ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

Grado en ingeniería electromecánica – Itinerario Eléctrico

Designing the Protections for a Transmission Line

Proyecto Fin de Grado

Autor: Borja Cifuentes Olea

Director: Fernando de Cuadra García

Madrid, Julio 2016

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Fdo.: Fernando de Cuadra García Fecha: 7/ 7/ 2016

Vº Bº del Coordinador de Proyectos

Fdo.: Fernando de Cuadra García Fecha: 7/ 7/ 2016

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ACKNOWLEDGEMENT

First of all, I would like to thank all my peers in New Mexico State University, without them all this project would not have been possible, since we shared many hours discussing about Power Systems. Their deep knowledge and motivation have arisen in me a strong commitment to research about this topic.

Thanks to my university Universidad Pontificia de Comillas (ICAI) for giving me the possibility to spend a fantastic year in the USA in which I have had wonderful experiences. The knowledge and work-capabilities acquired along the last years have been extremely important in my personal and professional development.

Last but not the least, I would like to thank also my family and close friends for these intense years, their enormous support and cuddle have allowed me to finish this challenge step of my life .

Designing the Protections for a Transmission Line

Author: Borja Cifuentes Olea

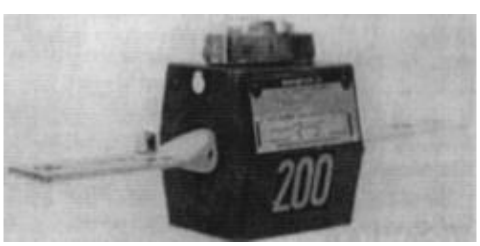
Supervisors: Ferndo de Cuadra García

ABSTRACT OF THE PROJECT

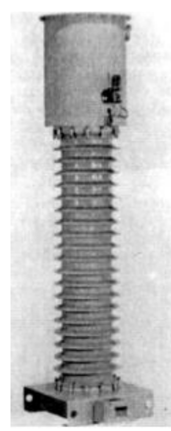
Introduction

The main objective of system protection is to provide isolation of the faulted area in the power grid, so the rest of the system keeps in normal conditions. It should be noted that the use of the term protection does not mean that the protection devices can prevent trouble, such as faults or electric shocks because of human contacts. The protective relays trip after the fault has occurred, so protection means that the protection device minimizes the duration of the trouble and limits the potential damage and problems. Transmission protection devices are designed to identify and isolate the faulted section. The biggest challenge for the electrical engineers focus on protection is to reach the aim without compromising the security of the system. The device selected should provide redundancy to limit the impact of device failure, and back-up protection to ensure dependability.

Protective relays require accurate reproduction of the conditions in the power system for correct sensing and operation. This input information from the electrical grid is provided by the current transformer (CT) and voltage transformer (VT). CTs and VTs provide a reduction of the primary current and primary voltage magnitudes. The secondary side of these devices is standardized for the convenience of application and relay design.



Voltage transformer



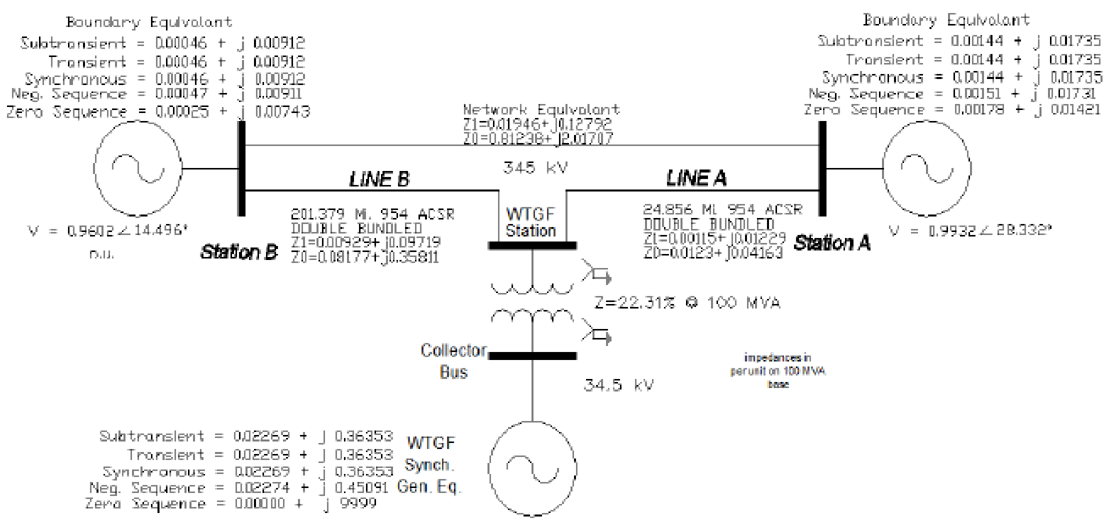
Current transformer

The most common protection technique now is known as differential protection. This protection strategy is based on the concept that the electrical quantities entering and leaving the protected zone are compere through current transformers (CTs). Hence, if the difference between both magnitudes is zero or small enough is assumed that there is no fault. This is because generally internal faults produce huge operating currents. This technique is applicable to all parts of the system, from generators, lines, buses to capacitors or reactors. In this project we have protected the transformer with a differential protection.

Transmission lines are a key part of the electrical system, because the transmission lines serve as the path to transfer power between generation and load. Typical transmission lines work at voltages levels from 69 KV to765 KV. The fast growing current population, along with economic and environmental concerns have pushed utilities to operate the system really close to its limits.

The physical construction of the transmission line also affect the protection system, since the type of conductor, the space between conductors and the size of the conductor determine the impedance of the line. In order to demonstrate that all the inputs affect the impedance of the line, an electrical transmission line model has been developed through MATLAB.

The goal of this dissertation is to provide a protection system, which includes distance relays and differential relays, to protect lines A and B, along with the transformer.



Furthermore, as the transmission lines are connected through a transformer to a wind farm, our aim is to demonstrate the effects of wind variability on the reaches of the zones of distance relays.

Methodology

The study is aimed to provide a protection system design for lines A and B, which are separated by a wind farm. The system needs to be protected against faults, so a detailed study has to be carried out. Initially and based on stability considerations (assuming 30 degrees angle difference across the lines) the current load is computed, this calculation allows to determine the necessary switchgear implemented to protect the system, the first step is to select the current transformers (CTs) required. These current transformers are standardized, so based on the load current flowing through the line the CTs are chosen.

Furthermore, the relays have to be set. Distance relays are preferred over overcurrent relays, because distance relays achieve selectivity on the basis of impedance rather than current. For distance relays the three protection zones have to be set depending on the specifications, in this project, protection zones are assumed to be (Zone 1 = 90% of line, Zone 2 = line 1 + 50% of next line and Zone 3 = line 1 + line 2). On the other hand, the differential protection applied to the transformer is based on the connection of the windings and also is based on the rated currents of the transformer.

Eventually, in order to study the effect of wind variability on the reaches of the zones of distance relays, the simulation is made based on two different scenarios, the first one is carried out with the wind farm fully operational and the second one with the wind farm not operational (the wind does not blow). To illustrate both cases, the operating point for a three-phase fault at Station B is plotted on the relay X-R characteristics at station A.

Results

When a three phase-fault occurs at Station B, the relay located at Station A should trip in the third zone due to the settings. But when the wind farm works fully operational, this source increases the current in line B and therefore the impedance seen by the distance relay at station A also increases, the demonstration is the following:

$$V_A = Z_A * I_A + Z_B * (I_B + I_{WF})$$

$$Z_{RelayA} = \frac{V_A}{I_{\ LineAB}} = \frac{Z_A * I_{LineAB} + Z_B * (I_{LineAB} + I_{WF})}{I_{LineAB}}$$

$$Z_{RelayA} = Z_A + Z_B + Z_B * \frac{I_{WF}}{I_{LineAB}}$$

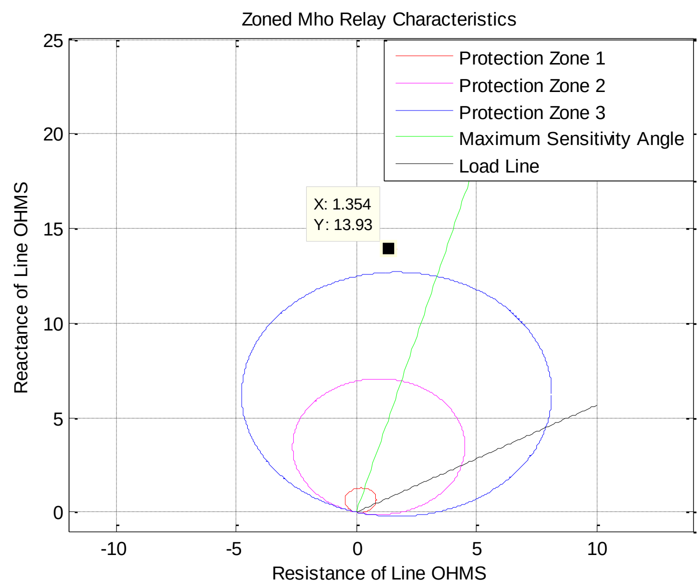
The increase in the value of impedance seen by the relay makes that the relay does not trip. On the other hand, when the wind farm does not work operational, this mean that there is not wind blowing and therefore the current supplied to the transmission line is zero (I_{WF}=0). Hence, the impedance seen by the relay would be:

$$Z_{RelayA} = Z_A + Z_B$$

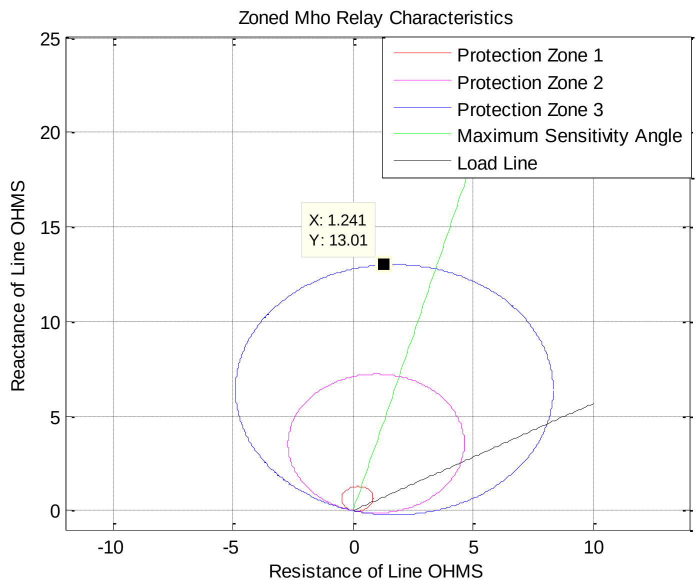
Conclusions

This project has carried out a detailed analysis about protection systems, the focus of this project has been to select and set the different protection systems available in the market. The main choice has been to pick distance relays to protect the electrical transmission line. This decision was made based on the principle that distance protection is much simpler to apply than overcurrent relays to transmission lines. Overcurrent relays are used for distribution systems, where there is just one source. This is a key factor, because if one line is fed by more than one source, then the protection of the line with overcurrent relays would become really complex.

The phenomenon of infeed is present in this analysis. This basically means that extra sources of power upset the normal behavior of protection systems, as it is detailed in the memory of the project extra power produces that distance relays see more impedance and therefore the settings of the relays have to be changed. The project shows two cases. In the first case, the wind farm is working at its maximum performance, the operational point should lie on zone 3 protection line but due to the infeed, the operational point lies outside the protection zone. Hence, the Relay at station A does not trip in this case for a three phase fault at station B, and therefore this backup protection does not make its job, upsetting the safety of the system. On the other hand, second case shows how the protection system trips at the right point. The following graphs display the operating point in both cases.



