Automatic fault location in electrical distribution networks with distributed generation

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Automatic Fault Location in Electrical Distribution Networks with Distributed Generation

Doctoral Thesis

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A mis padres, sin su
continuo apoyo y amor esta
tesis no hubiese visto la luz.

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I would like to remark that the idea of this thesis started due to my job has been close to the topic of this document. Therefore, to thank to Schneider Electric the knowledge that I have received from several colleagues in the network protection, fault detection and communication architecture such as Manuel Járrega, Pierre Bertrand, Francesc Juan and Philippe Stachel.

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Abstract

Nowadays the electrical network is continuously evolving due to the increasing deployment of Information Technologies and the Distribution Energy Resources. This scenario affects directly to the quality of service in the electrical distribution networks. For this reason, the Power Quality is a key important concern to make the electrical network evolve towards a Smart Grid.

Power quality is defined through three important focal points: availability, wave quality and commercial quality. From the network operation point of view, the availability in a distribution network is a very important point in order to keep a grid with a high level of reliability. For this reason, to locate a fault is a priority for the operator of electrical network to offer a high grade of comfortability to the loads, generators and prosumers of this network. In fact, the presence of the Distribution Energy Resources in the current electrical distribution network is showing a new scenario where the fault detection is more complex due to the flow current is in both directions. The implementation of the Smart Grid concept in this kind of networks depends on the automation of the procedures such as Fault Location Isolation and Service Restoration. This kind of systems can contribute considerably in the availability's performance of the electrical network in order to have a fast answer in front of the faults due to these networks cannot operate in front of a fault.

This thesis is focused in the analysis of several methods to locate a fault in electrical distribution network and also how the current communication standards can improve considerably this fault location. It is important to remark that the main contribution of this thesis is in the analysis of several propositions and algorithms to enhance the fault location in a distribution network using the current Intelligent Electronic Device with international standards such as IEC 61850. All of these algorithms have been focused to work in a mesh distribution networks due to this is the evolution of the new network deployment, first the radial system evolved to a ring system towards a joint of several rings conforming a mesh.

Another important contribution of this thesis is in the adaptive protection system in order to isolate correctly the fault in a ring system distribution. Although this proposition could be extended to a mesh network where the elements of the network can operate under a fault.

Additionally, the document reviews also the state of the art of fault location within the perspective of availability as one of the pillars of the power quality in a new world where the Internet of Things has a specific weight. The different proposed algorithms can contribute in several applications in order to enhance the network.

Finally, the thesis concludes that the use of communication standards and Internet of Things with current developed Intelligent Electronic Devices technology can contribute significantly to enhance the current and future electrical network distribution.

Contents

List of figures

List of tables

List of graphs

Abbreviations

3GPP	3rd Generation Partnership Project
3P	Three-Phase fault
2P	Phase to Phase fault underground
2PG	Phase to Phase Grounded fault
AC	Alternating Current
ACSI	Abstract Communication Service
ADA	Advanced Distributed Automation
ADMS	Advanced Distribution Management System
ADSL	Asymmetric Digital Subscriber Line
AED	Advanced Electronic Device
AFL	Automatic Fault Location
AHP	Analytic Hierarchic Process
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
ANN	Artificial Neural Network
ASAI	Average Service Availability Index
ASIFI	Average System Interruption Frequency Index
ASIDI	Average System Interruption Duration Index
BRCB	Buffered Report Control Block
BPLC	Broadband Power Line Communication
BPSK	Binary Phase-Shift Keying
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CB	Circuit Breaker
CEMI	Customers Experiencing Multiple Interruption
$CEMSMi_n$	Customers Experiencing Multiple Sustained and Momentary Events

CIS	Customer Information System
CT	Current Transformer
CTAIDI	Customer Total Average Interruption Duration Index
DA	Data Attribute
DAS	Distribution Automation System
DB	Distance Brick
DC	Direct Current
DER	Distributed Energy Resource
DFPI	Directional Fault Passage Indicator
DG	Distributed Generation
DMS	Distribution Management System
DNP	Distributed Network Protocol
DO	Data Object
DPC	Data Processing Centre
DS	Data Set
DSM	Demand Side Management
DSO	Distribution System Operator
EAM	Enterprise Asset Management
EES	Electrical Energy Systems
EIoT	Energy Internet of Things
EMS	Energy Management System
EPRI	Electric Power Research Institute
ERP	Enterprise Resource Planning
ETSEIB	Escola Tècnica Superior d'Enginyeria Industrial de Barcelona
EV	Electric Vehicle
FLB	Fault Location Brick
FDANN	Fault Distance Artificial Neural Network

FIFO	First In First Out
FO	Fibre Optic
FL	Fault Locator
FLISR	Fault Location, Isolation and Service Restoration
FMEA	Failure Modes and Effects Analysis
FPI	Fault Passage Indicator
FTP	File Transfer Protocol
GCB	GOOSE Control Block
GI	General Interrogation
GIS	Geographic Information System
GOOSE	Generic Object Oriented Substation Event
Gp	GOOSE published
GPRS	General Packet Radio Service
Gs	GOOSE subscribed
GSM	Global System for Mobile
HAN	Home Area Network
HSRP	Hot Standby Router Protocol
HV	High Voltage
IEA	International Energy Agency
ICT	Information Communication Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronic Engineers
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technologies

LAN	Local Area Network
LD	Logical Device
LN	Logical Node
LoRaWAN™	Long Range Wide Area Network
LPVT	Low Power Voltage Transformer
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LV	Low Voltage
MAC	Media Access Control
MAIFI	Momentary Average Interruption Frequency Index
$MAIFI_E$	Momentary Average Interruption Event Frequency Index
MINETAD	Ministerio de Energía, Turismo y Agenda Digital
MLPNN	Multilayer Perceptron Neural Networks
MMFS	Manufacturing Message Format Specification
MMI	Man Machine Interface
MMS	Manufacturing Message Specification
MV	Medium Voltage
NB-IoT	Narrowband IoT
NIEPI	Número de Interrupciones Equivalente de la Potencia Instalada
OMS	Outage Management System
OSI	Open System Interconnection
PLC	Programmable Logic Controller
PLC	Power Line Communication
PRP	Parallel Redundancy Protocol
QoS	Quality of Service
R-GOOSE	Routed Generic Object Oriented Substation Event
RBFNN	Radial Basis Function Neural Network

RCB	Report Control Block
RSTP	Rapid Spanning Tree Protocol
RTU	Remote Terminal Unit
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SBO	Select Before Operate
SCADA	Supervisory Control and Data Acquisition
SCL	Substation Configuration Language
SDU	Software-Defined Utility
SIM	Subscriber Identify Module
SPG	Single Phase to Ground fault
SVP	Sample Values Protocol
TCP/IP	Transmission Control Protocol / Internet Protocol
TIEPI	Tiempo de Interrupción Equivalente de Potencia Instalada
TSO	Transmission System Operator
UCA	Utility Communication Architecture
UPC	Universitat Politècnica de Catalunya
UPS	Uninterruptible Power Supply
URCB	Un-buffered Report Control Block
V2G	Vehicle to Grid
VT	Voltage Transformer
VLAN	Virtual Local Area Network
VPP	Virtual Power Plant
WAMPAC	Wide Area Monitoring Protection and Control
WAN	Wide Area Network
WIS	Weather Information System
XML	eXtensible Mark up Language

1. Summary

The electrical distribution network is in front of stage of several changes, the communication network joint to the Information Technologies (IT) is taking a relevant importance where the Power Quality has been defined as one of the fundamental vectors of the electrical utilities.

