Protection Coordination in Networks with Renewable Energy Sources

Protection Coordination in Networks with Renewable Energy Sources

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Zhiqi Han

School of Electrical and Electronic Engineering

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List of Abbreviations

DG Distributed Generator

OC Overcurrent

CB Circuit Breaker

CT Current Transformer

VT Voltage Transformer

IDMT Inverse Definite Minimum Time

SI Standard Inverse,

VI Very Inverse

EI Extremely Inverse

MMT Minimum Melt Time

TCT Total Clearing Time

TMS Time Multiplier Setting

CTI Coordination Time Interval

Abstract

The increased distributed generators (DGs) in distribution networks are causing protection coordination problems. Due to the many generation sources supplying the distribution network, the conventional protective devices have become insufficient to ensure the proper protection coordination in case of a fault.

This dissertation illustrates the summary of the DGs' influences and an overview of the approaches for selecting and coordinating the protection system with or without DGs. Two example networks have been used to demonstrate the specific coordinating methods and problems for an overcurrent-based scheme and a distance-based scheme with the help of the DIgSILENT PowerFactory software package. One example is a radial medium voltage network mainly protected by overcurrent (OC) relays, which has potential false tripping and blinding effects. Another one is a typical UK meshed distribution network which may suffer the under reaching for distance relays that occurs on the basis of the distance-based protection scheme. The protection system for each network will be used to prove the success of the derived settings and also the successful coordination of protective devices by discussing the time-overcurrent plot, *R-X plot* and time-distance plot. The proposed new protection schemes for these distribution networks have achieved the orderly protection operation in case of a fault, namely the appropriate protection coordination.

Declaration

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

Intellectual Property

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I would like to express my gratitude to my supervisor, Professor Vladimir Terzija, who has given me the chance to pursue this degree and perform this research work under his guidance. His great help has supported me not only in terms of academic knowledge but also in my life abroad. I would also like to thank Mr. Georgios Peltekis, who has given me valuable materials for my dissertation and support when I required.

Finally, for their encouragement and support I would like to thank my parents. They have given me so much comfort and care during the past year.

1. Introduction

Historically, electric power systems were designed as a pure radial networks, which have gradually evolved into meshed networks. Radial operations have been applied for years in order to protect medium voltage distribution networks and their greatest benefit is their simplicity. However, with a much greater focus on the improvement in power quality, system reliability and environmental problems, meshed networks and the penetration of distributed generators are becoming the preferred options.

Despite the positive aspects of the meshed configuration and DG connection, there are also some difficulties such as protection coordination problems once they have been applied. One of the most significant concerns is the coordination between protective devices. As the conventional distribution network is radial in nature, the primary substation is the only power source to supply the downstream load and to sustain the fault current (an example of a radial network can be found in Section 5.3, the distribution network with DGs connected can be found in Section 5.4). Distributed resources in a meshed structure invalidate the natural radial configuration of the distributed network (Section 6.2). Obviously, the presence of DG would have an impact on the fault current level. Moreover, the conventional network is fed by a utility active resource while the system with the DGs connection is supplied by more than one active resource. This causes a change in the fault currents' directions. In this dissertation, the feeder protection issues that result from DG propagation are considered. Sensitivity and selectivity are the typical feeder protection requirements. The relay operation can be delayed or, even worse, totally blocked because of the blinding operation (Explained in Section 4.4), which will then have an impact on sensitivity. In addition, unnecessary tripping occurs at the adjacent feeder that the DG is connected to. This can adversely affect selectivity. These effects become a problem when considering the protection coordination, which is decided by the DG capacity, the DG location and the number of DGs connected to the system. Moreover, the complexity of the network topology makes the calculation process extremely difficult.

This dissertation firstly gives a brief introduction to power system protection in Chapter 2, which includes the basic elements of an overcurrent protection system and a distance protection system. Then Chapter 3 shows an analysis of coordination problems, and then discusses the various protection schemes in a conventional radial network with a single source, a distribution network with DG connections and a mesh network with or without DGs. The protection coordination problem is discussed in detail in these protection schemes, which include the coordination of fuses, overcurrent relays and distance relays. The effects caused by the proliferation of DGs are given in Chapter 4. There are 4 major influences: loss of coordination grading, false tripping, blinding, and under reaching. Each effect is explained and solutions are proposed. Chapter 5 and Chapter 6 illustrate the protection system in examples of distribution networks in detail. The protection systems for each network are simulated in DIgSILENT software, which includes the network modeling, the coordination procedures, the analysis of the *time overcurrent plot*, and the setting of relay parameters. The project summary and future work are discussed in Chapter 7.

2. Protection system

2.1 Chapter introduction

This chapter gives a brief explanation about protection systems in terms of overcurrent protection and distance protection, including the description of different types of protective devices that will be used in this project.

2.2 Basic elements of a protection system

The protection arrangement for any power system must take into account the following basic principles: reliability (including dependability and safety), speed and selectivity. The reduction in the number and duration of the interruptions to the electricity users can enhance the reliability of the power supply. Power quality can also be improved with a faster pick up time to minimize the likelihood of voltage sags, voltage flicker etc.

The protective relay is the most frequently used protection device and a basic element in a protection system. The role of a protective relay is to detect system abnormalities and to selectively execute appropriate commands to isolate only the faulty component from the healthy system [1]. Protective relays are connected to the power system over instrument transformers: the current transformer (CT) and the voltage transformer (VT). Figure 2-1 shows a typical singe line diagram in which a protective relay is connected to the power system. The relay itself is also connected to the circuit breaker, which receives trip commands to selectively eliminate the fault. VT is optional, but essential for directional and distance relays.

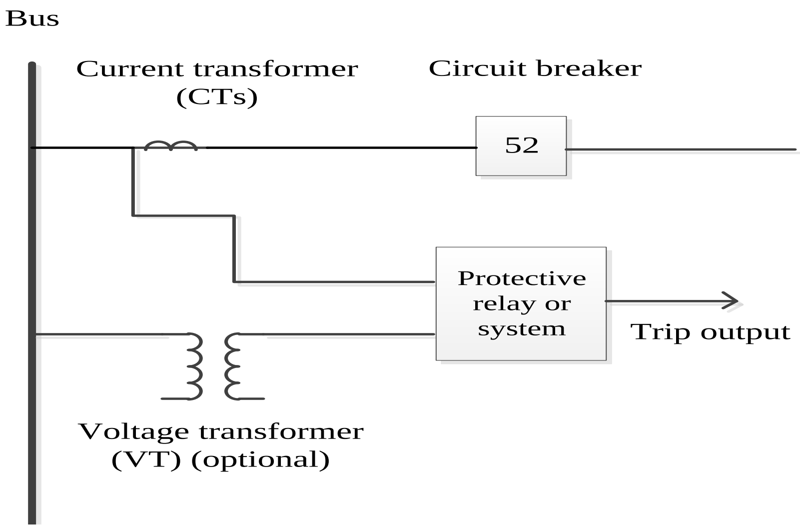


Figure 2-1 Single-line connection of protective relay

Protection relays can be classified in accordance with their function:

1. overcurrent
2. directional overcurrent
3. distance
4. differential
5. overvoltage
6. others

The simplest network topology is a radial system, and overcurrent (OC) relaying is the most widely used type for its protection due to the large current and the low cost for OC relays. However, OC relays and fuses may not be enough to protect power system networks with distributed generators (DGs) connected to the grid. To ensure a reliable and secure protection of networks involving DGs, more complex protective devices must be used: e.g. directional, or distance relays.

2.3 Overcurrent protection

2.3.1 Overcurrent relaying

Overcurrent relaying is the most common form of protection used to eliminate system faults followed by excessive currents. Based on the relay operating characteristics, overcurrent relays can be classified into three major groups [2]:

1. definite-current or instantaneous
2. definite-time
3. inverse time

The characteristics curves of these three types are shown in Figure 2-2, the horizontal axis (*I*) is the current and the vertical axis (*T*) is the time, *t1* is the tripping time when the current reaches the pick up value. Additionally, the combination of an instantaneous with inverse time characteristic is also illustrated.

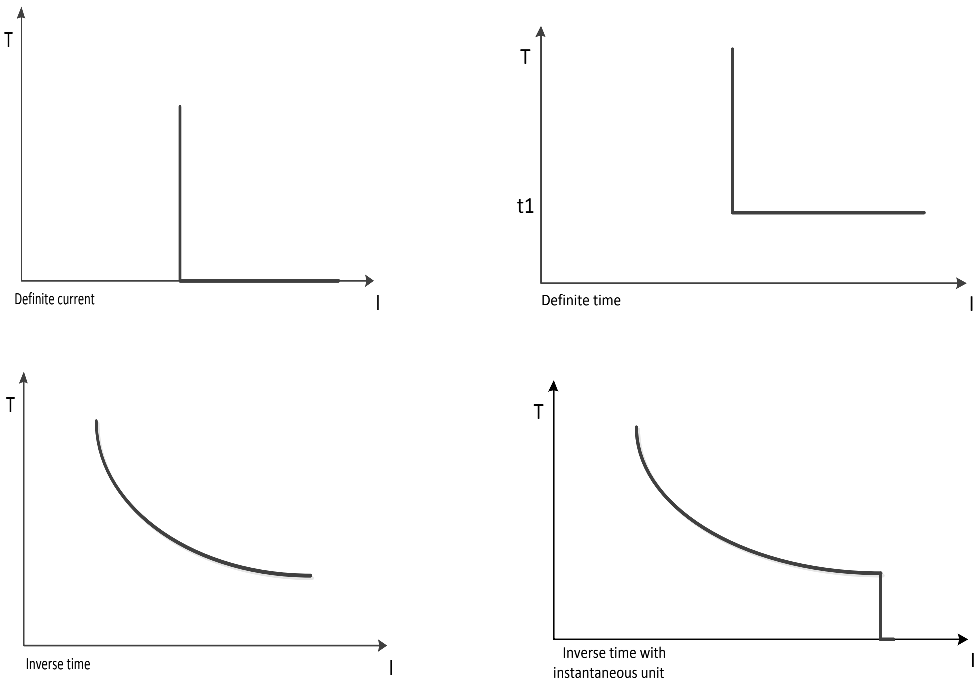


Figure 2-2 Different characteristics of OC relays

The instantaneous relay operates instantaneously when the current reaches the pick-up value. It is commonly used in situations when the fault current is relatively high to ensure the security by providing fast tripping. Definite time characteristics of relays operate with a pre-defined time when the current reaches the pick-up value and enables the setting to be varied to cope with different levels of current. The main disadvantage of this relay is that faults near to the source have a bigger current that may have a relatively longer tripping time and which may cause damage to the equipment.

The inverse definite minimum time (IDMT) relays are inversely proportional to the magnitude of the current, which indicates that IDMT OC relays have fast tripping times for higher fault currents. When a fault current decreases, a longer operating time is needed to isolate a fault. The current/time tripping characteristics of IDMT relays may need to be varied according to the tripping time required and the characteristics of other protection devices used in the network. For this purpose, IEC 60255 defines a number of standard characteristics as follows [4]: Standard Inverse (SI), Very Inverse (VI), and Extremely Inverse (EI) summarized in Table 2-1.

Standard Inverse (SI)	$t = \mathrm{TMS} \times \frac{0.14}{I_R^{0.02} - 1}$
Very Inverse (VI)	$t = \mathrm{TMS} \times \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = \mathrm{TMS} \times \frac{80}{I_r^2 - 1}$

Table 2-1 Relay characteristics according IEC 60255

Where:

Ir = If/Ip

Ip = relay current setting

If = fault current

TMS = Time Multiplier Setting

2.3.2 Fuses

Fuses are also one of the most commonly used elements of a protection system. They disconnect the faulty circuit if the current reaches a pre-defined value. Speed and cost are the main merits of fuses. Their drawback is that they cannot be reset or readjusted by themselves and they need to be replaced after each operation. The fuse nominal current should be greater than the maximum continuous load current at which the fuse operates. The characteristic curve of a fuse in the *time overcurrent plot* is given below in Figure 2-3. This is an example of the distribution network shown in Figure 5-1. The X-axis represents for the current and the Y-axis represents for the time. Further details are in the Appendix A.1.3. The Minimum Melt Time (MMT) is the time between initiation of a current large enough to cause the current-responsive element to melt and the instant when arcing occurs. The Total Clearing Time (TCT) is the total time elapsing from the beginning of an overcurrent to the final circuit interruption; i.e. TCT = minimum melt + arcing time.

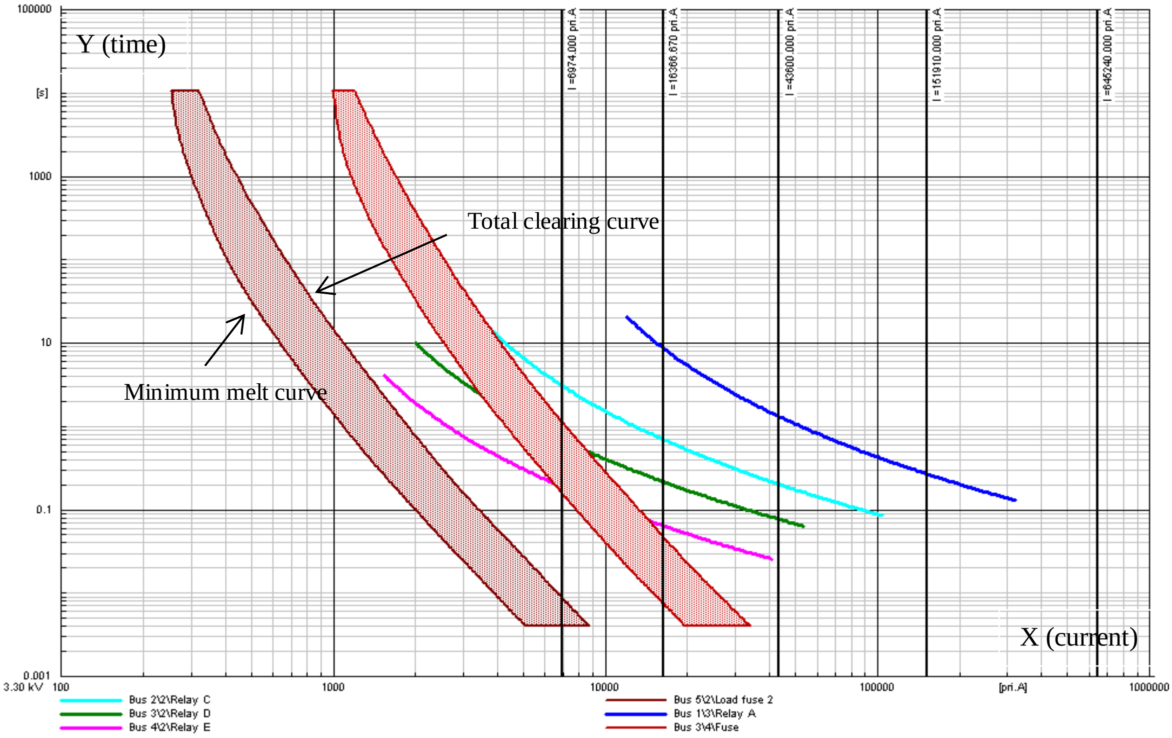


Figure 2-3 A *time overcurrent plot* of for the fuses

2.3.3 Directional relays

When the fault current can flow in both directions through the relay location, it is necessary to make the response of the relay directional by the introduction of a directional control facility [4]. The directional facility is provided by the use of additional voltage inputs to the relay. The voltage signal is used as a reference parameter and the angle position between the current and the voltage decide whether the relay should block or operate. For instance, a directional relay on the forward direction only operates when the fault occurs in front of the relay but a fault located behind the relay does not operate.

The typical directional relay characteristic is shown in Figure 2-4. This is a 30^o type unit. The maximum operate torque occurs when the current flows from polarity to non polarity (I_{pq}) and leads by 30^o the voltage drop form polarity to non polarity (V_{rs}). The operate zone of the unit is the half plane, which is bordered by the zero torque line. It will operate from currents almost lagging the reference voltage V_{rs} at 60^o as opposed to leading the reference voltage by almost 120^o. There are also 45^o, 60^o, 0^o units available in basic deign characteristics of a directional relay.

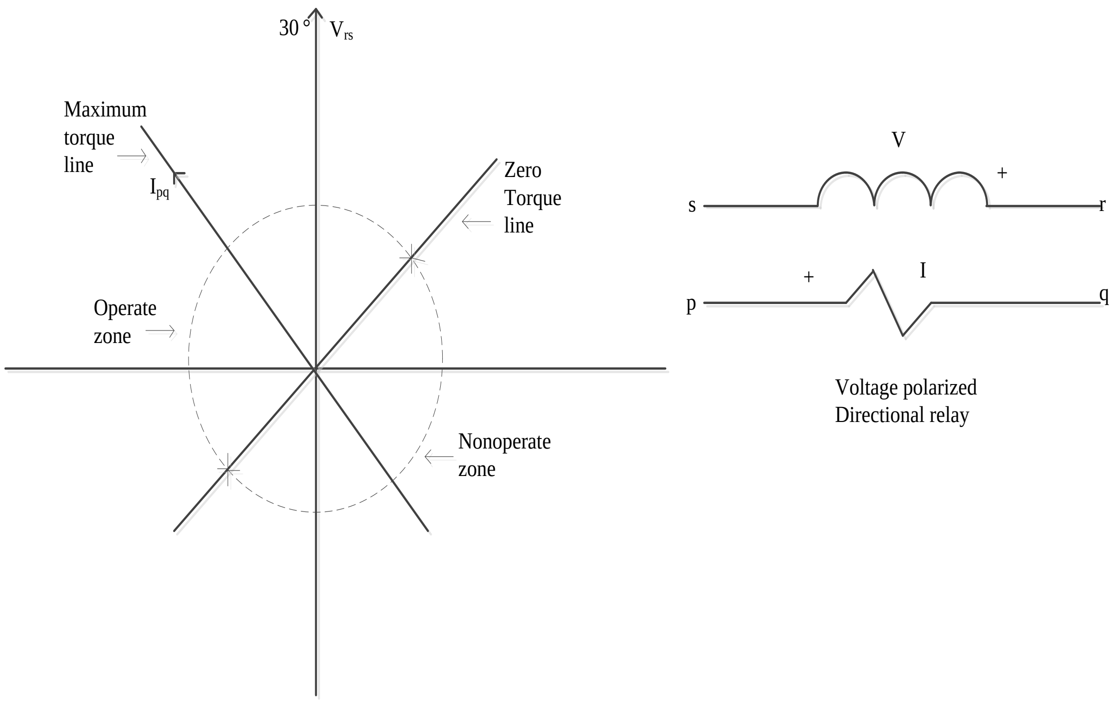


Figure 2-4 Typical directional relay characteristic (30^{o} type unit)

2.3.4 Current and voltage transformer

Current or voltage instrument transformers are essential to isolate the protection, control and measurement equipment from the high primary currents and voltages of a power system. Supplying the equipment with the appropriate values of the current and voltage—generally these are 1 A or 5 A for the current coils, and the 120 V for the voltage coils. The behaviour of current and voltage transformers during and after the occurrence of a fault is critical in electrical protection since errors in the signal from a transformer may cause mal-operation of the relays.

The nominal primary voltage of a VT is generally chosen with the higher nominal insulation voltage (kV), and the nearest service voltage in mind. The nominal secondary voltage is generally standardized at 115 and 120 V. In order to select the nominal power of a VT, it is usual to add together all the nominal loadings of the apparatus connected to the VT secondary winding. In addition, it is important to take into account the voltage drops in the secondary wiring, especially if the distance between the transformers and the relays is large.

Almost all CTs universally have a 5 A secondary rating. Other ratings exist, such as 1 A but are not common. When selecting a CT, it is important to ensure that the fault level and normal load conditions do not result in saturation of the core and that the errors do not exceed acceptable limits. The transformation ration of the CTs is determined by the larger of the following two values [2]: nominal current or maximum short-circuit current without saturation being present.

2.3.5 Equipment damage curves

When a fault occurs, the equipment will suffer a significant fault current and could be damaged because of the extremely high current after a prolonged period. Damage can be thermal or mechanical. As with OC protection, it is usual to plot damage curves of cables or transformers on a log-log graph along with the relay characteristics. When assessing the protection system in a network, we should consider that the protection characteristic curves must be below and to the left of the damage curves of any plant that they are responsible for protecting [5]. An example of the damage curves can be seen in Figure 2-5, in the *time overcurrent plot*, relay F is protecting the cable C 2-6 from probable permanent damage.

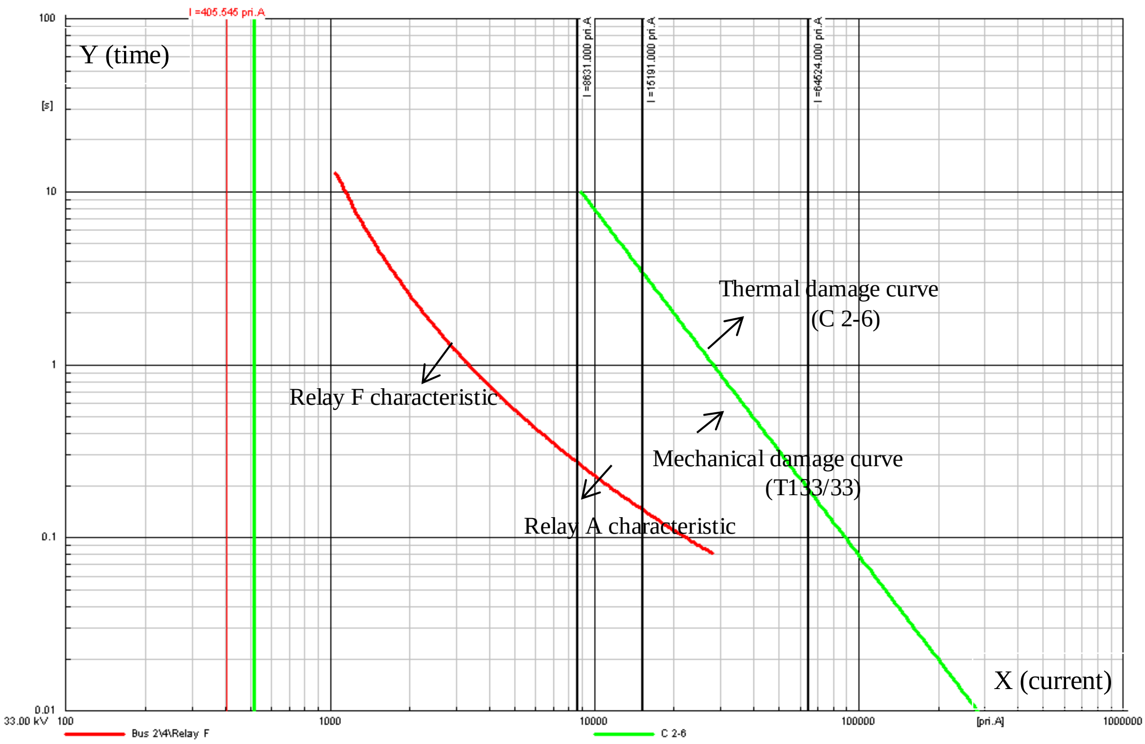


Figure 2-5 Example of a cable damage curve

2.3.6 Transformer inrush current

When a transformer is energized, a transient current refers to the maximum, instantaneous input current that can flow for several cycles. The selection of overcurrent protection devices such as fuses and circuit breakers is made even more complicated when high inrush currents must be tolerated. The overcurrent protection must react quickly to overload or faults but must not interrupt the circuit when the inrush current flows. The duration of an inrush current can only be sustained for a few cycles, while the breaking time of a protective device usually lasts for several seconds. As long as the tripping time of protective devices is longer than the duration time of an inrush current, the false distinguishing problem caused by an inrush current can be eliminated [6].

2.4 Distance protection

2.4.1 Distance relay

Distance relaying can be applied when overcurrent relaying cannot fulfill the protection requirements such as sensitivity, and selectivity. Distance relays are capable of measuring the impedance of a line to a reach point and are designed to operate only for faults occurring between the relay location and the reach point, and thus can distinguish faults that may occur beyond the protected zone. The reach point of a relay is the point along the line impedance locus that is intersected by the boundary characteristic of the relay [4]. As this is determined by the division of the voltage and current and phase angle, it is plotted on an *R-X plot* for a clear observation.

2.4.2 Types of distance relays

Distance relays are classified depending upon their characteristics in the *R-X diagram,* where the resistance *R* is the abscissa and the reactance *X* is the ordinate. Under any circumstance the origin is the relay location and the operating area is usually in the first quadrant. Whenever the ratio of the system voltage and current fall within the circle shown, or in the cross-hatched area, the unit operates [6].

Typical characteristics of the distance relays on these axes are displayed in the following figures. Figure 2-6 shows two distance relay characteristics, the left diagram is impedance characteristic. The impedance characteristic will operate in all the 4 quadrants. This design needs an extra directional-sensing unit since it operating in all four quadrants. Thus, this type is obsolete design. The MHO characteristic is a circle whose circumference passes through the origin, which combines the properties of impedance and directional relays. This states that the impedance element is inherently directional and, therefore, it will operate only for faults in the forward direction.

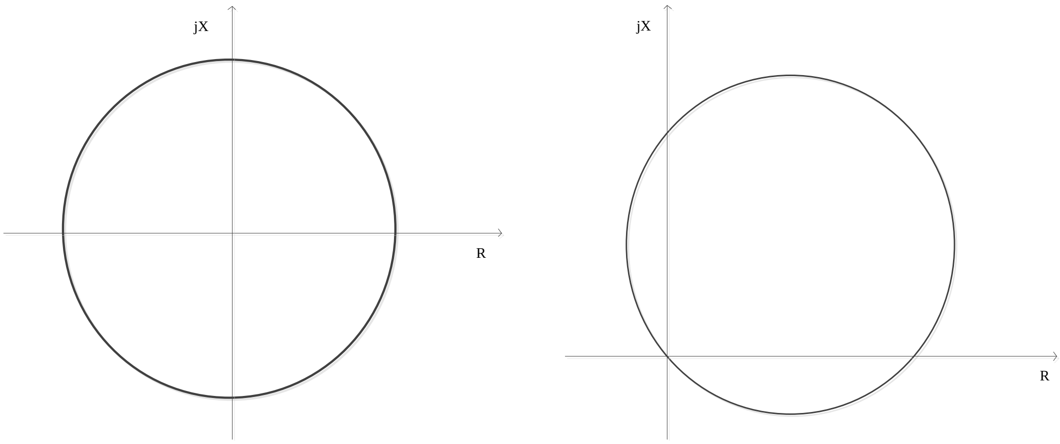


Figure 2-6 Distance relay characteristics on the *R-X diagram*

An MHO distance relay requires the voltage to operate correctly. However, the voltage will be very small or approaching zero for a fault right at the relay location. If the voltage falls to zero during a fault, the tripping of the relay could be inoperative or inactive. For a three-phase close-in fault, the operation of any of the MHO functions may be jeopardized because there will be very little, or no voltage available to develop the polarizing quantity [7]. A memory circuit may be used to prevent the immediate decay of voltage applied to the relay terminals when a three-phase short-circuit occurs close to the relay bus [4].

2.4.3 The effect of arc resistance on distance protection

The impedance measured by a distance relay is made up of resistance and inductance up to the fault point. Nevertheless, the fault may involve an electric arc or an earth fault including additional resistance. The impedance angle is then affected by the value of the resistance of fault impedance, which might result in the total resistance seen by the relay outside the characteristic or the circle. Thus a relay characteristic with an angle setting equal to the line angle will have an under-reach problem. It is common to set the relay characteristic angle a little less than the line angle in order to accept a small amount of fault resistance without producing under reaching.

Figure 2-7(a) shows the effect of arc resistance on the MHO relay. R is the arc resistance and Z_f is the impedance of the line up to the fault point F. The relay characteristic angle is equal to the line characteristic angle μ. For a fault at F, the impedance measured by the relay is $Z_f + R$ and is outside the characteristic circle. This displays the arc resistance and causes under reaching. If the MHO characteristic is shifted, the characteristic angle α of the MHO relay will be less than the angle μ in Figure 2-7 (b). In this case, the impedance $Z_f + R$ measured by the relay remains within the characteristic circle. The characteristic angle of the relay is less than the characteristic angle of the line and could have a greater tolerance for the arc resistance.

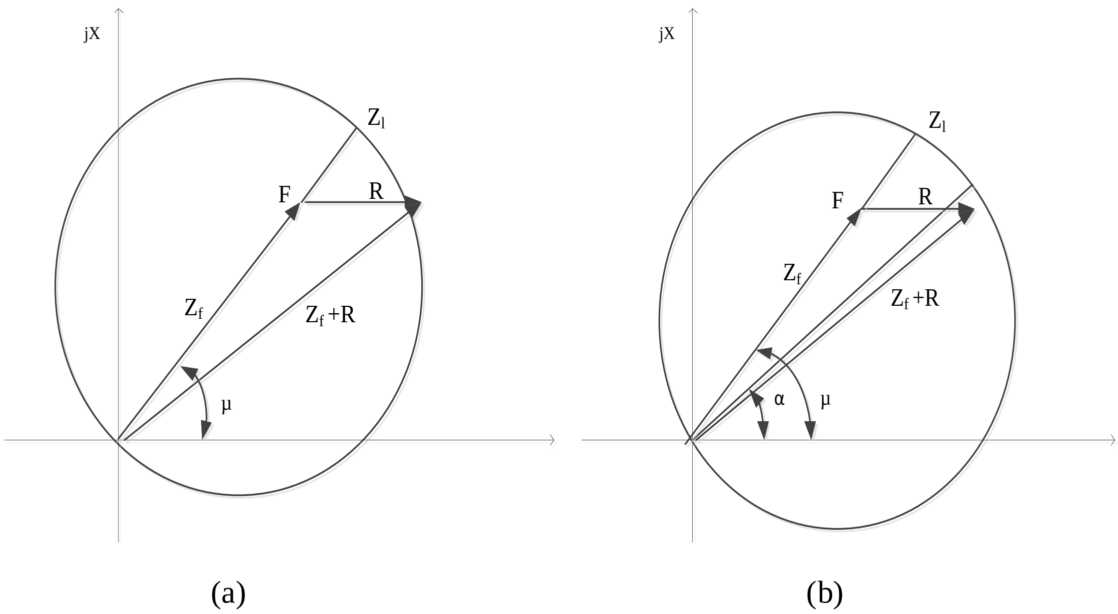


Figure 2-7 The effect of arc resistance on the MHO relay

2.5 Chapter summary

Basically, a protection system is made up of instrument transformers, protection relays, circuit breakers and auxiliary power supplies. The suitable protective devices (current transformer, voltage transformer, overcurrent relays, directional relays, distance relays, fuses etc.) are selected for different networks. In the meantime, each protective device should be considered in details regarding pick-up current settings, characteristic curves, the reaching of a protection zone, etc. When considering protective devices, some noticeable issues (such as equipment damage curves, the arc resistance) are discussed as well.

3. Protection coordination

3.1 Chapter introduction

This chapter describes what protection coordination involves and how to coordinate the protective devices in different network topologies.

The protection coordination problem is about determining the sequence of relay operations for each possible fault location and to provide sufficient coordination margins without an excessive time delay [8]. Coordination margin or coordination grading or coordination time interval is the time delay between the operation of the main and the back-up protective devices. Its value is, usually 0.2-0.5s. As mentioned before, all protective device settings in the network must be carefully calculated to ensure that the coordination between protective devices is successful. A relay only trips the circuit breaker in situations when the fault location is within its protection zone. It is essential that any fault is efficiently isolated, thus, wherever possible, every element in the power system should be protected by both primary (main) and back-up relays. If a fault occurs, the main protection should trip the circuit breaker instantaneously. After that, after a time delay (coordination margin), the back up protection should operate if the primary protection does not respond properly.

3.2 Overcurrent protection coordination in different network configurations

3.2.1 Basic overcurrent protection coordination rules

The basic rules for a correct overcurrent relay coordination can generally be stated as follows [4]:

a) Whenever possible, use relays with the same operating characteristic in series with each other

b) Make sure that the relay remotest from the source has a current setting equal to or less than the relays behind it, that is, the primary current required to operate the relay in front is always equal to or less than the primary current required to operate the relay downstream it

The coordination of time overcurrent relays is the process of determining settings for the relays that will provide a proper protection operation in case of a fault [8]. IDMT characteristics are the most widely used where grading is possible over a wide range of currents and relay can be set to any value of definite minimum time required. The selection of settings will now be explained in detail.

There are two main settings that need to be considered when using IDMT relays: the pick-up current and the time multiplier setting (TMS). These are discussed in Section 2.3.1. The pick-up current is the threshold that indicates the minimum operating current for the IDMT relay. The current setting must be chosen so that the relay does not operate for the maximum load current in the circuit being protected, but does operate for currents equal or greater than the minimum expected fault current. The TMS is applied to ensure the coordination between protective devices, providing a family of curves so that two or more relays sensing the same fault current can operate at different times [6]. The time interval that must be allowed for the operation of two adjacent relays to achieve correct discrimination between them is called the grading margin [6]. Usually the same grading margin will be applied across the entire protection system, which is normally 0.25s for numerical protection relays.

The coordination of the overcurrent scheme starts with the remotest downstream device and then is coordinated with each upstream device back towards the source. Downstream means the point is further away from the source and upstream means the point is close to the source. Devices are coordinated by the combination of the current and the time. A practical and effective method for verifying the protection coordination between protective devices is to analyze the time-overcurrent curves of devices.

3.2.2 Overcurrent protection coordination in radial network

Conventional OC protections normally have radial topology, which is characterized by a utility source at the upstream side; therefore, the fault current has only one direction, this direction is from an upstream single source to the downstream fault point. The selectivity of a protection system can be clearly observed in the time-current diagram of a radial network with a single resource. A relay close to the fault point operates in the largest fault current, and a relay near to the source operates in the shortest operating time. Thus for a particular fault, all the relays connected in the radial feeder see the fault current but are set to operate at different times by selecting different time current characteristics [9].

For instance, consider Figure 3-1, a radial network with only one source that supplies the power system. This is a simplest configuration and the selectivity can be easily achieved. Relays A, B, and C used to protect the network are OC IDMT relays. The selection of the upstream relay B needs to be coordinated with the downstream relay C and the grading between two relays will take place at the maximum fault current at line C-D. For a fault at line C-D, relay C should trip first as the main protection and relay B works as a back-up protection and has a higher TMS. If relay C fails to operate, relay B will trip after a time delay (grading margin). After selecting the appropriate IDMT characteristic curve for relay B, the same procedure should be repeated for the coordination between relay B and relay A.

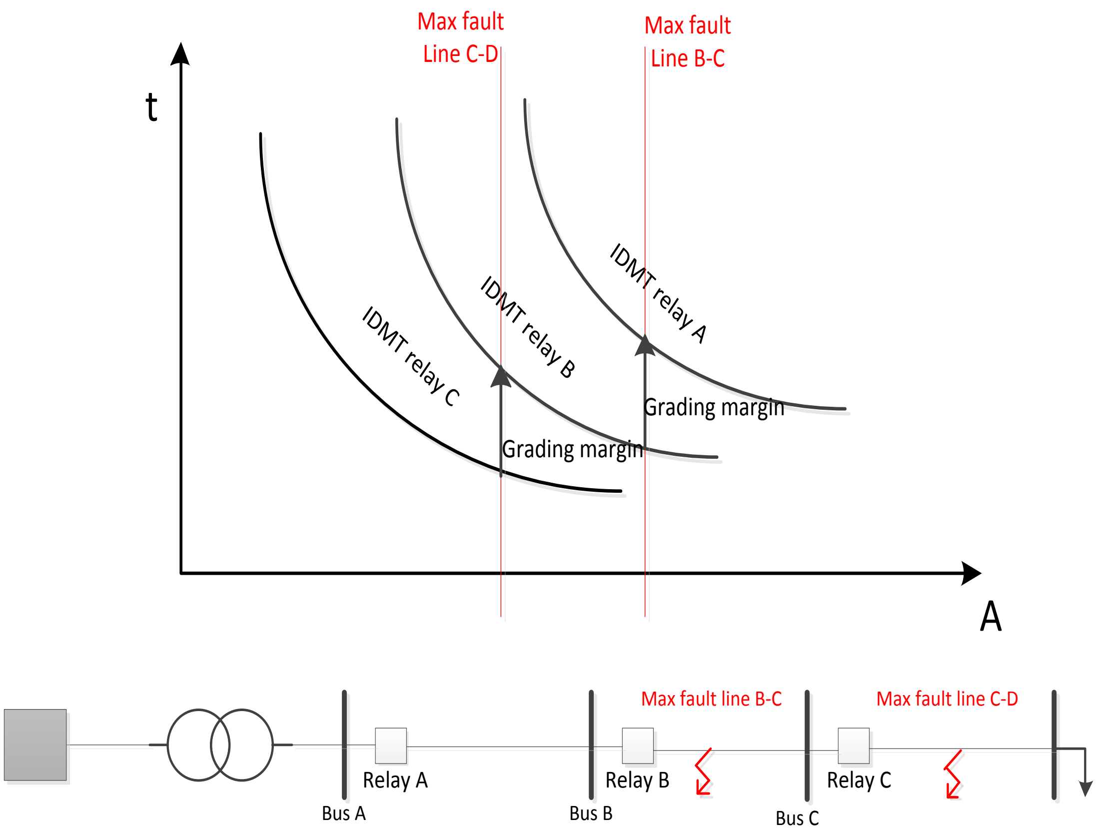


Figure 3-1 The coordination of IDMT relays

3.2.3 Protection coordination in networks with multiple sources

A distribution network can be supplied by multiple sources to increase the reliability of power supply for customers. Nevertheless, it also costs more and makes the protection consideration more demanding. In the network supplied by two sources (see Figure 3-2), the network should be protected by directional OC relays. The vertical axis (T) represents time and the horizontal axis (L) shows the relative distance from relay to the source. If E2 does not exist, then the tripping sequence of relays 1, 2 and 3 would be the same as in the case with a single source E1. If relays 1, 2 and 3 are directional OC relays and they only trip when the fault current flows into the line, then the coordination procedures for OC relays mentioned before can be used here to achieve the proper coordination between relays 1, 2 and 3. The coordination between relays 4, 5 and 6 is the same, but now E1 should be ignored and relay 1 is the farthest remotest downstream from E2 and should be set first. In the network with two sources, we need to repeat the coordination procedures twice and they are independent of each other. The second diagram represents the tripping sequence for relays in the network below.

