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Transmission Line Protection Using SIPROTEC Numerical Relays

Presented by:

- **KHELIFAOUI Nacera**
- **DIB Lynda**

Supervisor:

Dr.M. BOUCHEHDANE

Co- Supervisor:

Mr.T. Laloui

Registration Number:……/2018

Abstract

The aim of this project is to discuss theoretically the protections provided for transmission lines and perform tests on some protective numerical relays to verify their good performance. A protection system designed to function selectively and efficiently is playing a key role for the safe operation of the electrical power system. All its various elements are today relevant for power generation, transmission, distribution and industrial applications. Numerical relays are the most important element of this system. They are constructed by different integrated electronic circuits which are subjected to failures. These phenomena expose the protection to operate in an unreliable way. To prevent damaging the power system components, periodic maintenance and testing of the protective relays is recommended throughout their life-cycle. Due to technological evolution of these multifunctional numerical products, the way they are tested is changing over the years. This work consisted on testing the Siemens Protection Technology 4 (SIPROTEC 4) protection provided to a transmission line of 60kV, considering different protection functions. The results recorded were successful for all the experiments which ensures the proper operation of these elements and their good working condition.

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Table of Content

Abstract I

Acknowledgements II

Table of Content III

List of Tables VI

List of Figures VII

List of Abbreviations IX

Introduction 1

Chapter 1 Power system protection 2

I.1. Introduction 2

I.2. Power System Network 3

I.3. Power System Protection 4

I.4. Power System Protection Devices 6

I.4.a. Fuses 6

I.4.b. Instrument Transformers 6

I.4.c. Circuit Breakers 7

I.4.d. Breaker Failure 8

I.4.e. Batteries 8

I.4.f. Relays 9

I.4.g. Automatic circuit reclosers 9

I.4.h. Automatic line sectionalizers 9

I.5. Protective relays 10

I.5.a. Historical Review 10

I.5.b. Protection types 11

I.6. Conclusion 13

Chapter 2 Protection of Transmission Lines 14
II.1. Introduction 14
II.2. Transmission Lines 15
II.3. Transmission Line faults 16
II.3.a. Three-Phase (3PH) Faults 16
II.3.b. Line-to-Line (L-L) Faults 17
II.3.c. Double Line-to-Ground (2LG) Faults 17
II.3.d. One-Line-to-Ground (1LG) Faults 18
II.4.Protection of Transmission Lines 19
II.4.a. Ground Fault Protection 19
II.4.b. Overcurrent Protection 19
II.4.c. Distance Protection 20
II.4.d. Pilot 23
II.4.e. Differential Protection 27
II.5. Conclusion 28
Chapter 3 Testing SIEMENS SIPROTEC 4 Relays 29
III.1. Introduction 29
III.2. Equipment 30
III.3. Software 31
III.4. Transmission Line Distance Test 7SA612 32
III.4.a. Permissive Underreach Transfer Trip PUTT 34
III.4.b. Broken conductor 35
III.4.c. Quick tripping after reclosing with permanent fault 36
III.5. Transmission Line Differential 7SD87 test 37
III.6. Transmission Line Overcurrent 7SJ80 Test 38
III.7. Breaker Failure Protection Test 40
III.8. Changing Groups 42

III.9. Conclusion 43
Conclusion 44
Future Work 45
References I

List of Tables

Table I.1:ANSI code of protective relays.. 13
Table III.1: Active Setting Group. 42

List of Figures

Figure I.1: Power system network [1]. 3
Figure I.2: Power system protection [21]. 4
Figure I.3: Common connection of instrument transformers [6]. 7
Figure I.4: Breaker failure function principle [14]. 8
Figure I.5: Typical Digital Relay Hardware Architecture [10]. 11
Figure I.6: Differential protection principle of operation [11]. 12
Figure II.1:Three phase fault [22]. 16
Figure II.2:Asymmetrical transmission line faults [9]. 17
Figure II.3: Symmetrical component circuit for double line to ground fault [9]. 18
Figure II.4: Asymmetrical transmission line faults [9]. 18
Figure II.5: (a) Use of three OC relays; (b) Use of EF relay with three OC relays [14]. 20
Figure II.6: Use of an EF relay and two relays on phases [14]. 20
Figure II.7: Distance Relay Protection Zones [16]. 21
Figure II.8:Distance Relay characteristics [14]. 23
Figure II.9: General view of a pilot protection system [2]. 23
Figure II.10: Classification of pilot protection schemes. 25
Figure II.11: Permissive Underreaching Transfer Trip [14]. 26
Figure II.12: Basic current differential scheme (normal situation) [13]. 27
Figure II.13: Basic current differential scheme (in case of a fault) [10] 28
Figure III.1: Single line representation of 60kV TL. 30
Figure III.2: Test Universe 3.20 software front page. 32
Figure III.3: Test zone 1 phase to phase fault. 33
Figure III.4:Report given by the 7SA protection. 33
Figure III.5: Test injected in ZB1 to test PUTT function. 34
Figure III.6:Protection report for PUTT function. 34
Figure III.7: Injected quick CMC values for broken conductor. 35
Figure III.8: Protection report about the broken conductor. 36
Figure III.9: Injected values to test quick tripping after reclosing with permanent fault. 36
Figure III.10:7SA report for general tripping and blocked reclosing. 37
Figure II.11: Injected Currents to the 7SD and corresponding phasor diagram. 38
Figure III.12: Signalization Report for Differential Protection Test. 38

Figure III.13: : Injected Currents to 7SJ and corresponding phasor diagram. 39
Figure III.14: Graphical Report for Overcurrent Protection Test. 39
Figure III.15: Injected Current to the 7VK protection via Quick CMC. 40
Figure III.16: CBs at normal case representation in HMI 40
Figure III.17: BCs after BF operation represented in the HMI. 41
Figure III.18: tripping times given by HMI of the protection. 41
Figure III.19 Setting group change option in DIGSI configuration 42
Figure III.20: Signalization Report for changing of groups. 43
Figure 0.1: Bloc Diagram of Proposed Protection Method For Busbars. 45

List of Abbreviations

2LG: double line-to-ground

3PH: Three Phase

AC: Alternative Current

BF: Breaker Failure

CB: Circuit Breaker

CFC: Continuous Function Chart

CT: current transformer

DC: Direct Current

EF: earth fault

HMI: Human Machine Interface

IEC: International Electrotechnical Commission

IED: Intelligent Electronic Devices

ILG: one-line-to-ground

L-L: line-to-line

OC: overcurrent

OF: Optical Fiber

PLC: Power Line Carrier

SIPROTEC: Siemens Protection Technology

TL: Transmission Line

VT: voltage transformer

Introduction

Power engineers have been facing several challenges to keep the power system well maintained and reliable; some of which are the increasing complexity and the technological evolution of this system. Transmission lines are one part of the power system that permits the transfer of power from generation plants to distribution stations.

As any electrical system, TLs are subjected to some conditions causing failure interrupting the electrical flow. Protection engineers have designed protective systems, constituting on different equipment, which main function is to provide the detection of abnormalities in the network and prevent its damages. These systems have a main component which is protective relays.

Relays evolved from electromechanical to multifunctional numerical relays with developed technologies. Using different algorithms, they guarantee a reliable operation of the system. As any electronic based device, numerical relays could be failed. Observed field return data show that Siemens SIPROTEC relays have a mean failure of about 0.167% (1/600) failures per year. Meaning that, for every 600 relays, it expects one or fewer failures per year. This measurement is the result of over 1.2 million relays installed worldwide.

To maximize the failures of these devices, they shall be tested and maintained in a period way. Performing tests is done in deferent manners, and as relays evolved, even the technology used for testing them have been developed in such a way tests would be efficient.

This report covers the protections provided to transmission lines and give methods of testing relays produced by Siemens which are SIPROTEC 4 relays, this is given as follows:

- **Chapter 01:** In this chapter, basic ideas about the protection of the power systems have been introduced; the equipment constituting a protective system, relays and their function have been also discussed.
- **Chapter 02:** Transmission lines have been given there faults and the protections designed to detect and isolate them are presented.
- **Chapter 03:** this chapter is devoted to the experimental results and discussions of the tests performed on SIPROTEC 4 relays.

Chapter 1

Power system protection

I.1. Introduction

Power generated at low voltage is stepped up to a higher voltage to be transmitted to various stations and then distributed to customers. This process is done through a complex power system network starting by power generation, then, power transformation, power transmission and finally power distribution. At each level, equipment such as generators, transformers busbars or even lines face different phenomena that can lead to power system failure. A crucial task for engineers is to design and implement a power system protection based on methods permitting a fast detection and clearing of these faults to restore normal operation.

In this chapter, we begin with some basic ideas about power system network. We then progress to reviewing the faults at all levels and their associated basic equipment that constitute a protective system. Each equipment, such as fuses, circuit breakers, instrument transformers and relays, will be explained accordingly. Since protection system has evolved from primitive devices with limited capability to complex intelligent electronic devices, the emphasis will be on the brain of protective systems, which are numerical relays.

I.2. Power System Network

Electrical power is extracted from nature by converting mechanical rotating energy into electrical one. This conversion is done in power plants through generators or alternators. Different plants are constructed in specific areas all over the world to feed cities and manufactories with needed power. The most efficient one is hydro power plant with an efficiency of forty percent, other plants such as steam, wind, nuclear and solar have more losses. Ways to transmit and distribute electricity are designed in such way losses will be minimized.

Figure I.1 illustrates the parts of a Power System. Power is generated at low level in power stations and stepped up, then, by means of power transformers to a higher voltage resulting in small currents, to be transmitted to other stations with minimum line losses. Some factories are directly supplied with the required high voltage lines, others are fed, as well as cities, by medium or low voltage levels from distribution stations where step down transformers are used.

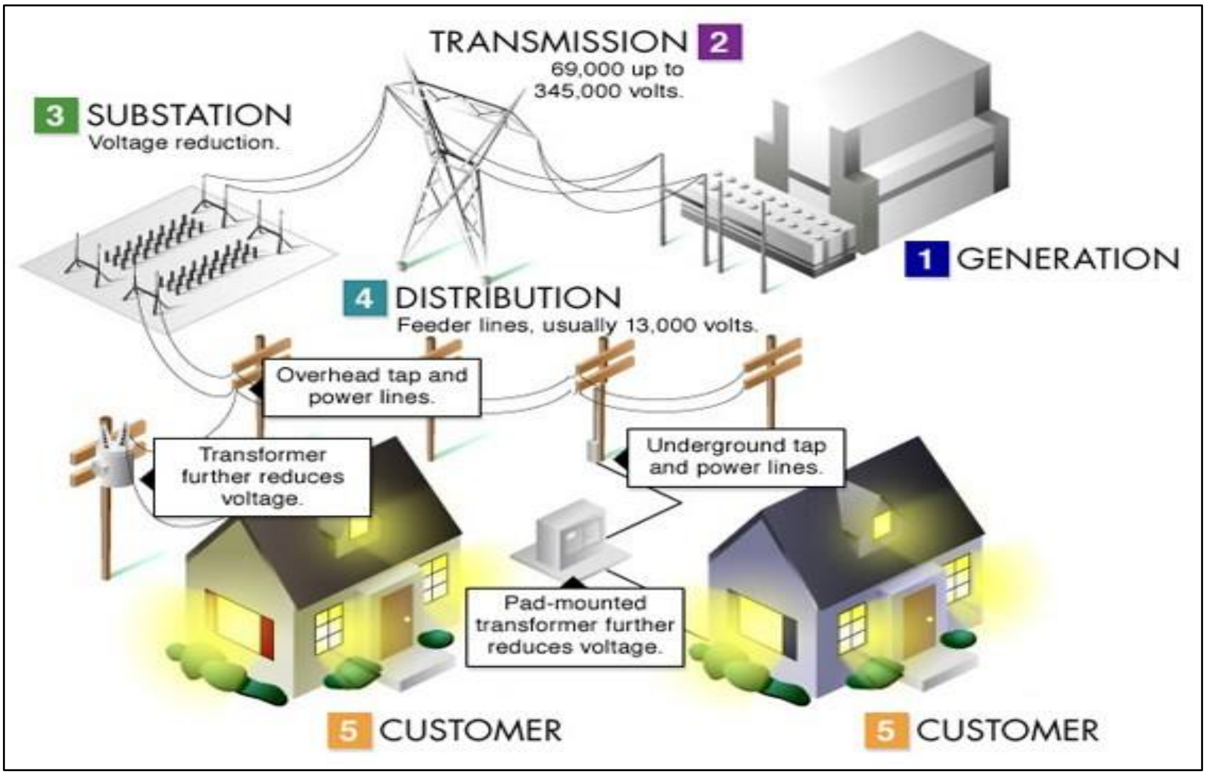


Figure I.1: Power system network [1].

Through all network, disturbances may occur and interrupt the flow of electricity. These abnormalities are caused by equipment failure such as transformers or rotating machines, environmental conditions or even human errors. Nature phenomena like storms and high wind affect the network causing faults on it. Human error may be a reason for short circuits and equipment function failure. Very sophisticated and well-designed protection systems are implemented at generation plants, busbars, transformers, transmission and distribution stations to ensure continuous power supplies and eliminate faults in a selective reliable way.

I.3. Power System Protection

Short circuit faults on power systems are usually shunt disturbances of three-phase (3PH), phase-to-phase(L-L), two-phase-to-ground(2LG) or one-phase-to-ground(1LG) short circuits. The total current flowing to the fault depends on the type of fault and the phase in which the current is measured. It also depends on the locations in the system where the fault occurs, since the Thevenin equivalent impedance seen looking back into the system varies with location, with the amount of generation in service at the time, and with the branch switching of the network. All of these variations can be important, both in determining the exact fault current available at a given place and time, but also in fixing the critical parameters of the protective system [2]. The figure bellow illustrates the different parts of a power system and the associated protections provided for each one:

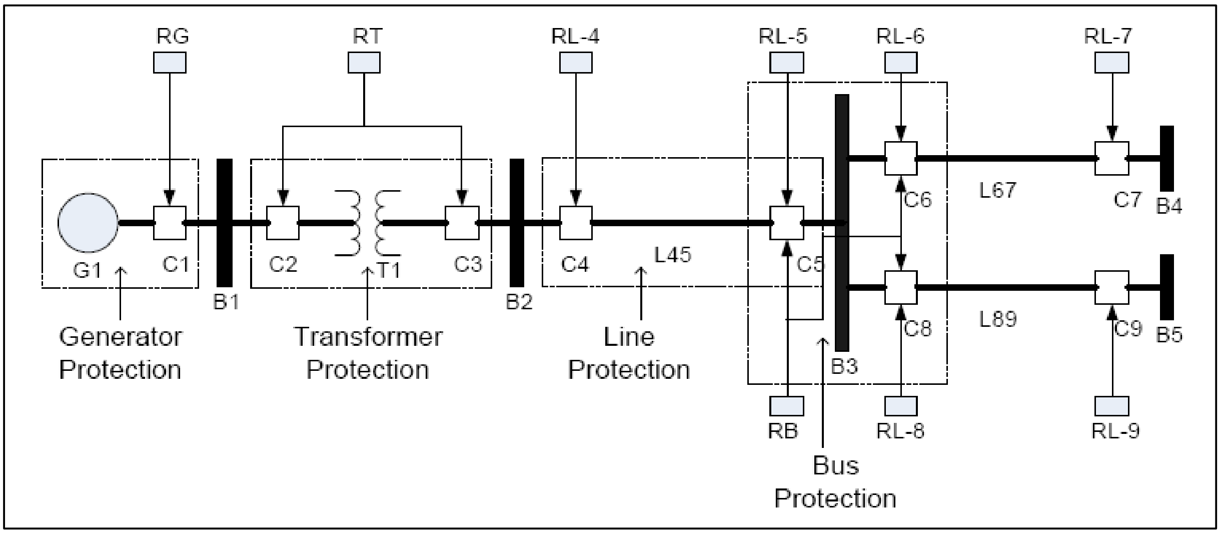


Figure I.2: Power system protection [21].