The Power Quality is the concept which tries to standardize in the electrical networks its standard of the quality. This concept is divided in three important spotlights: the availability, the wave quality and the commercial quality. This thesis is based in the first of these three pillars.

The availability is a key point in order to keep a high-reliability level in the electrical network. In fact, it is possible to indicate that it is the most important in front of the others because without it never it will be possible to have a properly ready network.

This chapter exposes the motivation for which the fault location problem is present in electrical distribution networks. Following the object and the tasks which are needed to reach this achievement are presented. Finally, the organization of the document and the content of each chapter are indicated.

This PhD thesis has been developed during the period 2014-2018 in Escola Tècnica Superior d'Enginyeria Industrial de Barcelona (ETSEIB) from Universitat Politècnica de Catalunya (UPC), although some researchers has been developed and published in a previous period in several congresses and journals since 2011 by the author.

1.1 Motivation

Nowadays in the current electrical distribution networks the availability has been implemented correctly until now. In recent years the penetration of Distribution Energy Resources (DER) has had a big impact in electrical distribution network. This fact can difficult considerably the fault detection in these networks because the current can flow in both direction and it will depend on the current topology in every moment. However, these new actors will provide more efficiency to the network in front of the traditional generation.

It is important does not forget the other pillars of the Power Quality: wave quality and commercial quality. Both points are very important in order to have a good quality in the network, therefore it is necessary to analyse the impact of DERs also in these features of the networks, overall in wave quality.

In front of this scenario is very important to introduce new kind of automation which aims to help to locate a fault and after that to establish a quick restoration. Systems such as Fault Location Isolation and Service Restoration (FLISR) can contribute considerably in order to enhance the availability of the system.

As mentioned before the IT has evolved considerably in recent years although the Internet of Things (IoT) has taken a big relevance in the industry and other sectors of the society but today is the moment of the electrical network. The number of sensors in electrical distribution networks were not high and the information of the process was hide until recent year. It is important to highlight that in last years the Distribution System Operator (DSO) has increased the sensors in the network in order to have more information and to enhance the commercial quality. This is the moment to introduce new algorithms and new procedures in order to enhance the availability of the network. In fact, the Transmission System Operator (TSO) has also enhanced their networks due to the introduction of new DERs.

1.2 Goals

This thesis studies the implications that the automation can provide to the current and future electrical distribution network. Therefore, the first goal of this document is to establish the state of the art of the automatic fault location in distribution networks and in a second term to define the bases to develop an algorithm about fault location to enhance the Power Quality of the electrical distribution networks.

The first of these goals includes a previous study about the current situation of fault location in distribution network. The study was started in the subject Power Electric Systems, in ETSEIB, where a report was required to fulfil with all the conditions of this subject. This initial report established several points to analyse the problems related with automatic fault location in the network. This document was the first step to establish the knowledge and the bases to develop the PhD thesis. Therefore, in this document it is possible to find the first knowledge about automatic fault location, although this document has evolved along the period of PhD because there has been a continuously evolution in this area.

On the other hand, the second goal tries to define the main important points to develop an algorithm focused in two important features: location and restoration in electrical network distribution. In fact, a network electric operator has a huge issue when there is a fault in a network, for this reason one of the goals of this document is to pose algorithms which can combine the two properties: Location and Restore.

1.2.1 Goal: State of the art

The State of the art about automatic fault location is focused in the elaboration of a document with a lot of references which develop the topic. As it has been defined in the introduction, the document is composed by four important points: network quality, faults, fault location and restoration.

These four points are the four steps to define correctly the state of the art because it is the four questions to ask after a fault in the network. The first of these questions is to know the quality system of the network to know the possibilities to isolate the fault, after this point it is necessary to know the kind of the fault to start the process to develop the isolation process. Later to know the location is a fundamental point to start the isolation process opening the circuit breakers and switch-disconnectors in the distribution network. Once time the fault is isolated the next step is to restore the network in order to recover the users without supply.

The state of the art of this topic has a huge dimension due to there are different ways to detect a fault in the network. For this reason, one of the goals of this initial document is to reach a definition about the different ways to detect all the defects.

This goal is completed with other topics such as IEC 61850 and IoT standards which can contribute significantly in the new stages for automation in the electrical distribution networks. It is important to highlight that this kind of standards can help significantly in the evolution of the procedures to reconfigure the network.

1.2.2 Goal: fault locator algorithm

This document shows different papers about simple algorithms focused in fault location combining the restoration. These algorithms have been the first stone to develop the fault locator algorithm proposed in this document.

The proposed algorithm seeks to make a first stage to locate a fault in the network through different parameters and in a second stage to propose a process restoration of the network in order to isolate the fault and recover the supply for the users of the network.

The main goal of the fault Locator algorithm is to reach a sustainable level of fault detection in order to enhance the quality in electrical network. In fact, the improvement of quality is focused in several concepts as the document will be presented in next chapters although one of them is the availability of the energy supply. Therefore, after a fault there are two important problems: the fault and the availability of the energy for the users, knowing the fault is possible to establish a possible solution to recover the supply in the customers to maintain or improve the quality indices of the network.

1.3 Contents

In order to develop this state of the art, several points have been studied. The first one has been the network quality where three parts can be found: the availability quality, the wave quality and the commercial quality. As the most related part with the goal of this document is the availability quality, it is possible to find the description of quality indices to evaluate the network. Besides in this part, the network architectures are analysed.

Another part of the document is the analysis of the faults in the electrical network where it is possible to find a classification about the topology of the network faults. This kind of faults can be actives or passives.

It is important to develop this point to understand the different situations which are in electrical network under a fault.

In another part there is an analysis about detection faults in electrical network distribution. This is a key point inside of this PhD thesis due one of the goal of this is to contribute in the development of this area. In this part it will be analyse the concept of fault locator and the different devices and network control systems to detect a fault in order to conclude finally in some algorithms to detect them.

Following, different control technologies are showed to manage an electrical distribution network. In this part there will be an introduction of the Smart Grid concept and the current status of the Feeder Automation concept. In this chapter the IoT standards and IEC 61850 are explained such as key tools for the automatization of the network.

Finally, the distribution network restoration is showed with different centralized and decentralized restoration procedures which contribute to complement the Feeder Automation concept for the electrical network distribution.

As additional points, there are the mentioned references in this document from different publications and the appendix about the publications, participations in committees and congress presentations of the author related with the topic.

2. Introduction

Currently the electrical grid is a huge complex system which defines a critical infrastructure. For this reason, the DSOs have been adopted a conservative attitude regarding changes due to the dimensions of the system. In fact, the electrical distribution networks are brittle due to they were built during large period of time without safety systems. In a lot of countries these networks barely have operated and also the installation conditions have been to delivery energy without fine control. The evolution has been different in each country although it is important to highlight that in last decade the DSOs have been developing and implementing new systems to improve the control of these networks and therefore the quality of them.