For instance, if a fault occurs between relay 3 and relay 4, relay 3 will trip first to break the fault; if relay 3 fails, then relay 2 will trip with a time delay; the final relay which has the longest tripping time is relay 1 and the fault will be disconnected from source E1 if any of them have tripped. At the same time, relay 4 has to disconnect source E2 as well.

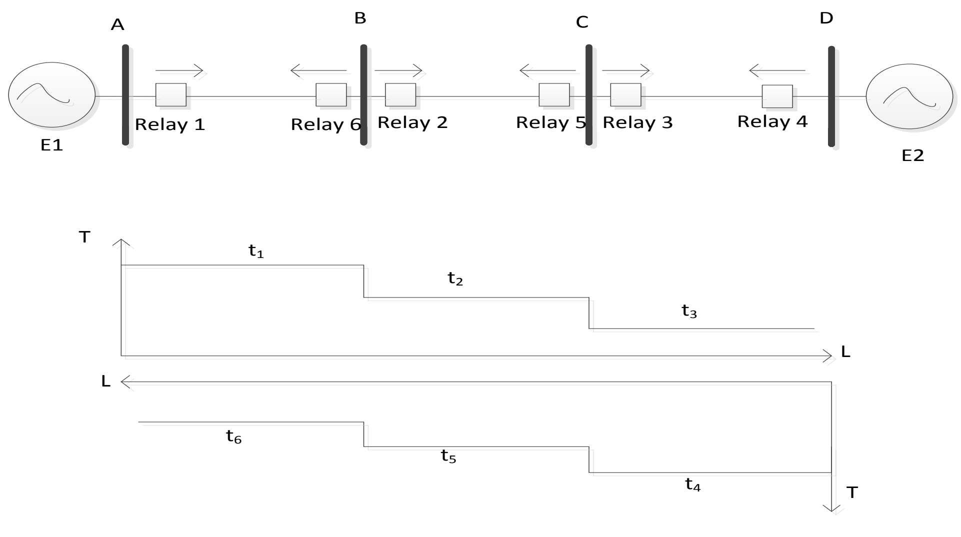


Figure 3-2 Coordination in a multiple sources system

3.2.4 Protection coordination in meshed networks

With the fast growing expansion of modern power systems and the high demand for power supply quality, the meshed network with multi resources is becoming a hot spot. A meshed network can have one close-loop or several close-loops and are much more complicated than a radial network. The diagram below is an applicable loop network and shows how to coordinate such a network configuration.

For a special meshed network (ring or close-loop network) displayed in Figure 3-3, there are 3 sources that provide the fault current. One is an external grid and the other two are asynchronous machines. Directional overcurrent (OC) relays are necessary in the system with multiple sources. There are six directional OC relays with IDMT characteristics installed at both ends of the line. Each directional unit will operate when the current flows into the line section.

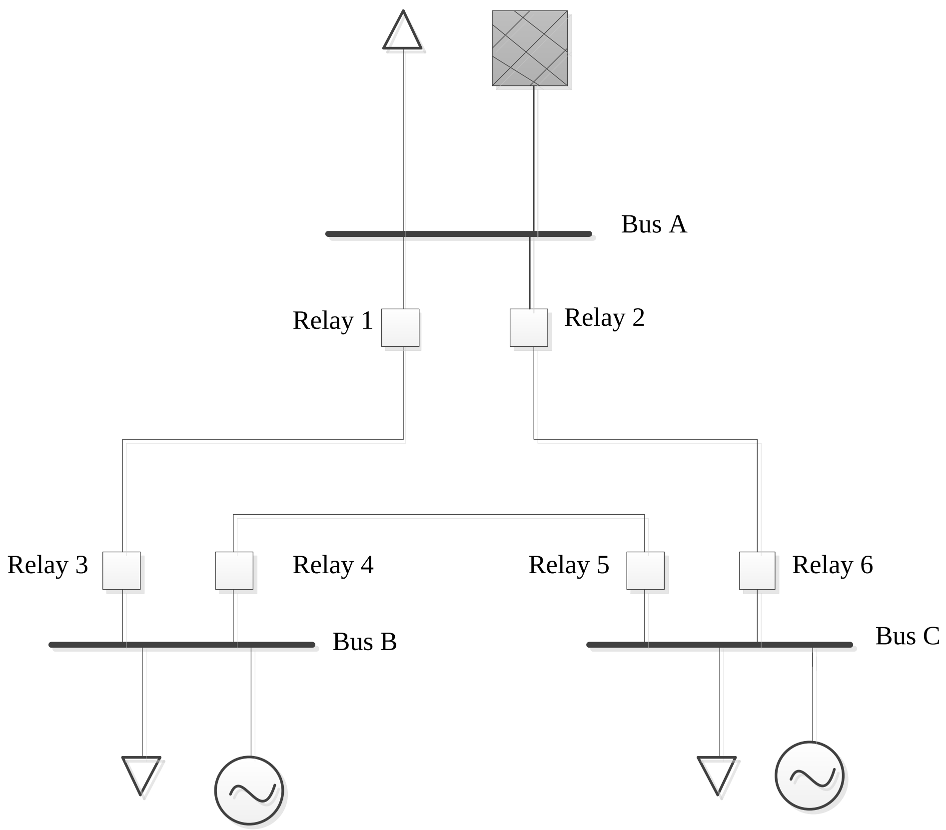


Figure 3-3 A meshed network with multiple sources

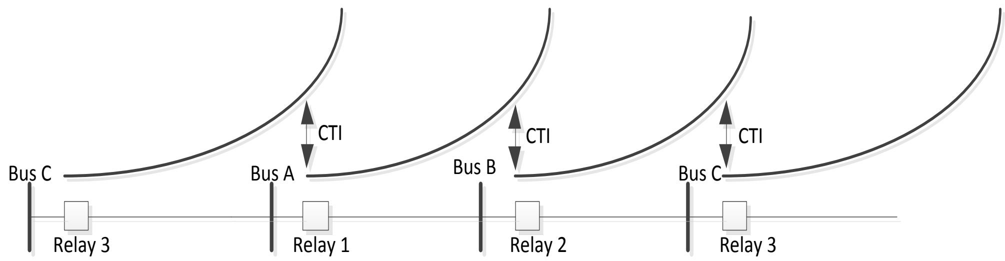


Figure 3-4 Coordination between directional IDMT relays around clockwise

In setting relays around a loop, a good general rule is to attempt to set each relay to operate in less than 0.2s for the close-in fault and at least 0.2s plus the CTI (coordination time interval) for the far-bus fault [6]. A fault close to relay is known as close-in fault for the relay and a fault at the end of the line is know as far-bus fault for the relay. Taking Figure 3-4 for example, the tripping time takes longer when the fault current decreases. The IDMT characteristics of each relay are a curve which indicates that the tripping time takes longer when the fault location is far from the relay. Relay 1 should coordinate with relay 3 as the main protective device for the fault between bus A and bus B, and should coordinate with relay 2 as the back-up protective device for the fault between bus B and bus C. Relay 1 coordinates with relay 3 for the close-in fault formula and it coordinates with relay 2 for the far-bus faults restraint. This is the same procedure and requirement for relay 2 and relay 3. Further information regarding the explanation can be found in [6].

3.3 Distance protection coordination

The protection of a distributed network becomes challenging once the amount of generation has increased, which may be either directly connected to the network, or indirectly connected to the network, i.e. through step-up transformers. Specifically, prospective fault currents can vary over a wide range, and may become bi-directional. This causes the grading of the overcurrent relays very difficult [10]. This difficulty applies equally to radial circuits protected by directional relays. Furthermore, to maintain the stability of distributed generators, fault clearance times should be kept to a minimum [11]. The characteristics of a distance element can be shaped and distance relays are inherently directional. Moreover, a distance relay installed can make the OC element directional with a distance element providing the torque control [12]. Distance protection can enhance the performance, with or without a DG connected.

The protection coordination becomes more complex and varied with the introduction of distance relays to the network. Without distance relays, one simply takes the coordination between OC relays into consideration. However, after the distance relays are employed in the protection system, the coordination between the distance relays and the coordination between the distance relay and the OC relay must be taken into account.

3.3.1 Protection coordination between distance relays

The coordination between distance relays is relatively less complicated compared to the OC relays. A careful selection of the relay reach settings and tripping times for the various zones of measurement enables the correct coordination between distance relays in a power system [4]. Basic distance protection comprises instantaneous Zone 1 which normally has a reach setting of up to 80% of the protected line impedance. Zone 2 of the distance protection must cover the remaining 15-20% of the line. To ensure full coverage of the line, Zone 2 protection should be set to cover all of the protected line plus 50% of the next shortest line or at least 120% of the protected line impedance. In order to coordinate with the primary relaying applied to adjacent circuits that fall within the Zone 2 reach, the tripping time of Zone 2 must be time-delayed and is usually 0.25-0.4 s. Zone 3 is set to cover all of the protected line plus 100% of the second longest line, plus 25% of the next shortest line. The operating time for Zone 3 is usually in the range of 0.6 to 1.0 s.

All zones of the protection systems of various plant items have to be coordinated to ensure their discrimination [14]. Figure 3-5 shows the coordination of distance relays on adjacent lines.

3.3.2 Protection coordination between distance and overcurrent relays

The primary or main protective device is the nearest to the fault location and it must respond to the fault as quickly as possible. Back up protective devices are devices that will be tripped within a time-delay after the main relay fails to eliminate the fault. The delay time is called the coordination time interval (CTI) or grading margin, and we can generalize the constraint between the main and back up relay as follows [16]:

$$T_b - T_m \geq CTI \tag{3-1}$$

where T_b and T_m are the operating times of the backup and main relays respectively.

The derivation of the coordination arrangement for the systems where the OC and the distance relays are installed is discussed with the aid of Figure 3-6. There are two important constraints [15]-[16].

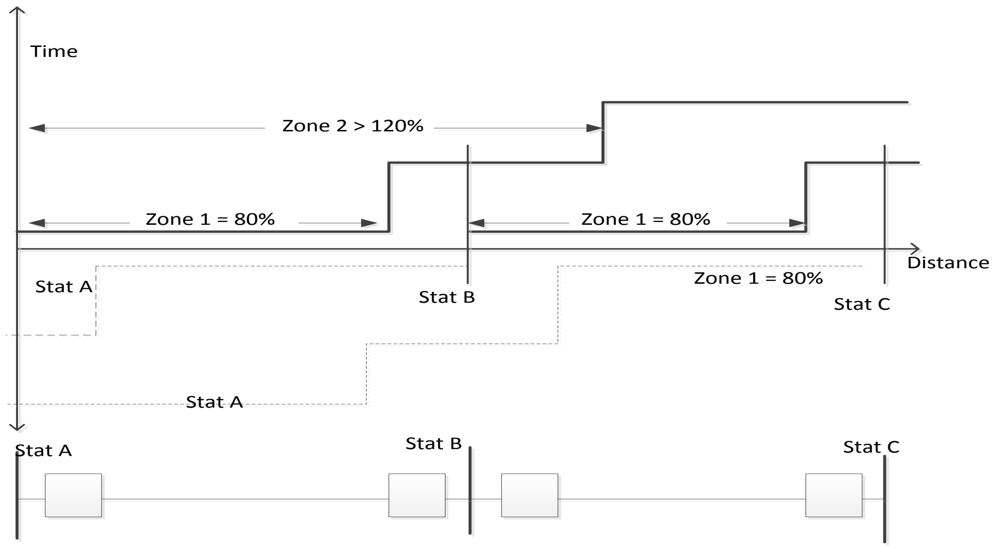


Figure 3-5 Coordination between distance relays

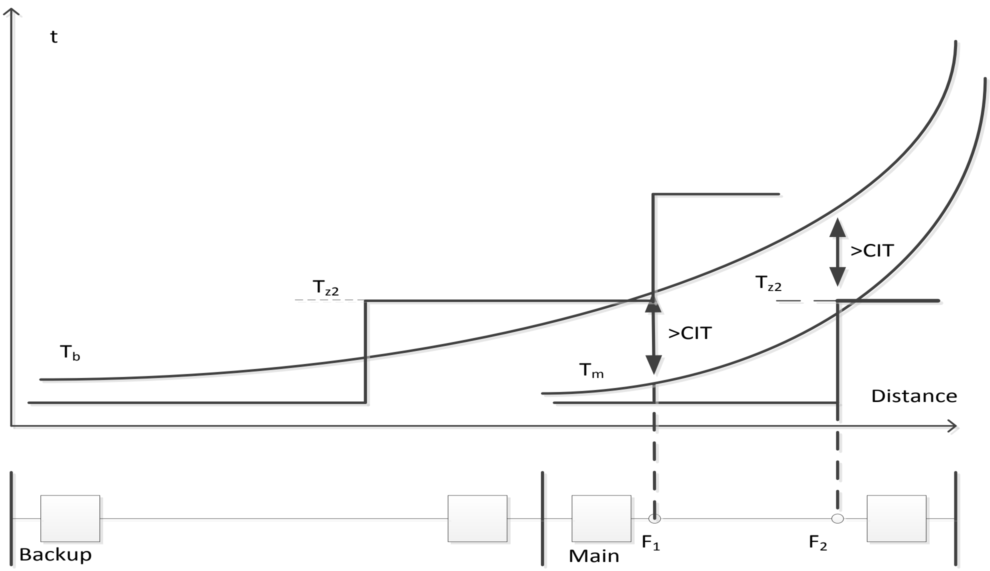


Figure 3-6 Coordination between distance and OC relays

a. The second zone backup distance relay must be slower than the OC main relay, which can be stated as follows:

$$T_{z2\ backup} - T_{oc\ main} \geq CTI \tag{3-2}$$

b. The OC backup relay must be slower than the second zone of the main distance relay:

$$\boldsymbol{T_{oc\ backup} - T_{z2\ main} \geq CTI} \tag{3-3}$$

T_{oc} is the operation time of the OC relay and T_{z2} is the operating time of the second zone of the distance relay. It indicates that both types of relays are taken into account.

Constraints show that: if a fault occurs, the main relay should operate faster than the backup relay. In Figure 3-9, if the primary protection (main OC relay or Zone 2 of the main distance relay) could not break the fault at F2, the backup OC relay should trip after a determined grading margin, or CTI. For a fault at F1, if Zone 1 of the main distance relay or the main OC relay is unable to clear the fault, Zone 2 of the backup distance relay or the backup OC relay should operate to clear the fault after a CTI. Some examples of CTI are shown in Figure 3-6 in the *time overcurrent plot* and also in Figure 3-1.

3.4 Chapter summary

In conclusion, the protection coordination ensures a faster pick-up time of protective devices; it minimizes the interruption time; it ensures that only the faulted elements are disconnected from the system and it keeps the healthy items unaffected in a protection scheme. In different protection schemes and network configurations, the coordination procedures and consideration are not the same. This Chapter provided detailed explanation on how to coordinate between overcurrent relays in radial networks, radial networks with multiple sources and meshed networks. Moreover, the procedures of protection coordination between distance relays and the rules and formulas of how to coordinate between distance relays and overcurrent relays were discussed as well.

4. Impacts of renewable energy sources on protection coordination

4.1 Chapter introduction

Most Distributed Generators (DGs) are defined as renewable energy, green energy sources and are gradually being utilized to provide a power supply for conventional distribution networks. Distributed generators are made up of induction and synchronous machines. Loss of the power source to the circuit to which an induction generator is connected will normally cause the generator to shut down. The induction generators can not usually become self-excited because they do not have a separate excitation system. A source of excitation current for magnetizing is required for the stator to induce rotor current. There is no sustained fault current as an induction generator draws its magnetizing current from the network. Thus, they are not capable of supplying isolated loads or sustained fault currents when separated from the power system [27]. The usage of DGs not only gives advantages to electricity users, but it also brings benefits to utilities. The merits of the application of DGs can be summarized as: increased voltage stability, loss reduction and high efficiency, environmental concerns and low pollution [17]-[19].

The purpose of protection coordination is to decide the sequence of relay trips and to ensure acceptable coordination grading margins without excessive time delay. DG connections will have a significant influence on the protection coordination. When DGs are connected to the main grid, the protective devices connected will detect different fault current levels and sense the fault current flow in more than one direction. A summary of the influence of DGs on the network, in terms of coordination problems, is given in the following chapter.

4.2 False tripping of overcurrent relays

In an active distribution network, both DGs and the external source will be subject to a fault current, whereas in a passive distribution network the fault current flows only from a single resource. Hence, a protective device located in the DG feeder in an active network may see a fault current flow from the DG caused by faults elsewhere in the system. To illustrate this problem in Figure 4-1, there are two sources supply the network, one is an external grid, another is a distributed generator. The relay A should trip for a short-circuit fault on the adjacent feeder 1; however, the relay B will see the fault current as well and may cause false tripping and then disconnect the non-faulted feeder 2. A solution to this problem, as stated in [20]-[21] is to apply directional relays to protect the feeders that may bring about false tripping. .

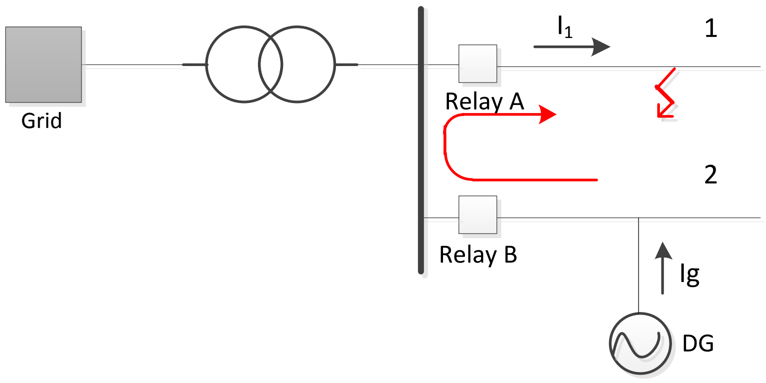


Figure 4-1An illustration of a situation where false tripping may occur

4.3 Loss of protective devices grading

The current injected by DGs will change the fault level both in magnitude and direction, which thereby results in a loss of selectivity. The protective devices are designed to sense a certain minimum fault current, which normally includes the ends of the feeder. As the penetration of the DG increases, it is more difficult to detect or sense a fault in overcurrent devices with the settings that were based on the minimum fault current before the DGs was connected. Additionally, the coordination margin is also used to distinguish the operating time of the relays. With more DGs installed out on the feeder, they will cut into the margin [22]. The problem can be resolved by readjusting the settings of the OC relays to build the new grading margin and to acquire the appropriate relay characteristics.

4.4 Blinding of overcurrent relays

When a DG is downstream of a relay and upstream of the fault point, the DG will contribute to the total fault current, but it will decrease the fault current seen by the relay at the same time. This may cause delayed tripping of the relay and could, potentially, in the worst scenario lead to the non-tripping of the relay. This problem is referred to as "Blinding of OC protection" [21]-[24].

Figure 4-2 displays a simple network with or without DG connection. I_r is the fault current sensed by the relay and I_f is the fault current flow into the fault location. Without the DG connected, $I_{r(1)} \approx I_{f(1)} \approx \frac{1}{z_r+z_f}$. With the DG connected: $I_{r(1)} \approx \frac{1}{Z_r+(1+Z_r/Z_g)Z_f} \approx I_{f(1)}$, $I_{f(1)} \approx \frac{1}{Z_R//Z_g+Z_f} > I_{f(2)}$. These equations show that the total fault current is increased and the fault current seen by the relay is decreased with the DG connected.

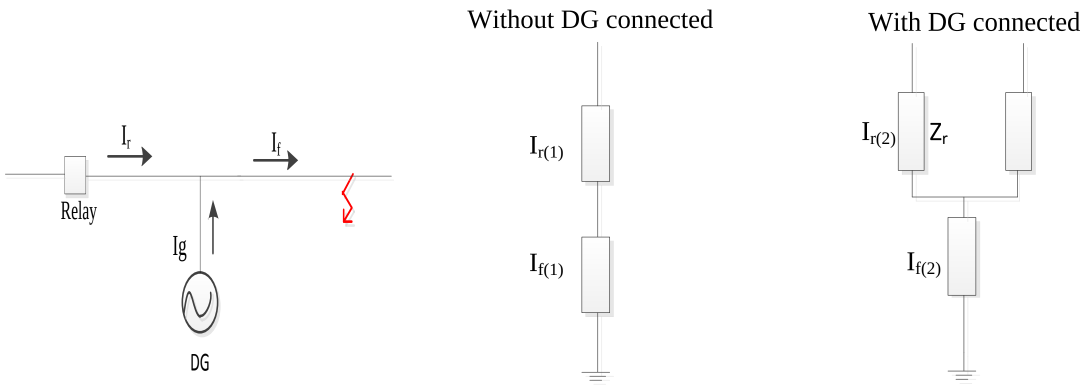


Figure 4-2 An example of blinding

The most straightforward method to avoid such a problem is to reduce the tripping time in order to assure correct operation, despite the blinding. A definite-time OC protection characteristic operates with a fixed time delay; when a definite-time characteristic is used there is no risk of binding because the tripping time is fixed no matter how the fault current changed. On the contrary, the operating time of IDMT characteristics will change as the fault current value varies. Therefore, a combination of an IDMT and a definite-time OC relays can be employed to tackle this difficulty. The following *time overcurrent plot* (Figure 4-4: *T* means time, *I* means current) demonstrates the characteristics of relay A and relay B. Relays A and B are both IDMT overcurrent relays. The coordination margin between relay A and B will obviously shrink after the definite-time characteristic has been introduced in relay A.

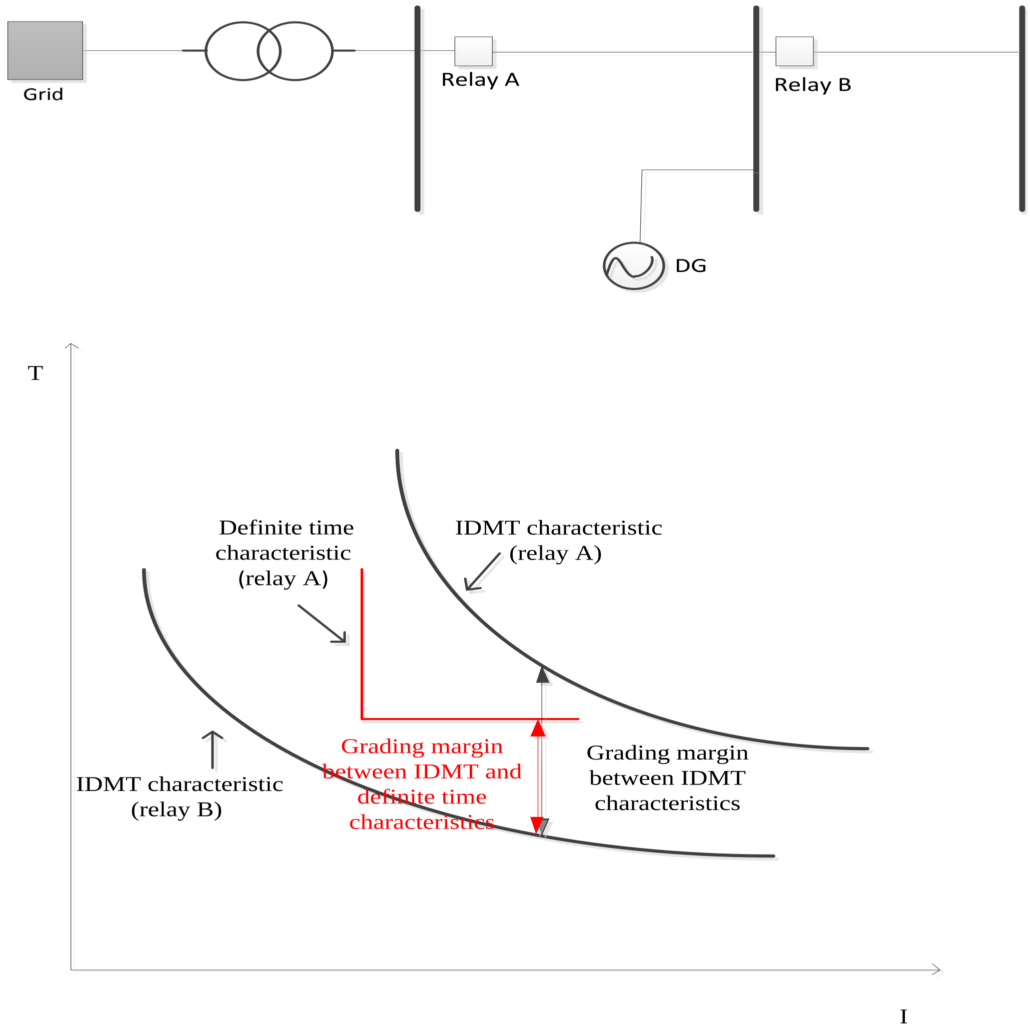


Figure 4-3 An example solution for the blinding problem

4.5 The effect of infeed on the distance protection

On the basis of the impedance measured, distance relays have the advantage that they can distinguish faults in different parts of a network. Essentially, this involves comparing the fault current, as seen by the relay, against the voltage at the relay location to determine the impedance down the line to the fault [15]. The effect of infeed needs to be taken into account when there are one or more generation sources within the protection zone of a distance relay which can contribute to the fault current without being seen by the distance relay [1].

Analysing the case presented in Figure 4-1, it can be seen that the actual impedance to the fault is Z_A+Z_B, but when the current I_B flows, the impedance appears to the relay as Z_A+Z_B+$(I_B/I_A)Z_B$. The impedance seen by the distance relay for a fault beyond busbar B is greater than what actually occurs. This effect is called the “infeed effect”.

The presence of the DG can cause the “infeed effect”. When DGs are added to the distribution network, the fault current from the generation adds to the fault current from the utility [26]. In Figure 4-3, if the current I_B flows from the DG connected to bus C, the distance relay may not operate according to its defined zone as the relay sees the impedance influenced by the DG as well as the infeed current.

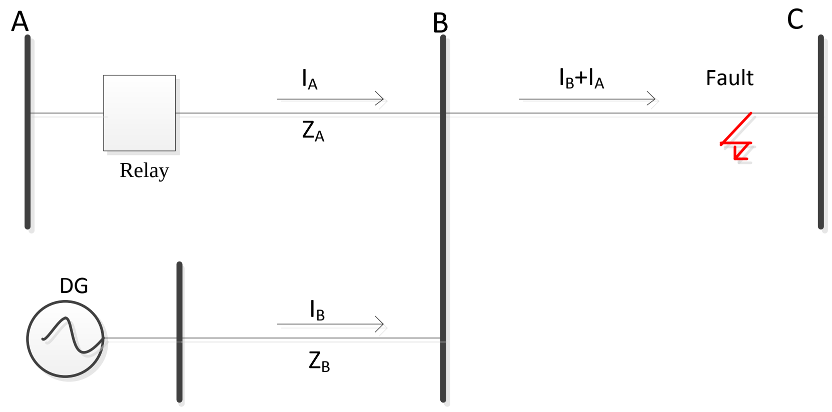


Figure 4-3 Example of infeed effect

The influence of the DG is the reduction in the reach of the distance relay, which can be summarized in as follows [26]: “When a fault occurs downstream of the bus where the DG is connected to the utility, the impedance measured by an upstream relay will be higher than the real fault impedance.”

Due to the penetration of DGs, the setting of Zone 2 and 3 for the relay should then take the following form:

$$\boldsymbol{Z_{relay}} = \boldsymbol{Z_A} + (\boldsymbol{1} + \boldsymbol{K})\boldsymbol{Z_B} \tag{4-1}$$

where K, the infeed constant, is given as: $K = \frac{I_{total\,infeed}}{I_{relay}}$

Since the value of the infeed constant depends on the zone under consideration, several infeed constants, referred to as K_1, K_2 and K_3, need to be calculated. K_1 is used to calculate the infeed for Zone 2. K_2 and K_3 are used for Zone 3. K_2 takes into account the infeed on the adjacent line and K_3 that in the remote line [2]. The calculation process in detail can be found in [2].

As far as the under reach problem (distance relay) is concerned, readjustment of the relay setting for each zone can make the relay operate correctly. The influence on zone reaching, caused by the DG, can be minimized or eliminated through a careful calculation process that considers the infeed constant. An adaptive distance scheme for the distribution system with DG can be found in [26]. This method focuses on the value settings of Zone 2 based on protected characteristics.

4.6 Chapter summary

As a result of the penetration of the DGs in distributed networks, some problems (false tripping, loss of grading, blinding, the effect of infeed) related to protection coordination have arisen. Through a proper design of the protection concept and protection coordination, each of these issues can be solved. Loss of grading margin is an inevitable issue when it comes to protection coordination and necessary readjustment is needed. In terms of overcurrent relays, false tripping and blinding problems could affect the sensitivity and selectivity of the protection system. The solution is to adopt directional overcurrent relays to prevent the circuit from potential false tripping. As for blinding of overcurrent relay, a combination of IDMT and a definite time characteristics is the solution. The effect of the infeed current could result in under reaching of the protected zone, which should be taken into account when studying the coordination between distance relays.

5. Computer simulation faulted distribution networks using DIgSILENT

5.1 Chapter introduction

The purpose of this chapter is to focus on how to use DIgSILENT to simulate faulty networks and to demonstrate the selection of setting and operation of protection systems. In this chapter the medium voltage (MV) network adopted from [27] will be employed to illustrate the protection coordination procedures with the help of two possible DIgSILENT networks:

1. radial network without DGs
2. distribution network with DGs

5.2 Network modeling

The power system software called DIgSILENT PowerFactory [25] can be applied to simulate and analyze the protection system of a network. By using a single database, containing all the required data for all the equipment within a power system (e.g. transmission lines data, cables data, generator data, protection data, signal distortions data, controller data), PowerFactory can easily execute a number of network planning applications. Some of these applications are load flowing, short-circuit calculations, harmonic analysis, protection coordination, stability calculations and model analysis [25]. The PowerFactory protective devices are all stored in the cubicle connected to the busbar and branch element, with CTs, VTs, circuit breaker and relays. Further information regarding the software is given in Appendix 1.

The 132 kV, 50 Hz external grid supplies the system through a 132/33 kV/kV transformer (see Figure 5-1). All loads are both static and balanced and their total loading is 28.1 MW. In the simulation, a large wind farm will connect to bus 2 through a T33/11 kV/kV transformer and a small wind farm will integrate to the system (bus 3) directly. All circuit breakers are stored in the same cubicle where relays locate in.

The large wind farm (See Figure 5-2) has six 11 kV strings and is comprised of 30 wind turbines, while the small wind farm (See Figure 5-3) contains two strings, and 10 wind turbines. Both of them are modelled using an induction machine as the wind turbine (0.96 kV, 1200 kVA) and each string is composed of five turbines. Each turbine is connected to the 11 kV collection busbar via the 11/0.69 kV transformers.

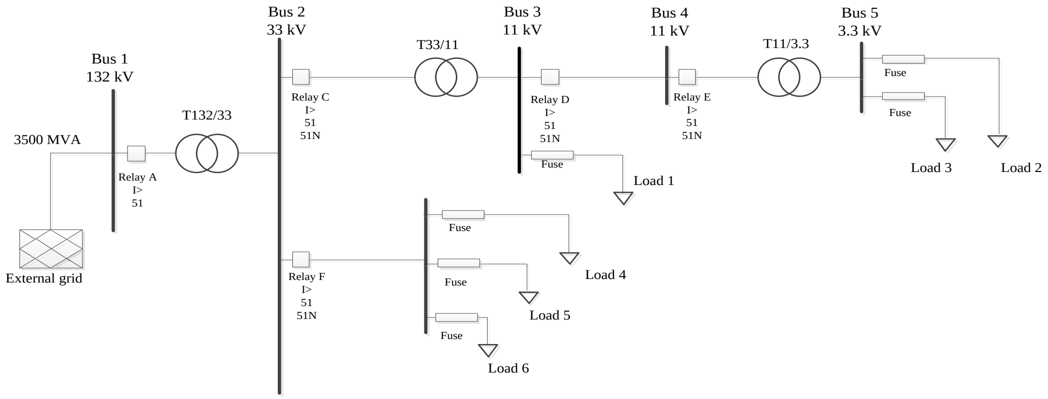


Figure 5-1 Singe line diagram of the distribution network without DGs

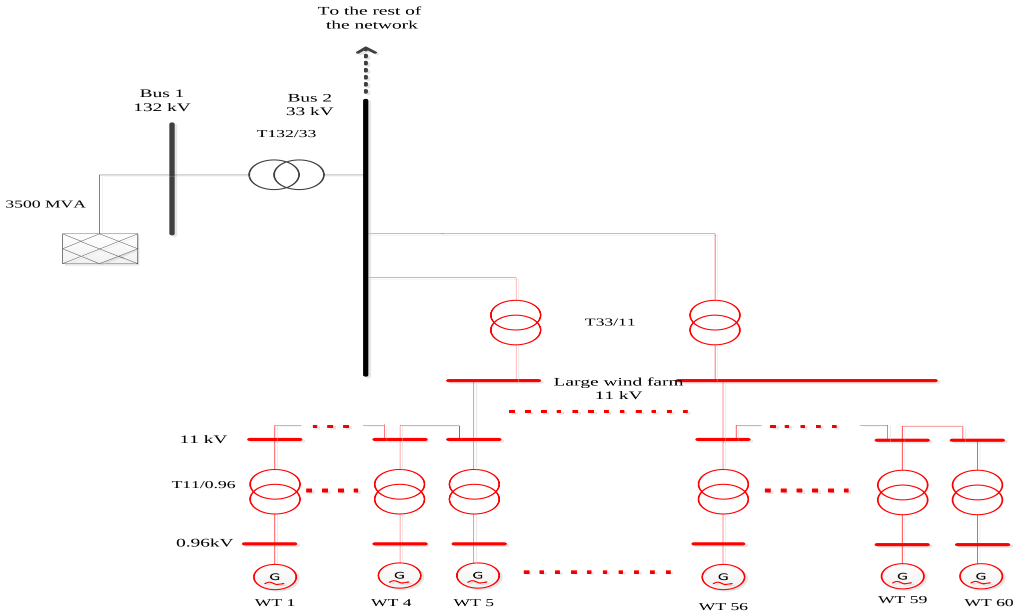


Figure 5-2 Singe line diagram of the large wind farm

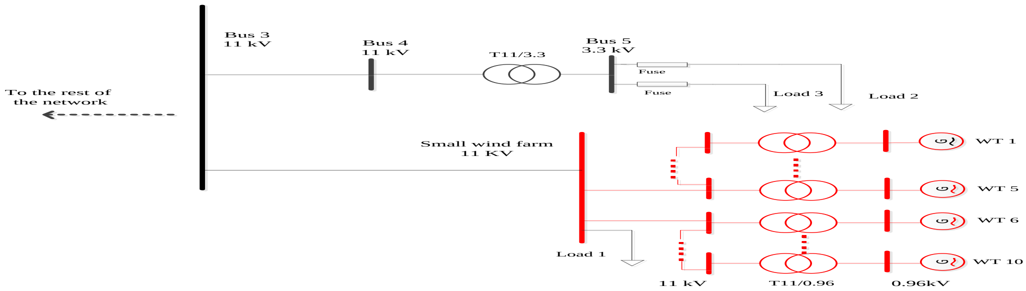


Figure 5-3 Singe line diagram of the small wind farm

5.3 Protection coordination in a MV network prior to the DGs connection

The overall single line diagram of the network with protection devices installed in the radial network was connected is shown in Figure 5-1. Overcurrent protection has been used to protect the radial network.

The coordination of time overcurrent relays is the process of determining settings for the relays that provide a selective response for a fault [8]. PowerFactory has provided users the application for protection analysis. For example: different relay types (direction, distance, OC) are available for use in the Global Library, the calculation of fault current is applicable. On the basis of the protection system feature, the proper protection system is selected on. In this network, the overcurrent protection devices (fuses, OC relays) are explained and more information regarding other types of protection can be found in the DIgSILENT user's manual [25].

5.3.1 Selecting protective devices

The main and the back-up protection across the network are comprised of the OC phase and earth faults protection that are selected from the Global Library. Loads are initially protected by fuses. All OC relays used to protect the radial network are set based on the basic rules for correct relay coordination (as described in Section 3.1). Specifically, relays selected in this case are numerical relays (IAC77A805A) that have a phase and an earth OC element, and both follow an Extreme Inverse (EI) Characteristic (IAC Extreme Inverse (EI) GES7005B). The reason for choosing the EI characteristic is because relays must be properly coordinated with their downstream fuses. Due to the HV delta connection of all transformers in the network, earth faults occurring at the LV winding of the transformer will not result in zero sequence current flowing on the HV side. Therefore, if a transformer is located in the middle of two relays, the phase element of the upstream relay must be able to provide the back up protection for the earth element of the downstream relay.

Without doubt, the OC relays require a three-phase current transformer to deliver an input signal for both the phase and earth faults. The secondary nominal current of the CT setting in this network is 5A. The C100 core CTs are used and the total burden for each CT is 1 Ω; the selection of proper CTs ratio can be found in Section 2.2.4.

5.3.2 Pick-up currents of relays and fuses

After selecting the appropriate protective devices for the network, the next stage is to calculate the pick-up current of the OC relay; the phase and earth element need to be calculated and set separately. The relay settings should be calculated by the shortest operating time according to the maximum fault current and the setting should be sensitive enough to pick up when the minimum expected fault current occurs. The OC relays do not provide an overload protection as their responsibility is to separate faulted zones from the network; therefore, the relay pick-up current setting must be greater than the maximum load current to prevent mal-operation. The fuses adopted are both of the medium voltage type in DIgSLIENT and the rated frequency is 50 Hz. The settings are explained in Section 2.2.2. The overall fuse data are provided in the Table 5-1 below.

