Microgrid Protection Strategies for the Swedish Power System

Master Thesis

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Lund University, LTH
2023

Thesis for the Degree of Master of Science in Engineering

ISRN: LUTMDN/TMHP-23/5558-SE

ISSN: 0282-1990

Lund 2023

Abstract

In a traditional power system, the electric power is often generated in remote locations and flows in one direction through transmission and distribution networks to the consumers. With the increasing number of renewable-based micro-generation near consumer premises, it is possible to operate the local power system on its own. Such a local power system is called a microgrid, which can be operated either in grid-connected or islanding mode. A microgrid has different protection strategies based on its mode of operation since power can flow in both directions and the fault current level can differ depending on the mode of operation.

If a fault occurs it is necessary to disconnect only the faulty part to maintain system reliability. This thesis mainly focuses on the protection strategies of microgrids for the Swedish power system in the medium voltage distribution system and specifically on the three-phase fault and earth faults protection strategies. For the analysis of both faults, different grid-connected, and islanding operations are simulated using DIgSILENT Power Factory. The simulation shows that using a distance protection strategy for a three-phase fault in the microgrid, the fault can be detected on cable in grid-connected and in islanding operations but it creates blinding of the relay in backup protection when the fault location is near the grid side in grid-connected mode and near the distributed generator side in islanding mode. In Sweden medium voltage distribution system uses peterson coil earthing thus fault current is low during earth fault. Directional earth fault protection with a communication line method is employed for the selective detection of the earth fault of the system. By using this method, the earth fault can be selectively clear during grid connection and islanding operation with low fault resistance value. For high fault resistance values, the fault current is lower than the rating of the current transformer, so it is not possible to detect earth faults.

Acknowledgments

I would like to thank DNV for initiating this thesis project. With this opportunity, I have completed my Master's degree in Sustainable Energy Engineering and was able to investigate such an interesting topic for their account. I am very grateful to my wonderful supervisors, Johan Stelin and Lars Messing at DNV for investing so much time in helping me through this project. It would not have been possible to complete this thesis without your kindness, patience, and expertise. My thesis work would not have been possible without the input of DNV's staff. I would like to thank my supervisor Dr. Olof Samuelsson for constant motivation and valuable comments during my work.

I also wish to thank you, my family, and friends, who help me in my journey toward my master’s thesis.

Lund, 2023

Zalak Shah

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Abbreviations

BESS - Battery Energy System

CT - Current Transformer

CB - Circuit Breaker

DGs - Distributed Generators

EMS - Energy Management System

EMS - Energy Management System

KCL – Kirchoff current law

LES - Local Energy System

MG- Microgrids

OC- Overcurrent relay

P.U. – Per Unit

PCC - Point of Common Coupling

RES - Renewable Energy Sources

Rf – fault resistance

V.T – Voltage Transformer

1. Introduction

1.1 Background

Many nations around the world have agreed through global political agreements to reduce greenhouse gas emissions in the future. In Europe, this is initiated by the European Union. With the ambition to develop the renewable electricity industry, the Swedish government wants to increase renewable electricity production and set a 50 % more efficient energy use target by 2030. It also wants all the electricity generated in Sweden by 2040 to be derived from fossil-free sources or without generating CO_2 emissions. Climate change concerns are driving the shift to renewable energy sources (RES) in power generation [1].

Mostly synchronous generators have been used in centralized power plants for electricity generation, and frequency control systems and fault-clearing systems have been developed. There is increasing use of renewable energy sources, such as solar and wind energy, and power grid infrastructure has moved away from a centralized generation model. Microgrids, where several small generators are connected, may operate within island mode or grid-connected mode through a common coupling point. A small part of the power system can be operated using distributed generation with batteries in island operation. Many advantages and benefits can be derived from microgrids, including possible limitations of grid investment, increased reliability, reduction of interruption of electricity supply, increased resiliency, cost reduction, transmission loss reduction, and reduced CO_2 emissions [2].

When the microgrid is operated in islanding mode it has a different fault current level than in grid connected so the detection of faults and the fault clearing method are different from the conventional power system, where power and fault current flow in one direction.

Almost 70–80% of the faults are single line-to-ground faults, and 2–5% are three-phase short-circuit faults[3].

System earthing has a major impact on designing the protection strategies for the power system. In Sweden, especially in the medium voltage distribution system, earthing is normally done using a petersen coil, so detecting earth fault current will be more challenging compared to the solid earthing system.

1.2 Objective and Task

The main objective of the master thesis is to study protection strategies for microgrids to support grid owners in making informed decisions about the design of protection systems for microgrids. More specially, the work aims at identifying protection strategies that are sufficient to fulfill the requirements for the detection of short circuit fault and earth fault, and disconnection during grid connection and islanding operation, the transition to islanding operation, and the start of islanding operation from a de-energized state.

Master thesis is carried out as follows:

• A literature study on protection strategies in microgrids main focus of the literature survey is protection strategies used in microgrids such as E. ON's Simris and Vattenfall's microgrid on the Arholma Project and other relevant projects.

• Finds different protection strategies for microgrid protection and those strategies should consider fault detection and disconnection during both grid connection and island operation.

• A comparison of various protection strategies for microgrids shall be done which is both including the outcome of the literature survey and other alternative fault detection and clearing methods.

• Both challenges and opportunities shall be highlighted and investigated including other methods that can be used as alternatives to the traditional protective equipment and design.

• An analysis of the case study based on the Simris project for protection strategies for the microgrid will be done, preferably using the simulation tool DIgSILENT Power Factory.

1.3 Report Structure

The first chapter includes the introduction of the project and the main objective of the master thesis, the further flow of the report, and some limitations of the project.

The second chapter includes the importance of the microgrid, and challenges associated with microgrid protection and includes the different microgrid projects mainly focusing on Simris and Arholma projects and other projects but mainly focusing on projects in Europe.

The third chapter includes the basic theory of three-phase fault and the comparison of the different protection methods for the microgrid based on the literature survey.

The fourth chapter includes the basic theory of the earth fault, the Swedish earthing system in the medium voltage distribution system, and a comparison of the different protection methods for the earth fault protection.

The fifth chapter includes the case study model based on the Simris project, different methodology applies for the protection of the three-phase fault and earth fault. Different cases are analyzed for both faults.

The sixth chapter includes the results and discussion of the different cases for the three-phase faults.

The seventh chapter includes the results and discussion of the different cases for the earth faults.

The eighth chapter includes different challenges associated with the applied protection strategies for three-phase and earth fault.

The ninth chapter covers the conclusion of strategies applied during three-phase faults and earth faults and includes future strategies for microgrid protection.

1.4 Limitations of the Project

In the pre-fault situation, the case study model is a balanced three-phase system in terms of voltage and active Power.

Simulation of earth fault in islanding operation without a synchronous generator is not performed in DIgSILENT Power Factory as this causes problems, which seem to be numerical.

2. Microgrid Protection

2.1 Need for Microgrid

The world population will reach around 9.8 billion in 2050, with an increasing population energy demand will also increase. The conventional power plant is interconnected with the bulk transmission and distribution networks which require high investment and construction cost. To meet the necessary demand, researchers came up with the idea of connecting several small generators known as micro sources/ distributed Generators (DG) such as solar power plants, wind power plants, fuel cells, gas turbines, and small hydroelectric power plants, and this gave rise to the development of a new concept known as "Microgrid (MG)". The microgrids are closer to the load center so it has the potential to reduce transmission and distribution costs [4] [5] [6].

According to Cigre WG6.22 definition, “Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded”[7]. Figure 1 shows an example of the microgrid structure.

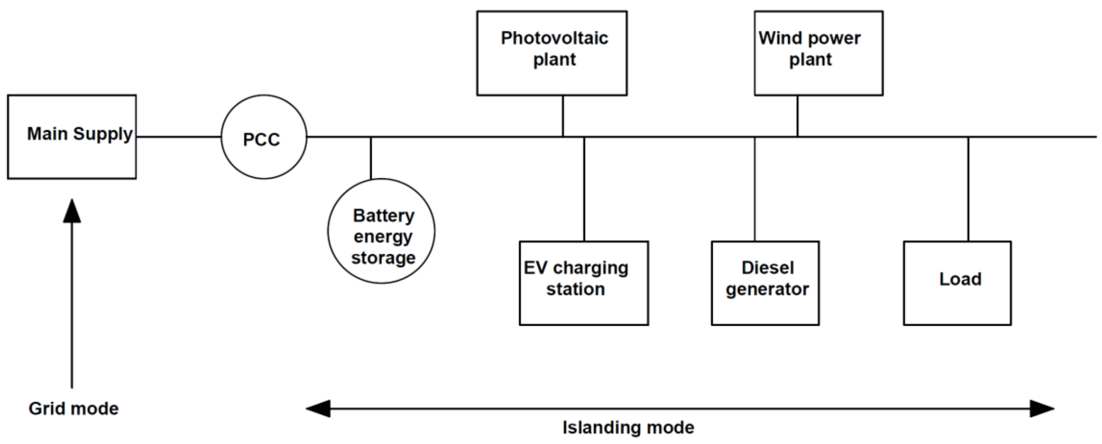


Figure 1 Microgrid Structure

Power grids are mostly reliable, but blackouts can be catastrophic and costly, so utilities and companies are collaborating to build more microgrids (MG). The microgrid can operate in either grid-connected or island-connected mode due to its autonomous management, control, and protection capabilities. It is possible to connect or disconnect a microgrid from the main grid at the point of common coupling (PCC) [8].

In Sweden, there is the possibility to increase renewable energy base generation in the power system, but the transmission and distribution network capacity is needed. For example, moving from fossil fuels to electric vehicles will increase the need for electricity in the future, so researchers are looking for solutions that will overcome those challenges and provide resilient power while helping reduce grid investment [1].

2.2 Protection

Protection is needed for the power system to ensure the safety of persons, for reliable operation, and to reduce the damage to non-faulty parts. The main objective of the microgrid is to provide a reliable power supply to its consumers, and if external faults(outside the microgrid) occur in grid-connected mode, the microgrid should be disconnected from the main grid and operate in island mode [9].

When the fault occurs, the current transformer (CT) measures the fault current and relay gives the tripping signal to the circuit breaker (CB). The CB is used to disconnect the faulty part as quickly as possible. A microgrid can supply reliable power supply, by transferring from grid-connected mode to islanding mode, if there is an external fault that occurs in the grid-connected mode. Any protection system should not operate when there is no fault and must operate under abnormal situations to ensure the system's security and reliability. Selectivity, sensitivity, speed of operation, and reliability are necessary for the reliable operation of the system [8] [10] [11].

2.2.1 Sensitivity

When referring to the minimum operating level of relays, such as the current, voltage, power, or a complete protection scheme, the term sensitivity is used as an expression describing the minimum operating level. It is also possible to define sensitivity as the speed at which a protective relay or response to an abnormal condition reacts in the least possible time so as not to cause damage to equipment or disrupt stability [12].

2.2.2 Selectivity

Circuit breakers should only trip when they are required to isolate the fault in the protection. The property of selective tripping is also called discrimination and is achieved by time grading and unit protection. Time grading is that in which protection systems in the selective area have operating times that are intentionally different. Unit protection is that it responds to fault conditions within a clearly defined zone. Restricted earth fault and differential protection are examples of this unit protection[12].

2.2.3 Reliability

Dependability and security are major factors in the reliability of protection. Dependability means the circuit breaker should trip when there is a fault in the power system and security means protection against unexpected tripping, it should not trip when there is no fault. Dependability is the correct operation after faults in a system while security means the relay will not operate incorrectly and together these two terms define reliability [13] [14].

2.3 Protection Challenges

Conventional short-circuit protection for radial medium voltage grids are designed for high fault current levels in one direction, but if microgrids operate in grid-connected mode or island mode, they have different fault current levels. In the near future, most distributed generators (DG) units will be based on converter interfacing, which limits the fault current. Fault currents are mainly determined by the nature of distributed generation, its type, penetration, location, and the mode in which the microgrid operates, such as grid-connected mode or islanding mode [2] [15]. As a number of DG are connected in the MG several challenges such as bidirectional power flow, short circuit current limitation due to the type of DG (inverter or synchronous generator), blinding operation (section 2.3.2) and false tripping (section 2.3.3) need to be considered [2] [15]. This affects the sensitivity and selectivity of the relay. Figure 2 shows challenges associated with the protection of the microgrid.

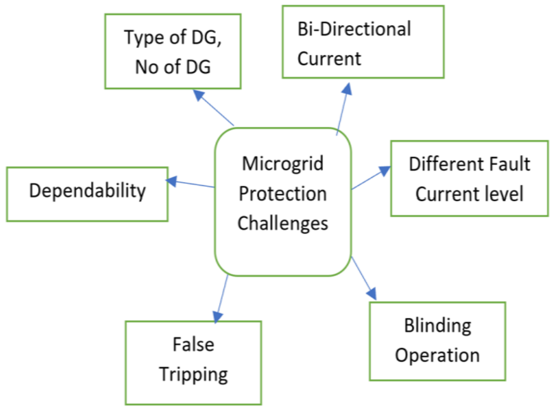


Figure 2 Microgrid Challenges

2.3.1 Bi-direction and Different fault current Levels

In a conventional distribution grid, power flows are unidirectional from the substation to the loads but if distributed generator (DG) is connected to the distribution system, power flows can be bidirectional.

In MG there is a change in fault level current due to the grid-connected mode and the islanding mode. Further, DGs are connected to the grid via inverters and the power electronics used in inverter base DG has a maximum fault current that is two times its rated current, while synchronous generator based DG has a fault current of 6 to 7 times its rated current. Thus, the fault current level is primarily decided by the type of DG interfacing with the grid [15].

2.3.2 Blinding Operation

Over-current base protection, the relay setting is to be less than the fault current and greater than the maximum load current. As shown in figure 3, at fault location F, DG and grid both supply fault current so overall the fault current level is increased but due to the short circuit impedance, the fault current measured by relay 1 is decreased and it creates blinding operation. If protection is done by inverse-time relay then it will cause delayed operation of the protection due to the low current measurement. If DG is not connected to the system, then over current relay 1 will measure the fault current according to their setting and will trip, but if the DG is connected to the system, then short circuit impedance will change and measured fault current by relay 1 will decrease and it will cause blinding operation [9]. Blinding operation is also depending on the location of the fault and the size of DG is connected to the system.

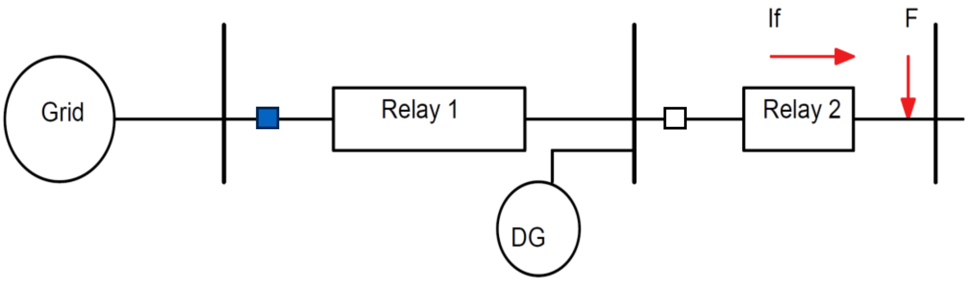


Figure 3 Blinding of Relay [9]

2.3.3 False tripping

As shown in Figure 4, two feeders are fed from the same substation and DG is connected with one of the feeder ends. If the fault occurs in the system as shown in figure 4, then DG and grid will supply fault current. If the direction of fault current supply by DG is not recognized by relay 2 and the relay setting is such that the relay will operate even if there is no fault in the DG feeder, the relay will cause unnecessary tripping of the DG. Thus, it will create false tripping in the network. When the DG unit is not connected to the power system then, the fault current will flow in the direction to the load, and it will not cause any problems but when a large capacity of DG is connected, and the fault location is near the substation then false tripping is happened. Power systems will be significantly unreliable if false tripping occurs in the microgrid [2] [4] [16].

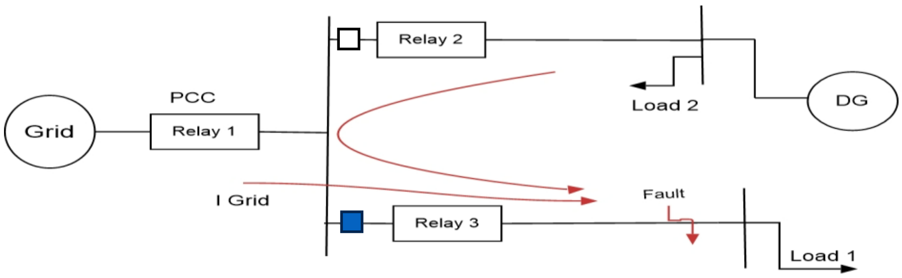


Figure 4 False Tripping [16]

2.4 Micro Grid Projects in North Europe and Other Country

2.4.1 Simris project, Sweden

With the increasing integration of renewable energy sources (RES), E. ON has decided to develop a technical pilot trial in 2015 in the small village of Simris in the south of Sweden. This microgrid's primary source of energy is a wind turbine, and ground-mounted solar PV which is supported by a battery storage system (BESS), and a diesel generator. If microgrid RES are not sufficient to deliver power in islanded mode, then a diesel generator is employed. The test site has approximately 11 km of low voltage cables connecting the consumers and 5 km of 10 kV cables feeding seven secondary substations. Out of seven, five substations will supply all (150) customers. Total load is 800 kW. When the system is operating as an island, the system is entirely supported by its PV plant, wind turbine, and BESS that are connected to the grid through power electronics, and a diesel generator is also connected in islanding operation when demand is higher than the generation to extend the islanding operation [17]. Figure 5 shows the schematic diagram of the simris project.

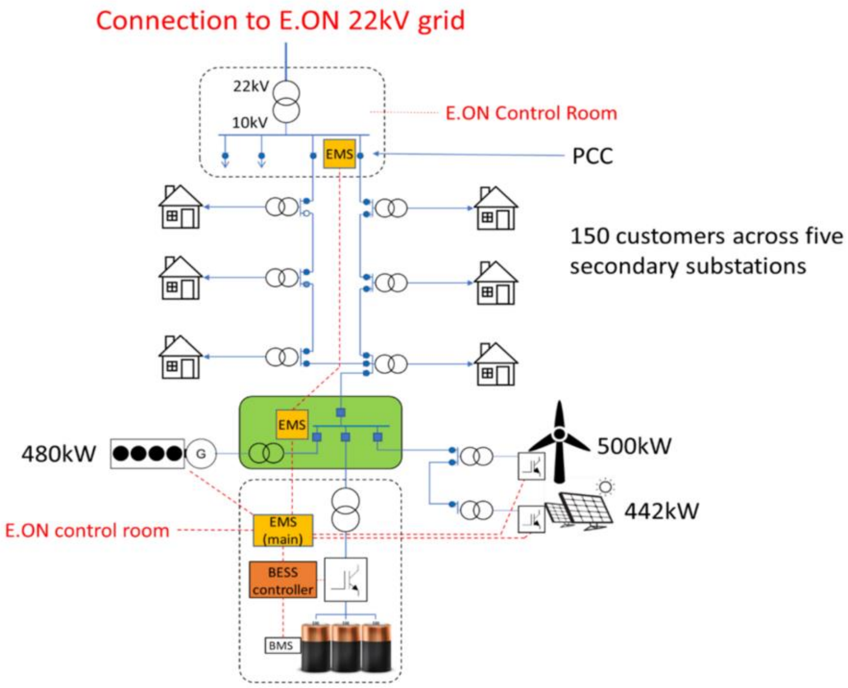


Figure 5 Simris Project*[18]*

Distributed Energy System (DER) substations in Simris are fully equipped with all communications, protective relays, and control system devices necessary for islanding operation. In all power production unit locations, the energy management system (EMS) has access to relevant information, such as measurements from current and voltage transformers, and indications of status from circuit breakers and disconnectors. The EMS can command island mode by opening the circuit breaker at the Point of Common Coupling (PCC).

When the MG is switched between grid and islanding mode, the battery energy storage system (BESS) controls reactive power as a function of voltage and active power as a function of frequency. BESS helps in a smooth transition between grid-connected and islanding mode. A circuit breaker at PCC is activated by the EMS when the system is ready for islanding. In islanding operation, the battery energy system (BESS) controls power electronics generation and maintains voltage, frequency, and total harmonics distortion (THD) within the required limit. In the project, for safe and reliable grid-connected and islanding mode operation, relay protective systems with two different settings, one for grid connected mode and one for islanding mode were recommended [17] [19].

2.4.2 Arholma project, Sweden

Vattenfall's Arholma microgrid project is comprised of two battery storage devices of 160 kVA and 330 kWh respectively and one solar cell production unit. The project began in the spring of 2017 and is expected to be completed by 2023. Figure 6 shows the Arholma project site diagram.

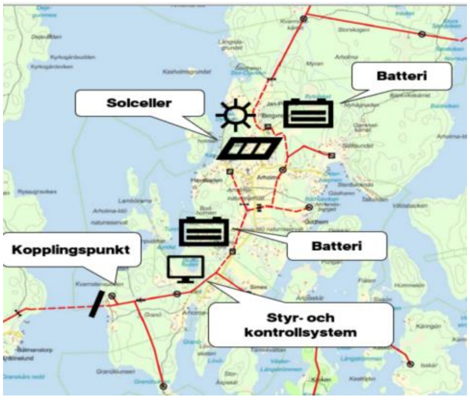


Figure 6 Arholma Project*[20]*

If the main grid fails, the arholma electric grid can be operated in islanding mode and become self-sufficient in electricity for a few hours with the help of two battery energy storage systems and a solar panel. During peak hours, islands can be operated for 1 hour if batteries are fully charged and it is possible to disconnect power from the main grid without reducing electricity supply [21].

According to a research project carried out about the arholma project, DG will support grid capacity shortages, increase the reliability of supply, reduce grid losses and reduce environmental impacts [22].

2.4.3 Hailuoto island project, Finland

In the Baltic Sea, Hailuoto is the largest island in Finland and the Northern Gulf of Bothnia, with over 1000 residents and 600 holiday homes. In Islanding operation, a 20 kV overhead distribution feeder can be supported by one 0.5 MW wind turbine and one 1.5 MW diesel generator. The maximum load of island is 1883 kW and 587 kVAr. The diagram of Hailuoto island is shown in figure 7.