Three important concepts are basic to the design of any protection system; selectivity, reliability and security. Selectivity requires that the protection system must be dependable in identifying faults in its zones of protection. This is achieved by the relay designer, who uses logic for fault detection and line tripping. Reliability requires that the protection system be operable, that is, that the overall design will ensure appropriate protective action even if some portion of the protective apparatus may have failed. This is achieved by using equipment of high quality, by performing routine testing to ensure that the equipment remains operable, and by designing protective system that has redundancy. Some engineers insist that the backup system should be of a different design or operate on a different principle than the primary system.

Power transformers in power system are given more consideration for their high cost and long outage time when they fail. Faults on transformers are divided into external and internal classes. Hazards occurring outside are external stresses including short circuits, overvoltage, under frequency and overload faults causing overheat that tends to damage the unit. Faults within the transformer may be incipient faults that develop slowly to major ones if cause is not detected, or active faults caused by insolation or other components breakdown. Protection designed for transformers is unit protection or differential protection by taking measurements at both terminals.

Electric machines are very complex and complicated systems, one of the reasons why they are subject to failure. Their ac winding faults are the same of those of transformers. Other abnormalities occur in the magnetic lamination insulation, cooling system, overheating, mechanical motion and vibrations. Most of generators are of synchronous type, and protections provided to them are of different types. Almost all generators have stator short circuit protection using differential principle. Other protections are rotor, loss of excitation, overspeed, generator motoring, vibration, bearing failure, coolant failure and fire protection.

Busbars permitting link between lines from different stations are the most sensitive part. Most of bus faults are ground faults caused by human error, leaving safety grounds connected to the bus after repair or routine maintenance work. The largest number of failures are due to flashovers and insulation failures, which are often initiated by inclement weather. Faults on bus section account for only 6-7% of all faults, whereas line faults account for over 60% [2].

This section is protected by differential protection using several different methods, backup line relays, fault bus and combined bus and transformer protections.

Transmission lines, being overhead or underground, are more exposed to environmental conditions. Protecting this part of network is of major importance since minimizing human and equipment errors is possible, but nothing can be done with nature phenomena. The main protection used for lines is the distance protection with pilot schemes; differential and overcurrent protection are also used in specific cases.

For ensuring a correct operation of the protective system, maximum and minimum currents and voltages are required to recognize other abnormalities as open lines. One line and two lines open are presented by an unbalanced current flow and hence, should be considered as faults. Three lines open is considered as line being open and requires no special protective system except recloser.

I.4. Power System Protection Devices

I.4.a. Fuses

A fuse is an overcurrent protective device with a circuit-opening fusible part that is heated and severed by the passage of overcurrent through it [3]. It means that if a fault occurs, or if the loads generate excessive currents, the fuse “blows” and an open circuit is created allowing the disconnection of the faulted circuit. There exist different types of fuses used in protection systems. The main two categories are: low voltage fuses and high voltage fuses.

For circuits operating at 600 volts and above, fuses are called "power fuses," although the standards make a distinction between a "distribution cutout" and a "power fuse" [2]. Actually, distribution cutouts are fuses being used in primarily in distribution feeders and circuits while power fuses are adapted to stations and substations.

I.4.b. Instrument Transformers

In a power system network, current and voltage ratings vary largely, from transmission to distribution system. It is not reasonable from size and cost point of view to design and install monitoring relays appropriate to the ratings of each part of the system. Therefore, Instrument transformers are used; they continuously step down high line currents and voltages to values safe and suitable to actuate their associated protective relays.

These transformers provide insulation against the high voltage of the power circuit, and also supply the relays with quantities proportional to those of the power circuit, but sufficiently reduced in magnitude so that the relays can be made relatively small and inexpensive [4]. Instrument transformers are: voltage and current transformers.

Current Transformers

The primary winding of a current transformer (CT) is connected in series with the circuit carrying the line current to be measured; and the secondary winding is connected to protective devices, instruments, meters, or control devices. A standard connection is shown in figure I.3. The secondary winding supplies a current in direct proportion and at a fixed relationship to the primary current [5]. Standardly the current at the secondary side of the transformer is either 1A or 5A. There exist different types of Current transformers, the four common ones are: Wound CT, Bar CT, Window CT and Bushing CT.

Voltage Transformers

In general, two types of voltage transformers are used in protective circuits; the Electromagnetic type (VT) which is adopted in circuits up to 110/132 KV, and the Capacitor type (CVT) for higher voltages.

The secondary voltage of a VT is accurate, whenever the primary voltage is kept around more or less than 10% of the rated voltage. As shown in figure I.3, voltage transformers are always connected in parallel with the line. The transformer must be connected phase to phase or phase to Neutral and the secondary is connected to the relay.

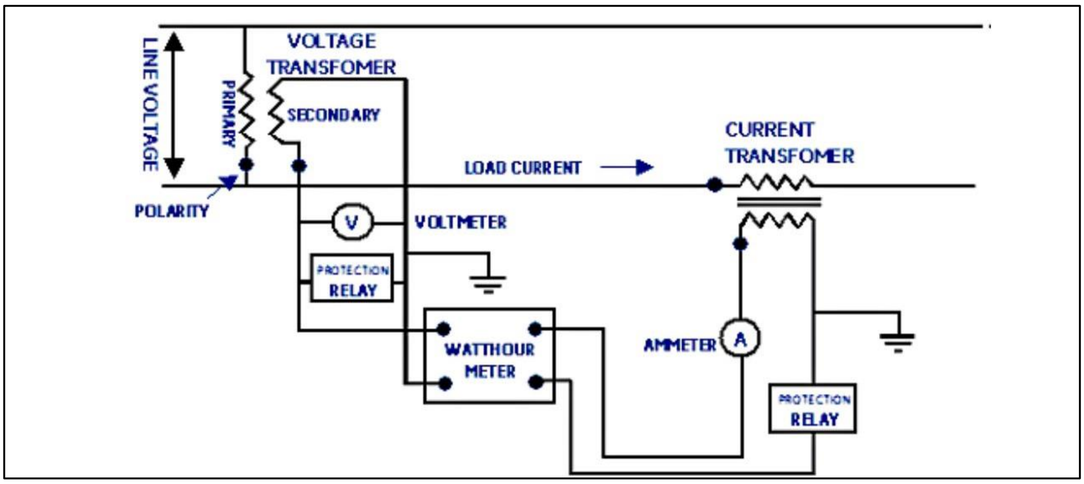


Figure I.3: Common connection of instrument transformers *[6]*.

I.4.c. Circuit Breakers

As defined a circuit breaker is a mechanical switching device, capable of making, carrying, breaking currents under normal circuit conditions and also, making and carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit [3]. This device is classified according to the medium in which breaker opens and closes; the most used are oil, air, vacuum and SF6 circuit breakers. They can also be classified as single or double break circuit breakers, where single break means that only the busbar end is isolated and with the double break, both the busbar and the line can be isolated.

I.4.d. Breaker Failure

The breaker failure protection function can be illustrated as in figure I.4. A breaker failure is a protection function installed in stations as an auxiliary protection in case of principle protection failure or circuit breaker operation failure. As the main protection generates a trip command, the circuit breaker opens and after few milliseconds the fault current drops below the pre-defined normal level. At the same time of sending trip command, the Breaker failure starts down counting; if the CT still measures the same faulted current, then a trip command from BF must be generated for all backup circuit breakers to clear the fault. In other terms, breaker failure protection is a high-speed protection scheme that will trip surrounding breakers in the event that a circuit breaker fails to clear a fault [7].

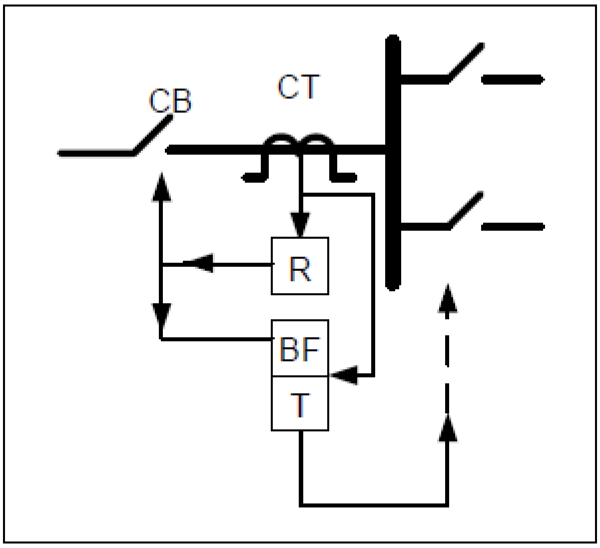


Figure I.4: Breaker failure function principle [14].

I.4.e. Batteries

The direct current (DC) supplies or batteries are used in power plants and substations as auxiliary power supplies. DC power is used to feed essential services such as circuit breaker trip coils and associated relays, and communication equipment. This stored power is not used all time but when the direct supply is interrupted. At normal conditions, equipment to be supplied by DC voltage are directly connected to the line voltage through AC-DC converters and filters. When faults or blackout occur, circuit breakers open the lines and no more electricity flow through them, for that, auxiliary power supplies are used. These batteries discharge at operation and are, then, charged from power system when faults are cleared.

I.4.f. Relays

Quantities such as voltages and currents are measured by CTs and VTs and introduced to protective system which compares them, or some combinations of these quantities, to threshold settings. These settings are computed by engineers. Upon comparison conditions, if a fault is detected, a tripping decision signal will be sent to concerned elements which are usually circuit breakers ordered to open. This operation is characterized by a time called clearing time. This duration is defined as the sum of comparison, decision, and action time of the protection system including the circuit breaker operation time. All these details are logic functions constructed inside protective relays. Relays are the principle elements in protection systems and will be well discussed in the next section.

I.4.g. Automatic circuit reclosers

A type of circuit interrupters with self-contained controls to sense overcurrent, reclosers are used in distribution systems where currents are limited. They open the circuit on faults instantaneously or with a time delay. They can be programed to initiate automatic reenergization of the circuit at variable intervals if the fault persists, and eventually to lock out. They use either oil or vacuum interrupting medium for both arc interruption and basic insulation. Reclosers are designed with both hydraulic and electronic controls.

Hydraulically controlled reclosers sense overcurrent by means of a series trip coil, connected in series with the line. Electronically controlled reclosers are more flexible and accurate than hydraulically controlled ones but are also more expensive. The electronic control can be easily adjusted to change the time-current tripping characteristic, minimum trip setting, and the closing sequence of the recloser [2].

I.4.h. Automatic line sectionalizers

Simply called sectionalizers, automatic line sectionalizers are circuit-isolating mechanisms that do not interrupt faulted currents. They open the main electrical circuit while their source power is disconnected. The circuit opening action takes place after sensing a predetermined number of successive main-circuit impulses of a predetermined magnitude as they may be manually operated. Sectionalizers work in junction with reclosers and circuit breakers. Often installed on poles on overhead distribution circuits, they provide a convenient protection to branch lines.

I.5. Protective relays

These relays underwent, through more than a century, important changes in their functionalities and technologies. Each change brings with it odds and improvement in both technical and financial aspects [8]. Relay technology has changed, from the electromagnetic relay, static relay, to digital and numerical relays, improving considerably their reliability and availability.

I.5.a. Historical Review

Electromagnetic Relays: These are the first generation of relays in the power system protection, they are constructed with electrical, magnetic and mechanical elements. They were developed in early 1900s. An Electromechanical relay operates principally by action of an electromagnetic element that is energized by the input quantity [3]. In other words, Current flows through one or more windings on a magnetic core, energizing an electromagnetic element in the relay, therefore inducing a relay contact.

Static Relays: The term 'static' implies that the relay has no moving parts. This is not strictly the case for a static relay, as the output contacts are still generally attracted armature relays. In a protection relay, the term 'static' refers to the absence of moving parts to create the relay characteristic. Their design is based on the use of analogue electronic devices instead of coils and magnets to create the relay characteristic. Early versions used discrete devices such as transistors and diodes with resistors, capacitors and inductors. However, advances in electronics enabled the use of linear and digital integrated circuits in later versions for signal processing and implementation of logic functions [9].

Digital Relays: This generation of relays is introduced in the early 1980s. They suppressed almost all the problems previous relays were facing. A microprocessor is the unit implementing the protection, it processes the measured data that have to pass through an analog to digital converter first.

Numerical relays: They are the result of the development of digital relays. They possess more memory and processing capacity then digital relays. Figure I.5 shows a typical numerical relay architecture. They are characterized by one or multiple microprocessors dedicated to digital signal processing, a Human Machine Interface(HMI), input/output ports, memory blocks, and a data bus to ensure communication between the different parts and the power supply. It is a real time operating system; the key point in its function is the conversion of analog input data (current and voltage for example) to digital values that are stored in internal memory. The relay is continuously getting new values to replace the previous ones through short defined periods of time. This process permits to closely follow the state of the protected circuit, and to detect faults whenever occurred.

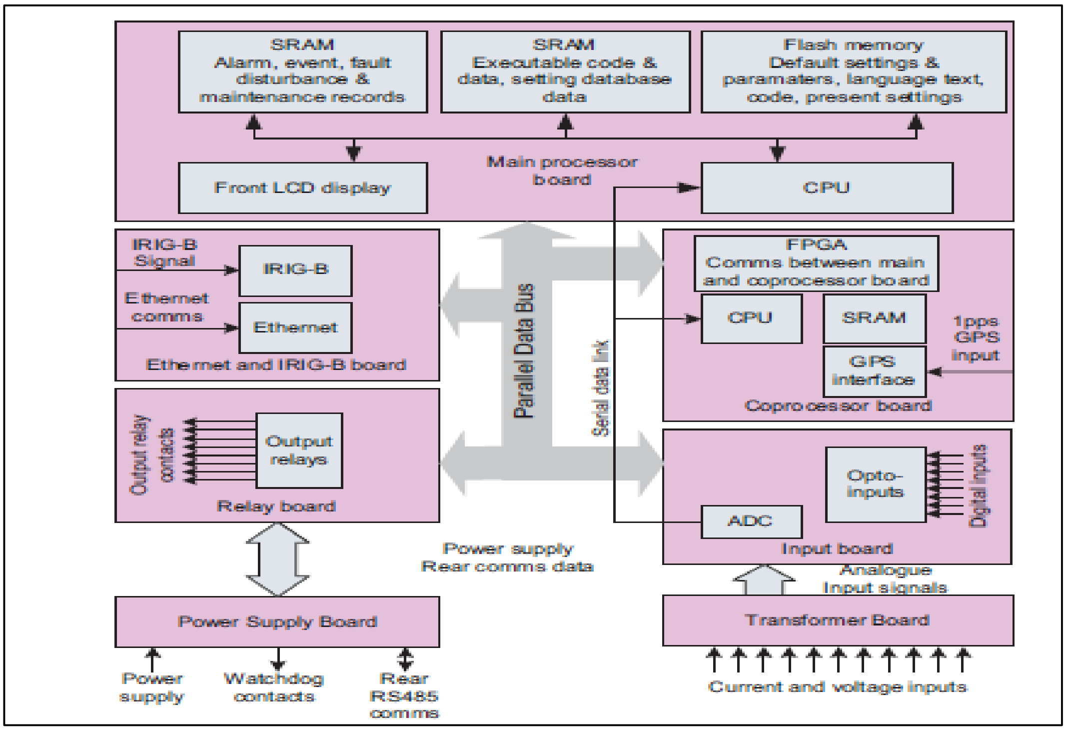


Figure I.5: Typical Digital Relay Hardware Architecture [10].

I.5.b. Protection types

Relaying signals that are supervised to detect abnormalities in any part of the power system can be changes in voltages and currents, the frequency, the phase shift angle, the direction of the power flow, or even the difference between the current interring to and coming out of any equipment.

Protective relays are of different types, each assigned to specific equipment and fault and operates when its input values are inside the range of operation. Being designed to provide a protection for individuals and equipment, relays may be of different types:

- **Overcurrent relay:** one type of non-directional relays that operates when the measured current exceeds a predetermined pick up value. Its operations may be instantaneous or inverse time where the higher the current is, the smaller the operating time will be. Different characteristic curve may be used according to the application requirements; as for inrush currents, the curve chosen is the one with higher operating time to prevent unnecessary tripping. There are three main factors affecting the fault current which are the fault location, the fault resistance and the sources supplying the fault.