Fuse	Rated voltage (kV)	Rated current (A)
Load fuse 1	11	224
Load fuse 2	4	200
Load fuse 3	4	200
Load fuse 4	33	200
Load fuse 5	33	200
Load fuse 6	33	200

Table 5-1 Fuse data

5.3.3 Explanation of the protection coordination

A *time-overcurrent plot* is comprised of the characteristic curves of relays and fuses from which the pick-up current, short circuit values, TMS and grading margin can be read. Further details are in the Appendix A.1.3. The coordination procedures between IDMT relays use a time-overcurrent plot, which has been pointed out previously (as described in Section 3.2.2, Figure 3-1). In a large system like this, the calculation of protection settings could be enormously complicated. Fortunately, DIgSILENT can be used to help with the calculation and process. The method used in this case is to manually adjust the relay characteristic curves or to reset the settings of each curve in the time-overcurrent diagram provided by DIgSILENT. The diagram allows the coordination between the two devices to be done graphically as well, by moving their characteristics (Section A.1.3).

Figure 5-4 below as shows an example for adjusting the relay characteristic curves: the original characteristic is labelled "1", the new position as "2", and the grading margins are labelled "a". The proper coordination margin between relays can be done through this method. In this network, the grading margin is at least 0.2s because the numerical OC relays were installed in the protection system and they could deliver a faster response in case of a fault.

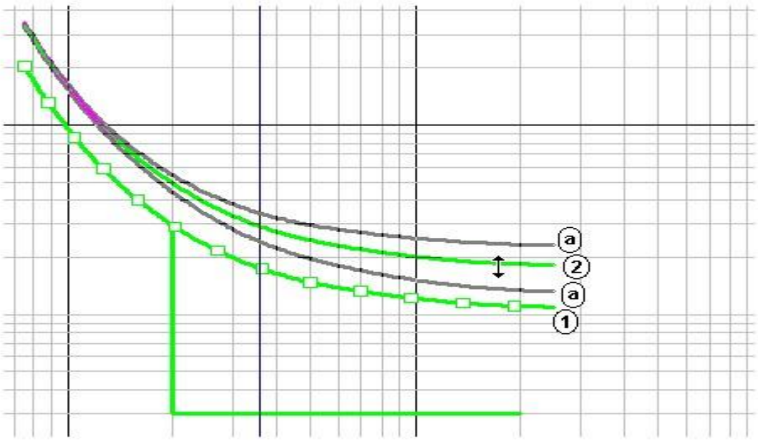


Figure 5-4 Moving characteristic showing the grading margin

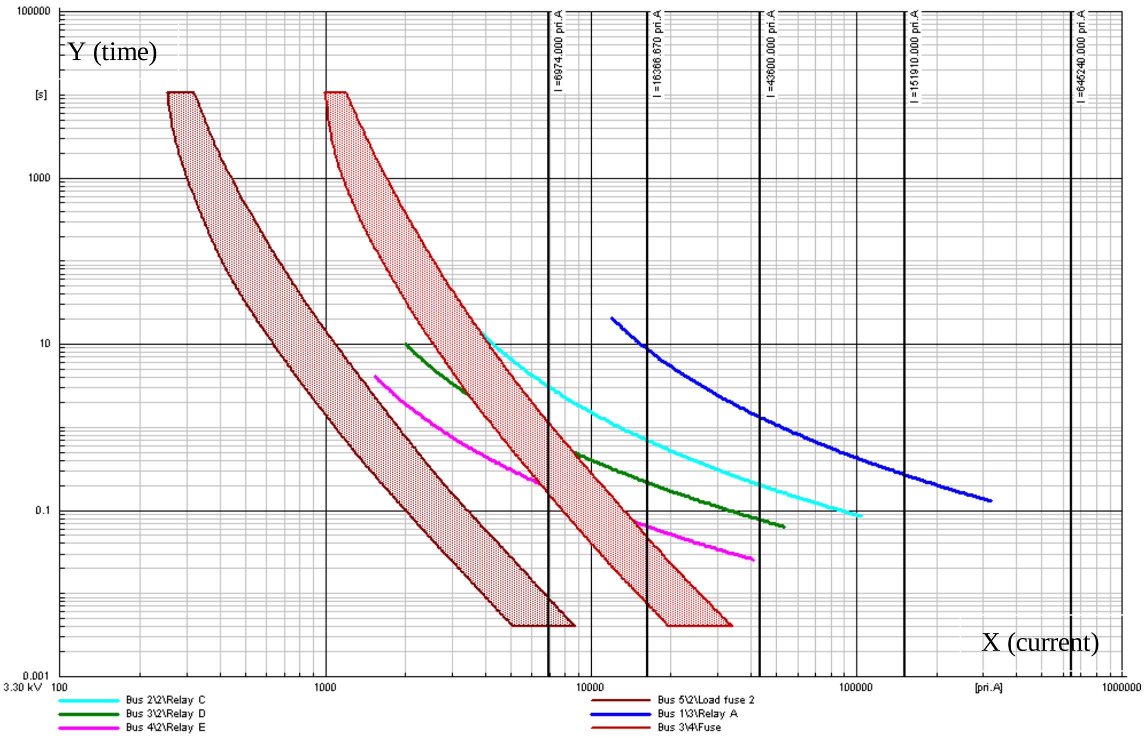


Figure 5-5 The phase element of relay characteristics in the *time overcurrent plot*

In Figure 5-5, the *time overcurrent plot*, where the characteristics of the phase element of OC relays from bus 5 to bus 1 are shown. Clearly, the coordination between all relays and fuses from downstream to upstream can be observed from the plot. The characteristic curve of the protective device (load fuse 2) that is furthest from the source is displayed in the plot on the furthest left. Whereas, the characteristic curve of the nearest protective device from the source is shown in the plot on the furthest right (Relay A).

5.3.4 Equipment damage curves and inrush current

As mentioned already in Section 2.2.5, the equipment damage curves and transformer inrush current also need to be emphasized when plotting the relay characteristic curve. The protection characteristic curves of the relays must be set below and to the left of the damage curves of any plant that they are responsible for protecting. For instance, the acceptable protection for transformer T132/33 from both thermal and mechanical damage is provided by relay A in Figure 5-6. Moreover, through the assessment of the inrush current, it is clear that the tripping time of relay A is longer than the period of the transformer inrush current, as shown in Figure 5-6. As a result, relay A can tolerate the inrush current and not interrupt the circuit.

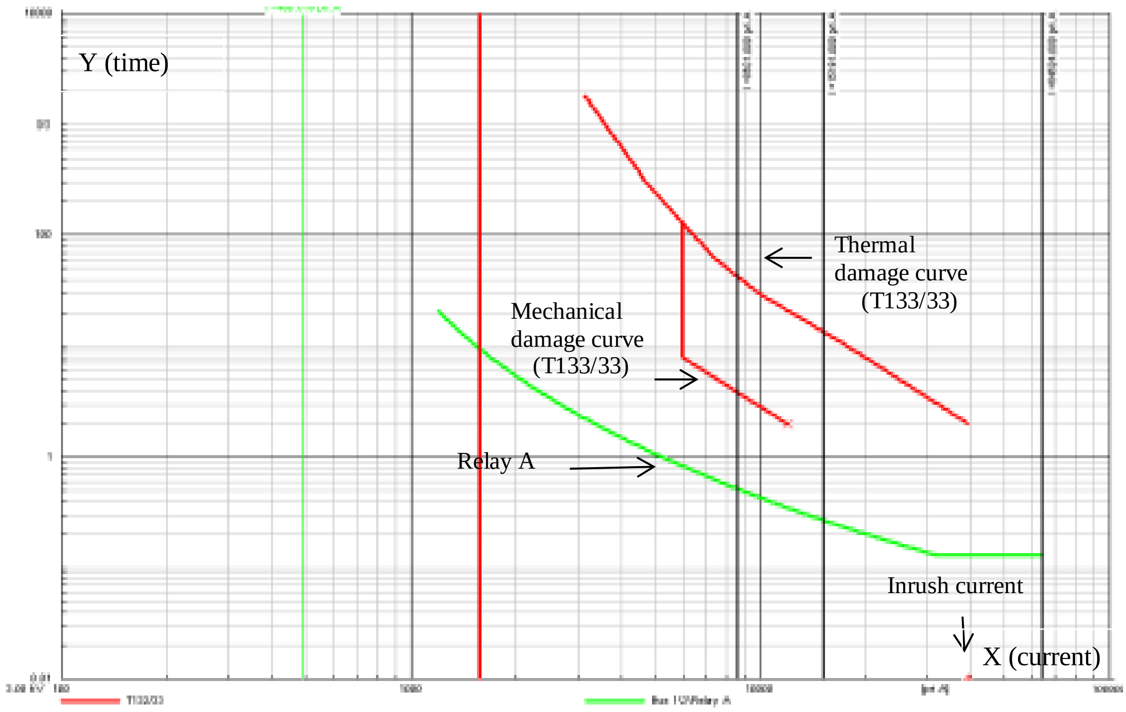


Figure 5-6 Example of transformer damage curve and inrush current

5.3.5 Relay parameters

The protection system for the radial network and the protection coordination between all protective devices is successfully achieved through proper adjustments. Figure 5-7 is the list of settings for all protective relays (relays A, C, D, E, F) in the radial network without DGs. The list is given by DIgSILENT and the protection coordination is succeeded according to these settings. For example, see the settings for the relay A in Figure 5-7, the relay type is IAC77A805A; the ratio of current transformer that is connected to the relay A is 1000A/5A; the pick up current is 1 A and the time dial (TMS) is 4, the characteristic is Extremely Inverse (EI), for the phase element of the relay A. The same information can be read for the earth element of relay A as well.

```
------------------------------------------------------------------------------------------
|        Radial Without DG        |   DIgSILENT  | Project: Protection                   |
|                                 | PowerFactory |---------------------------------------|
|                                 |    14.1.3    | Date:   10/29/2013                    |
------------------------------------------------------------------------------------------
| Relay A                           Relay Type : IAC77A805A                              |
|   Location      :  Cubicle        : Cub_1        Branch     : T132/33                  |
|                    Busbar         : 132 kV                  / Bus 1                    |
|----------------------------------------------------------------------------------------|
|   CT A                                                Ratio       : 1000A/5A           |
|     No. Phases     : 3          Phase 1     : a       Phase 2     : b                  |
|     Connection     : Y                                                                 |
|                                                                                        |
|   Measurement                                                                          |
|     Nominal Current ( 5.0            A      ) :      5.00 A                            |
|                                                                                        |
|   Toc              ( IEC: I>t   ANSI: 51    )          Out of Service    : No          |
|     Tripping Direction                      : None                                     |
|     Current Setting ( 0.5  - 12.0    sec.A ) :      1.000 sec.A                       |
|     Time Dial       ( 0.5  - 10.0          ) :      6.100                             |
|     Characteristic                          : IAC Extremely Inverse GES7005B           |
|                                                                                        |
|   Toc Earth        ( IEC: IE>t  ANSI: 51N  )          Out of Service    : No          |
|     Tripping Direction                      : None                                     |
|     Current Setting ( 0.01 - 2.6     sec.A ) :      1.000 sec.A                       |
|     Time Dial       ( 0.5  - 10.0          ) :      4.100                             |
|     Characteristic                          : IAC Extremely Inverse GES7005B           |
|                                                                                        |
|   Logic                                                 Out of Service    : No        |
|     Breaker                            Cubicle     Branch                              |
|      T2.2                  \ Bus 1       Cubicle_S   CB3                               |
------------------------------------------------------------------------------------------
| Relay C                           Relay Type : IAC77A804A                              |
|   Location      :  Cubicle        : Cub_1        Branch     : C 2-Tr                   |
|                    Busbar         : 33 kV                   / Bus 2                    |
|----------------------------------------------------------------------------------------|
|   CT C1                                               Ratio       : 1000A/5A           |
|     No. Phases     : 3          Phase 1     : a       Phase 2     : b                  |
|     Connection     : Y                                                                 |
|                                                                                        |
|   Measurement                                                                          |
|     Nominal Current ( 5.0            A      ) :      5.00 A                            |
|                                                                                        |
|   Toc              ( IEC: I>t   ANSI: 51    )          Out of Service    : No          |
|     Tripping Direction                      : None                                     |
|     Current Setting ( 0.5  - 4.0     sec.A ) :      1.300 sec.A                       |
|     Time Dial       ( 0.5  - 10.0          ) :      4.000                             |
|     Characteristic                          : IAC Extremely Inverse GES7005B           |
|                                                                                        |
|   Toc Earth        ( IEC: IE>t  ANSI: 51N  )          Out of Service    : No          |
|     Tripping Direction                      : None                                     |
|     Current Setting ( 0.01 - 2.6     sec.A ) :      1.210 sec.A                       |
|     Time Dial       ( 0.5  - 10.0          ) :      4.000                             |
|     Characteristic                          : IAC Extremely Inverse GES7005B           |
|                                                                                        |
|   Logic                                                 Out of Service    : No        |
|     Breaker                            Cubicle     Branch                              |
|      T1.4                  \ Bus 2       Cubicle_S   CB2                               |
------------------------------------------------------------------------------------------
| Relay D                           Relay Type : IAC77A805A                              |
|   Location      :  Cubicle        : Cub_1        Branch     : C 3-4                    |
|                    Busbar         : 11 kV                   / Bus 3                    |
|----------------------------------------------------------------------------------------|
|   CT D                                                Ratio       : 500A/5A            |
|     No. Phases     : 3          Phase 1     : a       Phase 2     : b                  |
|     Connection     : Y                                                                 |
|                                                                                        |
|   Measurement                                                                          |
|     Nominal Current ( 5.0            A      ) :      1.00 A                            |
|                                                                                        |
|   Toc              ( IEC: I>t   ANSI: 51    )          Out of Service    : No          |
|     Tripping Direction                      : None                                     |
|     Current Setting ( 0.5  - 12.0    sec.A ) :      4.000 sec.A                       |
|     Time Dial       ( 0.5  - 10.0          ) :      3.000                            ||
```

```
-------------------------------------------------------------------------------------
|   Toc Earth          ( IEC: IE>t  ANSI: 51N  )        Out of Service   : No      |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.01 - 2.6    sec.A ) :      2.400 sec.A                   |
|     Time Dial       ( 0.5 - 10.0           ) :      5.600                         |
|     Characteristic                           : IAC Extremely Inverse GES7005B     |
|                                                                                   |
|   Logic                                               Out of Service   : No      |
|     Breaker                             Cubicle    Branch                         |
|      T1.4                 \ Bus 3        Cubicle_S  CB2                           |
-------------------------------------------------------------------------------------
| Relay E                          Relay Type : IAC77A805A                          |
|   Location     :  Cubicle        : Cub_1       Branch    : C 4-Tr                 |
|                   Busbar         : 11 kV                 / Bus 4                  |
|-----------------------------------------------------------------------------------|
|   CT E                                           Ratio      : 200A/5A            |
|     No. Phases    : 3          Phase 1    : a     Phase 2    : b                  |
|     Connection    : Y                                                             |
|                                                                                   |
|   Measurement                                                                     |
|     Nominal Current ( 5.0           A      ) :      5.00 A                        |
|                                                                                   |
|   Toc                ( IEC: I>t   ANSI: 51   )        Out of Service   : No      |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.5 - 12.0    sec.A ) :      7.700 sec.A                   |
|     Time Dial       ( 0.5 - 10.0           ) :      1.200                         |
|     Characteristic                           : IAC Extremely Inverse GES7005B     |
|                                                                                   |
|   Toc Earth          ( IEC: IE>t  ANSI: 51N  )        Out of Service   : No      |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.01 - 2.6    sec.A ) :      2.360 sec.A                   |
|     Time Dial       ( 0.5 - 10.0           ) :      4.000                         |
|     Characteristic                           : IAC Extremely Inverse GES7005B     |
|                                                                                   |
|   Logic                                               Out of Service   : No      |
|     Breaker                             Cubicle    Branch                         |
|      T1.4                 \ Bus 4        Cubicle_S  CB2                           |
-------------------------------------------------------------------------------------
| Relay F                          Relay Type : IAC77A805A                          |
|   Location     :  Cubicle        : Cub_1       Branch    : C 2-6                  |
|                   Busbar         : 33 kV                 / Bus 2                  |
|-----------------------------------------------------------------------------------|
|   CT F                                           Ratio      : 1000A/5A           |
|     No. Phases    : 3          Phase 1    : a     Phase 2    : b                  |
|     Connection    : Y                                                             |
|                                                                                   |
|   Measurement                                                                     |
|     Nominal Current ( 5.0           A      ) :      1.00 A                        |
|                                                                                   |
|   Toc                ( IEC: I>t   ANSI: 51   )        Out of Service   : No      |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.5 - 12.0    sec.A ) :      3.500 sec.A                   |
|     Time Dial       ( 0.5 - 10.0           ) :      3.800                         |
|     Characteristic                           : IAC Extremely Inverse GES7005B     |
|                                                                                   |
|   Toc Earth          ( IEC: IE>t  ANSI: 51N  )        Out of Service   : No      |
|     Tripping Direction                       : None                              |
|     Current Setting ( 0.01 - 2.6    sec.A ) :      2.560 sec.A                   |
|     Time Dial       ( 0.5 - 10.0           ) :      3.700                         |
|     Characteristic                           : IAC Extremely Inverse GES7005B     |
|                                                                                   |
|   Logic                                               Out of Service   : No      |
|     Breaker                             Cubicle    Branch                         |
|      T2.4                 \ Bus 2        Cubicle_S  CB4                           |
-------------------------------------------------------------------------------------
```

Figure 5-7 Relay parameters with the DG connected

5.3.6 Assessment of different fault cases

After the appropriate selection and the setting of protective devices, and the right displacement of characteristic curves, different fault situations have been studied.

In the first scenario, a single phase fault at 50% C-load 4 near bus 6 will be cleared by the fuse 4 after 0.022s. If fuse 4 fails to operate, then the relay C2 will respond after 0.332s. (Figure 5-8)

Another short circuit situation at cable C 3-4 is a three phase balanced fault. Skss (The capacity of the short circuit) is 139 MVA, Ikss (The value of the short circuit) is 7.3 kA is. It will be cleared by main protective relay D (0.137s) or by the back-up relay C (0.4s). (Figure 5-9)

Finally, a 2-phase short circuit at bus 5 will result in the operation of relay E (main) and relay D (back-up). Their operation times are 0.216s and 0.881s, respectively. (Figure 5-10)

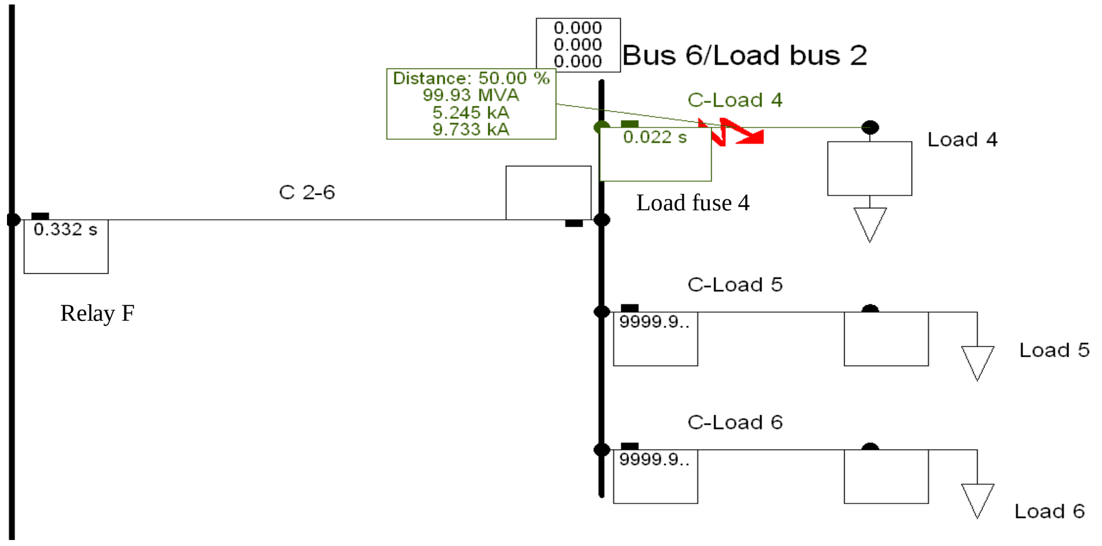


Figure 5-8 Single phase fault

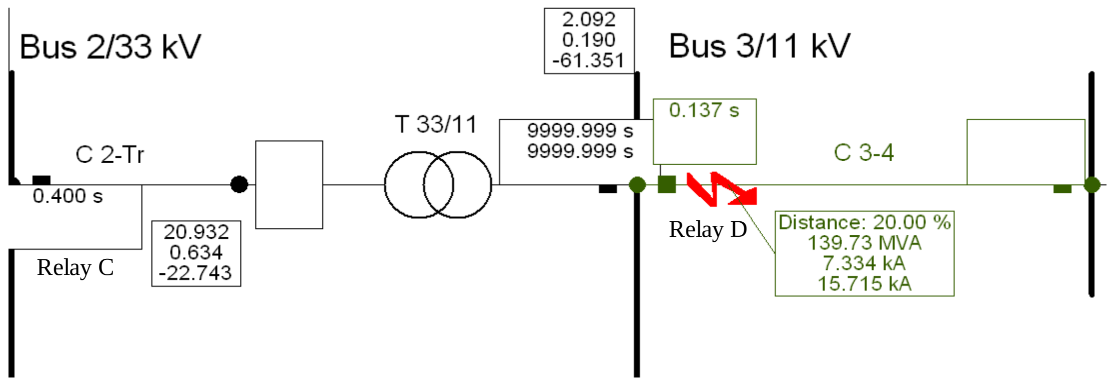


Figure 5-9 Three phase fault

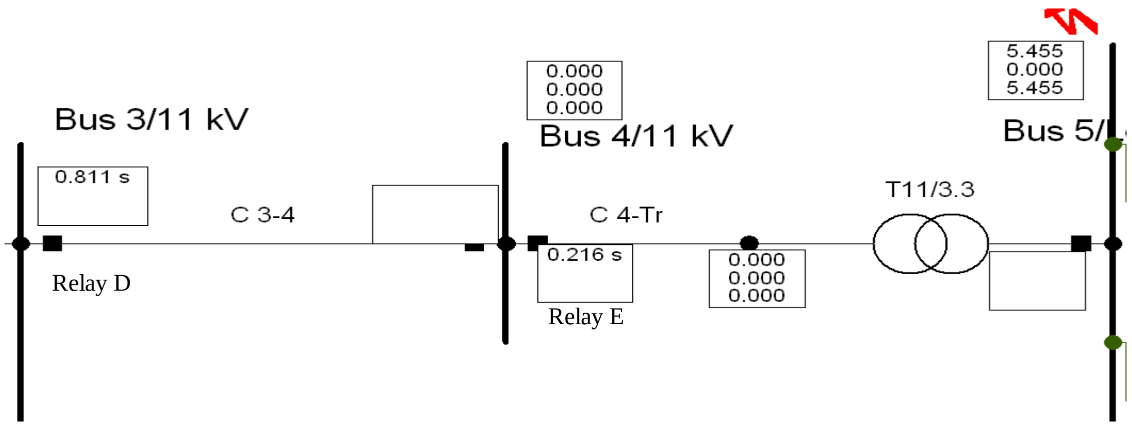


Figure 5-10 Two phase fault

5.4 Protection coordination in a MV network with DG connected

The protection system designed for the radial network has acquired the protection coordination requirements. Then the additional DGs are connected to the radial network, which result in the reconsideration about the protection system. There are two wind farms integrated in the MV network. As we can see from Figure 5-11, After the DGs have been connected, additional DG OC directional protection must also be provided (red color in Figure 5-11). The OC directional protection protects the utility system from harm caused by the DG, and it also serves to protect the DG from events that may originate in the utility system. The protection system is divided into two parts, one part is OC directional protection and the other part is main network protection.

The directional OC relays should be installed at every busbar (located in the red part of Figure 5-11). The coordination procedures of directional OC relays are employed as mentioned in Section 3.2.3. In the meantime, attention needs to be paid to the proper coordination between the OC directional relays and the OC relays located in the main network.

As for the main network, now that the power comes from multiple sources, part of the main network may detect different fault currents and fault directions. The OC relays located in the cables that see fault currents flow from more than one source should be replaced by directional OC relays (relay A, relay B, relay C, relay D1a).

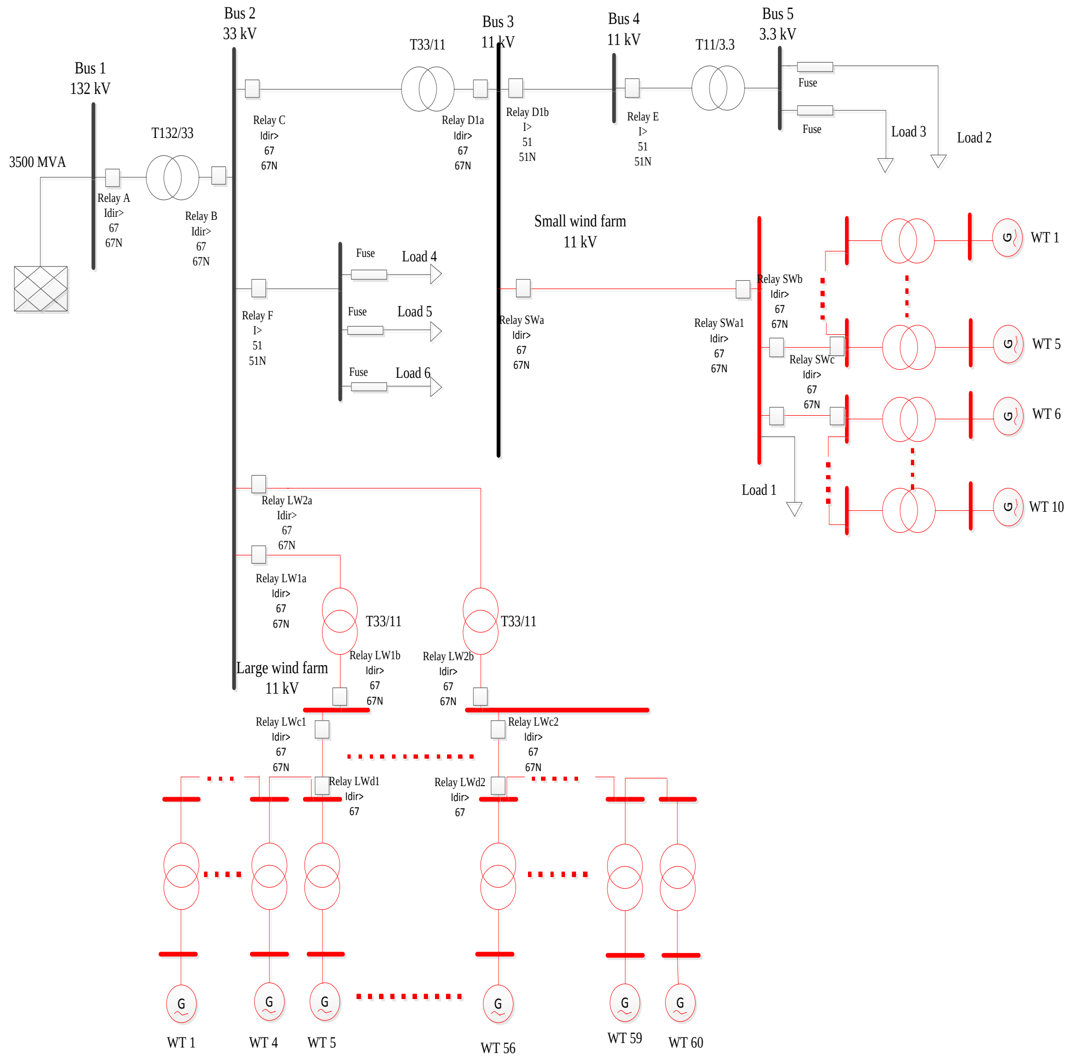


Figure 5-11 Overall diagram of the protection system after DG integration

A planning process that properly coordinates the protective devices after the proliferation of DGs is presented in the flow chart in Figure 5-12. As stated before in Section 2.2.5, the equipment curves of components need to be re-checked after the penetration of the DGs. In order to cope with the different situations observed, the relay settings might be changed to assure the correct thermal limits. After this, the operation of protective devices must be studied in different fault situations. The study into the operation of protective relays related to sensitivity problems was normally based on the smallest fault current. The 2-phase fault that occurs at the electrically furthest point dictates the smallest potential fault current. Furthermore, in the event of a fault on the adjacent feeders, there should not be any protective devices tripping in the non-faulted feeder. It is necessary to follow the flow chart process and to adjust relay settings until the appropriate coordination has been acquired with the DGs connected to the network. When checking the operation of a protection system, there are three main influences mentioned before and the following sections give the specifications in detail.

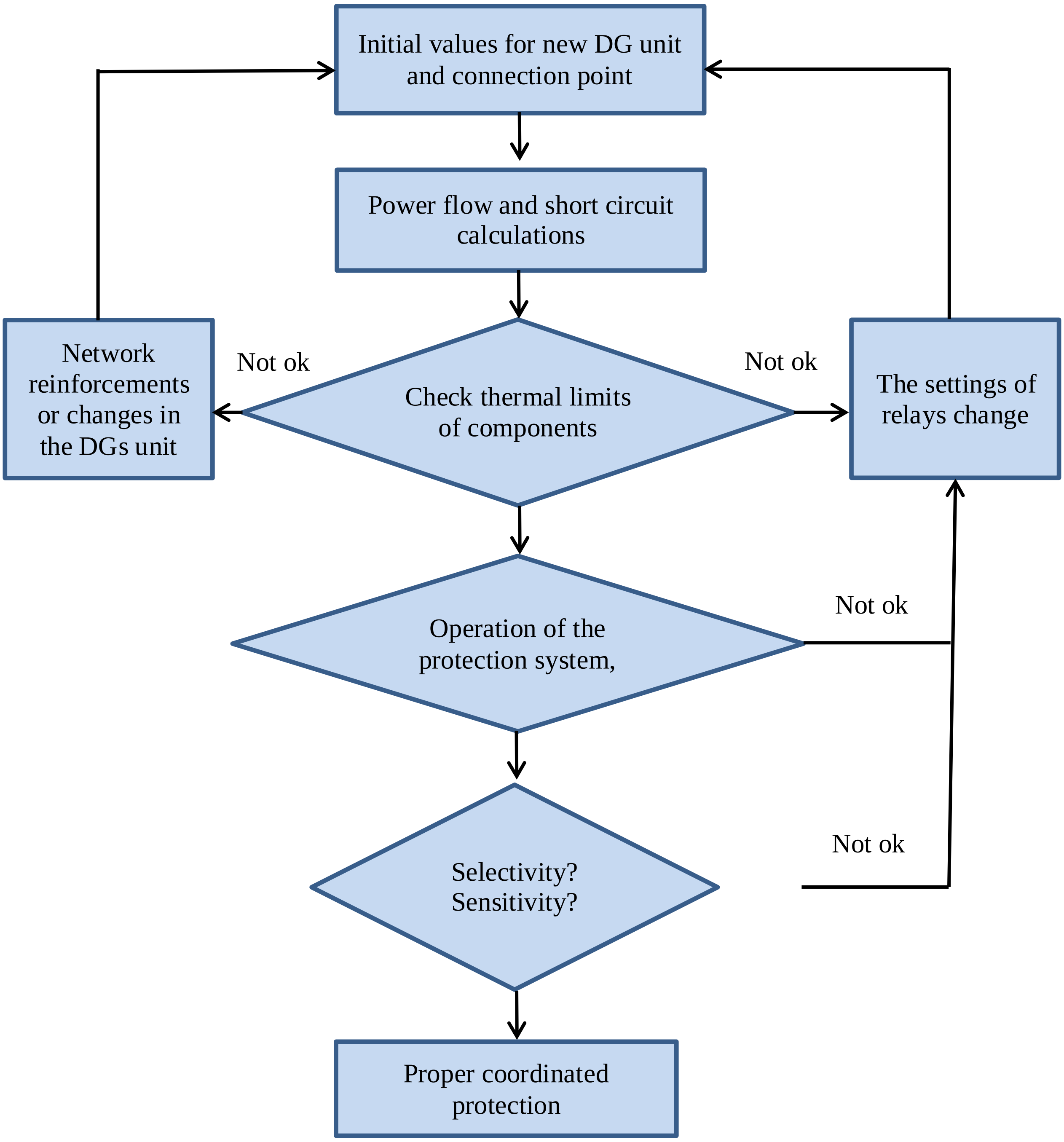


Figure 5-12 Flow chart on the coordination process after DG connection

5.4.1 Loss of grading

First of all, the impact on the grading margin of the main network should be considered. Before the DGs penetration, the coordination in the main network (black part in Figure 5-11) was successfully achieved. However, the coordination margin was cut off after the DG integration. The simulation carried out by DIgSILENT detected and recorded the problems. Figure 5-13 shows that 3-phase fault occurred near bus 5 and was cleared by the fuse after 0.019s and the back-up relay E after 0.216s. Nonetheless, it is clear in the second diagram that the small wind farm connected to bus 4 has injected more fault current: *Ikss* increased from 6.297 kA to 6.984 kA. The selectivity of the protective device failed: the back-up relay disconnected the circuit after 0.186s and the requirement for a coordination margin was not achieved (in this protect, the coordination margin is at least 0.2s).

The coordination procedures in Section 3.2.3 were repeated until the proper coordination was achieved in the main network again. In order to check whether protection coordination has been acquired properly, it would be necessary to test for key faults (the minimum fault current, the maximum fault current) instead of simply observing the *time overcurrent plot*. In a *time overcurrent* plot of a single source network, relays see the same fault current in a short circuit and the coordination between them can be seen from the characteristic curves. However, if DGs locate between an upstream relay and a downstream relay, the relays will sense different fault currents. Thus, in the same *time overcurrent plot* the correct coordination is not reflected from the position of the characteristic curves of the relays.