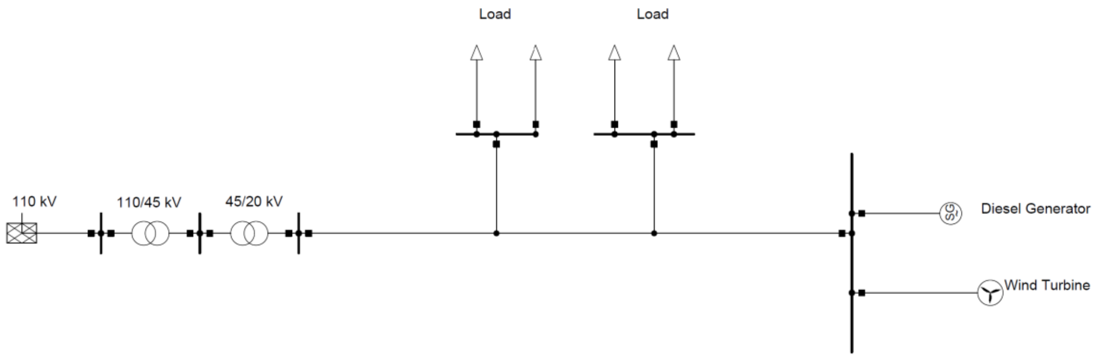


Figure 7 Hailuoto Island

Adaptive protection is used in the Microgrid operation. For protection, microprocessor-based digital protective relays or IEDs (intelligent electronic devices) are used which can store and use several setting groups. A centralized controller installed at the substation with IEC 61850 and IEC 60870–5-104 based communications is used for data integration from the medium voltage feeder and distributed energy source IEDs.

For this pilot project, the synchronous generator is always connected during islanding operation, and for three-phase short circuit protection, directional over current protection with the communication link between different IED devices is used.

For the earth fault, the time setting of residual voltage protection is different for the grid-connected mode and islanding mode, and by using proper communication links between different IEDs devices then both directional over-current and residual voltage can operate faster without losing sensitivity. Communication links can be achieved by using high-speed GOOSE interlocking signals between the different IEDs.

It is possible to develop an advanced adaptive protection system that enhances the coordination of the protective devices in microgrids by combining the IEC 61850 utility automation protocols with the server technology running at the substation central controller. This is a practical example of Microgrid operation [23].

2.4.4 Aalborg project, Denmark

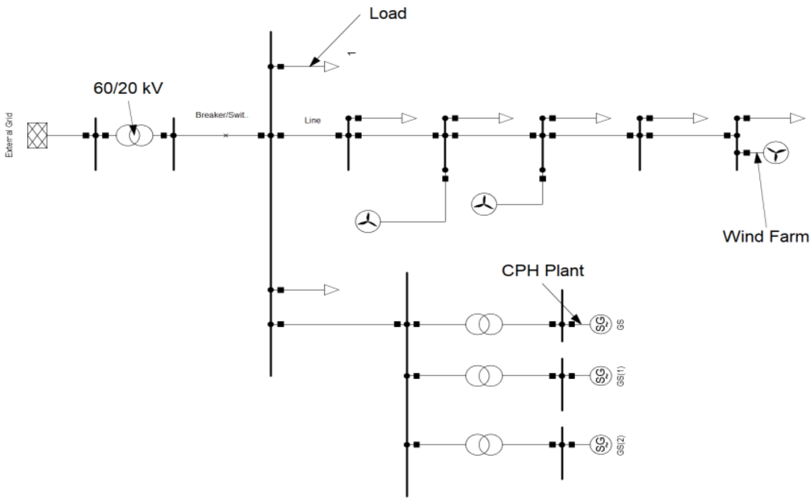


Figure 8 Diagram of the Aalborg project

The Microgrid network is part of Himmerlands Elforsyning (HEF) in Aalborg, Denmark. This project contains a combined heat and power (CHP) plant with three 3.3MW gas turbine generators and three 630 kW Wind Turbine Generators as shown in figure 8.

For three-phase faults, the tripping time of the distance protection relay has good selectivity because it measures impedance instead of fault current. According to the result, the microgrid network works well in grid-connected and islanding mode with all the wind farms operating at rated capacity and 20% of its rated capacity [24].

2.4.5 Biomass Microgrid, Malaysia

Figure 9 shows a biomass microgrid in Malaysia. For the protection of the network against faults at various locations directional overcurrent relays are used. The relays have an inverse definite time characteristic, and their phase overcurrent is set at 30% above the maximum load current. For earth fault protection at various locations, directional earth fault relays with definite time characteristics are used, and relay settings are 30% to 40% of the full load current for earth faults [25].

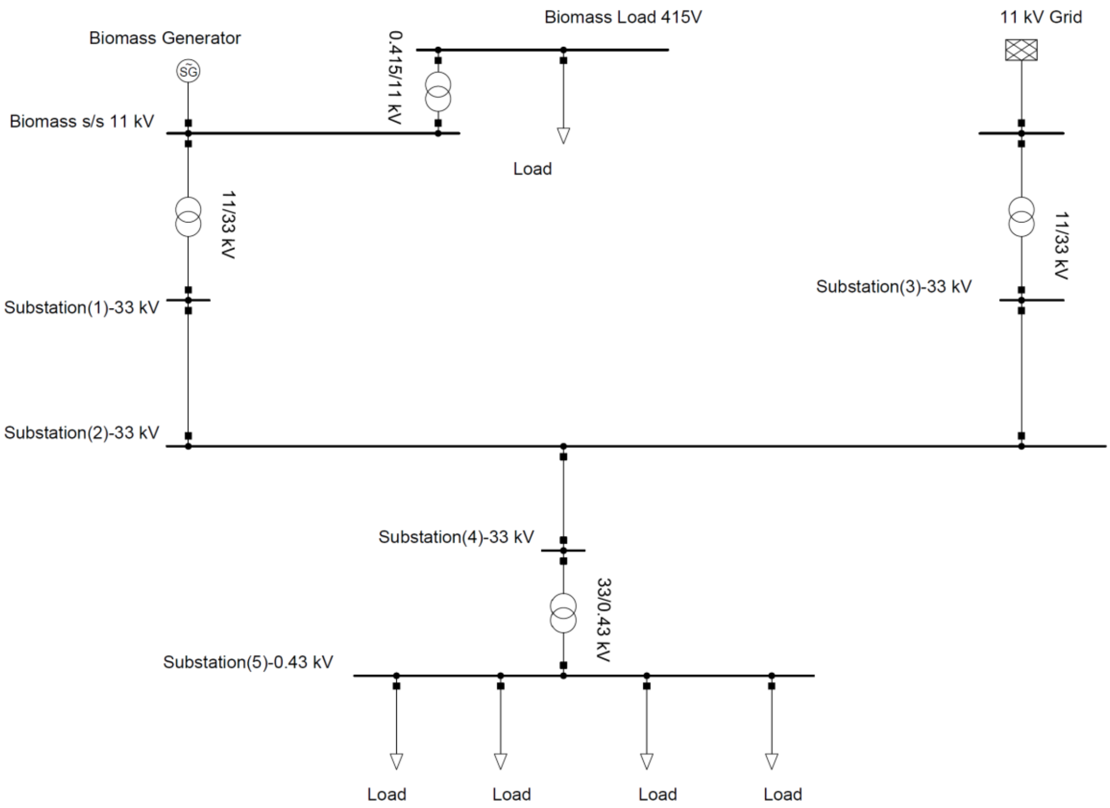


Figure 9 Biomass Microgrid, Malaysia

2.4.6 Summary of protection solutions in microgrid projects

Table 1 Protection methods for different projects

Project	Three - phase fault protection	Earth fault Protection
Simris Project, Sweden	Overcurrent protection*	Residual voltage protection*
Arholma Project, Sweden	Overcurrent protection*	Residual voltage protection*
Hailuoto island project, Finland	Directional Overcurrent with the Communication line	Residual voltage protection
Aalborg project, Denmark	Distance Protection	No Information
Biomass project, Malaysia	Directional Overcurrent	Directional Earth fault protection

* According to Simris and Arholma's project literature, there is no information regarding protection, but my supervisor has provided me with some information on this subject.

3.Three-phase Fault and Protection Methods

3.1 Fault in the Power system

Faults occur in power systems due to insulation failure, flashover, physical damage, and many more. An electric power system can have two types of faults: shunt faults and series faults. However, shunt faults are the most common type of fault. It occurs when conductors short-circuit one another or when conductors short-circuit to the ground. A shunt fault may be symmetrical or asymmetrical. Three-phase faults may be symmetrical whereas line-to-ground fault (earth fault), line-to-ground fault, line-to-line fault, and double line-to-ground are always asymmetrical faults [28].

3.2 Three-Phase Fault (Bolted Fault)

In a bolted (0 Ohm) three-phase faults, the fault currents are symmetrical and displaced by 120 degrees, and are associated with high fault currents in each phase. A balanced three-phase fault can be analyzed using an equivalent single-phase circuit [29].

When a three-phase fault occurs, the short circuit current rises to thousands of amps during the short circuit, which is higher than the normal current. Due to the higher current, thermal damage to the equipment, buses, and windings can occur so short circuit needs to be addressed as soon as possible. Approximately 5% of the total faults in the power system are caused by this type of fault and it is not affected by system earthing. It may take 5 to 20 cycles for protective equipment to operate at medium voltage [30].

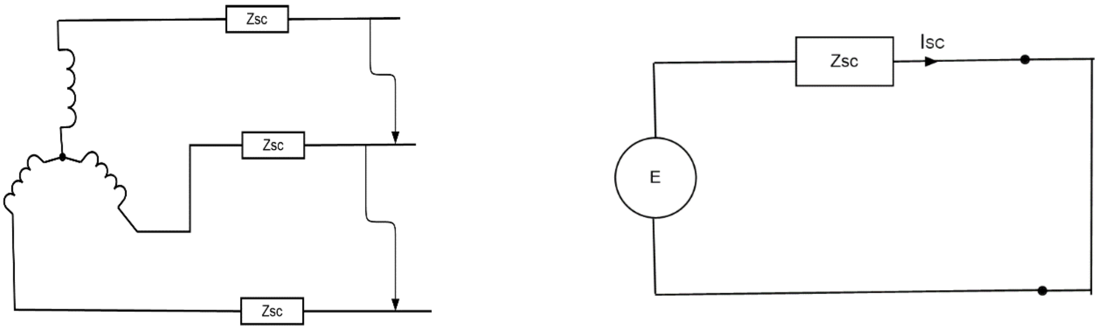


Figure 10 Bolted three-phase fault short circuit

As shown in Figure 10, during the three-phase fault, short circuit current (Isc) flow in the system is calculated by equation 2.1.

$$Isc = \frac{E}{\sqrt{3} \times Zsc} \qquad 2.4$$

Where E is the phase-to-phase voltage before the fault occurs and Z_{sc} is the short circuit impedance.

Normally overcurrent, distance, and differential protection are used in power system protection against faults, which is explained in sections 3.3, 3.4, and 3.5 respectively.

3.3 Overcurrent Protection

An overcurrent relay operates when the load current exceeds a preset value. Overcurrent protection uses different time current characteristics, i.e. definite time overcurrent relays, and inverse time overcurrent relays. Definite-time overcurrent relay operates after a fixed time when the current exceeds its pick-up value and an inverse-time overcurrent operating time decreases with increased current. The distribution network is radial, and it uses overcurrent protection when using solid grounding or resistance grounding because it is cheap. The fault current in the DG is low so protection based on overcurrent is difficult when the microgrid is operated in island mode. Overcurrent protection with directional sensitivity has some advantages, however, coordination remains a problem when several DGs are connected. Overcurrent relays with communication lines can be used to resolve some problems of increasing the number of DG, however, the problem remains due to the cost of the relay and other related issues [5] [6]. According to [7] overcurrent relay has low reliability and sensitivity when it is used for MG protection.

Fault Clearing Time

At the occurrence of a short circuit in the three phases, the fault must be clear as early as possible to maintain power system stability. Total fault clearing time includes relay operating time and CB interruption time as shown in figure 11. Relay operating time in distance protection is typically 20 milliseconds (ms) and CB interruption time is 60 ms which includes a CB operating time of 45 ms and arcing time of 15 ms in the medium distribution network. The total fault-clearing time is 80 ms [8] [30].

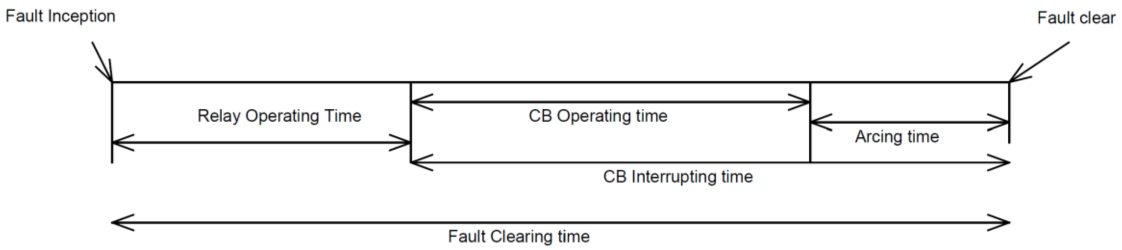


Figure 11 Fault Clearing Time [30]

3.4 Distance Protection

The power system is divided into different zones for protection. Each zone is protected by a suitable protective method. Whenever there is a fault in a zone, the primary relays of that zone are responsible for isolating the faulty element. The first line of protection is the primary relay. If the primary relay fails to operate for any reason, there is a backup protective scheme in place to clear the fault as a second line of protection [6].

Distance protection uses voltage and current to calculate the impedance to the fault point and determine whether a fault falls within the protection zone. Distance relay settings are done by voltage to current ratio so it is more sensitive than only the current base setting thus, even if the fault current levels of the island-operated network are reduced, distance protection can remain reliable. Distance protection follow with zone-wise protection where zone 1 set with calculated impedance is 80% of series impedance of the line, with instantaneous tripping, whereas zone 2 set with calculated impedance is 80% to 120% of series impedance of the line with a time delay of 400 millisecond, so discrimination is achieved with zone 1. In zone 3, set with calculated impedance is 240% of series impedance of the line with time delay of 600 millisecond thus distance protection use as backup protection which can be considered as an additional advantage, as per paper [7] there are several advantages of distance relays, including good sensitivity, selectivity, and reliability in microgrid. Furthermore, distance relays are much cheaper than differential protection because they will not depend on the communication line [9][10].

3.5 Differential Protection

Differential protection works on the principle of Kirchoff's current law (KCL), comparing the current flowing in and out of the protected object. Differential protection is unit protection so it cannot provide backup protection for adjacent zones. The differential relay is capable of detecting faults in their protected zone in a short period irrespective of the type, location, and size of DGs. It is designed to protect both grid-connected and islanding operations. This protection is not affected by a weak infeed where it can detect internal faults even without having any DGs connected. However, differential protection might be expensive since protective devices must be placed on every line segment of the network and use communication lines between the beginning and end of the protected line segment, it usually has absolute selectivity and sensitivities, but it is expensive [10] [11]. If a relay is set too sensitive, the small differential current flowing through the relay may cause it to operate under no-fault conditions because of the impedance of the cable.When a large capacitive current flows through the cable during an earth fault, the differential relay protection will trip incorrectly [12].

3.6 Comparison of Protection Methods

In the power system protection sensitivity, selectivity and reliability is the key factor and protection should be such that it is economic. Table 2 shows a relative comparison of overcurrent, distance, and differential protection in the microgrid.

Table 2 Comparison of overcurrent, distance, and differential relay

Protection	Selectivity	Sensitivity	Reliability	Cost
Overcurrent	Low	Low	Low	Low
Distance	Good	Good	Good	Low
Differential	High	High	Moderate	High

4. Earth Fault Protection

In power system networks, earth faults are where at least one phase is connected to the ground. An earth fault can not be analyzed using the single-phase equivalent because it is an unsymmetrical fault that can be analyzed by sequence components. Sequence component analysis can be done by positive, negative, and zero sequence components to easily analyze faulted or unbalanced conditions. Figure 12 shows three-phase quantities for each zero, positive, and negative sequence diagram, respectively.

The first step in analyzing an unsymmetrical system is transforming each sequence network into a two-terminal network. In such a network, all three-phases generated in zero, positive or negative sequence diagram show only the equivalent impedance of the network. For earth fault representation positive, negative, and zero sequence two-terminal networks are connected in series with each other and with the fault resistance (times 3), so during the earth fault, the total fault current I_f is three times the zero sequence current [35]. Figure 13 is a network representation during the earth fault.

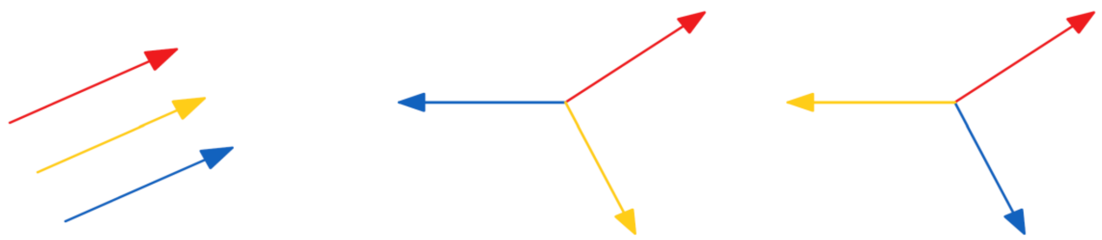


Figure 12 Zero, Positive and Negative Sequence Diagram

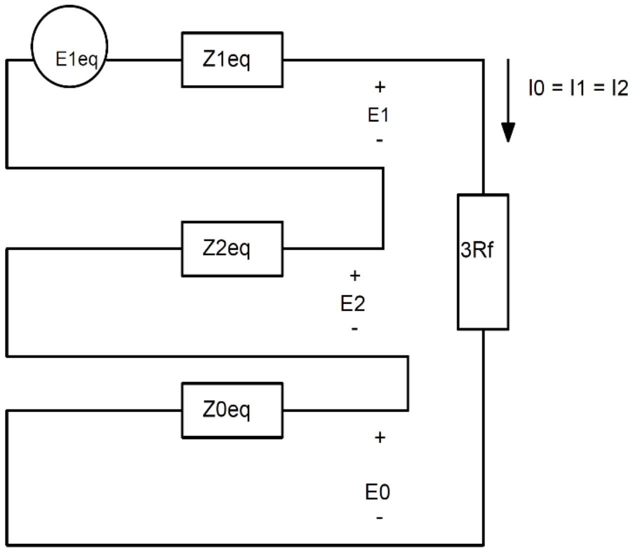


Figure 13 Network representation during earth fault

So, the value of the earth fault current (I_f) is.

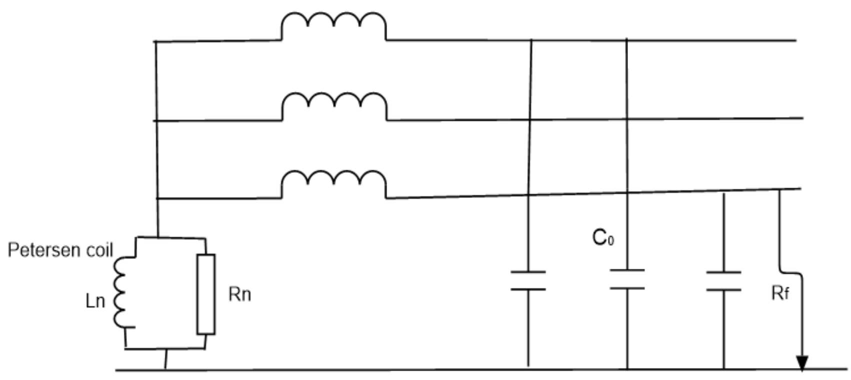
$$I_f = \frac{\sqrt{3} \times E}{(Z1 + Z2 + Z0 + 3R_f)} \qquad 4.1$$

Where Z1, Z2 and Z0 are the positive, negative, and zero sequence impedance and E1, E2, and E0 are the positive, negative, and zero sequence voltage respectively and R_f is the fault resistance.

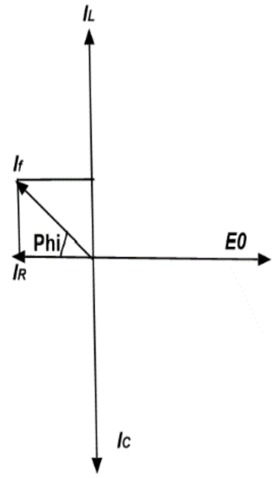
4.1 Swedish Earthing System and Earth fault current

In power system, there are four types of earthing solidly earthed, resistance earthed, isolated/unearthed and compensated/resonant-earthed systems. In Sweden, especially in the 10 - 20 kV lines petersen coil (reactance) earthing is used. Earth fault protection in medium voltage lines must detect and disconnect the earth fault with sensitivity within a limited time. Earth fault protection should be selective so that only the faulty part of the system is disconnected [36].

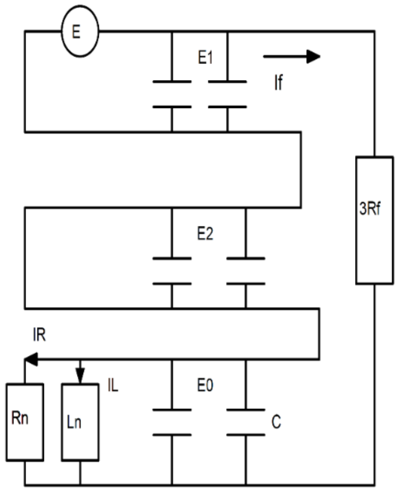
In large overhead and cable line systems, there is a strong capacitive connection between phases and ground, so in the instance of a fault, a large capacitive current will flow and that should be minimized for safety regulation. When an earth fault occurs, a fault loop is formed not only by the capacitive impedance to the earth but by the reactance at zero point as well. In petersen coil earthing as shown in figure 14, large capacitive earth fault current is reduced by connecting a reactor (Ln) (neutral point reactor) to the neutral point of the transformer to compensate for the capacitive current of the cable (Ic). For selective detection during the faults, zero-point resistance (Rn) is connected in parallel with the zero-point reactor (Ln), so the faulted current component flows in resistance (Rn),this resistive component of the fault current will only flow in the faulted feeder if there are many feeders and thus permits selective detection of the faulted line [35].



a. Earth fault in the network



b. Vector diagram



c. Network representation during fault

Figure 14 Earth fault in power system [37]

So, earth fault current is defined as

$$I_f = I_R + j\, I_c - j\ I_L \qquad 4.2$$

Further, earth fault current will decrease when increasing the fault resistance with equation 4.3.

$$I_f = \frac{E_1}{Z_0 + 3R_f} \qquad 4.3$$

4.1.1 Earth fault disconnection requirements

Earth fault must be disconnected according to the requirements set out in the "Electrical Safety Authority's regulations". According to this the maximum disconnection time depends on the size of the earth fault current, see Table 3 and the earth fault detection should be highly sensitive, see Table 4 [38].