Wind farm fully operational



Wind farm not fully operational

Diseño de las Protecciones para una Línea de Transmisión

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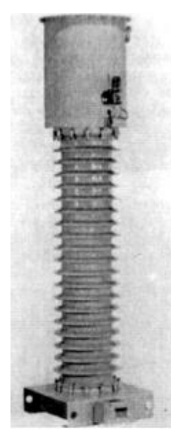
RESUMEN DEL PROYECTO

Introducción

El objetivo principal de un sistema de protección eléctrico es aislar la parte afectada por una falla del resto del sistema eléctrico, quedando el resto del sistema en condiciones normales. Aunque el término “protección” a priori de a entender que al sistema actúa para prevenir los potenciales problemas, como fallas o accidentes eléctricos sufridos por los seres humanos. Los relés actúan después de que la falla haya ocurrido, por lo tanto en este caso, protección significa que los dispositivos empleados para proteger el sistema eléctrico minimizan la duración de la falla y limita los potenciales problemas que puedan surgir. Los sistemas de protección son diseñados para identificar y aislar la sección afectada por la falla eléctrica. El mayor reto para los ingenieros eléctricos es lograr el objetivo de proteger el sistema sin comprometer la seguridad del mismo. El método empleado deberá minimizar las posibilidades de que el sistema de protección falle, y a la vez asegurar que existe una protección que actúe en el caso de que la protección principal falle y así asegurar fiabilidad en la protección.

Los relés necesitan recibir información precisa de las condiciones del sistema eléctrico para poder actuar de forma correcta. Los valores de la corriente y la tensión que circulan por el sistema en ese momento la reciben a través de los transformadores de intensidad (TIs) y de los transformadores de tensión (TTs). Los TIs y TTs reducen la intensidad y la tensión respectivamente, para que los relés puedan recibir dichas magnitudes. El lado secundario de estos dispositivos de protección esta estandarizado para que así sea más cómodo el diseño del relé.

Transformador de Tensión



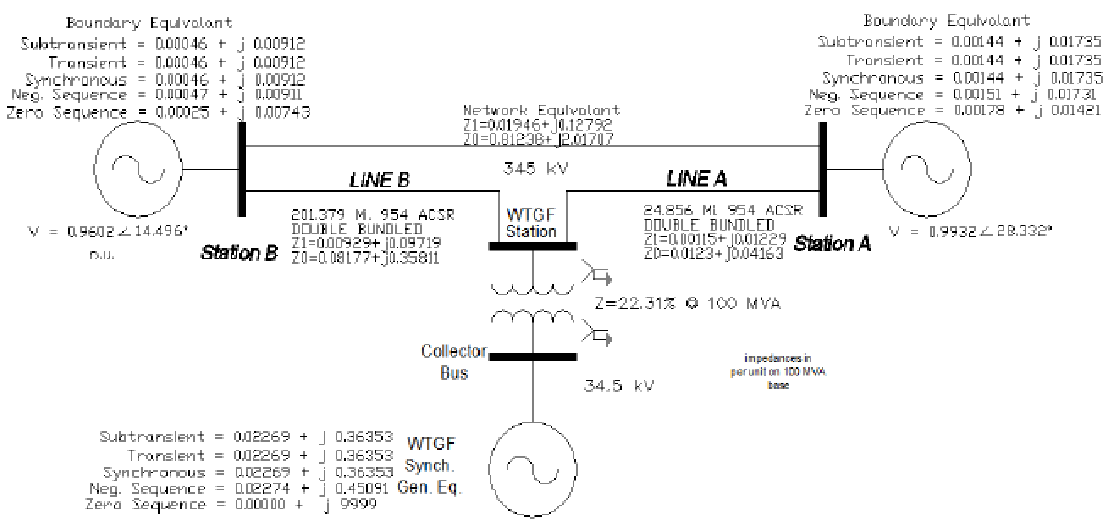
Transformador de Intensidad

El método más común de protección es conocido como protección diferencial. Esta estrategia de protección se basa en el concepto de que las magnitudes eléctricas que entran y salen de la zona protegida son comparadas mediante los transformadores de intensidad y tensión. Por lo tanto, si la diferencia entre ambas magnitudes es cero o muy pequeña se asume que no hay ninguna falla en el elemento protegido. Esta suposición se basa en que las fallas internas son corrientes extremadamente elevadas. Este método de protección es aplicable a todas las partes de un sistema, desde generadores, líneas, nudos hasta condensadores y bobinas. En este proyecto se protege el transformador mediante una protección diferencial.

Las líneas de transmisión son una parte importante del sistema eléctrico, ya que las líneas de transmisión sirven para transportar la energía desde los generadores hasta las cargas. Las típicas líneas de transmisión eléctrica funcionan a tensiones de entre 69 KV hasta 765 KV. El rápido aumento de la población, junto con las preocupaciones económicas y medioambientales ha llevado a las empresas a cargar el sistema hasta estar próximo a su límite.

El cómo esté construida la línea de transmisión también afecta al sistema de protección, ya que el tipo de conductor, el espacio entre conductores y el tamaño del conductor afectan directamente a al valor de la impedancia de la línea. Para demostrar que todos estos factores afectan a la impedancia de la línea y por tanto al sistema de protección, el proyecto incorpora un modelo creado con MATLAB en el que en función de los inputs introducidos, la línea tiene una impedancia determinada.

El objetivo de este proyecto es proporcionar un sistema de protección, el cual incluye relés de distancia y relés diferenciales, para proteger las líneas A y B, junto con el transformador:



Por otra parte, como las líneas de transmisión eléctrica están conectadas entre sí mediante un transformador a un parque eólico, nuestro objetivo es demostrar el efecto que tiene la variabilidad del viento en el alcance de las zonas de protección de los relés de distancia.

Metodología

El estudio tiene como finalidad diseñar un sistema de protección para las líneas A y B, las cuales están separadas mediante un parque eólico. El sistema tiene que estar protegido contra las fallas eléctricas. Mediante consideraciones de estabilidad (asumiendo 30 grados de diferencia máxima entre ambas líneas) la corriente nominal es calculada, este cálculo permite determinar la aparamenta necesaria para proteger el sistema, el primer paso es escoger los transformadores de corriente (TIs). Estos transformadores de corriente están estandarizados, así que en función de la corriente nominal que circule por la línea de transmisión elegiremos los TIs adecuados.

Por otro lado, los relés tienen que ser ajustados. Los relés de distancia son preferibles a los relés de intensidad, debido a que los relés de distancia logran selectividad mediante la impedancia en vez de mediante la intensidad. Las zonas de protección de los relés de distancia han de ser configurados en función de las especificaciones oportunas, en este proyecto, se han asumido las siguientes zonas de protección (Zona 1 = 90% de la línea, Zona 2 = línea 1 + 50% de la línea 2 y Zona 3 = línea 1 + línea 2). Por el otro lado, el diseño de la protección diferencial del trasformador, depende de la conexión de los arrollamientos y de las corrientes nominales del propio transformador.

Finalmente, para estudiar el efecto de la variabilidad del viento en el alcance de las zonas de los relés de protección, la simulación se realiza teniendo en cuenta dos escenarios, el primero es realizado con el parque eólico funcionando a pleno rendimiento, mientras que en el segundo caso se asume que hay cero viento y por lo tanto la contribución del parque a la red es nula. Para enseñar el comportamiento del sistema en ambos casos, se ha simulado una falla trifásica y se ha representado el punto en el que opera el relé de distancia en un gráfico X-R.

Resultados

Cuando una falla trifásica ocurre en la estación B, el relé situado en la estación a debería actuar en la zona 3 debido a la configuración que posee. Pero cuando el parque eólico funciona a pleno rendimiento, la corriente que circula por la línea B aumenta y con ello aumenta también la impedancia vista por el relé, la demonstración matemática es la siguiente:

$$Z_{ReléA} = \frac{V_A}{I_{\ LineaAB}} = \frac{Z_A * I_{LineaAB} + Z_B * (I_{LineaAB} + I_{PE})}{I_{LineAB}}$$

$$Z_{ReléA} = Z_A + Z_B + Z_B * \frac{I_{PE}}{I_{LineaAB}}$$

El aumento de la impedancia vista por el relé provoca que este dispositivo de protección no actué cuando debería actuar. Por otra parte, cuando el parque eólico no está generando energía, esto significa que no hay viento y la corriente suministrada a la línea de transmisión es cero (I_{PE}=0)

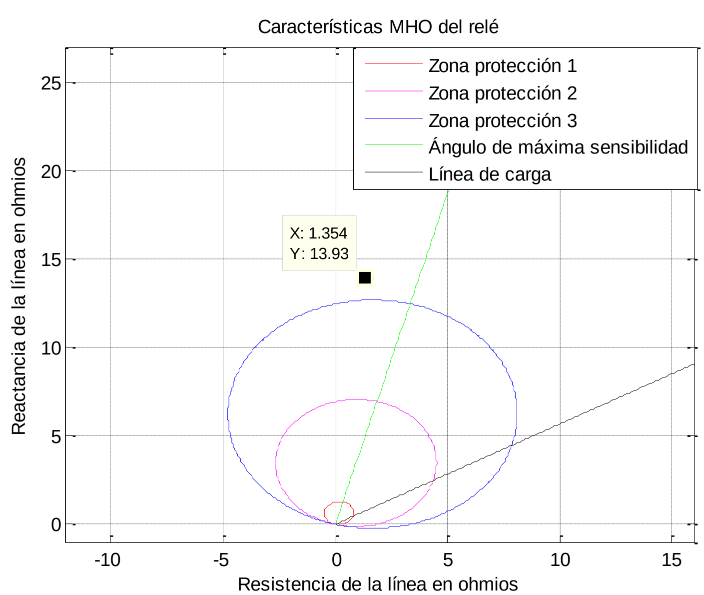
Así, la impedancia vista por el relé sería:

$$Z_{ReléA} = Z_{lineaA} + Z_{lineaB}$$

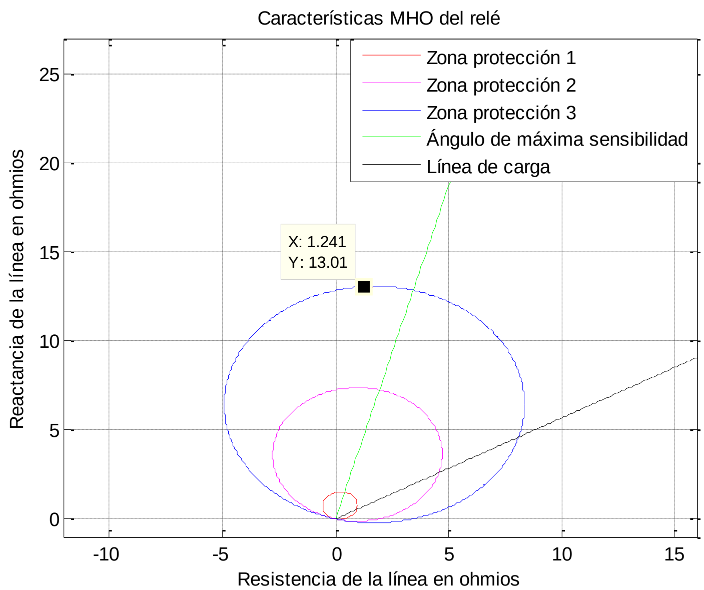
Conclusiones

El proyecto analiza detalladamente el sistema de protección empleado, principalmente el proyecto se centra en seleccionar y configurar los principales sistemas de protección en el mercado. La decisión principal consiste en seleccionar los relés de distancia para proteger la línea de transmisión eléctrica. La decisión se basa fundamentalmente en que los relés de distancia son más fáciles de usar que los relés de sobre corriente para proteger líneas de transmisión. Los relés de sobre corriente son empleados en los sistemas de distribución, donde solo existe un generador. Este es un factor clave, porque cuando una línea es alimentada por más de una fuente, la protección de la línea con relés de sobre corriente se convierte en una tarea mucho más difícil.