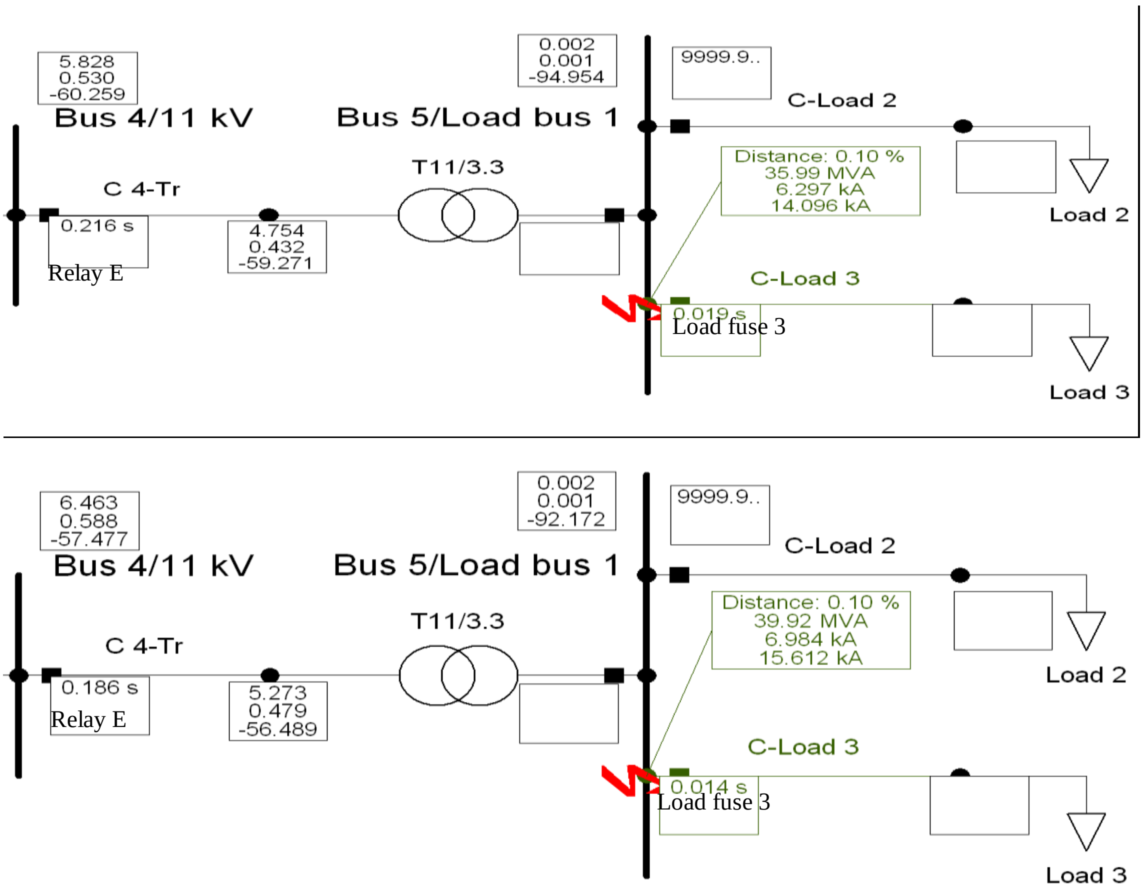
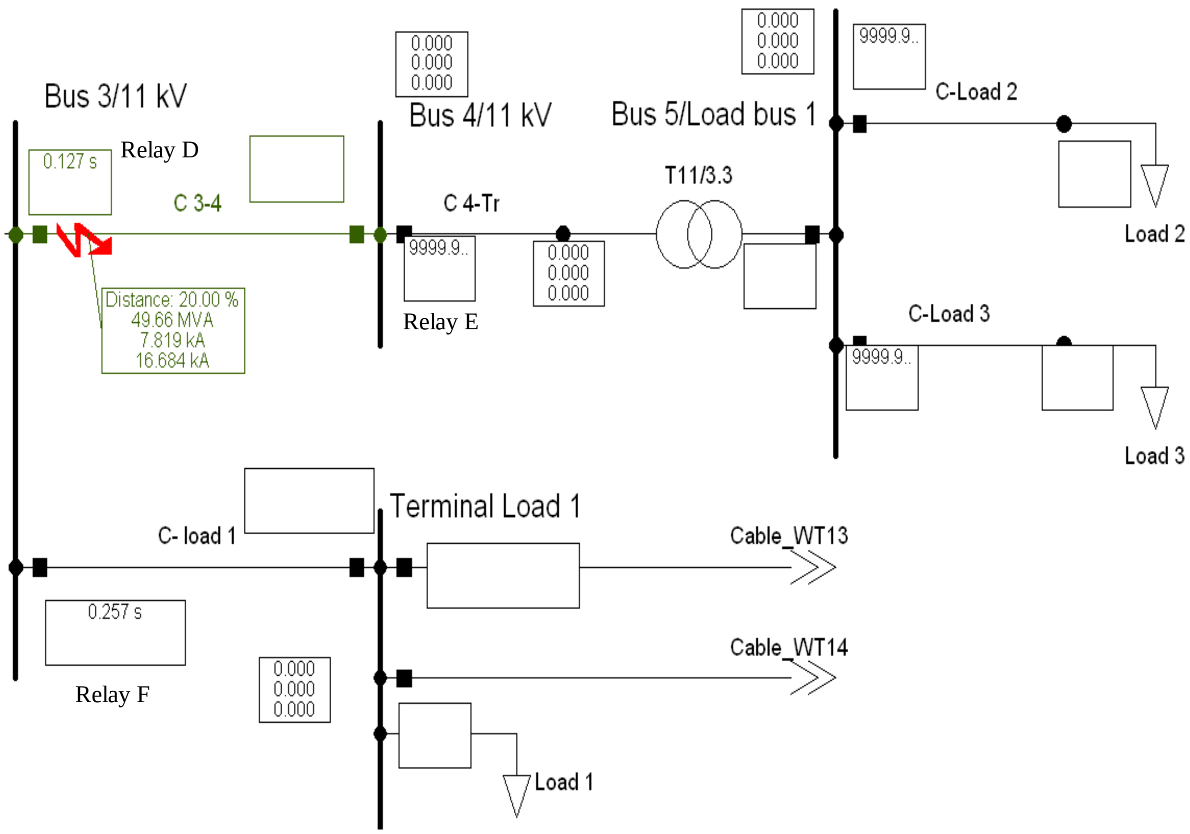


Figure 5-13 Examples of three phase faults with or without DGs being connected

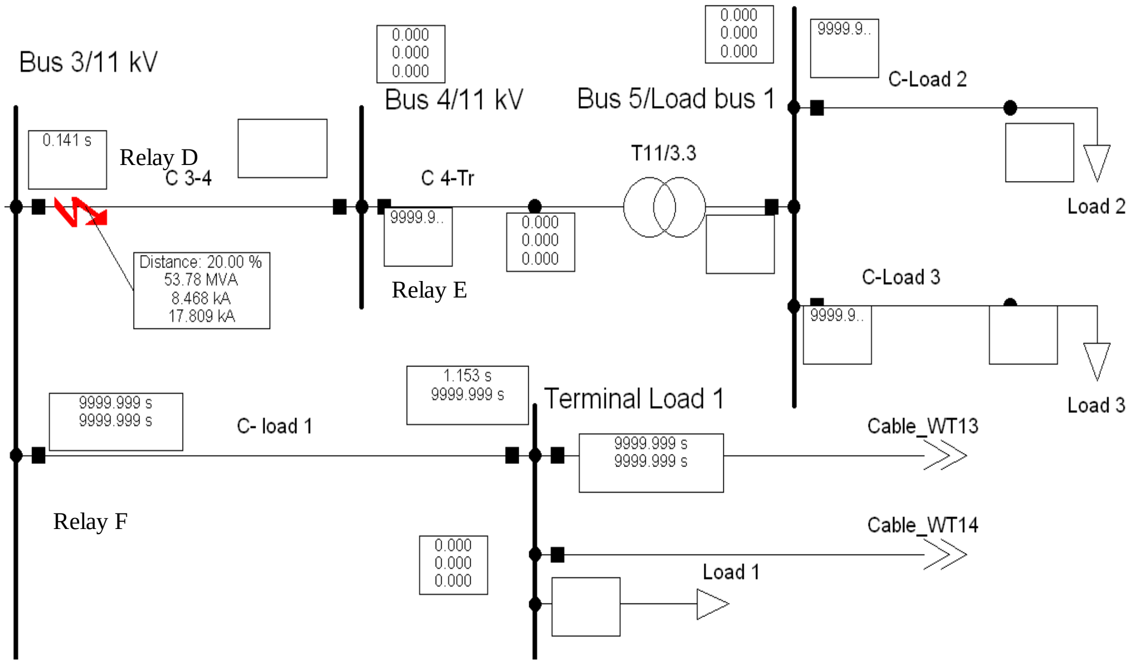
5.4.2 False tripping

The DGs penetrate into the system and do not only change the fault current level but modify the fault current in a specific direction. This results in false tripping. If a fault occurs on the feeder, the operating devices should be the devices located in that faulted feeder, e.g. the circuit breaker. Nevertheless, the circuit breaker at the adjacent feeder of the DGs connection may trip and result in unreasonable interruption to this healthy feeder. The solution to tackle the false tripping problem is to replace a non-directional device by a directional relay.

For instance, in this network, there is a small wind farm connected to bus 3 in parallel with load 1. A 2-phase fault at the C 3-4 cable will result in false tripping of the fuse (0.257s) located in the adjacent healthy feeder in Figure 5-14 (a). After the fuse has been replaced by the directional relay in Figure 5-14 (b), the false tripping problem no longer exists when the same 2-phase fault occurs.

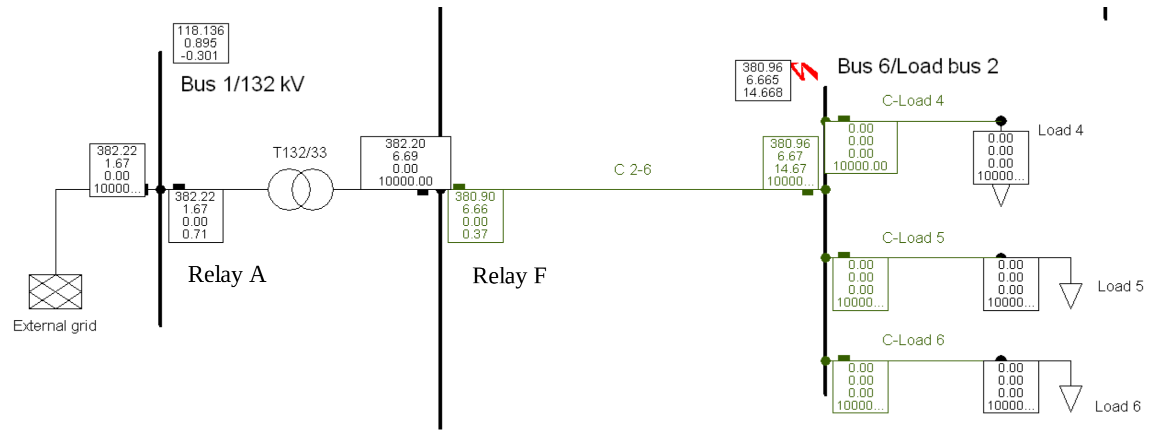


(a)

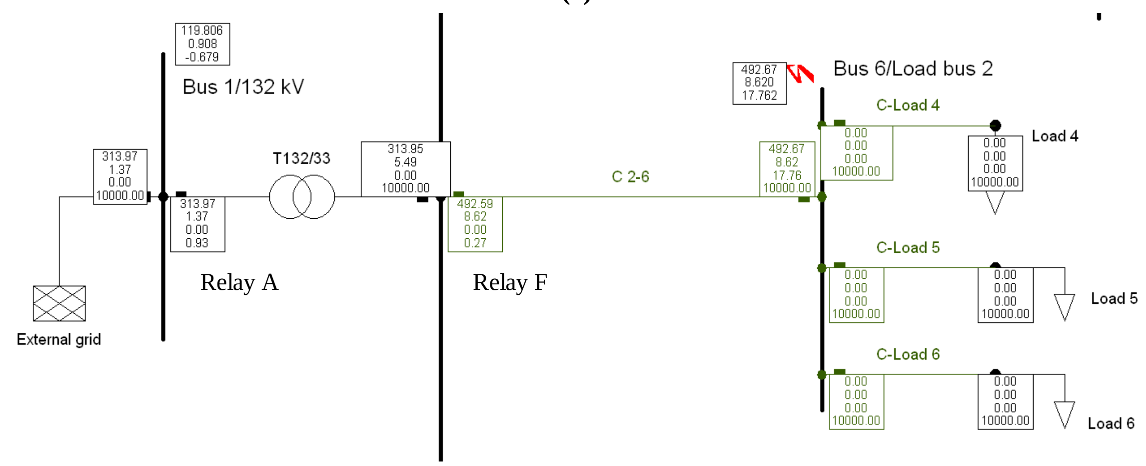


(b)

Figure 5-14 False tripping (a) Fuse (b) directional relay



(a)



(b)

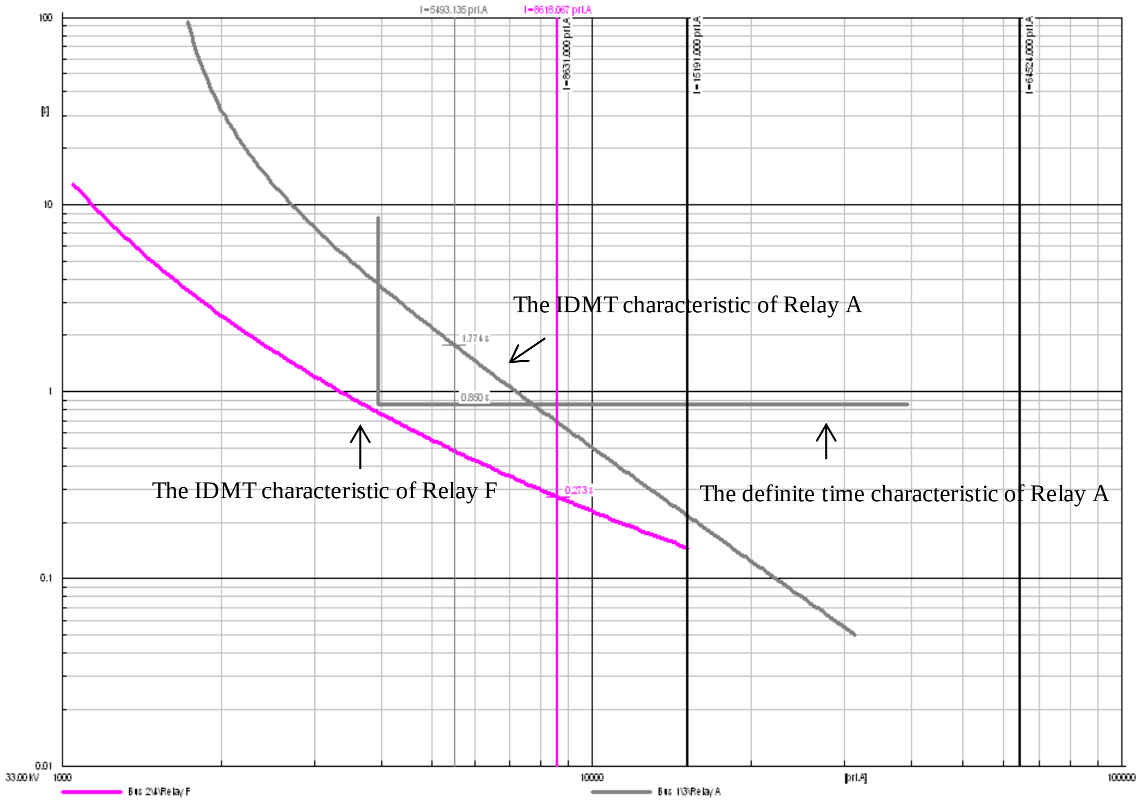
Figure 5-15 Example of a 3-phase fault for blinding

5.4.3 Blinding

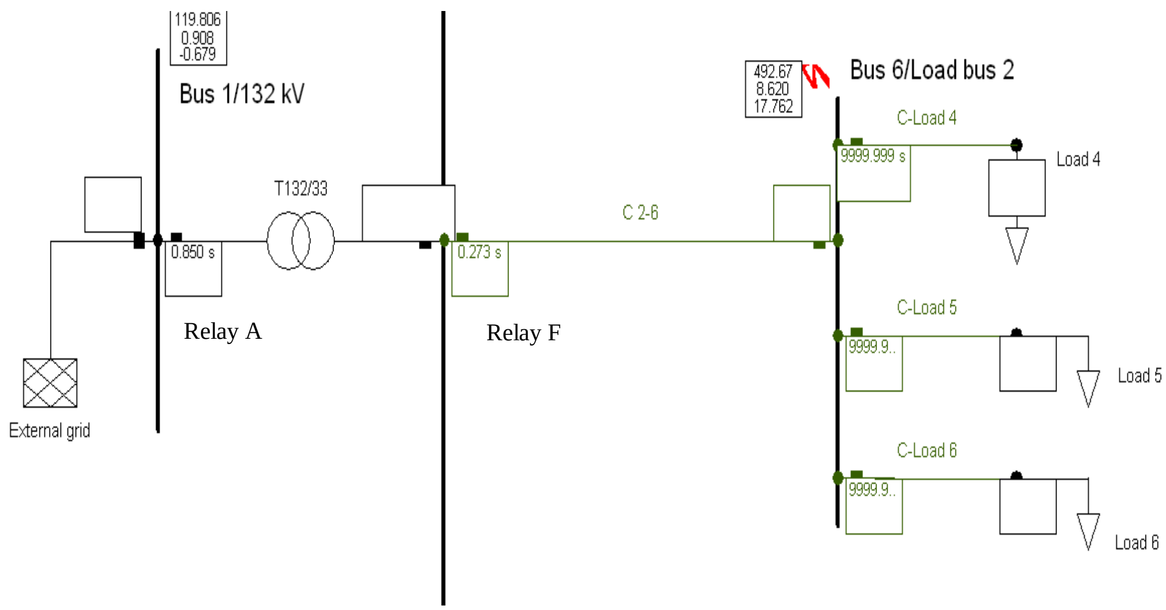
The final issue is protection blinding. The fault current seen by the OC relay decreases due to the DG contribution in situations when the DG is located between the fault point and the OC relay. All the relays employed in the main network are IDMT relays following an EI characteristic. The tripping time of the IDMT relay increases when the fault current decreases, as explained in Section 4.4. When a 3-phase fault occurs at bus 6, the false current flowing in back-up relay A (T132/22 cable) in Figure 5-15 (a) is 1.67 kA, and the tripping time for this fault is 0.72 s. As can be seen in Figure 5-15 (b), after the DGs have been connected, relay A will clear the fault after 0.93 s as the false current flowing through relay A decreases to 1.37 kA. On the contrary, the tripping time for the main protective relay F for this fault drops from 0.37 s to 0.27 s. The DGs proliferation has expanded the coordination margin between the main and back-up devices from 0.33 s to 0.66 s.

Replacing the OC relays located in cables supplied by two sources by directional relays, adding directional relays to the new wind farm feeders, and repeating the coordination procedures does not solve the problem. Instead, these measures further aggravate the time delay (the tripping time of relay A decreases to 1.774 s) and result in poor operation of the back-up protection. In order to solve the problem, one may consider again the OC coordination procedure, but it will imperil the selectivity on other feeders, so it is impossible and blinding still exists.

In this network, definite-time OC relays have been added to the point where the back-up relay has been affected since the operating time of the definite-time OC relays will not be influenced by the DGs. Employing the IDMT characteristic combination with definite-time characteristic for relay A, which can be seen from the diagram, the tripping time for a three phase fault occurring on bus 6 drops from 1.774 s to 0.85 s. Figure 5-13 (a) displays two tripping times in the time-overcurrent plot; the grey characteristic curve represents relay A; the upper grey one is the IDMT characteristic, which is still 1.774 s and another grey one is the definite-time curve of 0.85 s. Since they both trip the same circuit breaker, the switch must be opened and the faulted area can be disconnected within a 0.8 s time delay. The same blinding problem could occur at relay C and so the functional OC relay with IDMT and definite-time characteristics should be installed here as well. The blinding problem result from DGs could be solved appropriately.



(a)



(b)

Figure 5-16 A 3-phase fault located at Bus 6 showing in

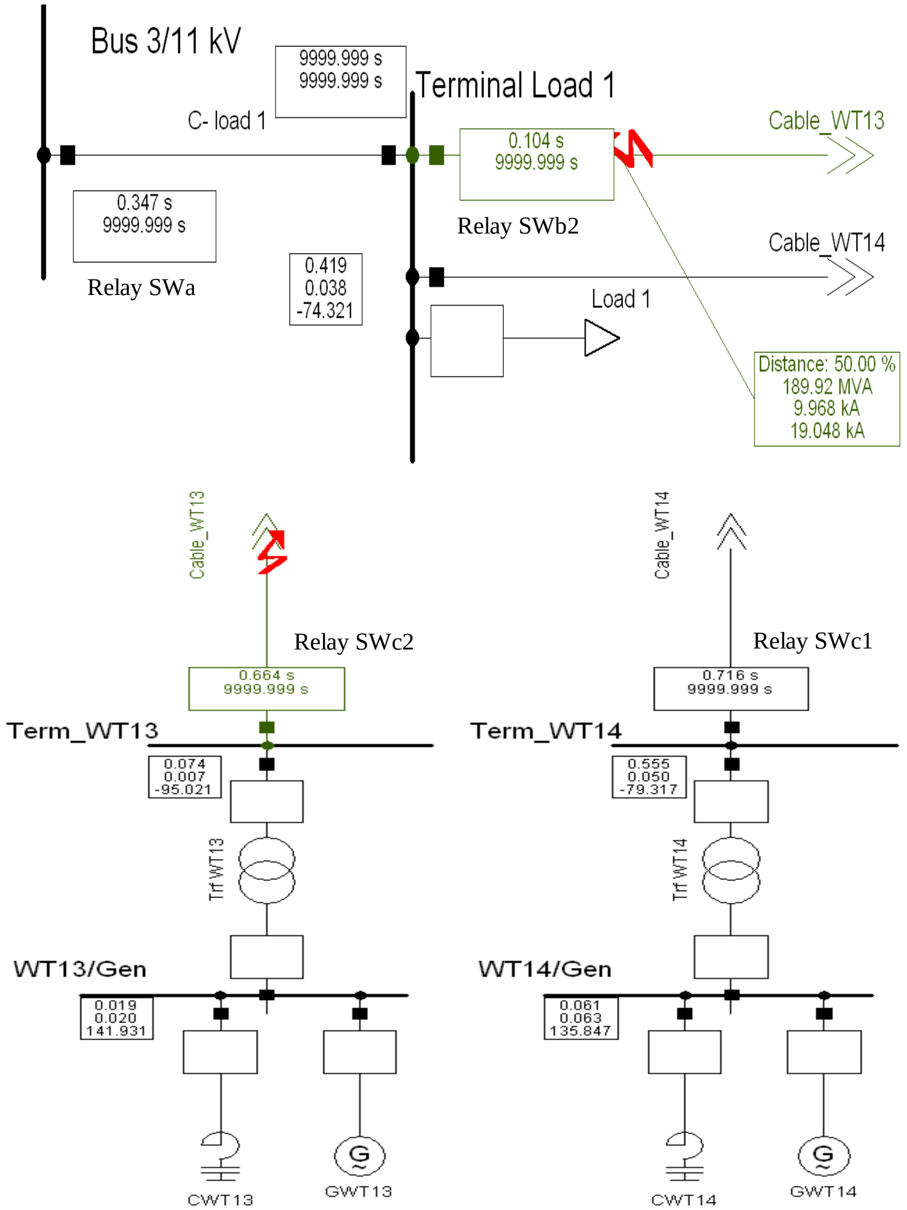
(a) time-overcurrent plot displaying both IDMT and definite time characteristics and in

(b) non-blinding with the combination of IDMT and definite time

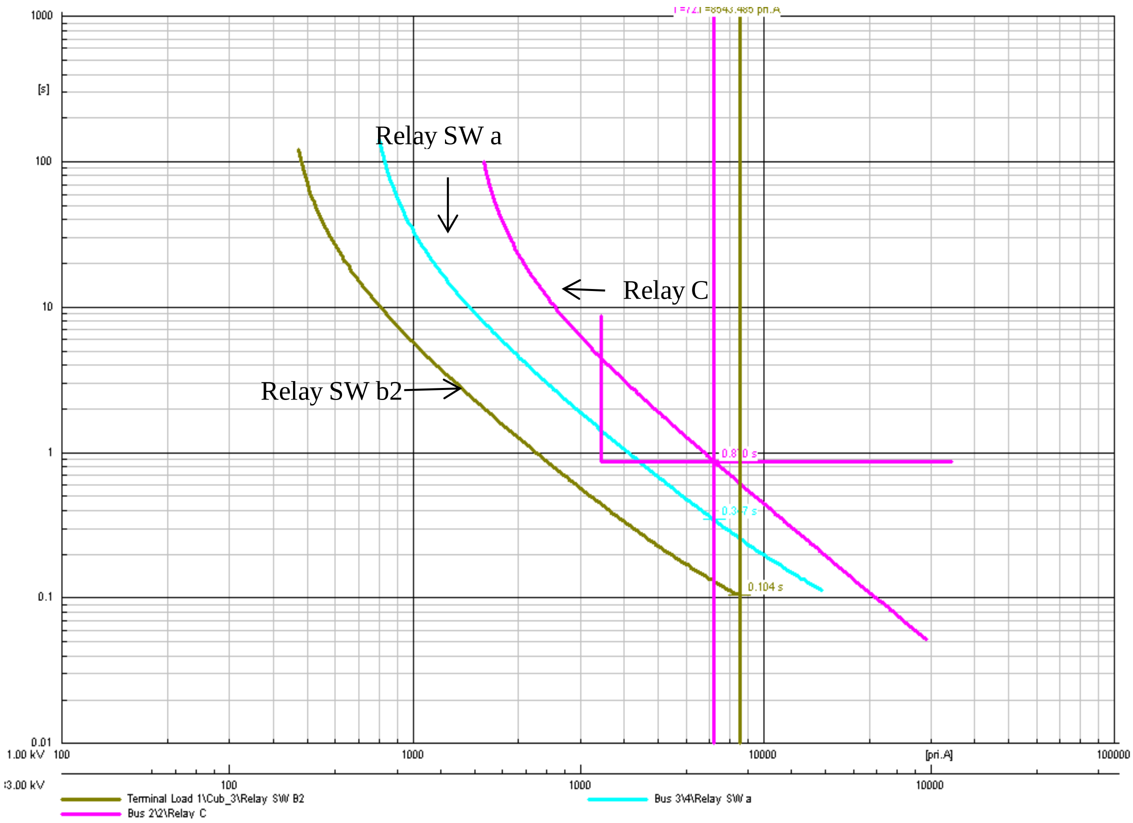
5.5 Assessment of different fault cases

The different fault cases are examined after the proper protection system and coordination have been acquired.

A balanced three phase fault occurs at cable WT13 (see Figure 5-17 below). The short circuit current flows from two directions and the relays at both ends of the cable should trip for the fault. Relay SWb2 operates after 0.104 s as the main protective device and relay SWa provides back-up support after 0.347 s if the fault has not been cleared. In addition, for fault current flow from the DGs, relay SWc2 disconnects the DG source WT13 after 0.664 s and relay SWc1 cuts off the WT14 after 0.716 s if relay SW b2 fails to operate.



(a)



(b)

Figure 5-17 Three-phase fault at small wind farm, showing

(a) the relay tripping time and in

(b) *time overcurrent plot* displays the characteristics

In the second case, when a single phase to the earth fault occurs at cable C-LW2 of one of the collection transformers, directional OC earth relay LW1a trips this fault after 0.245 s and the directional OC relay A operates as back-up device after 0.85 s. For this reason the earth fault occurs at the LV side of the transformer and is unable to cause zero sequence current flowing in the HV side. The phase element of relay A will provide support because the earth element of relay A will not sense the fault. From Figure 5-18, the singe phase to the ground fault also causes the phase element of relay LW1a to trip after 0.27s. However, both the earth element and the phase element of the relay will trip the same circuit breaker and act independently. As long as they satisfy the requirement for selectivity, the correct coordination or tripping sequence can be guaranteed.

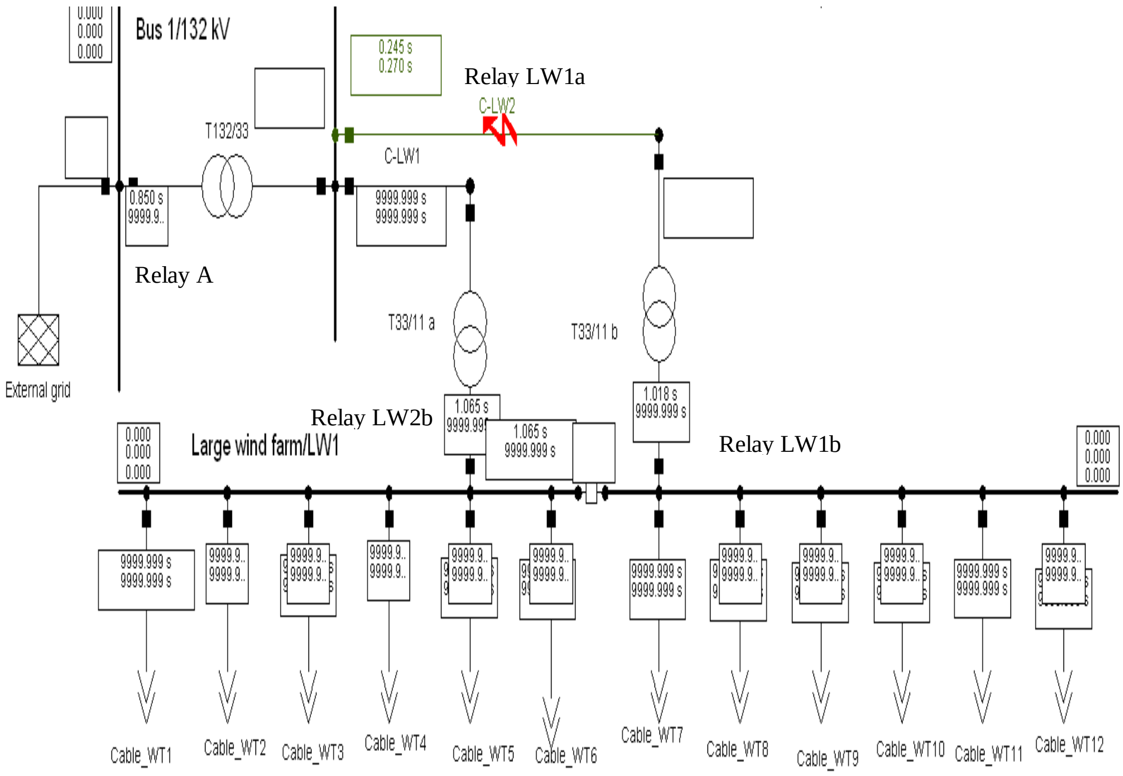


Figure 5-18 Single phase fault at the large wind farm

5.6 Chapter summary

The protection schemes for the network in two situations (with or without DGs) have been successfully achieved and the problems related to DGs have been solved through the readjustment on the relay parameters, the install of new directional relays, the replacement of new characteristics on the relays. Both of them were simulated in the DIgSILENT software, which includes the network modeling, fault current analysis, *time overcurrent plot* display, and the operation of protective devices in case of a fault. The protection system without DGs connection is compromised with overcurrent relays and fuses, and the protection coordination is the coordination between overcurrent devices. However, after the proliferation of DGs, the original protective devices need to be adjusted and new protective devices must be added into the system. The proper protection coordination requires reconsideration.

```
-----------------------------------------------------------------------------------------------
|          With DG                  |   DIgSILENT   | Project: Radial                         |
|        Main network               | PowerFactory  |-----------------------------------------
|                                   |    14.1.3     | Date:   10/29/2013                      |
-----------------------------------------------------------------------------------------------
| Relay B                            Relay Type : Rel-Toc-Dirextst                            |
|   Location     :   Cubicle        : Cub_1       Branch      : T132/33                       |
|                     Busbar         : 33 kV                   / Bus 2                         |
|---------------------------------------------------------------------------------------------|
|   CT B                                                 Ratio       : 300A/5A                |
|     No. Phases     : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection     : Y                                                                       |
|                                                                                             |
|   VT B                                                 Ratio       : 33000V/110V            |
|     Connection     : Y                                                                       |
|                                                                                             |
|   Measurement                                                                               |
|     Nominal Current ( 5.0             A      ) :     5.00 A                                 |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                                 |
|                                                                                             |
|   Toc              ( IEC: I>t    ANSI: 51    )         Out of Service    : No              |
|     Tripping Direction                         : Forward                                    |
|     Current Setting ( 0.01 - 10.0    sec.A ) :      1.670 sec.A                             |
|     Time Dial       ( 0.05 - 3.2           ) :      0.130                                   |
|     Characteristic                           : IEC 255-3 extremly inverse                    |
|                                                                                             |
|   Dir              ( IEC: I->    ANSI: 67    )         Out of Service    : No              |
|     Tripping Direction                            : Forward                                 |
|     Angle Operating Sector     ( 20.0 - 90.0     ) :   90.00 deg                            |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                          |
|     Max. Torque Angle     ( -90.0 - 90.0 deg    ) :     0.00 deg                           |
|                                                                                             |
|   Logic1                                                Out of Service    : No              |
|     Breaker                                  Cubicle    Branch                              |
|      T1.2                   \ Bus 2           Cubicle_S  CB1                                |
|   Logic 2                                               Out of Service    : No              |
|     Breaker                                  Cubicle    Branch                              |
|      T1.2                   \ Bus 2           Cubicle_S  CB1                                |
-----------------------------------------------------------------------------------------------
| Relay B earth                      Relay Type : Rel-Earth-Ioc-Dirextst                      |
|   Location     :   Cubicle        : Cub_1       Branch      : T132/33                       |
|                     Busbar         : 33 kV                   / Bus 2                         |
|---------------------------------------------------------------------------------------------|
|   CT B                                                 Ratio       : 300A/5A                |
|     No. Phases     : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection     : Y                                                                       |
|                                                                                             |
|   VT B                                                 Ratio       : 33000V/110V            |
|     Connection     : Y                                                                       |
|                                                                                             |
|   Measurement                                                                               |
|     Nominal Current ( 5.0             A      ) :     5.00 A                                 |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                                 |
|                                                                                             |
|   Io>              ( IEC: I>>    ANSI: 50    )         Out of Service    : No              |
|     Tripping Direction                         : None                                       |
|     Pickup Current  ( 0.1 - 100.0    sec.A ) :      0.400 sec.A                             |
|     Time Setting    ( 0.0 - 10.0     s     ) :      0.300 s                                 |
|                                                                                             |
|   Dir IoUo         ( IEC: I->    ANSI: 67    )         Out of Service    : No              |
|     Tripping Direction                            : Forward                                 |
|     Angle Operating Sector     ( 90.0     deg    ) :   90.00 deg                            |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                          |
|     Max. Torque Angle     ( -90.0 - 90.0 deg    ) :     0.00 deg                           |
|                                                                                             |
|   Logic 1                                               Out of Service    : No              |
|     Breaker                                  Cubicle    Branch                              |
|      T1.2                   \ Bus 2           Cubicle_S  CB1                                |
|   Logic 2                                               Out of Service    : No              |
|     Breaker                                  Cubicle    Branch                              |
|      T1.2                   \ Bus 2           Cubicle_S  CB1                                |
-----------------------------------------------------------------------------------------------
```

```
Relay D1b                                  Relay Type : IAC77A805A
  Location      :   Cubicle            : Cub_1          Branch      : C 3-4
                    Busbar             : 11 kV                     / Bus 3
----------------------------------------------------------------------------
  CT D1b                                                Ratio       : 1000A/5A
    No. Phases      : 3           Phase 1      : a      Phase 2     : b
    Connection      : Y
----------------------------------------------------------------------------

----------------------------------------------------------------------------
  Measurement
    Nominal Current ( 5.0            A       ) :      5.00 A

  Toc              ( IEC: I>t    ANSI: 51    )          Out of Service   : No
    Tripping Direction                         :  None
    Current Setting ( 0.5 - 12.0     sec.A ) :      2.000 sec.A
    Time Dial       ( 0.5 - 10.0             ) :      3.600
    Characteristic                             :  IAC Extremely Inverse GES7005B

  Toc Earth        ( IEC: IE>t   ANSI: 51N   )          Out of Service   : No
    Tripping Direction                         :  None
    Current Setting ( 0.01 - 2.6     sec.A ) :      1.200 sec.A
    Time Dial       ( 0.5 - 10.0             ) :      5.600
    Characteristic                             :  IAC Extremely Inverse GES7005B

  Logic                                                 Out of Service   : No
    Breaker                              Cubicle        Branch
     T1.4                  \ Bus 3        Cubicle_S      CB2
----------------------------------------------------------------------------
Relay A earth                              Relay Type : Rel-Earth-Ioc-Dirextst
  Location      :   Cubicle            : Cub_1          Branch      : T132/33
                    Busbar             : 132 kV                    / Bus 1
----------------------------------------------------------------------------
  CT A                                                  Ratio       : 1000A/5A
    No. Phases      : 3           Phase 1      : a      Phase 2     : b
    Connection      : Y

  VT A                                                  Ratio       : 132000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A       ) :      5.00 A
    Nominal Voltage ( 110.0          V       ) :    110.00 V

  Io>              ( IEC: I>>    ANSI: 50    )          Out of Service   : No
    Tripping Direction                         :  None
    Pickup Current  ( 0.1 - 100.0    sec.A ) :      0.100 sec.A
    Time Setting    ( 0.0 - 10.0     s       ) :      0.300 s

  Dir IOUO         ( IEC: I->    ANSI: 67    )          Out of Service   : No
    Tripping Direction                             :  Forward
    Angle Operating Sector      ( 90.0      deg   ) :     90.00 deg
    Polarizing Voltage     ( 0.01 - 10.0   sec.V ) :      0.01 sec.V
    Max. Torque Angle      ( -90.0 - 90.0  deg   ) :      0.00 deg

  Logic 1                                               Out of Service   : No
    Breaker                              Cubicle        Branch
     T2.2                  \ Bus 1        Cubicle_S      CB3
  Logic 2                                               Out of Service   : No
    Breaker                              Cubicle        Branch
     T2.2                  \ Bus 1        Cubicle_S      CB3
----------------------------------------------------------------------------
Relay A                                    Relay Type : Rel-Ioc-Toc-Dirext
  Location      :   Cubicle            : Cub_1          Branch      : T132/33
                    Busbar             : 132 kV                    / Bus 1
----------------------------------------------------------------------------
  CT A                                                  Ratio       : 1000A/5A
    No. Phases      : 3           Phase 1      : a      Phase 2     : b
    Connection      : Y

  VT A                                                  Ratio       : 132000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 1.0            A       ) :      5.00 A
    Nominal Voltage ( 110.0          V       ) :    110.00 V

  Toc              ( IEC: I>t    ANSI: 51    )          Out of Service   : No
    Tripping Direction                         :  None
    Current Setting ( 1.0 - 10.0     sec.A ) :      1.960 sec.A
    Time Dial       ( 0.05 - 3.2             ) :      0.250
    Characteristic                             :  IEC 255-3 extremly inverse

  Ioc              ( IEC: I>>    ANSI: 50    )          Out of Service   : No
    Tripping Direction                         :  None
    Pickup Current  ( 0.1 - 100.0    sec.A ) :      4.940 sec.A
    Time Setting    ( 0.0 - 10.0     s       ) :      0.830 s
----------------------------------------------------------------------------

----------------------------------------------------------------------------
  Dir              ( IEC: I->    ANSI: 67    )          Out of Service   : No
    Tripping Direction                             :  Forward
    Angle Operating Sector      ( 90.0      deg   ) :     90.00 deg
    Operating Current      ( 0.01 - 10.0   sec.A ) :      0.01 sec.A
    Polarizing Voltage     ( 0.0001        sec.V ) :      0.00 sec.V
    Max. Torque Angle      ( -90.0 - 90.0  deg   ) :      0.00 deg

  Logic                                                 Out of Service   : No
    Breaker                              Cubicle        Branch
     T2.2                  \ Bus 1        Cubicle_S      CB3
----------------------------------------------------------------------------
Relay D1a                                  Relay Type : Rel-Toc-Dirextst
  Location      :   Cubicle            : Cub_1          Branch      : T 33/11
                    Busbar             : 11 kV                     / Bus 3
----------------------------------------------------------------------------
  CT D1a                                                Ratio       : 1000A/5A
    No. Phases      : 3           Phase 1      : a      Phase 2     : b
    Connection      : Y

  VT D1a                                                Ratio       : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A       ) :      5.00 A
    Nominal Voltage ( 110.0          V       ) :    110.00 V

  Toc              ( IEC: I>t    ANSI: 51    )          Out of Service   : No
    Tripping Direction                         :  Forward
    Current Setting ( 0.01 - 10.0    sec.A ) :      0.740 sec.A
    Time Dial       ( 0.05 - 3.2             ) :      1.440
    Characteristic                             :  IEC 255-3 extremly inverse

  Dir              ( IEC: I->    ANSI: 67    )          Out of Service   : No
    Tripping Direction                             :  Forward
    Angle Operating Sector      ( 20.0 - 90.0     ) :     90.00 deg
    Polarizing Voltage     ( 0.01 - 10.0   sec.V ) :      0.01 sec.V
    Max. Torque Angle      ( -90.0 - 90.0  deg   ) :      0.00 deg

  Logic1                                                Out of Service   : No
    Breaker                              Cubicle        Branch
     T1.2                  \ Bus 3        Cubicle_S      CB1
  Logic 2                                               Out of Service   : No
    Breaker                              Cubicle        Branch
     T1.2                  \ Bus 3        Cubicle_S      CB1
----------------------------------------------------------------------------
Relay E                                    Relay Type : IAC77A805A
  Location      :   Cubicle            : Cub_1          Branch      : C 4-Tr
                    Busbar             : 11 kV                     / Bus 4
----------------------------------------------------------------------------
  CT E                                                  Ratio       : 300A/5A
    No. Phases      : 3           Phase 1      : a      Phase 2     : b
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A       ) :      5.00 A
```

```
  Toc                 ( IEC: I>t    ANSI: 51    )          Out of Service    : No
    Tripping Direction                          : None
    Current Setting ( 0.5 - 12.0      sec.A )   :      5.00 sec.A
    Time Dial       ( 0.5 - 10.0             )  :      1.500
    Characteristic                              : IAC Extremely Inverse GES7005B

  Toc Earth           ( IEC: IE>t   ANSI: 51N   )          Out of Service    : No
    Tripping Direction                          : None
    Current Setting ( 0.01 - 2.6      sec.A )   :      1.500 sec.A
    Time Dial       ( 0.5 - 10.0             )  :      4.000
    Characteristic                              : IAC Extremely Inverse GES7005B

  Logic                                                    Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.4               \ Bus  4       Cubicle_S   CB2
-------------------------------------------------------------------------------------
 Relay D1a earth                     Relay Type : Rel-Earth-Ioc-Direxts t
  Location     :   Cubicle         : Cub_1        Branch     : T 33/11
                   Busbar          : 11 kV                  / Bus 3
-------------------------------------------------------------------------------------
  CT D1a                                          Ratio         : 1000A/5A
    No. Phases       : 3           Phase 1     : a       Phase 2     : b
    Connection       : Y

  VT D1a                                          Ratio         : 11000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A       ) :      5.00 A
    Nominal Voltage ( 110.0           V       ) :    110.00 V

  Io>                 ( IEC: I>>    ANSI: 50    )          Out of Service    : No
    Tripping Direction                          : None
    Pickup Current  ( 0.1 - 100.0    sec.A )    :      0.130 sec.A
    Time Setting    ( 0.0 - 10.0     s      )   :      0.250 s

  Dir IOUO            ( IEC: I->    ANSI: 67    )          Out of Service    : No
    Tripping Direction                             : Forward
    Angle Operating Sector     ( 90.0      deg   ) :    90.00 deg
    Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :      0.01 sec.V
    Max. Torque Angle      ( -90.0 - 90.0 deg   ) :      0.00 deg

  Logic 1                                                  Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.2               \ Bus  3       Cubicle_S   CB1
  Logic 2                                                  Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.2               \ Bus  3       Cubicle_S   CB1
-------------------------------------------------------------------------------------
 Relay C                             Relay Type : Rel-Ioc-Toc-Dirext
  Location     :   Cubicle         : Cub_1        Branch     : C 2-Tr
                   Busbar          : 33 kV                  / Bus 2
-------------------------------------------------------------------------------------
  CT C                                            Ratio         : 1000A/5A
    No. Phases       : 3           Phase 1     : a       Phase 2     : b
    Connection       : Y

  VT C                                            Ratio         : 33000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 1.0             A       ) :      5.00 A
    Nominal Voltage ( 110.0           V       ) :    110.00 V

  Toc                 ( IEC: I>t    ANSI: 51    )          Out of Service    : No
    Tripping Direction                          : None
    Current Setting ( 1.0 - 10.0      sec.A )   :      2.420 sec.A
    Time Dial       ( 0.05 - 3.2             )  :      0.260
    Characteristic                              : IEC 255-3 extremly inverse

  Ioc                 ( IEC: I>>    ANSI: 50    )          Out of Service    : No
    Tripping Direction                          : None
    Pickup Current  ( 0.1 - 100.0    sec.A )    :      5.720 sec.A
    Time Setting    ( 0.0 - 10.0     s      )   :      0.850 s

  Dir                 ( IEC: I->    ANSI: 67    )          Out of Service    : No
    Tripping Direction                             : Forward
    Angle Operating Sector     ( 90.0      deg   ) :    90.00 deg
    Operating Current      ( 0.01 - 10.0  sec.A ) :      0.01 sec.A
    Polarizing Voltage     ( 0.0001        sec.V ) :      0.00 sec.V
    Max. Torque Angle      ( -90.0 - 90.0 deg   ) :      0.00 deg

  Logic                                                    Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.4               \ Bus  2       Cubicle_S   CB2
-------------------------------------------------------------------------------------
 Relay C earth                       Relay Type : Rel-Earth-Ioc-Direxts t
  Location     :   Cubicle         : Cub_1        Branch     : C 2-Tr
                   Busbar          : 33 kV                  / Bus 2
-------------------------------------------------------------------------------------
  CT C                                            Ratio         : 1000A/5A
    No. Phases       : 3           Phase 1     : a       Phase 2     : b
    Connection       : Y

-------------------------------------------------------------------------------------
  VT C                                            Ratio         : 33000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A       ) :      5.00 A
    Nominal Voltage ( 110.0           V       ) :    110.00 V

  Io>                 ( IEC: I>>    ANSI: 50    )          Out of Service    : No
    Tripping Direction                          : None
    Pickup Current  ( 0.1 - 100.0    sec.A )    :      0.200 sec.A
    Time Setting    ( 0.0 - 10.0     s      )   :      0.250 s

  Dir IOUO            ( IEC: I->    ANSI: 67    )          Out of Service    : No
    Tripping Direction                             : Forward
    Angle Operating Sector     ( 90.0      deg   ) :    90.00 deg
    Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :      0.01 sec.V
    Max. Torque Angle      ( -90.0 - 90.0 deg   ) :      0.00 deg

  Logic 1                                                  Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.4               \ Bus  2       Cubicle_S   CB2
  Logic 2(1)                                               Out of Service    : No
    Breaker                          Cubicle      Branch
     T1.4               \ Bus  2       Cubicle_S   CB2
-------------------------------------------------------------------------------------
 Relay F                             Relay Type : IAC77A805A
  Location     :   Cubicle         : Cub_1        Branch     : C 2-6
                   Busbar          : 33 kV                  / Bus 2
-------------------------------------------------------------------------------------
  CT F                                            Ratio         : 1000A/5A
    No. Phases       : 3           Phase 1     : a       Phase 2     : b
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A       ) :      5.00 A

  Toc                 ( IEC: I>t    ANSI: 51    )          Out of Service    : No
    Tripping Direction                          : None
    Current Setting ( 0.5 - 12.0      sec.A )   :      3.500 sec.A
    Time Dial       ( 0.5 - 10.0             )  :      3.800
    Characteristic                              : IAC Extremely Inverse GES7005B

  Toc Earth           ( IEC: IE>t   ANSI: 51N   )          Out of Service    : No
    Tripping Direction                          : None
    Current Setting ( 0.01 - 2.6      sec.A )   :      2.560 sec.A
    Time Dial       ( 0.5 - 10.0             )  :      3.700
    Characteristic                              : IAC Extremely Inverse GES7005B

  Logic                                                    Out of Service    : No
    Breaker                          Cubicle      Branch
```