Table 3 Earth fault disconnection time

Earth fault current	Time for disconnection
Earth fault current higher than 500 A	Within 0.5 second
Earth fault current below than 500 A	Within 5 second

Table 4 Resistance value according to standard

High voltage installation	Resistance value
Overhead line with covered conductor	5000 Ohms
Overhead line with cable	
Overhead line in reinforced design	
Overhead line without above case	3000 Ohms

4.2 Earth fault current protection

Non-directional earth fault relays operate with total residual current (3I0) which is fed from the protected line and can be measured from the current transformer. In this protection, setting is done with current parameters and time delay and this protection is suitable for detecting and providing rapid disconnection of double simultaneous earth faults [36].

4.3 Directional Earth fault Current Protection

Directional earth fault protection measures I_R in figure 14, which is the active component of the current to the protection (in phase with the zero-sequence voltage) this gives high sensitivity. In directional earth fault protection, the sum of residual current(3I0) can be measured by the current transformer with an iron core enclosing all three phases, or from phase current transformers parallel connected additionally, the phase angle of the current is compared with a reference voltage's phase angle. This reference voltage is normally constituted by zero-sequence voltage ($3V_0$) fed from an open-delta voltage transformer group [36].

4.4 Residual voltage protection

For medium voltage networks especially 10-20 kV distribution lines, zero sequence voltage protection is an effective and simple earth fault protection method. Zero-sequence voltage can then be obtained from three-phase voltage transformers with open delta secondary windings. Due to the neutral point voltage being relatively constant throughout the network regardless of fault location, this type of protection does not enable selective disconnection of earth faults. The voltage-based method is therefore used as backup protection with a relatively long-time delay. An earth fault cannot be selectively cleared using voltage-based methods. While it detects the earth fault, it cannot determine which element is faulty [36].

4.5 Earth fault protection with the communication line

Each end of the protected line\cable is protected by the two-directional earth fault protection as shown in figure 15. Earth fault relay 1 is set towards the protected line and provide a tripping signal after the set time and the second earth fault relay 2 is directed from the protected line the in reverse direction and provides momentary blocking signal and sends relay 1.

If an internal fault occurs, relay 1 will start and it will send a trip signal to the circuit breaker to relay 2. If the earth fault occurs beyond the protected line then the backward stage relay 2 will start and after a short delay sends a blocking signal to relay 1 so nonselective tripping does not happen [36].

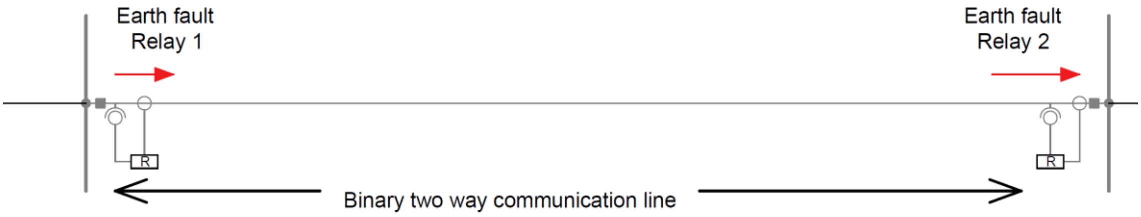


Figure 15 Directional earth fault relay with communication line

4.6 Comparison of different methods

In Sweden, petersen coil earthing is used in medium voltage distribution network, so fault current could be as low as 10 - 15 A during the earth fault, though it will further decrease with the increasing fault resistance value, so overcurrent, distance base protection is not used for the earth fault detection. Table 5 shows a comparison of different methods used for earth fault protection.

Table 5 Comparison of different methods used for earth fault protection

Protection	Selectivity	Sensitivity	Reliability	Cost
Residual over current	Low	Low	Low	Low
Residual voltage	None	High	High	Low
Directional earth fault	High	High	Good	Low
Two directional earth fault relays with communication line	High	High	Good	High

5. Case study

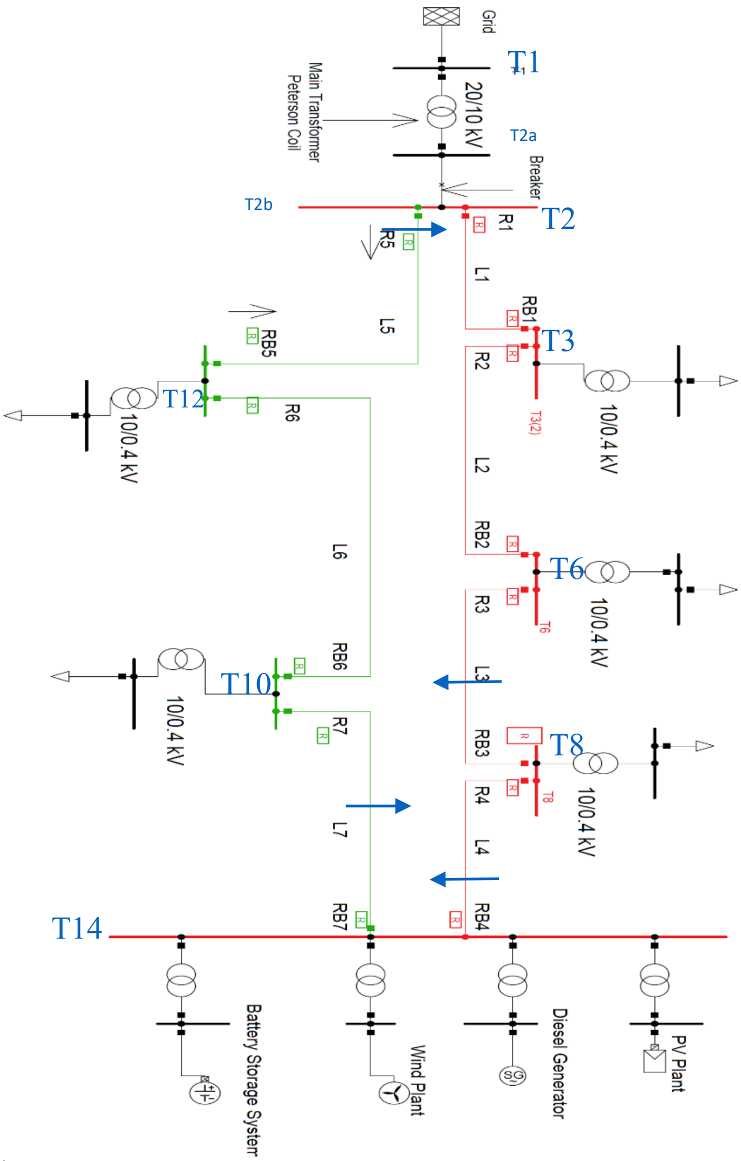
In recent years, the Swedish distribution network has undergone extensive cabling in rural areas. This chapter include the case study assumption which is based on the Simris project and protection methods are applied for the three-phase faults and earth faults for different fault locations in grid connected and islanding mode.

5.1 Simris Model Assumption

In Simris village, a medium voltage distribution grid of a10 kV is used, in which grid side main transformer of 20/10 kV is connected to five 10/0.4 kV substations with the point of common coupling (PCC) which is indicated by breaker switch between buses T2a and T2b in figure 16, The five substations are connected to each other by 50 mm^2, 1 km long underground cable. The substations supply 150 E.ON customers. The distributed energy generation (DGs) consists of one solar PV plant of 440 kWp, one wind plant of 500 kW, and one battery storage system (BESS) of 800 kW. For backup generation- a diesel generator of 500 kW is also connected to the system. In grid-connected mode main breaker is closed and supplies the current from the main grid, and in islanding mode main breaker is open so it disconnects from the main grid, thus the system is supplied with only DGs [18] [39].

Each end of the cable will be protected by a relay. At the occurrence of a fault, the protective relay will sense a fault and give a signal to the circuit breaker (CB) and clear the fault. The case study model is based on the Simris project as shown in figure 16, and the location of the relays is shown in Table 6.

5.2 System Model



Peterson coil Rn = *577* Ω, *Ln* = *18* Ω

Figure 16 Simris case model

Table 6 Relay location in the case model

Cable	Relay Location			
	Beginning of the cable	Colour**	The Far end of the cable	Colour**
L1	R1	Light Blue	RB1	Black
L2	R2	Orange	RB2	Dark Green
L3	R3	Pink	RB3	Turquoise
L4	R4	Light purple	RB4	Light Pink
L5	R5	Blue	RB5	Gray
L6	R6	Green	RB6	Yellow
L7	R7	Red	RB7	Purple

The case model is a simple mesh network with two parallel 10 kV distribution feeders operated as a loop. In the first distribution feeder, cable lines are represented by L1, L2, L3, and L4, and in the second distribution feeder, cable lines are represented by L5, L6, and L7. Because of the mesh network if a fault is on a one of the distribution feeder near the grid/DG side (cable L1, L5 or L4, L7) then power can be transmitted with a second distribution feeder. Fault analysis is done on the different cables with different fault location which is shown in the table 7 and 8 respectively.

5.3 Different Study Cases

The following cases are considered for three-phase faults and earth faults at different locations as shown in table 7 and 8.

5.3.1 Three-phase fault

Case 1- Grid-connected mode with all the DGs

Case 2 - Islanding mode with diesel generator

Case 3 - Islanding mode without diesel generator

5.3.2 Earth fault

Case 1- Grid-connected mode with all the DGs

Case 2 - Islanding mode with diesel generator

The simulation of earth faults in islanding operations without synchronous generators is not performed in the DIgSILENT Power Factory due to numerical problems.

5.4 Three-phase fault

During the fault on the cable, relays connected at both ends of the cable will be operating in the first zone and the relays, which are in the adjacent cable line will be used as backup protection. Fault locations are chosen such as faults in the middle of the cable lines (50% from the grid-side end towards DG-side end), near the grid side (5% from the grid-side end towards DG-side end), and near the DGs side (70% from grid side end towards DG-side end) for the grid-connected mode and islanding mode analysis. For the three-phase fault, the value of fault resistance is taken as 0 Ω. Table 7 shows relays operation in Zone 1, Zone 2, and Zone 3 respectively, and different fault locations on the cables. The same fault location is used for analysis of different cases.

Table 7 Relay and fault location in three-phase fault

Cable	Fault location grid-side end towards DG-side	Zone 1 with Primary protection	Zone 2/3 with Backup protection
3	50%	R_3, RB_3	R_2, RB_4
4	70%	R_4, RB_4	R_7, R_3
5	5%	R_5	RB_5, RB_1, RB_6
7	50%	R_7, RB_7	R_4, R_6

5.5 Earth fault

For earth fault protection, relay and fault location are shown in Table 8. The fault location is in the middle of the cable line, near the grid side and the DGs side (like for the three-phase fault) for the analysis. The value of fault resistance is 200 Ω and 3000 Ω to see the difference in how the relay operates at low and high fault resistance values.

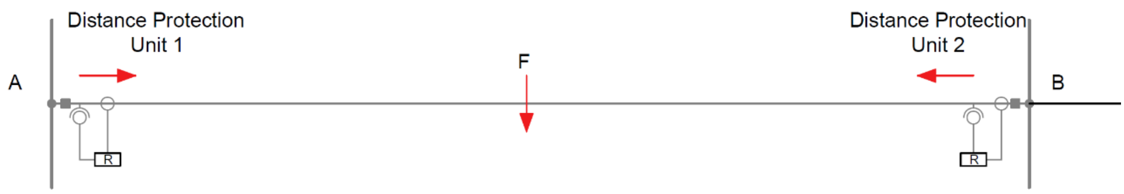
Table 8 Relay and fault location in earth fault

Cable	Fault location grid-side end towards DG-side	Primary Protection
3	50%	R_3, RB_3
4	70%	R_4, RB_4
5	5%	R_5, RB_5
7	50%	R_7, RB_7

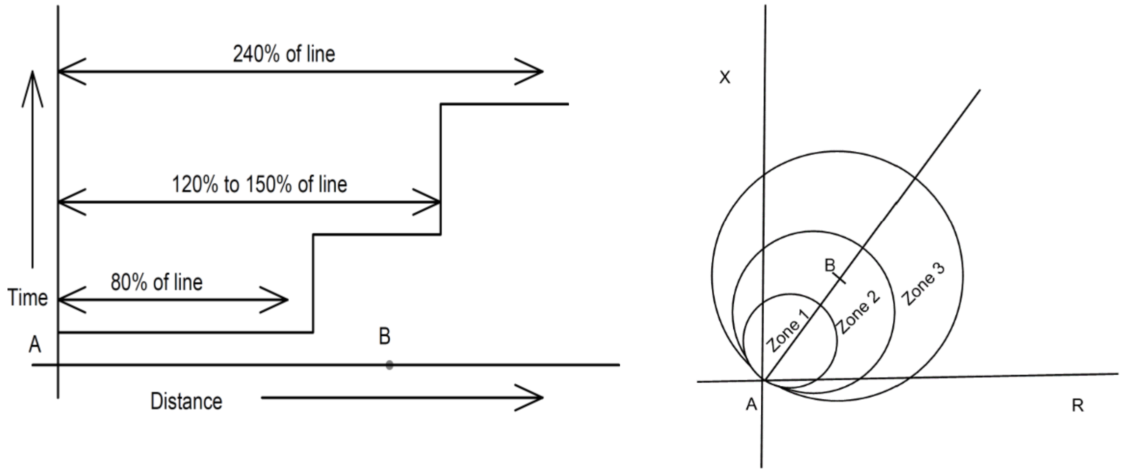
5.6 Methodology

5.6.1 Distance protection at both end of the cable

For three-phase fault protection distance protection is used, see 2.4. It calculates impedance with voltage and current measured at the line end and translates this to the location of a zero-ohm fault by comparing the impedance value to the series impedance of the line. Protection Unit 1 protects the cable from the upstream in the forward direction whereas protection unit 2, protects the cable from the downstream in the forward direction as shown in figure 17. Distance protection follows with zone-wise protection where zone 1 protects 80% of the length of the cable (calculated impedance is 80% of the series impedance of the line), with instantaneous tripping, whereas zone 2 protects 120% to 150% of the length of the cable with a time delay of 400 milliseconds, so discrimination is achieved with zone 1. In zone 3, protect 240% of the length of the cable to be protected and provide backup protection of the cable with a time delay of 600 millisecond [40]. Current transformer 100/1 A and voltage transformer 10000/110 V are used for the measurement of current and voltage during the fault. Time-distance diagram of distance relays as shown in figure 17. b and figure 17. c shows R-X diagrams of distance relays.



a. Distance relay at both ends of line AB.



b. Time-distance diagram c. R-X diagram

Figure 17 Distance relay use inline/Cable

5.6.2 Two-directional earth fault protection with the communication line

For earth fault protection, two-directional earth fault relays are connected on each end of the cable, if a fault occurs in the cable as shown in figure 18, unit 1 will send a blocking signal to unit 3. A blocking signal is required for selective protection. If the operating relay fails to send a blocking signal, then there is no selectivity is achieved. Unit 1 will send a momentary blocking signal to all relays that are in the same direction as the operating relay. The current transformer of 100/1 A and voltage transformer 10000/110 V is used for the measurement of the current and voltage during the fault.

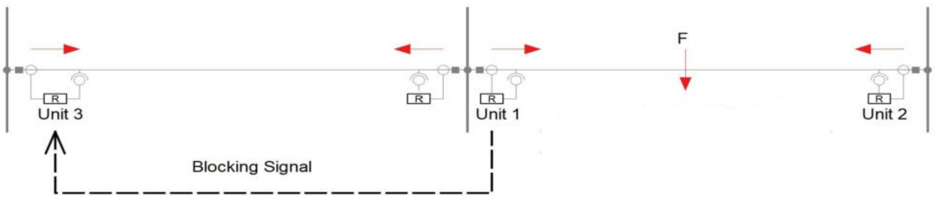


Figure 18 Directional earth fault relay

5.7 Modelling of different cases

5.7.1 Case 1- Grid-connected mode with all the DGs

Figure 16 shows the Simris project model with all the distributed generation (DGs) connected to the system, for three-phase fault, distance protection is applied as discussed in section 5.6.1. According to the simulation model, if the fault occurs in the middle of the line, then the fault current for a three-phase fault will be approximately 3500 A, and for an earth fault it will be approximately 10 A because of the petersen coil earthing.

Petersen coil is connected to the transformer connected to the terminal T1, shown in figure 16 and the value of coil resistance is 577 Ω, and coil reactance value is 18 Ω.

Further, the earth fault current is dependent on the system zero sequence impedance and the fault resistance (R_f), see equation 4.3. As the fault resistance is increase earth fault current decreases. According to Swedish earth fault protection requirements, earth faults should be selective in overhead lines up to fault resistance 3000 Ω and should be clear with low fault resistance values also. Therefore, fault resistance R_f=200 Ω, 3000 Ω is used for case 1 and case 2.

5.7.2 Case 2- Islanding mode with diesel generator and all DGs

This system should operate in islanding mode, with a PV plant of 20% generating capacity, a wind turbine of 40% generating capacity, a battery storage system, and a diesel generator of full capacity. If the three-phase fault occurs in the middle of the cable lines (same as case 1), then the fault current is approximately 318 A which is much lower than the grid-connected mode when the system is islanded. For the earth fault, the fault current is approximately 9 A. The fault resistance (Rf) value is the same as explained in case 1.

5.7.3 Case 3- Islanding mode without diesel generator

In this case, only the PV plant, wind, and battery storage system are connected to the system model with generating capacity same as case 2. For this case, if a fault occurs in the middle of the lines (same as cases 1 and 2), then the three-phase fault current is approximately 105 A. The fault current is lower than case 2 because of diesel generator is not connected to the system. In the earth fault case, simulation fails and no results can be given.

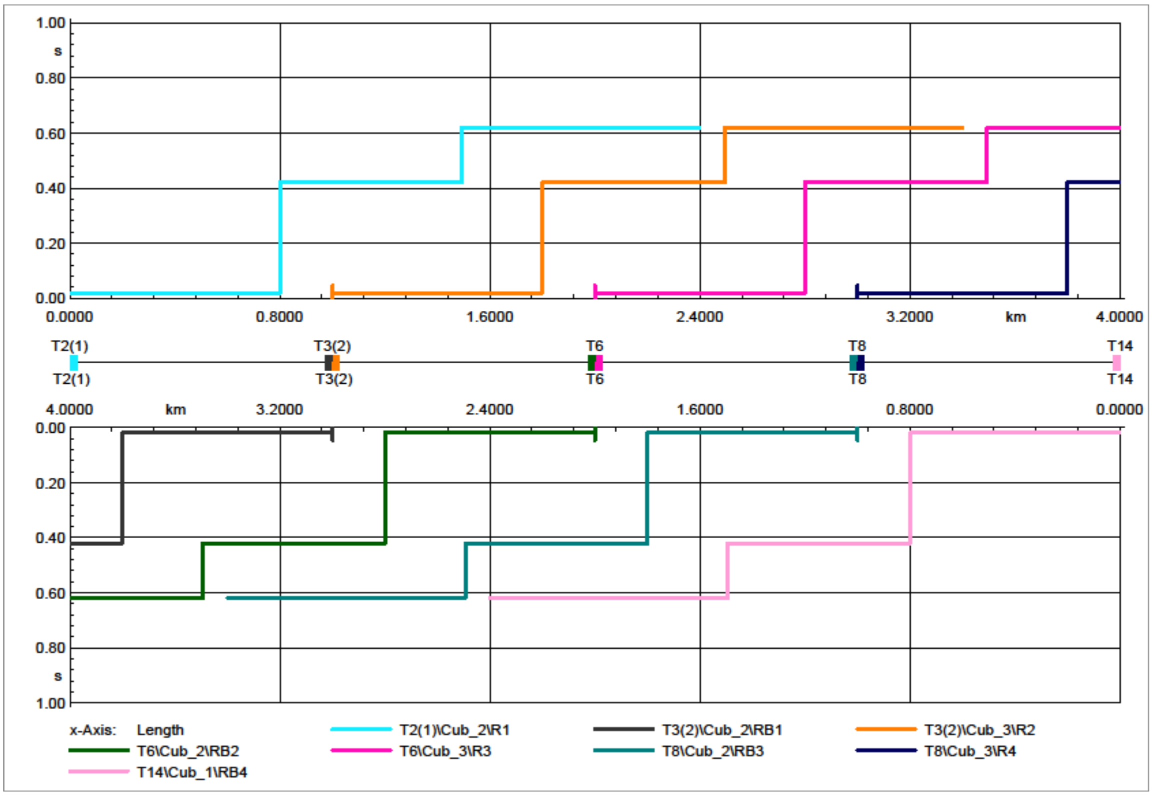
6. Result-Three-Phase Fault Protection

This chapter include results of three-phase fault analysis on different fault location on grid-connected mode and islanding mode.

6.1 Distance relays location and setting

Relay R1 will be set in the forward direction (from terminal T2 to T3) in zone 1, 80% protected cable line with 0.02 sec tripping time, in zone 2, 150% protected cable line with 0.42 sec tripping time, and in zone 3, 240% protected cable with 0.62 sec tripping time. In a similar manner, relays R2, R3, R4, R5, R6 and R7 are set according to relay R1 from terminals T3 to T6, T6 to T8, T8 to T14, T2 to T12, T12 to T10, and T10 to T14.