- **Differential relay:** usually called unit protection, its operation is based on the difference between incoming and outgoing electrical quantities of the protected unit. The concept of comparison in this protection can be understood referring to figure I.6.This protection drawback is that it requires measurements from both sides of the protected element which makes its application restricted to power apparatus such as generators, motors and transformers. It is also applied for transmission lines especially underground cables where sensitive protection is required.

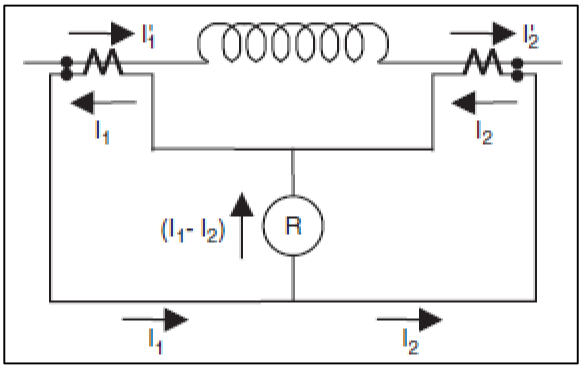


Figure I.6: Differential protection principle of operation [11].

- **Directional relay:** one type of relays used as overcurrent protection for multiple source circuits, when it is essential to limit relay tripping for faults in only one direction. It would be impossible to obtain correct relay selectivity through the use of a nondirectional overcurrent relay in such cases. If the same magnitude of the fault current could flow in either direction at the relay location, coordination with the relays in front of, or behind, the nondirectional relay cannot be achieved except in very unusual system configurations. Therefore, overcurrent relaying is made directional to provide relay coordination between all of the relays that can detect a given fault. Directional relays require two inputs, the operating current and a reference, or polarizing quantity (either voltage or current) that does not change with fault location [11].
- **Distance relay:** Distance function has been in use for many years and progressed from the original electromechanical types through analog types and now up to digital types of functions. This relay is designed to respond to current, voltage and the phase between them to compute the impedance of the fault and then determine its location along the protected line.

Based on these main operating functions, different relays are produced by different manufactories to protect power system equipment. The language used to communicate between the IED (intelligent electronic devices) is an international standard communication protocol named IEC61850 which stands for the International Electrotechnical Commission and protective relays are assigned ANSI codes (American National Standards Institute) some of which summarized in table I.1.

Table I.1: ANSI code of protective functions.

ANSI Code	Protective Relay Function	ANSI Code	Protective Relay Function
21	Distance relay	51N	Definite time earth fault overcurrent relay
26	Overtemperature relay	59	Overvoltage relay
27	Undervoltage relay	64	Earth fault relay
32	Directional overpower relay	67	Directional overcurrent relay
37	Underpower relay	67N	Directional earth fault relay
37	Undercurrent relay	79	Autoreclose relay
49	Thermal relay	81U	Under frequency relay
50	Instantaneous overcurrent relay	81O	Over frequency relay
51	Inverse time overcurrent relay	87	Differential relay
51G	Inverse time earth fault overcurrent relay	52	Circuit breaker

I.6. Conclusion

Power system requires well designed protection systems for each of its constructing element. In this chapter, the basic requirements of the protection systems were considered starting from protective system devices used and ending by the relays. To summarize, any system designed for protection purpose must obey to specific criteria that are reliability, selectivity, speed, sensitivity, simplicity and economics. Reliability is that the system trips when required (dependability) and block the protection when not required(security). Selectivity represents the elimination of the fault at the shortest time after detecting the fault (speed) with minimum disconnected elements and sensitivity is the system ability to detect even smallest faults. These requirements are considered in designing and configuration of the IEDs as seen in the protective relay section.

Chapter 2

Protection of Transmission Lines

II.1. Introduction

Transmission Line Protection is an extremely important part of the power system. Protective devices and methods used should meet different standards and requirements to provide a suitable primary and backup protection and therefore ensure the correct operation of this part of the power system. Actually, most high voltage transmission lines are interconnected in a complex network, this means that if a fault occurs on a certain line, currents may flow to the fault from both ends. Because of this, different types of relays with high selectivity and with good performance features are used nowadays in TL protection.

In this chapter, a brief review concerning transmission lines characteristics is given, then a section is reserved to the study of their associated faults. Next, a description of the different protections dedicated to TLs is presented; the first relay type to be discussed will be the overcurrent relay, the second one is distance relay, then pilot schemes are explored, and finally differential principle for line protection is explained

II.2. Transmission Lines

A Transmission Line (TL) has four parameters which affect its ability to fulfill its function. These parameters are: resistance, inductance, capacitance and conductance. The resistance and the inductance constitute the series impedance. The capacitance and the conductance constitute the TL's shunt elements. The shunt conductance is due to the leakage current flowing through line insulators. Since the current leakage is negligible compared to the line current, this conductance of overhead line is assumed to be zero [12]. Generally, even if real lines are not ideal, transmission lines are considered to have constant electric parameters per unit length. So, when studying the behavior of a TL of length "l"; the resistance, reactance per unit length of this line have to be multiplied by its total length.

For the sake of accurate modeling, transmission lines are classified into three types; short lines which have a length less than about 80km, medium lines, that are from 80km to 250km, and long lines that are 250km long or more. According to J.L. Blackburn and T.J. Domin, engineers in power engineering, there is another way to classify them, which is more appropriate in protection point of view. Two types are distinguished:

Radial Lines (feeders)

This type of line possesses only one source at one of its terminals. So, when a fault occurs on the line, it is only fed from the source end. But if a ground fault happens on a line that is grounded from both ends, then current will be flowing to the fault from both ends even though opening the line from the source end is sufficient to deenergize the fault.

Loop (Network)

A Transmission line is considered to be a Loop TL if it has two or more sources at its ends.

In general, these are all types of transmission lines and can include distribution circuits. Fault current to the line faults is supplied from these source terminals, and all source terminals must be tripped for both phase and ground faults [13].

Protection Objectives for TLs

- Faults should be cleared as fast as possible.
- During a system fault condition, only those breakers required to isolate the fault should trip.
- Overhead TLs should be reenergized automatically, following the clearing of a fault.
- Protection should not restrict the line from being loaded to its maximum short-term emergency load rating, to which it is operated [13].

II.3. Transmission Line faults

The transmission line, as all parts of the power system, is subjected to electrical faults mostly caused by environmental conditions. As this part is constructed with cables, then faults occurring in it are results of opening or shorting the circuit. Different methods are used to study these abnormalities to determine the maximum fault current and power which occur when the largest number of generators are in service, which usually occurs at peak load.

The maximum fault current should be computed at every node in the transmission system. It is required in order to determine the maximum interrupting rating of circuit breakers or other fault-current-interrupting devices. Four types of faults can be considered; three phase (3PH), double line-to-ground (2LG), one-line-to-ground (ILG), and line-to-line (L-L). Usually, either the 3PH or ILG are the most severe and the L-L the least severe [2]. Per unit calculations are usually based to do analysis of transmission system faults; a value of power greater than the maximum fault power is arbitrary chosen.

II.3.a. Three-Phase (3PH) Faults

This is a symmetrical fault, therefore, there are no negative or zero sequence currents for this type of fault. This means that there is no current through the ground impedance and it makes no difference if ZG is zero or infinite. This fault is fairly rare with an occurrence of about 5% of all faults. The balanced nature of this short circuit makes the calculations simpler and the short circuit current is the same at all phases.

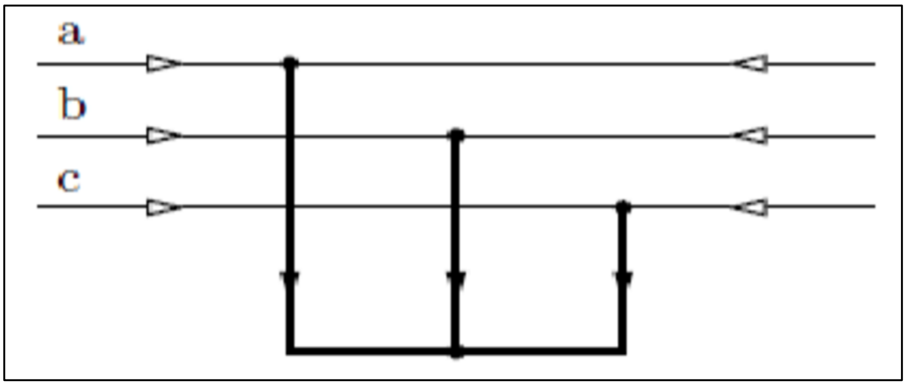


Figure II.1:Three phase fault [22].

The I_{sc} is expressed in Eq.1 where V_n is the phase to phase voltage, Z_{sc} is the impedance equivalent to all the impedances through which the fault current flows, from the source up to the presumed fault.

$$Isc = \frac{Vn}{\sqrt{3Zsc}} \quad (I.1)$$

II.3.b. Line-to-Line (L-L) Faults

This fault is an unbalanced fault that occurs with 15% of all faults. The faulted phase designation of the line-to-line fault is given in figure II.2. b. Usually, the positive and negative sequence impedances are taken to be equal impedances. No zero sequence current flows for the line-to-line fault since there is no path to ground.

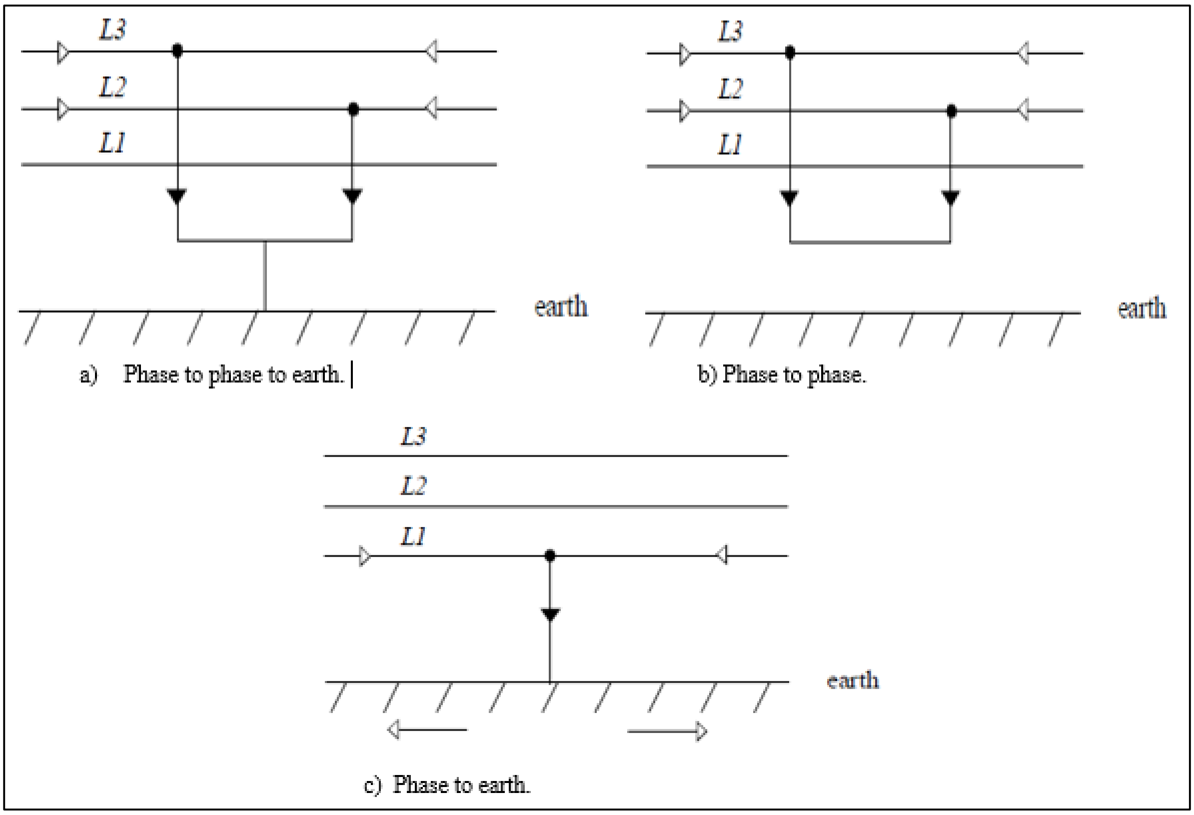


Figure II.2:Asymmetrical transmission line faults [9].

II.3.c. Double Line-to-Ground (2LG) Faults

It is an asymmetrical fault which makes its analysis quite complicated and done using symmetrical component method. The presence of ground in the phase domain makes obvious that the symmetrical component representation will include the positive, negative and zero sequence. The faulted phase designation and sequence network connection for the 2LG fault is shown in Figure II.3 where is noted that the sequence networks are connected in parallel.

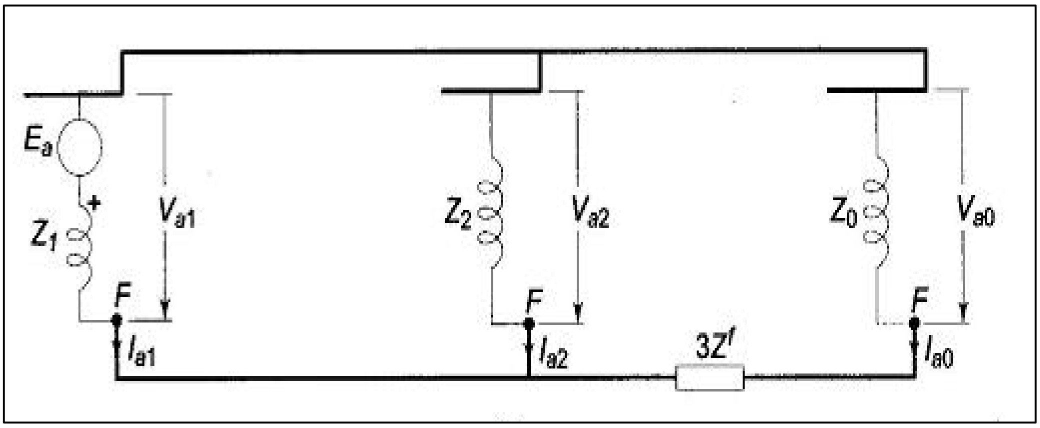


Figure II.3: Symmetrical component circuit for double line to ground fault [9].

II.3.d. One-Line-to-Ground (1LG) Faults

The 1LG fault is the most common fault in the network with an occurrence of 80% of all faults. The analysis of this fault is done using symmetrical components; if a fault is considered in phase a, then the symmetrical component equivalent circuit will be as in Figure II.4. Sequence currents for this type of fault flow in all the three sequence networks and are equal.

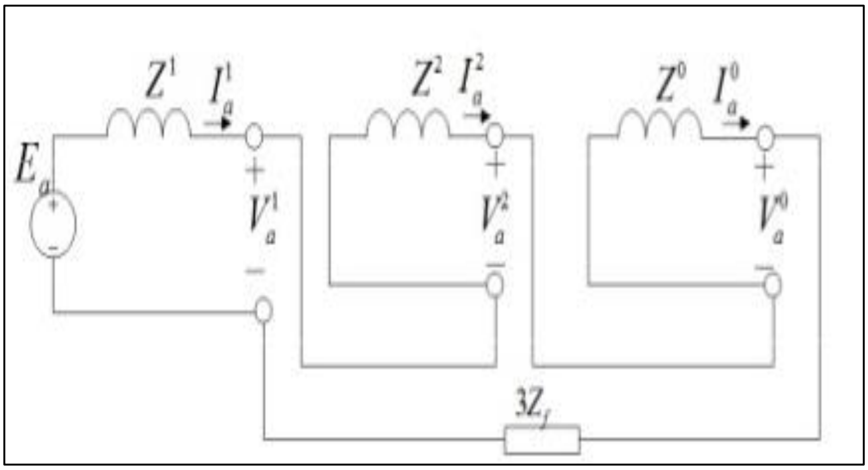


Figure II.4: Asymmetrical transmission line faults [9].