Figure 5-19 Relay parameters for the main network

```
---------------------------------------------------------------------------------------------
|           With DG                       |  DIgSILENT   | Project: Radial                 |
|       Large wind farm                   | PowerFactory |---------------------------------|
|                                         |    14.1.3    | Date:   10/29/2013              |
---------------------------------------------------------------------------------------------
| Relay LW1_A                          Relay Type : Rel-Toc-Dirextst                        |
|   Location     :  Cubicle          : Cub_1        Branch     : C-LW1                    |
|                   Busbar           : 33 kV                   / Bus 2                     |
|-------------------------------------------------------------------------------------------|
|   CT LW1_A                                          Ratio       : 1000A/5A              |
|     No. Phases     : 3          Phase 1     : a     Phase 2     : b                     |
|     Connection     : Y                                                                   |
|                                                                                           |
|   VT LW1_A                                          Ratio       : 33000V/110V           |
|     Connection     : Y                                                                   |
|                                                                                           |
|   Measurement                                                                             |
|     Nominal Current ( 5.0             A      ) :     5.00 A                              |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                              |
|                                                                                           |
|   Toc               ( IEC: I>t    ANSI: 51    )       Out of Service    : No              |
|     Tripping Direction                         : Forward                                  |
|     Current Setting ( 0.01 - 10.0    sec.A ) :      1.300 sec.A                          |
|     Time Dial       ( 0.05 - 3.2           ) :      1.280                                |
|     Characteristic                           : IEC 255-3 extremly inverse               |
|                                                                                           |
|   Dir               ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                              |
|     Angle Operating Sector     ( 20.0 - 90.0    ) :    90.00 deg                         |
|     Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                       |
|     Max. Torque Angle      ( -90.0 - 90.0 deg   ) :    45.00 deg                         |
|                                                                                           |
|   Logic1                                              Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       T2.2                   \ Bus 2       Cubicle_S   CB3                                |
|       LW1 terminal 33 kV     \             Cub_3       T33/11 a                           |
|   Logic 2                                             Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       LW2                    \ Large wind  Cubicle_S   CBS                                |
---------------------------------------------------------------------------------------------
| Relay LW1_A_earth                    Relay Type : Rel-Earth-Ioc-Dirextst                  |
|   Location     :  Cubicle          : Cub_1        Branch     : C-LW1                    |
|                   Busbar           : 33 kV                   / Bus 2                     |
|-------------------------------------------------------------------------------------------|
|   CT LW1_A                                          Ratio       : 1000A/5A              |
|     No. Phases     : 3          Phase 1     : a     Phase 2     : b                     |
|     Connection     : Y                                                                   |
|                                                                                           |
|   VT LW1_A                                          Ratio       : 33000V/110V           |
|     Connection     : Y                                                                   |
|                                                                                           |
|   Measurement                                                                             |
|     Nominal Current ( 5.0             A      ) :     5.00 A                              |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                              |
|                                                                                           |
|   Io>               ( IEC: I>>    ANSI: 50    )       Out of Service    : No              |
|     Tripping Direction                         : None                                     |
|     Pickup Current  ( 0.1 - 100.0    sec.A ) :      0.400 sec.A                          |
|     Time Setting    ( 0.0 - 10.0     s     ) :      0.300 s                              |
|                                                                                           |
|   Dir IOUO          ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                              |
|     Angle Operating Sector     ( 90.0      deg  ) :    90.00 deg                         |
|     Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                       |
|     Max. Torque Angle      ( -90.0 - 90.0 deg   ) :     0.00 deg                         |
|                                                                                           |
|   Logic 1                                             Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       T2.2                   \ Bus 2       Cubicle_S   CB3                                |
|       LW1 terminal 33 kV     \             Cub_3       T33/11 a                           |
|   Logic 2                                             Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       LW2                    \ Large wind  Cubicle_S   CBS                                |
---------------------------------------------------------------------------------------------
| Relay LW1_B                          Relay Type : Rel-Toc-Dirextst                        |
|   Location     :  Cubicle          : Cub_1        Branch     : T33/11 a                 |
|                   Busbar           : LW1                     / Large wind farm           |
|-------------------------------------------------------------------------------------------|
|   CT LW1_B                                          Ratio       : 1000A/5A              |
|     No. Phases     : 3          Phase 1     : a     Phase 2     : b                     |
|     Connection     : Y                                                                   |
|                                                                                           |
|   VT LW1_B                                          Ratio       : 11000V/110V           |
|     Connection     : Y                                                                   |
|                                                                                           |
|   Measurement                                                                             |
|     Nominal Current ( 5.0             A      ) :     5.00 A                              |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                              |
|                                                                                           |
|   Toc               ( IEC: I>t    ANSI: 51    )       Out of Service    : No              |
|     Tripping Direction                         : Forward                                  |
|     Current Setting ( 0.01 - 10.0    sec.A ) :      5.030 sec.A                          |
|     Time Dial       ( 0.05 - 3.2           ) :      0.220                                |
|     Characteristic                           : IEC 255-3 extremly inverse               |
|                                                                                           |
|   Dir               ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                              |
|     Angle Operating Sector     ( 20.0 - 90.0    ) :    90.00 deg                         |
|     Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                       |
|     Max. Torque Angle      ( -90.0 - 90.0 deg   ) :    45.00 deg                         |
|                                                                                           |
|   Logic1                                              Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       T01                    \ Large wind  Cubicle_S   CB.L1                              |
|   Logic 2                                             Out of Service    : Yes             |
|     Breaker                              Cubicle     Branch                               |
|       T01                    \ Large wind  Cubicle_S   CB.L1                              |
---------------------------------------------------------------------------------------------
| Relay LW1_B_earth                    Relay Type : Rel-Earth-Ioc-Dirextst                  |
|   Location     :  Cubicle          : Cub_1        Branch     : T33/11 a                 |
|                   Busbar           : LW1                     / Large wind farm           |
|-------------------------------------------------------------------------------------------|
|   CT LW1_B                                          Ratio       : 1000A/5A              |
|     No. Phases     : 3          Phase 1     : a     Phase 2     : b                     |
|     Connection     : Y                                                                   |
|                                                                                           |
|   VT LW1_B                                          Ratio       : 11000V/110V           |
|     Connection     : Y                                                                   |
|                                                                                           |
|   Measurement                                                                             |
|     Nominal Current ( 5.0             A      ) :     5.00 A                              |
|     Nominal Voltage ( 110.0           V      ) :   110.00 V                              |
|                                                                                           |
|   Io>               ( IEC: I>>    ANSI: 50    )       Out of Service    : No              |
|     Tripping Direction                         : None                                     |
|     Pickup Current  ( 0.1 - 100.0    sec.A ) :      1.200 sec.A                          |
|     Time Setting    ( 0.0 - 10.0     s     ) :      0.600 s                              |
|                                                                                           |
|   Dir IOUO          ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                              |
|     Angle Operating Sector     ( 90.0      deg  ) :    90.00 deg                         |
|     Polarizing Voltage     ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                       |
|     Max. Torque Angle      ( -90.0 - 90.0 deg   ) :     0.00 deg                         |
|                                                                                           |
|   Logic 1                                             Out of Service    : No              |
|     Breaker                              Cubicle     Branch                               |
|       T01                    \ Large wind  Cubicle_S   CB.L1                              |
|   Logic 2                                             Out of Service    : Yes             |
|     Breaker                              Cubicle     Branch                               |
|       T01                    \ Large wind  Cubicle_S   CB.L1                              |
---------------------------------------------------------------------------------------------
| Relay LW1_C1                         Relay Type : Rel-Toc-Dirextst                        |
|   Location     :  Cubicle          : Cub_1        Branch     : Cable_WT1                |
|                   Busbar           : LW1                     / Large wind farm           |
---------------------------------------------------------------------------------------------
```

```
----------------------------------------------------------------------------------------
   CT LW1_C1                                                Ratio        : 1200A/5A
     No. Phases      : 3          Phase 1     : a           Phase 2      : b
     Connection      : Y

   VT LW1_C1                                                Ratio        : 11000V/110V
     Connection      : Y

----------------------------------------------------------------------------------------
   Measurement
     Nominal Current ( 5.0              A      ) :      5.00 A
     Nominal Voltage ( 110.0            V      ) :    110.00 V

   Toc               ( IEC: I>t   ANSI: 51    )        Out of Service    : No
     Tripping Direction                          : Forward
     Current Setting ( 0.01 - 10.0    sec.A ) :      10.000 sec.A
     Time Dial       ( 0.05 - 3.2            ) :       0.060
     Characteristic                              : IEC 255-3 extremly inverse

   Dir               ( IEC: I->   ANSI: 67    )        Out of Service    : No
     Tripping Direction                              : Forward
     Angle Operating Sector     ( 20.0 - 90.0   ) :    90.00 deg
     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :    45.00 deg

   Logic1                                              Out of Service    : No
     Breaker                                 Cubicle    Branch
      T03                  \ Large wind   Cubicle_S   CB.L2
   Logic 2                                             Out of Service    : Yes
     Breaker                                 Cubicle    Branch
      T03                  \ Large wind   Cubicle_S   CB.L2
----------------------------------------------------------------------------------------
 Relay LW1_C1_earth                  Relay Type : Rel-Earth-Ioc-Dirextst
   Location       :  Cubicle          : Cub_1        Branch       : Cable_WT1
                     Busbar           : LW1                       / Large wind farm
----------------------------------------------------------------------------------------
   CT LW1_C1                                                Ratio        : 1200A/5A
     No. Phases      : 3          Phase 1     : a           Phase 2      : b
     Connection      : Y

   VT LW1_C1                                                Ratio        : 11000V/110V
     Connection      : Y

   Measurement
     Nominal Current ( 5.0              A      ) :      1.00 A
     Nominal Voltage ( 110.0            V      ) :    110.00 V

   Io>               ( IEC: I>>   ANSI: 50    )        Out of Service    : No
     Tripping Direction                          : None
     Pickup Current  ( 0.1 - 100.0    sec.A ) :       0.200 sec.A
     Time Setting    ( 0.0 - 10.0     s      ) :       0.300 s

   Dir IOUO          ( IEC: I->   ANSI: 67    )        Out of Service    : No
     Tripping Direction                              : Forward
     Angle Operating Sector     ( 90.0     deg  ) :    90.00 deg
     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

   Logic 1                                             Out of Service    : No
     Breaker                                 Cubicle    Branch
      T03                  \ Large wind   Cubicle_S   CB.L2
   Logic 2                                             Out of Service    : Yes
     Breaker                                 Cubicle    Branch
      T03                  \ Large wind   Cubicle_S   CB.L2
----------------------------------------------------------------------------------------
 Relay LW1_D1                        Relay Type : Rel-Toc-Dirextst
   Location       :  Cubicle          : Cub_4        Branch       : Cable_WT1
                     Busbar           : Term_WT1                  /
----------------------------------------------------------------------------------------
   CT LW1_D1                                                Ratio        : 300A/5A
     No. Phases      : 3          Phase 1     : a           Phase 2      : b
     Connection      : Y

   VT LW1_D1                                                Ratio        : 11000V/110V
     Connection      : Y

   Measurement
     Nominal Current ( 5.0              A      ) :      5.00 A
     Nominal Voltage ( 110.0            V      ) :    110.00 V

   Toc               ( IEC: I>t   ANSI: 51    )        Out of Service    : No
     Tripping Direction                          : Forward
     Current Setting ( 0.01 - 10.0    sec.A ) :       3.620 sec.A
     Time Dial       ( 0.05 - 3.2            ) :       0.210
     Characteristic                              : IEC 255-3 extremly inverse

----------------------------------------------------------------------------------------
   Dir               ( IEC: I->   ANSI: 67    )        Out of Service    : No
     Tripping Direction                              : Forward
     Angle Operating Sector     ( 20.0 - 90.0   ) :    90.00 deg
     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

   Logic1                                              Out of Service    : No
     Breaker                                 Cubicle    Branch
      Term_WT1             \                  Cub_4      Cable_WT1
   Logic 2                                             Out of Service    : Yes
     Breaker                                 Cubicle    Branch
      Term_WT1             \                  Cub_4      Cable_WT1
----------------------------------------------------------------------------------------
 Relay LW1_D1_earth                  Relay Type : Rel-Earth-Ioc-Dirextst
   Location       :  Cubicle          : Cub_4        Branch       : Cable_WT1
                     Busbar           : Term_WT1                  /
----------------------------------------------------------------------------------------
   CT LW1_D1                                                Ratio        : 300A/5A
     No. Phases      : 3          Phase 1     : a           Phase 2      : b
     Connection      : Y

   VT LW1_D1                                                Ratio        : 11000V/110V
     Connection      : Y

   Measurement
     Nominal Current ( 1.0              A      ) :      1.00 A
     Nominal Voltage ( 110.0            V      ) :    110.00 V

   Io>               ( IEC: I>>   ANSI: 50    )        Out of Service    : No
     Tripping Direction                          : None
     Pickup Current  ( 0.1 - 100.0    sec.A ) :       1.000 sec.A
     Time Setting    ( 0.0 - 10.0     s      ) :       0.300 s

   Dir IOUO          ( IEC: I->   ANSI: 67    )        Out of Service    : No
     Tripping Direction                              : Forward
     Angle Operating Sector     ( 90.0     deg  ) :    90.00 deg
     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.10 sec.V
     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

   Logic                                               Out of Service    : No
     Breaker                                 Cubicle    Branch
      Term_WT1             \                  Cub_4      Cable_WT1
----------------------------------------------------------------------------------------
```

Figure 5-20 Relay parameters for the large wind farm

```
-------------------------------------------------------------------------------------
|            With DG                    |  DIgSILENT  | Project: Radial             |
|      Small wind farm                  | PowerFactory |-----------------------------|
|                                       |   14.1.3    | Date:   10/29/2013          |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
| Relay SW B2                       Relay Type : Rel-Toc-Dirextst                   |
|   Location     :  Cubicle        : Cub_3       Branch     : Cable_WT13            |
|                   Busbar         : Terminal Load 1        /                       |
|-----------------------------------------------------------------------------------|
|   CT SW_B2                                        Ratio       : 500A/5A           |
|     No. Phases     : 3          Phase 1    : a      Phase 2     : b               |
|     Connection     : Y                                                            |
|                                                                                   |
|   VT SW_B2                                        Ratio       : 11000V/110V       |
|     Connection     : Y                                                            |
|                                                                                   |
|   Measurement                                                                     |
|     Nominal Current ( 5.0            A      ) :     5.00 A                        |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                        |
|                                                                                   |
|   Toc              ( IEC: I>t   ANSI: 51    )      Out of Service   : No          |
|     Tripping Direction                      : Forward                             |
|     Current Setting ( 0.01 - 10.0   sec.A ) :      4.280 sec.A                    |
|     Time Dial       ( 0.05 - 3.2          ) :      0.320                          |
|     Characteristic                          : IEC 255-3 extremly inverse          |
|                                                                                   |
|   Dir              ( IEC: I->   ANSI: 67    )      Out of Service   : No          |
|     Tripping Direction                         : Forward                          |
|     Angle Operating Sector     ( 20.0 - 90.0    ) :   90.00 deg                   |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                 |
|     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg                   |
|                                                                                   |
|   Logic1                                               Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Terminal Load 1       \              Cub_3       Cable_WT13                 |
|   Logic 2                                              Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Terminal Load 1       \              Cub_3       Cable_WT13                 |
-------------------------------------------------------------------------------------
| Relay SW B2 earth                 Relay Type : Rel-Earth-Ioc-Dirextst             |
|   Location     :  Cubicle        : Cub_3       Branch     : Cable_WT13            |
|                   Busbar         : Terminal Load 1        /                       |
|-----------------------------------------------------------------------------------|
|   CT SW_B2                                        Ratio       : 500A/5A           |
|     No. Phases     : 3          Phase 1    : a      Phase 2     : b               |
|     Connection     : Y                                                            |
|                                                                                   |
|   VT SW_B2                                        Ratio       : 11000V/110V       |
|     Connection     : Y                                                            |
|                                                                                   |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
|   Measurement                                                                     |
|     Nominal Current ( 5.0            A      ) :     5.00 A                        |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                        |
|                                                                                   |
|   Io>              ( IEC: I>>   ANSI: 50    )      Out of Service   : No          |
|     Tripping Direction                      : None                                |
|     Pickup Current  ( 0.1 - 100.0   sec.A ) :      0.590 sec.A                    |
|     Time Setting    ( 0.0 - 10.0    s     ) :      0.250 s                        |
|                                                                                   |
|   Dir IOUO         ( IEC: I->   ANSI: 67    )      Out of Service   : No          |
|     Tripping Direction                         : Forward                          |
|     Angle Operating Sector     ( 90.0     deg   ) :   90.00 deg                   |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                 |
|     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg                   |
|                                                                                   |
|   Logic 1                                              Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Terminal Load 1       \              Cub_3       Cable_WT13                 |
|   Logic 2                                              Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Terminal Load 1       \              Cub_3       Cable_WT13                 |
-------------------------------------------------------------------------------------
| Relay SW C2                       Relay Type : Rel-Toc-Dirextst                   |
|   Location     :  Cubicle        : Cub_2       Branch     : Cable_WT14            |
|                   Busbar         : Term_WT14              /                       |
|-----------------------------------------------------------------------------------|
|   CT SW C2                                        Ratio       : 500A/5A           |
|     No. Phases     : 3          Phase 1    : a      Phase 2     : b               |
|     Connection     : Y                                                            |
|                                                                                   |
|   VT SW C2                                        Ratio       : 11000V/110V       |
|     Connection     : Y                                                            |
|                                                                                   |
|   Measurement                                                                     |
|     Nominal Current ( 5.0            A      ) :     5.00 A                        |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                        |
|                                                                                   |
|   Toc              ( IEC: I>t   ANSI: 51    )      Out of Service   : No          |
|     Tripping Direction                      : Forward                             |
|     Current Setting ( 0.01 - 10.0   sec.A ) :      1.170 sec.A                    |
|     Time Dial       ( 0.05 - 3.2          ) :      1.330                          |
|     Characteristic                          : IEC 255-3 extremly inverse          |
|                                                                                   |
|   Dir              ( IEC: I->   ANSI: 67    )      Out of Service   : No          |
|     Tripping Direction                         : Forward                          |
|     Angle Operating Sector     ( 20.0 - 90.0    ) :   90.00 deg                   |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                 |
|     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :    45.00 deg                   |
|                                                                                   |
|   Logic1                                               Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Term_WT14             \              Cub_2       Cable_WT14                 |
|   Logic 2                                              Out of Service   : Yes     |
|     Breaker                              Cubicle     Branch                       |
|       Term_WT14             \              Cub_2       Cable_WT14                 |
-------------------------------------------------------------------------------------
| Relay SW C2_earth                 Relay Type : Rel-Earth-Ioc-Dirextst             |
|   Location     :  Cubicle        : Cub_2       Branch     : Cable_WT14            |
|                   Busbar         : Term_WT14              /                       |
|-----------------------------------------------------------------------------------|
|   CT SW C2                                        Ratio       : 500A/5A           |
|     No. Phases     : 3          Phase 1    : a      Phase 2     : b               |
|     Connection     : Y                                                            |
|                                                                                   |
|   VT SW C2                                        Ratio       : 11000V/110V       |
|     Connection     : Y                                                            |
|                                                                                   |
|   Measurement                                                                     |
|     Nominal Current ( 5.0            A      ) :     1.00 A                        |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                        |
|                                                                                   |
|   Io>              ( IEC: I>>   ANSI: 50    )      Out of Service   : No          |
|     Tripping Direction                      : Forward                             |
|     Pickup Current  ( 0.1 - 100.0   sec.A ) :      1.000 sec.A                    |
|     Time Setting    ( 0.0 - 10.0    s     ) :      0.700 s                        |
|                                                                                   |
-------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------
|   Dir IOUO         ( IEC: I->   ANSI: 67    )      Out of Service   : No          |
|     Tripping Direction                         : Forward                          |
|     Angle Operating Sector     ( 90.0     deg   ) :   90.00 deg                   |
|     Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                 |
|     Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg                   |
|                                                                                   |
|   Logic 1                                              Out of Service   : No      |
|     Breaker                              Cubicle     Branch                       |
|       Term_WT14             \              Cub_2       Cable_WT14                 |
|   Logic 2                                              Out of Service   : Yes     |
|     Breaker                              Cubicle     Branch                       |
|       Term_WT14             \              Cub_2       Cable_WT14                 |
-------------------------------------------------------------------------------------
```

```
Relay SW a                          Relay Type : Rel-Toc-Dirextst
  Location     :  Cubicle          : Cub_1       Branch     : C- load 1
                  Busbar           : 11 kV                   / Bus 3

  CT SWA                                           Ratio        : 1000A/5A
    No. Phases      : 3          Phase 1     : a   Phase 2      : b
    Connection      : Y

  VT SWA                                           Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A      ) :     5.00 A
    Nominal Voltage ( 110.0          V      ) :   110.00 V

  Toc               ( IEC: I>t   ANSI: 51    )        Out of Service    : No
    Tripping Direction                        : Forward
    Current Setting ( 0.01 - 10.0   sec.A )   :     3.650 sec.A
    Time Dial       ( 0.05 - 3.2            ) :     0.370
    Characteristic                            : IEC 255-3 extremly inverse

  Dir               ( IEC: I->   ANSI: 67    )        Out of Service    : No
    Tripping Direction                            : Forward
    Angle Operating Sector     ( 20.0 - 90.0   ) :    90.00 deg
    Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
    Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

  Logic1                                                Out of Service    : No
    Breaker                               Cubicle    Branch
     T2.4                 \ Bus 3          Cubicle_S  CB4
  Logic 2                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     T2.4                 \ Bus 3          Cubicle_S  CB4

Relay SW a earth                    Relay Type : Rel-Earth-Ioc-Dirextst
  Location     :  Cubicle          : Cub_1       Branch     : C- load 1
                  Busbar           : 11 kV                   / Bus 3

  CT SWA                                           Ratio        : 1000A/5A
    No. Phases      : 3          Phase 1     : a   Phase 2      : b
    Connection      : Y

  VT SWA                                           Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A      ) :     5.00 A
    Nominal Voltage ( 110.0          V      ) :   110.00 V

  Io>               ( IEC: I>>   ANSI: 50    )        Out of Service    : No
    Tripping Direction                        : None
    Pickup Current  ( 0.1 - 100.0   sec.A )   :     0.240 sec.A
    Time Setting    ( 0.0 - 10.0    s       ) :     0.600 s

  Dir IOUO          ( IEC: I->   ANSI: 67    )        Out of Service    : No
    Tripping Direction                            : Forward
    Angle Operating Sector     ( 90.0     deg  ) :    90.00 deg
    Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
    Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

  Logic 1                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     T2.4                 \ Bus 3          Cubicle_S  CB4
  Logic 2                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     T2.4                 \ Bus 3          Cubicle_S  CB4

Relay SW a1                         Relay Type : Rel-Toc-Dirextst
  Location     :  Cubicle          : Cub_5       Branch     : C- load 1
                  Busbar           : Terminal Load 1         /

  CT SW a1                                         Ratio        : 500A/5A
    No. Phases      : 3          Phase 1     : a   Phase 2      : b
    Connection      : Y

  VT SWa1                                          Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A      ) :     5.00 A
    Nominal Voltage ( 110.0          V      ) :   110.00 V

  Toc               ( IEC: I>t   ANSI: 51    )        Out of Service    : No
    Tripping Direction                        : Forward
    Current Setting ( 0.01 - 10.0   sec.A )   :     2.060 sec.A
    Time Dial       ( 0.05 - 3.2            ) :     1.130
    Characteristic                            : IEC 255-3 extremly inverse

  Dir               ( IEC: I->   ANSI: 67    )        Out of Service    : No
    Tripping Direction                            : Forward
    Angle Operating Sector     ( 20.0 - 90.0   ) :    90.00 deg
    Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
    Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

  Logic1                                                Out of Service    : No
    Breaker                               Cubicle    Branch
     Terminal Load 1      \                Cub_5      C- load 1
  Logic 2                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     Terminal Load 1      \                Cub_5      C- load 1

Relay SW a1 earth                   Relay Type : Rel-Earth-Ioc-Dirextst
  Location     :  Cubicle          : Cub_5       Branch     : C- load 1
                  Busbar           : Terminal Load 1         /

  CT SW a1                                         Ratio        : 500A/5A
    No. Phases      : 3          Phase 1     : a   Phase 2      : b
    Connection      : Y

  VT SWa1                                          Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0            A      ) :     5.00 A
    Nominal Voltage ( 110.0          V      ) :   110.00 V

  Io>               ( IEC: I>>   ANSI: 50    )        Out of Service    : No
    Tripping Direction                        : None
    Pickup Current  ( 0.1 - 100.0   sec.A )   :     0.300 sec.A
    Time Setting    ( 0.0 - 10.0    s       ) :     0.500 s

  Dir IOUO          ( IEC: I->   ANSI: 67    )        Out of Service    : No
    Tripping Direction                            : Forward
    Angle Operating Sector     ( 90.0     deg  ) :    90.00 deg
    Polarizing Voltage    ( 0.01 - 10.0  sec.V ) :     0.01 sec.V
    Max. Torque Angle     ( -90.0 - 90.0 deg   ) :     0.00 deg

  Logic 1                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     Terminal Load 1      \                Cub_5      C- load 1
  Logic 2                                               Out of Service    : No
    Breaker                               Cubicle    Branch
     Terminal Load 1      \                Cub_5      C- load 1
```

Figure 5-21 Relay parameters for the small wind farm

6. Meshed networks simulated in DIgSILENT

6.1 Chapter introduction

In the radial MV network, overcurrent relays are employed to achieve protection coordination. In the distribution networks with multiple sources, time-graded overcurrent relays with directional sensing units are used to achieve proper coordination in the protection scheme. However, in line with increased interest in the improvement of the quality of electricity distribution, meshed network, including closed-loop feeder operations, is becoming a subject of great interest and recognized to have the great potential [29].

Protection coordination has become even more complicated as the result of using the meshed mode. For such meshed networks with multiple sources, it is hard to satisfy the coordination requirements and the calculation process is complicated when using OC protection. Compared with the OC protection scheme, the distance protection scheme employed in protecting the meshed network is simpler and the coordination between relays is relatively easier to acquire. The distance-based protection schemes that protect the typical meshed distribution networks are demonstrated in this chapter.

6.2 Network modeling

A typical section of the distribution network is adopted from [30]. The network comprises a 33 kV, 11Hz external grid and supplies the 11 kV busbar through two parallel 33/11 kV/kV transformers. The total of the loads, 4.85 MW, are constant impedance static loads distributed along the feeder. A detailed description and parameters regarding the network are given in Appendix 3.

The general philosophy to design the protection system of a network is to divide the system into separate zones that can be individually protected and disconnected on the occurrence of a fault [3]. Each relay in a protection system has the responsibility to trip a predefined circuit breaker (CB) when the fault occurs in its required zones.

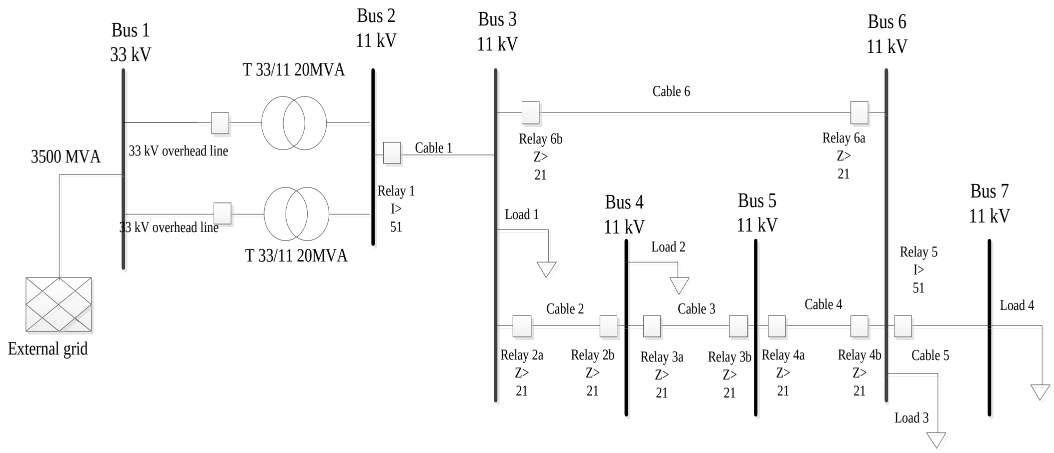


Figure 6-1 Singe line diagram of the meshed distribution network

6.3 Meshed network without DGs

6.3.1 The selection and settings of protective devices

The protection system designed for the meshed network can be divided into two parts. One part is the OC protection and overcurrent relays are installed to protect cable 1 and cable 5 from the short circuit events (Figure 6-1). Relay 1 and relay 5 are OC relays and both follow extremely inverse (EI) characteristics. The other part is the close loop protection, which is mainly comprised of feeders see currents flow from more than one direction (relays 2a, 2b, 3a, 3b, 4a, 4b, 6a, 6b). Distance relays are installed at both ends of every busbar with a directional sensing unit around the loop circuit. All distance relays adopted in the protection system follow the MHO characteristic. They are GE distance type. The GE distance relay type is selected from the DIgSILENT global library and needs to be set in each protection zone separately. The settings for distance relays have been explained in the previous Section 2.4.

The *R-X plot* represents the characteristic of a distance relay. The impedance of the connected lines and transformers in the network displayed also in the plot, allows us to clearly observe the reaching zone of each distance relay. The *R-X plot* can provide users with short circuit or load flow calculations as well. The following information can be read from it [25]: the name of the relay, measured impedances seen from the relay location, the fault type, the actual tripping time of the relay and which zone is tripped.

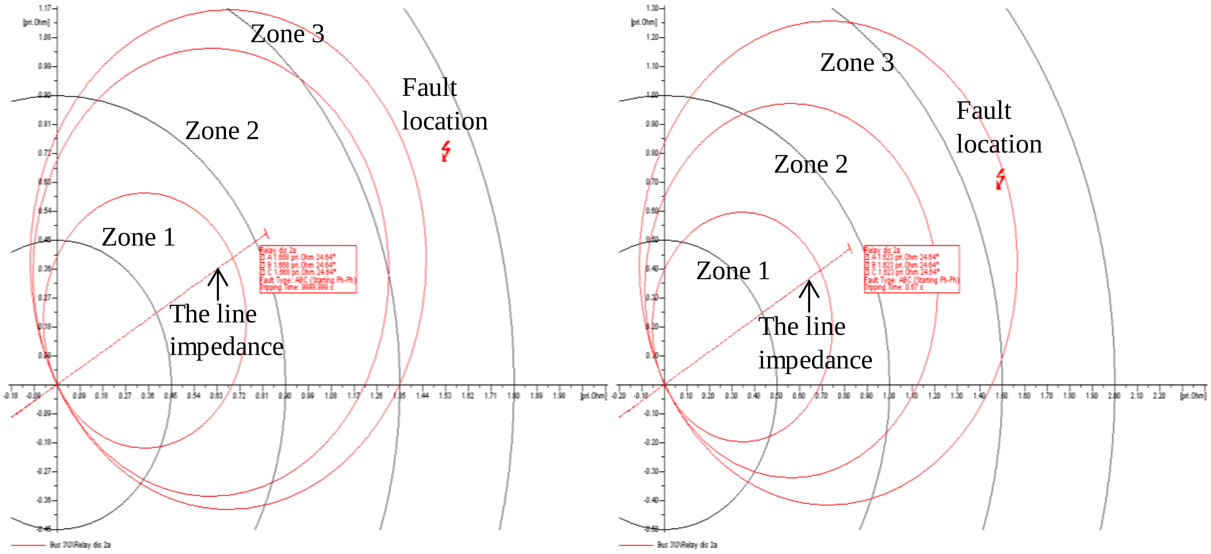


Figure 6-2 The R-X plots display a 2-phase fault

The information is essential when assessing the relay operation of the faults at the end of the zone in order to guarantee the sensitivity. For instance, as shown in Figure 6-2, if a 3-phase fault occurs at the zone 3 of the distance relay dis2a, the improper settings result in the relay dis2a not sensing the fault current. The circle should be set larger to include the fault. After the relay settings have been edited manually, the relay dis2 trips correctly when the same fault occurs (0.67 s). The information can be read from the *R-X plot*: the name is relay dis2a; the fault type is a 3-phase fault; the tripping time for this fault is 0.67 s; the fault location is within zone 3. Thus, the fault location can be distinguished directly and the correct reach of the zone can be adjusted.