Relay RB1 will be set as a relay R1 from terminal T3 in the forward direction (from T3 to T2) in zones 1, 2, and 3. Similarly, relays RB2, RB3, RB4, RB5, RB6, and RB7 are set according to relay RB1 from terminal T3 to T2, T6 to T3, T8 to T6, T14 to T8, T12 to T2, T10 to T12, and T14 to T10 respectively, as shown in figure 19.



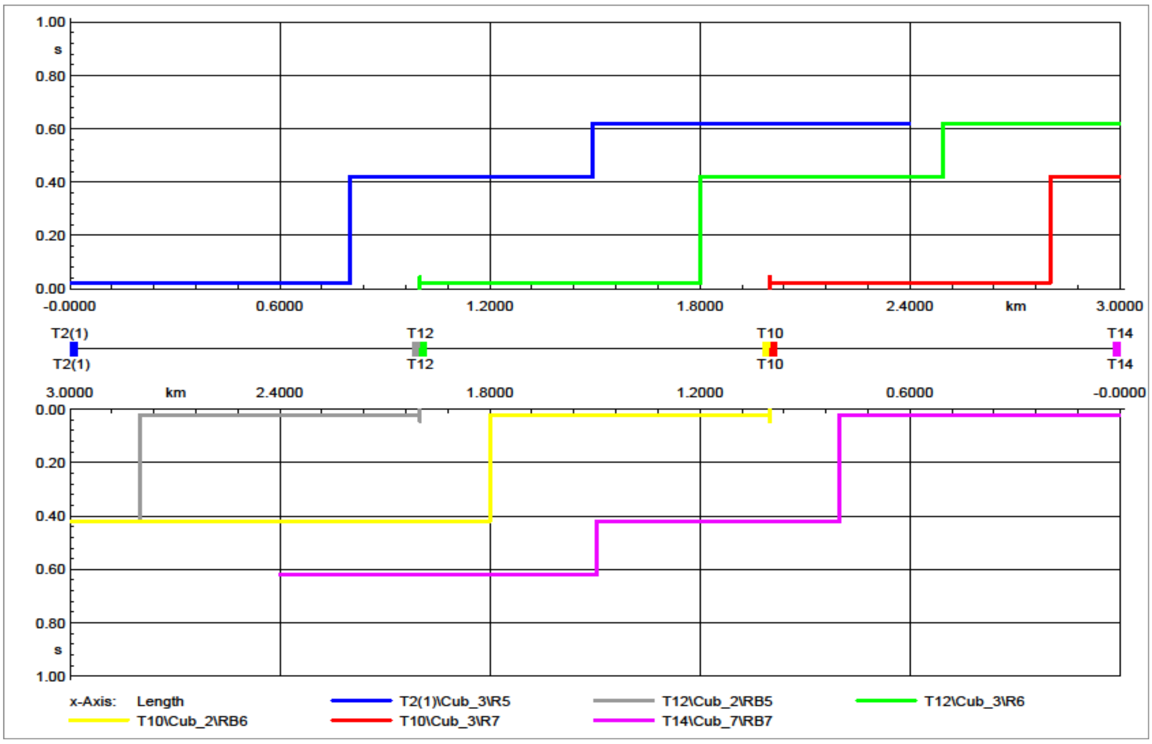


Figure 19 Time distance diagram of distance relays

** Colour in table 6 is use for different relay characteristics in the figure 19 onwards

6.2 Case 1- Grid Connected Mode with All DGs

The case study model is connected with the grid and DGs. R-X diagrams illustrate the characteristics of distance relays, which are based on relations between voltage, current, and phase angle between them. Figures 20, 21, 22, and 23 show the R-X diagram of the cable lines 3, 4, 5, and 7 respectively. Three-phase fault locations and relay locations are considered as explained in Table 9.

Table 9 Relays location and fault location

Cable	Fault location	Zone 1 / Primary protection	Zone 2/3 Back up protection
3	50%	R3, RB3	R2, RB4
4	70%	R4, RB4	R7, R3
5	5%	R5	RB5, RB6, RB1
7	50%	R7, RB7	R4, R6

6.2.1 Three-phase fault location on cable 3

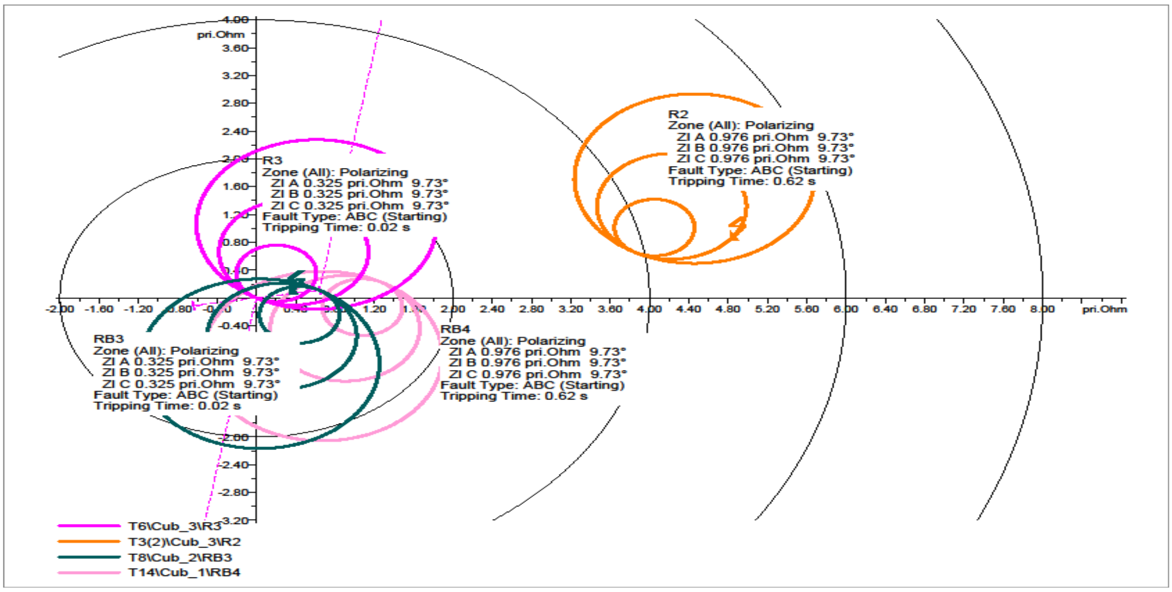


Figure 20 Three-phase fault – Grid operation, cable 3

The three-phase fault occurs in the middle of cable line 3 (50% from the grid-side end towards the DG-side end), and both grid and inverter-base DGs will supply fault current; therefore, the fault current will be bi-directional, and fault current value is high (3500 A). Fault location on cable 3, halfway between terminal T6 and T8 in Figure 16. The impedance measured by the relay is indicated by a flash and the relays will trip if the flash is inside its circle. The relays R3 and RB3 will measure impedance in zone 1 with a tripping time of 0.02 seconds. The relays R2 and RB4 provide backup protection since they detect faults in zone 3 due to their zone-wise setting and operate within 600 milliseconds. As shown in Figure 20, all relays will operate within their respective zones. The fault is situated in the middle of the cable line, and the cable location is far from the grid side and the DG side. During the fault the grid will provide maximum fault current compared to inverter-base DGs thus, the infeed current of DGs will not affect this location; therefore, microgrid challenges such as relay blinding and false tripping will not occur.

6.2.2 Three-phase fault location on cable 4

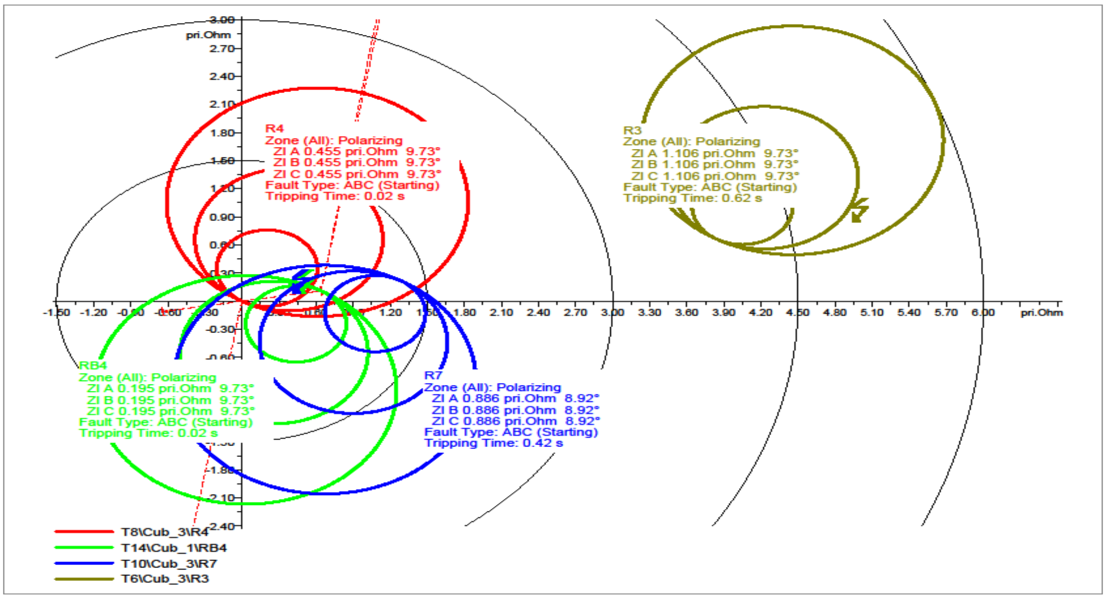


Figure 21 Three-phase fault – Grid operation, Cable 4

The three-phase fault occurs near the DGs side on cable line 4, 70% from terminal T8 to terminal T14 in Figure 16, and relays R4 and RB4 protected cable line 4. The impedance measured by the relay is indicated by a flash and the relays will trip if the flash is inside its circle. The fault is located near relay RB4, so its measured impedance is less than the measured impedance of relay R4, but both relays will see the fault in zone 1 with a tripping time of 0.02 seconds. Backup protection relays R7 and R3 detect faults in zones 2 and 3 and operate in 400 and 600 milliseconds, respectively, as shown in Figure 21. The fault is located near the DG side, but the grid is connected; it will supply the maximum fault current during the fault compared to the inverter-based DGs, and all relays will measure impedance within their respective zones. As a result, microgrid challenges such as relay blinding and false tripping cannot occur.

6.2.3 Three-phase fault location on cable 5

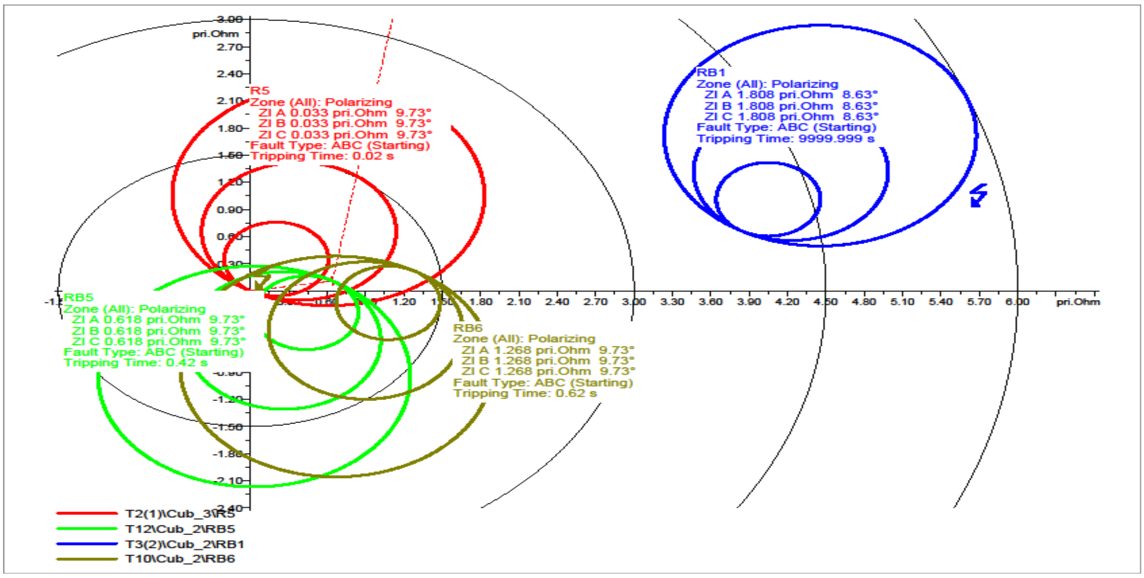


Figure 22 Three-phase fault- Grid operation, Cable 5

The three-phase fault occurs near the grid side on cable 5, 5% from terminal T2 to terminal T12 in Figure 17. The impedance measured by the relay is indicated by a flash and the relays will trip if the flash is inside its circle. Relays R5 and RB5 protect cable line 5. Since the fault is very near the relay R5, it will trip in zone 1 with a tripping time of 0.02 seconds, and relay RB5 will see the fault in zone 2 since the fault occurs in 95% of the protected lines from the relay location RB5. Relays RB5, RB6, RB1 will operate as backup protection. Relay RB6 will see the fault in zone 3 as it will protect 240% of the line and both the relay RB5 and RB6 will operate in zone 2 and zone 3 with a time delay of 400 and 600 milliseconds respectively. The fault location is very close to the grid side and the grid will provide maximum fault current at the fault location. As a result, the fault current measured by relay location RB1 is less than its calculated value, so its impedance measured by relay location RB1 is high, thus the relay will not operate. Relays R5, RB5, and RB6 will operate in their respective zones, but relay RB1 will not operate as shown in figure 22. Therefore, microgrid challenge blinding of the relay will occur at relay location RB1, and false tripping will not happen.

6.2.4 Three-phase fault location on cable 7

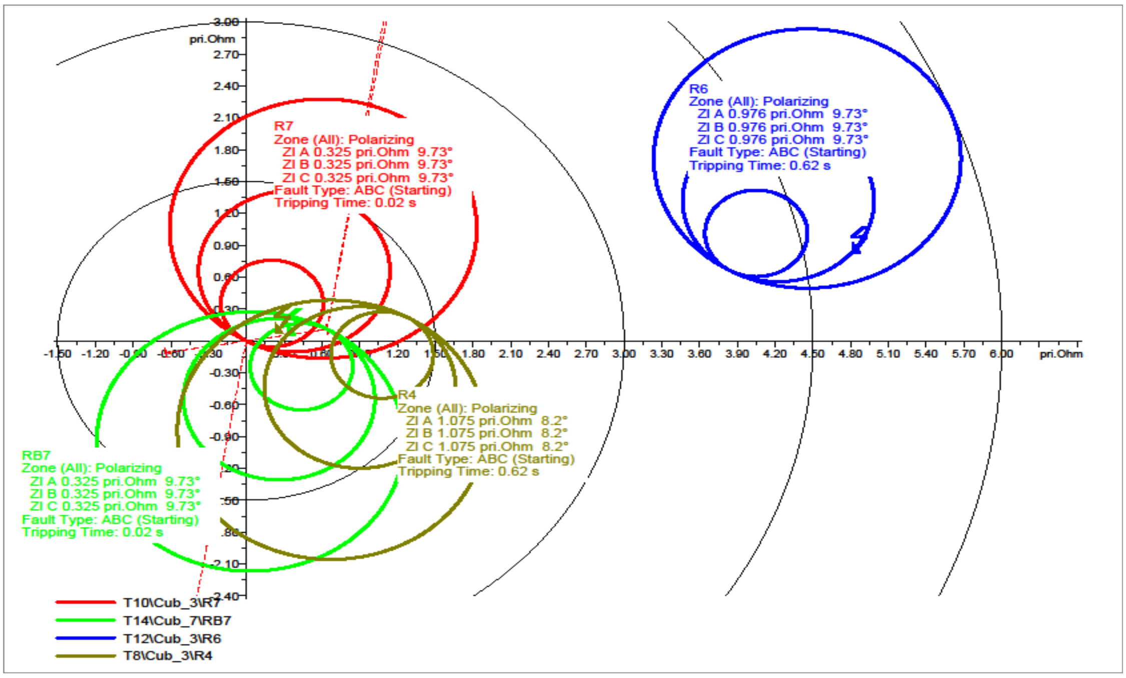


Figure 23 Three-phase fault-grid operation, Cable 7

The three-phase fault occurs on cable 7, halfway between terminal T10 and T14 in Figure 16, one end of cable 7 is connected to the DGs terminal T14. During the fault, grid and inverter-based DGs will supply a fault current. Relays R7 and RB7 protect cable 7 and the impedance measured by the relay is indicated by a flash and the relays will trip if the flash is inside its circle. Relays R7 and RB7 will measure impedance in zone 1 with a tripping time of 0.02 seconds. Relays R6 and R4 operate as backup protection as they detect faults in zone 3 and operate in 600 milliseconds as shown in Figure 23. As the fault is situated halfway of the cable line, far from the grid side but near the DG side, and since the grid will provide maximum fault current compared to inverter-based DGs, therefore infeed current of DGs will not effect relay R4 operation. Thus, microgrid challenges such as relay blinding and false tripping will not occur.

Total fault clearing time includes relay operating time and CB interruption time. Relay operating time is 20 milliseconds (ms) in zone 1 and the CB interruption time is 60 ms which includes a CB operating time of 45 ms and arcing time of 15 ms in the medium distribution network thus, the total fault clearing time is 80 ms in zone 1.

Table 10 shows the relay operating zone with tripping time and microgrid challenges at fault locations during grid-connected mode.

Table 10 Relays operation on grid-connected mode

Cable	Fault location	Zone 1 / Primary protection	Operating Time Zone 1 (ms)	Zone 2/3 Back up protectio n	Operating Time Zone 2/3 (ms)	Blinding of Relays	False Tripping
3	50%	R3, RB3	20	R2, RB4	600,600	No	No
4	70%	R4, RB4	20	R7, R3	400,600	No	No
5	5%	R5	20	RB5, RB6, RB1	400, 600, not operate	Yes	No
7	50%	R7, RB7	20	R4, R6	400,600	No	No

6.3 Case 2 – Islanding mode with a diesel generator and all DGs

The case study model is connected with the PV plant, wind plant, BESS, and synchronous generator. Fault location and relay setting are considered the same as case 1. The R-X diagram of cable lines 3, 4, 5, and 7 is shown in Figures 24, 25,26, and 27 respectively.

6.3.1 Three-phase fault location on cable 3

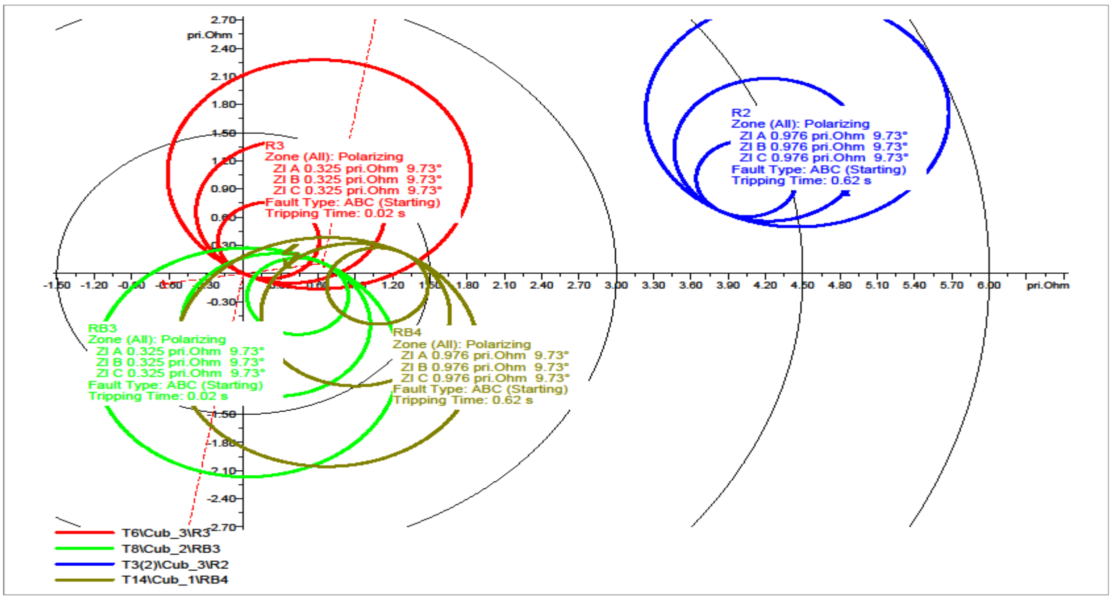


Figure 24 Three-phase fault-Islanding operation, Cable 3

The three-phase fault occurs in cable line 3 same as case 1. In this case grid is not connected so the inverter-based DGs and diesel generator will supply a fault current thus fault current (316 A) will be much less as compared to the grid-connected mode. Relay R3 and RB3 will measure impedance in zone 1 with a tripping time of 0.02 seconds. Relays R2 and R4 operate as backup protection as they detect faults in zone 3 and operate in 600 milliseconds as shown in Figure 24. A fault location is in the middle of the cable line but far from the DGs side, thus, at this point microgrid challenges such as relay blinding and false tripping will not occur.