The equations derived from the circuit are:

$$I0 = I1 = I2 = \frac{1}{3}Ia \tag{I.2}$$

$$I1 = \frac{Ea}{Z0+Z1+Z2+3Zf} \tag{I.3}$$

II.4. Protection of Transmission Lines

II.4.a. Ground Fault Protection

An important aspect of transmission line protection is related to the fast detection and clearing of ground faults on transmission systems that have grounded neutrals. In the protection of transmission lines, ground faults are given special treatment. Ground faults are detected using different relays than those used for phase faults, although it is possible that phase relays may detect and properly clear ground faults. Ground relays, however, take advantage of unique features of the power system that make it possible to detect grounded conditions very quickly. These special aspects of ground fault relaying are considered in this section [2].

II.4.b. Overcurrent Protection

The Overcurrent protection is considered generally as an emergency protection as in Algeria. It has to ensure protection against short-circuits and detect overloads on the lines. Whenever the distance principal protection and the complementary protection face any sort of problem, as in the case of absence of voltage information, distance protection is unavailable and the overcurrent protection activates automatically.

Overcurrent Relay Types

-Instantaneous relay: This relay sends the CB a tripping signal instantaneously after the current surpasses the predefined current threshold. This relay is convenient when dealing with dangerous faults with high currents for major importance elements in the network.

-Delayed relay: This type is suitable for faults that are less dangerous; for this relay to send a tripping signal, the current threshold has to be exceeded for a defined period of time. Therefore, if a transient fault occurs, it will vanish before the time allowed to send a tripping signal passes.

-Inverse time delay relay: This type is not affected by transient faults, but can react rapidly for high current faults. Actually, the tripping signal is sent after a period of time inversely proportional to the value of the measured current.

Directional relay

It is a function that can be added to any one of the three types cited above. To detect the direction of the fault, the relay has to detect the sign of the active power, in other words the phase displacement between the voltage and current. That is why, the relay must also be fed with voltage in order to find the phase discrepancy,

Overcurrent Protection Schemes

In general, three schemes are used, overcurrent relays may be installed on each one of the phases as shown in figure II.5.a. This method permits to detect any fault present in phases. Earth fault relay, as given in figure II.5.b, can be used to detect some earth faults that cannot be detected if only previous scheme is used.

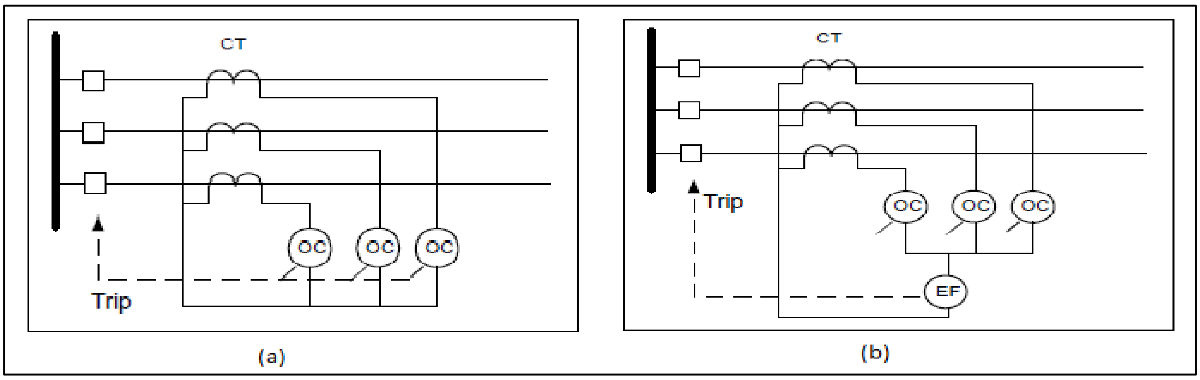


Figure II.5: (a) Use of three OC relays; (b) Use of EF relay with three OC relays *[14]*.

An economic and efficient method is to use an EF relay and only two OC relays for the phases as shown in the following figure.

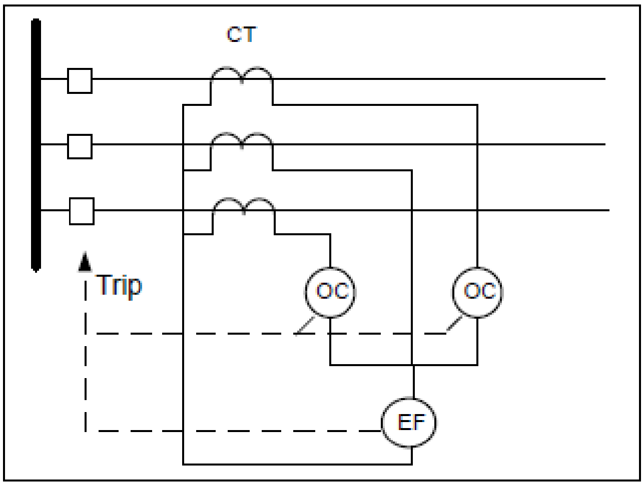


Figure II.6: Use of an EF relay and two relays on phases *[14]*.

II.4.c. Distance Protection

Distance protection is the main protection for overhead transmission lines as it can also play the role of backup protection for other network elements such as busbars and transformers. It is a short circuit protection whose principle relies on the evaluation of the impedance to the fault which permits the fault location definition. This protection is faster and more selective than overcurrent protection, and if a communication channel is used between the two-line ends, the distance protection will be similar to differential protection in selectivity point of view. The communication in distance protection requires narrow bandwidth channel, as only “tripping” or “no tripping” signals are sent.

Fundamentals of distance protection

Distance protection determines the fault impedance from the measured short circuit voltages and currents at the relay location (it calculates the ratio between the voltage and current). The measured fault impedance is then compared with the known line impedance. If the measured fault impedance is smaller than the set line impedance, an internal fault is detected and a trip command issued to the circuit breaker [15].

The distance protection, without teleprotection, is not a 100% selective protection, this is due to the inexactness of line parameters, instrument transformers errors and the measuring errors of the protection itself. That is why this protection is organized to work according to different zones; three or more forward zones and one or more backward protection zones. The zones are time graded.

Relay impedance

The distance relay receives the measured voltage and current of the transmission lines from the VT and CT and calculates an impedance that is the result of secondary values. The relay impedance values have to be converted using Eq.4. [15]

$$Z_{sec} = \frac{I_{prim}/I_{sec}}{V_{prim}/V_{sec}} * Z_{prim} \tag{I.4}$$

I_{prim}/I_{sec} CT transformation ratio ; V_{prim}/V_{sec} VT transformation ratio

Adjustment, setting of zones

To cover the line and provide a backup protection to other lines or parts of the system, there are three main zones as shown in figure II.7.

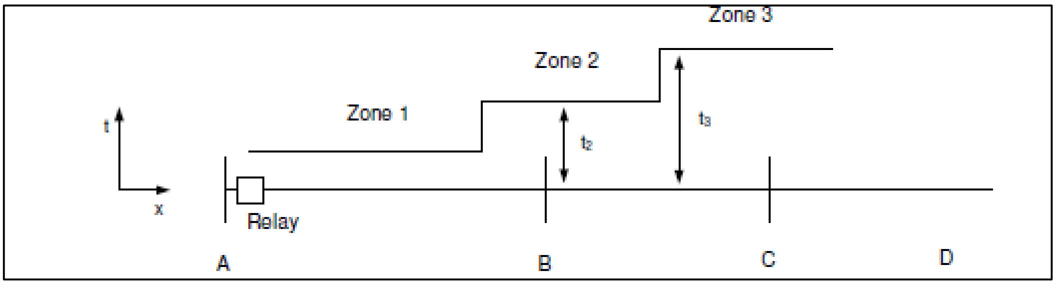


Figure II.7: Distance Relay Protection Zones [16].

- Zone 1: For an ordinary medium line the first zone can be set to reach 80% to 90% of the line length with no time delay, i.e. instantaneous trip.

- Zone 2: This zone has to cover all the line and a part of the following line. The classical setting is to put the zone 2 reach at 120% of the length of the line. But in the case of a long line followed by a short line, the reach is reduced, in other words 100% of the first line is taken with 20% of the second line. So the second zone is a protection for the dead zone of the line that cannot be protected with the first zone, and a backup protection for the following line.

  The second zone is time-delayed, if an electro-mechanical relay is used, the delay is between 0.4s to 0.5s and in the case of static or numerical relay the delay is from 0.25s to 0.3s. In Algeria, Sonelgaz uses 0.5s as delay for the electromechanical relays, and 0.3s for the others.

- Zone 3: This zone is made to protect the total of the first and second line with about 25% of the third line. It operates with time delay, in Algeria generally it is put to 3s.

  Other zones (zone 4, zone 5) can be set to work to detect fault in backward direction, they are also time delayed zones.

Impedance Diagram

Impedance diagram is an R-X plane (impedance plane) where the relay characteristic, measured load and short-circuit impedance are represented.

The operating characteristic of distance protection is defined by a fixed shape in the impedance diagram. The fault area is isolated from the load area, and the reach of the distance zones is determined [15]. The shapes of the protection zones have seen changes with the development of protection relays. Originally conventional relays had operating characteristic represented as a circle in the origin of the R-X plane (see figure II.8), these were non directional relays. The figure II.8 shows the Mho relay, the circumference of the circle, in this case, passes through the origin of the impedance diagram which makes it a directional relay. An ameliorated version of the mho relay is the combined characteristic, it is a combination of circles and straight lines. Static relays introduced the quadrilateral characteristic and this one is widely used in modern numerical relays. It offers to set independently the resistive and reactive reach.

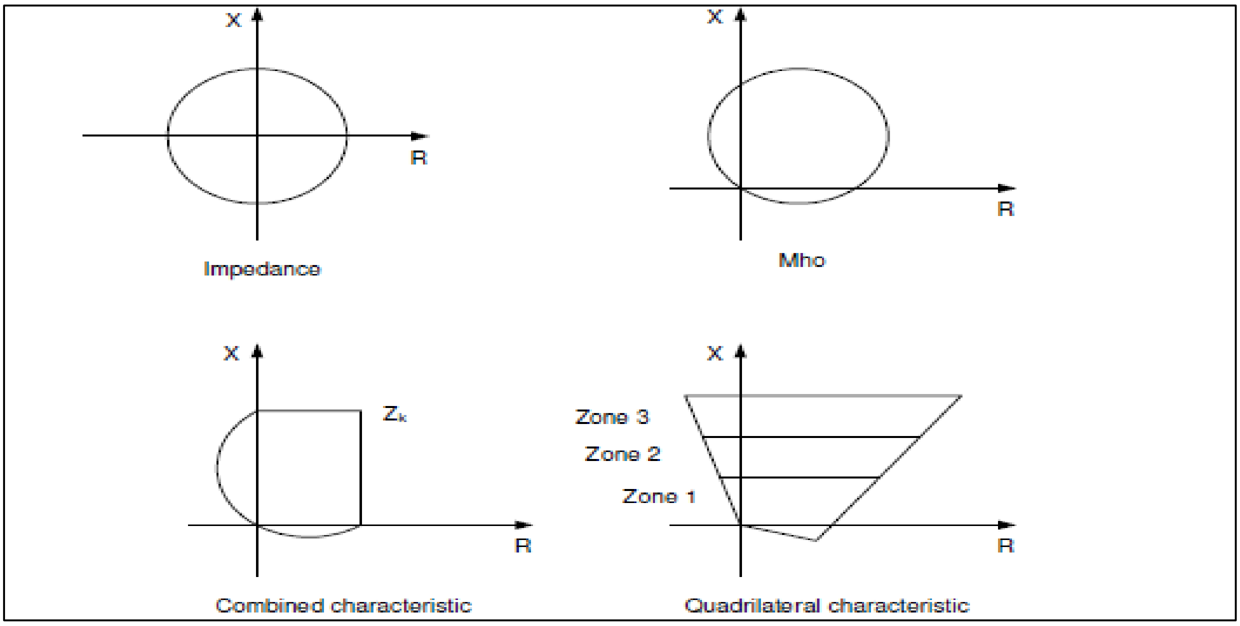


Figure II.8:Distance Relay characteristics *[14]*.

II.4.d. Pilot

Pilot protection is a form of line protection that uses a communication channel as a means of comparing electrical quantities at the terminals of the line [2]. Being an important and effective way for lines protection, it has the advantage to communicate with other devices providing a new dimension of information and permits more intelligent decision regarding location of the fault. For transmission lines, pilots are the most selective of all protections since correct tripping signal are sent based on combined observations at both sides of the protected line as shown in figure II.9. Pilot relaying is often named for the communication medium used in the application, including wire pilot, power line carrier pilot, microwave pilot and fiber optic pilot protection systems.

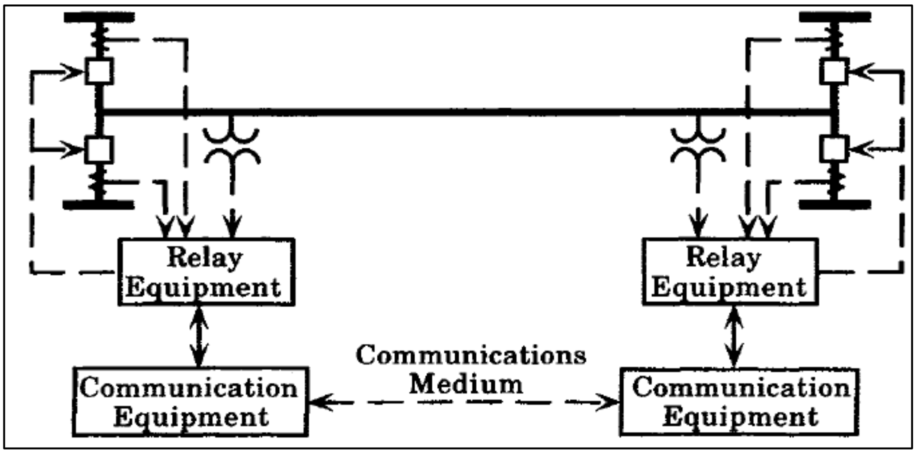


Figure II.9: General view of a pilot protection system [2].

Protective relays are equipped with tele-protection equipment including hardware and software that receives information from relay outputs and transmits it through telecommunication wires which represent the following communication medium:

- **Wire pilot:** Limited in use to short lines for the cost of their separate circuits installation, they are themselves a transmission line. Two types of wire pilot scheme are distinguished; the circulating current scheme and opposed voltage system. These wires must be protected from lightning and installed carefully. In general, the wire pilot is used when a pair of metallic communication wires less than 15km long is available for a two terminals line of less than 12km.

- **Power Line Carrier Pilot(PLC):** Signals from one relay to the other are transmitted over the power transmission line. It is used for permissive tripping, permitting both circuit breakers at both ends to trip when fault is on the line but closer to one side. PLC pilot is applicable for lines too long to use wire pilot, where data communication is not required and optical fiber is not available.

- **Microwave Pilot:** In this system, signals pass through the microwave modulator-demodulator to be transmitted at microwave frequencies to the other end of the line. A unique problem that faces microwave pilot is the transmission failure due to fading phenomenon caused by atmospheric conditions like water vapor. It is used for long lines protection where continuous monitoring and data and voice communication are required but PLC is inadequate.

- **Fiber Optic Pilot:** Based on high bandwidth, fiber optic(OF) is used for high speed data transmission. Relays are equipped with optical receiver and transmitter converting relay outputs to optical signals. It is used for short transmission lines; repeaters are installed every 50-100km. When there is no adequate carrier spectrum for PLC, using OF method is favorable.

Pilot protection may be classified into two categories: unit schemes and non-unit schemes. Unit schemes are similar in function to differential protection and treat the transmission line as a one protected unit where measurements are taken in both terminals and then compared to determine the tripping decision. Whereas non-unit schemes communicate only decisions or orders to trip or block the other CB without sharing measurements of both ends.

