 350 msec.

The developed model is adjusted to the proposed setting (Table 4.1), it is essential to mention that the model uses a Type 4 WT model which is available at the current project of Borselle — depicting a genuine scenario that could be expected at the developed wind farm connection that use this Type 4 WT. As stated earlier, the nominal WT model is of 6

| | |
|---|---|
| Current Transformer Ratio | 1250/1 |
| Current threshold (I>) | 1500A |
| Time Delay (t>) | 350 msec |

Table 4.1: Proposed Setting of ANSI 50 for Offshore Wind Farm Feeder

MW producing a steady state current of 0.0742 kA.The scaling component and the controls implemented depict the behaviour of the string connecting 10 WTs.

$$I_{rated_{windturbine}} = \frac{6MW * \sqrt{2}}{\sqrt{3} * 66kV} = 0.07422kA. \tag{4.1}$$

$$I_{rated_{string}} = \frac{6MW * \sqrt{2}}{\sqrt{3} * 66kV} * 10 = 0.7422kA. \tag{4.2}$$

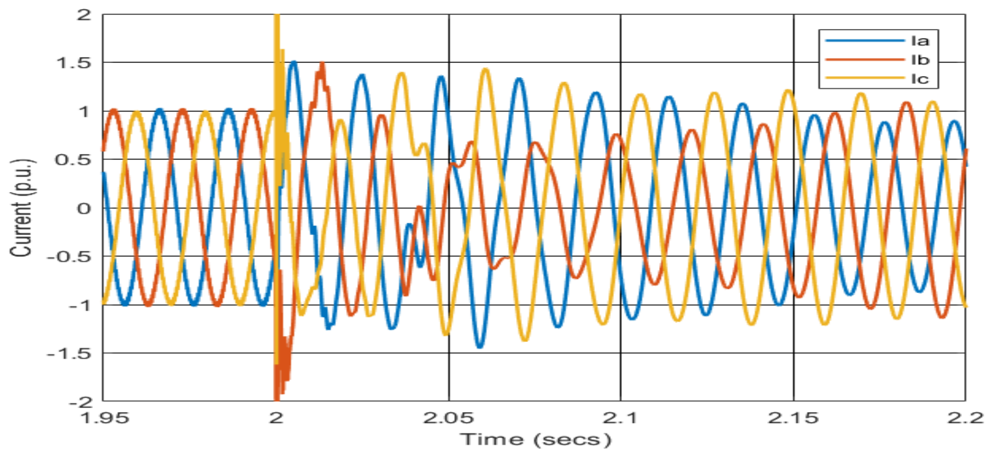


Figure 4.2: Wind Turbine current contribution during a Busbar Fault

Nominal currents measured at the 66 kV side of transformer winding is recorded to be 2.226 kA in the developed model. The proposed setting for the current threshold as well as the time delay (Table 4.1) are set in the overcurrent relay model. Current transformer, in this study, as not a primary scope of interest, is set as ideal with a Current ratio of 1250 / 1 A. Currents are measured on each string to provide input to the over-current protection relays. First, a fault on the 66 kV busbar has been created (permanent fault), and the above mentioned settings have been applied. As seen in Fig. 4.2, the fault current provided by this WT technology is limited to 1.1 to 1.2 p.u. following the initial transient period and not sufficient to trigger the relays to disconnect the faulty section. Fig. 4.3 show the currents that are fed to the fault location by the grid. A comprehensive and easy comparison can be made using these figures and can be stated that the WTs fail to supply high amounts of fault current. However, the currents from the grid side owing to high short circuit reactance of the transformers, provide high current making it possible to disconnect the faulty component using simple protection as an overcurrent relay. The CT currents that are received as an input to the relay are then again filtered out as stated in the previous sections, also shown in Fig. A.1 Later, a three phase to ground fault has been created at the connection cable, to study the response of overcurrent relay to this fault. Fig. 4.4, displays the currents measured by the CT on the string in case of fault at the connection cable. The overcurrent threshold proposed can be achieved in this case without any consequences, for the given time delay. However, this isolates the busbar from the faulty string in case of a string fault, but the connection cable continues to experience fault current from the wind farm. Hence causing permanent damages to the cable and affecting the connection for a longer time. Therefore, the overcurrent relay can successfully clear faults on the connection cable section and can be operated for the proposed setting. As discussed and seen from the figures, the busbar faults in this situation can be cleared or isolated from the high voltage side/grid side that feeds high current. However, the WTs keep feeding fault current to the fault location, which is an undesirable scenario. The provided setting as a result does not agree to the real scenario and fail to operate, further increasing the fault clearing time and waiting for the protection systems from the wind park owners to operate and clear the fault.

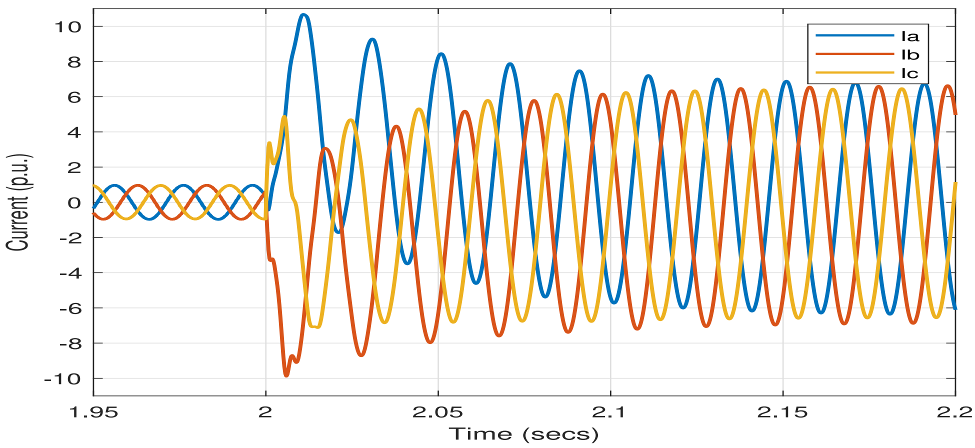


Figure 4.3: Grid Side current contribution during a Busbar Fault

## 4.3. FINDING THE MINIMUM SETTING FOR OVERCURRENT RELAY

As overcurrent relay being simple as well as an economical solution in the field of protection, it is also essential to investigate the possibilities of using this relay on the offshore network. This section focuses on finding a setting that helps to examine and comment on the scope of utilising an overcurrent relay on the 66 kV offshore network with the Type 4 WT technology. The steady-state waveforms for the currents flowing from the WTs are observed along with currents that flow during the fault from the Wind Farms as well as the High Voltage grid for the initial cycles.

In this section again, a busbar fault is created, and the current transformers are located on the strings (closer to the 66 kV busbar) which measure currents flowing into the busbar. The CT ratio is left the same, as mentioned in table 4.1. The pickup current of overcurrent relay is set to 1.2 p.u. with no time delay. This setting although looks favourable for the protection operation but may cause several unwanted trips during the normal operation of the power system, and causing frequent energization and issues related to loss of supply. The main reason for using an instantaneous trip is to utilise the magnitude of current peaks during the initial transient period of the fault. The current from the full converter type wind turbine during a steady state of the fault period does not exceed 1.1 to 1.2 p.u. The magnitude of current used for setting the relays can also occur during temporary overloads, which are very typical on a power system and can cause unwanted disconnection. Hence, however functional, this setting cannot be implemented due to the consideration of other factors and hence can be stated as impracticable.

## 4.4. TESTING OVERCURRENT RELAY ON THE EARTHING TRANSFORMER STRING

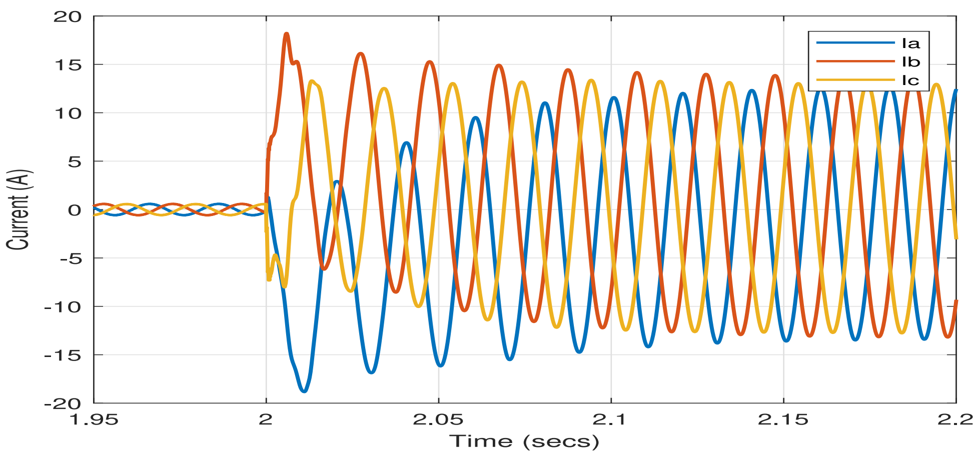


Figure 4.4: Currents at CT on earthing transformer string during string fault

To test the overcurrent relay fault has been created on the cable that connects the 66 kV busbar and the earthing transformer. The main function of this overcurrent protection is to operate as a backup in case of failure of primary protection of the earthing transformer. Another function is to operate for the faults occurring on the cable connecting the busbar and the earthing transformer, as tested in this section. The pickup value is calculated to be 1.06 A in CT secondary terms and to be operated instantaneously. The relay operates with ease, and the string can be disconnected during a fault. Fig. 4.4 shows the currents recorded by the CT on the earthing transformer string. The overcurrent element operates, in this case, owing to the high currents that are supplied by the strong grid along with the WTs that flow through the busbar and into the fault location. Consequently, providing large currents which can be observed or detected for the whole period of fault, also enabling to add a time delay to the relay, providing time to cross-check if the fault can be self cleared and also allowing the primary protection to operate first. The basic overcurrent function of the relay for this scenario faces no difficulties and helps in isolating the faulty part of the system.

## 4.5. NEW ADVANCED SCHEME USING OVERCURRENT PROTECTION

A novel scheme using overcurrent protection is proposed to overcome the challenges observed in the previous sections. It proposes to have CTs situated on all the strings supplying power to the busbar and these include the three WT strings, and one going to the 66 kV side of the transformer winding. However, the current transformers located on the WT strings are suggested to be not used for protection but only for measurement purposes. The CT located on the 400 MVA transformer side should then be used to trip the circuit breakers on either side of the busbar in case of a fault.

It is essential to mention that this current transformer always observes high currents irrespective the location of the fault (i.e.busbar fault or fault on the connection cable section). Hence, the Circuit Breakers (C.B.) can be tripped on both sides of the busbar but also including a time delay to confirm that it is a permanent fault. The currents hence are monitored and cleared, succeeding a fault for the set amount of time as seen in block 2 and 3 of the flowchart. This will as a result, isolate the whole busbar, the time delay that was provided before sending a trip signal enables the CT's located on the WT strings to record current for the period of fault. Now the most crucial part of the algorithm is to compare and observe the CT currents to identify a fault location. The CT's located on the strings observe a small amount of short circuit contribution as shown in the previous section for a busbar fault. However, for a fault in the connection cable the CT's will record much higher currents as compared during a busbar fault. Finally, a distinction can be made from these measurements and initiates a reconnect command following that all the checkpoints have been approved, further simplified using a flowchart below. The algorithm provides guaranteed isolation of the faulty part and a clear distinction between the busbar fault and the cable string fault.

The algorithm is also shown in 4.6 using a flowchart for better visualization. PSCAD implementation of the new scheme is shown in Fig. A.2. The status of CTs towards the wind farm side does not change following a busbar fault and are maintained at "0". No change in status confirms a busbar fault and the busbar section continues to remain isolated. The Fig. 4.5 shows the status of the relays obtained with the new proposed scheme, following a string fault at 2 sec. The faulty string status is changed to "1" and the healthy string remain at "0".

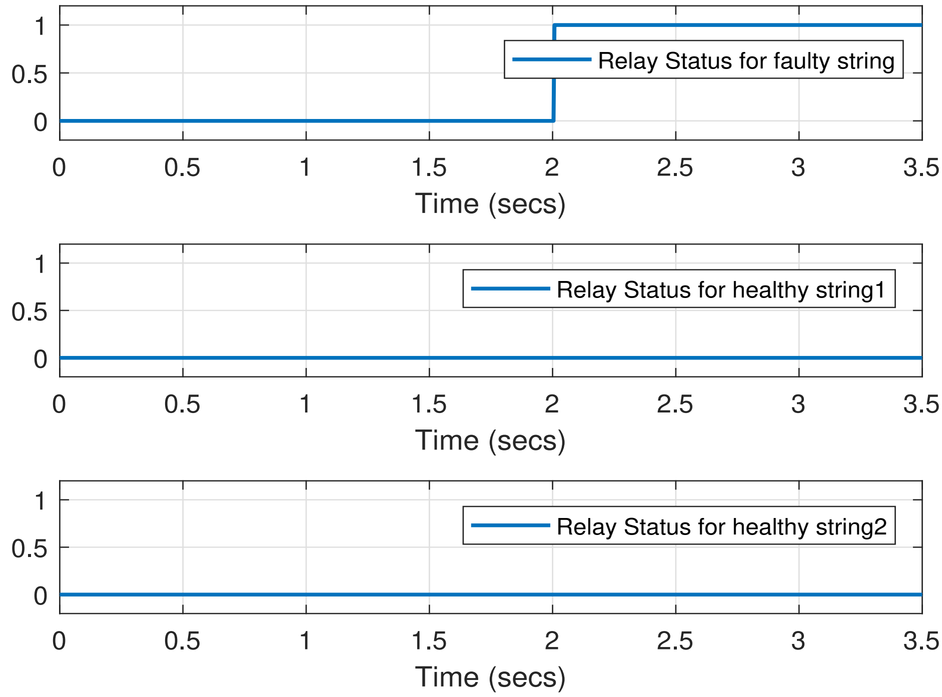


Figure 4.5: Relay status on WT strings for string fault

The change in status confirms a string fault and the healthy strings can be connected to the busbar.

The main drawback of this algorithm is the longer computation time because of the time delay that ensures the fault location before providing a selective reconnect signal. However, there is an advantage of discriminating the fault and providing a reconnect signal for the healthy strings in case of a single string failure. The main advantage of this algorithm is that it can be implemented with the existing equipment on the networks and only with a few modifications. A communication medium required for this algorithm can easily be implemented using a Programmable Logic Controller or a microprocessor or could also be hard wired. Hence no high costs are involved in implementing this protection algorithm.

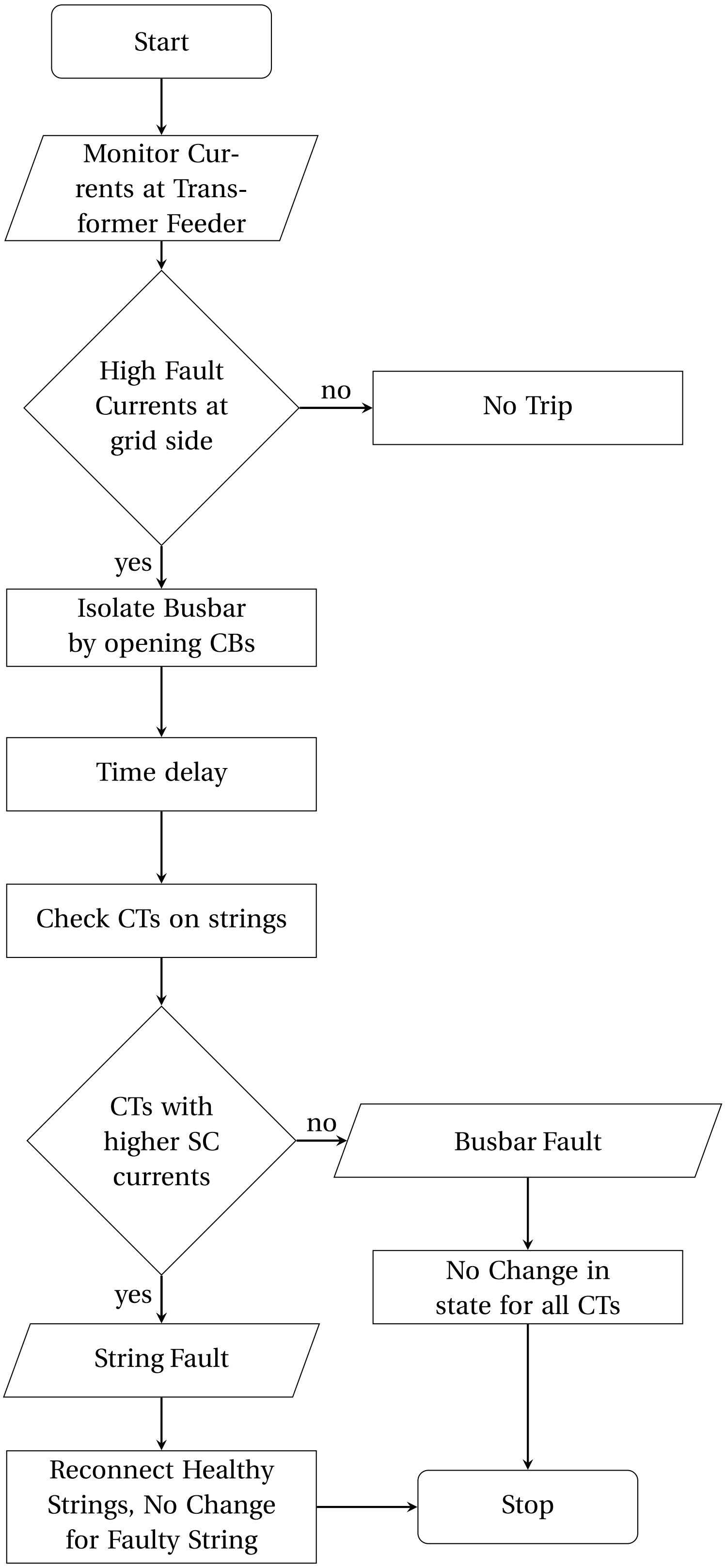


Figure 4.6: Flowchart for new proposed scheme - overcurrent protection

# 5

# Directional Overcurrent Protection (ANSI 67)

In this chapter, an overview of the functions of directional overcurrent is explained. The existing setting of directional overcurrent protection is tested, later a working setting possible with ANSI 67 is discussed, and finally, a new scheme is proposed.