It is common to set the relay characteristic angle a little smaller than the line angle in order to accept a small amount of fault resistance without producing under-reach (Section 2.4.3). Therefore, in this protection system, the characteristic angles of distance relays are set at 30^{o}, which is a little greater than the line impedance angle that is 29^{o}.
The directional distance relays are set to operate for faults occurring at the forward direction. However, when a 3-phase fault occurs at the busbar, the MHO relay locates in the feeder may become non-directional and trip the reverse busbar fault since the voltage at the busbar decreases to zero. A way to prevent this incorrect reverse operation is to authorize the voltage memory unit of the MHO distance relay to accept the polarizing voltage signal. This enables high speed MHO protection to operate

correctly on the close-in faults, provided that the protected circuit is energized before the short circuit is applied [4].

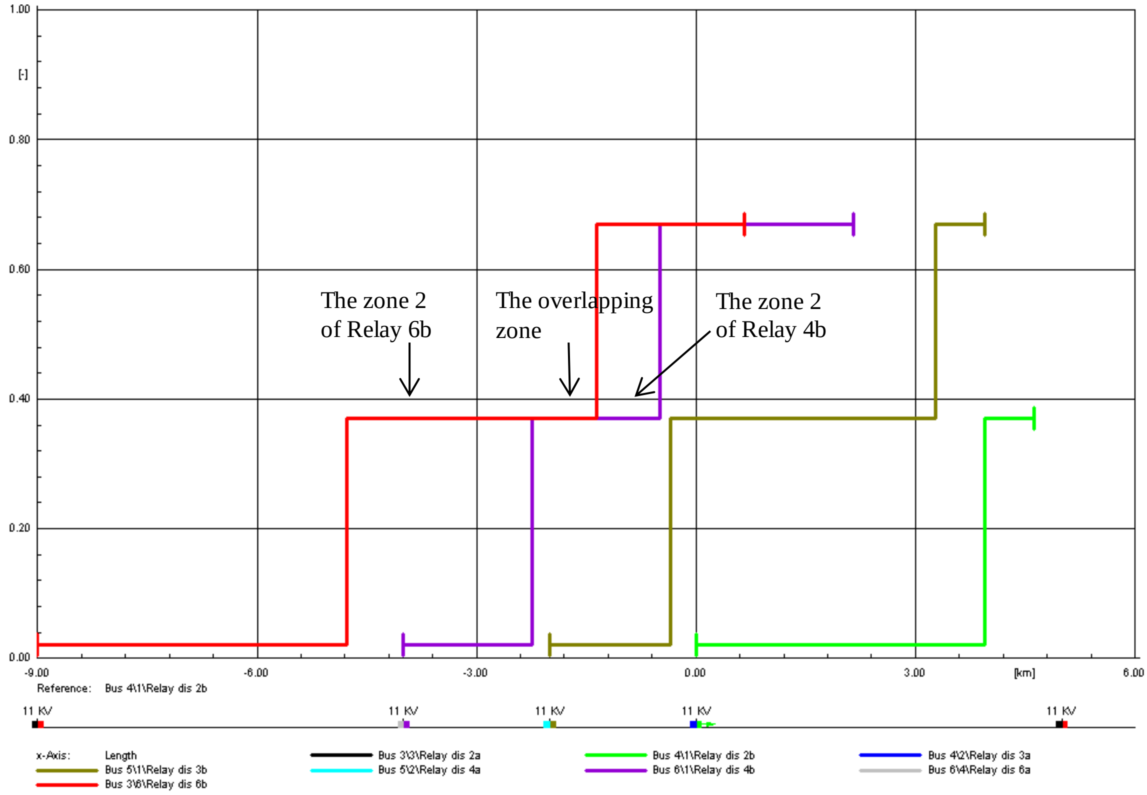
6.3.2 Explanation of the protection coordination

The protection coordination should be examined in two parts. One part is the coordination between the distance relays at the loop circuit, which is relatively simple. The traditional criterion for loop feeder coordination was explained in Chapter 3. Firstly, look around the loop, clockwise, relay dis 6b - relay dis 4b - relay dis 3b - relay dis 1b. Then begin with relay dis 2a on the reverse direction around the loop this time. Secondly, the appropriate settings are calculated based on the rules in Section 3.2 and need to be examined in the time-distance plot to ensure correct protection coordination.

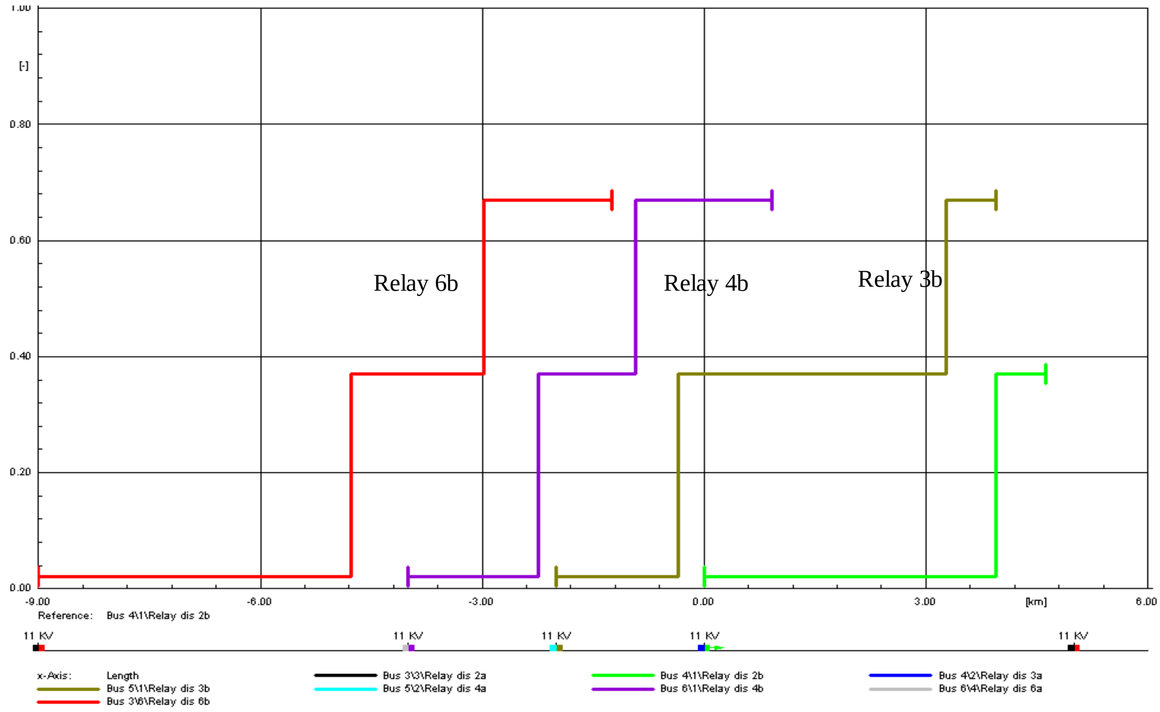
Figure 6-3 (a) displays the tripping time for the distance relays around counter clockwise; the red curve represents the relay dis 6b and the purple curve represents the relay dis 4b. It is clear to see that the zone 2 of the red curve is covered with a portion of the zone 2 of the purple curve. This means that for faults occurring at the overlapping zone, two relays will operate at the same time. Consequently, the coordination is lost and a readjustment should be considered. In Figure 6-3 (b), there ARE no longer exists the overlapping zones of distance relays after the resetting.

Another part is the coordination between distance relays locate at the loop feeder and overcurrent relays locate outside the loop. It can be clearly seen that the loop is not completely independent. The settings of some distance relays are also dependent on their downstream OC relays or upstream OC relays. There are two significant formulas mentioned in Section 3.2.1 that should be considered. For example, for the first rule and Equation 3-2, the zone 2 of relay dis 4a is set to cover all the protected line, plus 25% of the second longest line (cable 5) as illustrated before. Therefore, zone 2 of relay dis 4a should be set as the back up protection when a fault occurs within 25% of cable 5 and it only operates when the main protective relay 5 fails to operate. The operating time for zone 2 is usually in the range of 0.3 to 0.6 s. For this network, the operating time for zone 2 is 0.3 s, zone 3 is 0.65 s. Figure 6-4 shows an example; if a fault occurs at the main protective zone of relay 5 (between bus 6 and bus 7), it will operate faster than zone 2 and zone 3 of the distance relay (blue curve). This diagram is a time distance (T-

D) plot formed by DIgSILENT, and more information regarding the T-D path can be found in A.1.4.



(a)



(b)

Figure 6-3 Example for overlapping of distance relays

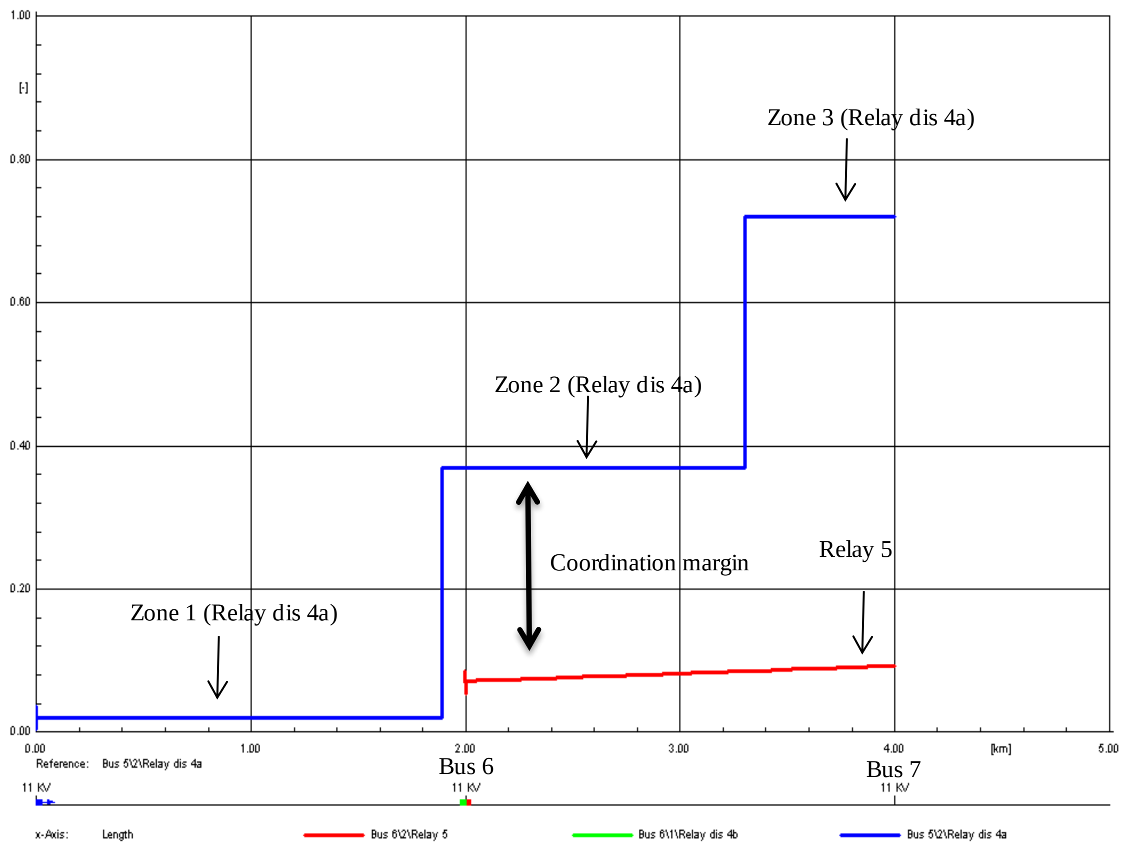


Figure 6-4 Time-distance plot displays the distance relay working as a back-up

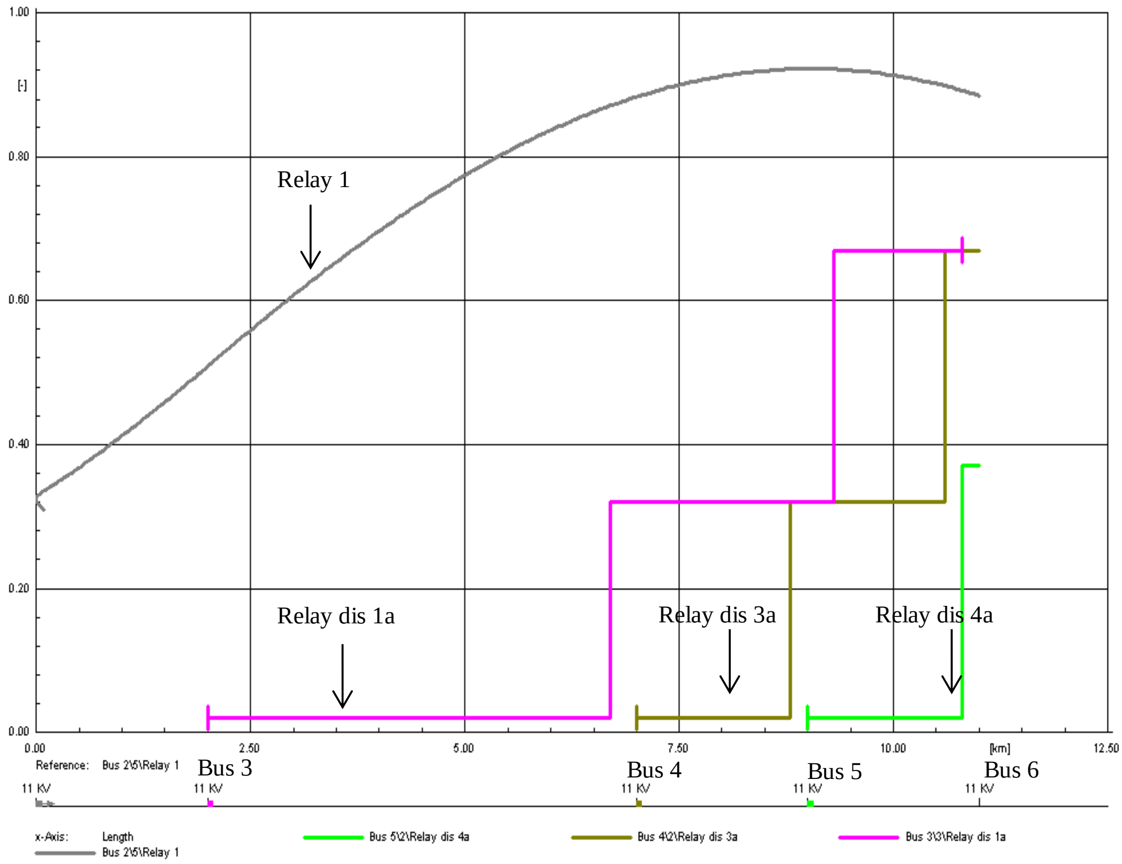


Figure 6-5 Time-distance plot that displays the OC relay working as a back-up

For the second criterion (Equation 3-3), the OC relay 1 operates as a back-up protection when the fault occurs on adjacent feeders, so relay 1 must be coordinated with its downstream distance relays (relays 1a, 6b). See Figure 6-5; enough coordinating margin is successfully achieved by observing the *time distance plot* formed by DIgSILENT. Relay 1 will correctly operate as back up protection slower than the main protection (the distance relays) for its downstream faults located between bus 3 and bus 6.

6.3.3 Relay parameters and characteristics

Figure 6-6 shows the parameters of the relay dis 3a. This is the output of relay parameters given by DIgSILENT. The type of the relay dis 3a is GE distance. The current transformer ratio is 300A/5A and the voltage transformer ratio is 11000V/110V. The settings of relay impedance of zone 1, zone 2 and zone 3 is 4 Ω, 6.7 Ω and 7 Ω. All 3 zones have the same characteristic angle (30^{o}) and they both trip for the forward direction. The tripping time of zone 2 is 0.3 s and the tripping time of zone 3 is 0.65 s. All the parameters regarding the rest of distance relays can be read from Appendix 4.

```
Relay dis 3a                              Relay Type : GE Distance
  Location      :  Cubicle       : Cub_1        Branch     : Cable 3
                   Busbar        : 2                       / Bus 4
-------------------------------------------------------------------------
  CT 3                                          Ratio        : 300A/5A
    No. Phases      : 3          Phase 1     : a   Phase 2   : b
    Connection      : Y

  VT dis 3a                                     Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0           A      ) :    5.00 A
    Nominal Voltage ( 110.0         V      ) :  110.00 V

  Polarizing

  Starting Ph-Ph           Type of Starting  : Overcurrent
    Current I>>       ( 0.1 - 100.0  sec.A ) :     1.800 sec.A

  ZD1              ( IEC: Z>>   ANSI: 21   )       Out of Service   : No
    Tripping Direction                       : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :    4.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :   30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :   90.000 deg

  ZD2              ( IEC: Z>>   ANSI: 21   )       Out of Service   : No
    Tripping Direction                       : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :    6.700 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :   30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :   90.000 deg

  ZD3              ( IEC: Z>>   ANSI: 21   )       Out of Service   : No
    Tripping Direction                       : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :    7.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :   30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :   90.000 deg

  ZDT2                                             Out of Service   : No
    Time Setting      ( 0.0 - 10.0    s      ) :    0.300 s

  ZDT3                                             Out of Service   : No
    Time Setting      ( 0.0 - 10.0    s      ) :    0.650 s

  Logic Ph-Ph                                      Out of Service   : No
    Breaker                         Cubicle     Branch
-------------------------------------------------------------------------
```

Figure 6-6 The parameters of relay 3a

Figure 6-7 displays the characteristics in the *R-X plot* for distance relays installed around clockwise in the loop circuit (relay 2a, relay 3a, relay 4a, relay 6a). Further information about the relay settings can be found in Appendix 4.

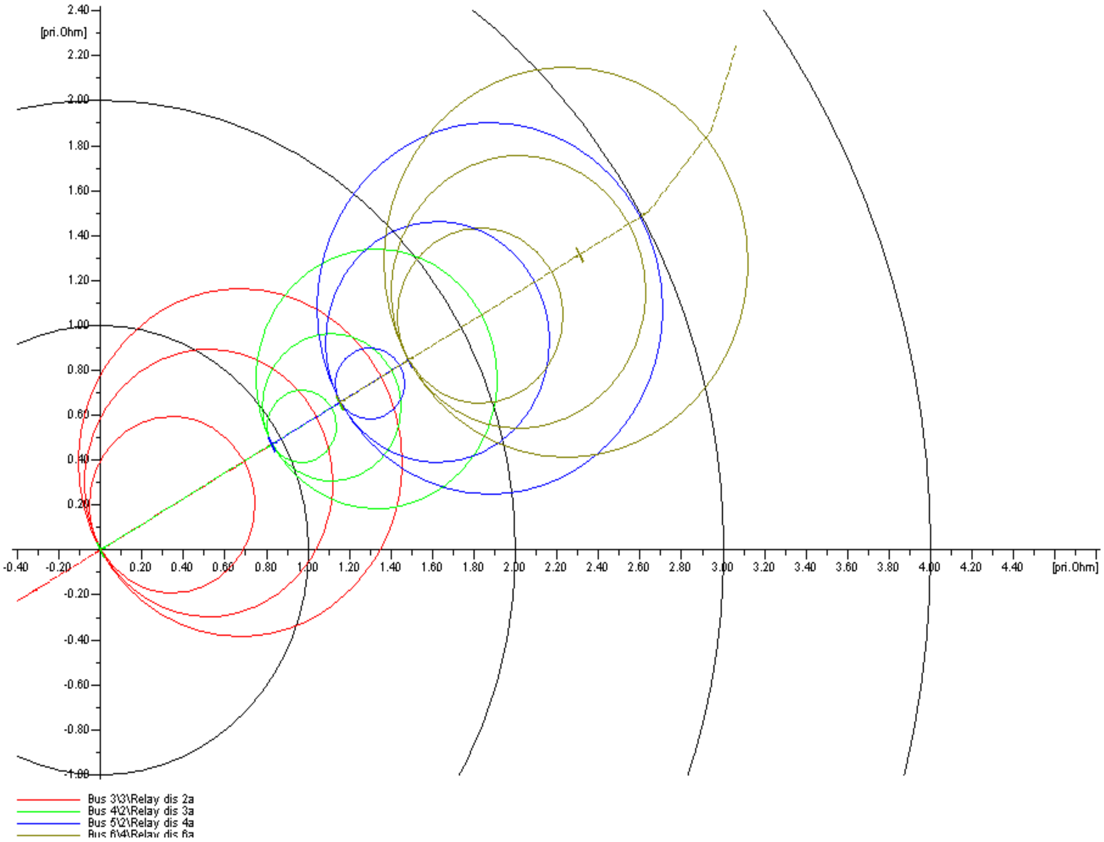


Figure 6-7 Characteristics of distance relays in clockwise direction

6.3.4 Assessment of different fault cases

The correct protection system for the meshed network is examined by the following fault situation.

In Figure 6-8, a three-phase short circuit occurs at 90% of cable 3 and is cleared by zone 2 of relay dis 3a after 0.32 s, and by relay dis 3b immediately. From the tripping times displayed, relay dis 2a operates with a time delay if the relay dis 4a fails to disconnect the circuit. The overcurrent relay 1 also sees the fault (0.96s). In the other direction, zone 2 of relay dis 4b and zone 3 of relay dis 6b sense the fault and trip the circuit breaker separately after 0.32 s, 0.67 s, respectively.

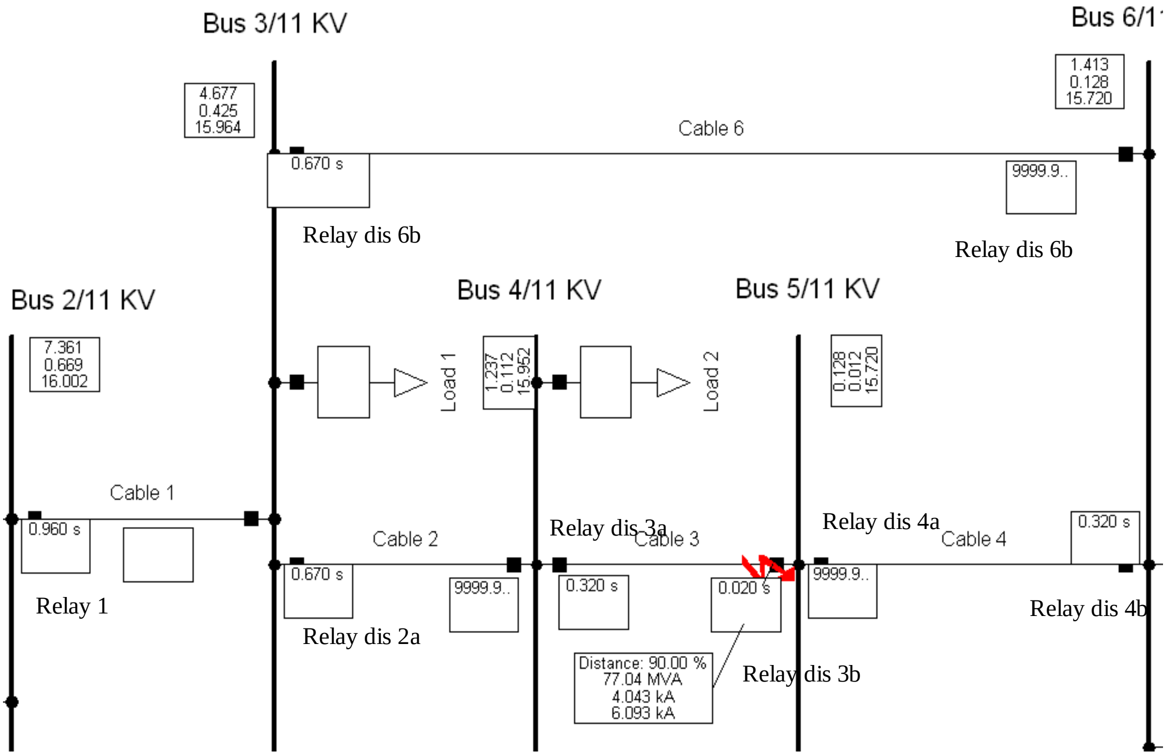


Figure 6-8 Three phase fault at 90% of cable 3

6.4 Meshed network with DGs connected

6.4.1 The network modeling and the protection system

The proper protection coordination has acquired in the meshed network. However, the additional DGs connected to the network need to be reconsidered. Figure 6-9 shows the two 5 MW wind farms are connected to the network through 11/0.69 kV/kV transformers, and the power output of the wind farm is 79% of the rated power output (3.9 MW). The wind farm is composed of ten paralleled standard induction generators each rated at 500 kW.

Due to the penetration of DGs, new protective relays need to be added to the protection system (Figure 6-9). Cable 1 now sees the fault currents flowing from multiple sources, so the directional OC relays should be installed at both ends of the cable 1. Consequently, relay 1a and relay 1b are adopted directional OC relays and they both follow the IDMT characteristics. As for the rest of the protection system, the existing relays can protect the network through proper adjustments. Relays 2a, 2b, 3a, 3b, 4a, 4b, 6a, and 6b are sill directional distance relays. Relay 5 sees the fault current flow from one direction and the OC protection is capable of protecting the circuit.

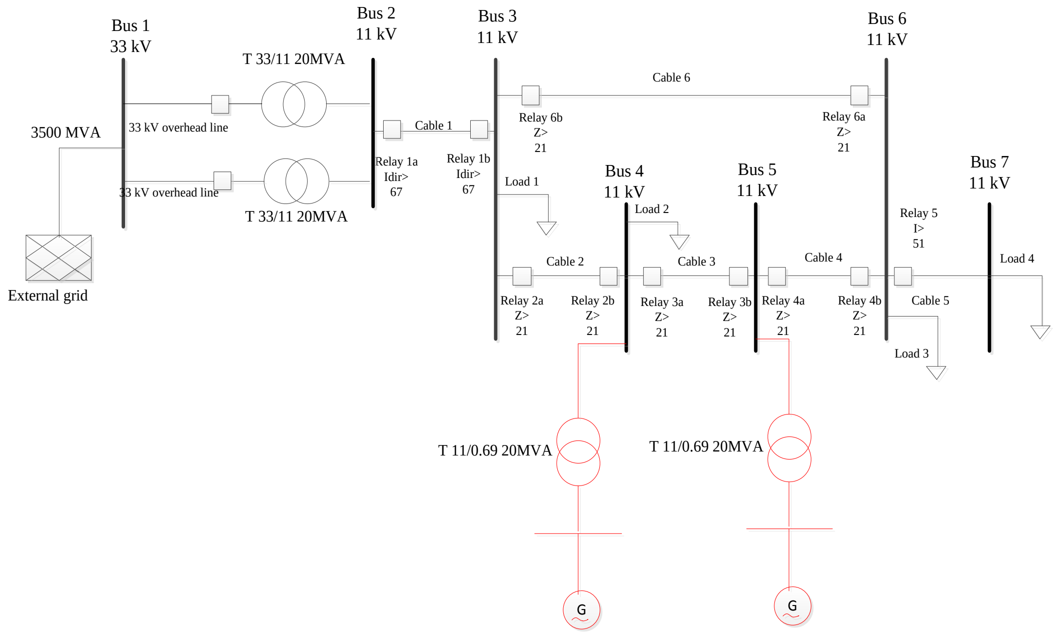


Figure 6-9 Singe line diagram of the meshed distribution network with DGs

6.4.3 Explanation of the protection coordination

The distance relays have the advantages such as fixed reach, and inherent directionality so that the distance-based protection can ensure the coordination easier than the OC protection in the meshed network. Nevertheless, the addition of distributed generators into the distribution network will produce raised impacts on the protection coordination.

In terms of distance protection, as stated in Section 4.4, the current flowing from the DGs may result in the unwanted under reaching problem. Figure 6-10 demonstrates a 2-phase short circuit that occurs at 50% of cable 3 and the fault location belongs to zone 2 of relay dis 2a. Without DGs connected, zone 2 of relay dis 2a could sense the fault and make the correct response after 0.32 s. In the case of DGs connected, although relay dis 2a still senses the fault, the fault is beyond the circle of zone 2 and will be regarded as a zone 3 fault and be cleared after 0.67 s. Predictably, the coordination is then lost and readjustment is crucial to adapt to the penetration of the DGs.

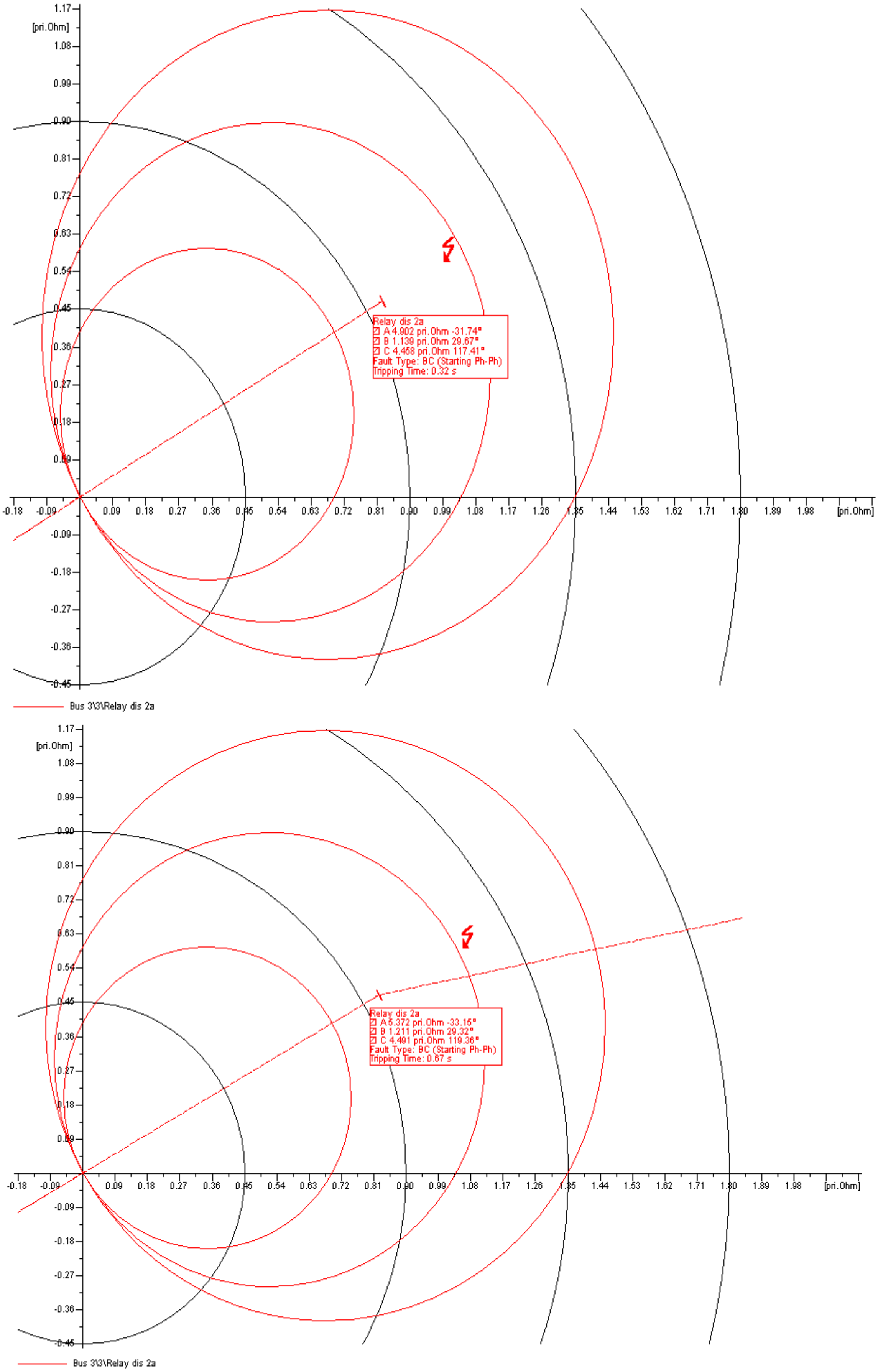


Figure 6-10 Example for under reaching of a distance relay

The conventional method recognizes the DGs as an infeed source and calculates the reaching of zone 2 and zone 3 with the infeed factor. Fortunately, when simulating the network in DIgSILENT, the *R-X* and *time distance plot*s are available. They have provided effective outcomes to study the coordination of distance-based protection (as described in Section 6.3.2). It is easier to verify the reaching zone of the distance relay according to the *R-X plot* (Figure 6-10). The *time distance plot* gives the tripping time of the distance relay and shows the protection coordination clearly. For example, Figure 6-11 shows that the proper coordination is acquired and the under reaching problem is solved around the counter clockwise direction (relay 2a, relay 3a, relay 4a, relay 6a).

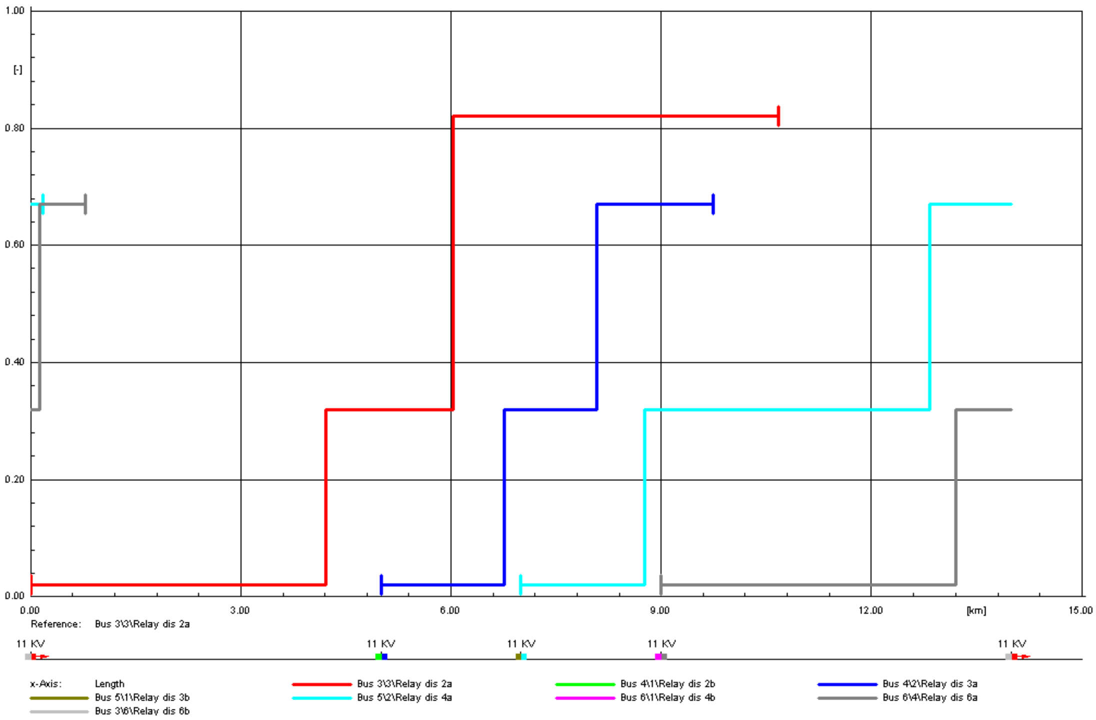


Figure 6-11 The *time distance plot* displays the relays in the clockwise direction

6.4.2 Assessment of different fault cases

After the readjustments and replacements for relays in the meshed network with DGs, the protection coordination has been achieved again. The different fault situations have been tested.

In the first scenario, Figure 6-12 shows that a two phase fault at 20% of cable 1 near bus 2 will be cleared by main protective devices at both ends of the cable in 0.947 s (relay 1a) and 0.09 s (relay 1b). Relay 2b and relay 6a will provide back-up protection for relay 1b after 0.32 s and 0.67 s respectively.

Another SC situation at cable 4 in Figure 6-13 is a three balanced fault at 80% of the cable. It will be cleared by the main protective relays 4a and 4b instantaneously. Relay 3a (0.67 s), relay 2a (0.82 s) and relay 1a (1.095 s) will all sense the fault current and provide back-up support for relay 4a. As for the other direction, zone 2 of relay 6b breaks the circuit if relay 4b fails to trip the fault.