6.3.2 Three-phase fault location on cable 4

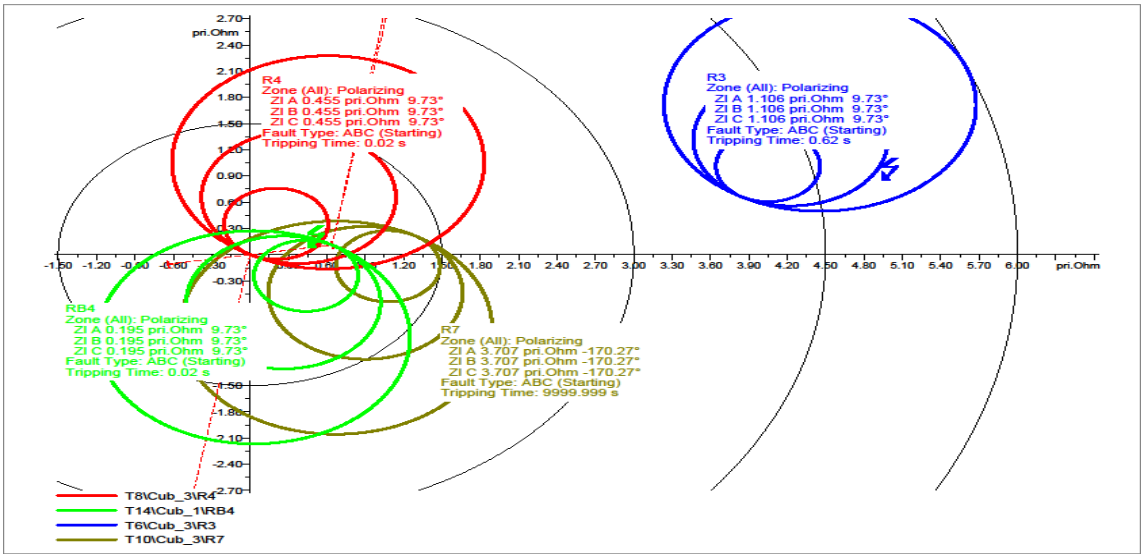


Figure 25 Three-phase fault-Islanding operation, Cable 4

The three-phase fault occurs near the DGs side of cable line 4, 70% from terminal T8 to terminal T14 same as case 1. The fault location is near the DGs side and fault current is delivered by inverter-based DGs (PV plant, wind Turbine, and BESS) and diesel generator. The fault location is near relay RB4 so the measured impedance is less than the measured impedance of relay R4 but both relays will detect the fault in zone 1 with a tripping time of 0.02sec, and Relays R7 and R3 will operate as backup protection. One end of cable 4 is connected with the DGs terminal, thus the infeed current of DGs will affect the relay R7 operation, which is located on the second parallel feeder line. Relay R7 measures improper fault current, and its impedance seen relay R7 is higher, and it will not operate as shoen in figure 25. Relay R3 location is far from the DGs terminal thus, the infeed current of DGs is not affected and it will operate in zone 3. Here microgrid protection challenge relay blinding will occur at relay location R7, but false tripping will not occur.

6.3.3 Three-phase fault location on cable 5

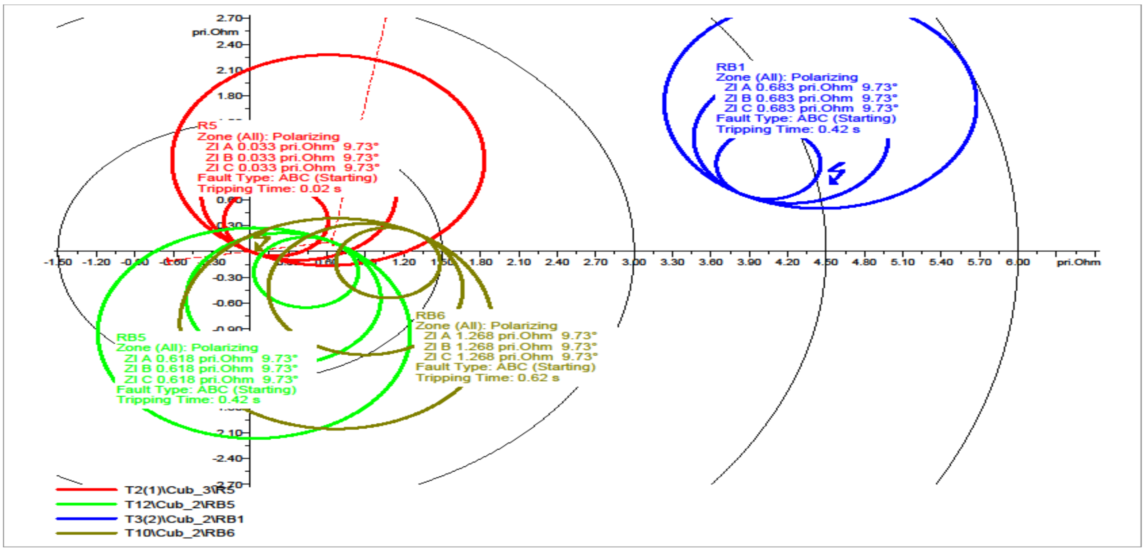


Figure 26 Three-phase fault-Islanding operation, Cable 5

The three-phase fault occurs on 5% of cable line 5 same as case 1. Relay R5 and RB5 are set with 80% of the protected line in zone 1 and relay R5 will detect the fault in zone 1. As the fault is very near to relay R5, it will operate in the first zone with a tripping time of 0.02 sec as shown in figure 26. Relay RB5 and RB1 will see the fault in zone 2 as the fault location is approximately 95% and 105% from their respective relay location. Relay RB6 will see the fault in zone 3. Grid is not connected to the system and fault current is supplied by only DGs and diesel generator. The fault location is far from the DGs side, so the infeed current of DGs will not affect relays operation and all the relays R5, RB5, RB1, and RB6 will operate in their respective zone with tripping times of 20, 400, and 600 milliseconds respectively.

6.3.4 Three-phase fault location on cable 7

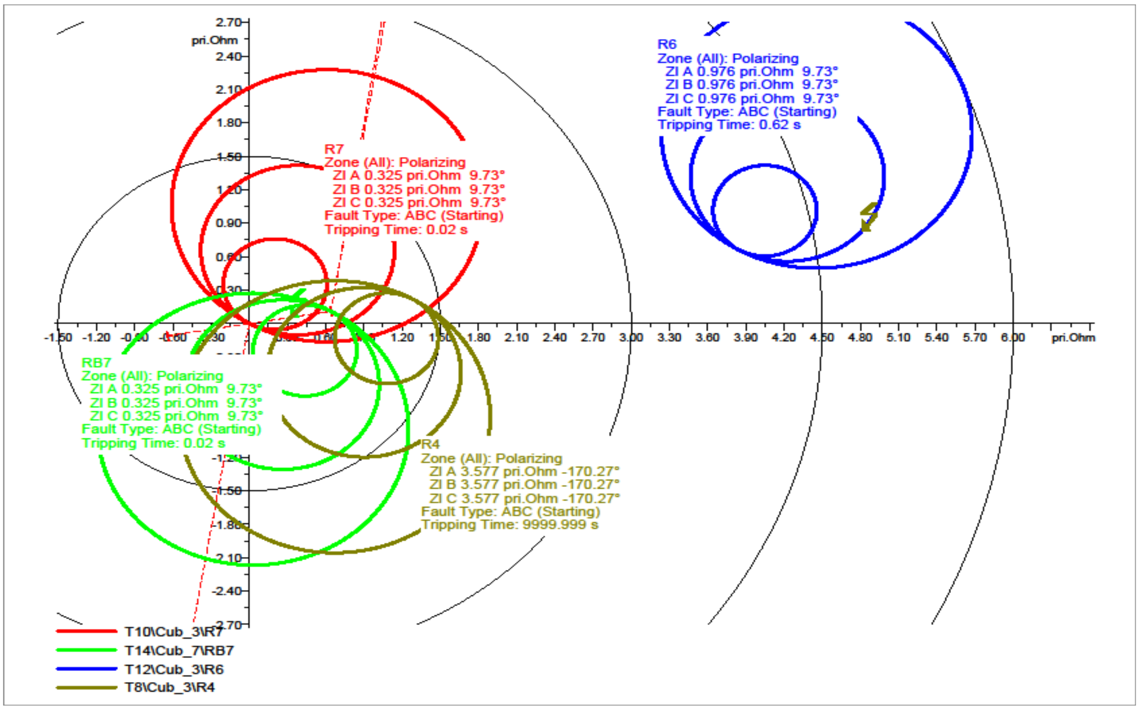


Figure 27 Three-phase fault-Islanding operation, Cable 7

The three-phase fault occurs halfway of the cable line 7 same as in case 1. One end of the cable is connected to the DGs terminal and fault current is delivered by inverter-based DGs (PV plant, wind Turbine, and BESS) and diesel generator. At this fault location relays RB7 and R7 operate in zone 1 with a tripping time is 0.02 sec and relays R4 and R6 will operate as backup protection. At the fault location infeed current of DGs will affect the relay R4 operation, which is located on the second parallel feeder line. Relay R4 measures improper fault current, and the impedance seen by relay R4 is higher than its setting and it will not operate as shown in figure 27. Relay R6 location is far from the DGs terminal thus infeed current of DGs is not affected and it will operate in zone 3, thus microgrid protection challenge relay blinding will occur at relay location R4, but false tripping will not occur.

Table 11 shows the relay operating zone with tripping time and microgrid challenges at fault locations during islanding mode.

Table 11 Relays operation on islanding mode with a diesel generator

Cable	Fault location	Zone 1 / Primary protection	Operating Time Zone 1 (ms)	Zone 2/3 Back up protection	Operating Time Zone 2/3 (ms)	Blinding of Relays	False Tripping
3	50%	R3, RB3	20	R2, RB4	600, 600	No	No
4	70%	R4, RB4	20	R7, R3	Not operate, 600	Yes	No
5	5%	R5	20	RB5, RB6, RB1	400, 600, 400	No	No
7	50%	R7, RB7	20	R4, R6	Not operate, 600	Yes	No

6.4 Case 3- Islanding mode without a diesel generator

The case study model is connected with a PV plant, wind turbine, and BESS. The diesel generator is not connected to the system. On the occurrence of three- three-phase fault at any location fault current (approximately 100 A) is lower than case 1 and case 2 due to the inverter-based DGs which limits the fault current. Because of low fault current no relays will be able to operate as shown in Table 12.

Table 12 Relay operation on islanding mode without a diesel generator

Cable	Fault location	Zone 1 / Primary protection	Zone 2/3 Back up protection	Tripping
3	50%	R3, RB3	R2, RB4	The relay will not operate.
4	70%	R4, RB4	R7, R3	
5	5%	R5	RB5, RB6, RB1	
7	50%	R7, RB7	R4, R6	

6.4.1 Three-phase fault location on cable 7

A fault occurs in the middle of the cable 7. Fault current is supplied by inverter-based DGs (PV plant, Wind turbine, and BESS) which limits fault current. Due to the low fault current protective relay will not operate. Thus, relays R7, R6, and R4 are not able to clear the fault. Figure 28 shows a fault at cable line 7.

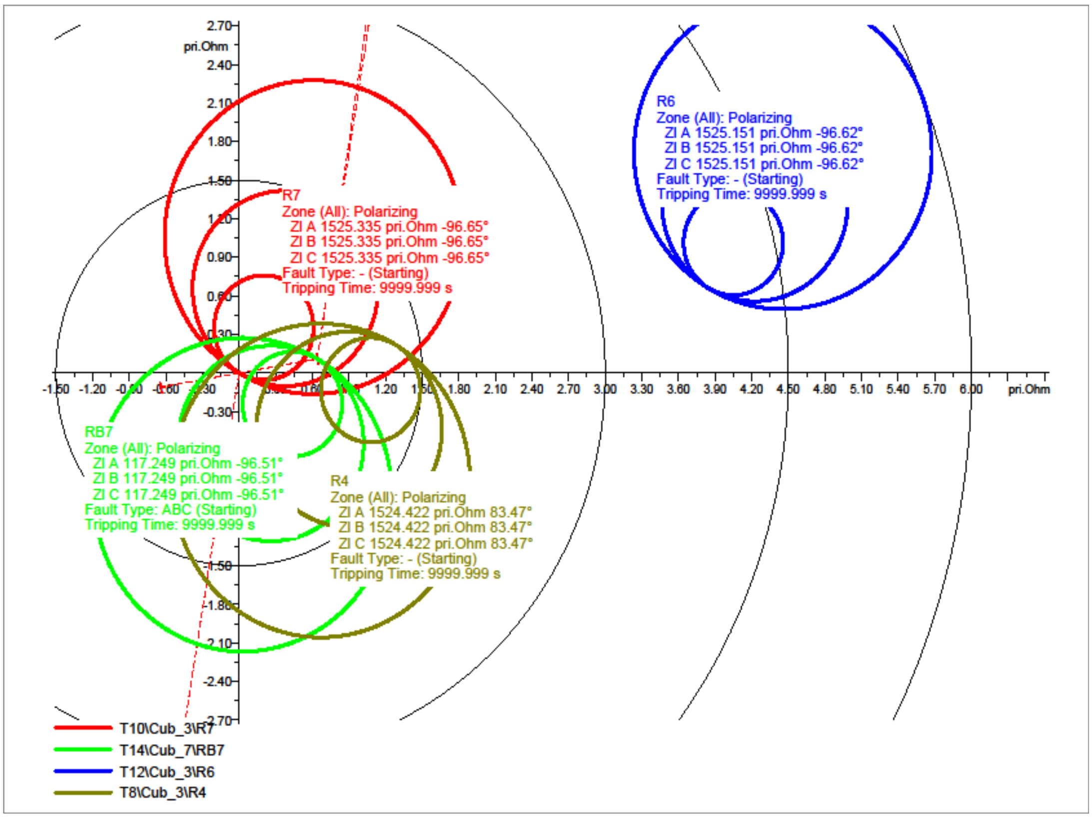


Figure 28 Three-phase fault-Islanding operation without a diesel generator, cable 7

7.Result- Earth Fault Protection

This chapter include results of earth fault protection on different fault location on grid-connected mode and islanding mode for various cases.

7.1 Case 1- Grid Connected Mode with All DGs

In this case, the system is connected to the grid with all distributed generators. The peterson coil is connected to the main transformer, terminal T1, and because of the high impedance earthing fault current becomes very minimal during the earth fault, and fault current even decreases with an increase in the fault resistance value. The fault locations and operating relays are shown in Table 13. Fault resistance values Rf = 200 Ω and Rf = 3000 Ω are taken for analysis in both cases.

Table 13 Earth fault Relays and Fault location on cable

Cable	Fault location	Primary Protection	Primary Protection
3	50%	R3	RB3
4	70%	R4	RB4
5	5%	R5	RB5
7	50%	R7	RB7

7.1.1 Earth Fault location on cable 7

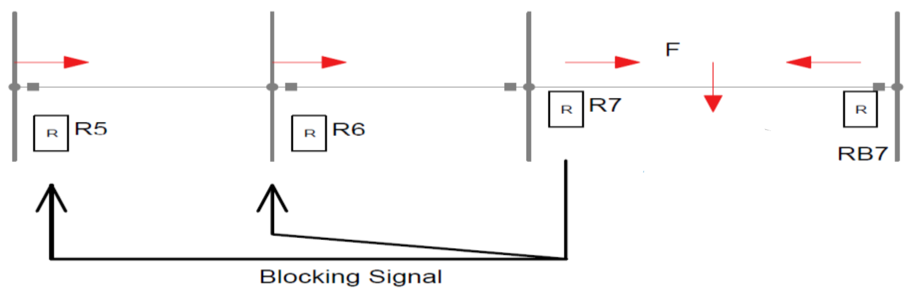


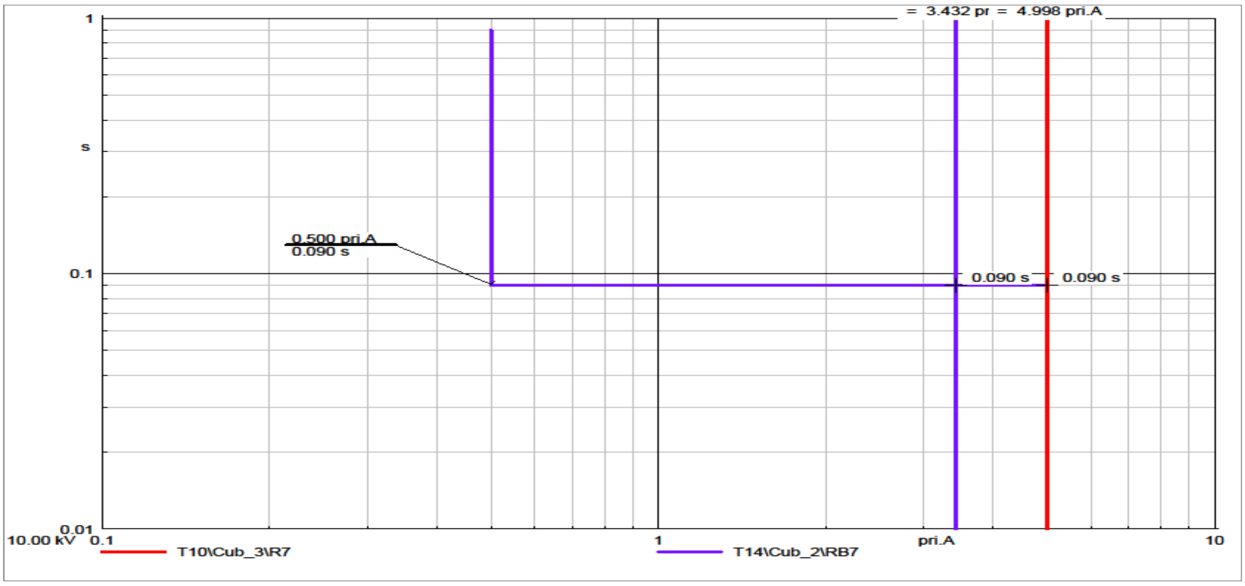
Figure 29 Earth fault on cable 7 line

As explained in the methodology, if a fault occurs in the cable, the respective protected element will send a momentary blocking signal to other relays to achieve selectivity of the system.

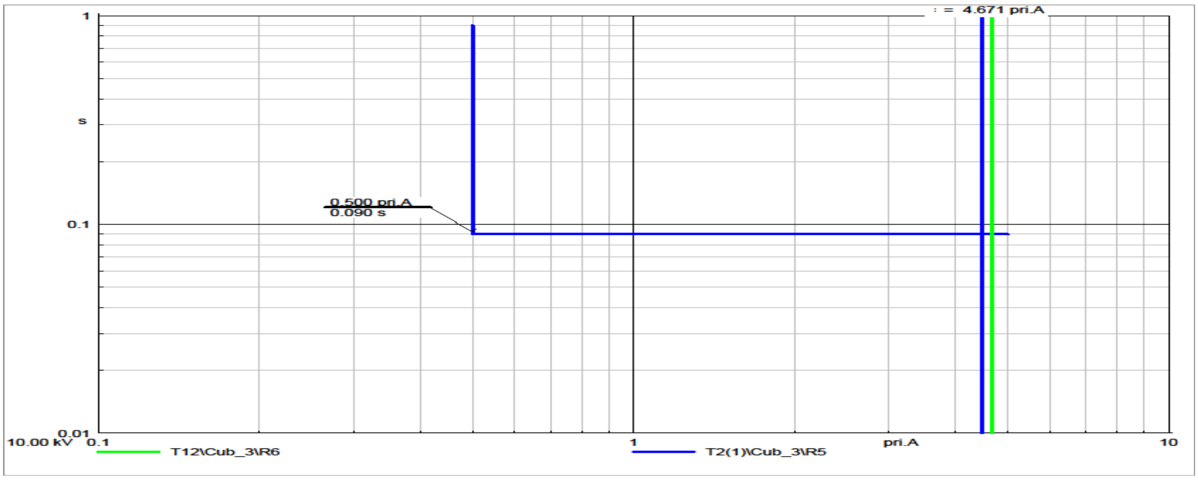
The relays have current settings of 0.5 A and time settings of 0.090 seconds. By using a time and current grading system, it is difficult to achieve selectivity because relays operate with residual current (3I0) value. Increasing the fault resistance will result in a decrease in the magnitude of the residual current.

Relay R7 and RB7 will be set with 0.5 A current and a time setting of 0.090 sec. When a fault occurs in cable 7 (50% from the grid-side end towards the DG-side end) halfway from terminal T10 to T14, relays R7 and RB7 (which is unit 1) will detect it, and relay R7 sends a blocking signal to relays R6 and R5 (which is unit 3) before tripping the signal, resulting in relays R6 and R5 not operating as sown in figure 29. Both relays R5 and R6 have a fault current similar to relay R7, but after receiving a blocking signal from relay R7 at 0.040 sec, both relays will not operate. Furthermore, relay R7 and RB7 will send blocking signals to all relays that have the same direction as relay R7 and RB7, which includes relays R1, R2, R3, and R4, so they will not operate.

Fault current is dependent on the system zero sequence impedance and the fault resistance, when the fault occurs on cable 7 line, fault current follows the path R5-RB5-R6-RB6-R7 and R1-RB1-R2-RB2-R3-RB3-R4-RB4-RB7. Figure 30(a) shows, when Rf = 200 Ω, fault currents on relay location R7 is 4.998 A (Red Colour) and relay location RB7 is 3.432 A (Purple colour) and both relays operate with 0.090 sec. Figure 30(b) shows the fault current at relays location R5, and R6 is approximately 4.671 A (Blue and green colour) which is the same as relay R7 fault current but they will not operate due to receiving a blocking signal (no tripping time is indicated in the graph).



a) Relay R7 and RB7 operation when Rf = 200 Ω



b) Relay R5 and R6 operation when Rf = 200 Ω

Figure 30 Earth Fault- Grid-connected mode, Rf = 200 Ω, Cable 7

Figure 31 shows when Rf = 3000Ω, fault currents at relay location R7 are 0.922 A (Red colour) and RB7 is 0.633 A (Pink colour) respectively. These fault currents are lower than the rating of the current transformer (1 on the current axis) so CT will not be able to measure small fault currents and the relay will not operate.