El análisis conlleva el estudio del suministro de potencia proveniente de una fuente de generación variable (parque eólico). Esta potencia intermitente extra afecta al comportamiento de las protecciones empleadas, como aparece detallado en la memoria del proyecto, la potencia extra produce el aumento de la impedancia vista por el relé de distancia y por lo tanto existe un desajuste con la configuración inicial de las protecciones. El proyecto ilustra dos casos. En el primer caso, el parque eólico trabaja a su máximo rendimiento, el punto de operación del relé se situa fuera la tercera zona de protección. Por tanto, el relé situado en la estación A no actúa en este caso para un falta trifásica en la estación B, anulando la seguridad de respaldo que proporciona la tercera zona de un relé de distancia, alterando la seguridad del sistema. Por otra parte, el segundo caso muestra como el sistema de protección actúa correctamente. Los siguientes gráficos muestran los puntos de operación de ambos escenarios.



Parque eólico a pleno rendimiento



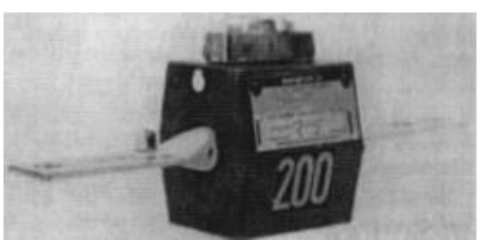
Parque eólico sin generación

CHAPTER 1. INTRODUCTION AND OBJECTIVES

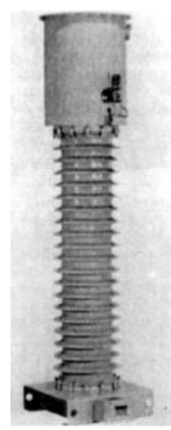
1.1 Introduction and motivation

System protection provides isolation of the faulted area in the power system, so the rest of the system keeps in normal conditions. It should be noted that the use of the term protection does not mean that the protection devices can prevent trouble, such as faults or electric shocks because of human contacts. The protective relays trip after the fault has occurred, so protection means that the protection device minimizes the duration of the trouble and limits the potential damage and problems. Transmission protection devices are designed to identify and isolate the faulted section. The biggest challenge for the electrical engineers focus on protection is to reach the aim without compromising the security of the system. The device selected should provide redundancy to limit the impact of device failure, and back-up protection to ensure dependability.

Protective relays require accurate reproduction of the conditions in the power system for correct sensing and operation. This input information from the electrical grid is provided by the current transformer (CT) and voltage transformer (VT). CTs and VTs provide a reduction of the primary current and voltage magnitudes. The secondary side of these devices are standardized for the convenience of application and relay design.



Voltage transformer



Current transformer

The most common protection technique now is known as differential protection. This protection strategy is based on the concept that the electrical quantities entering and leaving the protected zone are compere through current transformers (CTs). Hence, if the difference between both magnitudes is zero or small enough is assumed that there is no fault.

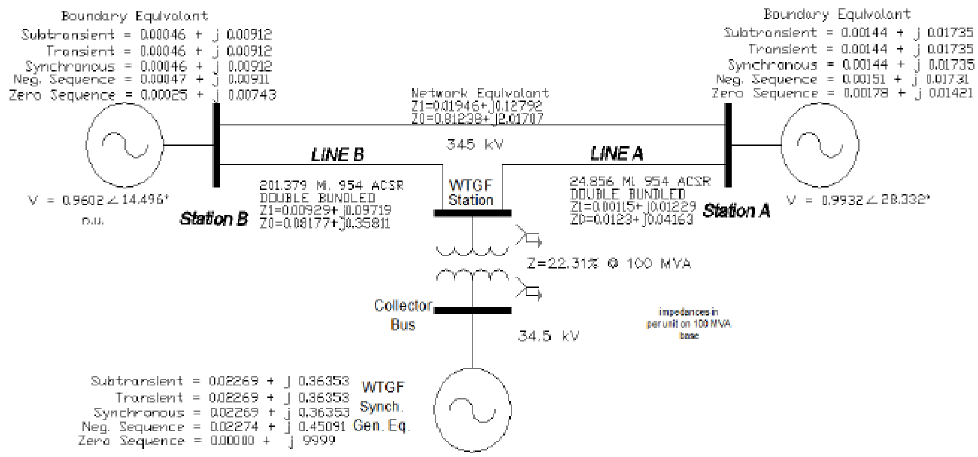
This is because generally internal faults produce huge operating currents. This technique is applicable to all parts of the system, from generators, lines, buses to capacitors or reactors. In this project we have protected the transformer with a differential protection. Moreover, distance realys are used to protect the transmission lines of the project. Distance relays are preferred over overcurrent relays, because distance relays achieve selectivity on the basis of impedance rather than current, so it has greater sensibility and easier to coordinate between them.

Transmission lines are a key part of the electrical system, because the transmission lines serve as the path to transfer power between generation and load. Typical transmission lines work at voltages levels from 69 KV to765 KV. The fast growing current population, along with economic and environmental concerns have pushed utilities to operate the syste m really close to its limits. The physical construction of the transmission line also affect the protection system, since the type of conductor, the space between conductors and the size of the conductor determine the impedance of the line. In order to demonstrate all the inputs that affect the impedance of the line, an electrical transmission line model has been developed through MATLAB.

The motivation of this project arise from the outstanding responsibility that the protection engineers have when they protect the most challenging system created by the human race. Protect the electrical system provide a deep knowledge of how is buil t the system and how the electrical system works, throughout this project many technical issues have been overcome in order to provide an optimal solution of the protection scheme.

1.2 Objectives

The goal of this dissertation is to provide a protection system, which includes distance relays and differential relays, in order to protect lines A, B and the transformer of the following power system.



Furthermore, as the transmission lines are connected through a transformer to a wind farm, our aim is to demonstrate the effects of wind variability on the reaches of the zones of distance relays. This wind variability is because of the wind farm supply power to the system depending on the wind that blows at that moment, this mean that for strong wind the wind farm operates at its highest performance, however if there is no wind blowing, the wind farm provides zero power to the system.

CHAPTER 2. Analyzing the system

2.1 Electrical transmission line model

The physical construction of the transmission line also affect the protection system, since the type of conductor, the space between conductors, the size of the conductor, the number of conductors per bundle and the distance between phases determine the impedance of the line. In order to demonstrate that all the inputs affect the impedance of the line, an electrical transmission line model has been developed through MATLAB. (Appendix C)

To demonstrate how the different inputs affect the transmission line, two different models have been simulated through MATLAB.

Simulation 1

```
Possible conductors:

1) Thrasher
2) Plover
3) Finch
4) Canary
5) Kiwi
6) Bluebird
7) Piover

Select the number of your desirable conductor: 4
Select the number of conductors per bundle, choose from 1 to 4: 3
Select phase-phase distance between A and B in meters: 2
Select phase-phase distance between B and C in meters: 2
Select phase-phase distance between C and A in meters: 2
Select distance between conductors in bundle in meters: 0.5

The value of the series resistance in Ohms/mile is:
    0.0395

The value of the reactance in Ohms/mile per phase is:
    0.3674
```

In this first simulation, this transmission line has been built with:

Type of conductor = Canary

Number of conductors per bundle = 3

Distance between phases = triangle configuration with 2 meters among each side

Distance between conductors = 0.5 meters

The impedance outcome is 0.0395 + 0.3674j Ω/mile

Simulation 2

```
Possible conductors:

1) Thrasher
2) Plover
3) Finch
4) Canary
5) Kiwi
6) Bluebird
7) Piover

Select the number of your desirable conductor: 5
Select the number of conductors per bundle, choose from 1 to 4: 4
Select phase-phase distance between A and B in meters: 5
Select phase-phase distance between B and C in meters: 5
Select phase-phase distance between C and A in meters: 10
Select distance between conductors in bundle in meters: 0.5

The value of the series resistance in Ohms/mile is:
    0.0128

The value of the reactance in Ohms/mile per phase is:
    0.3987
```

In this second simulation, this transmission line has been built with:

Type of conductor = Kiwi

Number of conductors per bundle = 4

Distance between phases = parallel configuration with 5 meters between each line.

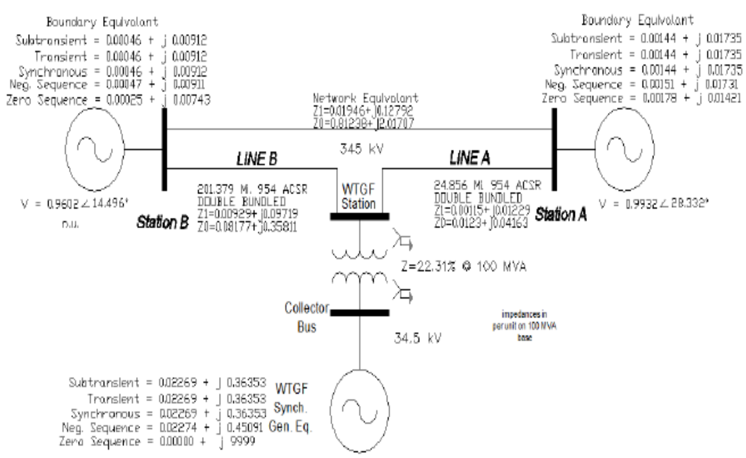
Distance between conductors = 0.5 meters

The impedance outcome is 0.0128 + 0.3987j Ω/mile

Clearly, the impedance of the line has changed with different types of conductors and physical changes in the construction, since these magnitudes are ohms per mile, if we have a long line the impedance difference between both lines can be huge.

2.2 Analyzed system

The system is made of three generators, two of them are typical generators and the other one located between the lines A and B is a wind farm, which provides intermittent power based on how the wind blows. Lines A and B are transmission lines, assuming that the construction of both lines is the same, line B is around eight times longer due to the higher impedance of line B. The bases of the system are shown in the table below.



Bases of the system

S_B	U_B	Z_B	I_B
100 MVA	345 kV	1190.25 Ω	167.35

CHAPTER 3. Designing the protections

3.1 Current transformers

3.1.1 Load current through line AB

In order to obtain the load current, which is the maximum current in normal conditions, we will compute this current based on stability considerations, assuming 30 degrees angle difference across each line. The real power is transferred through the line from the bus with the highest angle to the bus with the lowest angle, so as we can appreciate in the picture the real power will flow from Station A to Station B.

We can compute the power transfer from Station A to Station B using the power angle equation:

$$P = \frac{V_{ratedA} * V_{ratedB}}{X_{lineA+B}} * \sin(\delta_{difference})$$

Where,

P= Real power in MW
V_{ratedA} = Rated voltage at Station A
V_{ratedB} = Rated voltage at Station B
$X_{lineA+B}$= Positive reactance of the total line
$\delta_{difference}$ = Angle difference between stations.