The electrical network is improving day by day in service quality. In fact, this power quality as mentioned before is composed by three parts: availability, wave quality and commercial quality. Day by day the electric utilities are improving continuously their quality index such as System Average Interruption Duration Index (SAIDI), or System Average Interruption Frequency Index (SAIFI). This fact is very important in human society due to the electrical consumption is much extended in all devices including the vehicles.

Years ago, to keep stability in the electrical system were one of the most important concerns in the electrical network. Avoiding outages was a priority in the electrical network system. After years of research and new technologies development the big outages are decreasing due to there are more voltage control at least at High Voltage (HV), level to sure the global system. However, the rest of the network in Medium Voltage (MV) and Low Voltage (LV) level are can suffer issues.

The MV network can suffer more issues than other voltage levels due to exposure to environmental. In fact, there are a lot of problems caused by the nature of the area served such as animals and other weather conditions [1]. Besides the distribution network normally can adopt different architectures as radial or ring distribution and sometimes it is possible to find a mesh network with different possible ways to set.

On the other hand, this distribution network can be defined with different wires so this electrical network has different impedance in their parts. Moreover, it is possible to find in the network different kind of switchgears such as circuit breakers, switch-disconnectors, switches with fuse for overhead and underground networks and other cutting elements to open and close the network.

The main aim of electric utilities is to improve continuously the quality service and for this reason they are basing their quality axis in three areas, as before it has been mentioned: the availability, the wave quality and in last term the commercial quality. Analysing these three areas is a very important task to improve the quality service but probably the most important of these is the availability service due to a little issue can affect a lot of users.

However nowadays the standard user is focusing also in quality service because every day the home devices need a better-quality voltage although it is much protected against overvoltage or other unbalances effects.

After to analyse the current situation in the electrical network, there is an important challenge in the electrical network about the quality. Although it is important to highlight that the MV network is changing continuously. Among last decades the DERs have increased considerably. This new situation has established other principles in the network where the flow of the energy takes different directions. According to [2] there is a forecast for next decades where renewable energy resources will take an important relevance in the market.

Among these changes in the network it should not be forgotten that there are a lot of new actors in the electrical network both in MV and LV. These new actors such as electric vehicle, self-consumption, storage and other new electronic power controllers of the network are being implemented now. Therefore, to enhance the quality of electrical network is much more difficult that time ago because these new actors are modifying it. The vehicle to establish a way to make a relationship between all of the elements of the network is the Smart Grid [3] which is being defined through a set of standards [4] and several projects have become a new reality [5].

These new actors are not only the new changes in the network; in fact, there is an increase of the energy demand forecast towards 2040. According to World Energy Outlook 2014 from International Energy Agency (IEA) there will be an increase of 2° C in 2040 following the current scenario according to [6] and also to the report from IEA in 2016 [2]. This dangerous heating in combination with a stormy energy future due to geopolitical reasons may cause a difficult energy supply in order to cover the increase of future energy demand. The IEA estimates that energy demand will increase up to 37% towards 2040 with current scenario.

In order to fight against this dangerous forecast, it will be necessary to enhance the quality of the network to work efficiently and thus to cover the future scenario in the electrical world. One of the most important challenges is to enhance the fault detection and the restoration always keeping the stability of the network.

Although in front of this scenario there are new resources to fight against these adversities. The advance of the IT, the new standards such as IEC 61850 and new communication technologies LoRa and Sigfox among others can provide more dynamism to the electrical distribution networks due to it provides distributed intelligence. On the other hand, as mentioned before, the integration of DERs in the electrical distribution networks will increase in next years This fact will increase the difficulty to identify the fault in order to isolate it and to restore the network.

As mentioned before, IEC 61850 has begun to be an important standard to the electrical sector. This standard tries to integrate all the technologies presents in several substations for his efficiency [7] in the different voltages ranges. In fact, IEC 61850 has started to be in distribution networks where the Smart Grid concept is being developed [8]. Not only in substation is the place where the IEC 61850 standard is present also it is possible in the loads such as electric vehicle and vehicle to grid (V2G) [9] or components such as switch-disconnector [10] and even in the control centre [11]. Besides this standard has been implemented in several communication mediums such is the Power Line Communication (PLC) [12]. Therefore, the presented algorithm in this thesis has been proposed to be implemented in IEC 61850 communication standard in order to take in advantage the possibilities of this standard. The implementation of the algorithm in IEC 61850 provides fast fault detection and restoration process, using the information from field devices. In fact, the current Ethernet communication systems can provide, in almost real time, the information from several field devices to the control centres.

These new technological developments provide an important skill of the distribution electrical networks: the capability to give a fast answer in front of a fault, not only with a recloser system if not besides with another kind of restoration from the control centre or even a self-healing in the network as it is mentioned in [13] and in [14]. Although if the number of DERs has increased considerably it will be necessary to establish another kind of detection fault in order to identify the correct section where the fault is. In front of this difficulty it will be necessary to find an alternative to detect the section of the fault and the distance inside it to help in restoration process. This important change has finished in new studies such as [15] which presents an important analysis about the system protection in transmission networks due to the massive penetration of Distributed Generation (DG) with power electronics.

For these previous reasons this thesis and other related documents are trying to identify several tools in order to locate the fault in the network and to enhance the availability of the system. Nowadays the introduction of new technologies in the market and the application of them into the electrical distribution network are providing the way to introduce the Smart Grid. As Mark Twain quoted: “Continuous improvement is better than delayed perfection”, this has been the evolution of the electrical distribution network during last decades.

3. Quality level in the electrical distribution network

3.1 Power quality

A correct power quality is defined by a voltage which follows a sinusoidal function without any kind of distortion in amplitude or frequency. It is difficult to find a balance between a good wave quality and its cost, for this reason the utilities invest in this power quality when the minimum conditions are not fulfilled. It is important to remark that there are investments in electrical network continuously to reach the maximum level of requirements regarding current technology. Therefore, the electrical utilities are in front of a slow process in order to enhance their electrical networks through new technologies. For this reason, the research line in this document try to use technology easily adaptable in a current electrical network.

The power quality issue can be divided into many categories such as sags, wells, transients, noise, flicker, harmonic distortion and frequency variation… [16], although there are two of them that can impact directly in the devices which are connected into the network. These two issues are the interruptions and sags where the voltage decreased considerably and can interrupt the function of the network.

In last ten years the electrical utilities around the world has been started a campaign to establish a system to measure the different variables and thus to study the quality of the network with measurement equipment. Therefore, one of the important topics today in electrical network is the metering.

The Smart Grid concept [17] has provided to the network enhance of the metering. As a result of the information technologies evolution the smart metering has increased in few years. For this reason, a communicated metering of each point of the network can contribute significantly to the power quality due to there is an exhaustive control in the network.

3.1.1 Availability and reliability

Besides the power quality as it has mentioned in this document there are another important point which contributes directly to the quality in the network. This concept is the reliability of the electrical distribution network. The reliability is focused in outages and customer interruptions. In fact, this concept is applied in normal operating conditions of the network.

It is important to establish a difference between normal and stand by conditions. The stand-by situation implies a no normal situation due to the network is working properly and after a fault or maintenance situation the network is in standby mode waiting a new configuration.

Therefore, there are different events which can disrupt normal operating conditions and can lead to outages and interruptions. There are a lot of kinds of event which can affect to the reliability and thus to modify the network conditions. Among these events it is possible to find followings: contingency, open circuit, fault, momentary interruption, momentary interruption event and sustained interruption [16]. Every one of them can affect with more or less intensity in reliability of the electrical distribution network. In order to classify the potential of these events in the reliability's network; their descriptions are shown below.