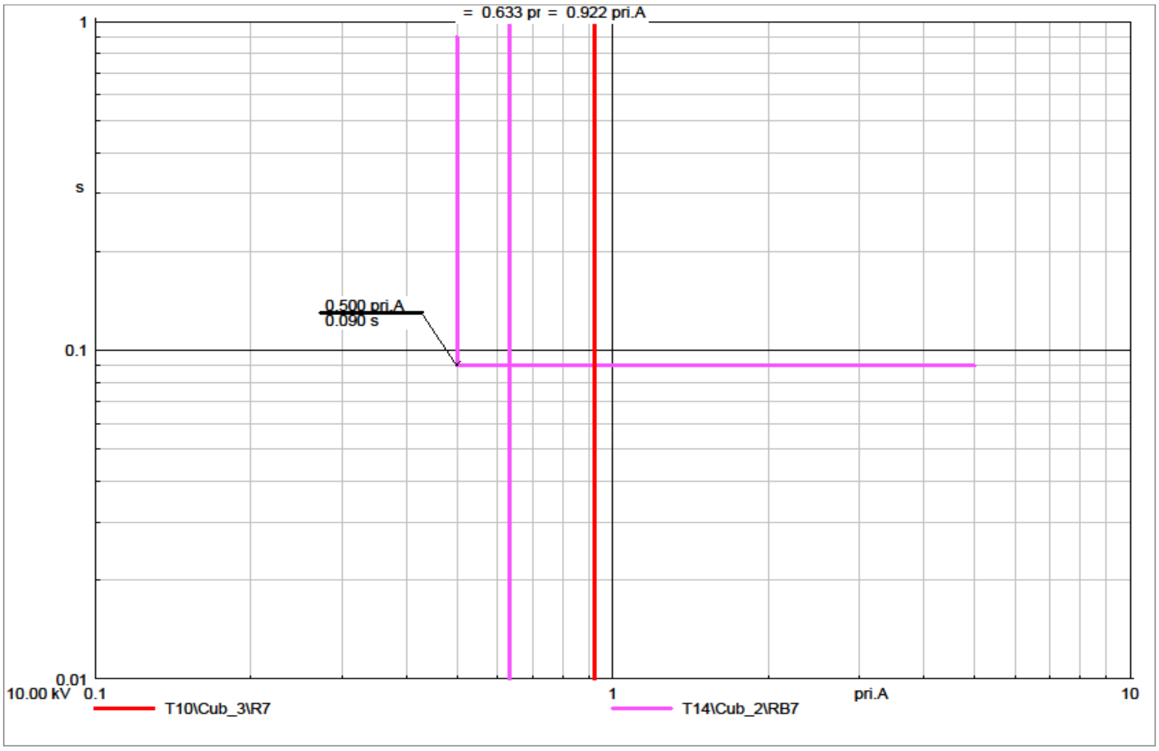
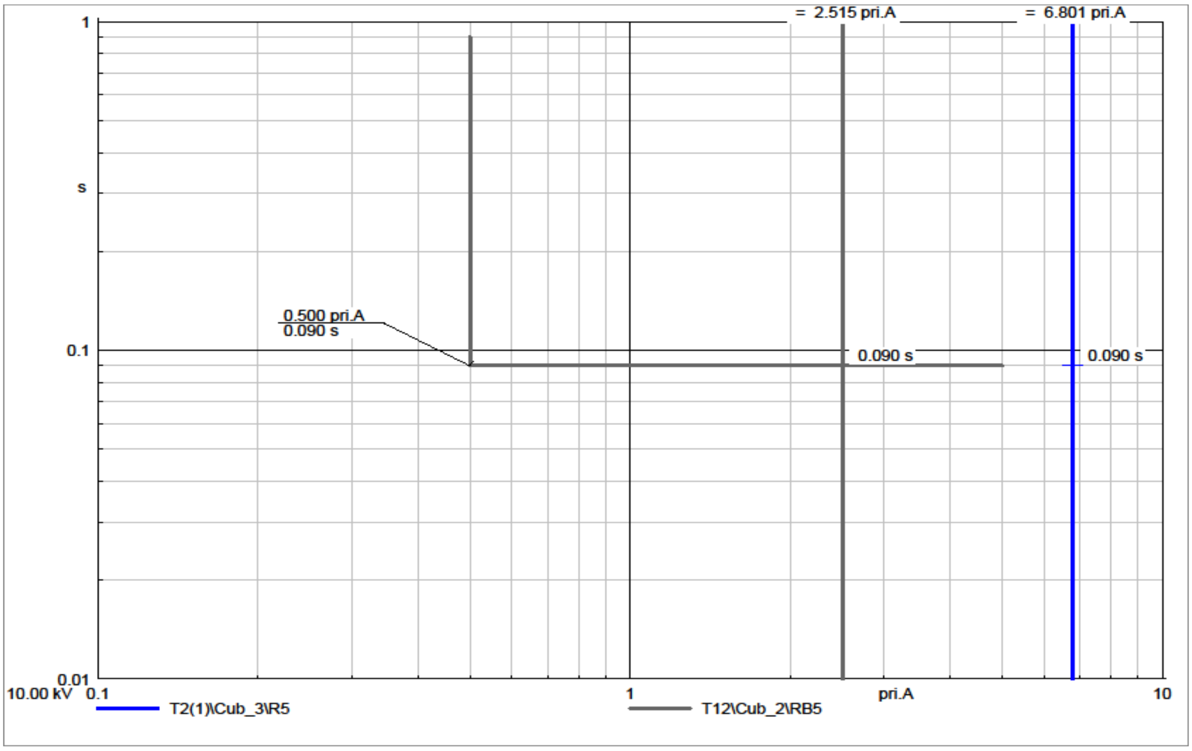


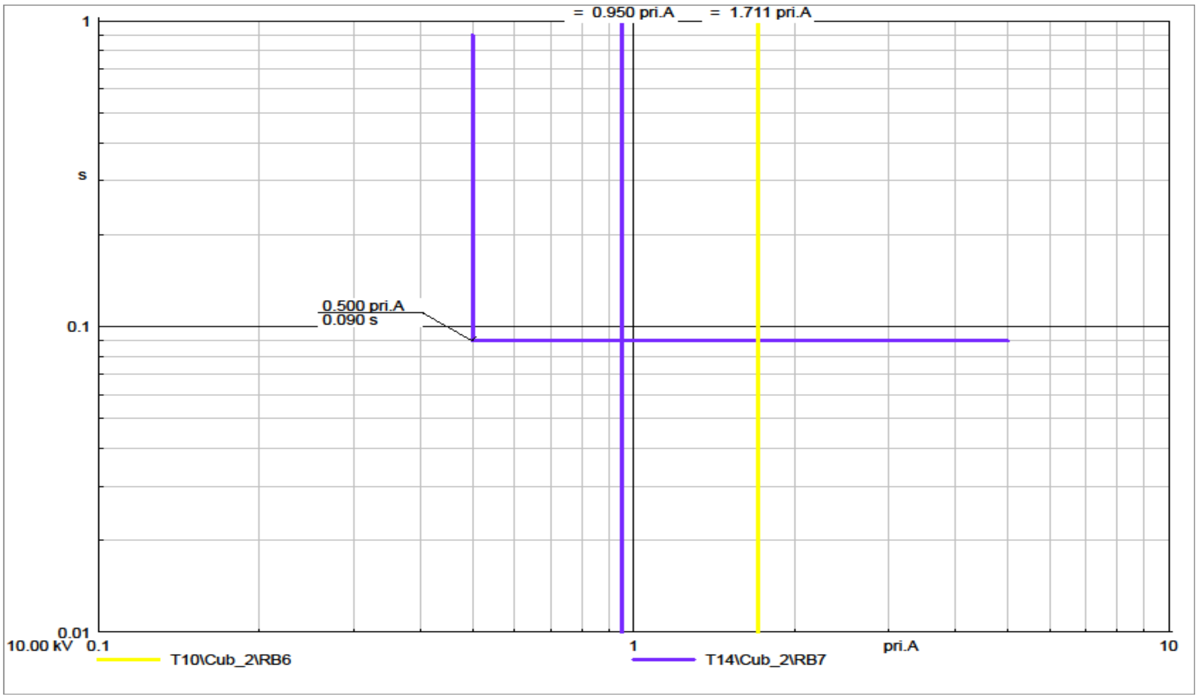
Figure 31 Earth Fault- Grid-connected mode, Rf = 3000 Ω, Cable 7

7.1.2 Earth Fault location on cable 5

Relay R5 and RB5 will be set with 0.5 A current and a time setting of 0.090 sec. When the fault is on cable 5 line (5% from the grid-side end towards the DG-side end) from terminal T2 to T12, then both the relays will detect the fault and send a blocking signal before the tripping signal to the relays whose direction is the same as the operating relay. Fault current follows the path R1-RB1-R2-RB2-R3-RB3-R4-RB4-RB7-R7-RB6-R6-RB5 at relay location RB5. Figure 32 (a) shows when Rf = 200 Ω, the fault currents on relay location R5 is 6.801 A (Blue line), and relay location RB5 is 2.5 A (Gray line) and both will operate in 0.090 sec. Relay R5 and RB5 will send a blocking signal to relays R1, R2, R3 and R4, RB6, and RB7. Figure 32(b) shows fault currents at relay location RB7 is 0.950 A (purple line) and relay location RB6 is 1.711 A (yellow line) and both relays will not operate after receiving a blocking signal (no tripping time is indicated in the graph).



a) Relay R5 and RB5 operation when Rf=200 Ω



b) Relay RB6 and RB7 operation when Rf= 200 Ω

Figure 32 Earth Fault- Grid-connected mode, Rf= 200 Ω, Cable 5

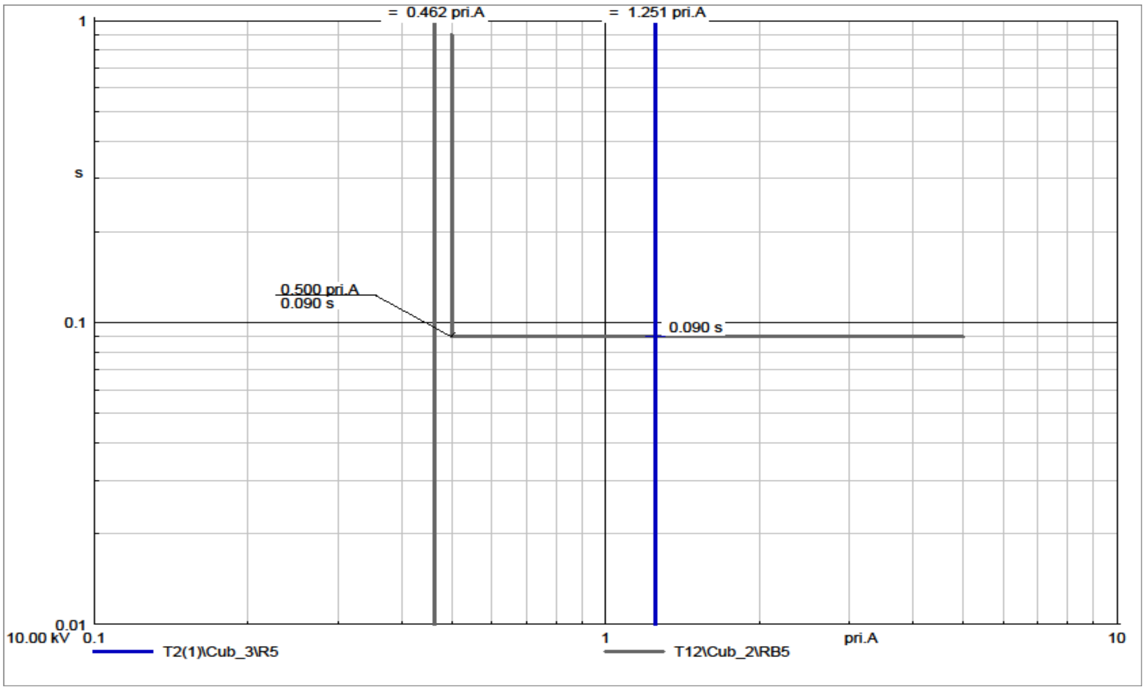
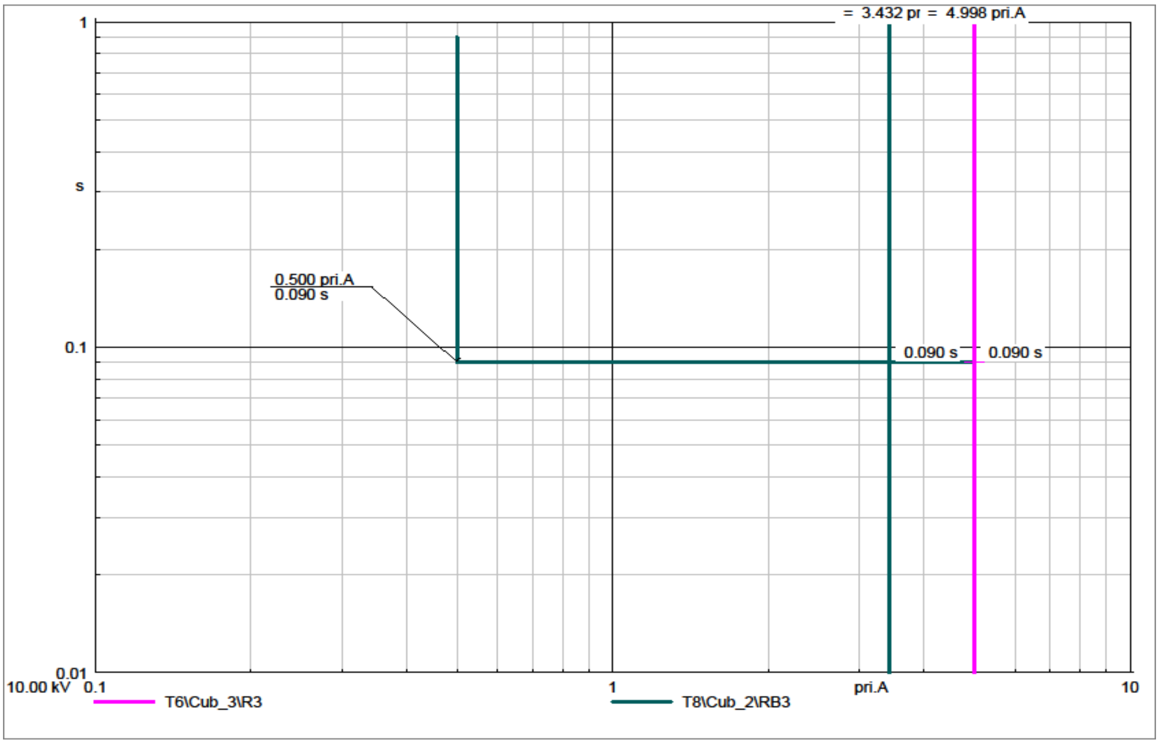


Figure 33 Earth Fault- Grid-connected mode, Rf= 3000 Ω, Cable 5

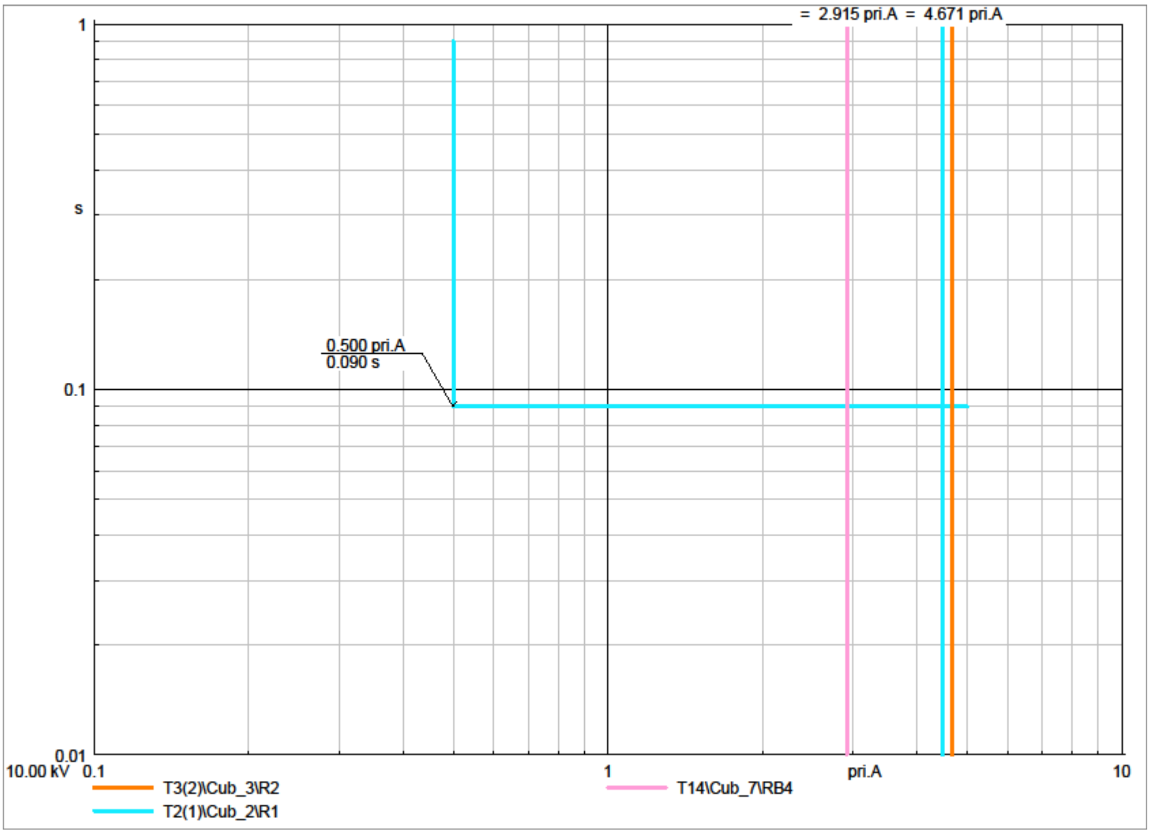
As shown in figure 33, when Rf = 3000 Ω, the fault current is very low and it is lower than the relay RB5 setting. Fault currents at relay location R5 are 1.251 A (Blue line) and relay location RB5 is 0.46 A (Gray line). The fault location is very near to the grid so even though the high fault resistance value fault current at relay location R5 is higher than the current transformer rating which is 1A and it will operate in 0.090 sec. The fault current at relay location RB5 is lower than the CT rating (1 on the current axis) thus relay RB5 will not operate.

7.1.3 Earth Fault location on cable 3

The current and time settings of relays R3 and RB3 are 0.5 A and 0.090 seconds, respectively. When a fault occurs on the cable 3 line (50% from the grid-side end toward the DG-side end), halfway from terminal T6 to T8, relays R3 and RB3 will detect the fault and send blocking signals to the relays whose direction is the same as the operating relay. Fault currents follow the path R1-RB1-R2-RB2-R3 at relay location R3 and R5-RB5-R6-RB6-R7-RB7-RB4-R4-RB3 at relay location RB3. When Rf= 200 Ω the fault currents value is 4.998 A (pink line) and 3.432 A (dark green line) at relay locations R3 and RB3 respectively. Both the relays will operate at 0.090 sec as shown in Figure 34(a). Figure 34(b) shows fault currents at relay locations R1, R2 is 4.67A (orange and blue line) and RB4 location is 2.91 A (pink line). Relay R3 will send a blocking signal to relays R2, R1, R5, R6, and R7 at 0.040 sec. Relay RB3 will send a blocking signal to the relay RB4 at 0.040 sec thus, relays R1, R2, and RB4 will not operate (no tripping time is indicated in the graph).



(a) Relay R3 and RB3 operation when Rf = 200 Ω



(b) Relay R1, R2 and RB4 operation when Rf = 200 Ω

Figure 34 Earth Fault- Grid-connected mode, Rf= 200 Ω, Cable 3

With the increase in fault resistance fault current will be reduced, when Rf = 3000 Ω fault currents at relay location R3 is 0.922 A (pink line) and relay location RB3 is 0.633 A (green line). Those fault currents are higher than the relay current setting but less than the rating of the CT (1 on the current axis) thus relays will not operate as shown in figure 35.