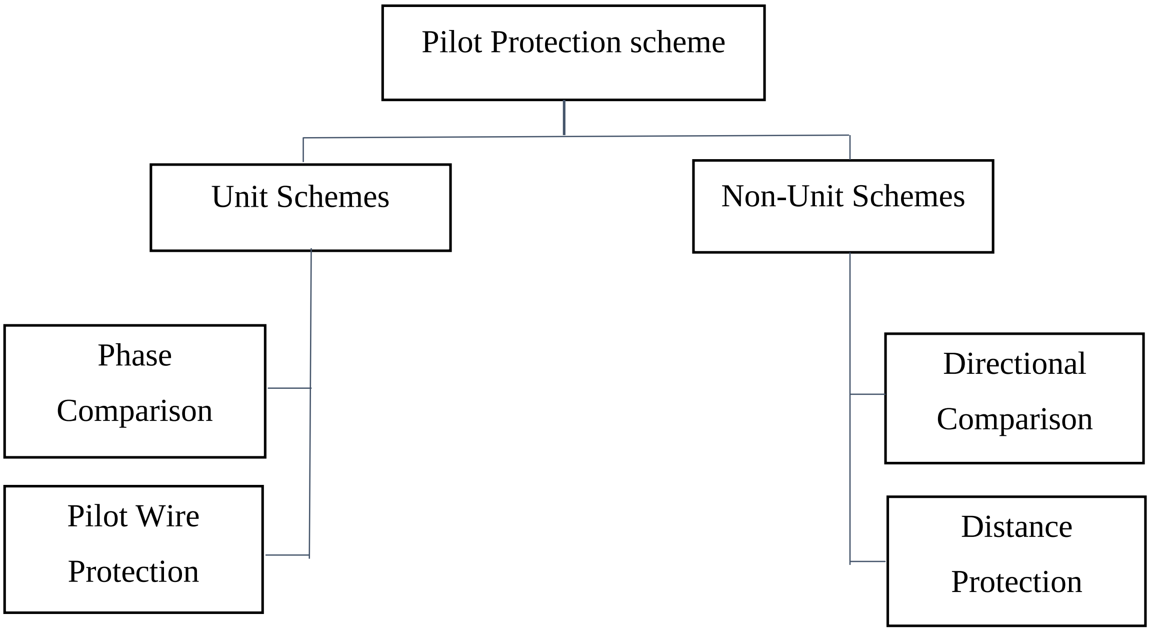


Figure II.10: Classification of pilot protection schemes.

Non-unit schemes

Non-unit schemes contain mainly two protection pilots for either transfer tripping or blocking signals. The transfer tripping signal is a function of the distance protection mostly used to minimize the fault clear time. The blocking signal is a function designed to prevent the remote relay from tripping when faults are outside the line protected.

Directional comparison schemes are based on detecting the direction of the fault. When a line is fed from both sides, at fault condition currents will flow from both sides toward the fault, then zero and negative sequence directional relays can be used by considering current quantities or even voltages.

Distance schemes are widely used and employed with distance relays to improve their performance with a better selective and secure application for faster fault clearing. Transfer trip pilot protection is designed for this purpose and also to provide the benefits of back-up protection. It can be direct, sending signal to the remote relay to trip without time delay, permissive, with logic based on line conditions to detect faults, or redundant systems requiring two received signals for more protection security.

Transfer trip schemes employ one transmitter and one receiver at each relay location; any failure in the communication system will cause lower speed tripping of faults. Its pilots are:

- **Direct Underreaching Transfer Pilot:** also called non-permissive underreaching transfer scheme. Its basic concept is that any detection of fault in zone 1 is followed by sending a trip signal to the CB and to the relay at the other end.

- **Permissive Underreaching Transfer Trip (PUTT):** it is based on AND gate whose inputs are a fault in the protected line seen in extended zone 1 which is practically zone 2 and a PUTT signal received from remote relay which sees the fault at zone 1.

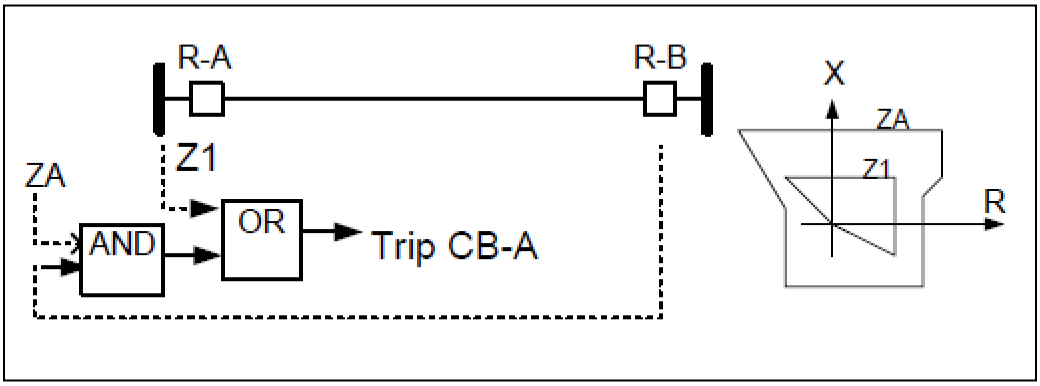


Figure II.11: Permissive Underreaching Transfer Trip *[14]*.

- **Permissive Overreaching Transfer Trip(POTT):** Mostly used for short lines, in case of high impedance faults where both relays see a forward fault and trip on zone 3. This pilot requires that relays at both ends see a forward fault in zone 1 or zone 2 and receive a signal from the front relay. If one side relay sends a signal to the other end relay, this one will trip only if it sees a fault at zone 1 or 2.

Blocking pilot operation principal is the inverse of transfer trip. A signal is send from one end relay to the remote relay to prevent tripping by opening its trip circuit when a fault is in the backward direction. Three main schemes are distinguished:

- **Direct Blocking Scheme:** This pilot uses both forward and backward or reverse looking directions. When the relay detects a fault at the reverse direction which is zone 3 or zone 4 for most relays, it sends a direct blocking signal for the relay at the remote line to block its function at zone 2 or any other zone covering more than 100% of the protected line.
- **Directional Comparison Blocking Scheme(DCB):** is flexible, reliable and simple in communication. Tripping here requires no signal, so faults are correctly eliminated with distance protection. It is designed to overcome overreaching errors since the opposite relay will send a DCB signal when it sees that the fault is backward.
- **Directional Comparison Unblocking:** this scheme keeps sending blocking signal, except when an internal fault occurs. The communication usually employs a frequency shift PLC signal, where a blocking frequency is transmitted continuously during normal conditions. On detection of an internal fault, the signal frequency is shifted to the

unblock (or trip) frequency. In some cases, the transmitted power is increased, say from 1 to 10 watts, during the unblocking signal period [2].

Unit schemes

Unit protection schemes is less used compared to non-unit schemes, it makes trip decision by comparing measured quantities at both terminals. It mainly contains phase comparison scheme and pilot wire protection. Phase comparison scheme itself has four types which are single-phase-comparison blocking, dual-phase-comparison blocking, dual-phase-comparison transfer trip and segregated phase comparison. The pilot wire protection, referred to as longitudinal protection, is applicable for line of about 20 km or less.

II.4.e. Differential Protection

For this protection, current of the two ends are used by the relay to determine the requirement for tripping. It measures the difference between the currents at two different points of measurement. A typical connection is shown in Figure II.12. Since there is no fault on the protected element, the current entering that element is exactly the same as the current leaving and the difference current, which flows through the relay, is zero [2].

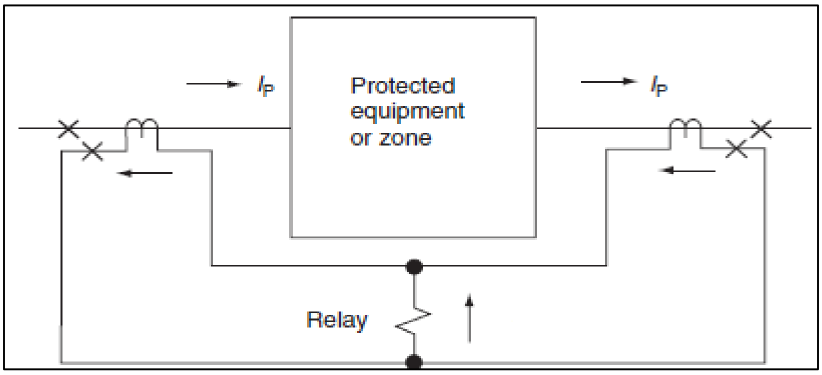


Figure II.12: Basic current differential scheme (normal situation) [13].

The relay, therefore, is a *current differential* device. The principle of the current differential relay is based on Kirchhoff's current law, which states that the sum of currents entering a point must be zero. For the device pictured in Figure II.12, the currents entering at the two terminals must be zero unless there is an internal fault, in which case a net current must flow to the fault point, as shown in Figure II.13. This type of fault is readily detected by the differential relay if there are no CT errors. Practical current transformers are subject to various errors, even if they are of the same type and rating. The errors may be due to manufacturing differences, differences in pre-fault loading, and differences in saturation, for example. These differences may require that the relay threshold be set higher than zero, and this reduces the relay sensitivity. The solution to this problem is to design the relay with two types of windings, called the *operating* and *restraining* windings. Currents in the operating winding tend to cause tripping, whereas those in the restraint windings prevent tripping. This is often done in a magnetic circuit, for example, such that the ampere-turns of the operate and restraint windings are arranged to oppose each other. Relays of this type are called *percentage differential relays* [2].

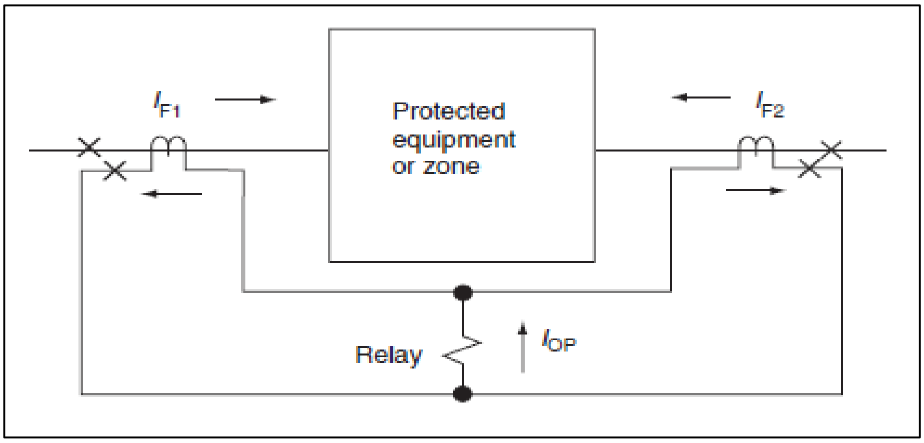


Figure II.13: Basic current differential scheme (in case of fault) [10]

II.5. Conclusion

Transmission lines protection is one of the most important protection systems. This chapter treated the faults that may occur on TLs and the protections provided. Overcurrent was noticed to be inadequate, so directional OC and distance protections were designed for a more reliable system. Many different distance relay characteristics are available upon the relay manufacturer. Pilot protection provides fast and secure protection. Differential protection treats the transmission line as a unit and is the most expensive.

Chapter 3

Testing SIEMENS SIPROTEC 4 Relays

III.1. Introduction

Protective relays are subjected to failure since they are made by different complex integrated electronic circuits. Reliability of the power system is required, so, the periodic maintenance and testing of all components composing the protective system is mandatory. Testing has different methods, for numerical relays of different manufacturers, Omicron presents a product that has various testing functions called Omicron injection test set.

This chapter will be all about tests performed on four SIPROTEC (Siemens Protection Technology) protections used for transmission lines. These are distance with its auxiliary functions, differential with a distance auxiliary protection, overcurrent and breaker failure as backup protections. An example of a normal transmission line of 60kV with a length of 120km will be considered. The resistance and the reactance of the lines will be real values from the Algerian network given by GRTE enterprise and the settings of the relays were based on their setting and configuration philosophy.

According to these, the resistance over line is given by 0.11Ω/km and the reactance is 0.42Ω/km which results in a line impedance of 13.2+i50.4Ω. The transformers values used are 600:1 for the CT and 60k:100 for the VT. Values used to test the protections are secondary values. Figure III.1 shows, in single line representation, the transmission line considered.

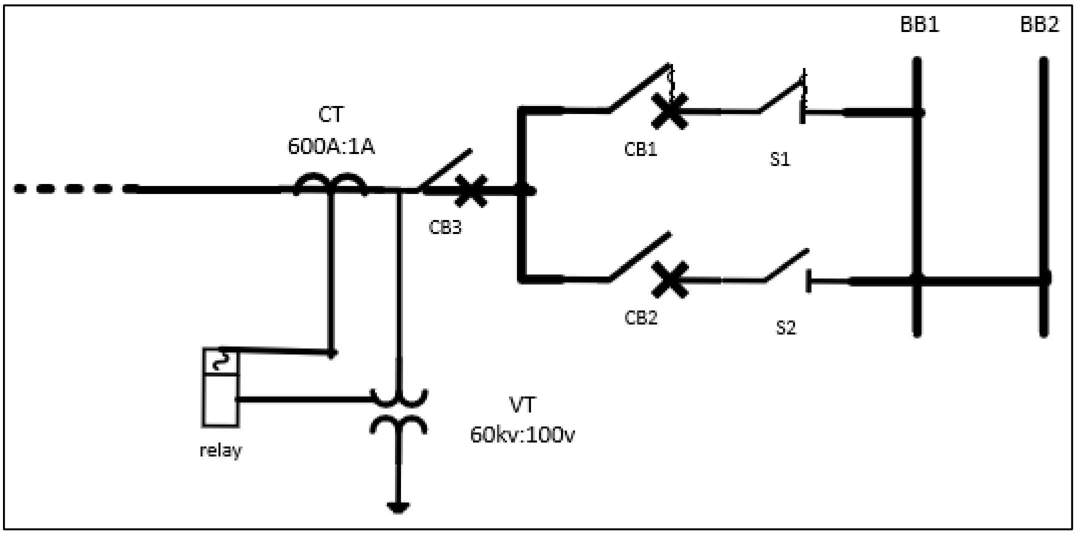


Figure III.1: Single line representation of 60kV TL.

III.2. Equipment

Four SIPROTEC 4 devices have been used; the 7SA612, the 7SJ80, the 7VK611, and the 7SD. These are tested using the OMICRON CMC 256-6 Test Set.

SIPROTEC 4 7SJ80: It is a relay that can be used with both line and feeder protection and also as a backup protection for transformers. The main functions of this relay are: instantaneous and definite time-overcurrent (OC) protection, directional OC protection, ground fault protection, breaker failure protection, undervoltage and overvoltage protection, synchronism check, undercurrent monitoring, rate of frequency change protection, auto reclosure and thermal overload protection.

SIPROTEC 4 7VK611: It is a breaker management relay suitable for networks of all levels of voltages, used to initiate and control the closing of a CB. This device possesses five main functions, which are: automatic reclosure function, synchronism and voltage check, circuit breaker failure protection, voltage protection and overcurrent protection.

SIPROTEC 4 7SA612: the distance protection relay 7SA612 is suitable for overhead lines and cables with voltages from 5 to 765kV. The main function of the 7SA6 relay is distance protection but it also englobes power swing protection, pilot protection, fault locator, auto reclosure, breaker failure Protection, thermal overload protection, overcurrent protection, quick tripping, over/underload protection, and over/underfrequency protection

SIPROTEC 4 7SD87: Generally speaking, two basic functions are available in the 7SD5 line protection relay, namely differential and distance protection. One of the protection functions can be configured at a time as the main protection function (Main1). As an alternative, differential protection can be selected as the main protection function, and distance protection as backup protection (Main2) [17].

OMICRON 256-6 In this work the CMC 256-6 test set has been used to test the four SIPROTEC 4 Relays cited above. PC controlling of the procedures is done using Test Universe 3.0 Software. CMC 256-6 test set is both a high precision calibrator and a universal testing unit for protection devices. It is used by relay manufacturers in the development of relays, in other types of relay testing.