Therefore, we compute the maximum real power transfer across the line, which is:

$$P_{max} = \frac{345 * 345}{(0.09719 + 0.01229) * 1190.25} * \sin(30) = 456.7\ MW$$

Once we have obtained the real power, we need to assume a typical power factor, in this case a power factor of 0.8 lagging is assumed in order to obtain the Load current.

$$|S| = \sqrt{3} * |U| * |I|$$

$$|I_{Load\_line}| = \frac{|P_{max}/\cos(\varphi)|}{\sqrt{3} * |U|} = \frac{(456.7 * 10^6)/0.8}{\sqrt{3} * 345 * 10^3} = 955.35\ A$$

3.1.2 Selection of current transformers

According to ANSI/IEEE standard, multi-ratio CTS have the following turns-selection available (each CT has a bar-type primary and 5 leads on the secondary, X1 through X5):

600:5: X1-X2=20, X2-X3=10, X3-X4=50, X4-X5=40 turns (120 turns total)

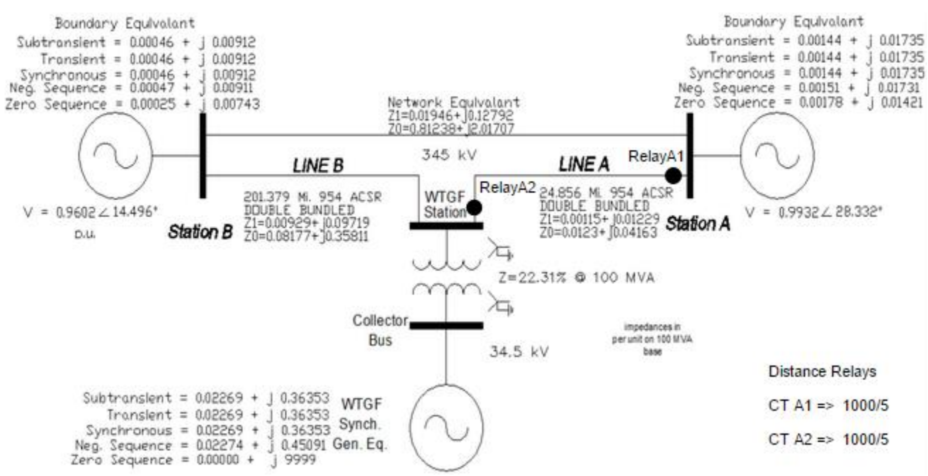
1200:5: X1-X2=40, X2-X3=20, X3-X4=100, X4-X5=80 turns (240 turns total)

2000:5: X1-X2=80, X2-X3=160, X3-X4=60, X4-X5=100 turns (400 turns total)

Line A and Line B are protected independently by 2 distance relays each one, this type of relay has six units (three for phase faults and three for ground faults). The distance relay estimates the positive sequence impedance to the fault using voltage and currents as inputs, the Current Transformer (also called CT) is used to convert high currents into low currents (transform primary currents in secondary currents), and the Voltage Transformer (VT) is used to convert from the primary voltage to the secondary voltage (typically 110 V)

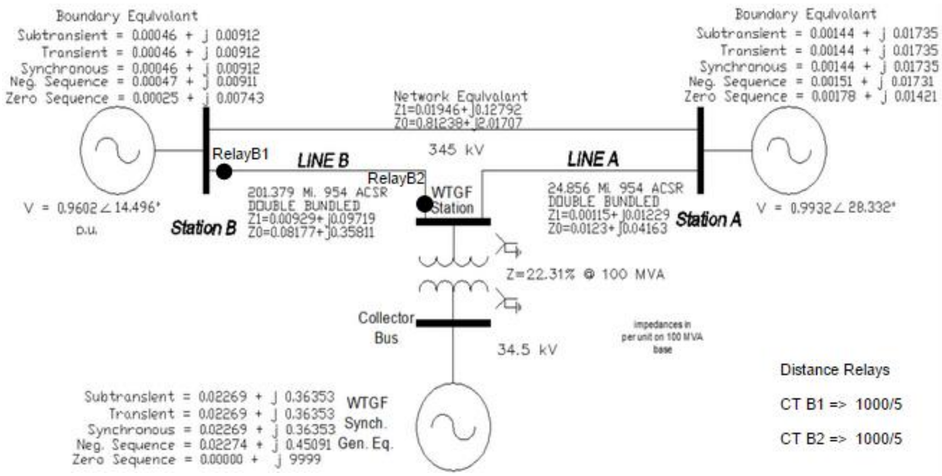
3.1.3 Current transformers line A

The load current flowing in line A is the load current of the line, which is 955.34 A, so the CT that matches with this current is 1000/5 (Multi-ratio CT 1200:5, wit connection X2-X5)



3.1.4 Current transformers line B

The load current flowing in line B is the load current of the line, which is 955.34 A, so the CT that matches with this current is 1000/5 (Multi-ratio CT 1200:5, wit connection X2-X5)



3.1.5 Current transformers of the transformer

The transformer is protected through a differential relay. The load current is given by the rated current at both sides of the transformer, high voltage (345 KV) and low voltage (34.5 KV)

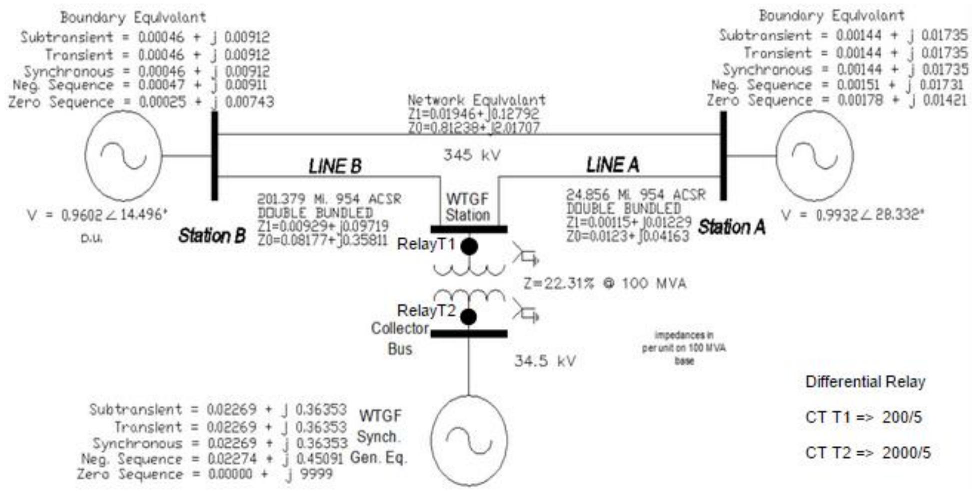
$$I_{ratedHV} = \frac{S}{\sqrt{3} * U_{HV}} = \frac{100 * 10^6}{\sqrt{3} * 345 * 10^3} = 167.34\ A$$

$$I_{ratedLV} = \frac{S}{\sqrt{3} * U_{LV}} = \frac{100 * 10^6}{\sqrt{3} * 34.5 * 10^3} = 1{,}673.47\ A$$

According to these rated currents, the CT´s that we have to choose are:

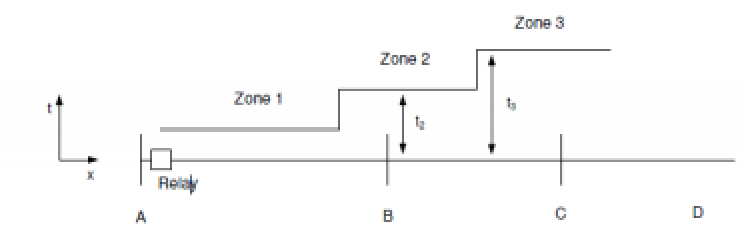
High Votage Side -> 2000/5 (Multi-ratio CT 2000:5, wit connection X1-X5)

Low Voltage Side -> 200/5 (Multi-ratio CT 600:5, wit connection X4-X5)



3.2 Setting of distance and differential relays

For distance schemes, the zones are set as zone 1 (90% of line), zone 2 (line 1 + 50% of next line) and zone 3 (line 1 + line 2).



3.2.1 Distance relays settings

The settings are set always in the secondary side because is where the relay is located and also the relay device can not exposed to the voltages and currents that circulate through the primary side, so we need to know the VT and CT ratios in order to convert the impedance to the secondary.

The CT ratio is 1000/5 = 200 and the chosen VT is 220 KV/110 V, hence the ratio is 2000.

The primary-secondary factor for the impedance is:

$$Z_{Secondary} = \frac{\frac{V_{Primary}}{VT_{Ratio}}}{\frac{I_{Primary}}{CT_{Ratio}}} = Z_{Primary} * \frac{CT_{Ratio}}{VT_{Ratio}}$$

$$Factor = \frac{CT_{Ratio}}{VT_{Ratio}} = \frac{200}{2000} = \frac{1}{10}$$

Relay A1 settings

For each distance relay we have to set 3 zones,

1) The first zone (Z1) is set to reach 90% of the line length and to operate with no intentional time delay. The margin of 10% is left for transient overreach, CT/VT errors and error in calculated impedance.

$$Z1_{Primary} = z_{LA} * Z_B * 0.9 = (0.00115 + 0.01229 * j) * 1190.25 * 0.9 = 13.2∟84.5° \, \Omega$$

$$\boldsymbol{Z1_{Secondary}} = 13.2∟84.5°/10 = \mathbf{1.32∟84.5° \, \Omega}$$

2) The second zone (Z2) is set to reach the entire line A plus 50% of the line B and will operate with a time delay T2.

$$Z2_{Primary} = z_{LA} * Z_B + 0.5 * z_{LB} * Z_B$$

$$Z2_{Primary} = (0.00115 + 0.01229 * j) * 1190.25 + 0.5 * (0.00929 + 0.09719j) * 1190.25$$

$$Z2_{Primary} = 72.8∟84.56° \, \Omega$$

$$\boldsymbol{Z2_{Secondary}} = 72.8∟84.56°/10 = \mathbf{7.28∟84.56° \, \Omega}$$

3) The third zone (Z3) is set to reach the entire line A and the entire line B and will operate with a time delay T3.

$$Z3_{Primary} = z_{LA} * Z_B + z_{LB} * Z_B$$

$$Z3_{Primary} = (0.00115 + 0.01229 * j) * 1190.25 + (0.00929 + 0.09719j) * 1190.25 =$$

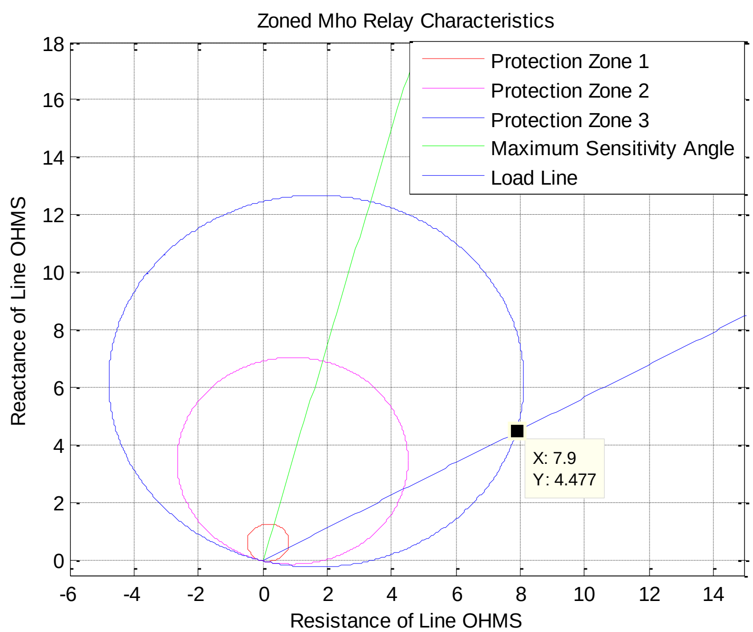
$$Z3_{Primary} = 130.89∟84.55° \, \Omega$$

$$\boldsymbol{Z3_{Secondary}} = 130.89∟84.55° /10 = \mathbf{13.09∟84.55° \, \Omega}$$

RELAY A1 SETTINGS	
Zone 1	$\mathbf{1.32 \llcorner 84.5° \, \Omega}$
Zone 2	$\mathbf{7.28 \llcorner 84.56° \, \Omega}$
Zone 3	$\mathbf{13.09 \llcorner 84.55° \, \Omega}$

Zoned mho relay characteristics-relay A1

Assuming a sensitivity angle of 75°**.** The Mho characteristics are shown in the picture bellow:



The small size of the Zone 1 is because the line B has a big impedance compared with the impedance of line A. (Around 8 times bigger)

Relay A2 settings

For each distance relay we have to set 3 zones,

1) The first zone (Z1) is set to reach 90% of the line length and to operate with no intentional time delay. The margin of 10% is left for transient overreach, CT/VT errors and error in calculated impedance.

$$Z1_{Primary} = z_{LA} * Z_B * 0.9 = (0.00115 + 0.01229 * j) * 1190.25 * 0.9 = 13.2\llcorner 84.5° \ \Omega$$

$$\boldsymbol{Z1_{Secondary}} = 13.2\llcorner 84.5°/10 = \mathbf{1.32\llcorner 84.5° \ \Omega}$$