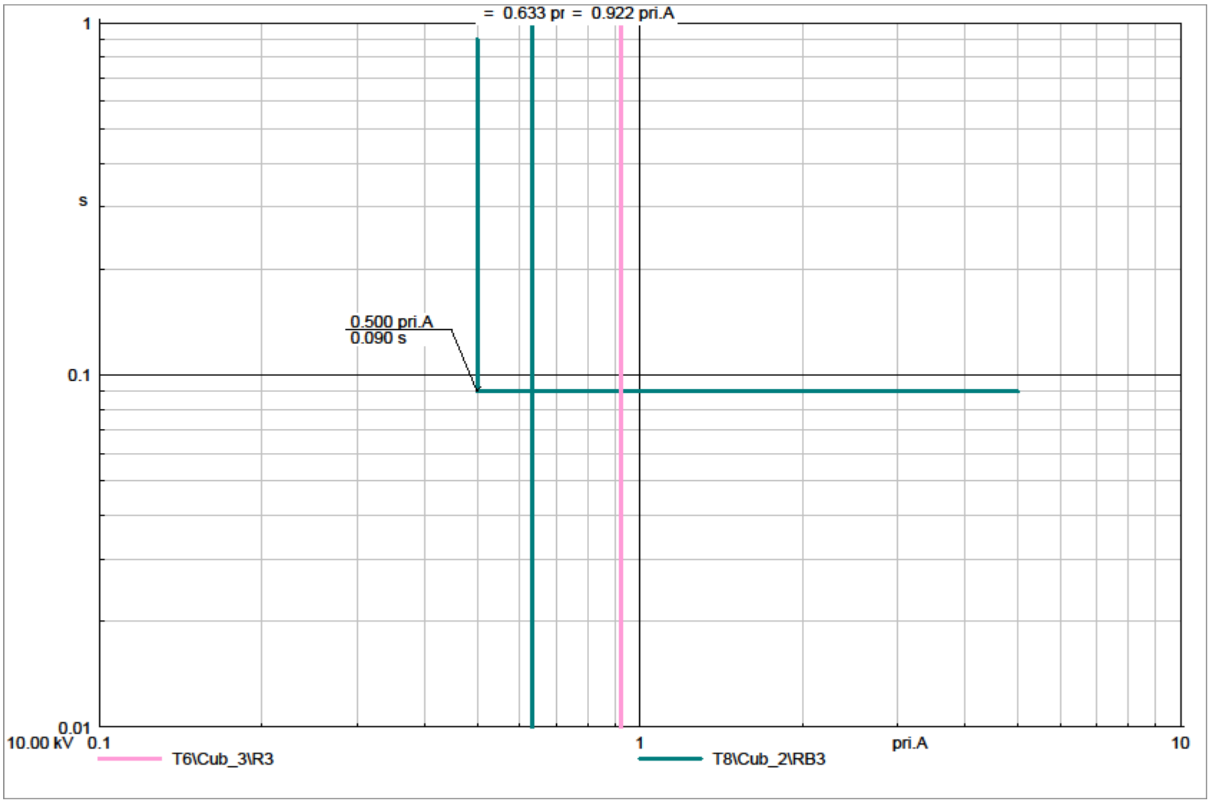
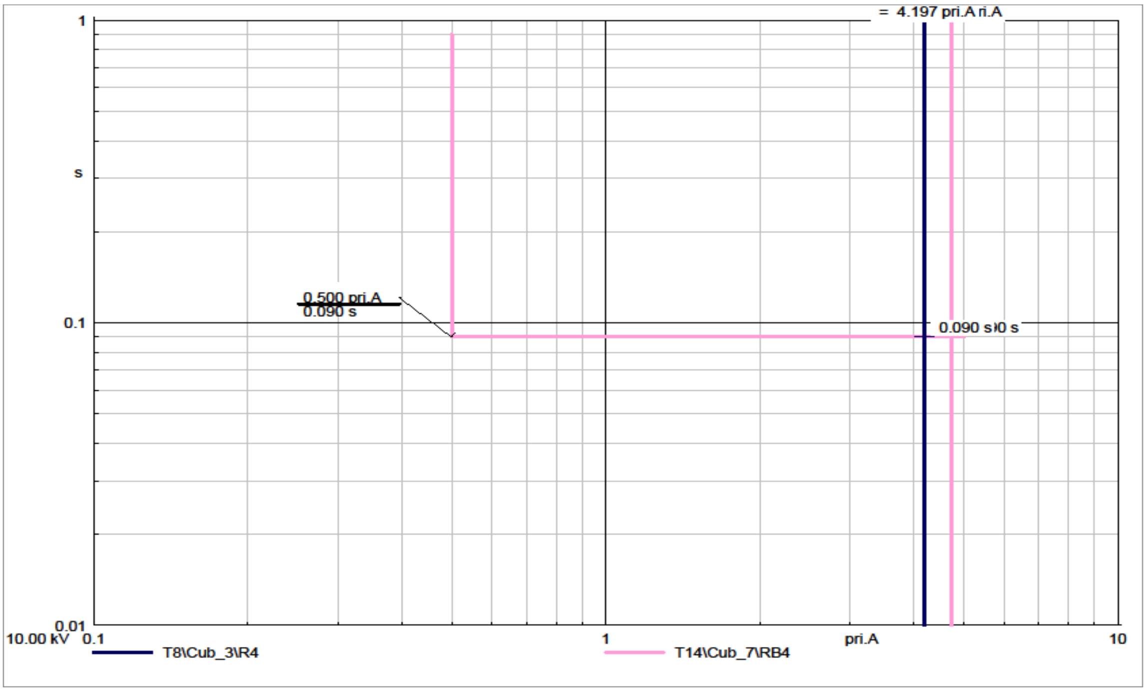


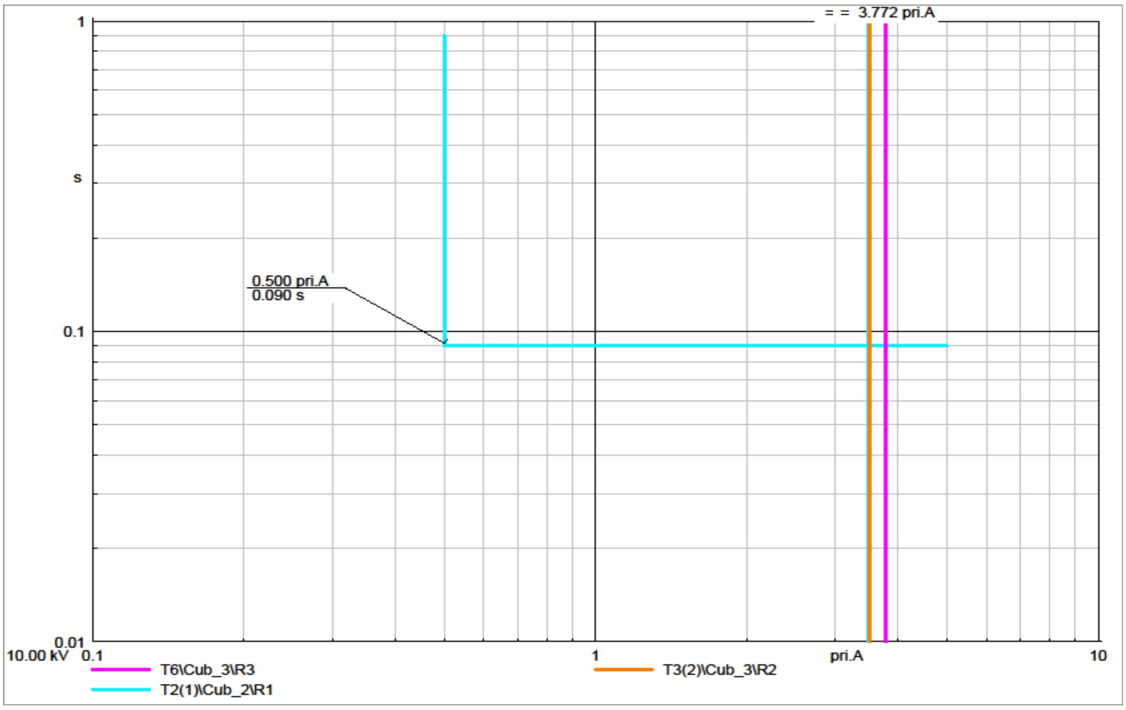
Figure 35 Earth Fault- Grid-connected mode, Rf= 3000 Ω, Cable 3

7.1.4 Earth Fault location on cable 4

Relays R4 and RB4 current setting is 0.5 A and the time setting is 0.090 sec. When a fault is on the cable 4 line (70% from the grid side end towards the DG-side end), then both relays will detect the fault and send blocking signals. Fault currents follow the path R1-RB1-R2-RB2-R3-RB3-R4 at relay location R4 and follow the second path R5-RB5-R6-RB6-R7-RB7-RB4 at relay location RB4. When Rf = 200 Ω, the fault currents value at relay location R4 is 4.197 A (Dark blue line), and relay location RB4 is 4.8 A (Pink line), and both relays will operate at 0.090 sec as per Figure 36(a). Relay R4 will send a blocking signal to all forward relays whose direction is the same as the direction of the relay R4. Figure 36(b) shows fault current at relay locations R1, R2, and R3 is approximately 3.772 A (pink, orange, blue line). Those relays will not operate after receiving a blocking signal at 0.040 sec even though they have fault current 3.772 A (no tripping time is indicated in the graph).



a. Relay R4 and RB4 operation when Rf = 200 Ω



b. Relay R3, R2 and R1 operation when Rf = 200 Ω

Figure 36 Earth Fault- Grid-connected mode, Rf= 200 Ω, Cable 4

When Rf = 3000 Ω, fault currents at relay location R4 is 0.79 A (Blue line) and relay location RB4 is 0.873 A (Pink line), both the fault current is higher than the relay current setting value but lower than the CT rating which is 1A (1 on the current axis), thus relays will not operate as shown in figure 37.

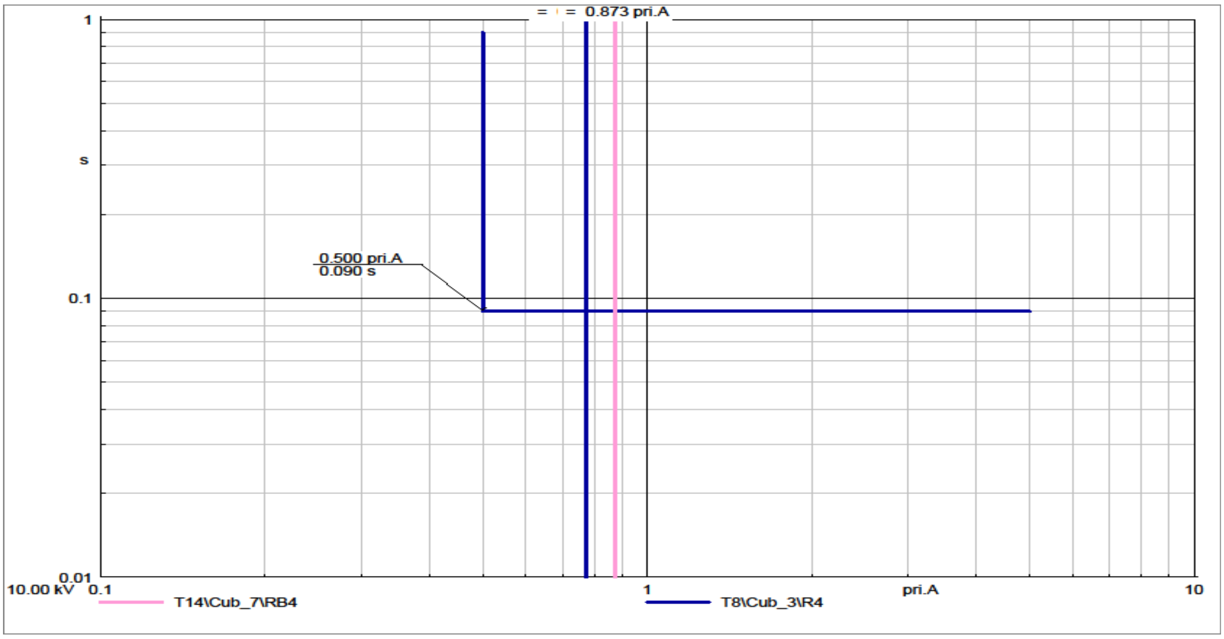


Figure 37 Earth Fault- Grid-connected mode, Rf= 3000 Ω, Cable 4

Table 14 shows relay operating time with different fault resistance values at different cable locations in grid-connected mode.

Table 14 Relay operating time with fault resistance – Grid-connected mode

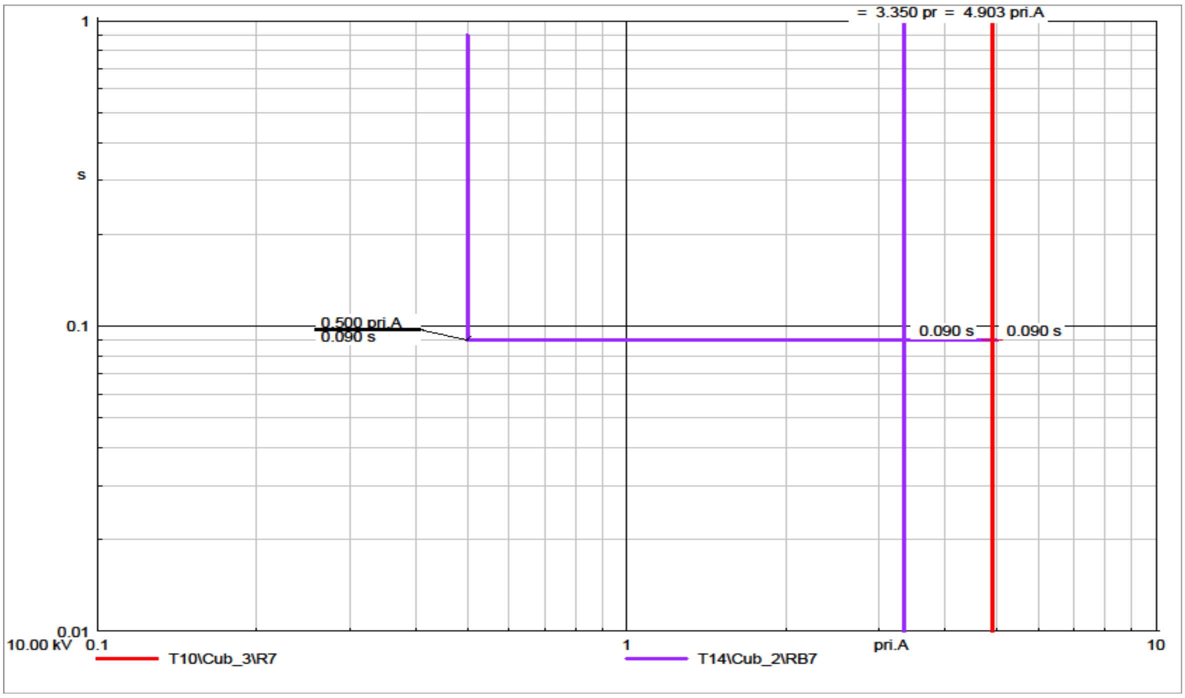
Cable	Fault location	Fault Resistance Rf (Ω)	Primary Protection Relay	Fault Current at R3 (A)	Operating Time (s)	Primary Protection Relay	Fault Current at RB3 (A)	Operating Time (s)
3	50%	200	R3	4.998	0.09	RB3	3.432	0.09
		3000		0.922	Not operate		0.633	Not operate
4	70%	200	R4	4.197	0.09	RB4	4.8	0.09
		3000		0.79	Not operate		0.873	Not operate
5	5%	200	R5	6.801	0.09	RB5	2.515	0.09
		3000		1.251	0.09		0.462	Not operate
7	50%	200	R7	4.998	0.09	RB7	3.432	0.09
		3000		0.922	Not operate		0.633	Not operate

7.2 Case 2- Islanding operation with all DGS

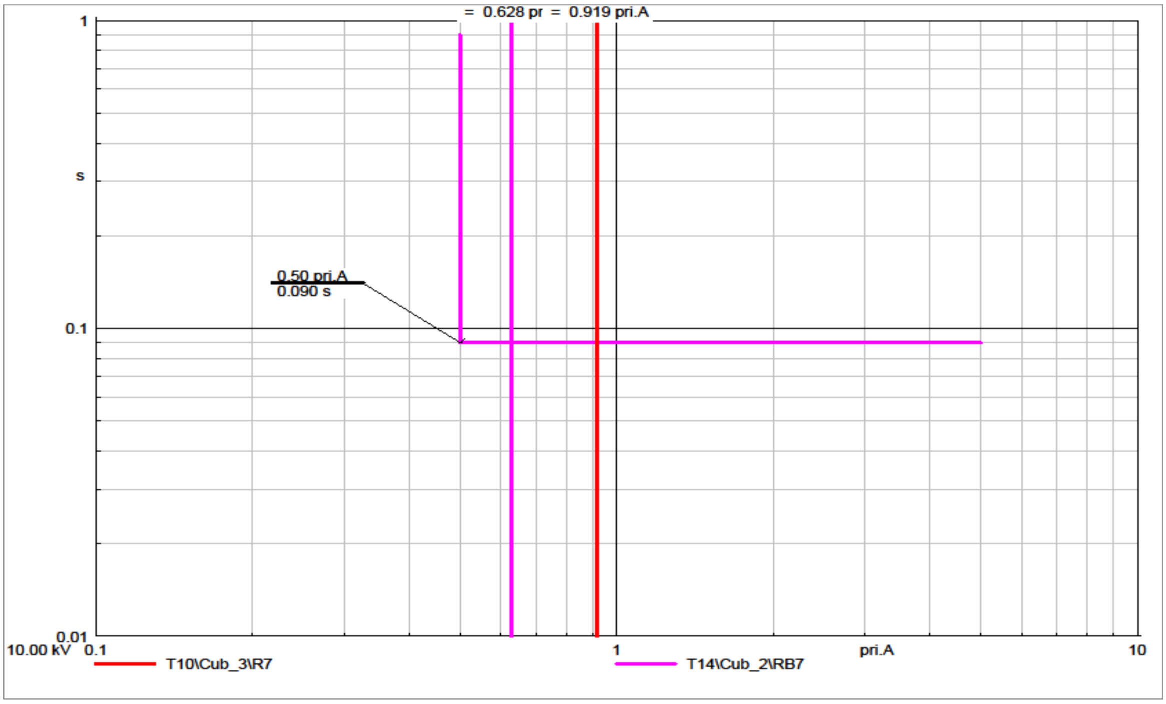
The system model is disconnected from the grid and it is connected to all DGs, including the synchronous generator. The peterson coil is connected at terminal T1, which is the same as in the grid-connected mode, and fault current will flow from the location of the peterson coil to the location of the fault. Further, fault current depends on fault resistance value. The Rf value was the same as in grid-connected mode which is Rf = 200 Ω and Rf = 3000 Ω.

7.2.1 Earth Fault location at cable 7

Earth fault occurs the same as grid-connected mode on cable 7 and both the protective relays R7 and RB7 will detect a fault and send a blocking signal to all the relay which has the same direction as relay R7 and RB7. Relays R1, R2, R3, R4, R5, and R6 will receive a blocking signal from relay R7 and it will not operate. The current setting and time setting of all relays are 0.5 A and 0.09 sec. When Rf = 200 Ω fault current at relay location R7 and RB7 is 4.9 A (Red line) and 3.350 A (Purple line) respectively both the relays will operate in 0.090 sec as shown in figure 38(a). When Rf = 3000 Ω fault currents at relay location R7 and RB7 are 0.919 A (Red line) and 0.628 A (Pink line) respectively, the fault currents value is lower than the rating of the current transformer (1 on the current axis) thus relay will not operate as shown in figure 38(b).



a. Relay R7 and RB7 operation when Rf = 200 Ω



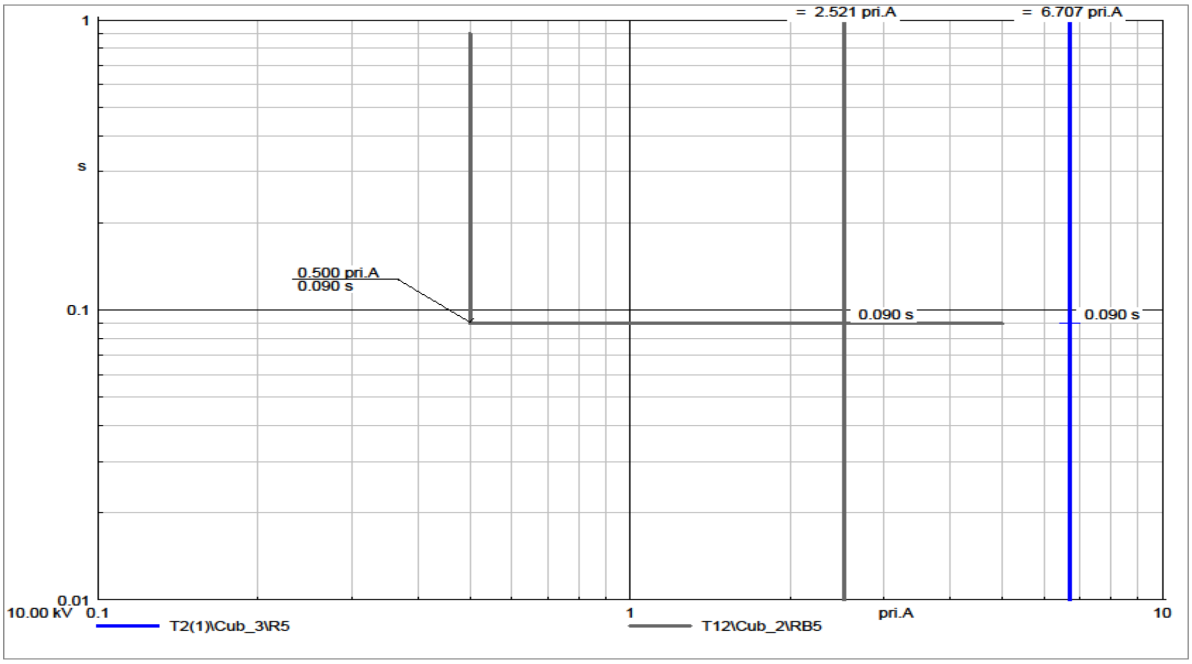
b. Relay R7 and RB7 operation when Rf = 3000 Ω

Figure 38 Earth Fault- Islanding mode, Cable 7

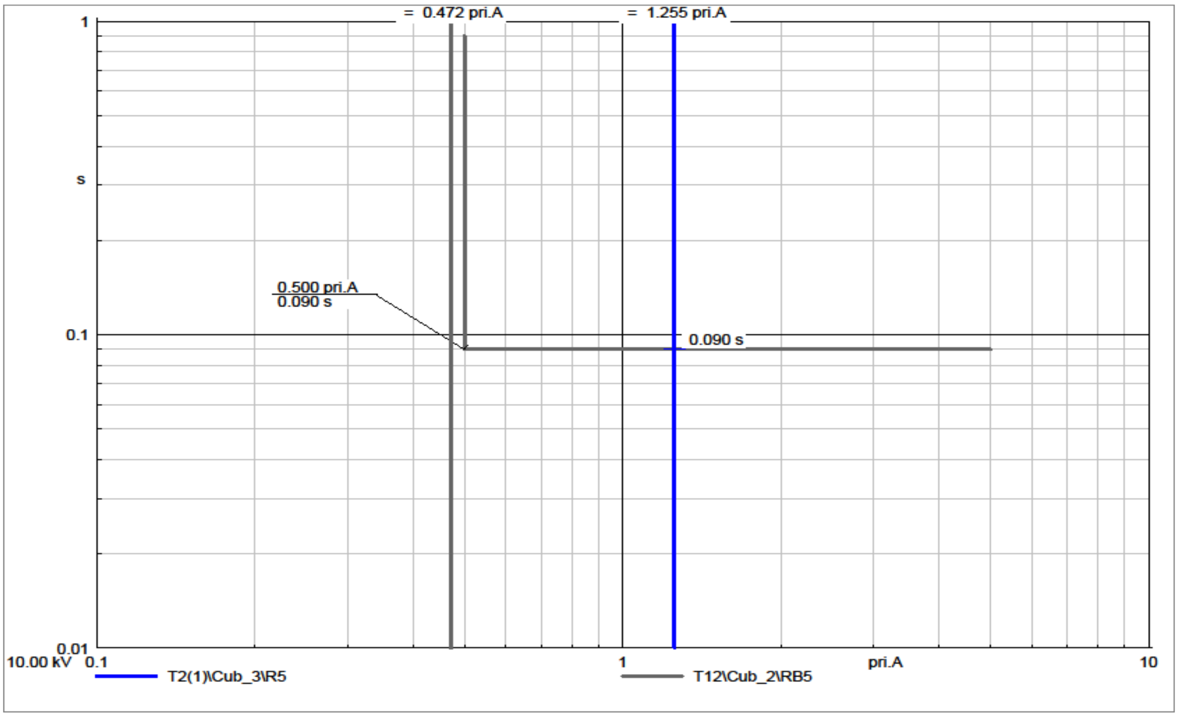
7.2.2 Earth Fault location at cable 5

Relay R5 and RB5 will set with 0.5 A current and 0.090 sec time value. Fault location is the same as a grid-connected mode on cable 5. Both relays will detect the fault and send a blocking signal to the relays whose direction is the same as the operating relay. Figure 39(a) shows when Rf = 200 Ω, the fault currents on relay location R5 is 6.7 A (Blue line), and relay location RB5 is 2.521 A (Gray line). Relays R5 and RB5 will send a blocking signal to all forward relays whose direction is the same as the direction of the relays R5 and RB5. Relay RB5 will send a blocking signal at 0.040 sec to the relay RB6 and RB7. Relay R5 will send a blocking signal to the relay R1, R2, R3, and R4.