## 5.1. Overview and function

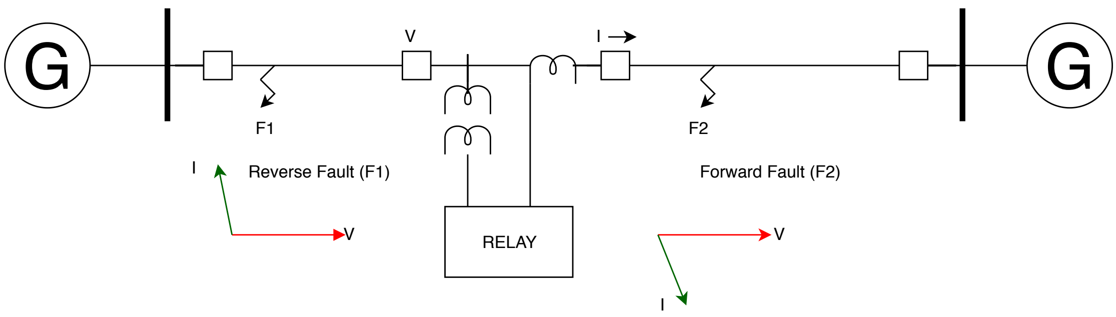


Figure 5.1: Basic Directional Overcurrent protection principle

As the power systems started becoming interconnected in the early $19^{th}$ century, the fault currents that flow during a fault on the power system can be fed by two different sources. Hence, disturbing the normal flow of power and forcing a current to flow in reverse direction in fault conditions. To better understand the concept of directional overcurrent protection, a simple double end fed radial system is shown in Fig. 5.1. A directional overcurrent relay is connected to protect for any fault between the two generators. The direction of current flow during normal grid operation is indicated with an arrow at the Ammeter. The voltage and currents measured with VT and CT are given as an input to the relay module. Two faults before and after the relay are created, and the phasor diagrams of voltage and currents during a fault are also shown. Fault F2 as observing no change in the direction of current flow during a fault is indicated as a forward fault. Fault F1, on the other hand, observe a change in normal direction of flow of current concerning the relay setting, as a result, indicating a reverse fault and is described with the phasor diagram. The relay uses a polarisation technique to detect/sense the change in the direction of the current. The basics of polarisation can be understood by considering a permanent magnet as opposed to the neutral relay that stores the magnetic flux during normal operation, when the direction of current changes, another part of the core stores the magnetic flux. Hence, providing information about the direction change and alerting the protection and measurement system. This relay is commonly used on the incoming feeders of the busbars, to identify a fault either towards the line or towards the busbar, to provide selectivity and locate the faulty section with greater accuracy. Their function is also sometimes included in busbar protection algorithms. Different studies have been conducted about the directional over-current relay that discusses its performance, and it suggests an effective operation in feeder protection. Directional protection scheme has also shown capabilities to provide the same function as a pilot wire differential scheme and avoiding risks involved due to communication failure owing to its independent operation [13].

The PSCAD model for directional over-current protection comprises of two setting groups with multiple phases and ground over-current elements similar to those in the ANSI 50 relay module. Definite and inverse time over-current characteristics are available, and simultaneous operation is possible. The module, however, does not allow separate settings for individual directions, hence limiting the functionality of the relay. The issue is further explained with an example in section 3 of this chapter. Polarization function is included since one of the directional algorithms uses polarized voltage as an input for its calculation. Similar, module of signal processing as used in ANSI 50 is implemented in this relay. Signal processing function uses a Discrete Fourier Transform (DFT) along with anti-aliasing filter, DC removal filter, frequency tracking algorithm to extract fundamental phasors and sequence components. The above options can be enabled or disabled manually by the user. The model further uses four types of polarisation algorithms, namely memory, cross, positive sequence, and positive sequence memory polarization, which can be individually enabled. After receiving the appropriate signals, the pickup and trip logic decides on the fault and issue a trip signal through external port T. To plot and develop more complex working algorithms various internal outputs are available, which can be used with external monitoring signals.

## 5.2. EXISTING SETTING AND FEASIBILITY

Following section outlines and tests the existing setting for the ANSI 67 relay used in this Borselle Project by the protection co-ordination document submitted. A 3 phase to ground fault has been created on the connection cable at 2 sec, and the relay setting calculation is listed in this section.

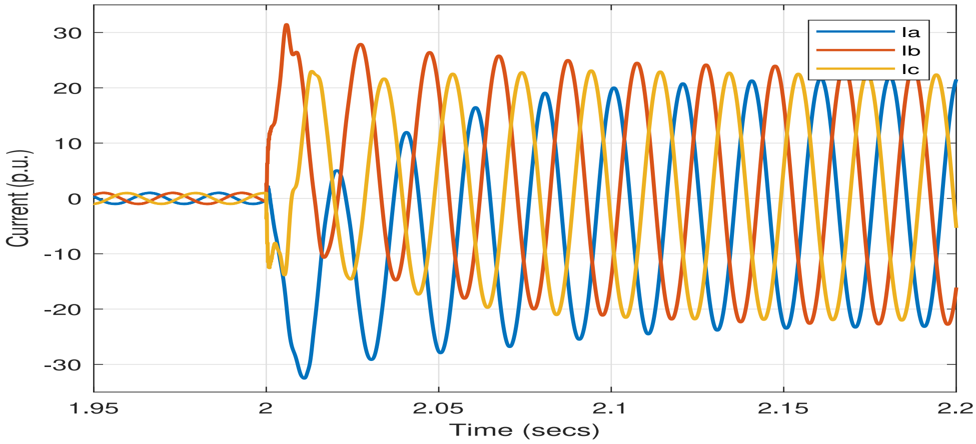


Figure 5.2: Short circuit currents during a fault on connection cable.

The directional overcurrent relay is not being used to its full potential as it is suggested to only operate for connection cable faults. The busbar fault, which is a critical fault location for the relay operation, has not been considered with this relay application. The forward direction of the relay is set towards the wind parks, and the proposed calculations are dependent on this setting. The fault on a string observes a high amount of current flowing from the strong grid in addition with contribution from the adjacent WT String. This is confirmed with Fig. 5.2, which shows the fault current recorded at the WT string during a fault on connection cable at 2 sec. The high contribution of currents is owing to the current contribution from the grid accompanied by the currents from WTs. Hence, a simple directional or non-directional relay should be able to trip for faults owing to the high amount of fault currents observed at the relaying point. The voltage observed at the busbar during a string fault can be seen in Fig. 5.3. The non-zero value of observed voltage assists directional element in making an accurate decision.

As seen in Fig. 5.4, during a fault on one of the WT string, the proposed setting operates as demonstrated with the time delay indicated. The time delay is only started after the relay has located the fault direction, Fig. 5.5 shows the time taken by the relay to make a directional decision. The relays on the wind park side are operated with a delay of 350 msec and that on the transformer feeder with a delay of 600 msec. The transformer feeder directional relay is acting as a backup for the relay on the string. In case of failure of directional relay, located towards the strings, the 66 kV side transformer feeder relay operates, as a result disconnecting the whole busbar section and isolating the faulty section with no selectivity. The CT ratio is 1250/1 A. The proposed rated current and the fault current calculation are as follows:

$$I_{rated} = \frac{400MVA}{3*2*\sqrt{3}*66kV} \tag{5.1}$$

$$I_{rated} = 583A. \tag{5.2}$$

The existing document has carried out the fault current setting depending on the minimum fault current that was observed in the grid during the testing phase, hence used to set

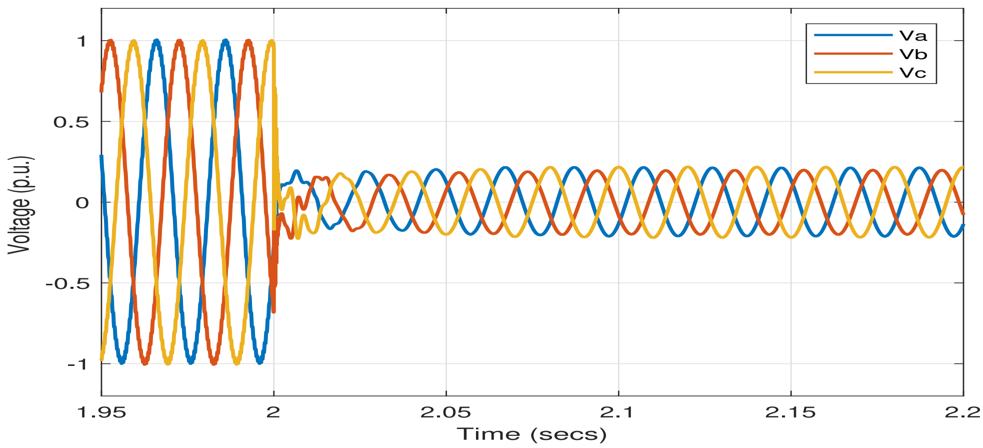


Figure 5.3: Voltage during a string fault

the relay pick up. The minimum fault current was observed during a single phase to earth fault in case of infeed via the link cable that was recorded as 2.54 kA. The link cable is the cable that connects the two busbars to provide redundancy. Hence considering a 20% safe margin for pickup current we get.

$$I_{setting} = 0.8 * 2540A = 2032A \tag{5.3}$$

As the proposed document is also fully dependent on the assumption that the WT used is of Type- 3 (i.e. Doubly Fed Induction Generator). The fault current setting for the relay is set with assumption that the fault current will be three times the nominal rated current. Once again, a safety margin of 10% is considered, the pick up value should be set higher than this value, therefore,

$$I_{setting} = 1.1 * 3 * 583A = 1924A. \tag{5.4}$$

The pickup threshold is therefore set between 2032-1924 A, for example 2000 A. Converting this to secondary terms,

$$I_{setting(secondary)} = 2000 * \frac{1}{1250A} = 1.60A \tag{5.5}$$

Since this relay is responsible only for clearing faults on the connection cable section, which is possible due to high magnitude of currents (also demonstrated with results), this test can be concluded as positive.

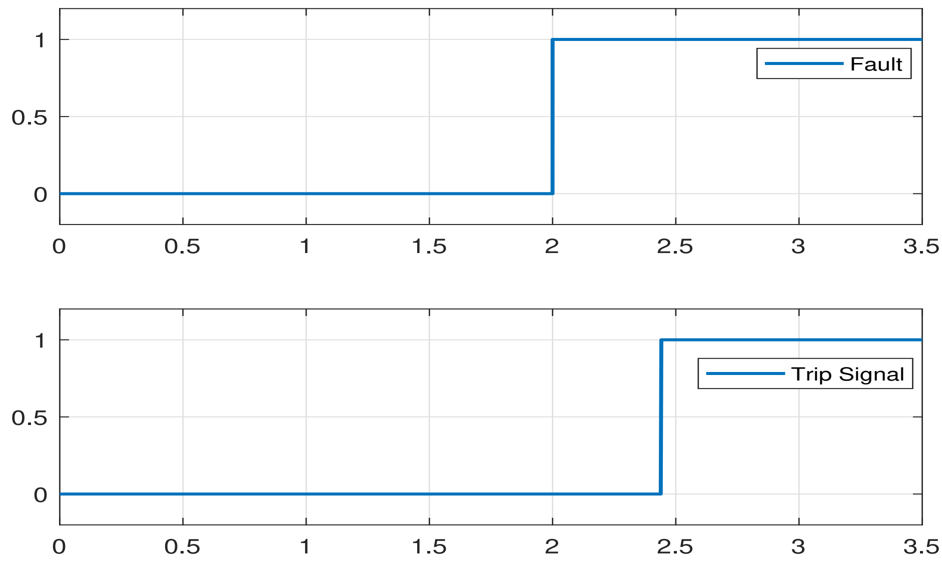


Figure 5.4: Fault and Trip signal with Directional Overcurrent for string fault

## 5.3. FINDING THE MINIMUM SETTING FOR DIRECTIONAL OVERCURRENT RELAY

As observed with the implementation of the ANSI 50 relay for a busbar fault, and the fault is fed by two directions. One side is the strong grid, the other is a Wind Park consisting of strings of WTs of Type 4 with a very low short circuit contribution. Setting the relay to a short circuit current value, which is as low as 1.2 p.u. could cause false trips on the system during a temporary overload. Also just like interim overloads, these short circuits provide a fault current as high as 1.1 ~ 1.2 p.u. for a fault period, except for a few high currents during the transient period, making it difficult to identify a fault. As there is no change in direction for currents flowing from the Wind Farms (during a busbar fault), the relay cannot disconnect the busbar unless the relay has been set as per the working setting described in 4.3 which was found to be unsuitable. The relay located at the 66 kV transformer side, however, trips after the preset time delay owing to high short circuit currents from the grid.

The directional overcurrent relay model uses voltage measurement for identifying the direction of current during a fault. During a 3 phase fault, there is not enough voltage available for the relay to make an accurate decision, leading to possible wrong tripping, causing an increased risk to the assets involved. The directional decision elements indecisive behaviour is shown in Fig. 5.6 during a busbar fault. Following a fault, at 2 sec, the directional decision is triggered and can be observed to have difficulty locating the direction of fault. Fig. 5.6 shows the directional element stabilizes at approximately 40 msec, i.e., the transient period but can be observed fluctuating again around 450 msec (the fault still exists.)

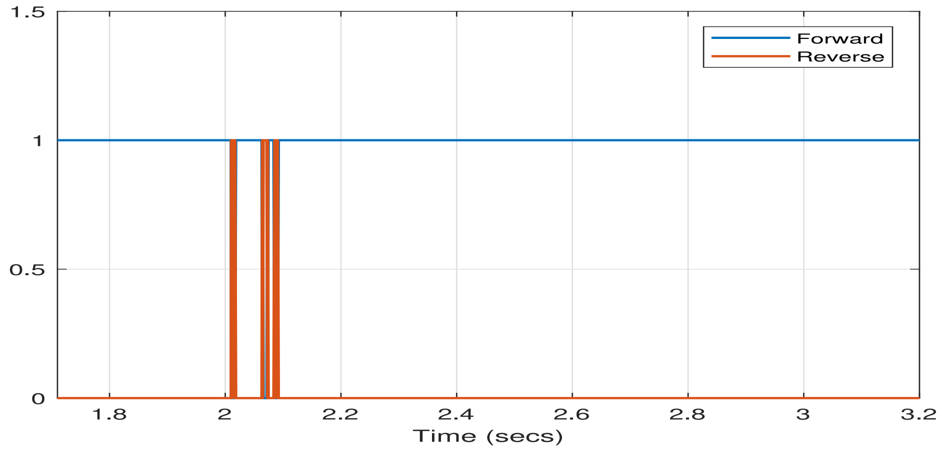


Figure 5.5: Directional Decision during a string fault

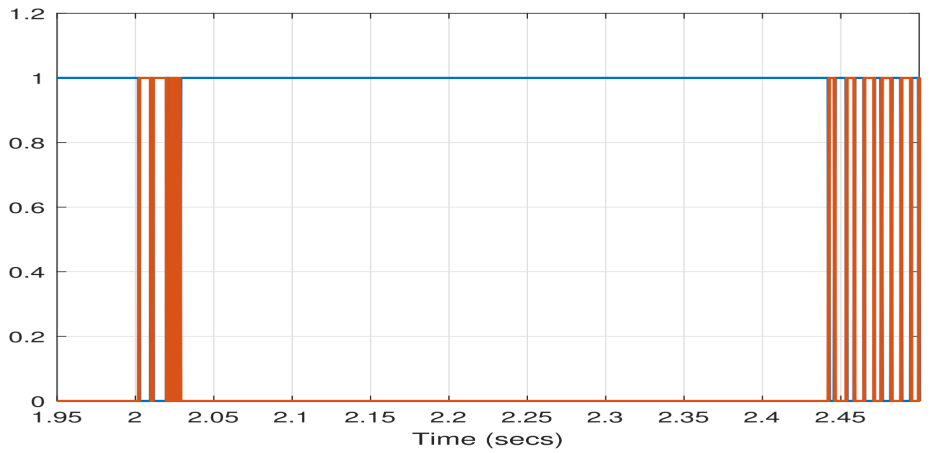


Figure 5.6: Direction relay maloperation during Busbar Fault

The existing location of the CT is studied on the WT strings. Faults on the busbars result in low availability of impedance compared to the faults on the connection cable section. In this case, the voltage during a bolted 3 phase faults is very low, and it is challenging to indicate a reverse fault occurring on the busbar unless it has a robust memory voltage components. As observed from the directional overcurrent model in PSCAD that the model indicates a Forward fault in the case when the relay is unable to decide the fault direction, majorly due to the lack of voltage. This could be a challenge observed in actual relays for faults very close to the relay and hence needs careful attention in setting the relay. The available model of the directional overcurrent relay in PSCAD does not allow individual settings for each direction of the current. For example, if the magnitude of current for reverse direction fault is set lower compared to the forward direction fault, but the time delay has been adjusted such that fault in the reverse direction has to be cleared faster than the forward fault.