OMICRON´s PC-controlled test sets generate the test signals digitally, resulting in highly accurate testing signals even at small amplitudes. Independent channels with low-level signals are available at the back of the test sets, which can be used to control external amplifiers for applications requiring more signal channels or higher currents, voltages or power [18].

III.3. Software

In accomplishing the testing of the SIPROTEC relays, the software for their configurations and settings used is the DIGSI 4.87; and for the Omicron injection test set, options of the Test Universe 3.20 software were used to set the faults currents, voltages and impedances values.

- DIGSI 4.87

DIGSI is a software designed by Siemens to configure their numerical protective relays. It is mainly divided into two function, the first is to set the relay and the second is to read information from the relay when abnormal signals are received. It has also the options of changing logics of the relay or even adding new ones and activate them. the information read are expressed in different curve forms and tables as this software can generate a general rapport containing all the details of the protection concerned.

- Test Universe 3.20

This software is designed by Omicron to support the test set with different options based to test protective and measurement devices in power systems. It is the most powerful and convenient for its detailed various packages consisting on precise settings of faults and measurements.

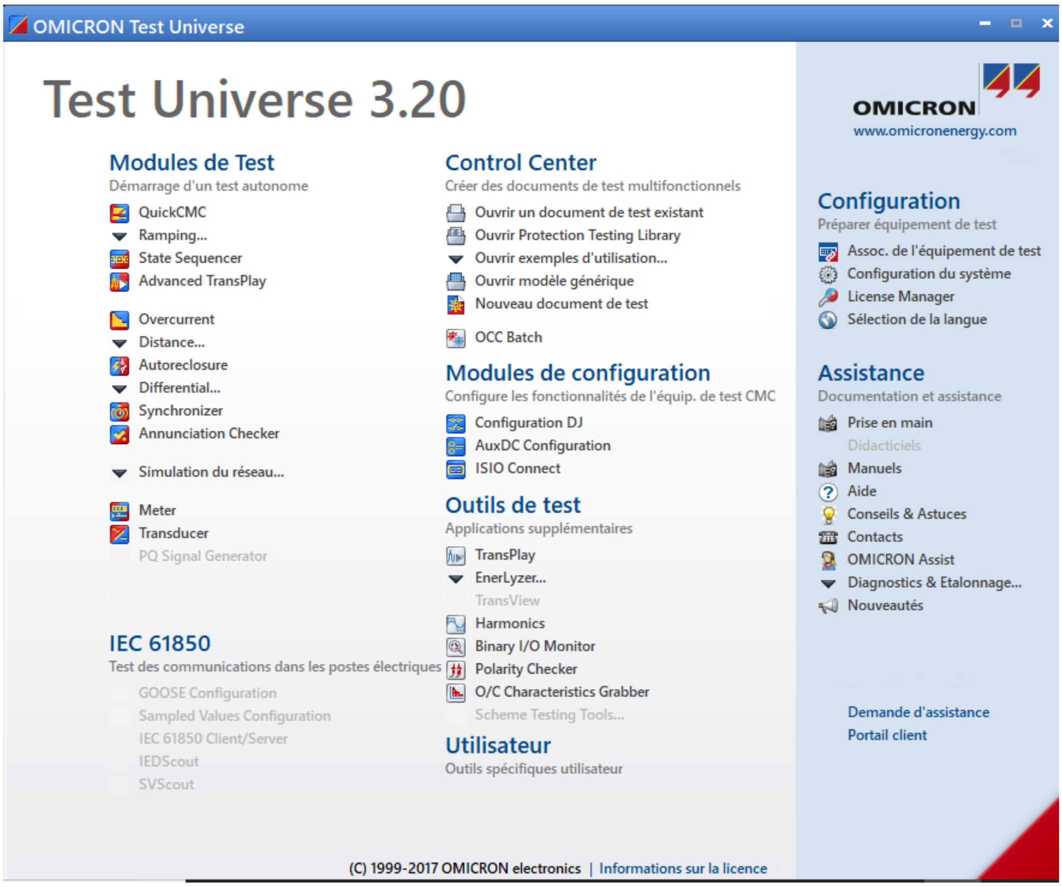


Figure III.2: Test Universe 3.20 software front page.

III.4. Transmission Line Distance Test 7SA612

For a distance protection operation, all voltages and currents of the three lines and the neutral are required. The 7SA was fed from Omicron 256 by these analog inputs, and the binary output coming from the protection to trip is inserted as a binary input in the test set to stop the injection in fault cases.

The settings of the distance protection were inserted via DIGSI and they consist of:

- Zone 1 at 80% (forward) of the line with instantaneous trip,
- Zone 2 at 120% (forward) of the line with 500ms time delay to trip,
- Zone 1 extended at 120% of the line with instantaneous trip (PUTT),
- Zone 3 at 140% (forward) of the line with 1.5s time delay to trip, and
- Zone 4 at 40% (backward) of the line with 3s time delay to trip.

The function Advanced Distance from Test Universe were used, rio.file from DIGSI were imported to draw the quadrilateral impedance characteristic curves there and then tests were done on different zones; figure III.3 is one of the tests performed.

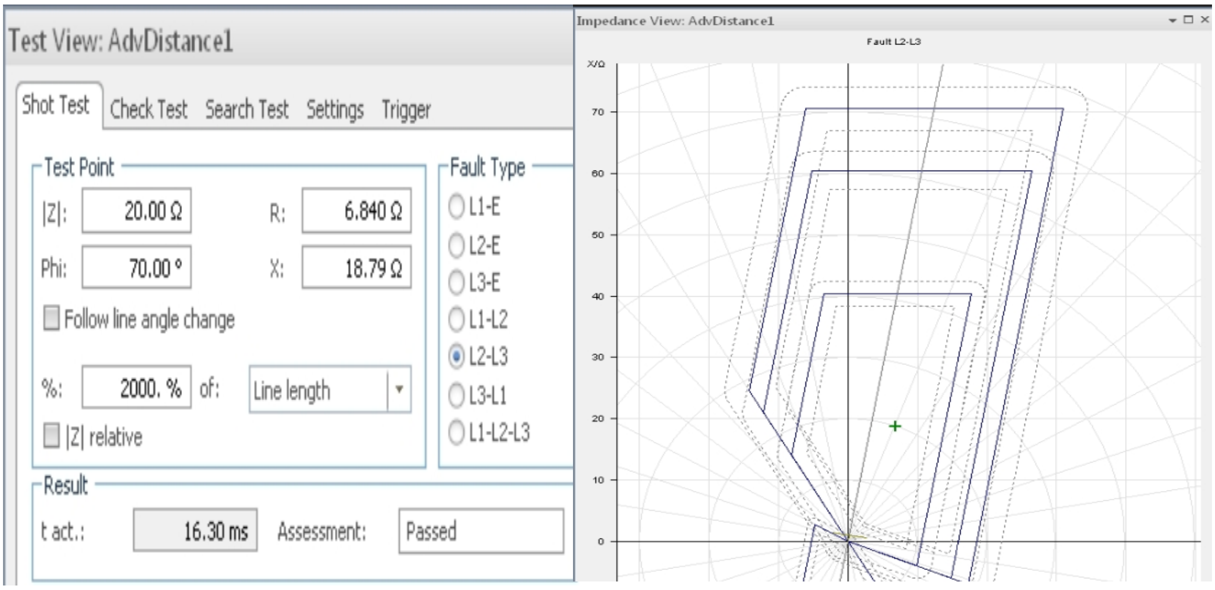


Figure III.3: Test zone 1 phase to phase fault.

For this test, the impedance chosen was about 38.3% of the line in zone 1 with a fault of phase-2 to phase-3 type, talking in kilometers, this is equivalent to 46km from the beginning of the line. Omicron received a tripping signal instantaneously, the 16.30ms are the time required to send and receive information from the relay. Figure III.4 represents the rapport recorded from the protection.

Courant de défaut primaire IL1	0.00 kA	4 ms
Courant de défaut primaire IL2	1.20 kA	4 ms
Courant de défaut primaire IL3	1.20 kA	4 ms
Boucle de mesure L2-L3	VENANT	59 ms
Résistance déf. calc. Ohm sec.	6.81 Ohm	59 ms
Réactance déf. calc. Ohm secondaire	18.86 Ohm	59 ms
Résistance déf. calc. Ohm primaire	6.81 Ohm	59 ms
Réactance déf. calc. Ohm primaire	18.86 Ohm	59 ms
Distance du défaut en km	44.9 km	59 ms
Distance du défaut en % de la ligne	37.4 %	59 ms
Déclenchement (général)	PARTANT	155 ms

Figure III.4:Report given by the 7SA protection.

Discussion

The protection recognized the phase-2 to phase-3 fault and recorded the phase fault currents. The injected impedance value is read with an error of 0.4%; this results in an error of 2% in the distance location of the fault but the tripping is instantaneous as expected.

The distance 7SA protection has a principal protection equipped with auxiliary functions, the following tests were done to verify their operation:

III.4.a. Permissive Underreach Transfer Trip PUTT

This function, as explained theoretically, is activated when a fault is detected in extended zone 1, represented by ZB1, and a binary input is received from the other side protection. To test it, the binary input configured to be active high is changed in the affectations to be active low, this way, the protection keeps receiving the signal all the time. Then, using Advanced distance, a ZB1 phase 2-ground fault is injected as illustrated in Figure III.5.

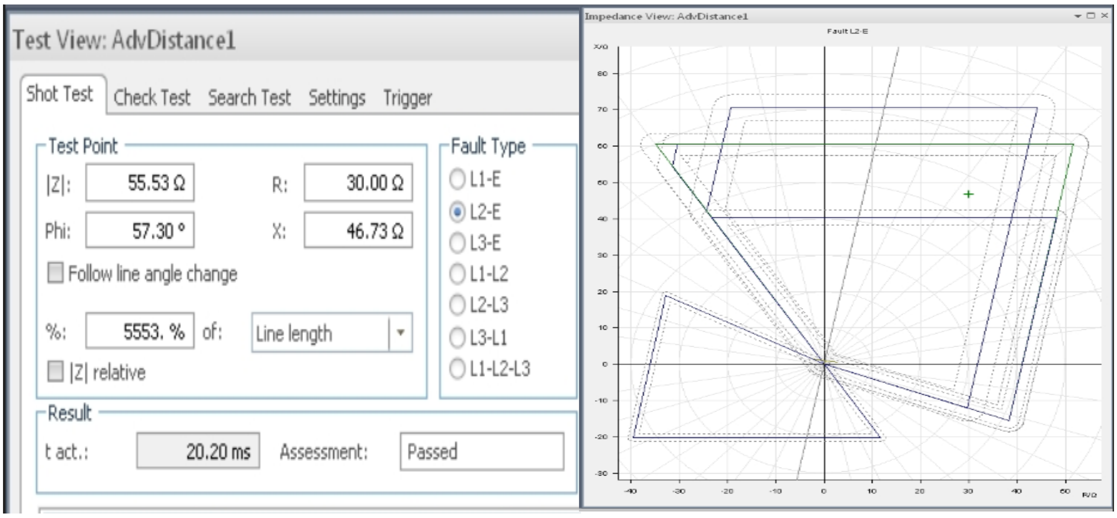


Figure III.5: Test injected in ZB1 to test PUTT function.

For this test, the impedance chosen was about 106.4% of the line which is in zone 1 extended with a fault phase-2 to ground type, equivalent to 127.7km from the beginning of the line. Omicron received a tripping signal instantaneously rather than tripping in after time delay even if the fault is in zone-2. Figure III.6 represents the rapport recorded from the protection.

Prot. dist.: démarrage phase L2-T	VENANT	41099 ms
Dist.: boucle choisie= L2T aval	VENANT	41099 ms
Prot. dist.:décl. triphasé	VENANT	41099 ms
Déclenchement définitif	VENANT	41099 ms
Courant de défaut primaire IL1	0.00 kA	41100 ms
Courant de défaut primaire IL2	0.44 kA	41100 ms
Courant de défaut primaire IL3	0.00 kA	41100 ms
Résistance déf. calc. Ohm sec.	30.18 Ohm	41156 ms
Réactance déf. calc. Ohm secondaire	47.10 Ohm	41156 ms
Distance du défaut en km	120.2 km	56 ms
Distance du défaut en % de la ligne	100.2 %	56 ms

Figure III.6:Protection report for PUTT function.

Discussion

Reading the protection rapport, we notice that the relay considered the extended zone 1 with errors in impedance values that does not exceed 0.8%; but the tripping time is with no time delay.

III.4.b. Broken conductor

in fact, this is not a fault, it is a cut in one of the lines without having contact with ground or any other phases. This results in an open or broken conductor. It is not detected by the distance or even the overcurrent since currents are not getting higher values. For this function operation, three conditions must be satisfied. The first condition is that the current flowing at one of the phases is the minimum current I_{min} and is smaller than the set minimum current value flowing in the line whereas the currents of the other phases I_{max} are greater. The second condition is that the ratio of the minimum I_{min} over the maximum I_{max} is smaller than the symmetrical factor set in the relay. The third condition is that the ratio of the maximum I_{max} is greater than the symmetrical pick up value set in the relay.

For our example, the symmetrical factor is set to 0.5, the symmetrical pick up value is set to 0.1A and the minimum current value flowing in the line is set to 0.4A

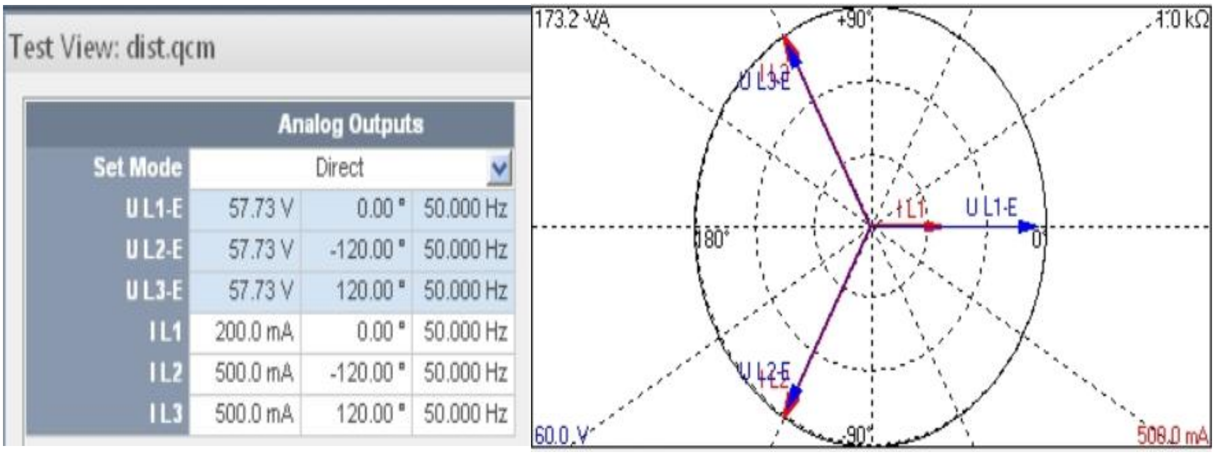


Figure III.7: Injected quick CMC values for broken conductor.

The values chosen to test this function satisfies the conditions listed above. The minimum current is 0.2A, smaller than the minimum current value flowing in the line which equals 0.4A and the maximum current is 0.5A. The ratio of the minimum and maximum are equal to the symmetrical factor and the maximum current is greater than the symmetrical pick up value by 0.4A. The rapport read from the 7SA protection is shown in Figure III.8.

Défaut symétrie I	VENANT
Défaut: Conducteur coupé	VENANT
Défaut symétrie I	PARTANT
Défaut: Conducteur coupé	PARTANT

Figure III.8: Protection report about the broken conductor.

Discussion

The relay, in this test, did not detect any fault but the broken conductor. In general, when a fault occurs and the protection detects it, two reports are recorded, one giving the values and the other giving only the facts. For this test, only facts were given and announce a symmetry abnormality and a broken conductor.

III.4.c. Quick tripping after reclosing with permanent fault

This function is designed in the protection to trip instantaneously when reclosing the circuit and the fault is still present in the network. Its test is done by injecting a fault and configuring the Advanced distance with a zero-pre-fault time and then inject a fault.