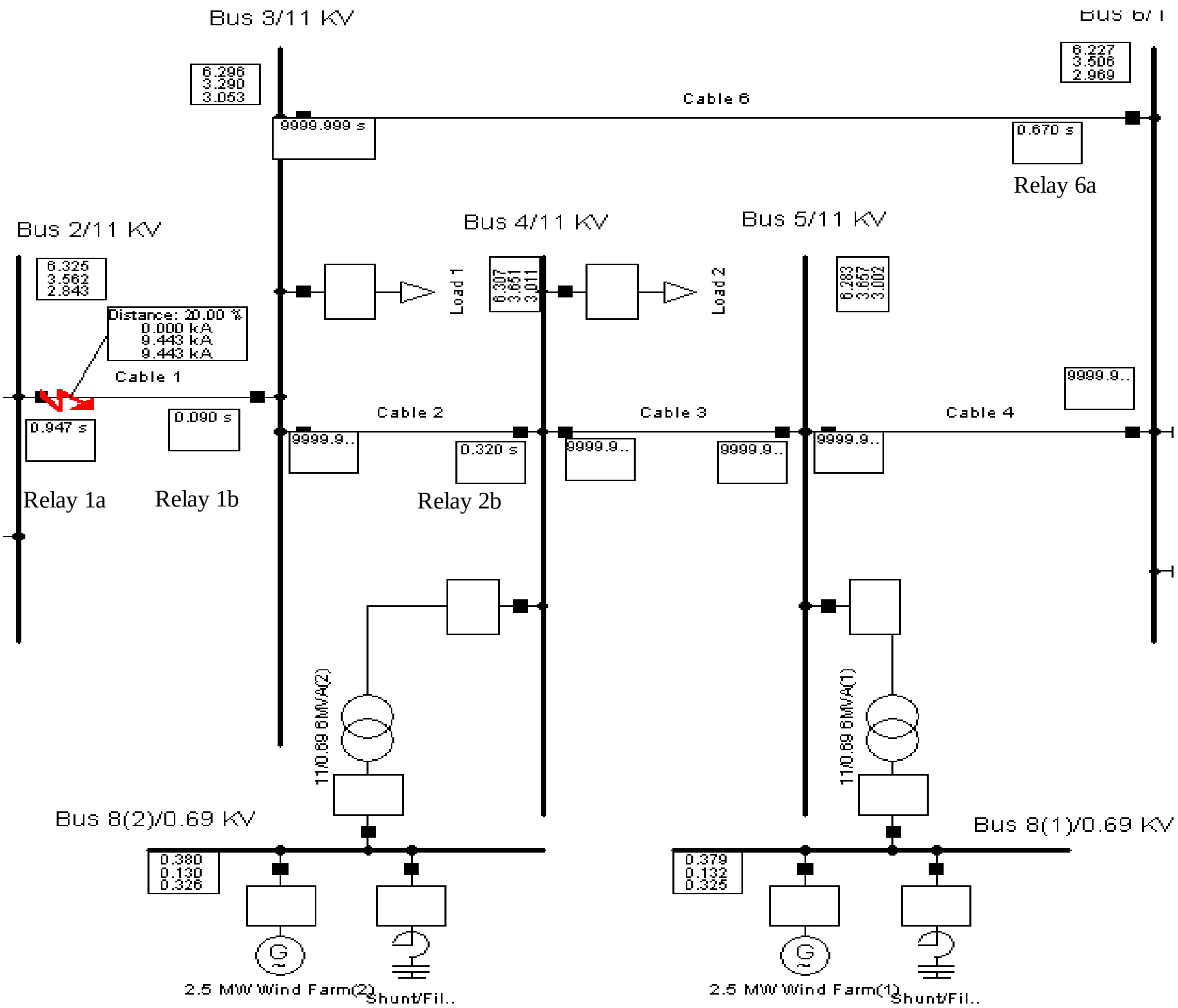


Figure 6-12 Two phase fault at cable 2

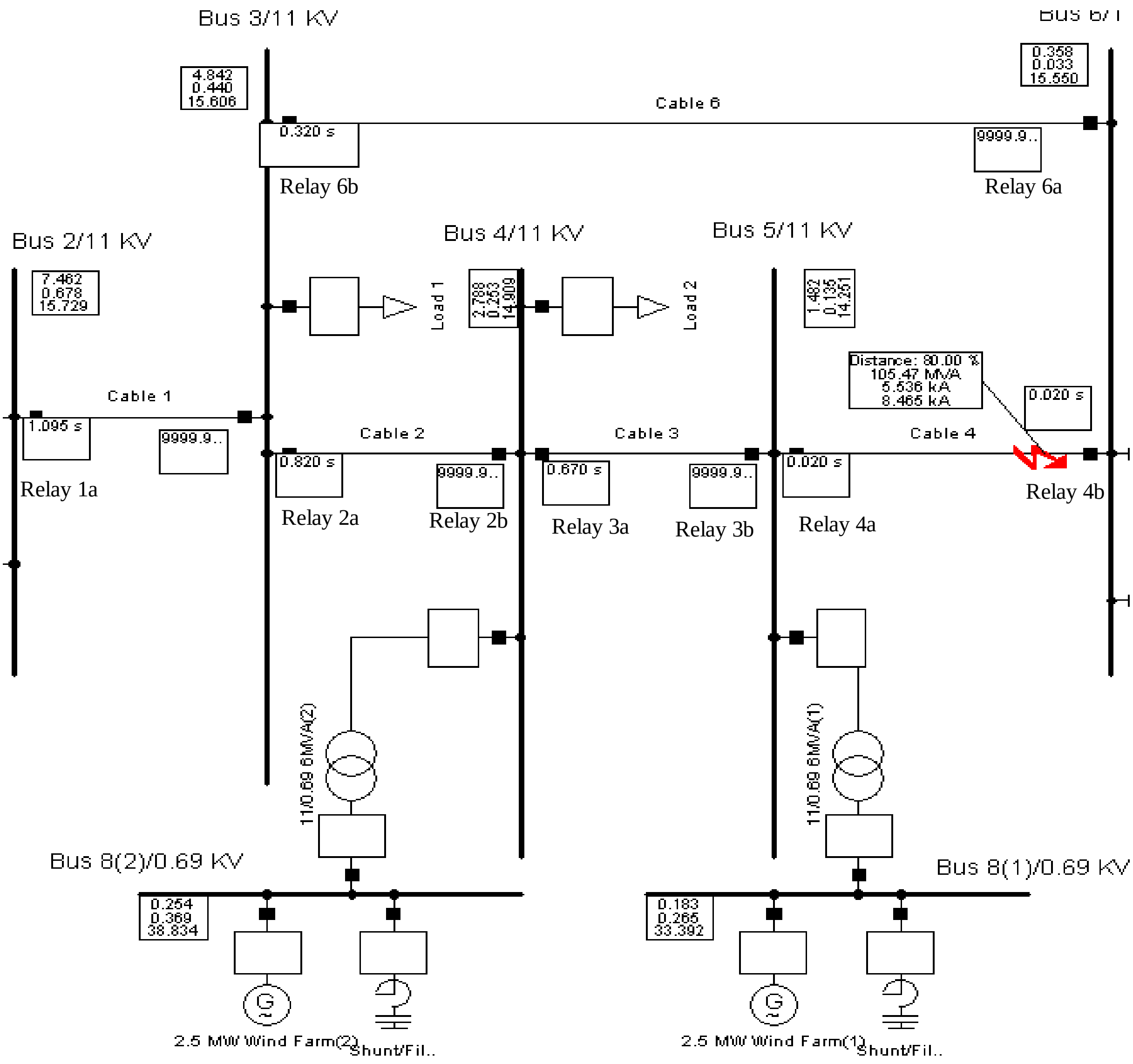


Figure 6-13 Three phase fault at cable 4

6.5 Chapter summary

In this chapter, it was shown that the distance-based protection scheme is capable of ensuring the protection coordination in the meshed networks. The protection coordination must be studied from two aspects; one is the coordination between distance relays and this can be acquired through appropriate settings (the *R-X plot*), and clearly displayed in the *time distance plot*; another aspect is the consideration on the distance and overcurrent relays, their coordination is studied with the help of *time distance plot* (including the tripping time of the overcurrent and distance relays). The under reaching is the influence caused by DGs and is clearly an issue, however, it can be eliminated to regain the coordination through readjustment.

7. Conclusion

In this chapter, an overview of the project is now provided, key points are summarized and the major conclusions are drawn. Furthermore, some of the issues that have not been elaborated are now discussed and recommendations for future work in the protection coordination related to DGs are provided.

7.1 Project summary

The first goal of this research was to define and describe the major steps in the protection coordination of a power network. The key challenges in this process have been pointed out. If the protection coordination has not been done properly, the protection would not protect the network appropriately. For example, the unwanted protective devices could trip for a fault occurring; the protective devices could not sense a fault and result in the damage on the network and interrunption in the power supply. The protection coordination has been investigatied using two typical test networks: a) a MV radial distribution network and b) a meshed distribution network. It has been concluded that the radial network can be protected by overcurrent (OC) protection and the protection coordination between OC relays has been successfully demonstrated (see Section 5.3). In this research the DIgSILENT software package has been applied and scrutinized from its applicability for the protection coordination. It has been concluded that the DIgSILENT software package can be successfully used for both the network modeling and protection coordination. The *time overcurrent plot* provided by DIgSILENT was a key tool to study the protection coordination between OC relays in the radial network. Another network analysed was a meshed distribution network. In this case the protection coordination has been determined by the network topology (see Section 6.3). Since the meshed network means that even the network is supplied by only one source, some of the network feeders may see currents coming from two different directions. Protection of such a meshed network was not possible by using the pure OC protection. It has been demonstrated how the distance-based protection can efficiently protect meshed networks and reach an optimal protection coordination. Here the attention must be paid on avoiding the overlapping zone of distance relays. The DIgSILENT software package has provided the *R-X plot* and the *time distance plot* to assist studying the protection coordination between different distance relays.

The second goal of this research was to explore the impacts caused by DGs on protection coordination. Using the DIgSILENT software package, the DGs were modelled and integrated in the abovementioned networks (radial and meshed). It has been concluded that the protection coordination was influenced because the fault current magnitudes and the fault current directions have been changed after introducing DGs in the networks. It has been concluded and demonstrated that in networks with DGs, the protection concepts must be based on the multiple supply sources for the grid. Therefore, the directional OC relays were introduced to protect the networks with DGs and DGs itself. The investigation of the protection coordination of the MV network with DGs revealed three main problems and dealt with their solutions (see Section 4.2-4.4, Section 5.4). These main problems were:

1. The loss of grading margin between the protective relays, which can be solved by readjusting the relay parameters with the help of the time overcurrent plot.
2. The false tripping problem, which can occur at the OC relays located in feeders with DGs connected. These OC relays were replaced by the directional OC relays.
3. The blinding issue, which can occur at the OC relays located between the fault point and the relay. A combination of IDMT and definite-time characteristics OC relays were used to solve this difficulty.

The discussion of the protection coordination in the meshed distribution network with DGs connected in Section 6.4 highlighted the DGs influence on the distance relays' settings. After the integration of DGs, the protection system was still designed as the distance-based protection. However, the coordination was lost because the DG could have an impact (e.g. the infeed current) on distance relays and cause under-reach issue. Therefore, the relay settings must be changed to adapt the extra fault current sources in order to regain the protection coordination. Attention should be also paid on the *time distance plot* provided by DIgSILENT, which assists the process of the protection coordination not only between distance relays, but also between distance relays and an OC relays.

The test networks used in the project were successfully simulated using the DIgSILENT software package. There were differences in the relay tripping time and the grading margin in situations with or without DGs provided by the examples simulated in DIgSILENT. In terms of each relay characteristic, they played a vital role in the coordination methods in this project. As a means to display the characteristic curves and to give us a clear understanding of coordination, the time-overcurrent plot, the *R-X plot* and the time-distance plot were provided by DIgSILENT. To proper design the protection system and acquire protection coordination, it was possible to select the proper protective devices from DIgSILENT, to set feasible parameters and do the proper coordination procedures with the help of DIgSILENT.

7.2 Future work

The DIgSILENT library has not provided suitable types of distance relays for earth faults protection so the obvious extension of this work would be to repeat the coordination process for the earth faults protection in the meshed distribution network.

As far as the problems caused by DGs concerned, the readjustment of the relay settings or additional relays installed can make the protection system work properly. However, relays can not respond to the fault correctly if the DGs are disconnected. For example, if the settings of distance relays are based on DGs, the distance relays may over-reach if the DGs are disconnected. Therefore, a more advanced adaptive protection scheme that can automatically make adjustments for different power system conditions will be inevitable.

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9. Appendices

Appendix 1: DIgSILENT PowerFactory

A.1.1 Introduction

The calculation program PowerFactory, as written by DIgSILENT, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization [25].

The name DIgSILENT stands for "DIgital SImuLation and Electrical NeTwork calculation program". It had been used in this dissertation for simulating the networks and analyzing protection schemes. In order to give a general DIgSILENT overview, some of its functions used are explained in this section. More information referring to the software can be found in the software User’s Mannual.

A.1.2 Short-Circuit Analysis

The short-circuit calculation in PowerFactory is able to simulate various kinds of faults using different representations and calculation methods. The following fault types are available: 3-Phase Short-Circuit, Single Phase to Ground, 3-Phase Short-Circuit (unbalanced), etc. Examples of these methods include the IEC 60909/VDE 0102 method, the ANSI method and the IEC 61363 method. As opposed to the calculation methods according to IEC/VDE and ANSI, which represent short-circuit currents by approximations, the complete method evaluates currents without using approximations. When it comes to accurate calculation of the currents after the onset of the fault, like in this project, the complete method is more appropriate.

An example of the short-circuit command dialogue is shown in Figure 9-1, which is used to define the general settings of the short-circuit calculation. In this case, the ‘complete’ method is employed to calculate the 3-phase short circuit fault. There are more options accessible in the short-circuit calculation indicated by the dialogue. One can manually edit the fault impedance for different purposes. Furthermore, the fault location is also available that allows setting the relative distance of the line. This is crucial when it relates to the reach zone of a distance relay.

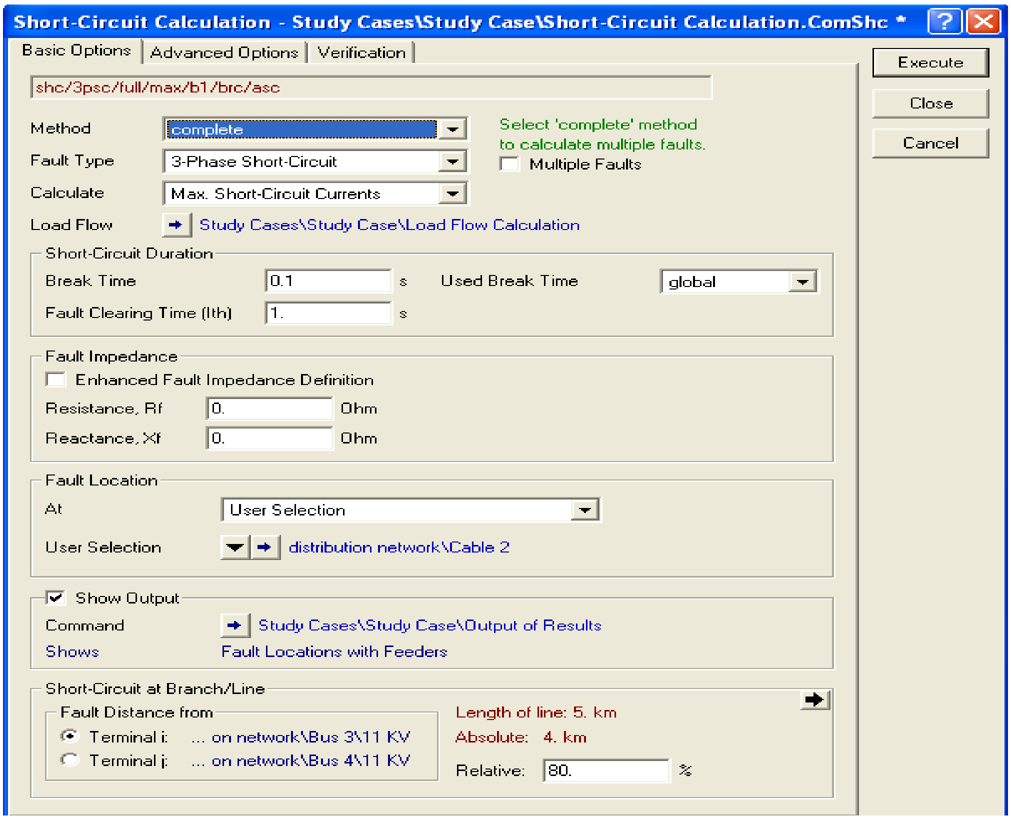

Figure 9-1 Short circuit with the 'Complete' method

A.1.2 Protection Analysis

The PowerFactory protective devices are all stored in the cubicle connected to the busbar and branch element, with CTs, VTs, circuit breaker and relays. Protective devices include fuses that could operate on a switch stored in the same cubicle without additional settings. Editing or adding new protective devices in the cubicle can be done through right-clicking on a switch-symbol in the single line diagram. Selecting the option to create a new protection device brings up a list with the following options [25]:

- Relay Model (ElmRelay)
- Fuse (RelFuse)
- Current Transformer (StaCt)
- Voltage Transformer (StaVt)

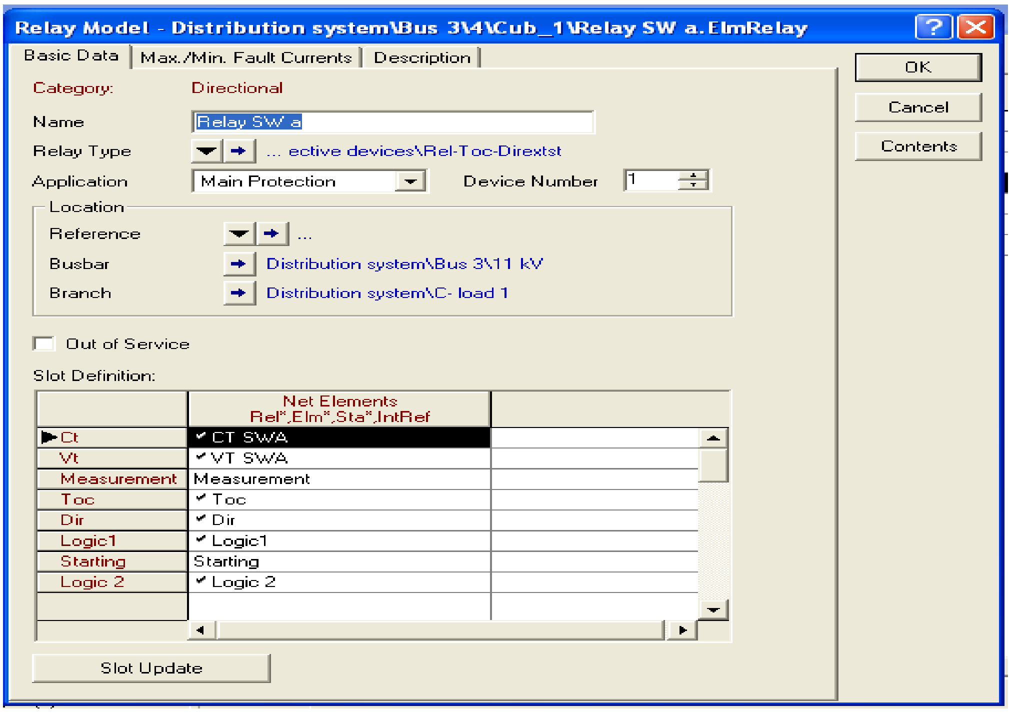

Figure 9-2 Relay model dialogue with selected type

Each of these options opens a dialogue to specify the device that is to be created. Newly created devices are stored in the cubicle that was selected [25]. For instance, Figure 9-2 demonstrates a relay model that is equipment with a directional relay with the combination characteristic of IDMT and definite time type (Rel-Ioc-Toc-Dirext). If the current and voltage transformers have been created before the creation of the relay type, they would be filling the slot automatically. If not, new VT and CT need to be defined as the correct slot element.

A.1.3 Time-overcurrent plot

The time-overcurrent plot shows [25]:

• The time-overcurrent characteristics of relays
• The damage curves of transformers or lines
• Motor starting curves
• The currents calculated by a short-circuit or load-flow analysis and the resulting tripping times of the relays

The time-overcurrent plot shows the results of short-circuit or load-flow analysis that could help setting the relay tripping time and pick-up current. Because the currents differ for each particular relay, a current line is drawn for each relay. The intersection of the calculated current with the time-overcurrent characteristic is labeled with the tripping time.

A 'grading margin' line, which shows the difference between the tripping times, may be added by right-clicking the plot and selecting "Show Grading Margins". The specific procedures of editing different curves can be accessed in DIgSILENT. The grading margins are shown as two lines in the diagram in DIgSILENT, plus and minus the grading margin above and below the dragged tripping characteristic.

A.1.4 Time-Distance diagram

The coordination between OC relays is fulfilled with the help of time-overcurrent plot, while the coordination between distance relays or distance relays and OC relays could be checked based upon the time-distance diagram. Similar with time-overcurrent plots, there are several methods to calculate the tripping time in time-distance diagrams. In this dissertation, the Short-Circuit Sweep Method was selected for the most accurate calculation. The diagram can be created only in the situation when a path has been defined before. In the user's manual, information on path definition is available. Figure 9-4 is an example of launching this function.