2) The second zone (Z2) is set to reach the entire line A plus 50% of the next line and it will operate with a time delay T2.

$$Z2_{Primary} = z_{LA} * Z_B + 0.5 * z_{LC} * Z_B$$

$$Z2_{Primary} = (0.00115 + 0.01229 * j) * 1190.25 + 0.5 * (0.01946 + 0.12792 * j) * 1190.25 = 91.68\llcorner 81.88° \ \Omega$$

$$\boldsymbol{Z2_{Secondary}} = 91.68\llcorner 81.88°/10 = \mathbf{9.17\llcorner 81.88° \ \Omega}$$

3) The third zone (Z3) is set to reach the entire line A and the entire line A again and will operate with a time delay T3.

$$Z3_{Primary} = z_{LA} * Z_B + z_{LC} * Z_B$$

$$Z3_{Primary} = (0.00115 + 0.01229 * j) * 1190.25 + (0.01946 + 0.12792 * j) * 1190.25$$

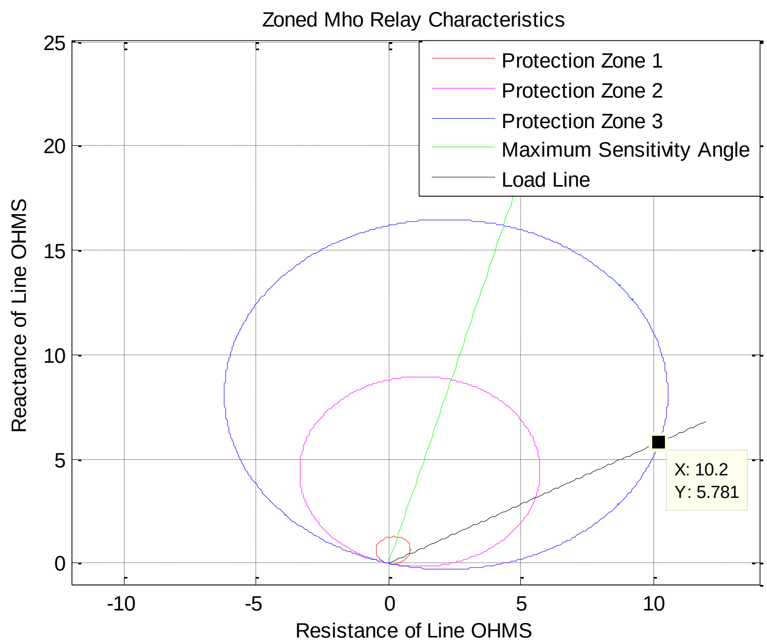
$$Z3_{Primary} = 168.68\llcorner 81.64° \ \Omega$$

$$\boldsymbol{Z3_{Secondary}} = 168.68\llcorner 81.64°/10 = \mathbf{16.87\llcorner 81.64° \ \Omega}$$

RELAY A2 SETTINGS	
Zone 1	$\mathbf{1.32\llcorner 84.5° \ \Omega}$
Zone 2	$\mathbf{9.17\llcorner 81.88° \ \Omega}$
Zone 3	$\mathbf{16.87\llcorner 81.64° \ \Omega}$

Zoned mho relay characteristics-relay A1

Assuming a maximum sensitivity angle of 75°**.** The Mho characteristics are shown in the picture bellow:



Relay B1 settings

For each distance relay we have to set 3 zones,

1) The first zone (Z1) is set to reach 90% of the line length and to operate with no intentional time delay. The margin of 10% is left for transient overreach, CT/VT errors and error in calculated impedance.

$$Z1_{Primary} = z_{LB} * Z_B * 0.9 = (0.00929 + 0.09719j) * 1190.25 * 0.9 = 104.58∟84.53°\ \Omega$$

$$\boldsymbol{Z1_{Secondary}} = 104.58∟84.53°/10 = \mathbf{10.46∟84.53}°\ \Omega$$

2) The second zone (Z2) is set to reach the entire line A plus 50% of the line B and will operate with a time delay T2.

$$Z2_{Primary} = z_{LB} * Z_B + * 0.5 * z_{LA} * Z_B$$

$$Z2_{Primary} = (0.00929 + 0.09719j) * 1190.25 + 0.5 * (0.00115 + 0.01229 * j) * 1190.25$$

$$Z2_{Primary} = 123.55∟84.54°\ \Omega$$

$$\boldsymbol{Z2_{Secondary}} = 123.55\angle 84.54°/10 = \mathbf{12.36\angle 84.54° \,\Omega}$$

3) The third zone (Z3) is set to reach the entire line A and the entire line B and will operate with a time delay T3.

$$Z3_{Primary} = z_{LB} * Z_B + z_{LA} * Z_B$$

$$Z3_{Primary} = (0.00115 + 0.01229 * j) * 1190.25 + (0.00929 + 0.09719j) * 1190.25$$

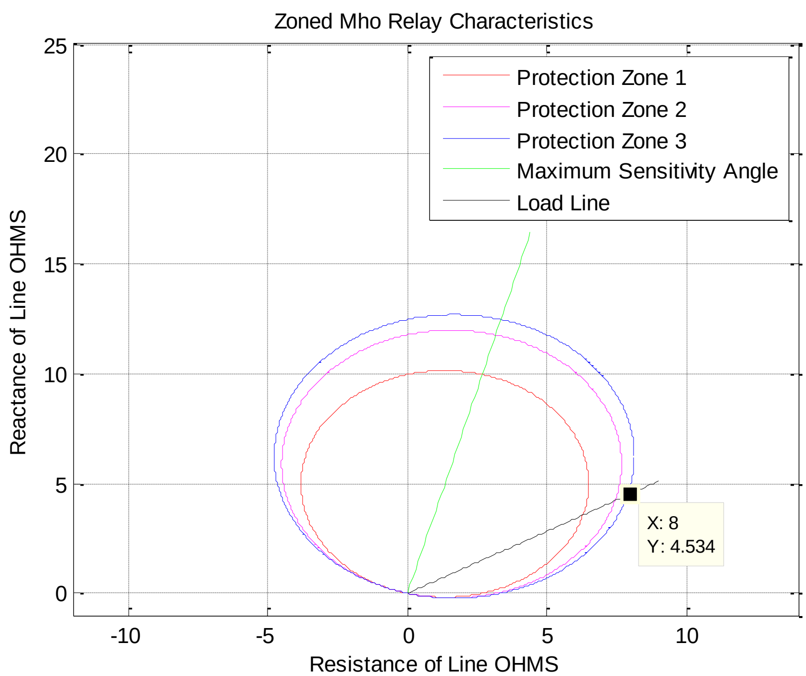
$$Z3_{Primary} = 130.89\angle 84.55° \,\Omega$$

$$\boldsymbol{Z3_{Secondary}} = 130.89\angle 84.55°/10 = \mathbf{13.09\angle 84.55° \,\Omega}$$

RELAY B1 SETTINGS	
Zone 1	$\mathbf{10.46\angle 84.53°} \,\Omega$
Zone 2	$\mathbf{12.36\angle 84.54° \,\Omega}$
Zone 3	$\mathbf{13.09\angle 84.55° \,\Omega}$

Zoned mho relay characteristics-relay B1

I assume a maximum sensitivity angle of 75°**.** The Mho characteristics are shown in the picture bellow:



Relay B2 settings:

For each distance relay we have to set 3 zones,

1) The first zone (Z1) is set to reach 90% of the line length and to operate with no intentional time delay. The margin of 10% is left for transient overreach, CT/VT errors and error in calculated impedance.

$$Z1_{Primary} = z_{LB} * Z_B * 0.9 = (0.00929 + 0.09719j) * 1190.25 * 0.9 = 104.58\llcorner 84.53° \, \Omega$$

$$\boldsymbol{Z1_{Secondary}} = 104.58\llcorner 84.53°/10 = \mathbf{10.46\llcorner 84.53°} \, \Omega$$

2) The second zone (Z2) is set to reach the entire line B plus 50% of the same line and it will operate with a time delay T2.

$$Z2_{Primary} = z_{LB} * Z_B + 0.5 * z_{LC} * Z_B$$

$$Z2_{Primary} = (0.00929 + 0.09719 * 1i) * 1190.25 + 0.5 * (0.01946 + 0.12792 * j) * 1190.25$$

$$Z2_{Primary} = 193.14\llcorner 83.26° \, \Omega$$

$$\boldsymbol{Z2_{Secondary}} = 193.14\llcorner 83.26°/10 = \mathbf{19.31\llcorner 83.26° \, \Omega}$$

3) The third zone (Z3) is set to reach the entire line A and the entire line A again and will operate with a time delay T3.

$$Z3_{Primary} = z_{LB} * Z_B + z_{LC} * Z_B$$

$$Z3_{Primary} = (0.00929 + 0.09719j) * 1190.25 + (0.01946 + 0.12792 * j) * 1190.25$$

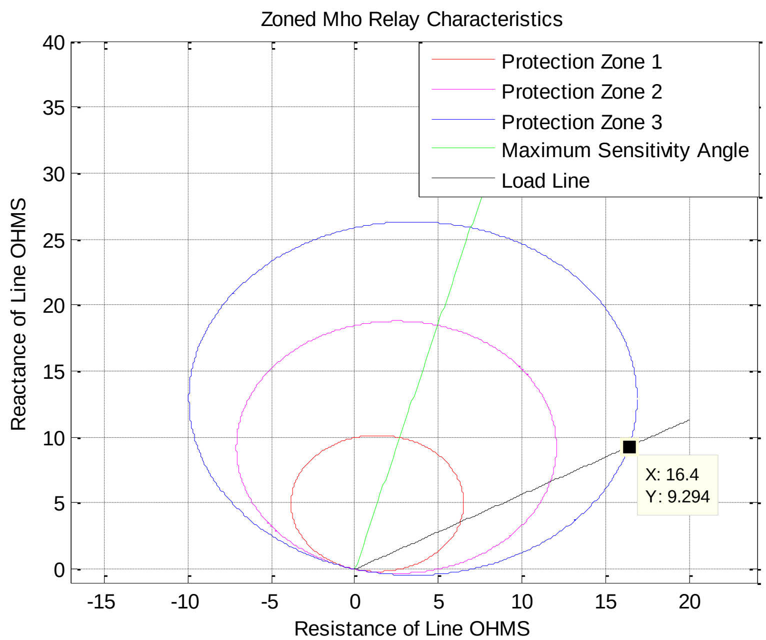
$$Z3_{Primary} = 271.62\llcorner 82.76° \, \Omega$$

$$\boldsymbol{Z3_{Secondary}} = 271.62\llcorner 82.76°/10 = \mathbf{27.16\llcorner 82.76° \, \Omega}$$

RELAY B2 SETTINGS	
Zone 1	$\mathbf{10.46\llcorner 84.53°} \, \Omega$
Zone 2	$\mathbf{19.31\llcorner 83.26° \, \Omega}$
Zone 3	$\mathbf{27.16\llcorner 82.76° \, \Omega}$

Zoned mho relay characteristics-relay B2

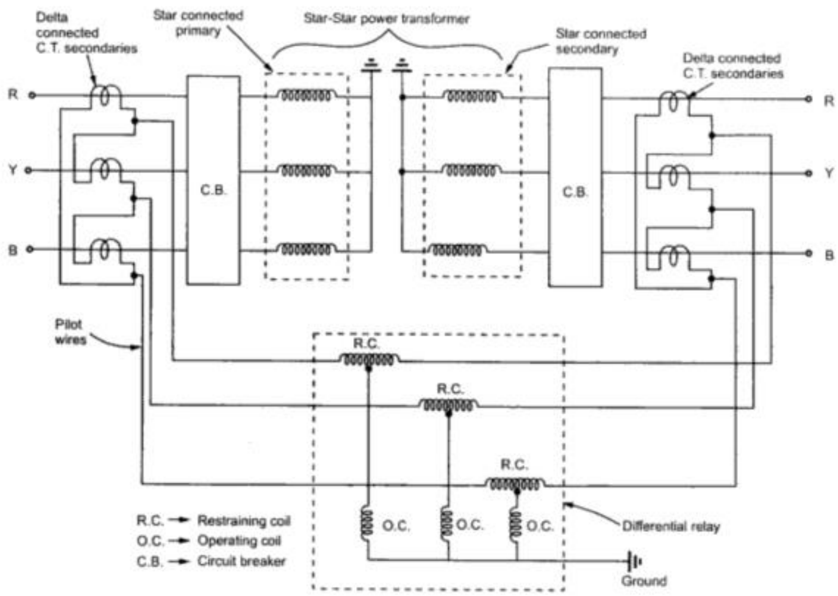
I assume a maximum sensitivity angle of 75°**.** The Mho characteristics are shown in the picture bellow:



3.2.2 Differential relay settings

The Current Transformers are 2000/5 and 200/5, for Low Voltage and High Voltage respectively. The connection of the trasformer is star-star connection (wye-wye connection), hence our CT´s are connected in the same way at both sides of the transformer, in this case I have chosen the delta connection.