- **Contingency**. This is an unexpected event such as a fault or an open circuit. This event has not been scheduled by system operator.

- **Open circuit**. This situation appears when the current flow is interrupted without a fault in the system. A bad operation within system operator control centre or a false trip in a device such an overhead or underground circuit breaker.

- **Fault**. It is possible to find different kind of faults in an electrical distribution system although probably the most important is a short circuit. The cause of this fault can be established by different issues but normally is caused by dielectric breakdown of insulation system. It highlights that this kind of fault can be classified by their duration. Regarding this parameter these faults can be self-clearing, temporary and permanent. A self – clearing fault appears when it is extinguished after the first instants. In this situation the system does not fall due to the fault is extinct before. A temporary fault is a fault which brings down the system although after one or several attempts the system is recovered. On the other hand, a permanent fault gets bring down the electrical network definitely and the system can be recovered repairing the point fault or changing the configuration of the system.

- **Outage**. This kind of problem appears when a part of the network is de-energized. As a difference of a fault, the outage can be scheduled or unscheduled

- **Momentary Interruption**. This kind of interruption are identified due to the time. In this case the time of this momentary interruption is lower than few minutes. If after a fault there is a reclosing and it was not achieved then there are two momentary interruptions.

- **Momentary Interruption event**. It is possible to considerer that a momentary interruption as a repetitive problem inside one. In a reclosing operation it is possible to find some interruption after different attempts, although only there is a momentary interruption event.

- **Sustained Interruption**. This kind of problem appears when after a momentary interruption event stills remain on time during more than few minutes. It is possible to find it after a circuit is opened or a fault has affected the network.

The big difference between a momentary interruption and sustained interruption is the time as it has been commented before. It is not easy to establish the border between sustained and momentary interruption due to the time to restore the network is improving continuously therefore a momentary interruption has a lower time each time. The Institute Electrical and Electronic Engineering (IEEE), has defined a five minutes time to the momentary interruption. Although in other countries such as Spain this time is three minutes.

After the analysis of power quality and reliability there are a third point to define the quality on the electrical network system. This point is the probability of an electrical part of the network being energized. Therefore, the availability is measured in percent.

In fact, the availability works with the probability of being in an interrupted state. Therefore, it is possible to consider this factor into the reliability. Some problem in the network can allow an availability problem, for this reason the reliability is into the power factor.

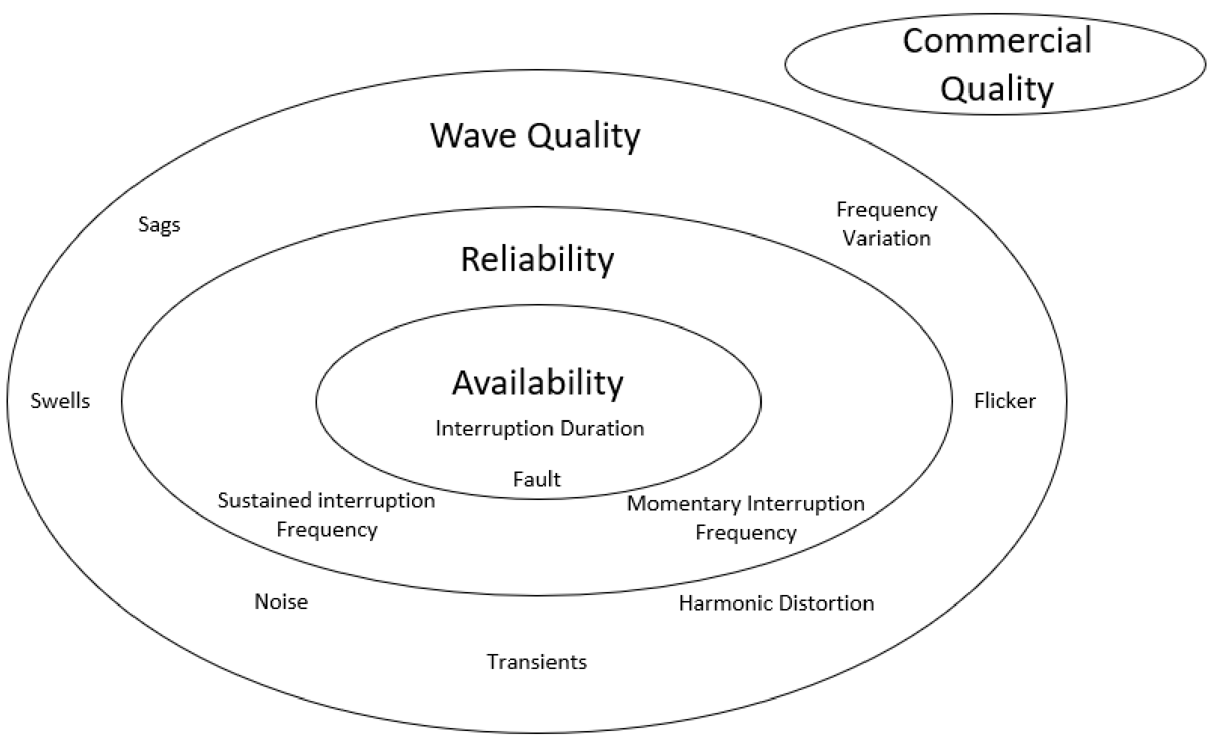


Figure 3.1 Power quality in the electrical distribution networks

The figure 3.1 shows the scheme about the relationship between power quality, reliability and availability according to [16]. The previous figure is indicating that the availability of the network is inside of reliability, in fact in front of a fault; the reliability measures the number of times that the fault appears therefore the frequency term appears. Therefore, the reliability quantifies the interruption frequency and the availability quantifies the duration as the figure shows. Into the following points will be find several indices to measure both parameters. Maybe the concept of reliability could be a term inside availability but it establishes the duration of the fault so it defines the quality level of the service.

3.1.2 Wave quality

As the figure 3.1 shows it is important to highlight that the wave quality is wrapping the two previous terms and besides is covering more parameters regarding the quality of the energy supply. For this reason, it is appearing a lot of issues which have been exposed before. Notwithstanding it is important to take into account these issues because contribute considerably in the power quality; their descriptions of the most important are shown below.

- **Voltage sag**. The sags are short-duration reductions in the voltage value in a range between 0.1 and 0.9 per unit. The duration of the sag could be between 0,5 cycles and 1 minute. The causes of this issue are given by: energization of heavy loads, starting of large induction motors, earth faults, and power transients. Sometimes an Uninterruptible Power Supply (UPS) or another storage source to prevent this phenomenon [18].

- **Short and long interruption**. The short interruption has a duration up to 3 minutes according to IEEE-1159 [19]. On the other hand, the long interruption has a duration over 3 minutes. In the part 3.3 the long interruptions will be analysed. According to IEC 61000-2-8 [20] the long interruption is considered also over 1 minute although the reconnection time could be around 3 minutes. It is important to remark that this short and long interruption in wave quality are different to the momentary and sustained interruption described before. Below in quality indices these interruptions are classified regarding the fault time.

- **Voltage Spike**. This issue is a short duration in transient which could be produced by lightning strikes, power outages, tripped circuit breakers, short circuits, power transients and other situations which can appear in the electrical network.