## 5.4. NEW ADVANCED SCHEME USING DIRECTIONAL OVERCURRENT PROTECTION

A novel scheme to overcome the observed challenges is proposed in this section. The PSCAD representation of the scheme is shown in A.4 also a flowchart in 5.8. The new scheme makes use of the direction indication mechanism, however, does not allow a direct tripping command. The directional element was observed to have a successful operation for faults on the cable section. Therefore, faults on the cable section result in a change in state for the directional identification element. The condition is used as a decision block 2 in the flowchart 5.8. The Current Transformers are advised to be located on each strings. This scheme provides a successful identification between a fault on the busbar and the individual connection cable section. Three conditions can be identified on the 66 kV network;

Assuming that 3 strings supplying constant current to the busbar which then sends this current into a single string to the transformer :

1. Steady state condition:

In this condition, the power flow direction is normal, and the sum of all the currents through the Wind Park strings is equal to the current measured at the 66 kV side of transformer feeder (basic KCL, checked in decision block 1 of the flowchart 5.8).

$$I_1 + I_2 + I_3 = I_4 \tag{5.6}$$

$$for\ example, \quad 5+5+5 = 15 \tag{5.7}$$

$$Also, \quad I_1 \uparrow, I_2 \uparrow, I_3 \uparrow \tag{5.8}$$

2. Fault on Busbar:

In this condition, the sum of all the currents entering the busbar is not equal to the currents leaving the busbar; hence, the KCL is not satisfied anymore. In this condition, the direction of current at the Transformer feeder at the 66 kV side is in the reverse direction and have a high magnitude.

$$I_1 + I_2 + I_3 \neq I_4 \tag{5.9}$$

$$for\ example, \quad 5+5+5 \neq -20 \tag{5.10}$$

$$But, \quad I_1 \uparrow, I_2 \uparrow, I_3 \uparrow \tag{5.11}$$

3. Fault on String:

In this condition, higher currents are present on one string and disconnecting the whole busbar is not a good alternative as selectivity is highly hampered in this situation. As the KCL, however, is satisfied in this condition the currents flowing through the strings is not equal, and the direction of the current flowing on the string and the 66 kV side transformer feeder is reversed.

$$I_1 + I_2 + I_3 = I_4 \tag{5.12}$$

$$for\ example, \quad 5+5-30 = -20 \tag{5.13}$$

$$-20 = -20 \tag{5.14}$$

$$But, \quad I_1 \uparrow, I_2 \uparrow, I_3 \downarrow \tag{5.15}$$

The algorithm then makes use of these conditions to determine the fault direction and location. From the above three conditions it can be further deduced that during a fault at any location, there exist two major conditions, this condition than are compared to provide a final decision. The algorithm is adjusted in such a way that during a steady state both the conditions provide a binary "1" which at the end is subtracted from each other, making the end condition "0", and indicating a steady state. For a busbar fault the output is "-1" and finally for the string fault output is set to "1". As a result, providing complete differentiation of the three situations. This is also depicted by the lower decision block 3 in the flowchart 5.8. The status output available from the described scheme implemented in PSCAD is shown in Fig. 5.7. As described, following a fault at 2 sec, a busbar fault is displayed by a change in status to "-1" and "1" for a fault on the string and maintained at "0" during steady state operation. The status signal changes state owing to the initial transients for approximately 15 msec after the fault and then provides a definite decision regarding the fault.

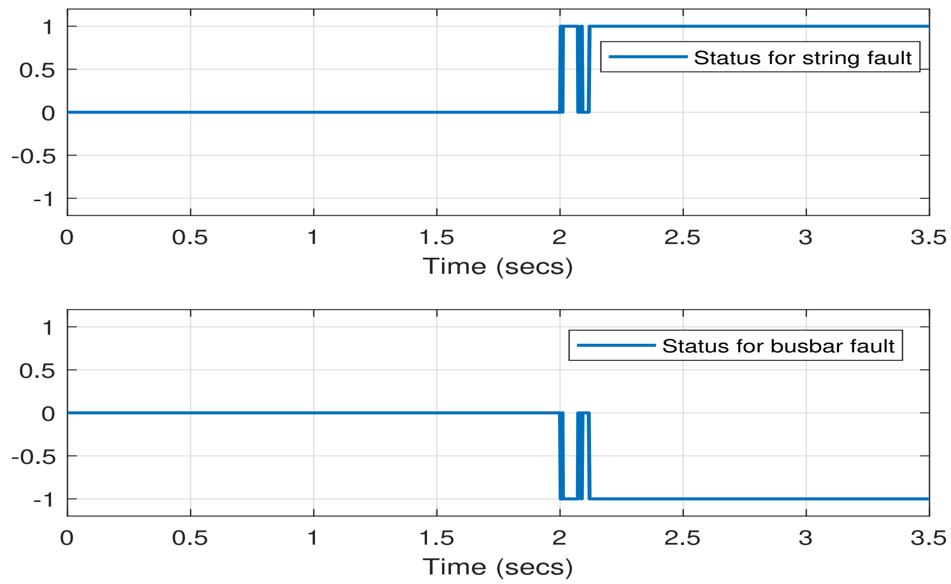


Figure 5.7: Output signals from the new proposed scheme

This can be easily implemented with a 2 pole switch, which stays at position zero during nominal conditions and changes state to either pole depending on the changing situations. The fact that all strings may or may not have the same amount of WTs connected at any given time is considered, however, the example is demonstrated with equal currents from each string, but it is only for explanation purposes. In reality, although the number of WTs at each string may not be same the KCL at the busbar is always satisfied, and also the normal operation of the power system ensures the nominal direction of power flow as indicated in the algorithm. The results displayed below clearly indicate that the algorithm can work correctly with the inclusions of directional overcurrent relays for all fault locations on the 66 kV network. The main advantage being that it is straightforward and can be implemented with the existing protection devices available.

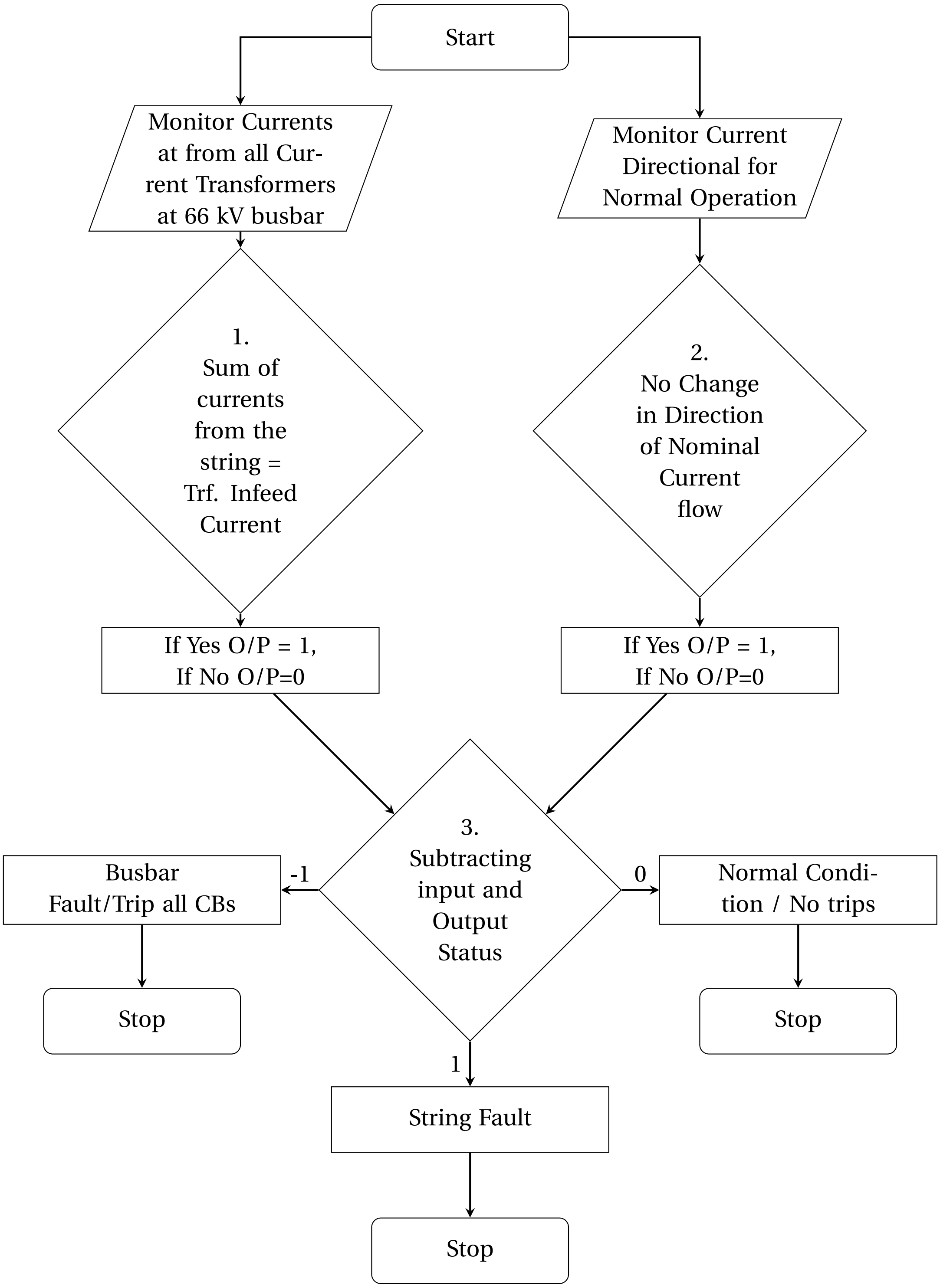


Figure 5.8: Flowchart for new proposed scheme - directional overcurrent protection

# 6

# UNDER VOLTAGE PROTECTION (ANSI 27)

A voltage which is below the optimum operational or rated value of a component, circuit or a device is termed as under voltage. Under voltage is the most common disturbance whose effect is much severe and is studied in this chapter.

## 6.1. OVERVIEW AND FUNCTION

Under voltage can be defined as short term reduction in voltage caused by short circuits, equipment failures and starting of large motors. Under voltage is classified as one of the common disturbance on the power systems. Table 6.1 describes the classification of under voltage conditions according to IEEE standards.

| Types of Under Voltage | Duration | Magnitude |
|---|---|---|
| Instantaneous | 0.5-30 cycles | 0.1-0.9 p.u. |
| Momentary | 30cycle-3 sec | 0.1-0.9 p.u. |
| Temporary | 3 sec-1min | 0.1-0.9 p.u. |

Table 6.1: Classification of under voltage

A few common causes of under voltage can be stated as closing and opening of a circuit breaker, faults, energizing, equipment failure, and motor starting [14]. An under voltage can cause excessive currents being drawn and eventually leading to permanent damage to the connected equipment, hence under voltage is as severe as over-voltage. A short circuit on the system leads to under voltage condition, which needs to be avoided by clearing the fault. Temporary under voltages can also be caused during normal power system operation; it is essential for the relay to distinguish these two scenarios to provide accurate tripping signals. For this reason, a comparator circuit inside the relay continuously monitor the voltage between the three phases and issuing a no trip signal during a normal operation of power system when the voltage is regulated within its limits.

The under voltage relay model by PSCAD is a combined model with features of under voltage, over voltage, rate of change of frequency, under frequency, over frequency, and vector shift operation. The block consists of the signal processing unit as described before for the earlier models; this signal processing block extracts the voltage magnitude component which is then divided by the nominal voltage value at the VT terminals, which is fed into the relay. Finally, all the settings in the model are then now available in per unit allowing easy implementation. Multiple thresholds can be set with a preferred time delay setting to get a fast response to dropping voltage scenarios.

## 6.2. SETTING AND PLACEMENT

Under voltage protection has not been used or proposed in the existing protection document for the mentioned project. This section however checks the suitability of under voltage protection relay to be used in combination of Type 4 WT source and the challenges associated with it, as were discussed before. A voltage transformer with a ratio of 66kV/110V is used, as per the existing specifications of Tennet for voltage transformer ratios.

Under voltage protection offers many advantages despite the type of generation technique implemented and the system configuration involved. Some of the advantages include simple, reliable, and fast operation following a fault. This section discusses the number of settings used in the under voltage relay and voltage measurement points on the studied networks. The voltage is measured using voltage transformers situated before the connection cable section, i.e., near the WT terminals for all the strings involved and at the busbar. The reason for measuring the voltage at the WT terminals is to make use of the cable impedance to observe the definite differences in voltages during the fault period. As any measurements on the strings of WTs closer to busbar on the offshore substation can be considered as measurement at the same node, owing to the low impedance section (the busbar) and the minimum length between the measurement points. Consequently, no significant variations in voltage can be observed. Under voltage relay can also be set inverse definite time voltage settings to achieve faster operation.

The VT's for measurement are located on all strings and the busbar. For faults on the 66kV network, the divergence between string voltages and the busbar voltages is compared to decide on the location of the faults, and the tripping signals can be initiated accordingly. The VT's are modelled as ideal because errors introduced by the voltage transformers are not the primary focus of the thesis. The under voltage relay model is set to only one setting i.e., if the measured voltage is observed under 0.25 p.u. for 0.4 secs a trip command is issued. This is a test scenario to check if the relay can operate with low voltage for such a long period, and faster trips can be achieved as mentioned before.

## 6.3. TESTING FOR A BUSBAR FAULT

A permanent fault is created at 2 sec. The results in Fig. 6.1 shows the voltages as seen by the relay model after the voltage signal has been processed in the relay model. As seen before 2 sec, the voltage on all strings along with the busbar voltage is maintained at 1 p.u. The voltage drops very quickly during the fault period and stays at zero (approximately) for the entire period of fault. The voltage measurement at all the strings and the busbar VT all depict the same behaviour hence confirming it is a busbar fault. The relay can be set for tripping settings similar according to the inverse definite time under voltage thresholds. For testing purposes, the relay is set to provide a tripping command if the voltage drops below 0.2 p.u. for 400 msec.

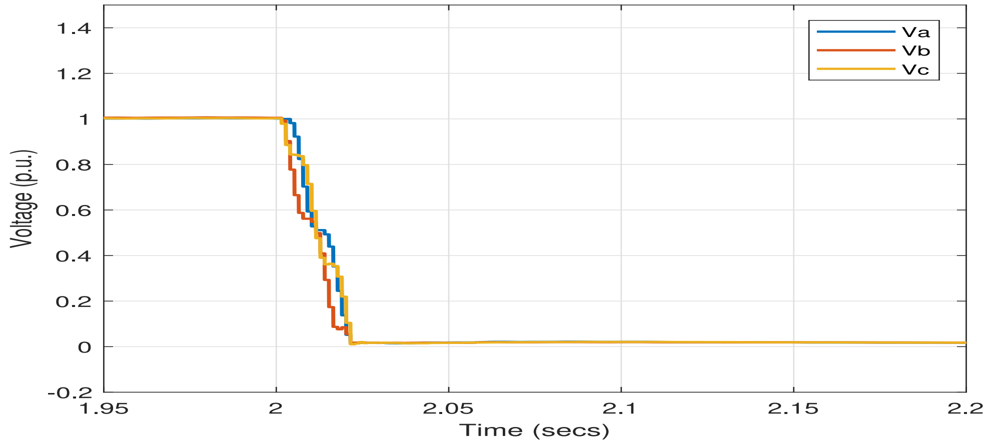


Figure 6.1: Busbar voltage observed inside the Relay Model.

## 6.4. TESTING FOR A STRING FAULT

A 3 phase fault has been created on one of the three strings, and the voltage relay is tested for the performance and its selective operation.

The voltage measurement points and the voltage transformer ratios are the same as in the previous section used for the Busbar fault. Fig. 6.2 shows that the voltage on the faulty string at 2 sec as observed by the relay model. The voltage does not follow the same trajectory as the voltage on the healthy string Fig. 6.3. The faulty string voltage reaches zero following a fault; however, the healthy string voltages does not drop to zero but to a lower value of approximately 0.2 p.u. As seen, the relay on faulted string issue a trip command following a fault in 400 msec, however, relays on the healthy string remain unaffected.