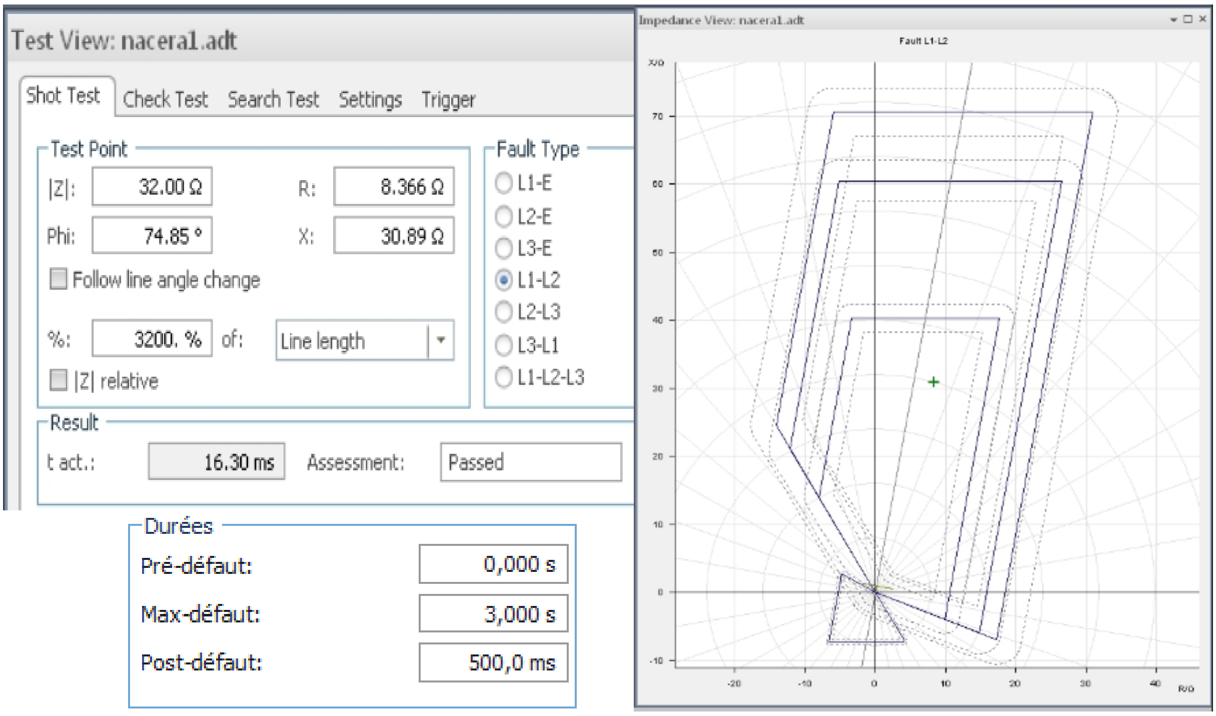


Figure III.9: Injected values to test quick tripping after reclosing with permanent fault.

The fault injected here were 61.3% of the line impedance. Its type is a phase-1 to phase-2 at zone1; the report generated by the 7SA protection relay is shown in Figure III.10.

Prot. dist.: démarrage phases L1-L2	VENANT	1 ms
Dist.: boucle choisie= L12 aval	VENANT	1 ms
Prot. dist.:décl. triphasé	VENANT	1 ms
Déclenchement définitif	VENANT	1 ms
Réencl: 1. cycle en cours	VENANT	2 ms
Courant de défaut primaire IL1	1.12 kA	2 ms
Courant de défaut primaire IL2	1.12 kA	2 ms
Courant de défaut primaire IL3	0.00 kA	2 ms
Boucle de mesure L1-L2	VENANT	60 ms
Résistance déf. calc. Ohm sec.	8.39 Ohm	60 ms
Réactance déf. calc. Ohm secondaire	30.92 Ohm	60 ms
Résistance déf. calc. Ohm primaire	8.39 Ohm	60 ms
Réactance déf. calc. Ohm primaire	30.92 Ohm	60 ms
Distance du défaut en km	73.6 km	60 ms
Distance du défaut en % de la ligne	61.3 %	60 ms
Déclenchement (général)	PARTANT	148 ms
Réenclencheur: momentanément indispon.	VENANT	148 ms

Figure III.10:7SA report for general tripping and blocked reclosing.

Discussion

An instantaneous three phase tripping was announced by the protection. Errors of measuring values were very small that the distance fault in percent of the line were exactly as expected. One feature of this tripping order is that the recloser is blocked till fault clearing.

III.5. Transmission Line Differential 7SD87 test

As done in the previous tests, all voltages and currents of the three lines and the neutral are required. The 7SD was fed from Omicron 256 by these analog inputs, and the binary output coming from the protection to trip is inserted as a binary input in the test set to stop the injection in fault cases.

Quick CMC function has been used to inject three currents to two relays ensuring differential protection to the line. As shown in the figure III.11, 500mA were injected for all phases of the first relay, and also for the 2nd and 3rd phase of the 2nd relay, while 800mA are injected to its 1st phase. The minimum difference current that allows tripping has been set to 200mA in the 7SD protection.

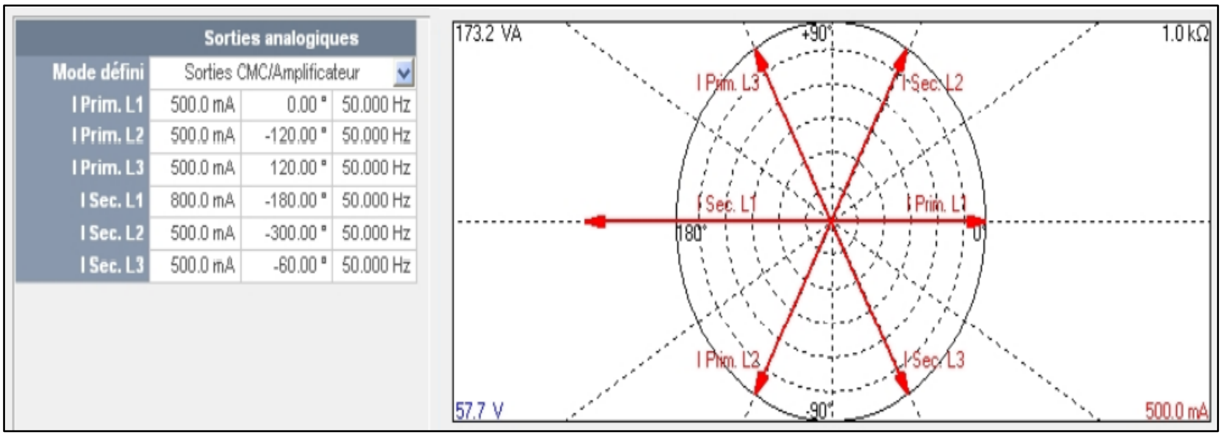


Figure II.11: Injected Currents to the 7SD and corresponding phasor diagram.

The 7SD protection recorded a primary fault current of 0.30kA (as it can be seen in the report in the figure III.12), which corresponds to 0.5A secondary current. This is exactly the value of current injected at one side of the line.

Diff: Fault detection	ON	0 ms
Diff: Fault detection in phase L1	ON	0 ms
Diff: TRIP L123	ON	0 ms
Diff: General TRIP	ON	0 ms
Relay Definitive TRIP	ON	1 ms
Primary fault current IL1	0.30 kA	2 ms
Primary fault current IL2	0.30 kA	2 ms
Primary fault current IL3	0.30 kA	2 ms

Figure III.12: Signalization Report for Differential Protection Test.

Discussion

From the results of the test, it can be seen that the differential protection activated instantaneously after detecting the difference in current (which is greater than the minimum set value) in only one of the phases. It confirms that the differential relay will send a tripping signal, as long as difference in currents is detected even if only present in one phase, as it has been seen in the previous chapter.

III.6. Transmission Line Overcurrent 7SJ80 Test

For the Overcurrent Protection 7SJ test, only the currents of the three lines and the neutral are required. The 7SJ was fed from Omicron 256 by these analog inputs, and the binary output coming from the protection to trip is inserted as a binary input in the test set to stop the injection in fault cases.

Pickup value of current is set to 1.2A in the DIGSI software and time delay before tripping is put to 2s. To test this protection, Quick CMC was utilized; three currents are injected in the secondary side: 1.300A, 1.000A ,1.000A (figure III.13), the phase 1 current value is greater than the pickup current(1.200A).

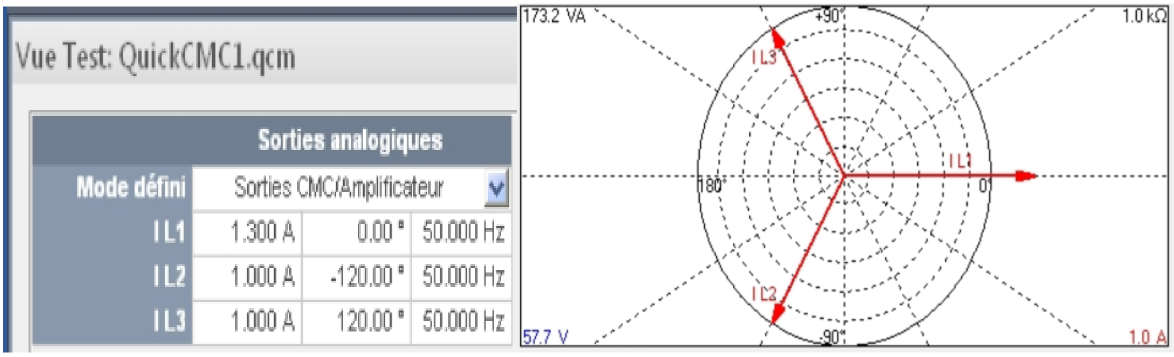


Figure III.13: Injected Currents to 7SJ and corresponding phasor diagram.

The report of the 7SJ protection (figure III.14) shows that the general tripping occurred after 2s by 39ms.

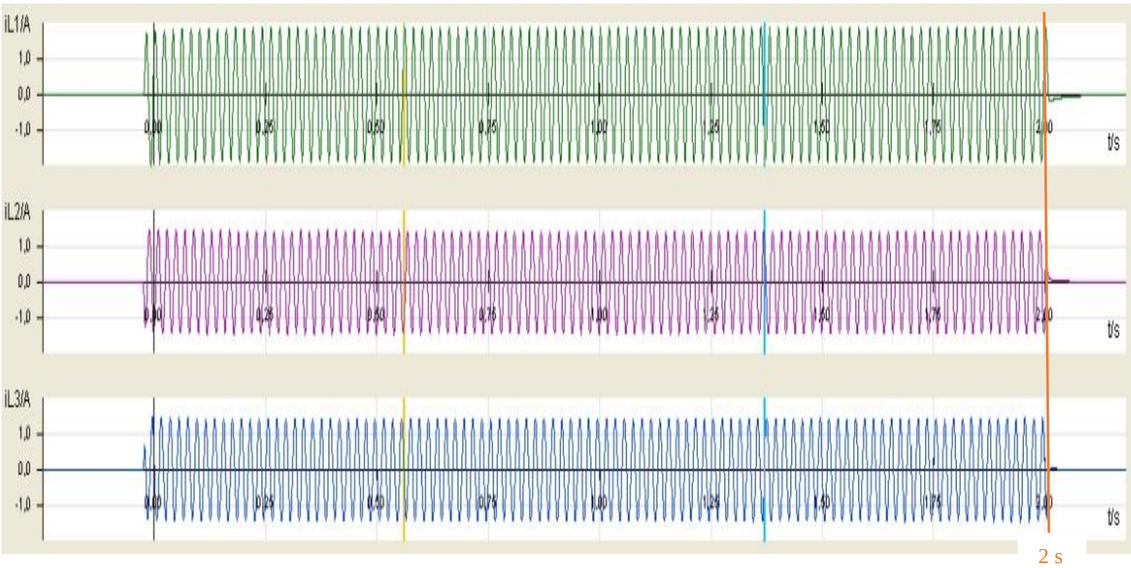


Figure III.14: Graphical Report for Overcurrent Protection Test.

Discussion

The fault current measured in phase 2 and phase 3 are the same as injected by the test set; and phase 1 is the faulted phase where the current injected is higher than the pick-up value. The graphical report representation given by the DIGSI software shows that the protection keeps measuring the faulted values and trips only after a time delay of 2s. The time required to stop the injection is 39ms as recorded by the protection.

.

III.7. Breaker Failure Protection Test

The breaker failure, as explained in chapter-1, is set to work when measured excessive current keeps flowing into the network after a time delay long enough to open the circuit by the principle protection but did not. Its analog inputs are just line currents. The pickup value, in our case, is set to 0.2A,

To test this protection, the affectations in the DIGSI software were used; a corresponding binary input specified to be active low activates the BF function. The faulted currents injected by QuickCMC are of greater value than the set pickup current; the three phase values can be seen in the following figure:

	Sorties analogiques		
Mode défini	Sorties CMC/Amplificateur		
I L1	500.0 mA	0.00 °	50.000 Hz
I L2	300.0 mA	-120.00 °	50.000 Hz
I L3	300.0 mA	120.00 °	50.000 Hz

Figure III.15: Injected Current to the 7VK protection via Quick CMC.

For our TL, the line and the transformer were connected to busbar 1 and busbar 1 was coupled with busbar 2, this configuration is illustrated in Figure III.16.

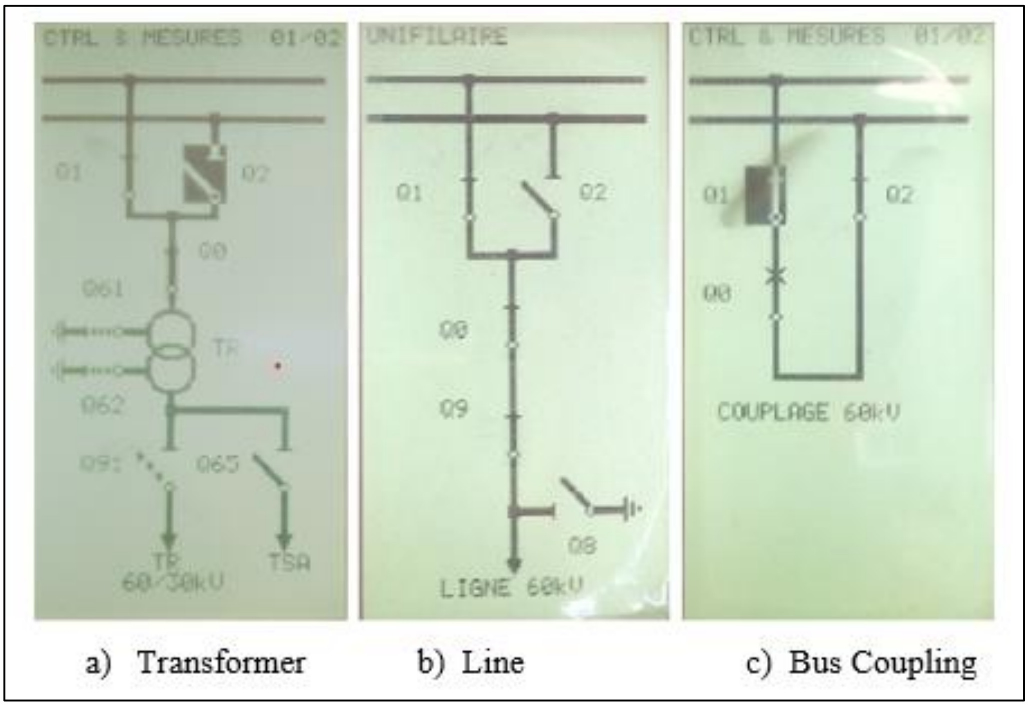


Figure III.16: CBs at normal case representation in HMI

When the breaker failure protection is activated, its function is to order all the circuit breakers connected to the busbar concerned to open. In our case, all lines, busbar and transformers connected to busbar 1 will be opened their CBs and this is shown in Figure III.17.