- **Voltage Swell**. The voltage swell is the opposite of voltage sag is an increase of voltage between 1.1 and 1.8 per unit with a duration between 0,5 cycles and 1 minute. In this case the causes could be different to the voltage sag, in instance: a switching off a large load, energizing a capacitor or even earth fault but in this case the opposite phase to the phase where the fault is [18].

- **Harmonics**. In general terms the harmonics provides to the network an issue not related with the availability or reliability as mentioned before. I this case there is an affection of wave quality produced by non-linear loads due to these loads draw a non-sinusoidal current from a sinusoidal voltage supply [21]. The harmonics can generate can generate negative effects in an electrical system. As examples of these negatives issues it is possible to find a reduction of the efficiency of the system, aging of the assets of the installation and even malfunction in several devices among other effects.

- **Voltage Fluctuation**. These fluctuations can be step-voltage changes, regular or irregular in time, and cyclic or random changes according to the variations produced in the load impedances. The variation could be among 0.9 and 1.1 per unit. These fluctuations could be caused by a flicker which is a continuous and rapid variation in the load current magnitude so it affects directly to the voltage magnitude.

- **Voltage Unbalance**. This unbalance is a result of a frequency variation in a three-phase power supply which arises due to unequal differences between the phase angles of the three respective voltages. This kind of fault can affect considerably to rotative machines.

- **Noise**. Signals with higher frequencies can be superimposed in the power system signal, although this issue has not a serious affectation in installation. The use of filters can help in order to eliminate this kind of problems.

The new deployment of DER will generate a new DG which will affect considerably to the wave quality regarding voltage issue which have been explained before, but this penetration will be affect in other points of the system such as in the hosting capacity or in harmonics [22]. The hosting capacity is the maximum DER penetration for which the power system operates satisfactorily, then the increase of DG in a network can affects considerably to the network.

3.1.3 Commercial quality

Finally, it is important to highlight that the power quality is completed through commercial quality. This concept is focused in the way to trade with the power between different actors of the electrical network distribution. The commercial quality is based mainly in several areas very related with the end customer. These aspects are related to consumer advice on contracting, billing, collection, consumption measurement and other aspects derived from the subscribed contract. In fact, these skills are very related with the service of the electrical utility with the customer a part of the energy supply. The political of advisement of the electrical utility nowadays is to help to the customers in order to select the best tariff according to their needs. Therefore, it is very important to take into account the DERs and other new elements which are appearing now.

Notwithstanding this concept was more related between the utilities and their customers nowadays new actors such as the prosumer [23] is changing the market towards new network models where there are DERs in specific areas such as [24] and Electrical Vehicles (EV) such as [25]. It is important to highlight that these changes will have a big impact in fault detection as mentioned before but it will affect considerably to the commercial quality.

These evolutions are making a new concept of the electrical network, the Digital Grid. This new electrical grid tries to give an answer to the need to integrate new DERs such as solar and wind plant generations and avoid to a small failure which can easily start cascading outages, resulting in large scale blackout [26]. This new concept segments the network which are connected asynchronously, via multileg IP addressed ac/dc/ac converters called digital grid routers. This idea is mixing customers from several countries or big areas in order to share energy and maintain a big stability in the system. Maybe in examples such as [27] it is possible to find a new market model where the storage and the sharing energy is established and where the concept of energy router appears in a rural area networks. It is important to remark that the storage can contribute to the power quality of the network regarding availability [28].

This new view of the network is evolving and will open a new vision to give the service from the utility to the customer and this point will affects considerably to commercial quality. In fact, the concept of community will appear between several prosumers, in examples such as the project EMPOWER [29] where there are established communities within prosumers working together in order to share energy and enhance their benefits.

Another future concept which will change the future of electrical sector is the blockchain where the economical transactions are decentralised. This decentralization could impact positively in an electrical network which trend to be decentralized [30].

3.2 Distribution network architectures

According to quality features in an electrical network one of the most important points which contributes directly is the selected architecture of the network. The topology of the network can help considerably to the restoration process after a fault. However, a complex architecture needs a special high control in order to handle the network and get ahead the best benefits in restoration process or in other situations such as an optimization injected power.

First of all, it is necessary to define the different labels of the traditional electrical system. The distribution network is called in some countries such as MV network; above this network it is possible to find the transmission system. This part of the network is known as HV network and finally under the MV network there is the distribution network to supply the end loads, this part of the grid is recognized as LV network. The HV and MV network is a three-phase network but the LV is a monophasic network where the neutral is distributed with other of the three phases.

Probably it is not possible to find a good definition about the HV, MV and LV levels and even in each country there is a different specification but according to the document from IEEE Std. 1585™ – 2002 the MV level is defined between 1 and 35 kV [31]. Although it highlights that an electrical network can adopt different voltage level for HV, MV or LV networks, as figure 3.2 shows there are a traditional representation of different voltage level of an electrical network. It is important to highlight that nowadays the transmission could be in levels such as 440 kV and even 1 MV [32]. Maybe MV level is considered a part of HV level, then HV level is defined from 1 kV.

In transmission system, HV networks, it is possible to find a meshed architecture where the connection between substations is point to point. This kind of architecture provides a good robustness to the network, although it is possible to find subs-transmission networks with similar architectures such as in the distribution networks [33]. There is a big interest to keep a good stability level in the transmission network due to a problem in this part of the network can give rise to a big outage.

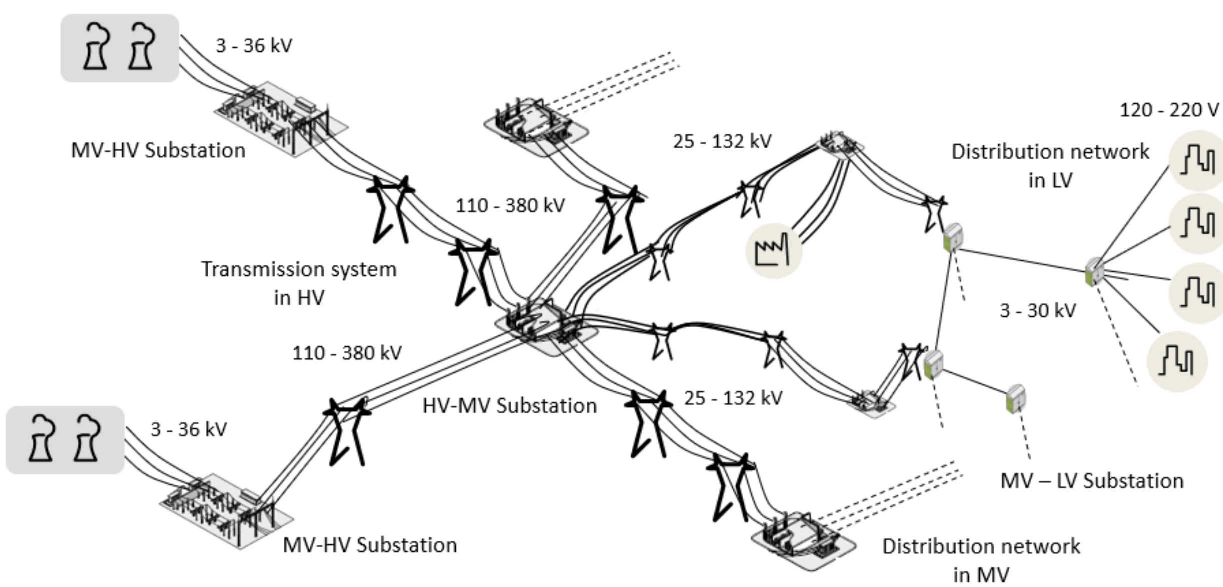


Figure 3.2 Voltage levels in electrical network

On the other hand, the LV network is defined normally with a radial architecture due to the level of loads are more concentrated that not in the other voltage levels. For this reason, is more difficult to establish complex architectures to restore the network. However, in electrical distribution network, MV networks, there is the possibility to establish several architectures to recover the network after a fault or in other conditions such as maintenance. The network is covered by transmission network and the number of customers under this level is enough to set the network several times.