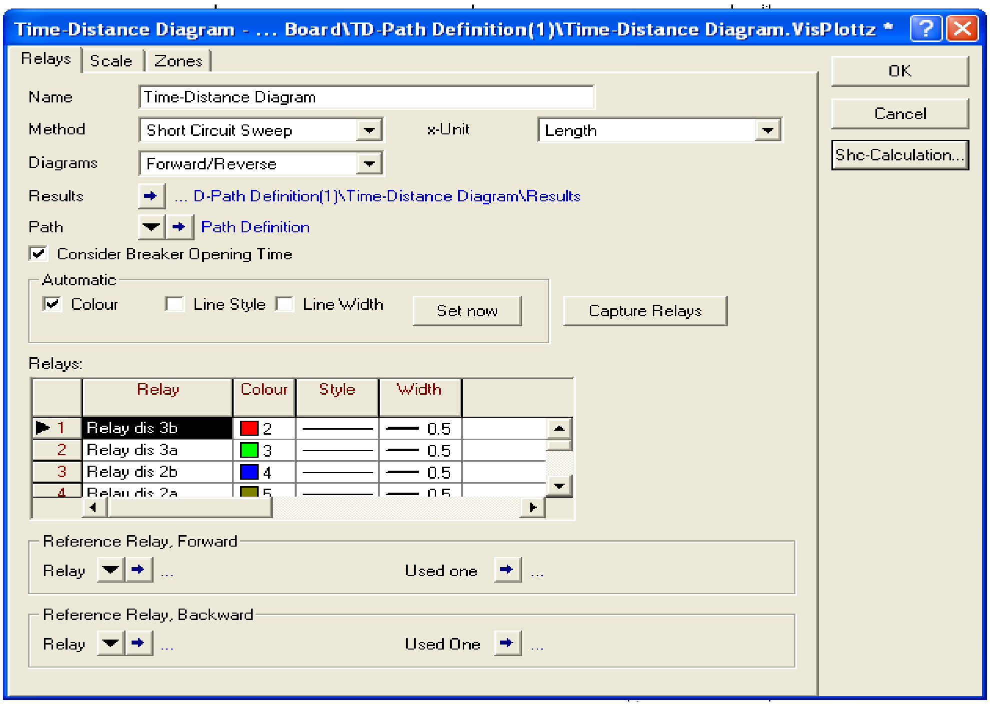

Figure 9-3 Short circuit sweep method

Appendix 2 Relay characteristics in the time-overcurrent plot

A.2.1 Without DGs connected

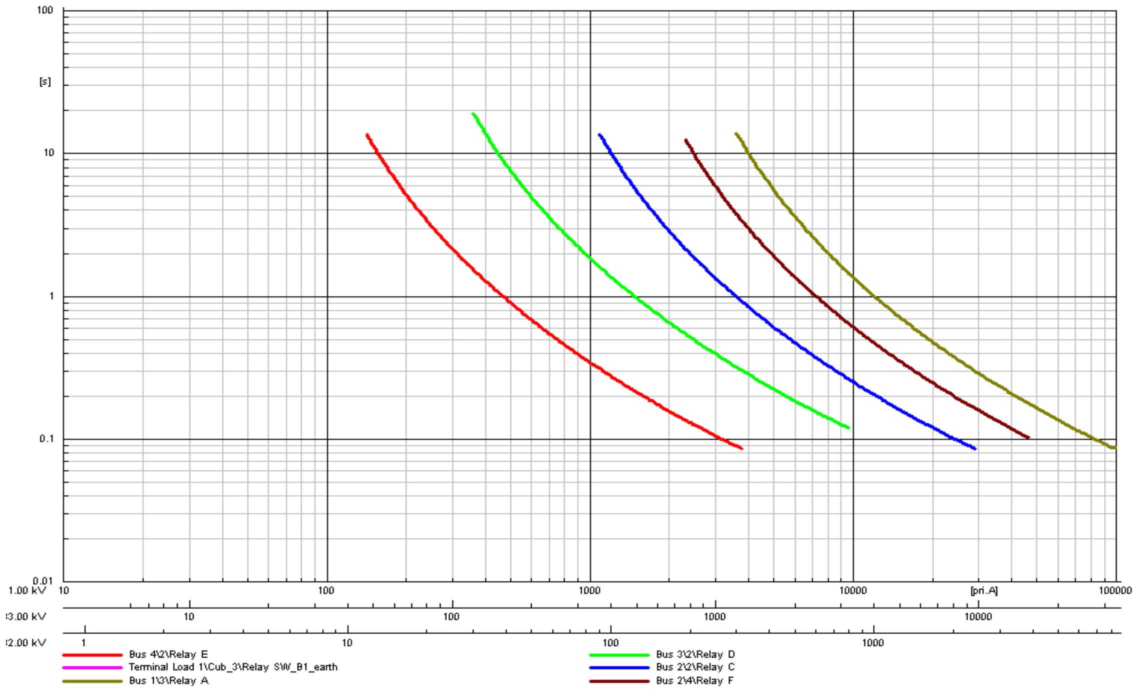

Figure 9-3 Relay characteristic curves for earth elements

A.2.2 With DGs connected

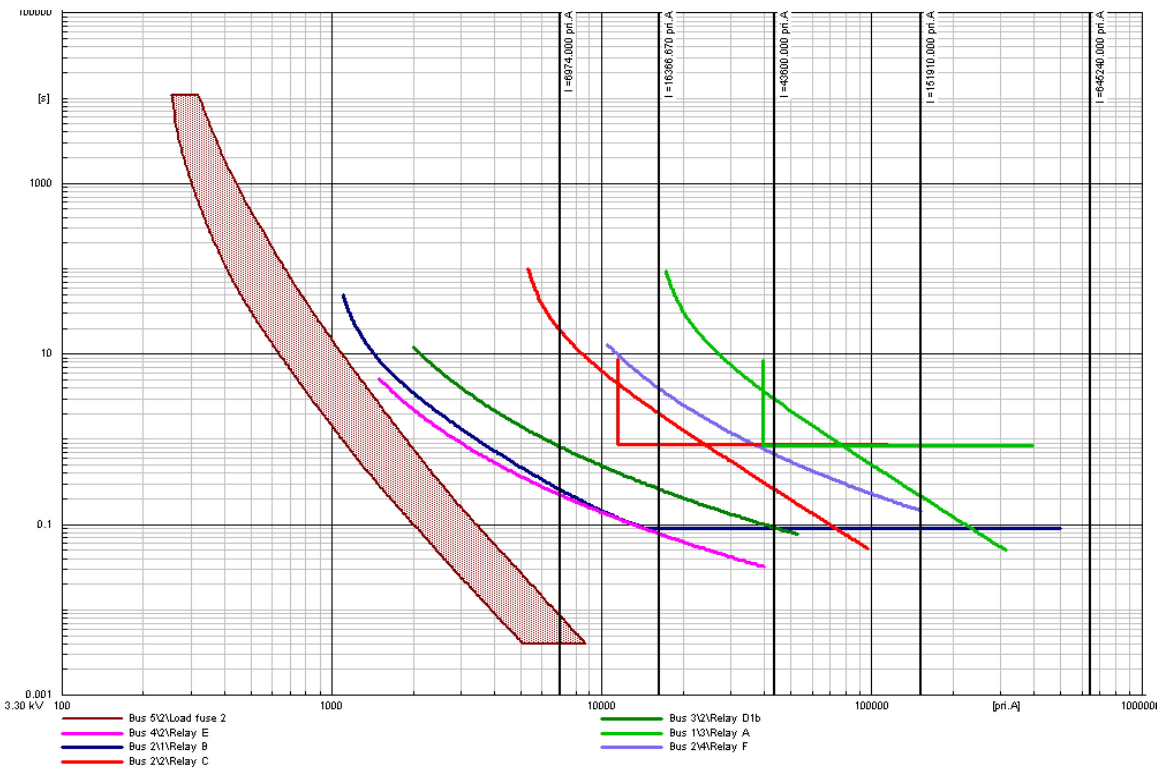

Figure 9-4 Relay characteristic curves for phase elements in the main network

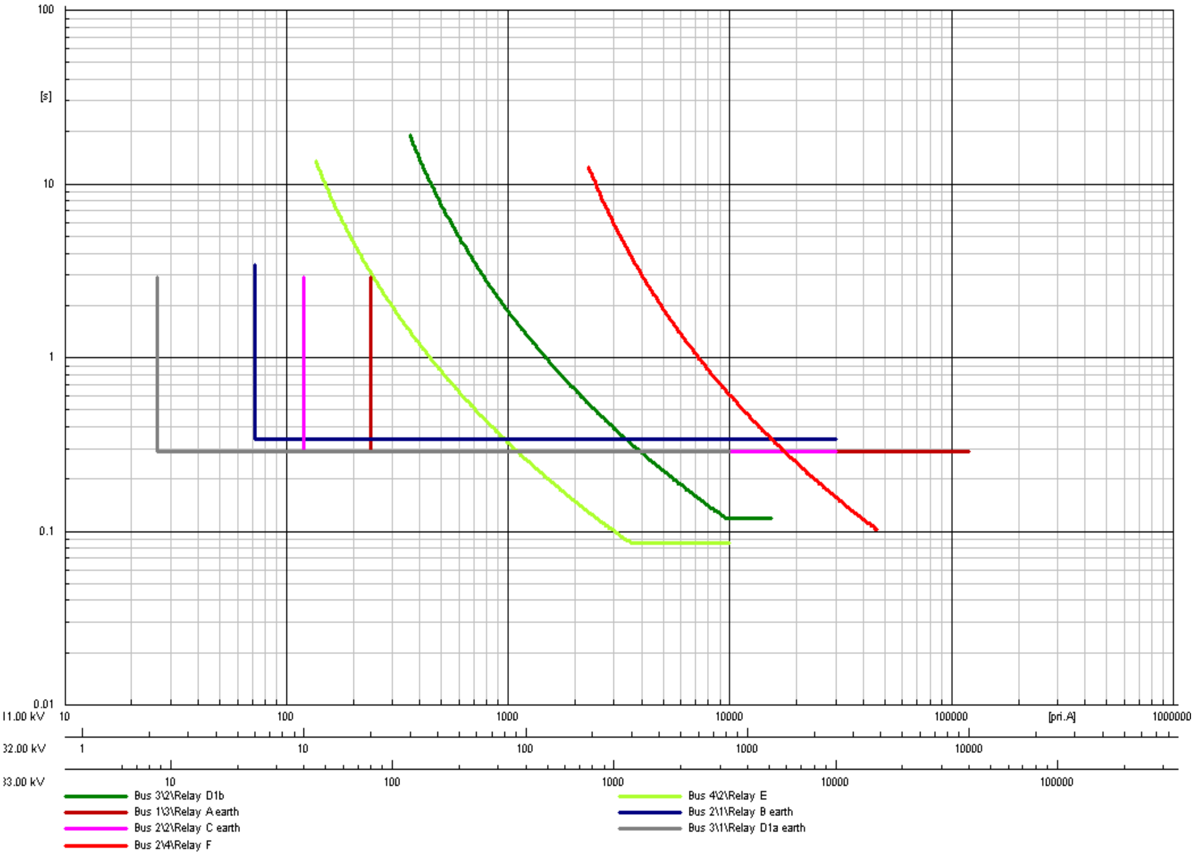

Figure 9-5 Relay characteristic curves for earth elements in the main network

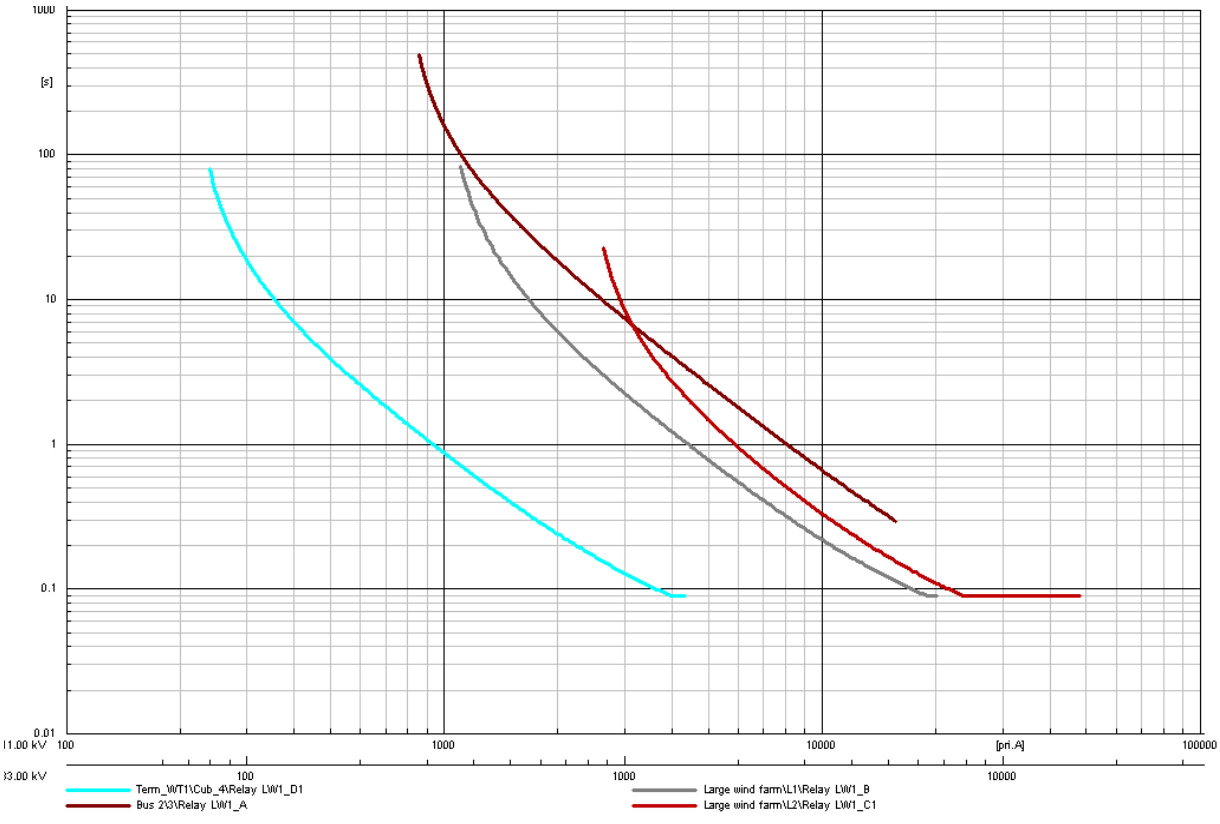

Figure 9-6 Relay characteristic curves for phase elements in the large wind farm

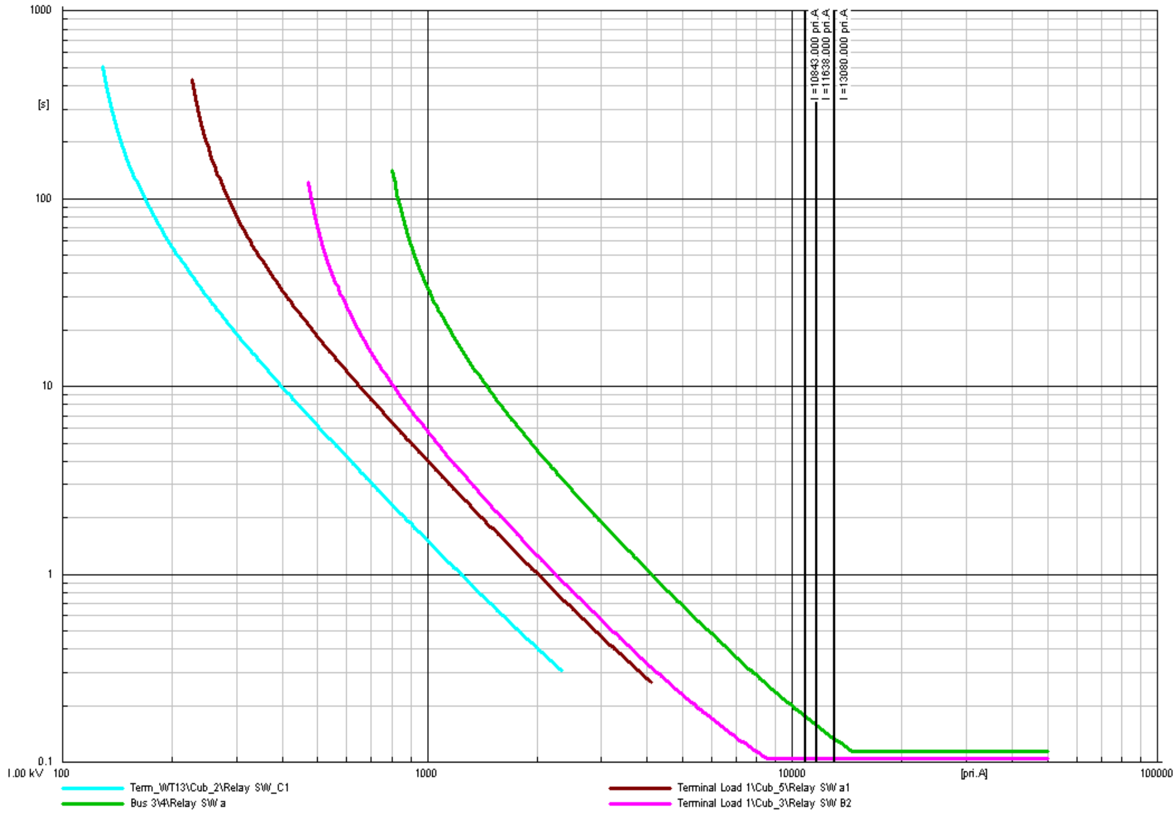

Figure 9-7 Relay characteristic curves for earth elements in the large wind farm

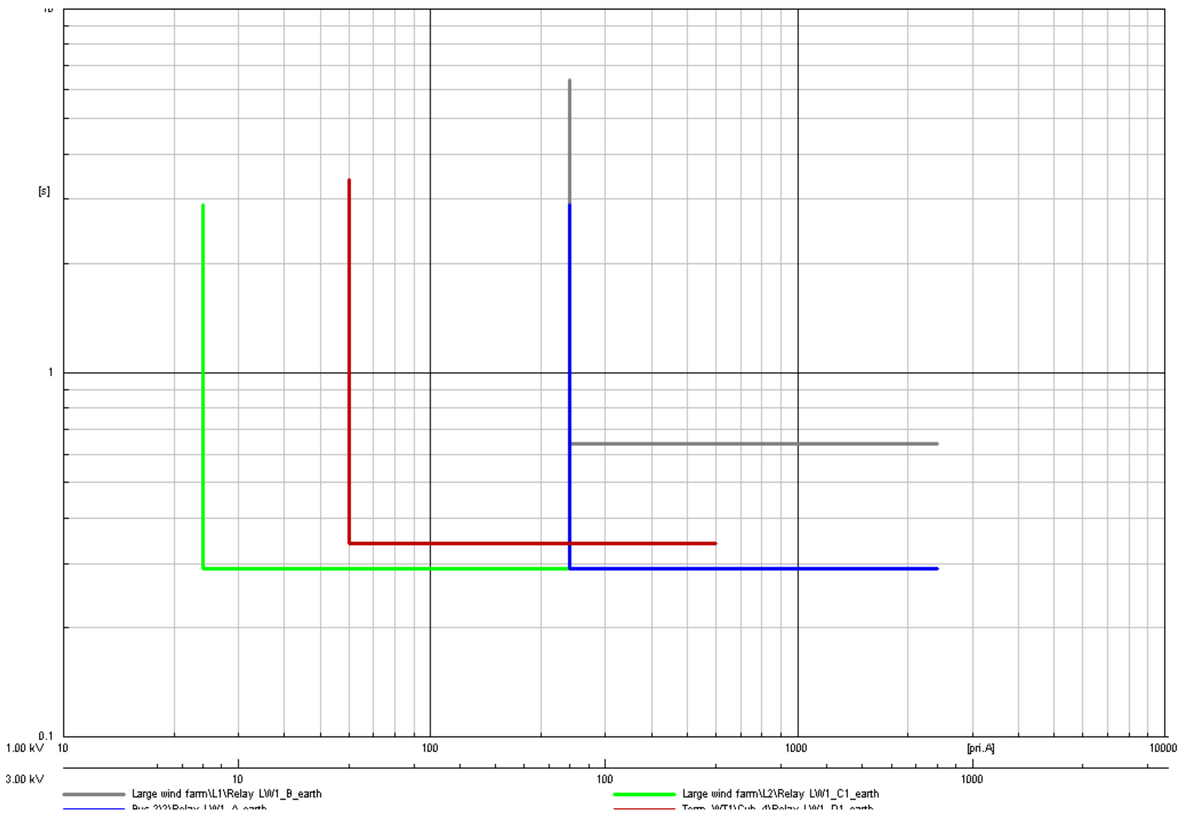

Figure 9-8 Relay characteristic curves for phase elements in the small wind farm

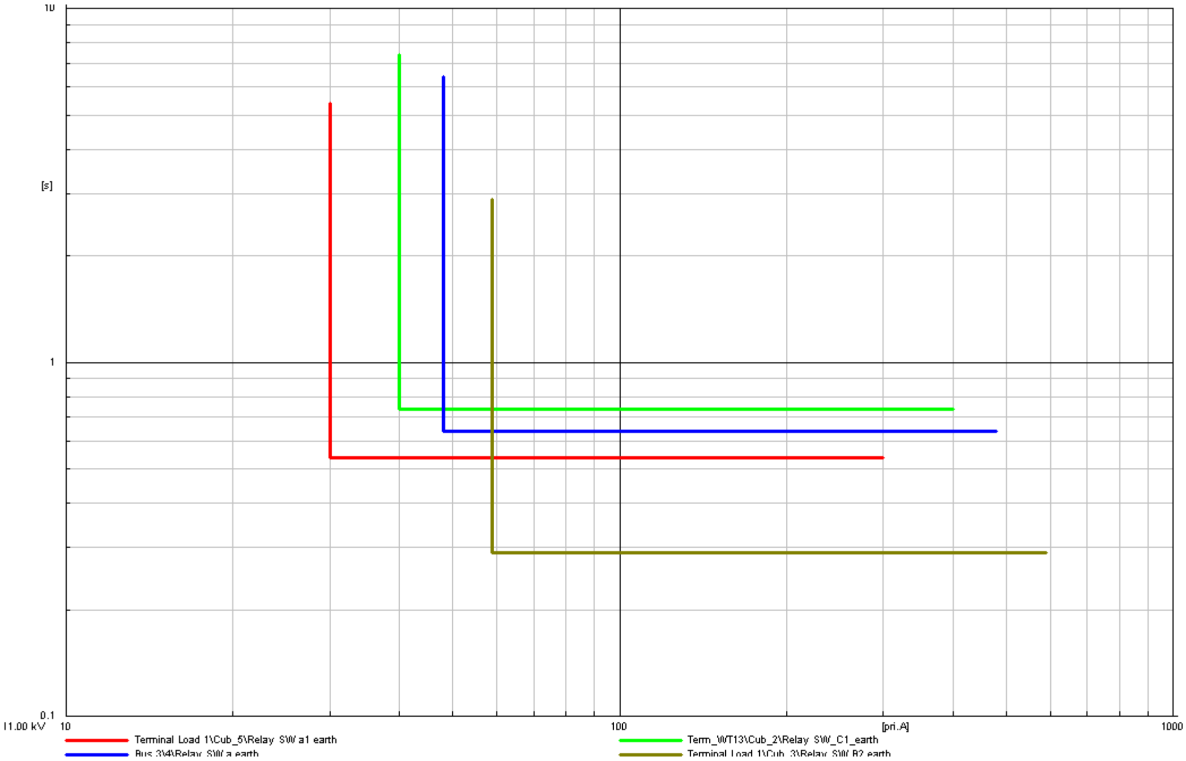

Figure 9-9 Relay characteristic curves for earth elements in the small wind farm

Appendix 3 Network data for meshed distribution network data

A.2.1 Induction generator parameters

Component Description	Value
Nominal voltage (kV)	690
Rated output (kW)	500
Nominal factor (pu)	0.92
Stator Resistance (pu)	0.02803771
Stator Reactance (pu)	0.01
Rotor Leakage Reactance (pu)	0.01
Mag Reactance (pu)	4.236279
Pole pair	1

Table 9-1 Induction generator parameters

A.2.2 Line data

The 5 km, 33 kV overhead line was aluminum core steel reinforced (ACSR) cable, with a cross sectional area of 150 mm2. The phase impedance data is:

$$ZOH = 0.1089 + j0.33759\ \Omega/km \tag{9-1}$$

The 11 kV line consisted of 2 km of underground cables, which were based on a 3-core, 185 mm^2 diameter aluminum conductors. The impedance data is:

$$ZUG = 0.165 + j0.094\ \Omega/km \tag{9-2}$$

A.2.3 Transformer data and load data

The transformer parameters for the network are given in Table 9-2

Component description	Value
Base (MVA)	20
Voltage ration (kV)	33/11
R (pu)	0.005
X (pu)	0.06
Vector group	Dyn11

Component description	Value
Base (MVA)	6
Voltage ration (kV)	11/0.69
R (pu)	0.01
X (pu)	0.05
Vector group	Dyn11

Table 9-2 Transformer data

The loads in the network are modelled as stated in Table 9-3

Load	Static load	
	Real power, P (MW)	Reactive power, Q (MVar)
1	0.30	0.0
2	0.20	0.0
3	0.35	0.0
4	0.40	0.6

Table 9-3 Load data

Appendix 4 Relay parameters for the meshed network

```
-----------------------------------------------------------------------------------------
|              Without DG                |   DIgSILENT   | Project: Mesh               |
|     Mesh distrtbution network          | PowerFactory  |-----------------------------|
|                                        |    14.1.3     | Date:  10/29/2013           |
-----------------------------------------------------------------------------------------
| Relay 1                                 Relay Type : IAC77A804A                      |
|   Location      :  Cubicle          : Cub_1        Branch     : Cable 1              |
|                    Busbar           : 11 KV                   / Bus 2                |
|--------------------------------------------------------------------------------------|
|   CT 1                                                Ratio       : 1000A/5A         |
|     No. Phases     : 3           Phase 1     : a      Phase 2     : b                |
|     Connection     : Y                                                              |
|                                                                                      |
|   Measurement                                                                        |
|     Nominal Current ( 5.0            A      ) :      5.00 A                         |
|                                                                                      |
|   Toc                ( IEC: I>t   ANSI: 51    )         Out of Service    : No       |
|     Tripping Direction                         : None                               |
|     Current Setting ( 0.5 - 4.0      sec.A ) :     2.100 sec.A                      |
|     Time Dial        ( 0.5 - 10.0           ) :    10.000                            |
|     Characteristic                            : IAC Extremely Inverse GES7005B      |
|                                                                                      |
|   Toc Earth          ( IEC: IE>t  ANSI: 51N   )         Out of Service    : No       |
|     Tripping Direction                         : None                               |
|     Current Setting ( 0.5 - 4.0      sec.A ) :      1.500 sec.A                     |
|     Time Dial        ( 0.5 - 10.0           ) :      0.500                           |
|     Characteristic                            : IAC Extremely Inverse GES7005B      |
|                                                                                      |
|   Logic                                                 Out of Service    : No       |
|     Breaker                              Cubicle    Branch                          |
|       T2.5                  \ Bus 2        Cubicle_5  CB5                           |
----------------------------------------------------------------------------------------
| Relay 2                                 Relay Type : IAC78A805A                      |
|   Location      :  Cubicle          : Cub_1        Branch     :                      |
|                    Busbar           : 11 KV                   / Bus 3                |
|--------------------------------------------------------------------------------------|
|   CT 2                                                Ratio       : 500A/5A          |
|     No. Phases     : 3           Phase 1     : a      Phase 2     : b                |
|     Connection     : Y                                                              |
|                                                                                      |
|   Measurement                                                                        |
|     Nominal Current ( 5.0            A      ) :      5.00 A                         |
|                                                                                      |
|   Toc                ( IEC: I>t   ANSI: 51    )         Out of Service    : No       |
|     Tripping Direction                         : None                               |
|     Current Setting ( 0.01 - 7.0     sec.A ) :      4.000 sec.A                     |
|     Time Dial        ( 0.5 - 10.0           ) :      8.000                           |
|     Characteristic                            : IAC Extremely Inverse GES7005B      |
|                                                                                      |
|   Toc Earth          ( IEC: IE>t  ANSI: 51N   )         Out of Service    : No       |
|     Tripping Direction                         : None                               |
|     Current Setting ( 1.5 - 12.0     sec.A ) :      1.500 sec.A                     |
|     Time Dial        ( 0.5 - 10.0           ) :      0.500                           |
|     Characteristic                            : IAC Extremely Inverse GES7005B      |
|                                                                                      |
|   Logic                                                 Out of Service    : No       |
|     Breaker                              Cubicle    Branch                          |
|       T2.2(1)               \ Bus 3        Cubicle_5  CB5                           |
----------------------------------------------------------------------------------------
| Relay dis 2a                            Relay Type : GE Distance                     |
|   Location      :  Cubicle          : Cub_1        Branch     : Cable 2              |
|                    Busbar           : 3                       / Bus 3                |
|--------------------------------------------------------------------------------------|
|   CT dis 2a                                           Ratio       : 500A/5A          |
|     No. Phases     : 3           Phase 1     : a      Phase 2     : b                |
|     Connection     : Y                                                              |
|                                                                                      |
|   VT dis 2a                                           Ratio       : 11000V/110V      |
|     Connection     : Y                                                              |
|                                                                                      |
|   Measurement                                                                        |
|     Nominal Current ( 5.0            A      ) :      5.00 A                         |
|     Nominal Voltage ( 110.0          V      ) :    110.00 V                         |
|   Polarizing                                                                         |
|                                                                                      |
|   Starting Ph-Ph            Type of Starting   : Overcurrent                         |
|     Current I>>        ( 0.1 - 100.0  sec.A ) :       1.200 sec.A                    |
|                                                                                      |
----------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------
|   ZD1                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       0.800 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
|   ZD2                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       1.200 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
|   ZD3                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      13.000 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
|   ZDT2                                                    Out of Service    : No      |
|     Time Setting       ( 0.0 - 10.0      s     ) :       0.300 s                     |
|                                                                                      |
|   ZDT3                                                    Out of Service    : No      |
|     Time Setting       ( 0.0 - 10.0      s     ) :       0.650 s                     |
|                                                                                      |
|   Logic Ph-Ph                                             Out of Service    : No      |
|     Breaker                              Cubicle     Branch                         |
|                              \                                                      |
----------------------------------------------------------------------------------------
| Relay dis 2b                            Relay Type : GE Distance                     |
|   Location      :  Cubicle          : Cub_1        Branch     : Cable 2              |
|                    Busbar           : 1                       / Bus 4                |
|--------------------------------------------------------------------------------------|
|   CT dis 2b                                           Ratio       : 500A/5A          |
|     No. Phases     : 3           Phase 1     : a      Phase 2     : b                |
|     Connection     : Y                                                              |
|                                                                                      |
|   VT dis 2b                                           Ratio       : 11000V/110V      |
|     Connection     : Y                                                              |
|                                                                                      |
|   Measurement                                                                        |
|     Nominal Current ( 5.0            A      ) :      5.00 A                         |
|     Nominal Voltage ( 110.0          V      ) :    110.00 V                         |
|                                                                                      |
|   Polarizing                                                                         |
|                                                                                      |
|   Starting Ph-Ph            Type of Starting   : Overcurrent                         |
|     Current I>>        ( 0.1 - 100.0  sec.A ) :       1.200 sec.A                    |
|                                                                                      |
|   ZD1                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       8.000 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
|   ZD2                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       6.000 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
|   ZD3                ( IEC: Z>>    ANSI: 21    )         Out of Service    : No      |
|     Tripping Direction                          : Forward                           |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       8.000 sec.Ohm               |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg                   |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg                   |
|                                                                                      |
```

```
  Logic Ph-Ph                                          Out of Service    : No
    Breaker                           Cubicle     Branch

 Relay dis 3a                       Relay Type : GE Distance
  Location     :  Cubicle          : Cub_1       Branch      : Cable 3
                  Busbar           : 2                     / Bus 4

  CT 3                                                Ratio        : 300A/5A
    No. Phases      : 3           Phase 1     : a     Phase 2      : b
    Connection      : Y

  VT dis 3a                                           Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0              A      ) :      5.00 A
    Nominal Voltage ( 110.0            V      ) :    110.00 V

  Polarizing

  Starting Ph-Ph            Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

  ZD1                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD2                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       6.700 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD3                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       7.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZDT2                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s

  ZDT3                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s

  Logic Ph-Ph                                          Out of Service    : No
    Breaker                           Cubicle     Branch

 Relay dis 3b                       Relay Type : GE Distance
  Location     :  Cubicle          : Cub_1       Branch      : Cable 3
                  Busbar           : 1                     / Bus 5

  CT dis 3b                                           Ratio        : 200A/5A
    No. Phases      : 3           Phase 1     : a     Phase 2      : b
    Connection      : Y

  VT dis 3b                                           Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0              A      ) :      5.00 A
    Nominal Voltage ( 110.0            V      ) :    110.00 V

  Polarizing

  Starting Ph-Ph            Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       2.800 sec.A

  ZD1                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       2.500 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD2                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD3                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       9.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZDT2                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s

  ZDT3                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s

  Logic Ph-Ph                                          Out of Service    : No
    Breaker                           Cubicle     Branch

 Relay dis 4a                       Relay Type : GE Distance
  Location     :  Cubicle          : Cub_1       Branch      : Cable 4
                  Busbar           : 2                     / Bus 5

  CT 4                                                Ratio        : 300A/5A
    No. Phases      : 3           Phase 1     : a     Phase 2      : b
    Connection      : Y

  VT dis 1a                                           Ratio        : 11000V/110V
    Connection      : Y

  Measurement
    Nominal Current ( 5.0              A      ) :      5.00 A
    Nominal Voltage ( 110.0            V      ) :    110.00 V

  Polarizing

  Starting Ph-Ph            Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

  ZD1                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD2                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      13.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZD3                ( IEC: Z>>   ANSI: 21    )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      10.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

  ZDT2                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s

  ZDT3                                                 Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s
```

```
--------------------------------------------------------------------------------
| Relay dis 4b                              Relay Type : GE Distance            |
|   Location     :  Cubicle          : Cub_1       Branch     : Cable 4         |
|                   Busbar           : 1                      / Bus 6           |
|-------------------------------------------------------------------------------|
|   CT dis 4b                                         Ratio      : 300A/5A      |
|     No. Phases     : 3          Phase 1    : a      Phase 2    : b            |
|     Connection     : Y                                                       |
|                                                                               |
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
|   VT dis 4b                                         Ratio      : 11000V/110V  |
|     Connection     : Y                                                       |
|                                                                               |
|   Measurement                                                                 |
|     Nominal Current ( 5.0            A     ) :    5.00 A                      |
|     Nominal Voltage ( 110.0          V     ) :  110.00 V                      |
|                                                                               |
|   Polarizing                                                                  |
|                                                                               |
|   Starting Ph-Ph           Type of Starting  : Overcurrent                     |
|     Current I>>        ( 0.1 - 100.0  sec.A ) :      1.800 sec.A              |
|                                                                               |
|   ZD1               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      4.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD2               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      8.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD3               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      9.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZDT2                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s                |
|                                                                               |
|   ZDT3                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s                |
|                                                                               |
|   Logic Ph-Ph                                         Out of Service   : No    |
|     Breaker                              Cubicle    Branch                     |
|                           \                                                   |
--------------------------------------------------------------------------------
| Relay dis 6a                              Relay Type : GE Distance            |
|   Location     :  Cubicle          : Cub_1       Branch     : Cable 6         |
|                   Busbar           : 4                      / Bus 6           |
|-------------------------------------------------------------------------------|
|   CT dis6a                                          Ratio      : 200A/5A      |
|     No. Phases     : 3          Phase 1    : a      Phase 2    : b            |
|     Connection     : Y                                                       |
|                                                                               |
|   VT dis 6a                                         Ratio      : 11000V/110V  |
|     Connection     : Y                                                       |
|                                                                               |
|   Measurement                                                                 |
|     Nominal Current ( 5.0            A     ) :    5.00 A                      |
|     Nominal Voltage ( 110.0          V     ) :  110.00 V                      |
|                                                                               |
|   Polarizing                                                                  |
|                                                                               |
|   Starting Ph-Ph           Type of Starting  : Overcurrent                     |
|     Current I>>        ( 0.1 - 100.0  sec.A ) :      5.300 sec.A              |
|                                                                               |
|   ZD1               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      5.300 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD2               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      7.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD3               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :     10.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
|   ZDT2                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s                |
|                                                                               |
|   ZDT3                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s                |
|                                                                               |
|   Logic Ph-Ph                                         Out of Service   : No    |
|     Breaker                              Cubicle    Branch                     |
|                           \                                                   |
--------------------------------------------------------------------------------
| Relay dis 6b                              Relay Type : GE Distance            |
|   Location     :  Cubicle          : Cub_1       Branch     : Cable 6         |
|                   Busbar           : 11 KV                  / Bus 3           |
|-------------------------------------------------------------------------------|
|   CT dis b                                          Ratio      : 500A/5A      |
|     No. Phases     : 3          Phase 1    : a      Phase 2    : b            |
|     Connection     : Y                                                       |
|                                                                               |
|   VT dis b                                          Ratio      : 11000V/110V  |
|     Connection     : Y                                                       |
|                                                                               |
|   Measurement                                                                 |
|     Nominal Current ( 5.0            A     ) :    5.00 A                      |
|     Nominal Voltage ( 110.0          V     ) :  110.00 V                      |
|                                                                               |
|   Polarizing                                                                  |
|                                                                               |
|   Starting Ph-Ph           Type of Starting  : Overcurrent                     |
|     Current I>>        ( 0.1 - 100.0  sec.A ) :      2.100 sec.A              |
|                                                                               |
|   ZD1               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      8.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD2               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :     10.000 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZD3               ( IEC: Z>>   ANSI: 21   )        Out of Service   : No    |
|     Tripping Direction                         : Forward                       |
|     Replica Impedance  ( 0.1 - 100.0  sec.Ohm ) :      7.700 sec.Ohm           |
|     Relay Angle        ( 10.0 - 80.0  deg     ) :     30.000 deg               |
|     Character. Angle   ( 10.0 - 170.0 deg     ) :     90.000 deg               |
|                                                                               |
|   ZDT2                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.300 s                |
|                                                                               |
|   ZDT3                                                Out of Service   : No    |
|     Time Setting       ( 0.0 - 10.0      s     ) :      0.650 s                |
|                                                                               |
|   Logic Ph-Ph                                         Out of Service   : No    |
|     Breaker                              Cubicle    Branch                     |
|       T6.2                \ Bus 3      Cubicle 5   CB6                         |
```

Figure 9-10 Relay parameters without DGs

```
------------------------------------------------------------------------------------------------
|           With DG                       |   DIGSILENT   | Project: mesh                      |
|   Mesh distribution network             | PowerFactory  |------------------------------------
|                                         |    14.1.3     | Date:  10/29/2013                  |
------------------------------------------------------------------------------------------------
| Relay 1a                                Relay Type : Rel-Toc-Dirextst                        |
|   Location       :  Cubicle          : Cub_1        Branch     : Cable 1                     |
|                     Busbar           : 11 KV                   / Bus 2                       |
|----------------------------------------------------------------------------------------------|
|   CT 1a                                                 Ratio       : 1000A/5A               |
|     No. Phases      : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection      : Y                                                                      |
|                                                                                              |
|   VT 1A                                                 Ratio       : 11000V/110V            |
|     Connection      : Y                                                                      |
|                                                                                              |
|   Measurement                                                                                |
|     Nominal Current ( 5.0            A      ) :     1.00 A                                   |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                                   |
|                                                                                              |
|   Toc                  ( IEC: I>t   ANSI: 51    )       Out of Service    : No               |
|     Tripping Direction                         : Forward                                     |
|     Current Setting   ( 0.01 - 10.0    sec.A ) :     1.500 sec.A                             |
|     Time Dial         ( 0.05 - 3.2           ) :     0.400                                   |
|     Characteristic                             : IEC 255-3 inverse                           |
|                                                                                              |
|   Dir                  ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                           : Forward                                   |
|     Angle Operating Sector      ( 20.0 - 90.0      ) :    90.00 deg                          |
|     Polarizing Voltage      ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                         |
|     Max. Torque Angle       ( -90.0 - 90.0 deg   ) :     0.00 deg                           |
|                                                                                              |
|   Logic                                                  Out of Service    : No              |
|     Breaker                                  Cubicle     Branch                             |
|      T2.5                    \ Bus 2          Cubicle_5   CB5                               |
------------------------------------------------------------------------------------------------
| Relay 1b                                Relay Type : Rel-Toc-Dirextst                        |
|   Location       :  Cubicle          : Cub_1        Branch     : Cable 1                     |
|                     Busbar           : 1                       / Bus 3                       |
|----------------------------------------------------------------------------------------------|
|   CT 1B                                                 Ratio       : 200A/5A                |
|     No. Phases      : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection      : Y                                                                      |
|                                                                                              |
|   VT 1b                                                 Ratio       : 11000V/110V            |
|     Connection      : Y                                                                      |
|                                                                                              |
|   Measurement                                                                                |
|     Nominal Current ( 5.0            A      ) :     5.00 A                                   |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                                   |
|                                                                                              |
|   Toc                  ( IEC: I>t   ANSI: 51    )       Out of Service    : No               |
|     Tripping Direction                         : Forward                                     |
|     Current Setting   ( 0.01 - 10.0    sec.A ) :     2.500 sec.A                             |
|     Time Dial         ( 0.05 - 3.2           ) :     0.050                                   |
|     Characteristic                             : IEC 255-3 extremly inverse                  |
|                                                                                              |
|   Dir                  ( IEC: I->    ANSI: 67    )       Out of Service    : No              |
|     Tripping Direction                           : Forward                                   |
|     Angle Operating Sector      ( 20.0 - 90.0      ) :    90.00 deg                          |
|     Polarizing Voltage      ( 0.01 - 10.0  sec.V ) :     0.01 sec.V                         |
|     Max. Torque Angle       ( -90.0 - 90.0 deg   ) :     0.00 deg                           |
|                                                                                              |
|   Logic                                                  Out of Service    : No              |
|     Breaker                                  Cubicle     Branch                             |
|                              \                                                               |
------------------------------------------------------------------------------------------------
| Relay 5                                 Relay Type : IAC78A805A                              |
|   Location       :  Cubicle          : Cub_1        Branch     : Cable 5                     |
|                     Busbar           : 2                       / Bus 6                       |
|----------------------------------------------------------------------------------------------|
|   CT 5                                                  Ratio       : 300A/5A                |
|     No. Phases      : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection      : Y                                                                      |
|                                                                                              |
|   Measurement                                                                                |
|     Nominal Current ( 5.0            A      ) :     5.00 A                                   |
|                                                                                              |
------------------------------------------------------------------------------------------------
|   Toc                  ( IEC: I>t   ANSI: 51    )       Out of Service    : No               |
|     Tripping Direction                         : None                                        |
|     Current Setting   ( 0.01 - 7.0     sec.A ) :     5.000 sec.A                             |
|     Time Dial         ( 0.5 - 10.0           ) :     1.000                                   |
|     Characteristic                             : IAC Extremely Inverse GES7005B              |
|                                                                                              |
|   Toc Earth            ( IEC: IE>t  ANSI: 51N   )       Out of Service    : No               |
|     Tripping Direction                         : None                                        |
|     Current Setting   ( 1.5 - 12.0     sec.A ) :     1.500 sec.A                             |
|     Time Dial         ( 0.5 - 10.0           ) :     0.500                                   |
|     Characteristic                             : IAC Extremely Inverse GES7005B              |
|                                                                                              |
|   Logic                                                  Out of Service    : No              |
|     Breaker                                  Cubicle     Branch                             |
|                              \                                                               |
------------------------------------------------------------------------------------------------
| Relay dis 2a                            Relay Type : GE Distance                             |
|   Location       :  Cubicle          : Cub_1        Branch     : Cable 2                     |
|                     Busbar           : 3                       / Bus 3                       |
|----------------------------------------------------------------------------------------------|
|   CT dis 2a                                             Ratio       : 500A/5A                |
|     No. Phases      : 3            Phase 1     : a      Phase 2     : b                      |
|     Connection      : Y                                                                      |
|                                                                                              |
|   VT dis 2a                                             Ratio       : 11000V/110V            |
|     Connection      : Y                                                                      |
|                                                                                              |
|   Measurement                                                                                |
|     Nominal Current ( 5.0            A      ) :     5.00 A                                   |
|     Nominal Voltage ( 110.0          V      ) :   110.00 V                                   |
|                                                                                              |
|   Polarizing                                                                                 |
|                                                                                              |
|   Starting Ph-Ph               Type of Starting   : Overcurrent                              |
|     Current I>>          ( 0.1 - 100.0   sec.A ) :      1.200 sec.A                          |
|                                                                                              |
|   ZD1                  ( IEC: Z>>    ANSI: 21    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                                 |
|     Replica Impedance  ( 0.1 - 100.0   sec.Ohm ) :      0.800 sec.Ohm                       |
|     Relay Angle        ( 10.0 - 80.0   deg     ) :     30.000 deg                           |
|     Character. Angle   ( 10.0 - 170.0  deg     ) :     90.000 deg                           |
|                                                                                              |
|   ZD2                  ( IEC: Z>>    ANSI: 21    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                                 |
|     Replica Impedance  ( 0.1 - 100.0   sec.Ohm ) :      1.250 sec.Ohm                       |
|     Relay Angle        ( 10.0 - 80.0   deg     ) :     25.000 deg                           |
|     Character. Angle   ( 10.0 - 170.0  deg     ) :     90.000 deg                           |
|                                                                                              |
|   ZD3                  ( IEC: Z>>    ANSI: 21    )       Out of Service    : No              |
|     Tripping Direction                             : Forward                                 |
|     Replica Impedance  ( 0.1 - 100.0   sec.Ohm ) :     22.000 sec.Ohm                       |
|     Relay Angle        ( 10.0 - 80.0   deg     ) :     27.000 deg                           |
|     Character. Angle   ( 10.0 - 170.0  deg     ) :     90.000 deg                           |
|                                                                                              |
|   ZDT2                                                   Out of Service    : No              |
|     Time Setting       ( 0.0 - 10.0      s       ) :     0.300 s                            |
|                                                                                              |
|   ZDT3                                                   Out of Service    : No              |
|     Time Setting       ( 0.0 - 10.0      s       ) :     0.800 s                            |
|                                                                                              |
|   Logic Ph-Ph                                            Out of Service    : No              |
|     Breaker                                  Cubicle     Branch                             |
|                              \                                                               |
------------------------------------------------------------------------------------------------
```

```
Relay dis 2b                              Relay Type : GE Distance
  Location      :  Cubicle         : Cub_1        Branch     : Cable 2
                   Busbar          : 1                       / Bus 4
-----------------------------------------------------------------------------
  CT dis 2b                                       Ratio        : 500A/5A
    No. Phases       : 3           Phase 1     : a      Phase 2      : b
    Connection       : Y

  VT dis 2b                                       Ratio        : 11000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A      ) :     5.00 A
    Nominal Voltage ( 110.0           V      ) :   110.00 V
-----------------------------------------------------------------------------

  Polarizing

  Starting Ph-Ph              Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       0.600 sec.A

  ZD1               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       8.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD2               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      10.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      32.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD3               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      30.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      40.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZDT2                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.300 s

  ZDT3                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.650 s

  Logic Ph-Ph                                           Out of Service    : No
    Breaker                                 Cubicle     Branch
                           \
-----------------------------------------------------------------------------
Relay dis 3a                              Relay Type : GE Distance
  Location      :  Cubicle         : Cub_1        Branch     : Cable 3
                   Busbar          : 2                       / Bus 4
-----------------------------------------------------------------------------
  CT 3                                            Ratio        : 300A/5A
    No. Phases       : 3           Phase 1     : a      Phase 2      : b
    Connection       : Y

  VT dis 3a                                       Ratio        : 11000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A      ) :     5.00 A
    Nominal Voltage ( 110.0           V      ) :   110.00 V

  Polarizing

  Starting Ph-Ph              Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

  ZD1               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm

    Relay Angle       ( 10.0 - 80.0   deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD2               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       6.700 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      27.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD3               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       7.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      28.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZDT2                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.300 s

  ZDT3                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.650 s
-----------------------------------------------------------------------------
  Logic Ph-Ph                                           Out of Service    : No
    Breaker                                 Cubicle     Branch
                           \
-----------------------------------------------------------------------------
Relay dis 3b                              Relay Type : GE Distance
  Location      :  Cubicle         : Cub_1        Branch     : Cable 3
                   Busbar          : 1                       / Bus 5
-----------------------------------------------------------------------------
  CT dis 3b                                       Ratio        : 200A/5A
    No. Phases       : 3           Phase 1     : a      Phase 2      : b
    Connection       : Y

  VT dis 3b                                       Ratio        : 11000V/110V
    Connection       : Y

  Measurement
    Nominal Current ( 5.0             A      ) :     5.00 A
    Nominal Voltage ( 110.0           V      ) :   110.00 V

  Polarizing

  Starting Ph-Ph              Type of Starting  : Overcurrent
    Current I>>        ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

  ZD1               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       2.500 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      30.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD2               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.800 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      27.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZD3               ( IEC: Z>>    ANSI: 21     )        Out of Service    : No
    Tripping Direction                        : Forward
    Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      20.000 sec.Ohm
    Relay Angle       ( 10.0 - 80.0   deg     ) :      27.000 deg
    Character. Angle  ( 10.0 - 170.0  deg     ) :      90.000 deg

  ZDT2                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.300 s

  ZDT3                                                  Out of Service    : No
    Time Setting       ( 0.0 - 10.0      s      ) :      0.650 s

  Logic Ph-Ph                                           Out of Service    : No
    Breaker                                 Cubicle     Branch
                           \
```

```
Relay dis 4a                              Relay Type : GE Distance
   Location      :  Cubicle          : Cub_1       Branch     : Cable 4
                    Busbar           : 2                      / Bus 5

   CT 4                                               Ratio        : 300A/5A
     No. Phases       : 3          Phase 1     : a    Phase 2      : b
     Connection       : Y

   VT dis 1a                                          Ratio        : 11000V/110V
     Connection       : Y

   Measurement
     Nominal Current ( 5.0             A      ) :     5.00 A
     Nominal Voltage ( 110.0           V      ) :   110.00 V

   Polarizing

   Starting Ph-Ph              Type of Starting  : Overcurrent
     Current I>>          ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

   ZD1                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD2                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      13.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD3                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      10.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZDT2                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.300 s

   ZDT3                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.650 s

   Logic Ph-Ph                                           Out of Service    : No
     Breaker                                Cubicle     Branch
                            \
Relay dis 4b                              Relay Type : GE Distance
   Location      :  Cubicle          : Cub_1       Branch     : Cable 4
                    Busbar           : 1                      / Bus 6

   CT dis 4b                                          Ratio        : 300A/5A
     No. Phases       : 3          Phase 1     : a    Phase 2      : b
     Connection       : Y

   VT dis 4b                                          Ratio        : 11000V/110V
     Connection       : Y

   Measurement
     Nominal Current ( 5.0             A      ) :     5.00 A
     Nominal Voltage ( 110.0           V      ) :   110.00 V

   Polarizing

   Starting Ph-Ph              Type of Starting  : Overcurrent
     Current I>>          ( 0.1 - 100.0  sec.A ) :       1.800 sec.A

   ZD1                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       4.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD2                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       8.200 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      27.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD3                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      14.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      27.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZDT2                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.300 s

   ZDT3                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.650 s

   Logic Ph-Ph                                           Out of Service    : No
     Breaker                                Cubicle     Branch
                            \
Relay dis 6a                              Relay Type : GE Distance
   Location      :  Cubicle          : Cub_1       Branch     : Cable 6
                    Busbar           : 4                      / Bus 6

   CT dis6a                                           Ratio        : 200A/5A
     No. Phases       : 3          Phase 1     : a    Phase 2      : b
     Connection       : Y

   VT dis 6a                                          Ratio        : 11000V/110V
     Connection       : Y

   Measurement
     Nominal Current ( 5.0             A      ) :     5.00 A
     Nominal Voltage ( 110.0           V      ) :   110.00 V

   Polarizing

   Starting Ph-Ph              Type of Starting  : Overcurrent
     Current I>>          ( 0.1 - 100.0  sec.A ) :       2.500 sec.A

   ZD1                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       5.300 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD2                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :       7.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      30.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZD3                ( IEC: Z>>    ANSI: 21    )        Out of Service    : No
     Tripping Direction                           : Forward
     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :      10.000 sec.Ohm
     Relay Angle       ( 10.0 - 80.0  deg     ) :      40.000 deg
     Character. Angle  ( 10.0 - 170.0 deg     ) :      90.000 deg

   ZDT2                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.300 s

   ZDT3                                                  Out of Service    : No
     Time Setting         ( 0.0 - 10.0      s      ) :    0.650 s

   Logic Ph-Ph                                           Out of Service    : No
     Breaker                                Cubicle     Branch
```

```
-----------------------------------------------------------------------------
| Relay dis 6b                      Relay Type : GE Distance                |
|   Location      :  Cubicle        : Cub_1      Branch     : Cable 6       |
|                    Busbar         : 11 KV                 / Bus 3         |
|---------------------------------------------------------------------------|
|   CT dis b                                     Ratio       : 500A/5A      |
|     No. Phases     : 3         Phase 1    : a    Phase 2     : b          |
|     Connection     : Y                                                    |
|                                                                           |
|   VT dis b                                     Ratio       : 11000V/110V  |
|     Connection     : Y                                                    |
|                                                                           |
|   Measurement                                                             |
|     Nominal Current ( 5.0          A     ) :    5.00 A                    |
|     Nominal Voltage ( 110.0        V     ) :  110.00 V                    |
|                                                                           |
|   Polarizing                                                              |
|                                                                           |
|   Starting Ph-Ph           Type of Starting  : Overcurrent                |
|     Current I>>       ( 0.1 - 100.0  sec.A ) :      2.100 sec.A           |
|                                                                           |
|   ZD1              ( IEC: Z>>   ANSI: 21   )      Out of Service   : No   |
|     Tripping Direction                     : Forward                      |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :     8.000 sec.Ohm        |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :    30.000 deg            |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :    90.000 deg            |
|                                                                           |
|   ZD2              ( IEC: Z>>   ANSI: 21   )      Out of Service   : No   |
|     Tripping Direction                     : Forward                      |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :    10.000 sec.Ohm        |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :    30.000 deg            |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :    90.000 deg            |
|                                                                           |
|   ZD3              ( IEC: Z>>   ANSI: 21   )      Out of Service   : No   |
|     Tripping Direction                     : Forward                      |
|     Replica Impedance ( 0.1 - 100.0  sec.Ohm ) :    17.000 sec.Ohm        |
|     Relay Angle       ( 10.0 - 80.0  deg     ) :    30.000 deg            |
|     Character. Angle  ( 10.0 - 170.0 deg     ) :    90.000 deg            |
|                                                                           |
-----------------------------------------------------------------------------
-----------------------------------------------------------------------------
|   ZDT2                                            Out of Service   : No   |
|     Time Setting      ( 0.0 - 10.0     s     ) :     0.300 s              |
|                                                                           |
|   ZDT3                                            Out of Service   : No   |
|     Time Setting      ( 0.0 - 10.0     s     ) :     0.800 s              |
|                                                                           |
|   Logic Ph-Ph                                     Out of Service   : No   |
|     Breaker                          Cubicle    Branch                    |
|      T6.2               \ Bus 3       Cubicle_S  CB6                      |
-----------------------------------------------------------------------------
```

Figure 9-11 Relay parameters with DGs