The voltage measurement at the neighbouring busbar connected through the 400 MVA offshore transformer also observes a drop in voltage (Fig. 6.4) however, not as severe com-

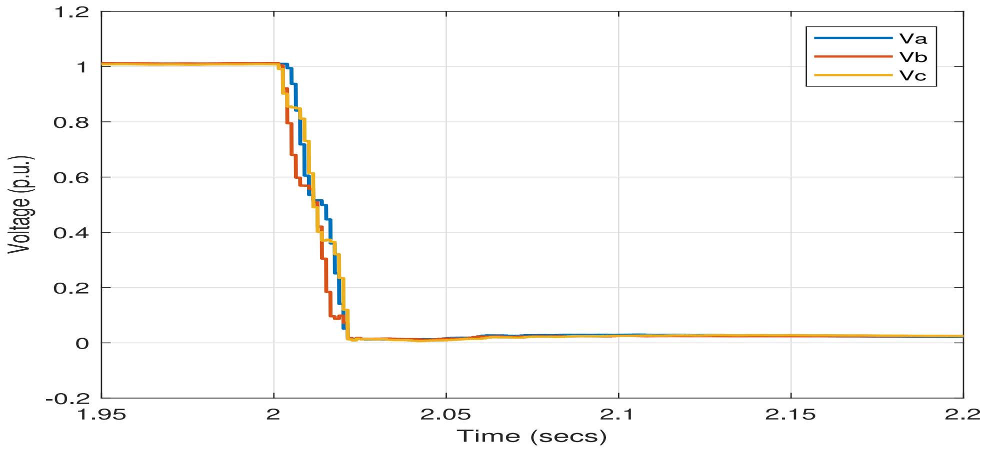


Figure 6.2: Voltage measured at the faulted string

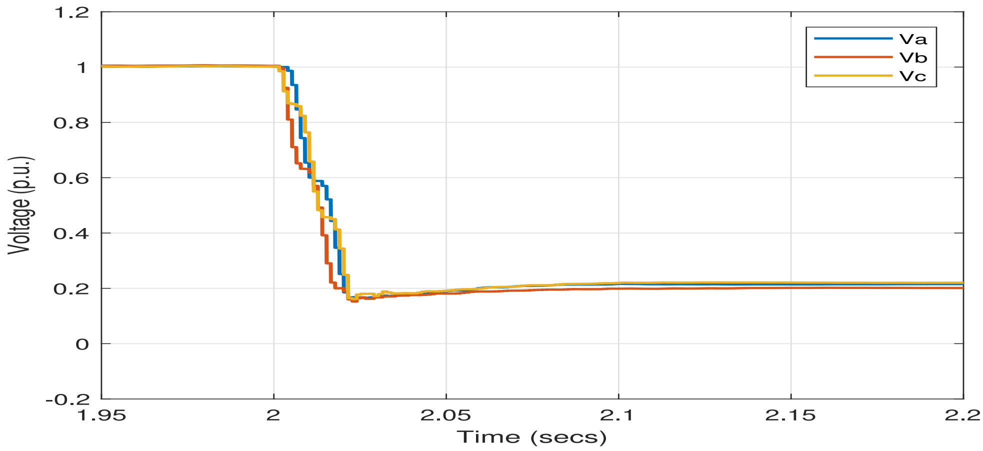


Figure 6.3: Voltage measured at the adjacent healthy string

pared to the faulted and the adjacent strings. This is due to the fault location being further away from the measurement/relay point, the voltage measurements from a different location on the offshore can be compared to make an accurate tripping decision.

## 6.5. REVIEW OF UNDER VOLTAGE RELAY

Under voltage relay, as seen in the above chapter is a very reliable and hands-down straight-forward relay system that can be employed on the 66 kV network for fault clearing. It is capable of clearing a fault at any location on the 66 kV network with the correct setting configured

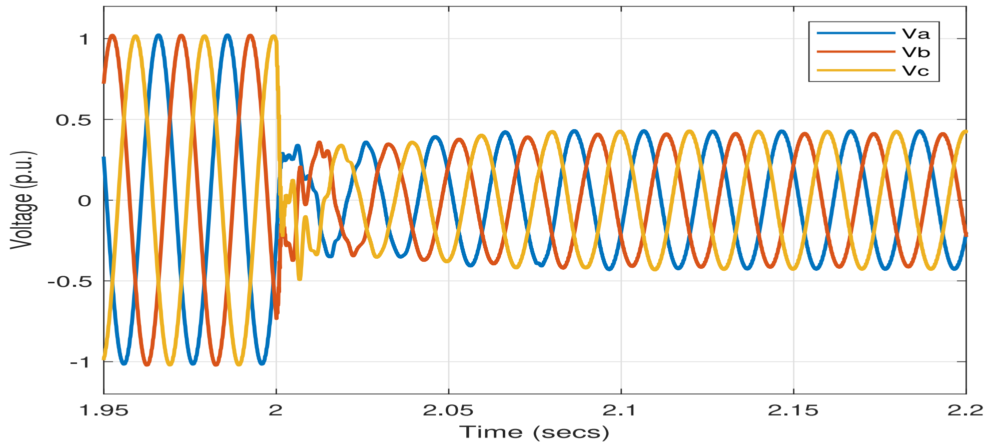


Figure 6.4: Voltage at the neighbouring busbar connected through a power transformer during a string fault

in the relay. In the tests performed in this chapter, although capable of fault clearing depending on the voltage level, the margin of discrimination for voltages in case of a string fault is very low ( the difference is no more than 0.18 p.u). This low setting may also lead to malfunction of the relay system causing unnecessary tripping in healthy part of the networks. Also as seen from the Fig. 6.2, Fig. 6.1 and Fig. 6.3, the voltage quantity needed for tripping is available for the whole period of fault, making this relay system more suitable for a primary protection located to follow a grid code envelope specified by the TSO. It is also essential that this relay system is receiving the correct input required for the time when the system is energized, otherwise causing tripping. Another critical point that has to be noted is the measurement of the voltages; in this model, the voltages on the string are measured near the WT terminals. In the actual case, it is possible that the cable coming to the busbar is also under the scope of the WPO, further causing non-technical issues (legal/monetary consequences). Measurement of voltages on the strings at the Busbar side does not provide any apparent differences for a busbar and a string fault, hence creating complexity in providing selectivity to the network. The extremely low impedance at the busbar section is the reason for this.

# 7

# Distance Protection (ANSI 21)

Distance protection relays are usually used on long transmission lines and cable sections [15]. It gets the name Distance protection as it operates depending upon the distance between the fault and the feeding point.

## 7.1. Overview and function

Distance relays are majorly used as primary and backup protection on many overhead lines and cables sections in transmission and distribution system. The impedance based characteristics allow the relay to isolate the faulty section of the system with high speed and helps in detecting the fault location. The distance relay uses zones to set the reach of the relay. The zone defines the range of operation; the trip command is generated only if the relay measures a change in impedance within a particular zone. The relay calculates the zone impedance from the location of the relay to the fault location. Zone 1 and Zone 2 is set to cover 80% and 120% of the line length respectively, Zone 3 and Zone 4 also have reverse looking characteristics in addition to forward zones that allows detecting the faults occurring behind the protected zone of the relay and can be used as a backup protection on distribution lines. The first zone is an instantaneous zone, the second and the third zones are backup zones that operate only when the fault happens on downstream branches and the protection of that branch does not trip at the right time. To provide selectivity and accurate trip signal a time delay is provided for each zone in distance protection [16]. For the accurate operation of the distance relay, the protected line or cable characteristic data has to be fed to the relay mode. The operating characteristics of the individual zones is defined by the operating impedance, $z_{op}$, obtained as a function of $\delta_p$, where $\delta_p$ is the angle of maximum torque [17]. The distance protection therefore operates when, $z_p \leq z_{op}$. $z_p$ is the impedance measured by the protection relay, where, $z_p = r_p + jx_p$; $r_p$ and $x_p$ are the resistance and reactance measured by the protection respectively. Distance relays are available with different characteristics for operation; some of them include mho, quadrilateral, non-directional, polygonal, elliptical, and offset mho. A typical distance relay zone representation is shown in Fig 7.1.

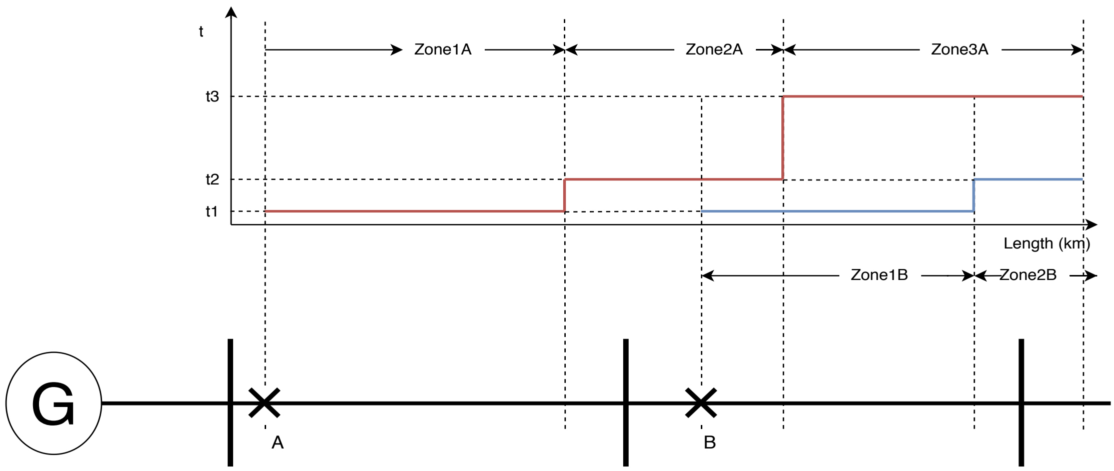


Figure 7.1: Representation of Distance Protection Zones]

[18] compares Mho and Quadrilateral characteristics in detail. The weak infeed tripping system background in [19] discusses a permissive tripping mode to improve the performance of the distance relay. This function further improves the sensitivity of the relay. However, a significant issue involving these sympathy trips can result in cascading tripping of parallel connections leading to significant disturbances [19]. Distance protection distinguishes load conditions from minimum and maximum short circuit conditions by measuring the impedance modulus and the angle between the voltage and current [20]. Distance protection, when used with wind farms, has shown that the performance of relay is affected by a series of factors which are further mentioned in [20]. When the impedance function is used for the pick-up of the distance protection, the occurrence of high inaccuracy and fluctuations of measuring impedance parameters are expected, especially in the transient states from the initial to steady fault conditions [21]. Co-ordination of the reactive components alone is insufficient to avoid over tripping during weak infeed faults [19].

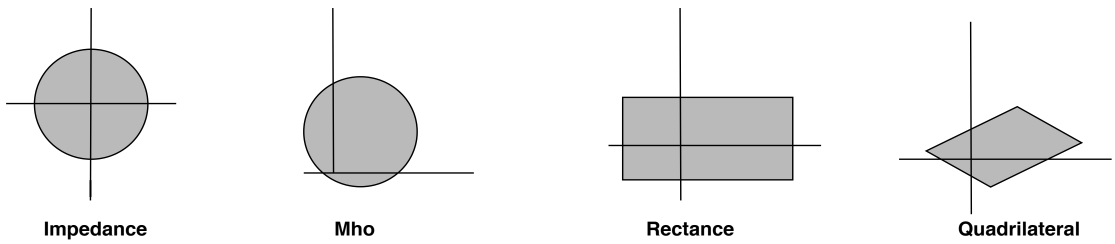


Figure 7.2: Distance Relay Types

The distance protection model provided by PSCAD consists of the same signal processing unit that was discussed earlier. Mho and quadrilateral characteristics are available and can be selected individually for every zone. The CT, VT ratio, rated CT current and nominal VT voltage are fed as stationary input to the relay. The line characteristics such as positive and zero sequence impedance magnitude and angles have to be specified to calculate zero sequence compensation factor for protected line and each mutually coupled line. Further, the X/R ratio for DC removal filter is calculated based on protected line information. Polarisation method can be selected from the available four types in the model namely; positive sequence, memory, cross, and positive sequence memory. Individual zone setting available for phase and ground enables the model to be further set with more complicated settings to achieve desired characteristics. Two directional supervision algorithms based on ERL phase relays and SEL relays are incorporated within the relay model. Fault type identification can be performed, which supervises the ground and phase elements to determine the type of fault. Furthermore, load encroachment and out of step functions are also added to the same relay models and can be activated separately. The trip logic uses these signals as inputs and provides a trip signal through port T when the required criteria are satisfied. Additionally, the signals from various settings are available to be visualised using the plot functions.

## 7.2. SETTING AND PLACEMENT

The section highlights the different and possible setting combinations and the placement of the relay to achieve maximum performance. At first, it is essential to understand that distance relay is not a part of the existing protection scheme for the studied project (Borselle), so this section proves as a test scenario to check the performance of PSCAD relay model under the given conditions. The connection cable, which is an asset of the Wind Park Owner has to implement primary protection in an ideal situation, and the protection by the TSO only serves as backup protection. However, the Wind Park Owner, like in this case, can choose not to have any protection implemented. This makes the system operators protection system as primary and expects to clear any faults on the cable section and the busbar to assure the safety of the assets. This being considered, placement of the distance protection of the relay has to be on the offshore substation by the system operator closer to the busbar/point of common coupling. The distance protection has two primary functions; first to act as backup protection to the primary protection of the busbar and finally disconnect the string in case of fault on the connection cable (with a time delay).

Zone 1 cover the 80 % and Zone 2 covering 120% of cable length. Zone 3 is set to cover the busbar section. All the zones have been time delayed as this relay is serving as backup protection. The CT and VT ratio is maintained the same as in the previous chapter i.e., 1250/1 A and 66 kV/110 V, respectively. The length of the cable is 5 km. Zone 1, 2 and 3 are time delayed for 0.3 sec., 0.5 sec. and 0.2 sec respectively. The setting are based on the next:

Step 1 : Calculating Z of the cable

R = 0.145 Ω /km and X = 0.128 Ω /km

Length of cable = 5 km

CT ratio = 1250/1 A and VT ratio = 66kV/110V

Therefore, Z = (R + jX) * 5 = (0.725 + j0.64) / (0.967 ∠ 41.43 67) Ω

Step 2 : Calculating Zone 1 impedance.

$$Z1 = 0.8 * 0.967 = \frac{0.77336 * 1250}{600} = 1.61\ \Omega \text{ (in secondary terms)}$$

Step 3 : Calculating Zone 2 impedance.

$$Z2 = 1.2 * 0.967 = \frac{1.1604 * 1250}{600} = 2.4175\ \Omega \text{ (in secondary terms)}$$

Step 4 : Zone 3 impedance. (reverse zone covering busbar)

Z3 = -3.5 Ω

Zone 3 impedance is set to a higher value after observations, to check if it can operate to detect a fault on the busbar section. As fault in Zone 3 i.e., the busbar section observes currents flowing from the wind parks and consisting of lower magnitudes and creating a troublesome situation for the distance protection algorithms. The mho5 characteristic of the relay is used with positive sequence memory to detect changing the direction of currents during a fault in reverse directions. With this setting, the two fault situations are studied as mentioned below, and their performance is analysed.

## 7.3. FEASIBILITY DURING BUSBAR FAULT

A 3 phase fault at 2 sec with fault resistance of 0.05 ohm and fault angle equal to 90 ° is created to evaluate the performance of the relay. The busbar has been covered by Zone 3 looking in reverse direction. The lower short circuit currents from Type 4 WT now feeds the fault location, and the distance relay measures the same. The relay, therefore, as seen in Fig. 7.3 cannot provide a trip signal, and the Wind Parks continue to feed the fault. The current and voltage magnitude observed inside the relay module are depicted in Fig. 7.4 and Fig.7.5 respectively. The PSCAD model is a blackbox model and displays slight differences in current magnitudes for a balanced system as can be seen in Fig. 7.4. The currents are observed to have initial transients succeeding a fault at 2 sec; these transients can be observed to reduce as the fault is sustained and the current magnitude returns approximately to the pre-fault value after 500 msec. The voltage, on the other hand, is observed to have a continuous drop in magnitude and reaches zero at approximately 25 msec and is maintained at zero for the entire duration of the fault. The voltage in the Fig. 7.5 is observed at close to zero but not completely zero following a fault and it is because of the negligible impedance of the busbar section. The relay model, therefore, has an unsatisfactory performance with the given conditions. The fault current direction, in this case, is the same as the usual power flow direction, and the relay must not indicate any change in direction. The model changes the centre co-ordinates following a fault and changing the zone characteristics. This has been observed only for Zone 1 and 2.

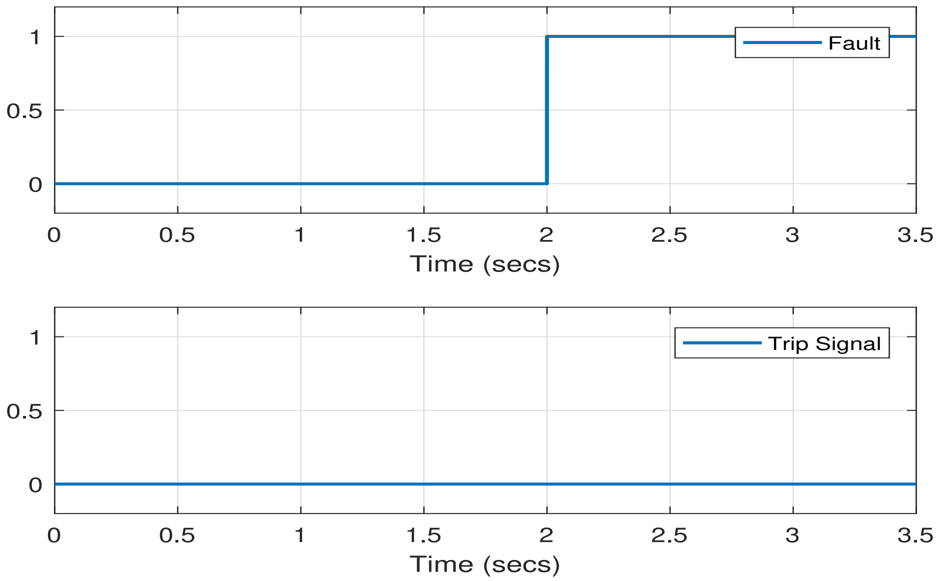


Figure 7.3: No trip observed for busbar fault

The voltage drops after the fault at 2 sec, the system losses all the three phase voltages and polarising voltage is lost. It is essential to mention that the fault is very close (behind) to the relay, hence the only impedance observed by the relay is the arc resistance caused during the fault period. The R/X diagram shown in Fig. 7.7 is seen to have maloperation for zone 1 and 2 following a fault. The zone impedance changes and operated dynamically following a fault, hence creating challenges in identifying a fault. The directional element in Fig. 7.6 can be observed for maloperation. The direction decision is issued at 100 msec after the fault but in the wrong direction.