This picture shows the connection of the CT´s:



The load current that the current transformers has to convert is given by the rated current at both sides of the transformer, high voltage (345 KV) and low voltage (34.5 KV)

$$I_{ratedHV} = \frac{S}{\sqrt{3} * U_{HV}} = \frac{100 * 10^6}{\sqrt{3} * 345 * 10^3} = 167.34\ A$$

$$I_{ratedLV} = \frac{S}{\sqrt{3} * U_{LV}} = \frac{100 * 10^6}{\sqrt{3} * 34.5 * 10^3} = 1{,}673.47\ A$$

The secondary currents flowing through the relays are:

High Voltage:

$$I_{HVsecondary} = \frac{I_{ratedHVprimary}}{CT_{ratioHV}} = \frac{167.34}{40} = 4.18\ A$$

$$I_{HVsecondary\,Delta\ connection} = I_{HVsecondary} * \sqrt{3} = \mathbf{7.24\ A}$$

Low Voltage:

$$I_{LVsecondary} = \frac{I_{ratedLVprimary}}{CT_{ratioLV}} = \frac{1{,}673.47}{400} = 4.18\ A$$

$$I_{LVsecondary\,Delta\ connection} = I_{LVsecondary} * \sqrt{3} = \mathbf{7.24\ A}$$

As our mismatch error is 0%, we don't need to use auxiliary CT´s, assuming 5% OLTC and 10% CT errors, the total error is 15%. Hence, the % differential slope of the relay is **20%.**

The third setting is the minimum current, which is provided to prevent operation due to no-load current. Let´s assume a min Tap Value of 7.

$$I_{minimum} = \frac{0.1 * I_{Nsecondary}}{Tap_{min}} * pu\ of\ tap = \frac{0.1 * 5}{7} * 7 = \mathbf{0.5\ A}$$

CHAPTER 4. Fault Analysis

4.1 Introduction

Once the protection scheme has been designed, a fault simulation is run in order to demonstrate the validity of the protection design. The fault is a three-phase fault at station B and the project studies the behavior of the relay A1 at station A. The fault is simulated under two different situations, first, the wind farm is fully operational and in the second case the wind farm is not operational. For fault analysis, load current is neglected for simplicity.

4.2 Operating point on the relay characteristics for a three-phase fault

4.2.1 Theoretical results

When a three phase-fault occurs at Station B, the relay located at Station A should trip in Zone 3 due to the settings. But when the wind farm is fully operational, this source increases the current in line B and therefore the impedance seen by the distance relay at station A also increases, the demonstration is the following:

$$V_A = Z_A * I_A + Z_B * (I_B + I_{WF})$$

$$Z_{RelayA} = \frac{V_A}{I_{LineAB}} = \frac{Z_A * I_{LineAB} + Z_B * (I_{LineAB} + I_{WF})}{I_{LineAB}}$$

$$Z_{RelayA} = Z_A + Z_B + Z_B * \frac{I_{WF}}{I_{LineAB}}$$

The increase in the value of impedance seen by the relay is produced by the power supplied by the wind farm. As the equation indicates, an extra term $Z_B * \frac{I_{WF}}{I_{LineAB}}$ appears, hence when the wind blows the impedance seen by the relay increases. On the other hand, when the WTGF is not operational, this mean that there is not wind blowing, the current supplied to the transmission line is 0, so I_{WF}=0. Hence, the impedance seen by the relay would be:

$$Z_{RelayA} = Z_A + Z_B$$

In order to demonstrate, how the distance relay measures the positive impedance of the lines. We are going to simulate a three phase fault at Station B and we are going to prove that the voltage at station A over the current flowing in the line A give us the positive sequence impedance measure by the distance relay for a three phase fault.

4.2.2 Methodology

The simulation of a three-phase fault at station B requires to build a mathematical model to generate the current and the voltage seen by the relay. In this case, the fault is a three-phase fault so the inputs needed by the relay are described in the table below, since it is a balance fault, the relay takes as voltage input Vab and as current input Ia-Ib.

Quantities fed to distance relays

	Relay Units	Relay Voltage	Input Current	Faults for which Relay Operates
Phase Relays	**A-B**	V_{AB}	$I_A - I_B$	**ABC, AB, ABG**
	B-C	V_{BC}	$I_B - I_C$	**ABC, BC, BCG**
	C-A	V_{CA}	$I_C - I_A$	**ABC, CA, CAG**
Ground Relays	**A-G**	V_{AB}	$I_A + I_0(Z_0 - Z_1)/Z_1$	**AG, ABG, CAG**
	B-G	V_B	$I_B + I_0(Z_0 - Z_1)/Z_1$	**BG, BCG, ABG**
	C-G	V_C	$I_C + I_0(Z_0 - Z_1)/Z_1$	**CG, CAG, BCG**

The MATLAB code (Appendix B) includes the entire procedure to calculate the current and the voltage seen by the relay, however these are the main steps to achieve the right mathematical model.

1) Pass from a delta configuration of the lines to a wye configuration.
2) Draw the positive network, since for a three-phase fault neither negative sequence nor zero sequence are needed.
3) Build the admittance bus, which contains the model of the system.
4) Compute the impedance bus, which contains the Thevenin impedance.
5) Voltages and currents are easy to calculate with the previous steps

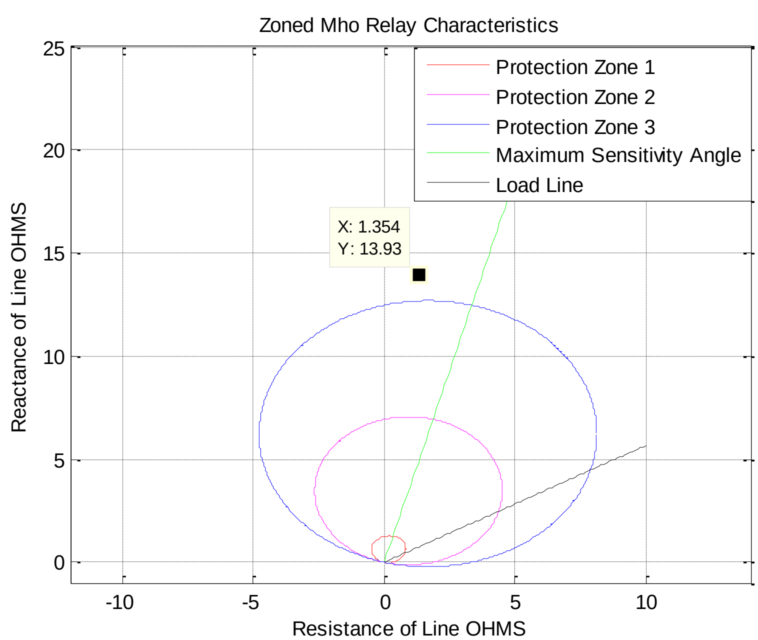
4.2.3 Operating point-wind farm fully operational

From the MATLAB output the current and voltage at station A are:

$$I_{LineA\_phaseA} = \frac{V_3 - V_4}{Z_A} = 1110.2 \llcorner -84.95^{\circ}\ A$$
$$V_{3\_phaseA} = 155.32 \llcorner -0.5^{\circ}\ KV$$

As it is a balance fault, the current and the voltages at phase b would have the same magnitude as in phase a but shifted 120° clockwise. Hence, the impedance seen by the relay in the secondary would be:

$$Z_{Relay} = \frac{V_{3\_AB}}{I_{LineA\_phaseA} - I_{LineA\_phaseB}} * \frac{CT_{Ratio}}{VT_{Ratio}} = 1.35 + 13.93j\ \Omega$$



The phenomenon of infeed is present in this analysis, the operational point should lie on the zone 3 line but due to the infeed the operational point lies outside the protection zone. Hence, the Relay A1 doesn't trip in this case for a three phase fault at Station B.

4.2.4 Operating point-wind farm not operational

However, when the wind farm is removed from our system, the operational point lies exactly on the 3 zone line. The impedance seen by the distance relay matches with the sum of the Line A impedance and the Line B impedance.
The Voltage in which we are interested is the voltage at Station A, so according with the network picture, this voltage correspond with the voltage at bus 3 and the current flowing across the line A is: (Now removing the Wind Farm Generator and the Transformer)

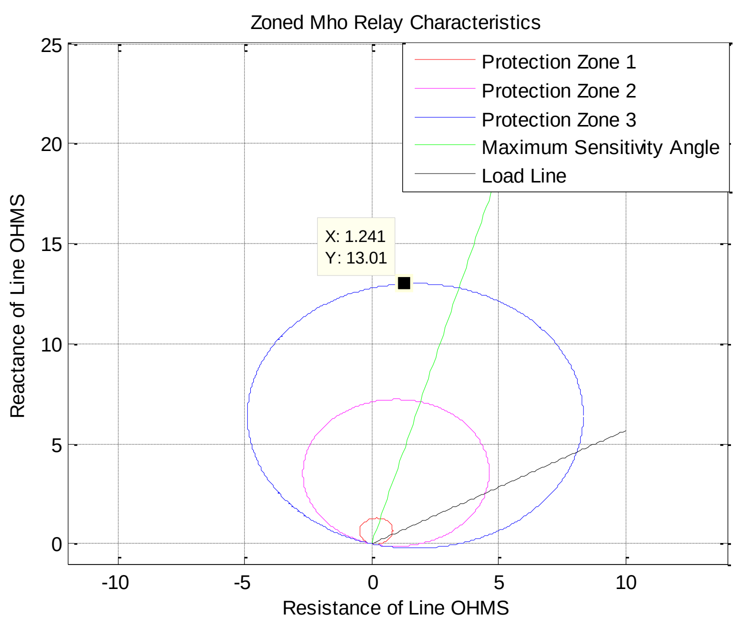
$$I_{LineA\_phaseA\_withoutWF} = \frac{V_3 - V_4}{Z_A} = 1178.8\angle - 85.04° \ A$$

$$V_{3\_phaseA\_withoutWF} = 154.04\angle - 0.49° \ KV$$

Since it is a balance fault, the current and the voltages at phase b would have the same magnitude as in phase a but shifted 120° clockwise

Hence, the impedance seen by the relay in the secondary would be:

$$Z_{Relay} = \frac{V_{3\_AB}}{I_{LineA\_phaseA} - I_{LineA\_phaseB}} * \frac{CT_{Ratio}}{VT_{Ratio}} = 1.24 + 13.01j \ \Omega$$



CHAPTER 5. Conclusions

This project has carried out a detailed analysis about protection systems, the focus of this project has been to select and implement the different protection systems available in the market. The main choice has been to pick distance relays to protect the electrical transmission line. This decision was made based on the principle that distance protection is much more simple to apply than overcurrent relays to transmission lines, also that overcurrent relays are used for distribution systems, where there is just one source. This factor is a key factor, because if one line is fed by more than one source, then the protection of the line with overcurrent relays would become really complex.