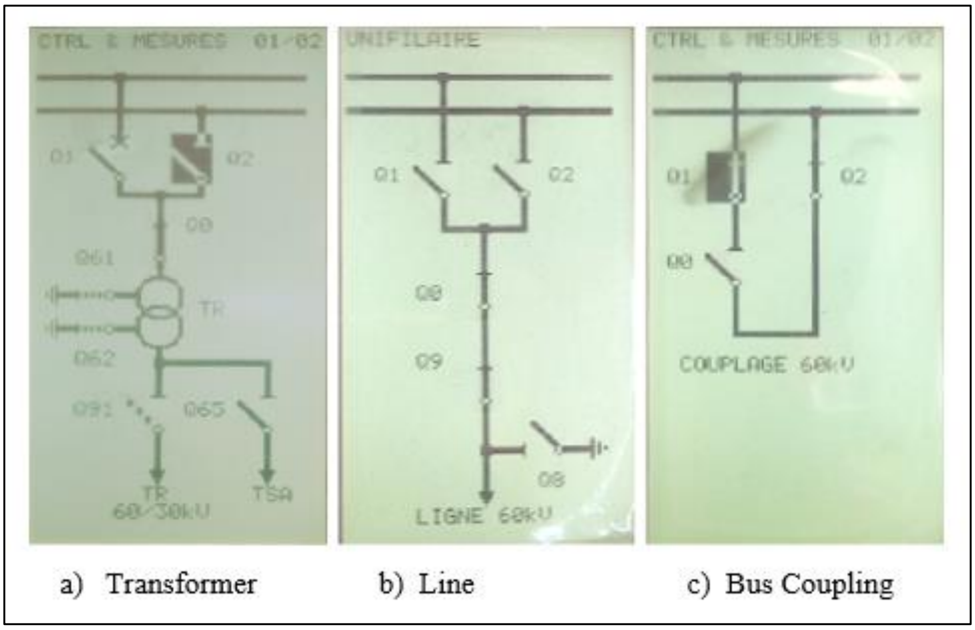


Figure III.17: BCs after BF operation represented in the HMI.

The rapport given by the breaker failure protection HMI is given in the figure below;

Figure III.18: tripping times given by HMI of the protection.

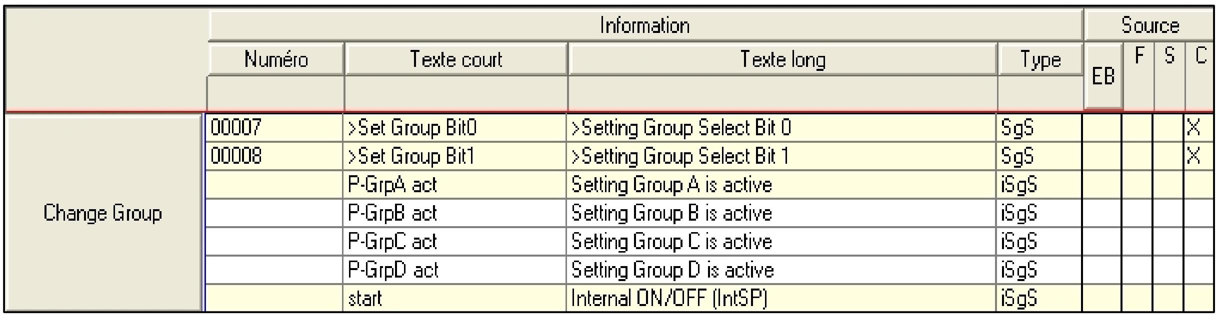
Discussion

Exciting the BF protection resulted in opening all the closed circuit breakers that were connected to busbar 1. This operation started after 200ms from detecting the fault as was expected.

III.8. Changing Groups

In modern relays it is common to find switchable setting groups, it permits the user to establish the relay's settings and Organize the entries into groups. Settings and even the type of protection used may vary from one group to the other and when needed, a group can be quickly loaded. The number of switchable groups depends on the device, for the 7SD relay used here, four active setting groups (A-B-C-D) can be created. The goal in this test, is to be able to change group using the function keys (f1, f2, f3, f4) that are available on the 7SD relay interface. To do it, The CFC (Continuous Function Chart) of the DIGSI software will be relied on. This element offers to connect a large variety of items of information to program protective or control functions not available initially in the SIPROTEC relays.

The first step is to enable the Setting Group Change Option in the DIGSI software, then specify that group change will be applied via binary input. After the activation of the Change Group, In the DIGSI configuration, a new group option is displayed (figure III.19).



	Information				Source			
	Numéro	Texte court	Texte long	Type	EB	F	S	C
Change Group	00007	>Set Group Bit0	>Setting Group Select Bit 0	SgS				X
	00008	>Set Group Bit1	>Setting Group Select Bit 1	SgS				X
		P-GrpA act	Setting Group A is active	iSgS				
		P-GrpB act	Setting Group B is active	iSgS				
		P-GrpC act	Setting Group C is active	iSgS				
		P-GrpD act	Setting Group D is active	iSgS				
		start	Internal ON/OFF (IntSP)	iSgS				

Figure III.19 Setting group change option in DIGSI configuration

With the binary inputs: Group select Bit 0 and Group Select Bit 1, four combinations can be set, they represent the information that can activate the changing of groups, table 2 shows how to specify a group using the two binary inputs.

Table III.1: Active Setting Group.

Group select Bit 1 / Group select Bit 0	0	1
0	A	C
1	B	D

A logic circuit is designed in DIGSI ‘s CFC, using two flip-flops. 1st flip flop has f1 as a “SET” input and f2 as a “RESET” input, and Group Select Bit 0 as an output. The 2nd flip flop has f3 as “SET” input and f4 as a “RESET” input, and Group Select Bit 1 as an output. To each group a LED is associated and turns ON whenever activated. The CFC chart was compiled successfully and the result is shown in figure III.20 in the DIGSI report, as combinations of the function keys have been used to get the conresponding group activation.

Setting Group B is active	OFF	03.05.2018 08:54:18.746
Diff: Active	ON	03.05.2018 08:54:18.752
Setting Group A is active	ON	03.05.2018 08:54:18.755
Diff: Diff. protection is switched off	OFF	03.05.2018 08:54:18.761
Distance is switched off	ON	03.05.2018 08:54:18.761
Internal ON/OFF (IntSP)	ON	03.05.2018 08:54:21.998
Internal ON/OFF (IntSP)	OFF	03.05.2018 08:54:22.106
Setting Group A is active	OFF	03.05.2018 08:54:22.858
Setting Group C is active	ON	03.05.2018 08:54:22.869
Distance is switched off	OFF	03.05.2018 08:54:22.878
Internal ON/OFF (IntSP)	ON	03.05.2018 08:54:33.698
Internal ON/OFF (IntSP)	OFF	03.05.2018 08:54:33.818
Internal ON/OFF (IntSP)	ON	03.05.2018 08:54:35.498
Internal ON/OFF (IntSP)	OFF	03.05.2018 08:54:35.618
Setting Group C is active	OFF	03.05.2018 08:54:36.410
Setting Group D is active	ON	03.05.2018 08:54:36.418

Figure III.20: Signalization Report for changing of groups.

Discussion

Originally the group A was Activated, after clicking on the f1 key, it changes to Group B. clicking on f2 (resetting 1st flip flop) sets the group A again. Resetting first flip flop with f2 and setting the second flip flop (f3) activates group C. Clicking on f1 then f 3 (11) Sets the group D.

III.9. Conclusion

In this chapter, the tests carried on the main protections of the TL were depicted. The 7SA distance relay and its auxiliary functions (PUTT, broken conductor, quick tripping after reclosing with permanent fault), the 7SD differential relay, the 7SJ overcurrent relay and the breaker failure were tested and a function for changing groups was programmed to the 7SD relay. With their results shown and discussed, it has been noticed that they were satisfying and confirming what have been seen in the previous chapter, beside that it has been observed that the relay error measurements were quite small. The appropriate option from OMICRON package should be chosen to perform tests in an efficient and reliable way.

Conclusion

In this project, transmission lines protective functions and schemes were investigated, and tests associated to these protections were carried out in the GRTE enterprise laboratory on SIPROTEC 4 relays using CMC 256-6 test set.

General definitions and concepts concerning the power system protection as a whole has been seen first, then focusing on TLs, the analysis of the different types of faults occurring in this part has been carried, and the operation of necessary protections of TLs were explained. As the relays are the main elements in the power protection system, their operation is primordial and testing of these equipment is very important.

One of the tests conducted on the 7SA distance relay principal protection, a phase to phase fault injected in the 1st zone, was presented, and results recorded were satisfying. Other auxiliary functions of this relay were tested as well. As for the PUTT function where the injected fault was detected in the extended first zone with no time delay for the tripping. Furthermore, as it was expected the broken conductor was not detected as an error but just signaled in the protection report. Quick tripping after reclosing with permanent fault test behaved as awaited, it is noticed that recloser is blocked whenever quick tripping activated till clearing the fault. The 7SD differential relay testing confirmed that detecting significant difference in only one of the phases is sufficient to activate the protection. In the test of the 7SJ overcurrent relay, fault current was detected in the time allowed, and the breaker failure proved that when activated, all the CBs connected to implicated busbar are opened. Finally, the DIGSI configuration and CFC functions were used to design a logic circuit to assign key function of the 7SD relay for the changing of groups.

The errors in relay measurement observed in the protection reports are all of small values, they can be considered to be insignificant. Through these tests, the proper operation of the numerical SIPROTEC 4 relays used has been demonstrated.

Future Work

It has been highlighted in the first chapter that Busbars are the most sensitive elements in the power system. Although their faults are not too frequent, serious disturbances can affect power system when they occur inasmuch as there exist interconnection of several circuits at them involving high levels of fault current. In Algeria, at many locations in the electrical network, the busbars have been left without their specific protection and rely only on the backup protection of the lines (which is a delayed protection in general, such that severe damages can occur in the network before the tripping signals are sent). In this section, a method, represented by a block diagram in figure IV.1, is proposed to be implemented on the line protective relay in order to procure a sufficient protection for the busbar being behind that relay in case of a fault. It can be programed on the distance 7SA relay for example.

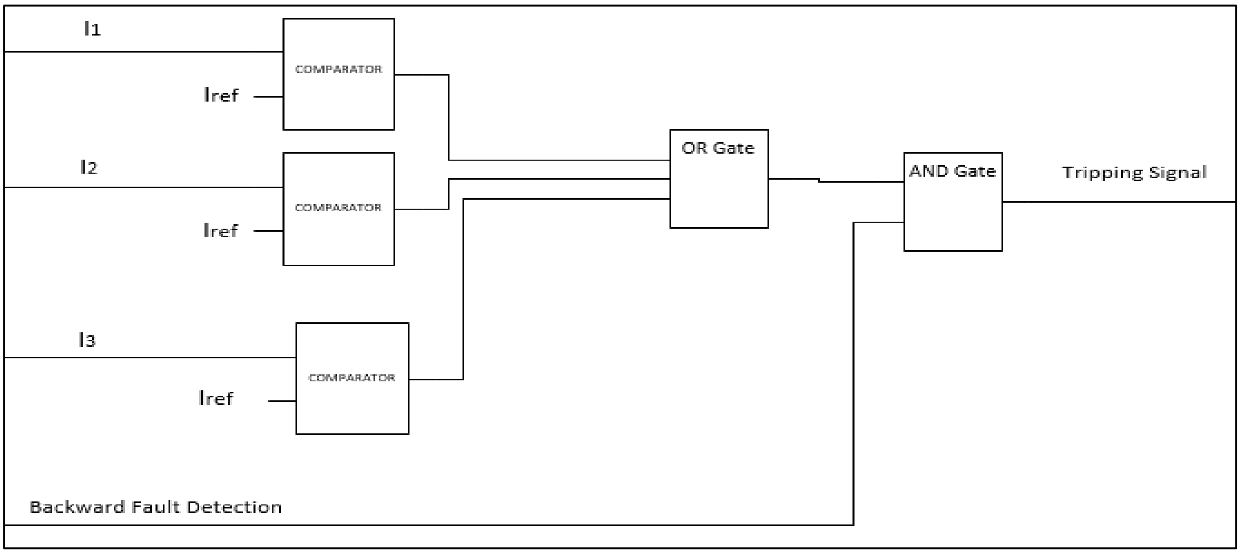


Figure IV.1: Bloc Diagram of Proposed Protection Method For Busbars.

Two conditions must be met to activate tripping signal. The first one is that the relay detects a backward fault (because of the busbar being behind the relay), if detected logic high enters the AND gate (see figure-40). The second condition, is that the measured currents are greater than a certain predefined fault current(Iref) that corresponds to busbar faults, to avoid tripping for a fault occurring on the line just behind the relay. I1, I2 and I3 are the measured current from the line, they are compared to Iref using three simple comparators, if one of them exceeds the Iref, the output of the OR gate would be logic high. The circuit can be directly designed using the CFC function of the DIGSI software and programmed to be instantaneous

References

[1] M. BEGBAGUI et A. MATI, *PC Based Numerical Protective Relay for Power Transmission Line*, 2015.

[2] P. M. Anderson, Power System Protection, JHON WILEY & SONS and IEEE PRESS, 1998.

[3] I. P. E. Society, IEEE Standard Definitions for Power Switchgear, New York: Institute of Electrical and Electronics Engineering, 1992.

[4] C. Mason, The Art and Science of Protective Relaying.

[5] IEEE, IEEE RECOMMENDED PRACTICE FOR PROTECTION AND COORDINATION OF INDUSTRIAL AND COMMERCIAL POWER SYSTEMS, IEEE, 2001.

[6] «Study Notes on Instrument Transformers and DVM's for Electrical Engineering Students,» [En ligne]. Available: https://gradeup.co/instrument-transformers-&-digital-voltmeter-i-eee99564-bb88-11e5-b73f-9bf9bb167252.

[7] «electrical engineering portal,» [En ligne]. Available: http://electrical-engineering-portal.com/the-philosophy-of-breaker-failure-protection.

[8] H. Bentarzi et A. Abdelmoumene, «A review on protective relays' developments,» *Energy in Southern Africa*, 2014.

[9] C. Prévé, Protection of Electrical Networks, ISTE ltd, 2006.

[10] ALSTOM, *NETWORK PROTECTION & AUTOMATION GUIDE*, ALSTOM GRID, 2011.

[11] Stanley H. Horowitz et Arun G. Phadke, Power System Relaying, John Wiley & Sons Ltd, and Research Studies Press Limited, 2008.

[12] A. Kheldoun, Lecture Notes, Power System Analysis EE432, University of Boumerdes.

[13] J. Lewis Blackburn et Thomas J. Domin, Protective Relaying,Principles and Applications, CRC Press, 2006.

[14] A. M. EL-Jilani, Power System Protection, Cairo, 2006.

[15] G. Ziegler, Numerical Distance Protection, principles and applications, Berlin: Siemens, 2008.

[16] «Study Notes on Switch-Gear & Protection 2 for Electrical Engineering Students.,» [En ligne]. Available: https://gradeup.co/principles-of-over-current-differential-and-distance-protection-i-02542583-bf47-11e5-bd40-b5675f9893b0.

[17] Siemens, *SIPROTEC 7SD5 Line Differential Protection Manual*, Siemens, 2007.

[18] OMICRON, *TEST SET CMC 256 Manual*, OMICRON.

[19] J.G.Andrichaak et G.E.Alexander, Distance Relay Fundamentals, General Electric.

[20] Siemens, *SIPROTEC 7SA6 Distance Protection Manual,* Siemens, 2004.

[21] «Power System Protecion services in India,» [En ligne]. Available: http://www.systemprotection.in.

[22] Theophilus Chukwudolue Madueme et Victor Ogboh, «Investigation of Faults on the Nigerian Power System Transmission Line Using Artificial Neural Network,» 2015.

[23] «PSN,» [En ligne]. Available: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRD8y-YxHuztcK5cM30m_ga1pA5mHBWqS5cmyhjZPGB8q44IB9oOw.

[24] [En ligne]. Available: https://i.pinimg.com/736x/f8/4f/06/f84f06b4061cd33573284ea818c13857--i-am-homes.jpg.