## 7.4. FEASIBILITY DURING A STRING FAULT

A 3 phase to ground fault is created to depict a permanent fault behaviour at the centre of connection cable (the distance of fault location on cable = 2.5 km). As the voltages and currents during a string fault are the same as discussed in the previous chapters, Fig. 5.3 and Fig. 5.2 can be referred. According to the zone setting calculations in the previous section, a fault at the 50 % of cable length should be picked up by Zone 1 first. Zone 1 successfully

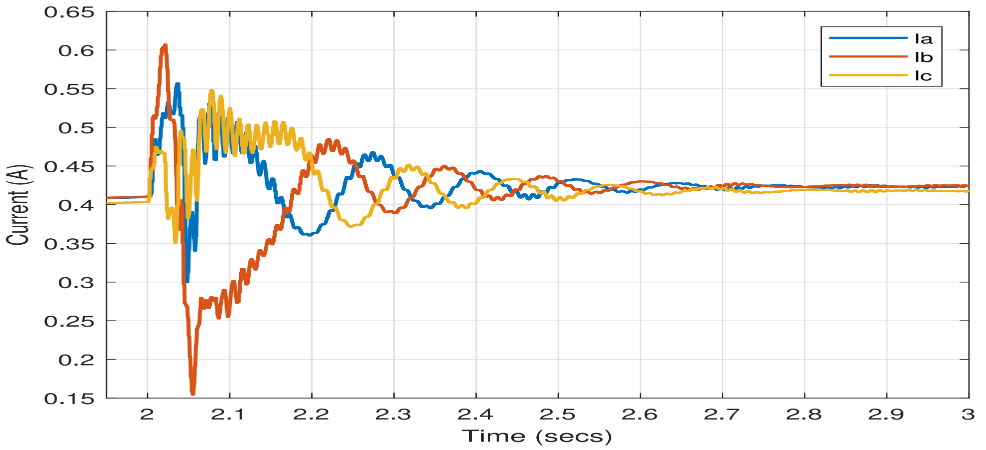


Figure 7.4: Relay observed current magnitude (RMS) for busbar fault

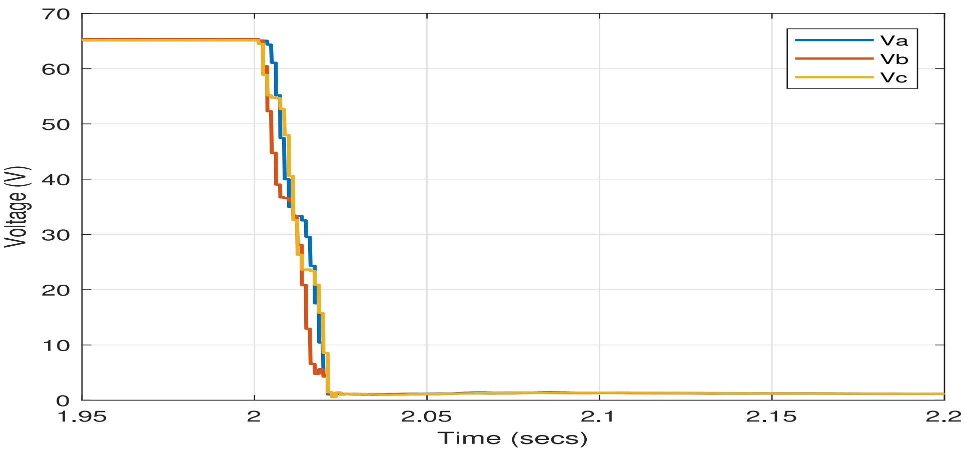


Figure 7.5: Relay observed voltage magnitude for busbar fault

picks up the fault after the direction element has decided on the direction of the fault. As was discussed earlier, the model outputs reverse direction as "1" during steady state condition as the forward direction of the relay is towards the Wind Park and forward direction of power flow is towards the busbar. Owing to the substantial amount of high currents flowing from the grid accompanied by the currents of the adjacent strings and the impedance of the cable section the distance relay can react to the fault and provide a trip signal. The direction element decision is shown in 7.10. However, there have been some important points that have to be analysed about model behaviour. The Fig. 7.8 shows the R/X plot for phase A during a string fault. The radius of zone 1 and zone 2 can be seen to change when the fault has occurred. The relay model, on the other hand, also fails to pick up the fault in phase C, which might have problems when operating for unsymmetrical faults. This is an important issue and may result in maloperation of the relay. The test can be considered successful.

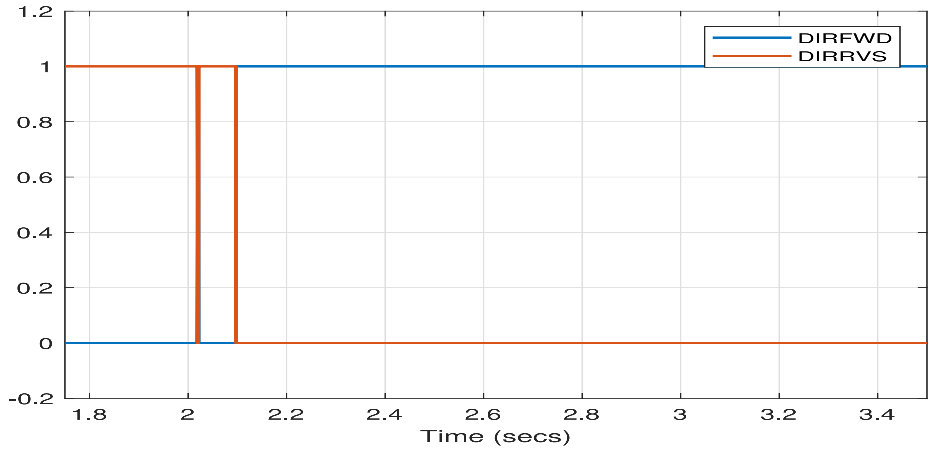


Figure 7.6: Direction element during busbar fault

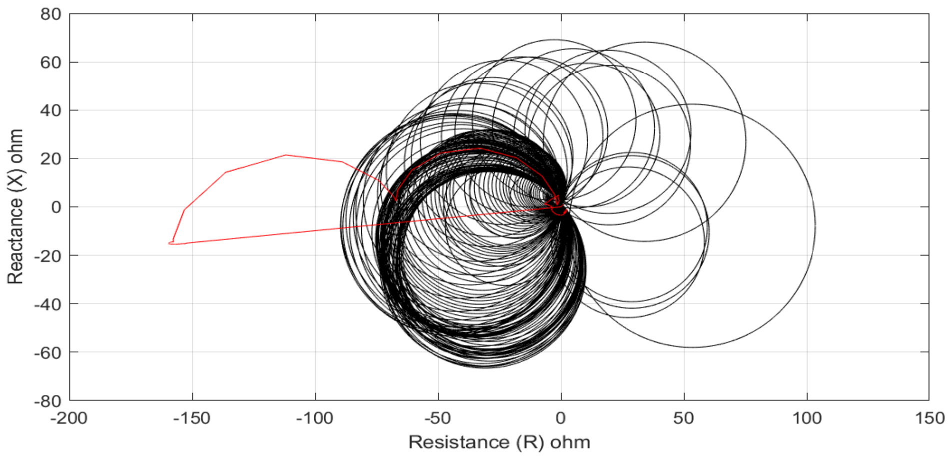


Figure 7.7: Maloperation of relay for zone 1 for busbar fault

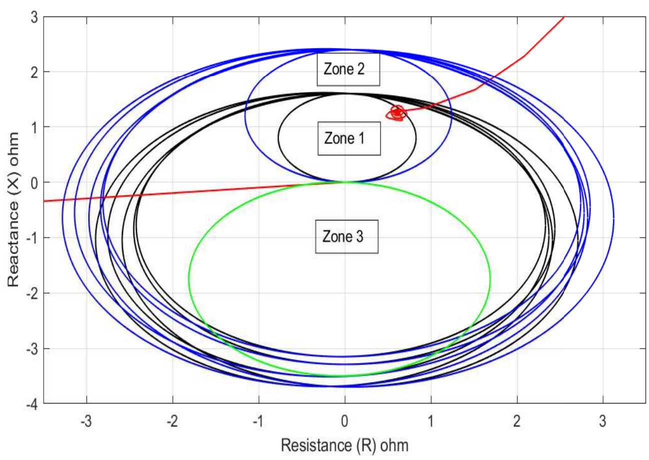


Figure 7.8: Maloperation of Zone 1 and Zone 2 for string fault

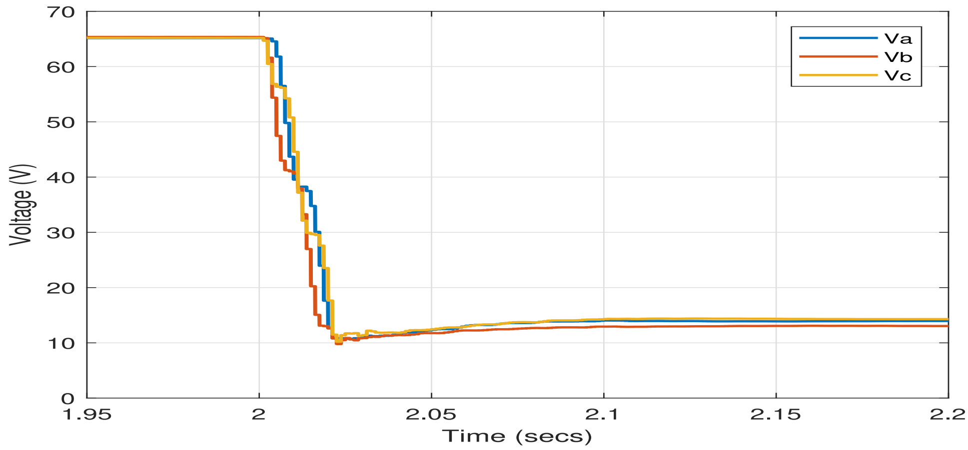


Figure 7.9: Relay observed voltage magnitude for string fault

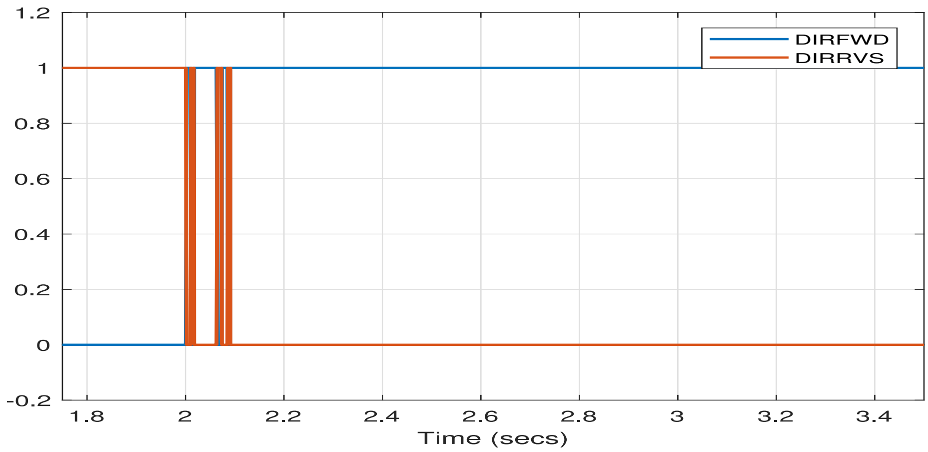


Figure 7.10: Direction element for string faults

The fault on the connection cable section is comparatively far from the relaying point than a busbar fault and as a result experiences impedance of the cable section in addition to the arc resistance. The voltage during a string fault at the relay is shown in Fig. 7.9, it does not drop to zero following a fault as observed for busbar faults in Fig. 7.5 but is maintained at approximately 15 V. Thus, the directional element is observed to have a successful operation following a fault, and it outputs the correct direction decision at approximately before 90 msec (shown in Fig. 7.10) Zone 1 and zone 2 are once again seen to shift to operate dynamically following a fault, as they now use polarising voltage during the memory period, compared to the steady state.

## 7.5. CONCLUSION

For faults on the busbar/PCC, the relay observes only the short circuit current contribution of a single string of WT, i.e., lower short circuit currents. The direction of the fault current is not changed concerning the relay setting for this case. The direction element, on the other hand, is observed to maloperate, indicating a change in forward direction. This is owing to the low voltage conditions near the relay, the lower impedance section of the busbar and a low short circuit current. The relay model is designed, such as to indicate a forward fault in cases when the voltage falls below a specific limit, and the relay has failed to analyse the direction. Zone 1 and Zone 2, as seen in Fig. 7.7 maloperate. Zone 3 and Zone 4, on the other hand, do not observe such issues. A fault on the string, however, observes large currents at the relay point and also a drop in voltage across the cable section. Finally, the voltage available at the relay point is higher compared to that during the busbar fault. The direction element, therefore, operates without any problem, but as seen in Fig. 7.10 it has difficulties in determining the direction in the early period of fault, which can be considered as errors observed during the transient period of the current and can be ignored. The distance protection, although very reliable protection, implemented in the grid with conventional generators, does not have satisfactory performance. The tests conducted in this chapter found various observations that need to be considered when discussing the failure of distance protection for busbar faults conducted. Firstly, the busbar fault is very close to the relaying point; therefore, it observes a very low voltage for the fault duration. The polarisation function of the relay maloperates and may lead to misleading trips on the grid. The fault occurs on a busbar section, which in principle has a low impedance indirectly affecting the voltage measured by the relay. The model also is unable to pick up faults on phase C, although the impedance falls inside the operating zone, as seen in Fig. 7.11. The cable circuits and the lower short circuit currents also have to be treated with special attention when setting distance relays.

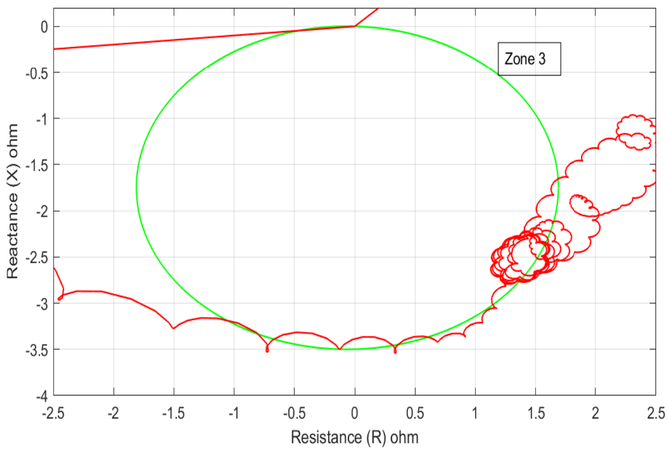


Figure 7.11: No pick up for phase C during a busbar fault in Zone 3

# 8

# Travelling Wave based Protection System

## 8.1. Overview and function

Travelling wave phenomenon occurs from microseconds to milliseconds. The phenomenon is associated with the propagation of electromagnetic waves resulting from short-circuits, the lightning or switching operations in the power system. A sudden and significant change in voltage in at least one place within the high voltage line leads to the initiation of an electromagnetic wave which propagates from that point in opposite directions [22]. The basic representation of generated travelling waves is described in Fig. 8.1. A fault occurring on the line generates waves travelling in the opposite direction, where they are reflected and refracted when encountered by a change in impedance. A simplified version is shown in Fig. 8.2 where the waves travelling towards busbar L and R are demonstrated. Where $l$ is the length of the total line and $m$ is the length of fault location from busbar L, the wave travelling towards the busbar L will encounter reflections and refractions before the wave travelling towards the busbar R. This is owing to the location of fault being closer to busbar L compared to busbar R.

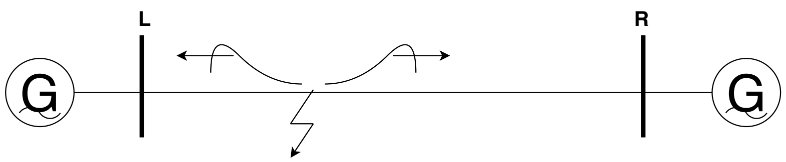


Figure 8.1: Travelling waves generated due to fault

The time taken by waves, generated due to a fault, to reach the end of the line depends on the parameters of the line. Hence, the velocity changes for overhead lines and cables. The attenuations, and distortions of the wave, during the travel, results in the reduction of amplitude and elongation of the wave. The proposed scheme describes identifying the first

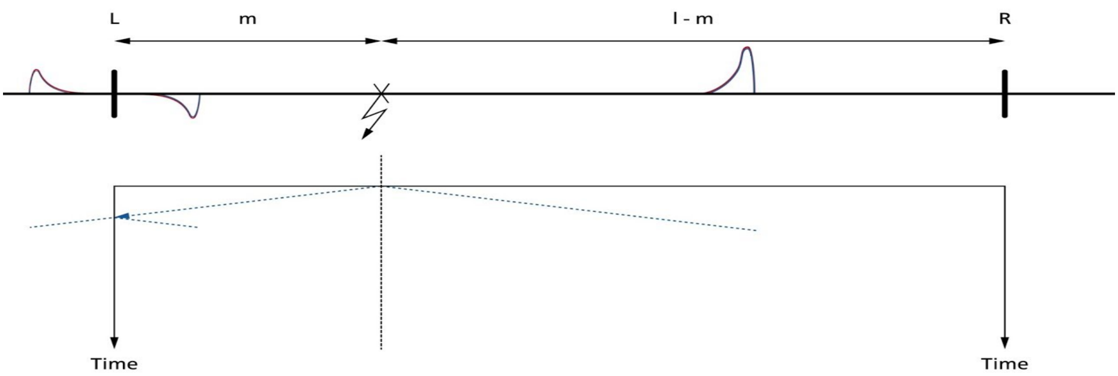


Figure 8.2: Travelling wave propagation after fault

waves that are received at the end of the cable section before it encounters any reflections. A basic representation of the concept has been shown in Fig. 8.3. G. Zou and H. Gao propose to set the relays looking away from busbar as the forward direction to detect the first arriving travelling waves during a fault.