Furthermore, Wind Energy Systems exhibit variability in their output power as a result of change in their prime movers. This introduces a new factor of uncertainty on the grid and poses a lot of challenges to the power system planners and the utility operators in terms of the power system grid. Renewable energy, such as wind energy, has the feature of being an intermittent source of energy. This particular characteristic of wind energy compels planners to study the protection schemes in a deep way. This project provide a deep analysis of the behavior of protection systems based on the variability of the power supply by the wind farm. The operating points on the distance relay characteristic show that the settings of the distance relay have to be set taking into account the extra supply of current coming from the wind farm: The first scenario, the wind farm fully operational, shows the error produced due to the extra power coming from the wind farm (the relay sees more impedance) and hence it does not trip.
However, the second scenario, with the wind farm not operational, shows that the rely works properly and it trips in zone 3, working as a backup protection.

Therefore, the protection engineer has to take into account all the inputs of power to the grid. If the source of power is variable, then he should analyze the system and take the proper decision.

LIST OF REFERENCES

- **Protective Relaying: Principles and Applications, Third Edition (J.Lewis Blackburn, Thomas J. Domin)**
- **http://www.gegridsolutions.com/multilin/notes/artsci/art14.pdf**
- **http://web.itu.edu.tr/yumakk/downloads/Lab_Notes_Distance_Protection_v1.pdf**
- **Handouts from New Mexico State University. Distance protection**
- **Handouts from New Mexico State University. Introduction to Power Systems**
- **Handouts from New Mexico State University. Transmission Lines**
- **Handouts from New Mexico State University. Transmission Line model**
- **Handouts from New Mexico State University. Protection devices**
- **http://dergipark.ulakbim.gov.tr/ijrer/article/viewFile/5000174431/5000157305**

TABLE OF APPENDIXES

A - MATLAB code: mho characteristics

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% FINAL PROJECT RELAYING
% Drawing MHO characteristics and the Operating Points

clc
clear

% Bases of the system

Ubase=345*10^3;
Sbase=100*10^6;
Zbase=(Ubase^2)/Sbase;

% Ratios of the CT and VT

CTR=200;
VTR=2000;

% Impedances of the lines in the secondary

lineA=((0.00115+0.01229*1i)*Zbase)*(CTR/VTR);
lineB=((0.00929+0.09719*1i)*Zbase)*(CTR/VTR);
lineC=((0.01946+0.12792*1i)*Zbase)*(CTR/VTR);

% This is the demonstration that my code is right =>

impedanceAplusB=lineA+lineB

% Full Impedance of the lines in the secondary side

first_Zline=lineA+lineB; % Impedance in the Secondary Side
second_Zline=lineC; % Impedance in the Secondary Side 0.2736+2.9256*1i

% Maximun sensitivity angle

max_sensitivity_angle_degrees=75;


% First let´s draw all the lines (with the impedance of each line)

point_1=first_Zline;
point_2=first_Zline+second_Zline;
point_3=first_Zline+second_Zline+third_Zline;

% Here we need to use the data of how much cover each zone Z1=90%Zline1,
% Z2= Zline1+ 50%*Zline2, Zline3= Zline1+Zline2
```

```
point1_circumference=0.9*first_Zline;
point2_circumference=point_1+0.5*second_Zline;
point3_circumference=first_Zline+second_Zline+third_Zline;

% Now we have 3 points which own to the circle, lets use the maximun
% sensitivity angle to find the diameter of the circle

% We need to find out the intersection between the diameter line (Maximun
% Sensitivity Angle Line) and the perpendicular through the line which
link
% the circunference point and the origin, this line have to pass through
% the circumference point.

% Maximun Sensitivity Angle Line

point_origin_R=0;
point_origin_X=0;
point_in_the_line_R=cos(max_sensitivity_angle_degrees*(pi/180));
point_in_the_line_X=sin(max_sensitivity_angle_degrees*(pi/180));

%Y_Line_Max_Sen_Angle=((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-point_origin_R))*x;

%Y=U*x

U=((point_in_the_line_X-point_origin_X)/(point_in_the_line_R-
point_origin_R));


% Drawing the Maximum Sensitivity Line

t=[0:0.1:9];

for x=1:91


Y_Line_Max_Sen_Angle(x)=((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-point_origin_R))*t(x);


end


% Protection Zone 1

% Perpendicular Line

% Y_perpendicular=(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-point_origin_R))))*x + C;

%Y=Bx+C
```

```
point1_circumference_real=real(point1_circumference);
point1_circumference_imag=imag(point1_circumference);

% Calculating the independing term of the line
% Y_perpendicular by point1_circumference_imag  and x by
point1_circumference_real

C=point1_circumference_imag-(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-
point_origin_R))))*point1_circumference_real;
B=(-1/(((point_in_the_line_X-point_origin_X)/(point_in_the_line_R-
point_origin_R))));

% System of 2 ecuations with 2 unknowns,  this give us the diameter point
% which is a vector with the origin in the center

x=C/(U-B);
y=(C*U)/(U-B);
diameter1=x+y*1i;
radio1=diameter1/2; %coincide with the center of the circle
center_circle1_R=real(radio1);
center_circle1_X=imag(radio1);

% Protection Zone 2

% Perpendicular Line to the Maximum Sensitivity Line and pass through the
% circumference point

% Y_perpendicular=(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-point_origin_R))))*x + C;

%Y=Bx+C

point2_circumference_real=real(point2_circumference);
point2_circumference_imag=imag(point2_circumference);

% Calculating the independing term of the line. I have substituded
% Y_perpendicular by point2_circumference_imag  and x by
point2_circumference_real

C=point2_circumference_imag-(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-
point_origin_R))))*point2_circumference_real;
B=(-1/(((point_in_the_line_X-point_origin_X)/(point_in_the_line_R-
point_origin_R))));

% System of 2 ecuations with 2 unknowns,  this give us the diameter point
% which is a vector with the origin in the center

x=C/(U-B);
y=(C*U)/(U-B);
diameter2=x+y*1i;
radio2=diameter2/2; %coincide with the center of the circle
center_circle2_R=real(radio2);
```

```
center_circle2_X=imag(radio2);

% Protection Zone 3

% Perpendicular Line to the Maximum Sensitivity Line and pass through the
% circumference point

% Y_perpendicular=(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-point_origin_R))))*x + C;

%Y=Bx+C

point3_circumference_real=real(point3_circumference);
point3_circumference_imag=imag(point3_circumference);

% Calculating the independing term of the line. I have substituded
% Y_perpendicular by point2_circumference_imag  and x by
point2_circumference_real

C=point3_circumference_imag-(-1/(((point_in_the_line_X-
point_origin_X)/(point_in_the_line_R-
point_origin_R))))*point3_circumference_real;
B=(-1/(((point_in_the_line_X-point_origin_X)/(point_in_the_line_R-
point_origin_R))));

% System of 2 ecuations with 2 unknowns,  this give us the diameter point
% which is a vector with the origin in the center

x=C/(U-B);
y=(C*U)/(U-B);
diameter3=x+y*1i;
radio3=diameter3/2; %coincide with the center of the circle
center_circle3_R=real(radio3);
center_circle3_X=imag(radio3);

% Drawing the Load Line

power_factor=0.87;
angle_radians=acos(power_factor); % radians

t1=[0:0.1:20];

for x=1:201


Iine_load(x)=(sin(angle_radians)/cos(angle_radians))*t1(x);


end

%x and y are the coordinates of the center of the circle, plot(x+xp,y+yp);
%r is the radius of the circle
%0.01 is the angle step, bigger values will draw the circle faster but
```

```
%you might notice imperfections (not very smooth)


% Zone 1
r1=abs(radio1);
ang=0:0.01:2*pi;
xp=r1*cos(ang);
yp=r1*sin(ang);

% Zone 2
r2=abs(radio2);
ang=0:0.01:2*pi;
xp2=r2*cos(ang);
yp2=r2*sin(ang);


% Zone 3
r3=abs(radio3);
ang=0:0.01:2*pi;
xp3=r3*cos(ang);
yp3=r3*sin(ang);

figure(1)