There are different architectures for electrical distribution networks although it is possible to define three kinds of them: radial, ring and mesh network. Considering a node of the network as a MV-LV substation, it is possible to connect these nodes between them using these three possibilities. In fact, the radial network is a special case of ring network and this last is a special case of the mesh network. Following the different kinds of network will be described.

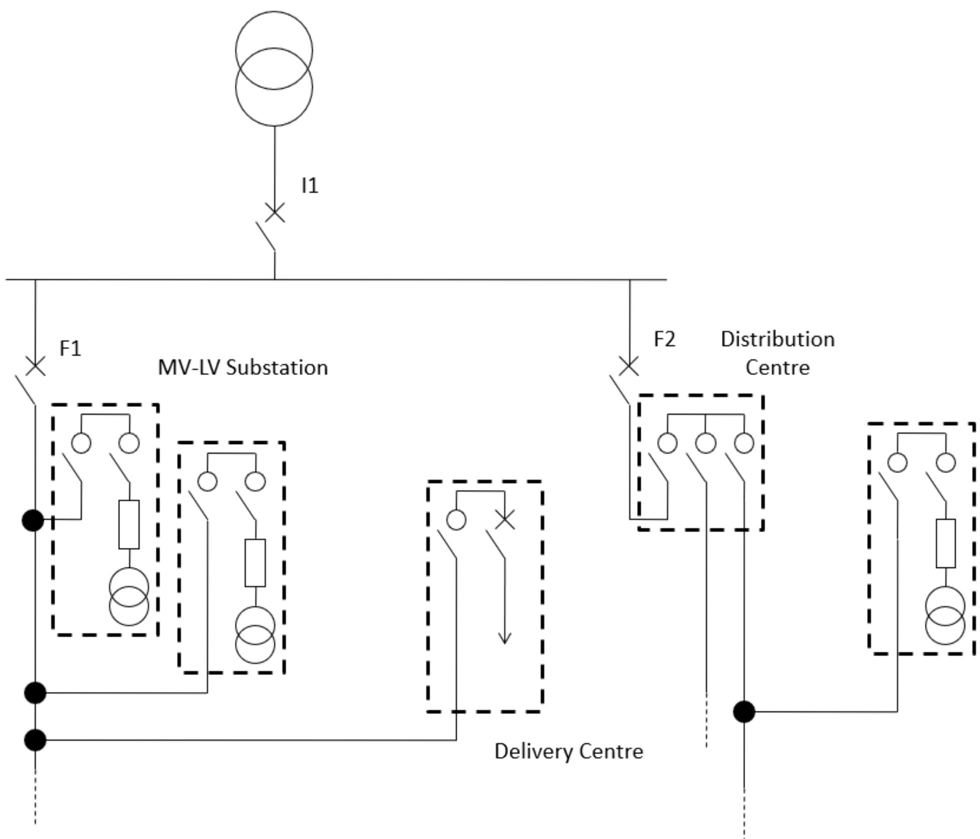


Figure 3.3 Radial architecture in MV network

3.2.1 Radial distribution

The radial distribution consists in a network with several MV-LV substations depending from the same feeder. The only possibility to receive fed from the feeder is through one way. Although it is very important to know this is an economical solution regarding the others architectures. In fact, with this architecture each MV-LV substation is using one feeder, the amount of wires is lower than other architectures and the number of connections between other MV-LV substations is not necessary. In the following figure there is the architecture of radial network.

In figure 3.3 there are MV-LV substations which are in charge to transform the voltage range from MV to LV. Besides, it is possible to find distribution centres in order to branch the network and several delivery centres to deliver energy in MV range. The unions between these centres to the output of the feeder is a direct connection without switch-disconnector.

The vast majority of MV network have the switch-disconnector as cutting element. It is a difference regarding the feeders and incomers in substation HV-MV. In this case the circuit breakers can open directly when there is a fault in the network, however the switch-disconnector cannot open under a fault because it has not the capability to isolate the current level [34].

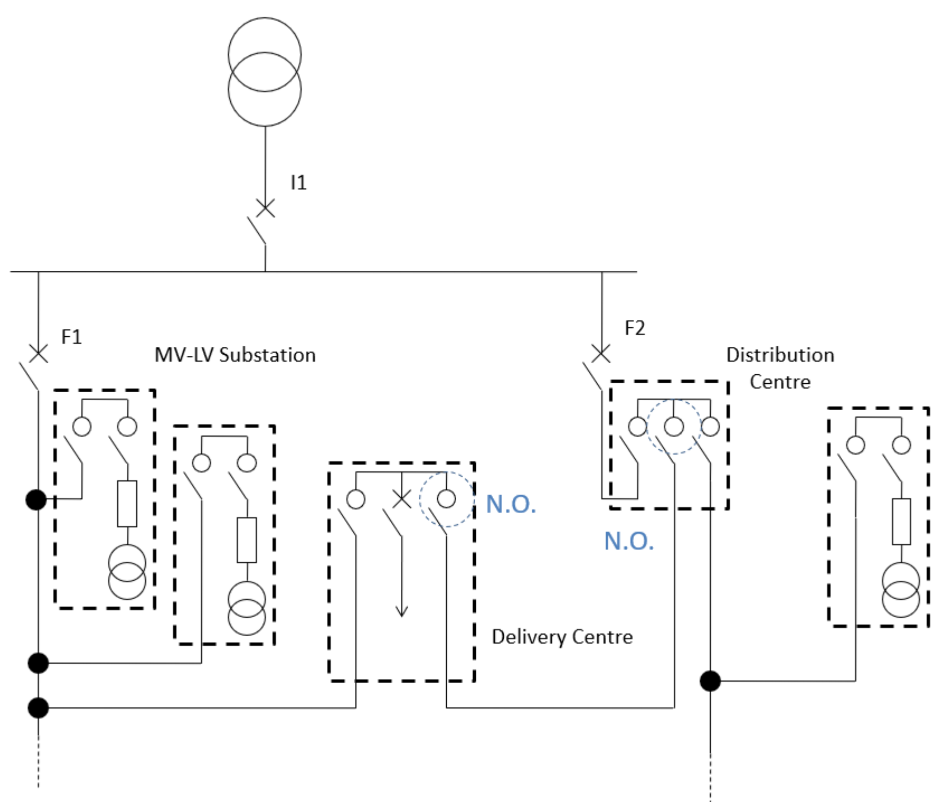


Figure 3.4 Double radial network

The radial network does not allow recovered-self after a permanent fault because there is no other alternative path. This situation is not a good input for quality service due to a fault of this kind will affect considerably to all users from the feeder where the problem is. However, a distribution like this provide an easy protection in the circuit breaker from the feeder, a better voltage control, an easy prediction and control of power flows and reduced cost [35]. Therefore, the use of this kind of network is applied in rural topology.