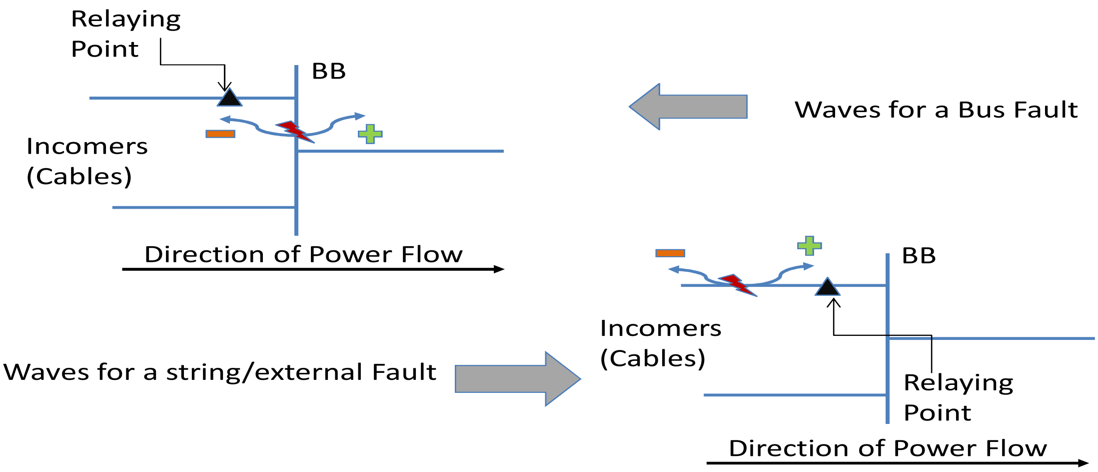


Figure 8.3: Travelling wave scheme concept

This configuration scenario describes two major fault scenarios i.e., faults on the busbar and faults on the lines, strings, incomers or feeders connected to the busbar. The first travelling wave to reach the relay in case of busbar fault would be the positive/forward wave and the negative/reverse travelling wave is observed at the relay in case of fault on the lines. Amplitudes of these travelling waves are then integrated over the time taken by the reflected wave to reach the relay, and further, a ratio of this amplitudes is used as a determining criterion to initiate a trip signal for the respective fault. This concept was tested in [23] with conventional type of sources which can provide a high amplitude of currents during a fault and longer lengths of transmission lines.

In this thesis, the concept described in [23] is tested for a shorter length of cables approximately 5 kilometres or less. The travel time is therefore shortened with the reduction of cable length. The relaying points are also located closer to the fault location, and the faults are fed by a full converter type of generator (Type 4 Wind Turbine), which provide a very low short circuit currents. The transient conditions that are used in the identification of the travelling waves are available irrespective of the type of load, consequently providing a reliable protection scheme. The implementation of this concept for the existing power system used for this study describes the availability and discusses the feasibility of this scheme with the available components and structure of the network.

## 8.2. IMPLEMENTATION

This section explains the implementation, assumptions, and modifications of the travelling wave based protection scheme. The cable section is modelled as a Frequency Dependent Model to accurately examine the travelling wave phenomenon during the faults. Modelling of such types creates a huge computation burden hence demanding a much lower time step from the model. A detailed model does not only create long run times but also increases the computation efficiency, however, only solving equations is not enough and hence needs smaller potting steps as well, further reducing the simulation time and increasing the computational burden. Owing to this limitation associated with the cable section, only one string has been developed using this technique, and all the other strings use a $\pi$-section to demonstrate the short cable behaviour. As expected and studied in literature [24], [25] a standard $\pi$ -section is unsuitable for changing frequency solutions and fails to depict the travelling wave phenomenon and hence is ruled out in major researches involving transient studies. When studying the travelling waves for a fault on the connection cable section, the fault is created on, the detailed frequency dependent cable model section as it was also essential to observe the behaviour of neighbouring/adjacent strings during a string fault and a busbar fault. A few assumptions have been considered;
Waves observed on the string consisting of detailed cable model depicts the closer to an actual/real-life scenario that is expected on the grids.
For faults on cable section, waves at the detailed model string depict an accurate scenario and the waves observed on the adjacent strings are aggregated or have lower accuracy due to use of $\pi$-section.
For internal and external faults the relaying point or the measurements are assumed near the busbar end of connection cable section and observes the reflections from cable section, considering the above scenarios the string with detail cable model depicts an accurate behaviour. Hence, the waveforms observed for the adjacent or healthy strings for both the fault cases are not incorrect but only less accurate compared to the detailed section. These assumptions can be supported as during a busbar fault, the waves generated originate from the busbar

and only reflected from the busbar end of the connection cable (waves travelled through the cable section are not considered). On the other hand, for a fault on the connection cable section waves originate from the fault point in the cable on the faulty string (considering waves travelling through the cable section) this has been taken into account by creating a fault only on the detailed model section. The waves then received at the busbar end of the connection cable are recorded for a string/connection cable fault.
The voltages and currents are measured on individual strings before the busbar to ensure local and accurate measurements. Only the data obtained in 200 microseconds after the fault is studied (but plotted for 1 millisecond range to observe more details), the initialisation time required by the wind turbines and some of the steady state period is neglected in the figures.

Three phase systems have significant coupling between the conductors. To observe the travelling waves in a three phase system, it is necessary to convert the three phases to modal components (both voltages and currents) [26]. The line/cable parameters are frequency dependent, and therefore, each component has different velocity and attenuation. Mode domain can help to introduce the effect of frequency on these parameters. The modal domain can be achieved by various transformations such as Karrenbauer, Clarke. Clarke transformation has better results for transposed lines, and we consider an ideally transposed section of cables in the model developed. Clarke transformation has an advantage that $T_i^{-1} = T_i^t$ and this makes the calculation of modal quantities simple. (where$T_i$ is the transformation matrix) Eq. 8.1 (Clarke Transformation) is used to transform the phase components to modal components in this thesis,

$$\begin{bmatrix} M_0 \\ M_\alpha \\ M_\beta \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & \sqrt{3} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{8.1}$$

Where $A$, $B$, $C$ represent the 3 phase system and 0, $\alpha$ and $\beta$ represent the modal components. $M_0$ is the ground mode component, and its magnitude is significant only during faults having a path to ground. $M_\alpha$,$M_\beta$ are the decoupled aerial modes. Such simple transformations are real and can be used with any transposed line [26]. The $\alpha$ mode component of voltage and current is therefore used for calculating the forward and reverse travelling wave. The beta component is not considered in this thesis.

The diversion from the original concept is to measure the voltages and currents in the normal direction of power flow i.e., by setting the relay direction towards the busbar as forward. In the implemented concept, relay observes the current flowing towards the busbar (also the steady state direction of power flow) as the forward direction. After achieving the modal components, the telegraph equations are used to obtain the transient voltage and current components as follows,

$$\Delta u = u^+\left(t - \frac{x}{v}\right) + u^-\left(t + \frac{x}{v}\right) \tag{8.2}$$

$$\Delta i = \frac{1}{z_c}\left[u^+\left(t - \frac{x}{v}\right) + u^-\left(t + \frac{x}{v}\right)\right] \tag{8.3}$$

where, $v = 1/\sqrt{LC}$ and $z_c = \sqrt{L/C}$ are the propagation velocity and characteristic impedance of the cable respectively. L and C are the inductance and capacitance per unit length of the cable and $u^+$ and $u^-$ represent the forward and backward wave travelling towards the positive and negative direction of the cable respectively. Equation 8.2 and 8.3 represent the transient voltage and current along the cable at any given point of time and is a superposition of forward and backward travelling wave. Equations 8.2 and 8.3 can further be solved to obtain the forward and backward travelling wave,

$$u^+ = \frac{(\Delta u + z_c \Delta i)}{2} \tag{8.4}$$

$$u^- = \frac{(\Delta u - z_c \Delta i)}{2} \tag{8.5}$$

Eq 8.4 represents the wave travelling in the forward direction (towards the busbar) and Eq. 8.5 the wave, travelling in the reverse direction (towards the Wind Park). The magnitudes of the first travelling wave received at the relaying point is then examined to identify a fault as internal (i.e., busbar fault ) or an external to the busbar. The criteria for examining the magnitude is explained in the concept section of this chapter. Hence this implementation has been tested, and the results have been discussed in the next section.

## 8.3. TESTING AND RESULTS

The measurement locations for voltage and currents was discussed in the previous section. The forward and backward travelling wave for busbar fault and a string fault, i.e., fault on the connection cable are observed in this section. Travelling waves are also studied on all the adjacent and healthy strings and are shown in Fig. 8.4, Fig. 8.6 and Fig. 8.7 for busbar fault and Fig. 8.9, 8.10 for string fault. The concept has been tested for its ability to detect the fault condition and to identify the fault as an internal (busbar fault) or an external (string fault). The main reason for considering the busbar fault as the internal fault is that the protection concept works to protect the busbar in case of primary protection failure and also disconnect a fault on connection cable or faults on the components of Wind Park Operators. The relay has also been tested for its robustness to accurately demonstrate the faulty section with changes in fault impedance and different lengths of connection cable on the strings.

Firstly, a permanent busbar fault has been created, details of the fault are mentioned in table 8.1. The length of cable sections for the first case is string 1 & 2 = 5km and string 3 = 10km.

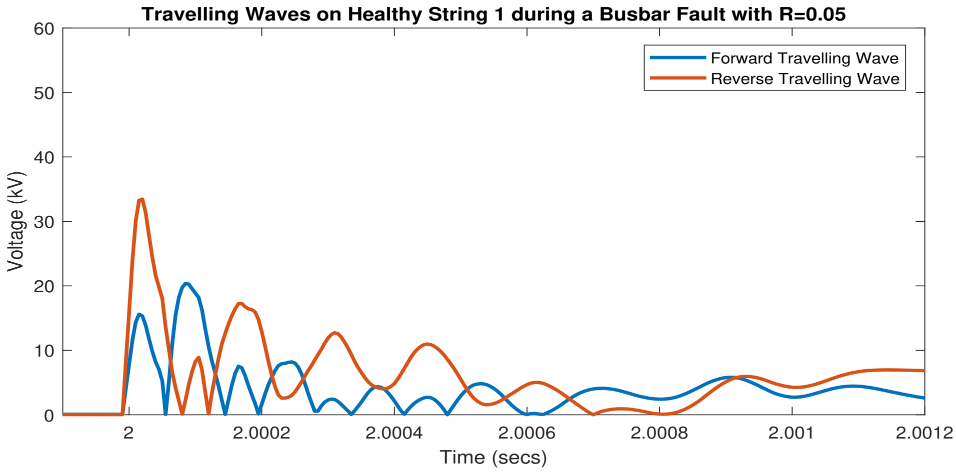


Figure 8.4: Travelling wave observed on String 1 (detailed model)

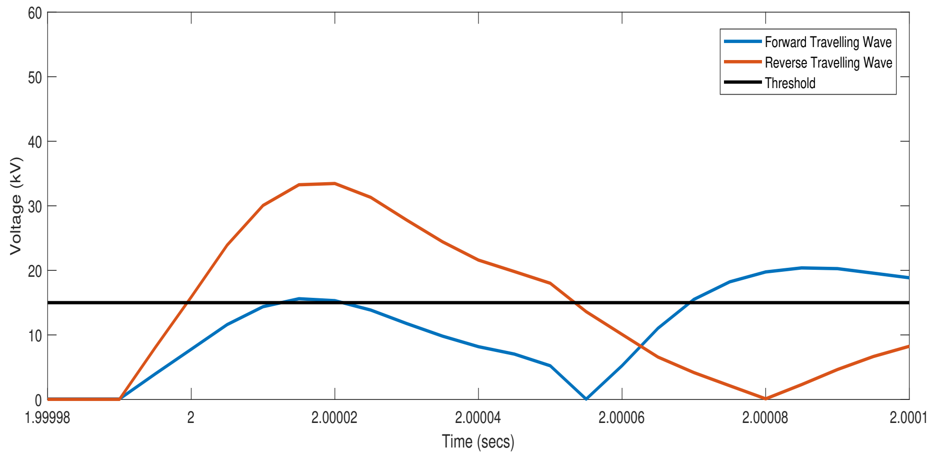


Figure 8.5: First travelling waves observed on String 1 (detailed model)

| | |
|---|---|
| Time of Fault | 2 sec |
| Fault type | 3 Phase to Ground |
| Fault location | 66 kV Busbar |
| Fault Impedance | 0.05 Ω |

Table 8.1: Fault Specifications

At 2 sec a busbar fault occurs. The voltage and currents change from their steady state values, and the waves are no more superimposed. As discussed before, the travelling waves in this smaller cable section travel with almost the velocity of the light. Hence the time scale has been narrowed down to msec range to observe the travelling waves and their reflections. The reverse travelling wave rises in amplitude higher than the forward travelling wave for a fault on the busbar on all the strings, as a result, indicating an internal fault. Travelling waves on all the strings during busbar fault are shown in Fig. 8.4 - 8.7. Following a fault at 2 sec the reverse and forward travelling wave rise in amplitude during the transient period. A zoomed image of the first travelling waves during a busbar fault is shown in Fig. 8.5. The reverse wave starts travelling towards the relay point located on the strings, and the forward wave travels away from the busbar in the direction of the offshore transformer. Hence the first travelling wave that is observed by the relay point on the WT string following a fault at 2 sec is a reverse travelling wave as observed in Fig. 8.4 - 8.7. The waves cross each other after approximately 100 μsec owing to the reflected waves that arrive at the relaying point and therefore are ignored. The relaying point being close to the fault location causes the fast reflections and refractions of wave and can be observed in Figs. 8.4 - 8.10. Waves arriving after reflections interfere with the measurements, hence it is important to record the first travelling waves arriving at the relay point. It is essential to mention that all the strings record different amplitudes of a positive and negative travelling wave; this is owing to the $\pi$-section representation of string 2 and 3. The $\pi$-section representation fails to produce an accurate demonstration of losses and hence resulting in lower amplitudes and the consideration of the length of the line is also essential.

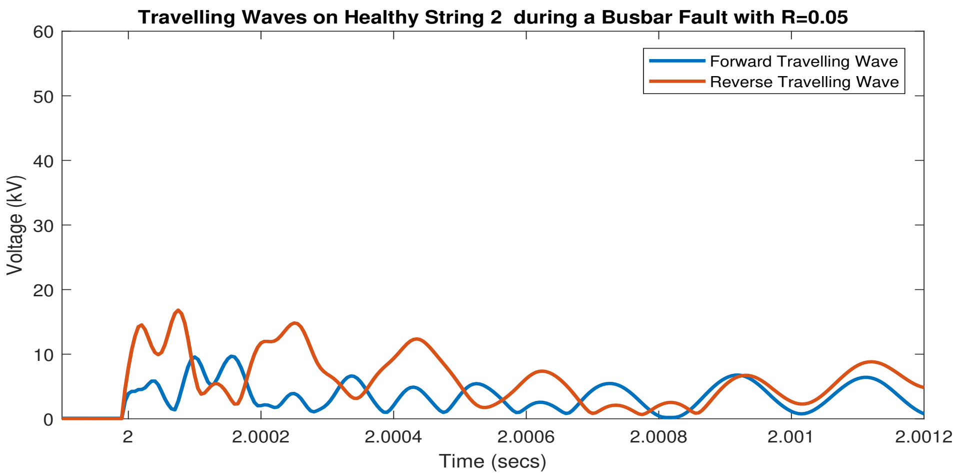


Figure 8.6: Travelling waves observed on String 2

All relays or the measuring points fail to record the same behaviour of the travelling wave phenomenon, and this is caused due to the difference in the cable modelling technique used. The string 1 being designed with detail parameters show more accurate representation and hence the higher amplitude shown in Fig 8.4 compared to string 2 and 3 in Fig.8.4 and 8.7 respectively.. However, it can be seen that as per the concept forward travelling wave does not reach the same amplitude as the reverse wave. In addition, the fault location is closer to the relay and the connection cable section; it can be seen that reflections in reverse travelling wave that now travels towards the direction of cable i.e., towards the generation appear early

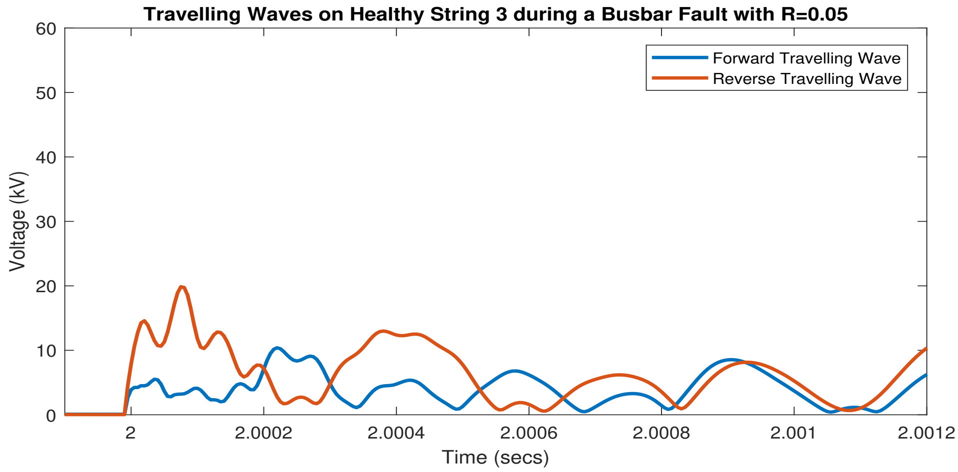


Figure 8.7: Travelling waves observed on String 3

compared to the forward travelling wave that travels from the busbar to the transformer. As seen from the figures, the proposed protection scheme does not deviate from its basic function or concept and always displays a higher amplitude reverse travelling waves compared to the forward travelling waves for a busbar fault.

| | |
|---|---|
| Time of Fault | 2 sec |
| Fault type | 3 Phase to Ground |
| Fault location | Middle of Connection Cable |
| Fault Impedance | 0.05 Ω |

Table 8.2: Fault Specifications

Finally, the concept is checked for external faults by creating a fault on the connection cable section. The fault has been created on the detailed model section, and waves at all the strings are observed. According to the concept discussed, the forward direction travelling now possess a higher magnitude as compared to the reverse travelling wave can also be confirmed in Fig. 8.8. The details of the fault are mentioned in table 8.2. The length of the cable strings is the same as for the busbar fault.