plot(center_circle1_R+xp,center_circle1_X+yp,'r',center_circle2_R+xp2,cent
er_circle2_X+yp2,'m',center_circle3_R+xp3,center_circle3_X+yp3,'b',t,Y_Lin
e_Max_Sen_Angle,'g',t1,Iine_load,'k',1.3537,13.9257,'*r');
legend('Protection Zone 1','Protection Zone 2','Protection Zone
3','Maximum Sensitivity Angle','Load Line')
title('Zoned Mho Relay Characteristics')
xlabel('Resistance of Line OHMS')
ylabel('Reactance of Line OHMS')
axis([-12,30,-1,39])
grid on;
```

Annex B - MATLAB code: Fault Analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% FAULT ANALYSIS for a three phase fault at station B
% Under two conditions:

% 1) Wind Farm fully operational
% 2) Wind Farm not operational

% The study of a three phase fault require to compute the positive
sequence
% thevenin.

% When the Wind Farm is connected, the system has a delta configuration
%(Line A, Line B and Line C)
clc
clear
% Ratios of the CT and VT

CTR=200;
VTR=2000;

% The impedances of the lines are

za= 0.00115+0.01229*1i;
zb= 0.00929+0.09719*1i;
zc= 0.01946+0.12792*1i;

% The impedance of the transformer, Wind Farm, Generator A and Generator
B:

zt= 0.2231*1i;
zwf= 0.02269+0.36353*1i;
zga= 0.00144+0.01735*1i;
zgb= 0.00046+0.00912*1i;

% The wye equivalent connection is:

z1= (zb*zc)/(za+zb+zc);
z2= (za*zc)/(za+zb+zc);
z3= (zb*za)/(za+zb+zc);

% Bases

Ubase=345*10^3;
Sbase=100*10^6;
Zbase=(Ubase^2)/Sbase;
Ibase=Sbase/(sqrt(3)*Ubase);

% The Thevenin impedance is:(check, because it matches with Zbus1(3,3))
```

```
zparallel= ((zc+zt+zwf)*(zb+zga))/(zc+zt+zwf+zb+zga);
zth= ((za+zparallel)*zgb)/(za+zparallel+zgb);


% Neglecting Load Current, Thevenin Voltage is:

vth=1;

% Ybus from the positive sequence network

Ybus1=[1/zgb+1/z1, -1/z1, 0, 0, 0;-1/z1, 1/z1+1/z2+1/z3, -1/z2, -1/z3, 0;
0, -1/z2, 1/z2+1/zga, 0, 0; 0, -1/z3, 0, 1/z3+1/zt, -1/zt; 0, 0, 0, -1/zt,
1/zt+1/zwf];

% Zbus inverting the Ybus

Zbus1= Ybus1^-1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Three phase fault

Ia1=vth/Zbus1(1,1);
Ia2=0;
Ia0=0;

% Variation Voltage positive sequence (1)

Variation_V1_1=[Zbus1(1,1),Zbus1(1,2),Zbus1(1,3),Zbus1(1,4),Zbus1(1,5)]*[-
Ia1;0;0;0;0];
Variation_V2_1=[Zbus1(2,1),Zbus1(2,2),Zbus1(2,3),Zbus1(2,4),Zbus1(2,5)]*[-
Ia1;0;0;0;0];
Variation_V3_1=[Zbus1(3,1),Zbus1(3,2),Zbus1(3,3),Zbus1(3,4),Zbus1(3,5)]*[-
Ia1;0;0;0;0];
Variation_V4_1=[Zbus1(4,1),Zbus1(4,2),Zbus1(4,3),Zbus1(4,4),Zbus1(4,5)]*[-
Ia1;0;0;0;0];
Variation_V5_1=[Zbus1(5,1),Zbus1(5,2),Zbus1(5,3),Zbus1(5,4),Zbus1(5,5)]*[-
Ia1;0;0;0;0];


% Voltage positive sequence (1)

% The voltage at bus 3 is the voltage seen by the relay

V1_1= 1+Variation_V1_1;
V2_1= 1+Variation_V2_1;
V3_1= 1+Variation_V3_1;
V4_1= 1+Variation_V4_1;
V5_1= 1+Variation_V5_1;


% Three phase voltages at bus 3 (Station A)
```

```
fprintf('\nPhase-voltage (Va) at Station A as phasor in KV\n\n');

Vbus3_phasea=([1,1,1]*[0;V3_1;0])*(Ubase/sqrt(3));
Vbus3_phaseb=([1,-0.5-0.866025*i,-
0.5+0.866025*i]*[0;V3_1;0])*(Ubase/sqrt(3));

% Voltage line to line AB at bus 3

Vbus3_AB=Vbus3_phasea-Vbus3_phaseb;
Vbus3_AB_real_magnitude=abs(Vbus3_AB)/1000
Vbus3_AB_real_angle=angle(Vbus3_AB);
Vbus3_AB_real_angle_degrees=angle(Vbus3_AB)*(360/(2*pi))


% The current flowing from Station A to the WTGF seen by the relay will be

% Three phase currents flowing from bus 1 to the fault as phasors in
% Amperes

fprintf('\nFault phase-current fed from Station A to the WTGF as phasor in
A is:\n\n');

I13_1=(V3_1-V4_1)/((0.00115+0.01229*i));
I13a=I13_1*Ibase;
I13b=(-0.5-0.866025*i)*I13_1*Ibase;

% Input current for the Relay

I_input_relay= I13a-I13b;
I13ab_magnitude=abs(I_input_relay)
I13ab_angle=angle(I_input_relay);
I13ab_angle_degrees=I13ab_angle*(360/(2*pi))


% Impedance seen by the Relay placed at Station A

fprintf('\nThe impedance seen by the Relay at Station A is:\n\n');

Zprimary=Vbus3_AB/I_input_relay;
Zsecondary=(CTR/VTR)*Zprimary


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%

% WTGF not operational

% Now we have removed the wind farm (including the transformer)

% The Ybus of the new system is
```

```
Ybus1_no=[1/zgb+1/z1, -1/z1, 0, 0;-1/z1, 1/z1+1/z2+1/z3, -1/z2, -1/z3; 0,
-1/z2, 1/z2+1/zga, 0; 0, -1/z3, 0, 1/z3];

% Zbus inverting the Ybus

Zbus1_no= Ybus1_no^-1;

% I have not get the same for Zth and Zbus(1,1), why?

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Three phase fault

Ia1_no=vth/Zbus1_no(1,1);
Ia2=0;
Ia0=0;

% Variation Voltage positive sequence (1)

Variation_V1_1_no=[Zbus1_no(1,1),Zbus1_no(1,2),Zbus1_no(1,3),Zbus1_no(1,4)
]*[-Ia1;0;0;0];
Variation_V2_1_no=[Zbus1_no(2,1),Zbus1_no(2,2),Zbus1_no(2,3),Zbus1_no(2,4)
]*[-Ia1;0;0;0];
Variation_V3_1_no=[Zbus1_no(3,1),Zbus1_no(3,2),Zbus1_no(3,3),Zbus1_no(3,4)
]*[-Ia1;0;0;0];
Variation_V4_1_no=[Zbus1_no(4,1),Zbus1_no(4,2),Zbus1_no(4,3),Zbus1_no(4,4)
]*[-Ia1;0;0;0];


% Voltage positive sequence (1)

% The voltage at bus 3 is the voltage seen by the relay

V1_1_no= 1+Variation_V1_1_no;
V2_1_no= 1+Variation_V2_1_no;
V3_1_no= 1+Variation_V3_1_no;
V4_1_no= 1+Variation_V4_1_no;


% Three phase voltages at bus 3 (Station A)

fprintf('\nPhase-voltage (Va) at Station A as phasor in KV with WTGF not
operational \n\n');

Vbus3_phasea_no=([1,1,1]*[0;V3_1_no;0])*(Ubase/sqrt(3));
Vbus3_phaseb_no=([1,-0.5-0.866025*i,-
0.5+0.866025*i]*[0;V3_1_no;0])*(Ubase/sqrt(3));

% Voltage line to line AB at bus 3

Vbus3_AB_no=Vbus3_phasea_no-Vbus3_phaseb_no;
Vbus3_AB_real_magnitude_no=abs(Vbus3_AB_no)/1000
Vbus3_AB_real_angle_no=angle(Vbus3_AB_no);
```

```
Vbus3_AB_real_angle_degrees_no=angle(Vbus3_AB_no)*(360/(2*pi))


% The current flowing from Station A to the WTGF seen by the relay will be

% Three phase currents flowing from bus 1 to the fault as phasors in
% Amperes

fprintf('\nFault phase-current fed from Station A to the WTGF as phasor in
A is:\n\n');

I13_1_no=(V3_1_no-V4_1_no)/((0.00115+0.01229*i));
I13a_no=I13_1_no*Ibase;
I13b_no=(-0.5-0.866025*i)*I13_1_no*Ibase;

% Input current for the Relay

I_input_relay_no= I13a_no-I13b_no;
I13ab_magnitude_no=abs(I_input_relay_no)
I13ab_angle_no=angle(I_input_relay_no);
I13ab_angle_degrees_no=I13ab_angle_no*(360/(2*pi))

% Impedance seen by the Relay placed at Station A

fprintf('\nThe impedance seen by the Relay at Station A is:\n\n');

Zprimary_no=Vbus3_AB_no/I_input_relay_no;
Zsecondary_no=(CTR/VTR)*Zprimary_no
```

Annex C- MATLAB code: Electrical Transmission Line Model

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Electrical Transmission Line Model
clc
% Name the wires

% Thrasher
rth=0.0482;
GMRth=0.05936/3.28;
radioth=(1.802/39.37)/2; % meters

% Plover
rpl=0.076;
GMRpl=0.0492/3.28;
radiopl=(1.465/39.37)/2; % meters

% Finch
rfi=0.0969;
GMRfi=0.04362/3.28;
radiofi=(1.293/39.37)/2; % meters

% Canary
rca=0.1185;
GMRca=0.0119/3.28;
radioca=(1.162/39.37)/2; % meters

% Kiwi
rdr=0.0511; % ohms/miles
GMRdr=0.057/3.28; % meters
radiodr=(1.735/39.37)/2; % meters

% Bluebird
rcar=0.0505;
GMRcar=0.0588/3.28;
radiocar=(1.762/39.37)/2; % meters

% Piover
rma=0.076;
GMRma=0.0493/3.28;
radioma=(1.465/39.37)/2; % meters

% Asking the user about which conductor does he want to pick

fprintf('PART A\n\n');
fprintf('Possible conductors:\n\n');
fprintf('1) Thrasher\n');
fprintf('2) Plover\n');
fprintf('3) Finch\n');
fprintf('4) Canary\n');
fprintf('5) Kiwi\n');
```

```
fprintf('6) Bluebird\n');
fprintf('7) Piover\n\n');

conductor = input('Select the number of your desirable conductor: ');

if (conductor>7 || conductor==0)
       fprintf('Sorry, choose an allow number\n\n');
       conductor = input('Select the number of your desirable conductor:
');
end

if (conductor>7  || conductor==0)
       fprintf('Sorry, choose an allow number\n\n');
       conductor = input('Select the number of your desirable conductor:
');
end

num_cond = input('Select the number of conductors per bundle, choose from
1 to 4: ');

if (num_cond>4 || num_cond==0)
       fprintf('Sorry, choose an allow number\n\n');
       num_cond = input('Select the number of conductors per bundle,
choose from 1 to 4: ');
end

if (num_cond>4 || num_cond==0)
       fprintf('Sorry, choose an allow number\n\n');
       num_cond = input('Select the number of conductors per bundle,
choose from 1 to 4: ');
end

phase_distab = input('Select phase-phase distance between A and B in
meters: ');
phase_distbc = input('Select phase-phase distance between B and C in
meters: ');
phase_distca = input('Select phase-phase distance between C and A in
meters: ');

if (num_cond>1)
       bundle_dist = input('Select distance between conductors in bundle
in meters: ');
end

% Now lets go to calculate the series resistance in Ohms/mile

if (conductor==1)
   r=(rth/num_cond);
   GMR=GMRth;
   radio=radioth;
   fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
   disp(r);
elseif (conductor==2)
   r=(rpl/num_cond);
```

```
    GMR=GMRpl;
    radio=radiopl;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
elseif (conductor==3)
    r=(rfi/num_cond);
    GMR=GMRfi;
    radio=radiofi;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
elseif (conductor==4)
    r=(rca/num_cond);
    GMR=GMRca;
    radio=radioca;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
elseif (conductor==5)
    r=(rdr/num_cond);
    GMR=GMRdr;
    radio=radiodr;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
elseif (conductor==6)
    r=(rcar/num_cond);
    GMR=GMRcar;
    radio=radiocar;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
elseif (conductor==7)
    r=(rma/num_cond);
    GMR=GMRma;
    radio=radioma;
     fprintf('\nThe value of the series resistance in Ohms/mile is:\n');
    disp(r);
else
        disp('\nSorry, choose an allow number');

end

% Now lets go to calculate Deq

Deq=(phase_distab*phase_distbc*phase_distca)^(1/3);

% Now lets go to calculate Ds=GMR
%Ds=GMR;

% The formula of the inductante is L=2*10^-7*ln(Deq/Ds)H per meter per
conductor

if (num_cond==1)
    Ds=GMR;
    L=(2*(10^-7)*log(Deq/Ds));
    X=2*pi*60*L*(1609);
    fprintf('The value of the reactance in Ohms/mile per phase is:\n');
    disp(X);
```

```
elseif (num_cond==2)
   Ds=(GMR*bundle_dist)^0.5;
   L=(2*(10^-7)*log(Deq/Ds));
   X=2*pi*60*L*(1609);
   fprintf('The value of the reactance in Ohms/mile per phase is:\n');
   disp(X);
elseif (num_cond==3)
   Ds=(GMR*(bundle_dist^2))^(1/3);
   L=(2*(10^-7)*log(Deq/Ds));
   X=2*pi*60*L*(1609);
   fprintf('The value of the reactance in Ohms/mile per phase is:\n');
   disp(X);
elseif (num_cond==4)
   Ds=1.091*(GMR*(bundle_dist^3))^(1/4);
   L=(2*(10^-7)*log(Deq/Ds));
   X=2*pi*60*L*(1609);
   fprintf('The value of the reactance in Ohms/mile per phase is:\n');
   disp(X);
else
    disp('Sorry, choose an allow number');
end

% The formula of the capacitance is C=(2*pi*e)/(log(Deq/Dsc)) F per meter
per conductor

e=8.85*10^-12;

if (num_cond==1)
   Dsc=radio;
   C=(2*pi*e)/(log(Deq/Dsc));
   Y=2*pi*60*C*(1609)*1i;
   fprintf('The value of the admitttance in S/mile per phase is:\n');
   disp(Y);
elseif (num_cond==2)
   Dsc=(radio*bundle_dist)^0.5;
   C=(2*pi*e)/(log(Deq/Dsc));
   Y=2*pi*60*C*(1609)*1i;
   fprintf('The value of the admitttance in S/mile per phase is:\n');
   disp(Y);
elseif (num_cond==3)
   Dsc=(radio*(bundle_dist^2))^(1/3);
   C=(2*pi*e)/(log(Deq/Dsc));
   Y=2*pi*60*C*(1609)*1i;
   fprintf('The value of the admitttance in S/mile per phase is:\n');
   disp(Y);
elseif (num_cond==4)
   Dsc=1.091*(radio*(bundle_dist^3))^(1/4);
   C=(2*pi*e)/(log(Deq/Dsc));
   Y=2*pi*60*C*(1609)*1i;
   fprintf('The value of the admitttance in S/mile per phase is:\n');
   disp(Y);
else
    disp('Sorry, choose an allow number');

end
```