Figure 39(b) shows when Rf = 3000 Ω, the fault currents at the relay location is R5 and RB5 are 1.25 A (Blue line) and 0.472 A (Gray line) respectively. At the relay location, the RB5 fault current is less than the current setting of the relay so relay RB5 will not operate, but the fault current at relay location R5 is 1.25 A which is higher than the rating of the current transformer and relay R5 will operate.



a) Relay R5 and RB5 operation when Rf = 200Ω

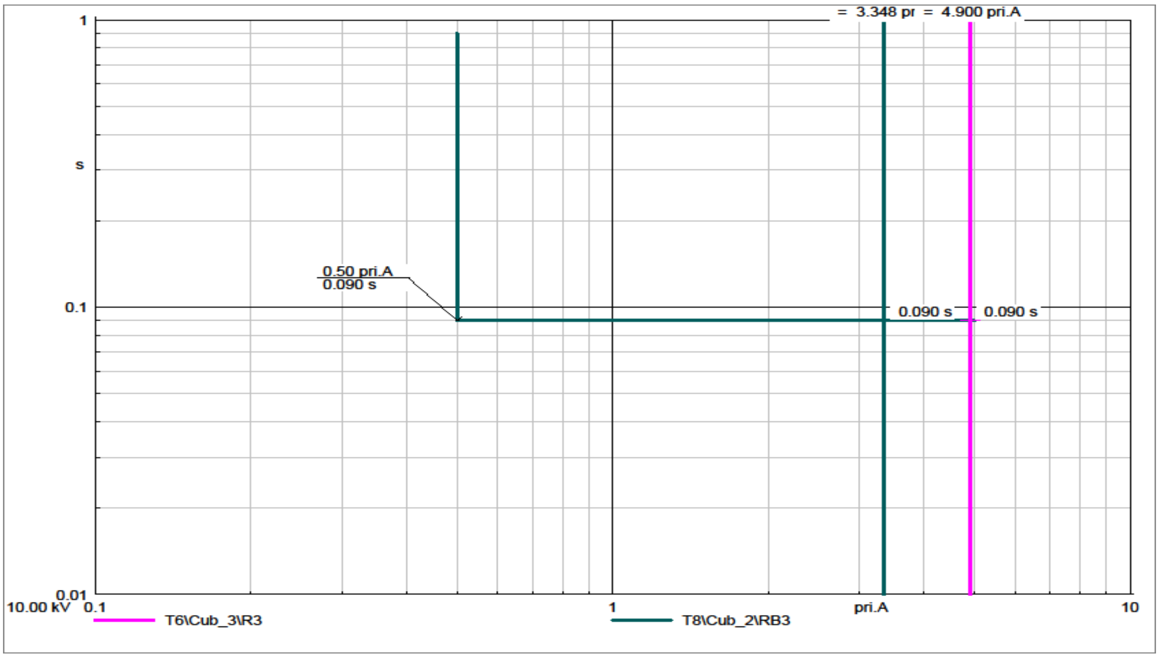


b) Relay R5 and RB5 operation when Rf = 3000Ω

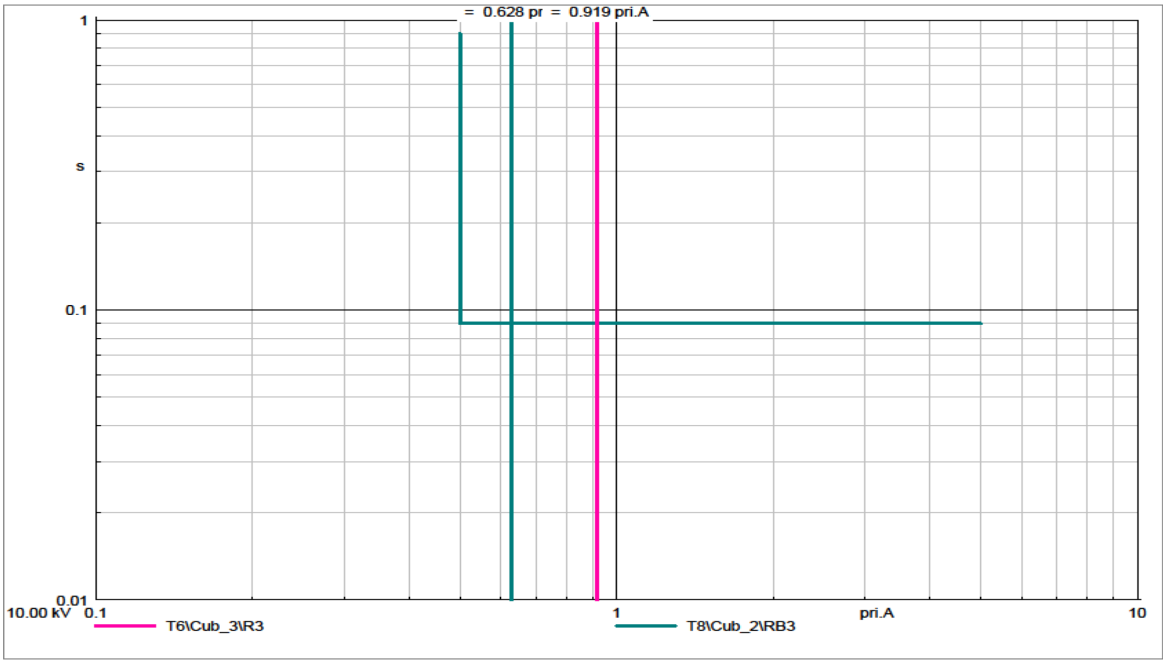
Figure 39 Earth Fault- Islanding mode, Cable 5

7.2.3 Earth Fault location at cable 3

Earth fault occurs at the same location as a grid-connected mode on cable 3 and both the protective relays R3 and RB3 will detect a fault and send a blocking signal to all the relay which has the same direction as relay R3 and RB3. Relays R1, R2, R5, R6, and R7 will receive a blocking signal from relay R3 and it will not operate. The current setting and time setting of relays is 0.5 A and 0.09 sec. When Rf = 200 Ω fault current at relay location R3 is 4.9 A (pink line) and RB3 is 3.348 A (Green line) respectively and both the relays will operate in 0.090 sec as shown in figure 40 (a). When Rf = 3000 Ω, the fault current at relay location R3 is 0.919 A (Pink line) and the fault current at relay location RB3 is 0.628 A (green line) respectively, those fault currents value is lower than the rating of the current transformer (1 on the current axis) thus relays will not operate as shown in figure 40 (b).



a) Relay R3 and RB3 operation when Rf = 200 Ω

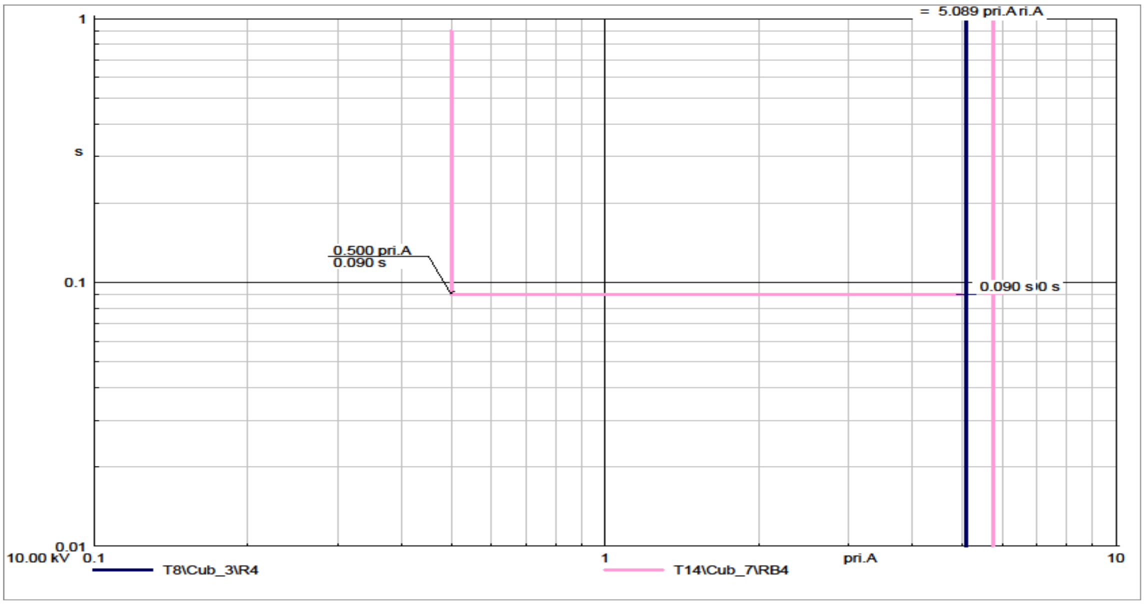


b) Relay R3 and RB3 operation when Rf = 3000 Ω

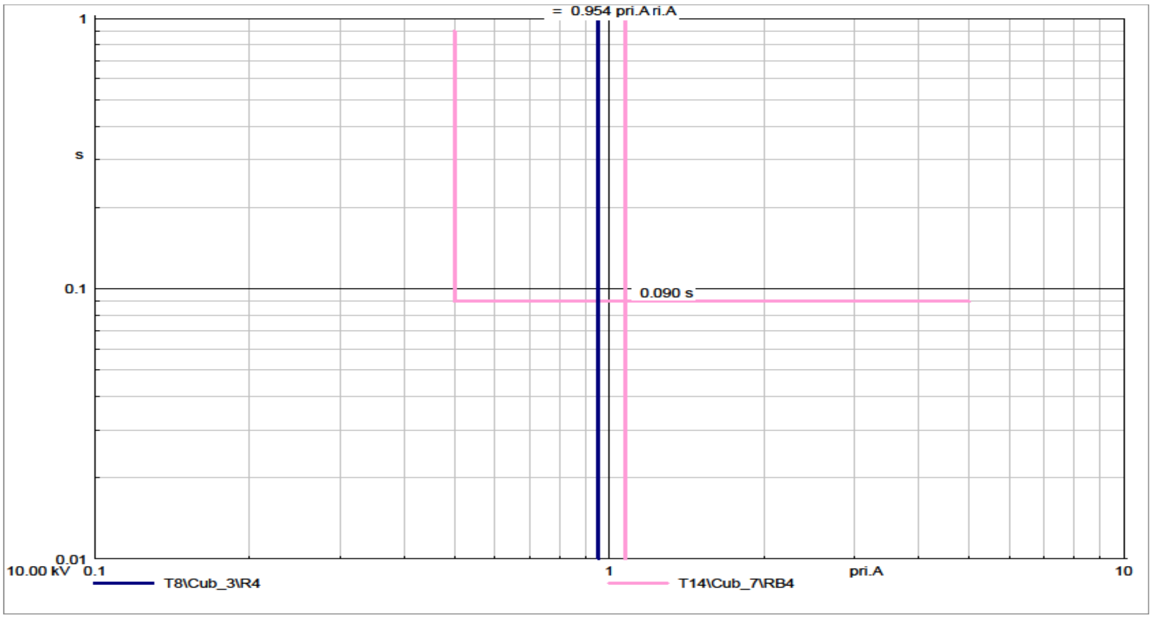
Figure 40 Earth Fault- Islanding mode, Cable 3

7.2.4 Earth Fault location at cable 4

Relay R4 and RB4 set with 0.5 A current setting and 0.090 sec time setting. The fault location is same as grid connected mode on cable 4 line, both the relay will detect the fault and send a blocking signal as explained in grid-connected mode. Figure 41(a) shows when Rf = 200 Ω, the fault currents is on relay location R4 and RB4 is 5.089 A (Blue line). Both the relays will operate in 0.090 sec. Figure 41(b) shows when Rf = 3000 Ω, the fault currents are relay location R4 is 0.954 A (blue line), and it will not operate where fault current at the relay location RB4 is 1.05A (pink line) and it will operate with 0.090 sec.



a. Relay R4 and RB4 operation when Rf = 200 Ω



b. Relay R4 and RB4 operation when Rf = 3000 Ω

Figure 41 Earth Fault- Islanding mode, Cable 4

Table 15 shows relay operating time with different fault resistance values at different cable locations in islanding mode.

Table 15 Relay operating time with fault resistance- Islanding operation

Cable	Fault location	Fault Resistance Rf (Ω)	Primary Protection Relay	Fault Current (A)	Operating Time (s)	Primary Protection Relay	Fault Current (A)	Operating Time (s)
3	50%	200	R3	4.90	0.09	RB3	3.348	0.09
		3000		0.919	Not operate		0.628	Not operate
4	70%	200	R4	5.089	0.09	RB4	5.8	0.09
		3000		0.919	Not operate		1.2	0.09
5	5%	200	R5	6.707	0.09	RB5	2.521	0.09
		3000		1.255	0.09		0.472	Not operate
7	50%	200	R7	4.903	0.09	RB7	3.350	0.09
		3000		0.919	Not operate		0.628	Not operate

8. Challenges

This chapter summarizes the challenges that have been observed for the protection strategies of the three-phase fault and the earth fault in both grid-connected mode and islanding mode.

8.1 Three-phase fault

- In grid-connected mode, when a fault occurs, the grid and DGs both supply fault current, so fault currents will be higher than islanding mode. When the fault location is very near the grid side (5% from the grid side to the DG side), the grid will supply a huge fault current to the fault location, so relays located in the second parallel feeder will measure inaccurate fault current at the relay location, and it will create blinding operation in backup protection.

- In islanding mode, the fault current is much lower compared to grid-connected mode. When a fault location is near the DGs side and only DGs will supply a fault current to the fault location. The relays located on the faulted cable will operate in the primary zone even if the fault current level is low, but relays located on the second parallel feeder cable will measure inaccurate fault current, and it will create blinding operation of the relay in backup protection.

- In islanding operation without a diesel generator, fault current will be very minimal, and it will not be able to operate the relays.

- Blinding of the relays may occur in cable because of the series reactance is much lower than the overhead line. In cable spacing between the conductor is shorter and the resistance of the cable is higher, so the X/R ratio especially the short cable is very small compared to the overhead line. Due to the low X/R ratio, during the occurrence of the fault, the impedance seen by the distance relay is mostly resistive in nature, and the fault current is nearly in phase with the voltage, and it may cause false tripping of the distance relay [41].

- The low X/R ratio of the short cable also creates an overreach problem in the distance relay. Overreach occurs when the impedance seen by the relay is higher than the setting of the relay. During the occurrence of the fault, the impedance seen by the relay has a longer reach because of the resistive component of the cable [42]. Further, due to lower fault current, the current transformer has measurement error, and it may lead to false tripping of the relays [43] [29] [44].

8.2 Earth Fault

- The relay setting of the directional earth fault relay should be done very precisely because it will affect the selectivity. According to the Swedish standard requirement, the relay should disconnect fault resistance up to 3000 Ω. With high fault resistance, the fault current will become less than CT rating (1 A), thus if the relay setting is not done precisely then it will affect the selectivity.

- CT should be correctly sized so that it can measure low fault current and give a signal to the protective relay. The selection of CT ratio is very important in the directional earth fault relay as it should have to measure very low fault current during very high impedance fault. If CT will not measure low fault current which is lower than its rating, then the relay will not operate in high impedance fault.
- Directional earth fault relay with a communication line will depend on the communication system, if the system is very complex and the relay will fail to send a blocking signal in time then it will affect the selectivity.
- The methodology applied in the earth fault protection in the case study cannot be used as backup protection. If the relay fails to detect the fault in primary protection then the power system is not able to detect the fault.
- The backup protection residual voltage protection should be used as it detects the earth fault in the power system but is not able to detect in which line fault occurs [45]. The resulting non selective clearing of the earth fault is normal for backup protection.
- When an earth fault occurs between the busbar and the relay location in the cable, then the directional earth fault relay is not able to detect the fault and it is difficult to implement in complex systems as relays use in both ends of the cable with communication line, so implementation of this method is very costly.

9. Conclusion and Future Work

In a power system when a fault occurs it should be removed as quickly as possible and only a faulty part of the power system can be disconnected to maintain a reliable power supply in the power system. In Simris, Arholma, and Hailuoto island microgrid projects used overcurrent with communication line protection for the three-phase fault and residual voltage protection for the earth fault protection. The Fault analysis of the Simris model in this work suggests the conclusion as explained below.

9.1 Conclusion

9.1.1 Three-Phase Fault

Distance protection measures current and voltage at the fault location and calculates impedance and depending on the measured impedance during the fault it will give a signal to the circuit breaker. According to the literature survey, distance protection which operates with an impedance that has a zone-wise setting and is used as backup protection is a good solution for the microgrid because a microgrid has different fault current levels due to its grid-connected and islanding mode and power can flow in both directions.

This work suggests the following conclusion:

Grid-connected mode:

- Distance relays can detect the three-phase faults on a cable which are located far from the grid terminal. Distance protection can detect the fault in the primary and backup protection when fault locations are 50% and 70% from the grid side to the DGs side on the cable. Further, it can also detect the fault in the primary and backup zone when the fault location is near the DGs side.

- When the three-phase fault location is very near to the grid terminal (5% grid side to the DGs side), distance protection is not able to operate in backup protection and it will create blinding of the relay in backup protection.

Islanding mode with diesel generator:

- When the three-phase fault location is far from the DGs terminal, distance protection will detect the fault in primary and backup protection even though the fault current level is reduced.

- Three-phase fault locations are near the DGs terminal, distance protection cannot detect a fault in backup protection and it will create blinding of the relays.

Islanding mode without a diesel generator:

- In any three-phase fault location, the fault current is small, and distance protection is not able to operate.

9.1.2 Earth fault

In Sweden, medium voltage distribution networks use peterson coil earthing. For the earth fault protection two directional earth fault relays with communication lines are used in the Simris case study model and the peterson coil is connected near the grid side transformer. The work of the case study suggests the following conclusion:

Grid Connected mode:

- Fault locations are (50%, 70%, and 5% from the grid side end to the DGs side end) the directional earth fault relay with communication line is a selective method for the low earth fault resistance value.
- High fault resistance (3000 Ω) value fault current will be less than CT rating (1 A), thus it is not able to clear the fault at any location.

Islanding mode with diesel generator:

- Fault locations are (50%, 70%, and 5% from the grid side end to the DGs side end) the directional earth fault relay with communication line is a selective method for the low earth fault resistance value in islanding mode.
- High fault resistance (3000 Ω) value fault current will be less than CT rating (1 A), thus it is not able to clear the fault at any location.

Further conclusions for the earth fault method are below:

- The relay setting of the directional earth fault relay should be done precisely, if the relay setting is not done correctly then it may not be able to detect the fault.
- Directional earth fault relay measures the residual component of the fault current. If the system is complex, then it may lead to the problem of blocking the signal and it affects the selectivity.
- Selection of the current transformer is important as it will measure low fault current during a high impedance earth fault. If the CT cannot detect the low fault current, then it is difficult to operate the protective relay and disconnect the fault part in the system.
- The methodology applied for earth fault protection is not used for backup protection.

9.2 Future Work

- Differential protection with the correct size of the current transformer may be evaluated for the three-phase fault and asymmetrical faults to avoid microgrid protection challenges such as false tripping and blinding of relays.
- The selection of a suitable current transformer for the detection of the earth fault during the high resistive fault may be evaluated, so that the CT can measure the small current and the protective relay can give a signal to the circuit breaker.
- In Sweden, medium voltage distribution line peterson coil earthing is used, when earthing is other than peterson coil then different protection methods may be evaluated for the unbalanced faults.
- For the Low Voltage distribution system, earthing is different than the medium voltage distribution system so protection strategies for microgrids for the low voltage distribution system may be evaluated.

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Appendix:

Cable Data

No core and cross-section area (mm^2)	Inductance (mH/km)	Capacitance (µF/km)	Ground Connection Power (A/km)	Normal Load Current in Soil (A)
3 x 50/25 AI	0.35	0.22	1.2	170 in 90°C
Short time current (1s)	Resistance (Ω/km)	Resistance R_0 (Ω/km) (µF/km)	Reactance X_0 (Ω/km)	Normal Load Current in Soil
4.7 kA	0.641	4.24	0.09	145 in 65°C

3- ϕ Transformer 22/10 kV

Rated Power (MVA)	Vector Group, Tap change	Short circuit ratio $u_{k\,(\%)}$	Copper Loss (kW)	No load losses (kW)
S = 6, 50 Hz	YN, 2.5 ± 2 %	8	37.1	4.7

3- ϕ Transformer 10/0.4 kV

Rated Power (MVA)	Vector Group, Tap change	Short circuit ratio $u_{k\,(\%)}$	Copper Loss (kW)	No load losses (kW)
S = 0.8, 50 Hz	Dyn30, 2.5 ± 2 %	6	7.7	1.7

Load

Type	Active Power (kW)	Reactive Power (Kvar)
AC, Balanced, 50 Hz	160	50

Circuit Breaker

Type	CB opening time	Arcing time

Vacuum CB	Less than 45 ms	Less than 20 ms

DG Plant

Plant	Capacity	Inverter Short circuit current
Solar Plant	440 kW	828 A
Wind Plant	500 kW	1 kA
Battery storage system	800 kW,333 kWh	1.6 kA
Diesel Generator	500 kW	

Protection Unit

Measuring Transformer	Ratio	Ratio
CT	110/1 A	100/1 A
VT	10000/110 A	10000/110 A
Relay	Altrom Micro Mho Relay	SEJ512, Genetic Relay