The occurrence of fault at 2 secs shows the separation of forward and reverse travelling waves from each other, unlike in steady state for all the WT strings Fig. 8.8 - 8.10. The Fig. 8.8 shows the forward and reverse travelling wave crossing each other at approximately 300 µsec compared to 100 µsec in Fig. 8.4. This is due to the location of the fault on the cable being away from the relaying point. The reverse wave travels through the cable section toward the WT transformer where it is reflected and refracted, travels back through the cable section and is altered by the fault section and is then received at the relay point.

The concept defines, for a string fault, only the faulty string will observe a forward travelling wave first and the reverse travelling wave will now stay lower in amplitude owing to the opposite direction of travel (i.e. towards the Wind Farms) and losing magnitude owing to the reflections that are caused until the wave is reached at the relaying location to be measured. This can be seen also be confirmed with Fig. 8.8 where the forward waves is seen higher in amplitude compared to the reverse travelling wave. However, the travelling waves observed on the adjacent healthy strings Figs. 8.9 and 8.10, show that reverse travelling wave rises higher in amplitude as compared to the forward travelling wave. This indicates two major information; 1. There is a fault situation on the network as the forward and reverse travelling waves are no more superimposed. 2. The amplitude of reverse travelling waves rising higher than the forward travelling waves demonstrated fault is external to the string and that the forward travelling wave encounters higher reflections as a result dropping in amplitude. The waves that are observed on the healthy strings in Figs. 8.9 and 8.10 are faster reflections approximately 150 µsec, because the waves generated are close to the busbar section and will observe reflections from the busbar section. The lower amplitude can be understood owing to non-detailed modelling of the healthy strings. Therefore, the travelling waves based protection system shows positive results in fault identification and detection.

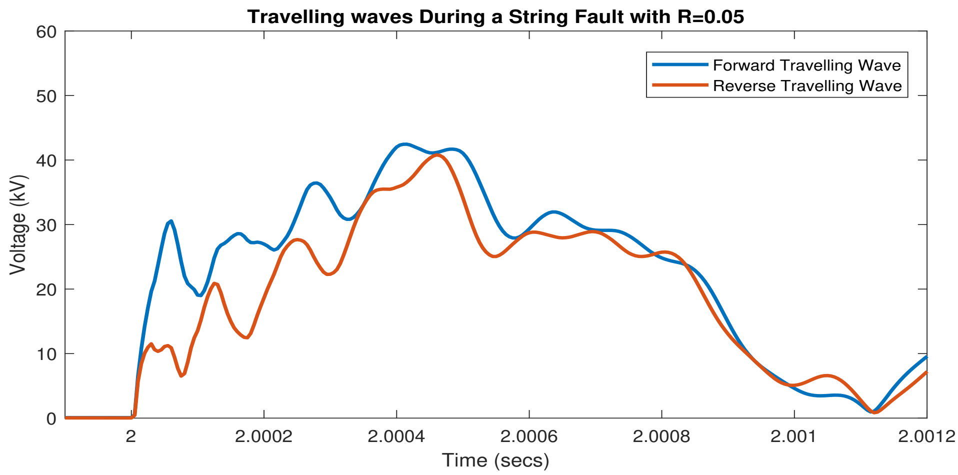


Figure 8.8: Travelling waves for string fault-faulty string

## 8.4. FEASIBILITY

As seen from the results in the previous section and the proposed concept can determine the difference between a fault on the busbar and fault on the string. It also successfully locates the faulty string, providing selectivity and the continuity of supply is not disturbed, avoiding the re-energising conditions. The length of the cable is extremely short for this study and in the existing grid, hence requires fast sampling rate and recording requirements to produce accurate tripping signals. The results on travelling wave demonstrate that the first travelling wave that is used to detect the fault and identify its position is received, giving the dimension

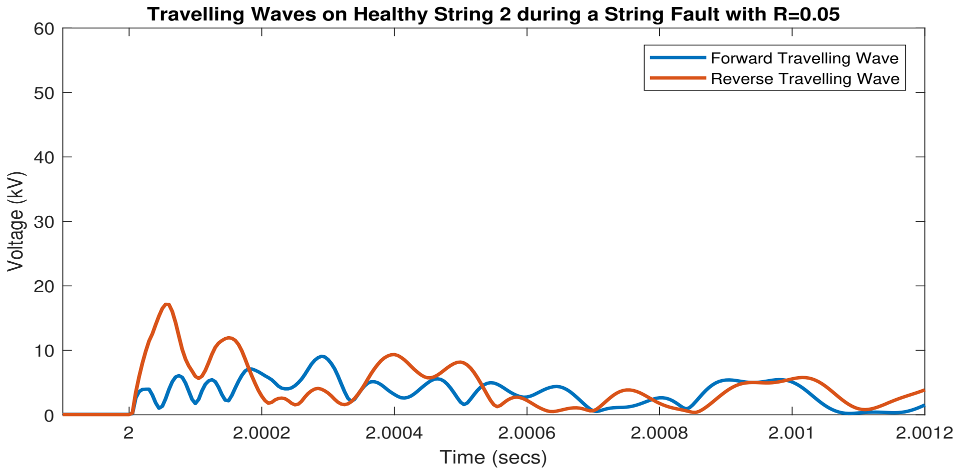


Figure 8.9: Travelling waves for string fault-healthy string

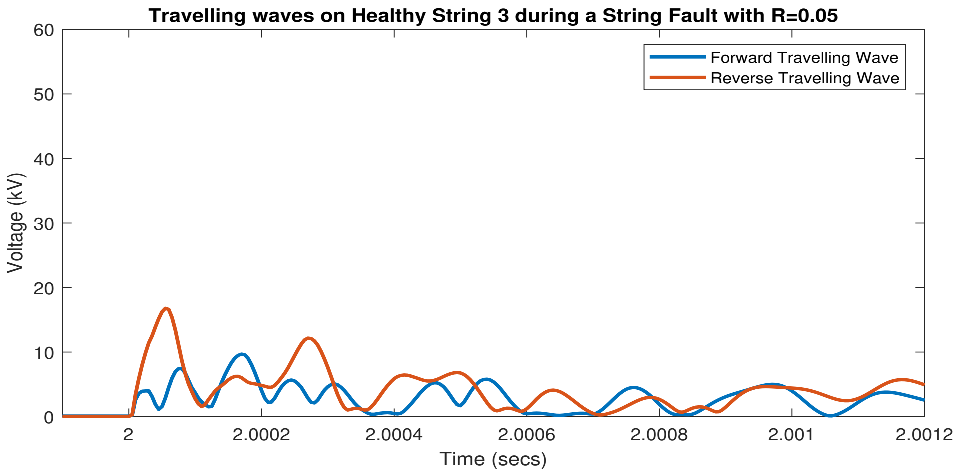


Figure 8.10: Travelling waves for string fault-healthy string

of 5km in approximately 0.1 msec. The model in PSCAD used a solution time step of 5 µsecs for this thesis and the time step is limited to a maximum of 14 µsecs given the connection cable design. The major advantage of this concept is that it allows recording, visualise and provide a trip signal command with a single component as compared to the market available devices using travelling waves which are majorly based on end to end solution. The protection concept demands highly sampled voltage, and current measurements at the relaying locations discussed before, the sampling component is expected to deliver an accuracy of 10 ~ 100 µsecs. However, it is also important to mention that travelling waves in cables are slower than in overhead lines; travelling waves in cable = 0.48*speed of light. [27]

This concept focuses on determining the difference in phenomenon available during different fault location; various criteria can then be described to provide the final trip command. To identify the location of the fault, two methods are proposed: 1. The magnitude of the pos-

| Fault Resistance | Busbar Fault | String Fault |
|---|---|---|
| 0.01 Ω | ✓ | ✓ |
| 0.1 Ω | ✓ | ✓ |
| 1 Ω | ✓ | ✓ |
| 10 Ω | ✓ | ✓ |
| 100 Ω | ✓ | ✓ |

Table 8.3: Simulation results for different fault resistances

itive and negative wave can be monitored at all time and during a fault condition the amplitude of the respective wave until the reflected wave appears at the relay point can be used to differentiate internal or external fault. For this method, the waves need to be converted to their absolute values and monitor the amplitude of the first wave. (higher reverse travelling waves for busbar faults and healthy strings during external/connection cable fault). 2. If absolute values of the waves are not used, then the polarity of the waves in case of internal and external faults can be used.

The major advantage of the proposed concept is that each relay is responsible for discriminating the fault on the respective string, therefore avoiding any communications needed, does not require synchronised data, consequently, providing a simple solution. [23] proposes a dual protection unit for each relay which can operate simultaneously to increase the reliability of the scheme. Fault location is not described in this thesis as it measures the fault generated transient waves, which would further require a higher sampling rate. The market available travelling wave bases relay are majorly end-to-end and also the proposed algorithms in [22], [28], [26] and [29] need two components or propose a master-slave strategy. However, after reviewing the proposed algorithms in [22], [26], [28] and [29], a manually generated travelling wave can be used to locate the distance of the fault. The type D locator proposed in [22] uses a wave generated by the closing of circuit breaker and records the receiving time of the reflected wave, however, a manually generated wave can also be fed by the protection device in case of connection cable fault, to identify the location. A reference data sheet consisting of pre-recorded reflection times of this waves per kilometer can be used to determine the fault location on the connection cable section.

To consider the impact of fault resistance on the operation of proposed relay scheme a list of tests have been carried out. The table 8.3 gives an overview of the operation of the results.

# 9

# Conclusions

The following chapter discusses the performance, reliability, and problems associated with the conventional protection systems that have been tested during this thesis. The advantage of using the new proposed travelling wave protection are also addressed for its capabilities to overcome the problems foreseen with the conventional relays.

## 9.1. General conclusions

The most sensitive fault locations on the studied 66 kV offshore networks were identified in Chapter 2. The challenges associated with this fault locations such as low impedance section of busbar, low short circuit currents from the Type 4 WT, cable circuits, and close fault locations were analysed throughout the study. These challenges, indulging directly or indirectly with the accurate operation of relay cause maloperation or unresponsive behaviour, exposing the valuable assets to be damaged permanently.

The present primary protection systems used on the busbar section involve differential protection with highly sophisticated algorithms to display and monitor different parameters in addition to protecting the busbar. A similar differential protection scheme can be extended for a cable section providing accurate monitored signals and trips for faults. As understood in this thesis, with the busbar being the point of common coupling it is not possible to have communication channels which have to be located at two connecting party premises.

1. **Overcurrent and Directional overcurrent protection:**

   Chapter 4 tests the definite time overcurrent protection for its performance on the sensitive fault points. The operation was found to be unsatisfactory for faults that were fed by lower magnitudes of short circuit currents by the converter based generator. For all short circuit locations that involved fault currents flowing from the high voltage grid have shown a successful operation. However, when dealing with faults on the point of common coupling, the two magnitudes of currents that feed the fault from two directions have a drastic difference of magnitudes. Hence, the assets involved are exposed to fault currents by the wind farms supplied with lower voltages. The definite time directional overcurrent is also an existing protection relay mentioned alongside the definite time overcurrent relay in the protection concept document. The direction element of the directional protection was also analysed earlier and majorly depends on the measured voltage at the relay terminals. For faults on connection cable the relay measured high currents, and the voltage is also higher compared to faults at PCC. Although indicating the correct fault direction during a connection cable fault, the relay observes difficulties in identifying the fault direction during a busbar / PCC fault. The definite time overcurrent and definite time directional overcurrent protection systems, which currently form part of protection scheme document were discovered to have unsatisfactory behaviour.

2. **Under voltage protection:**

   Chapter 6 checks the performance of under voltage protection system. As under voltage protection is not dependent on the current of the source in case of faults, they have independent and fast operations. The voltage, as seen through all the tests, was following the same trajectory. Hence, identifying the fault location depending on the voltage difference provides the selectivity as well.

   The under voltage relay has satisfactory performance following low voltages observed during a fault. Since the fault on one string observes changes on the adjacent strings. The adjacent strings notice a drop in voltage following a fault; however the relay at faulted string measures an almost zero voltage earlier compared to the healthier strings which measure a voltage drop around 0.2 p.u.

3. **Distance protection:**

   Distance protection function was studied for its performance in chapter 7. In this work, the distance relay is subject to lower short circuit currents from the WTs and shorter lengths of cable circuits, which were studied in the literature [30] to create challenges for the basic protection system. The mho characteristic was tested in this thesis. Another important observation of chapter 7 was the timings of relay operation, as with the increasing time during a fault the currents supplied by the wind turbines reach their nominal value. The distance protection can successfully identify the faults on the connection cable section owing to the high currents received from the grid. The relay in the test have been set to cover the busbar with a larger zone impedance and still fails to trip for faults on busbar. The currents flowing through the wind turbine create unfamiliar situations and consequently causing the distance protection to fail.

4. **Travelling wave based protection:**

   Observing the results and analysing the performance of conventional protection systems, a new travelling wave based protection scheme is implemented and tested on the studied network. The grid conditions are left unaltered. The concept has been tested for its performance in Chapter 8. For the busbar fault, the wave travels through the relay towards the cable section where it is again reflected and refracted before entering the cable section — creating faster deviations. The tests have been conducted with changing impedance of faults, to check the robustness of the protection. The protection overcomes the problems associated with conventional relays by providing accurate or unaltered measurements.

## 9.2. RECOMMENDATIONS

The recommendations mentioned in this section are based on the following assumptions: The accessibility of the offshore network is a critical aspect when employing protection devices, and their coordination also needs special care. A trip to the offshore substation for every small event happening on the grid not only involves a high risk to the person owing to unpredictable weather conditions but is also expensive for organisations as the transport has to be organised either with a helicopter or a vessel ( a boat carrying a small number of people). Following the unsatisfactory results obtained with overcurrent and directional overcurrent, the author proposes two new schemes involving these existing protection systems. The schemes have been mentioned in Chapter 4 and 5 to have successful operation for the studied fault locations. The major focus of these schemes is to maintain the continuity of supply, selective tripping, and avoiding frequent visits to the offshore substation following a fault.

The direction identification relays being set for the inductive currents flowing from the grid maloperates when the converter at the WTs forces balanced currents representing a capacitive behaviour. The direction detection algorithm implemented needs to take into consideration this current behaviour to implement a smart algorithm providing accurate direction decision.

Distance and under voltage protection do not form a part of the existing protection scheme implemented for the project. The distance relay zone setting to cover the faults on the busbar section was set to a higher value in order to find the optimum setting. However, setting the distance relay to such high zone coverage to trip for such sections, including lower impedances may result in incorrect tripping for faults occurring on the power system further away from the protected zone of the busbar. The distance relay model in PSCAD was tested as a black box and therefore, implementation of distance protection requires thorough and project specific testing with the actual hardware modules available. As the every manufacturer employs a different, smarter algorithm (the basic scheme remains same) the right module must be chosen after observing successful results with the given conditions. The zone settings to cover the busbar faults must be chosen accurately without disturbing the selectivity of the system and avoiding any over reach issues.

The implementation of under voltage protection by the TSO requires changes in location of VTs on the network to provide accurate voltage measurements. The VTs need to be installed towards the wind farm side to provide discrimination regarding the busbar fault and string faults. In addition, individual measurements on every incoming string are recommended compared to the existing common measurement at the busbar. The level of discrimination between a faulty string and healthy string is low and needs to be considered when setting the under voltage protection.

The travelling waves measured after a fault in this network are exposed to faster reflections and refractions owing to shorter lengths of cables. However, the basic principles of protection system employing travelling waves are very satisfactory and can also be used to replace the primary protection of the busbar.