Inside this kind of architecture there is the possibility to establish other option: the double radial. This network architecture joints two outputs from two feeders between them, so with this configuration is easy to recover the network.

This configuration provides two the network the possibility to feed a point from two sites. In the figure 3.4 is represented an architecture where there is an intermediate link between feeder F1 and feeder F2, between delivery centre and MV-LV substation. In this case it will be necessary to implement switch-disconnector, with normally open position, N. O., in order to join both networks [36]. This kind of architecture provides to the network the possibility to support one fault although it is necessary to install some additional switch-disconnector.

3.2.2 Ring distribution

The ring distribution can establish more possibilities to restore because each frame of the network is separated by two switch-disconnectors. By this way the network can be restored easily in front of a fault in one of their frames. In these architectures two feeders from one substation and from different substations are in the same frame.

Unlike the radial distribution, in this case MV-LV substations have switch-disconnectors in their input and in their output to link the different centres. The figure 3.5 shows this kind of architecture. In this case there are several switch-disconnectors in order to link the different nodes of the network and separate between them after some new configuration of the network. Inside of the ring there is normally open position in one of the switch-disconnector, under a fault only the outgoing feeders can react about it because there is a circuit breaker in each of them. When there is a fault in the ring one of the feeders will open the circuit breaker and this part of the ring will lose the voltage but not the whole ring because the current only will drive in one part of the ring through the feeder until to point of the fault.

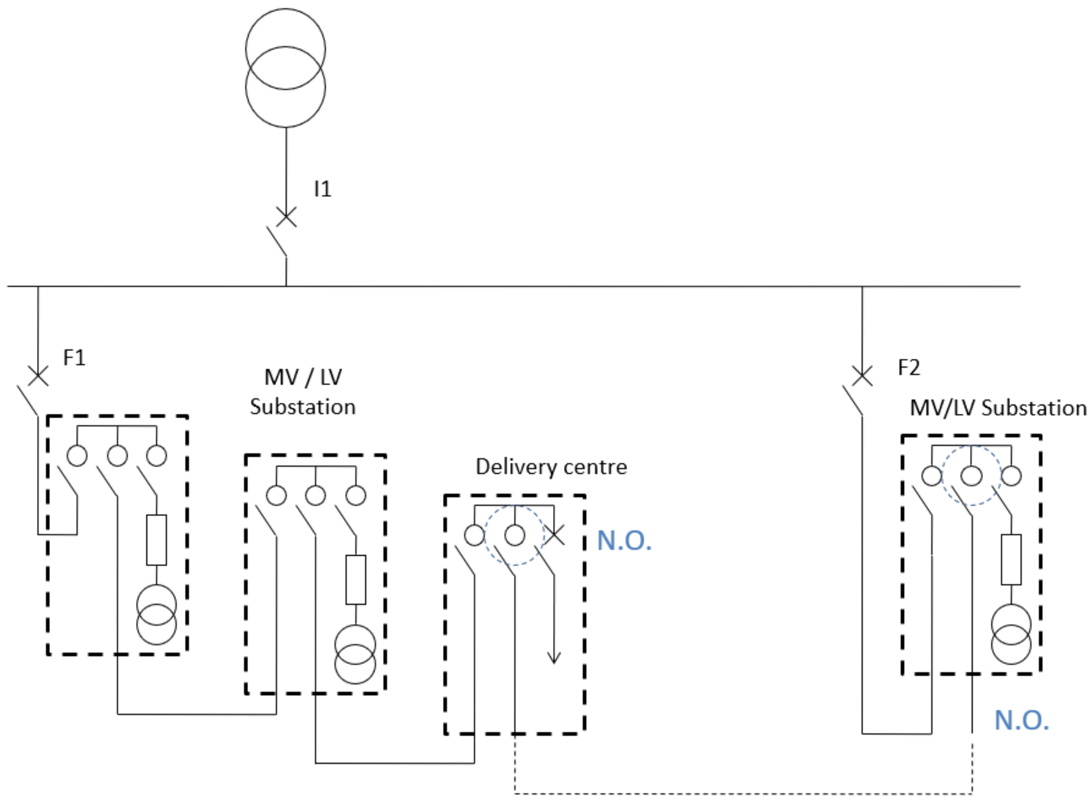


Figure 3.5 Ring distribution

Nowadays this kind of the architectures there are in the urban or industrial areas and even in industrial complexes. Unlike the radial distribution in the urban area the distances are too shorts and with electrical underground installation, this is a good opportunity to use a ring distribution because there is a possibility to restore the network and to give supply to the users.

This architecture can be improved using circuit breakers instead of switch-disconnectors in the MV-LV substation and other kind of centres. With this configuration it will be possible to open directly the circuit breaker most neared to the fault and isolate it in the network. Although with this kind of configuration it is necessary to establish some discrimination between circuit breakers in order to avoid several trips from different circuit breakers. The problem of this improvement is the cost of the system to implement and their components, however the reaction in the network is more establish because only a few users of the part of the ring will lose the supply in a first time before restore process.

3.2.3 Meshed distribution

Through last architectures showed before it is possible to define a new configuration in order to help substantially to reconfiguration process. This solution is a meshed distribution where there is a union between two or more rings such as the figure 3.6 shows. Therefore, in the case of a fault in the network it is possible to offer service again through other part of the ring.

This architecture improves the possibilities of the reconfiguration system and even the possibility to improve the energy distribution in the network. The mesh network allows different configuration of energy distribution from the distributed energy resources, DER, to the loads.

The union between rings is one of the possibilities of the mesh network although it is possible to make union between MV-LV substations independently. In instance the Dong Energy North network is located in urban areas with underground configuration. In this network, there are a lot of unions and back-ups between centres as it is showed in [37] and in [38]. In figure 3.7 there is this meshed topology of network to allow a fast restoration in front of faults.