## 9.3. CHALLENGES

Following challenges were identified during the course of this thesis:

1. Identifying an accurate PSCAD model representing genuine behaviour of Type 4 WT.

2. PSCAD model of protection devices were available as black box model hence creating challenges for trouble shooting the root cause of failure.

## 9.4. CONTRIBUTIONS

Contribution of the thesis are mentioned below:

1. The thesis provides a base for choosing protection systems for connections with Type 4 WT.

2. The thesis analyses the corrections needed in the existing protection scheme document for the tested project (Borselle) and provides a base to develop a new standard protection scheme for offshore network.

3. A detailed PSCAD model of the offshore connection string connecting the land station was realised in this thesis.

## 9.5. FUTURE SCOPE OF WORK

The existing protection scheme document available with the TSO needs to be revised with the exclusions of the overcurrent and directional overcurrent protection relays. The possibility to include the new proposed schemes described in chapters 4 and 5 with actual hardware in the grid has to be investigated. The under voltage protection if implemented by the TSO requires revision of the the voltage measurement location with VTs. A VT has to be installed on individual strings towards the WTs contrary to single VT located at the busbar (common voltage measurement for all incomers) which is currently implemented.

The distance protection, could be improved with smart algorithms that consider the adaptive settings with changing grid connections with respect to the number of Wind turbines connected to act for faults occurring on the network. The distance protection can be extended to protect the busbar behind the cable section with careful attention to detail, making it suitable to be used as secondary or back up protection. Every manufacturer employs its specific algorithm that is in most conditions unknown to the system operator. Hence the wind turbine and the protection manufacturers have to be more aligned to develop a protection system that works with the observed challenges.

At the moment, the travelling wave applications available in the market are usually an end to end solution involving communication channels, creating challenges in implementation at the PCC. However, other considerations have to be addressed by implementing a scheme that involves travelling waves. Since the travelling wave is a very fast phenomenon during a fault, and the protection system proposes the measurement of first arriving travelling waves. This requires a higher sampling rate, and it only gets higher with shorter lengths of cables. For faults occurring at the busbar, the sampling mechanism must be even faster to measure the accurate wave as the wave encounters a discontinuity very fast due to relaying point between the cable and the busbar. With rapid advancements in technology, the higher sampling rates for travelling wave protection could be possible for the near future. Travelling waves show immense potential to detect a fault with high speeds and accuracy.

There are currently need for generic models for the wind turbine generators and have to be well coordinated with the protection systems. Although the proposed scheme may require new devices on the offshore system and could prove to be expensive compared to the simple over current or directional overcurrent relays, the costs involved is substantially low when compared with the loss of generation, visits to the offshore stations or damage to the expensive assets such as transformers or sea cable. This document further helps in choosing a protection system for the system operator, which stays independent of the type of source connected and magnitude of currents provided.

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# A

# APPENDIX

Fig. A.1 shows the magnitude of fault current (fault occurring at 2 sec) observed inside the relay module after the signal processing block. The current gradually increases for 100 msec and then provides a steady fault current. The fault current consists of contribution from the WT and the strong onshore grid.

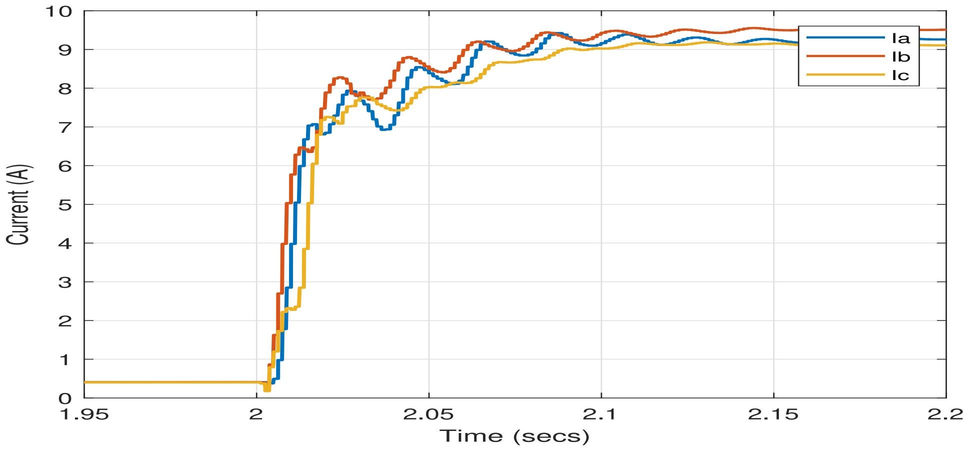


Figure A.1: Current measured in Relay module during a string fault

Fig. A.2 shows the implementation of the new proposed scheme in PSCAD using the overcurrent relays.

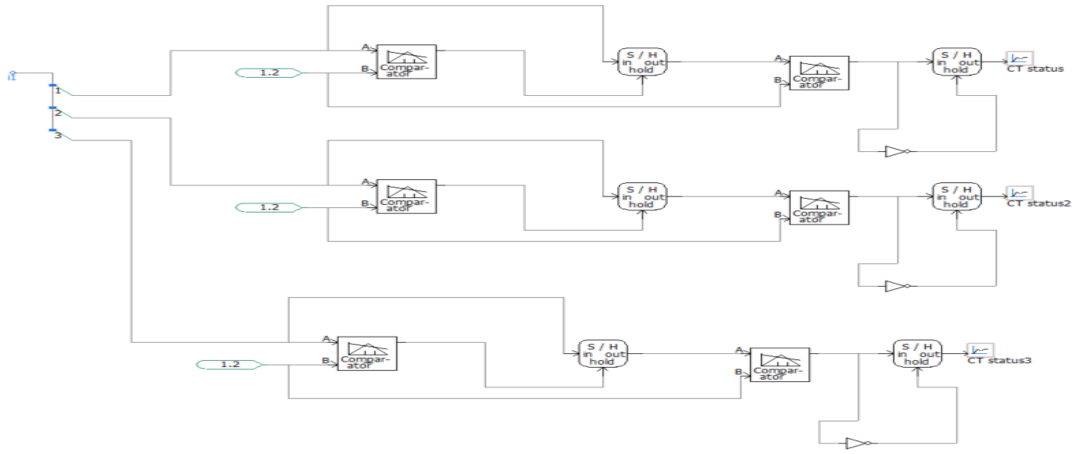


Figure A.2: PSCAD implementation of new scheme using ANSI 50

Fig. A.3 shows the contribution of Type 4 WT following a fault at 2 sec. The figure has been plotted with higher solution steps, and hence shows a higher resolution of the initial transients and then can be observed to settle at approximately 1.1 p.u. while supplying a steady state fault current.

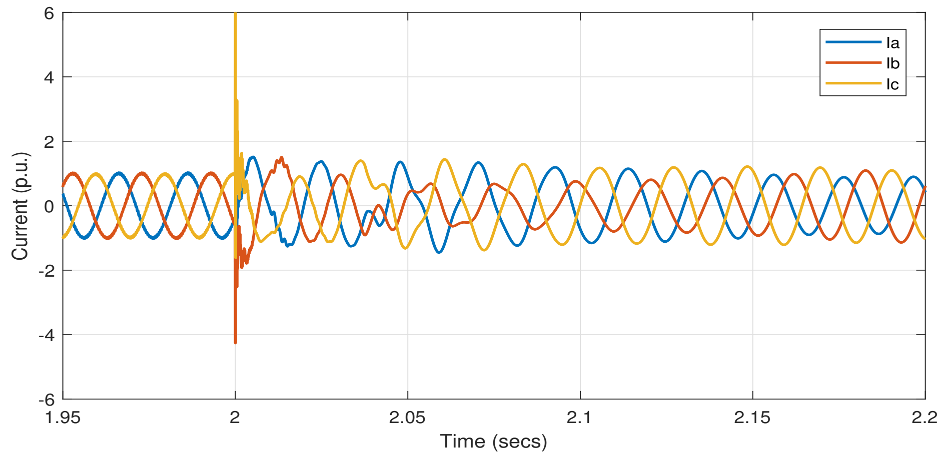


Figure A.3: Wind Turbine current contribution during a Busbar Fault with higher solution time step

Fig. A.4 shows the implementation of the new proposed scheme in PSCAD using the directional overcurrent relays.

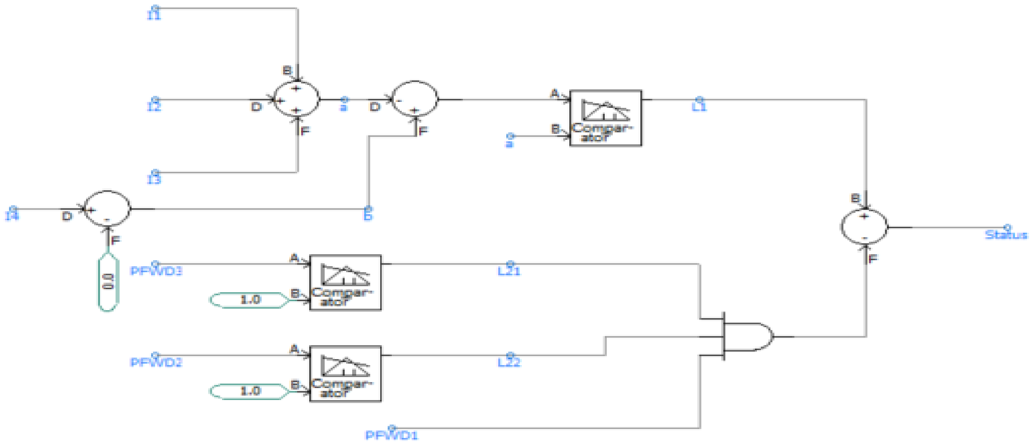


Figure A.4: PSCAD representation of the new scheme.

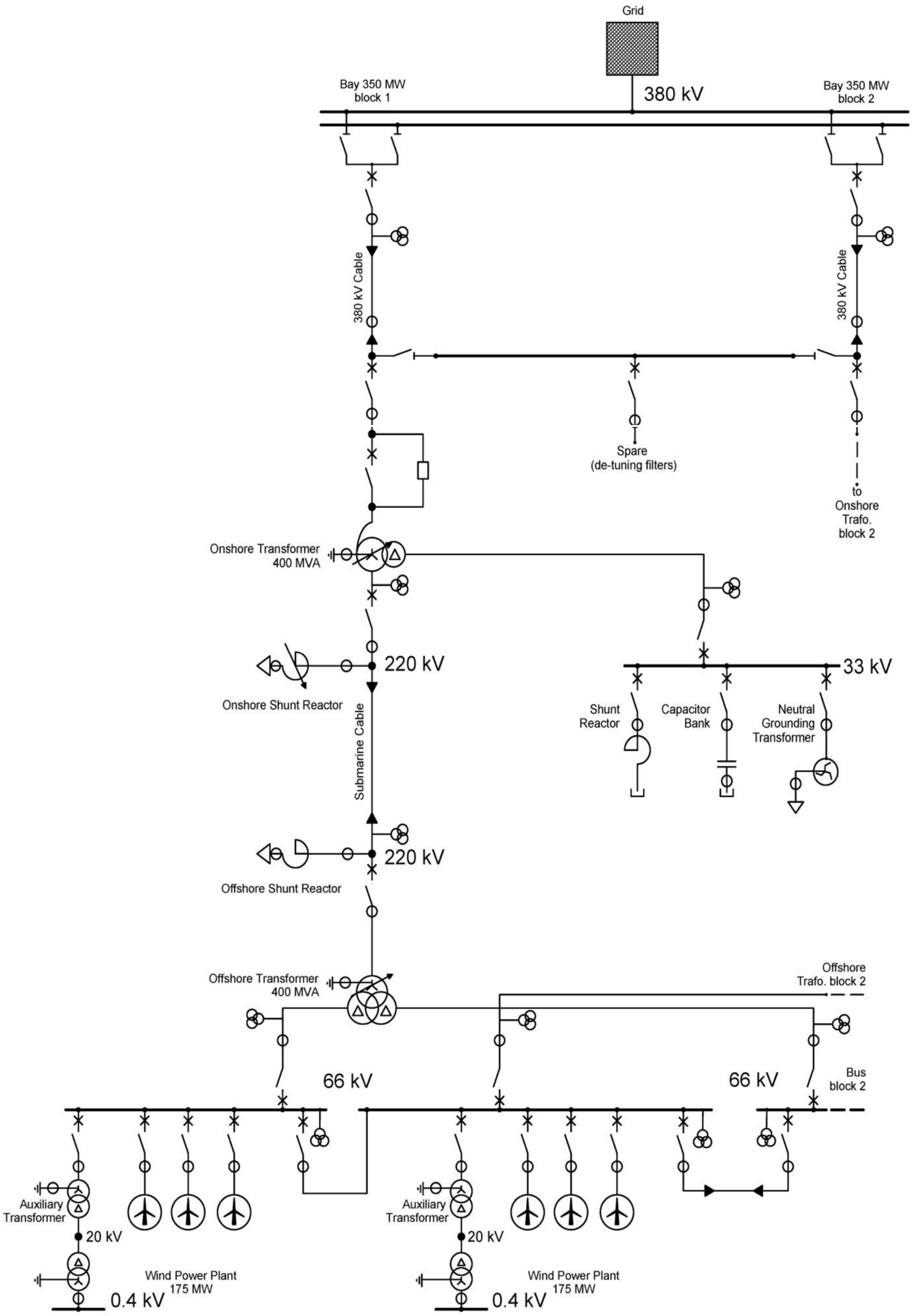


Figure A.5: Single line diagram of the Borselle Alpha A1 section

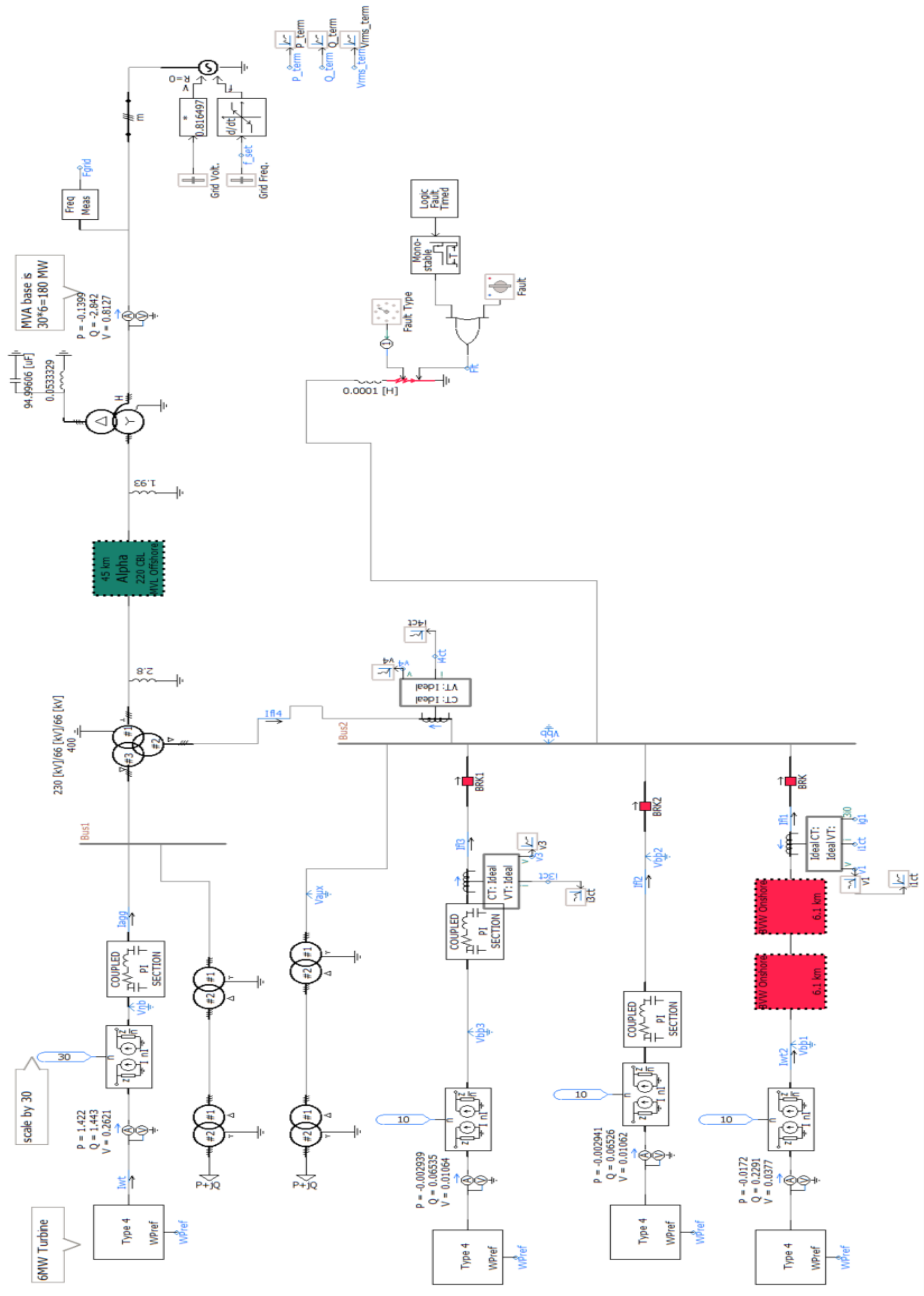


Figure A.6: Developed Model in PSCAD