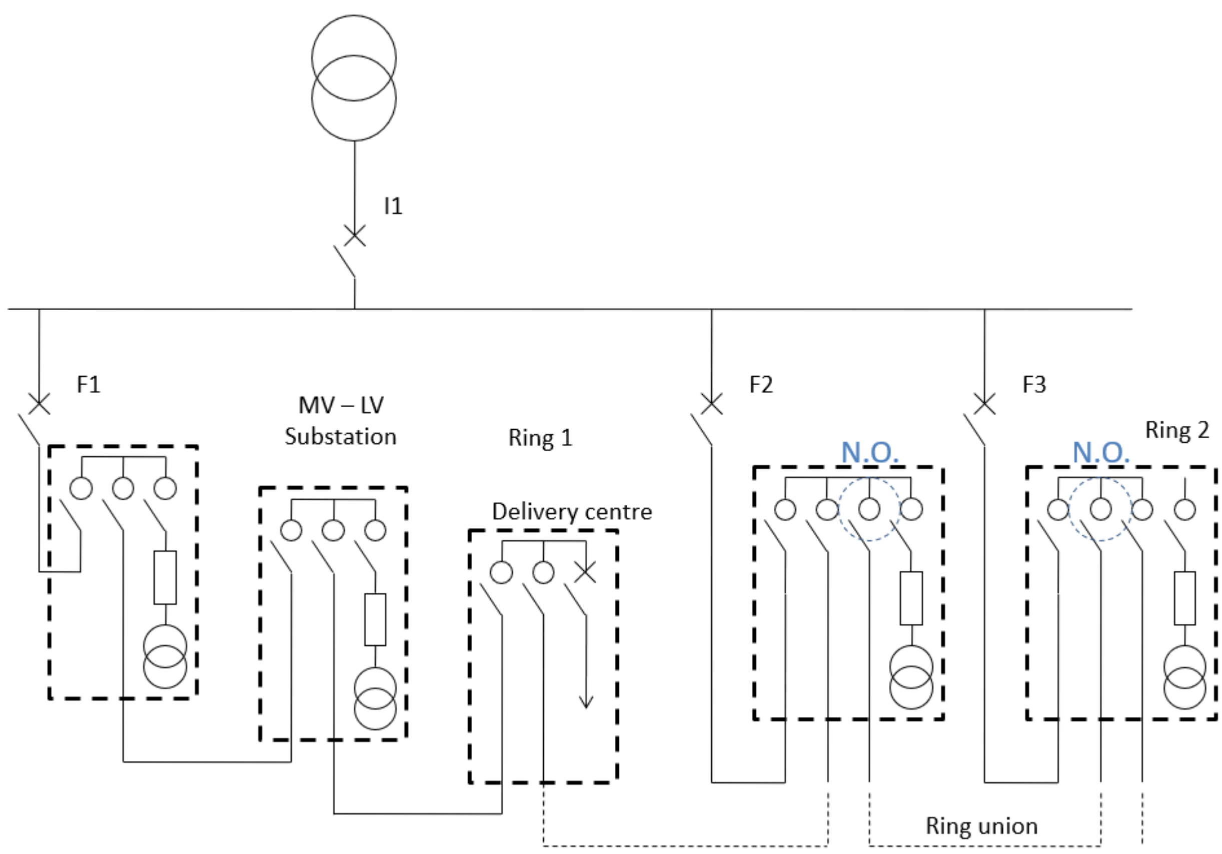


Figure 3.6 Mesh distribution network

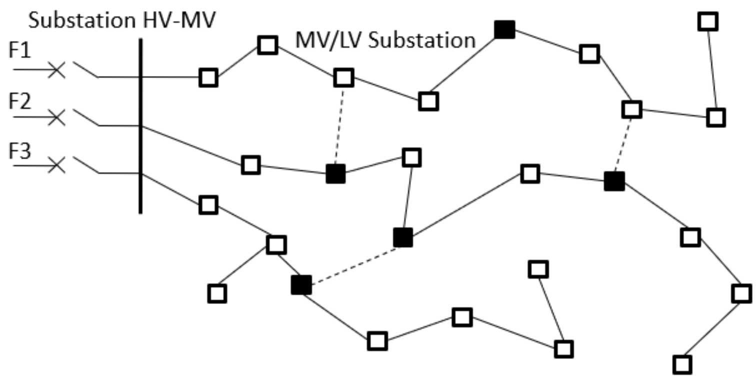


Figure 3.7 Dong Energy North network

3.2.4 Other distribution networks

It highlights there are more architectures which can give more reliability to the system such as the architecture for substation with double busbar in instance. The goal of this architecture is to establish a supply the feeder by two incomers from different transformers as the figure 3.8 shows.

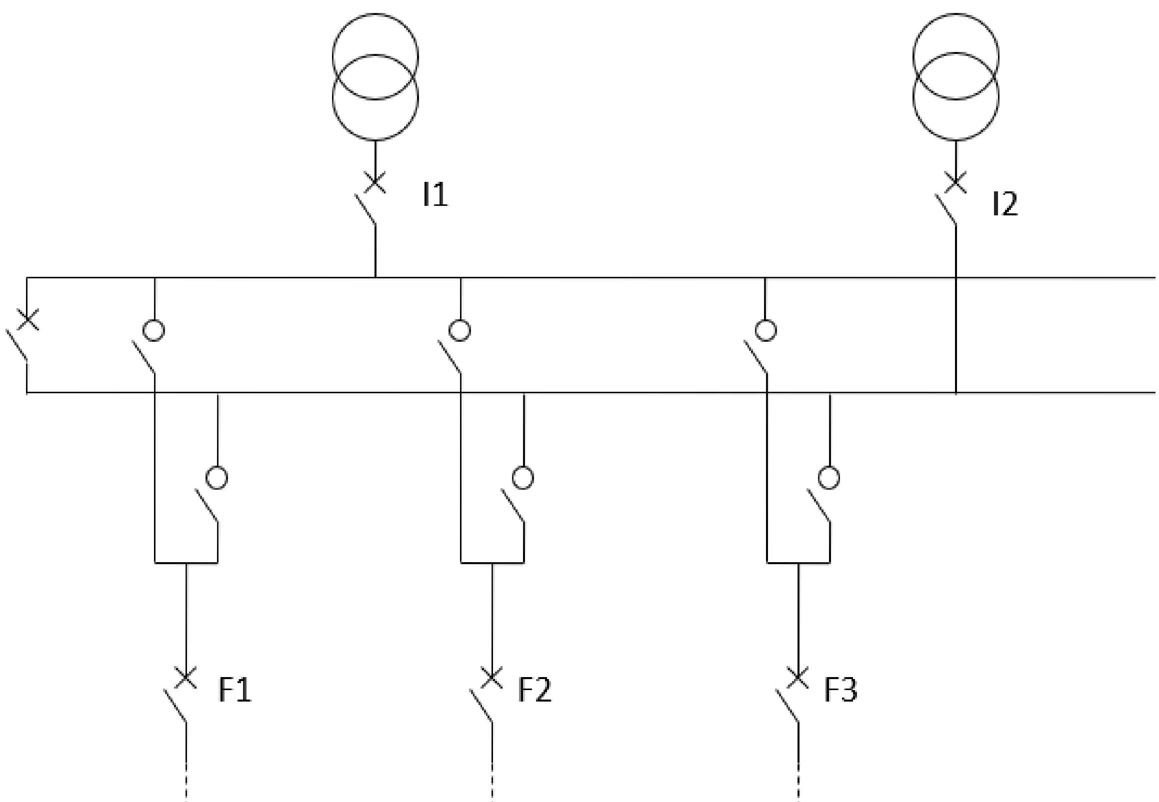


Figure 3.8 Double busbar in HV-MV substation

On the other hand, there is the possibility to feed in parallel each MV-LV substation receive supply from two feeders of different HV-MV substations with different transformers [39]. These auxiliary and redundant architectures contribute with reliability to the system although increase the cost of the investment. Therefore, this kind of architecture can be used when there is a critical area which needs an uninterruptible supply.

It is important to remark that this kind of networks could integrate DER instead of MV-LV substations such as the figure 3.9 shows. In fact, not only the DERs are directly in MV network, it is possible to find it in the LV network. In this last figure it is possible to see a DER in the LV distribution, therefore the distributed generation will be a new constant in the future networks for instance in applications such as applications like self-consumption. As mentioned before the EV will have a big deployment next years, so the electrical network will have to be prepared to assume this near future. It is important to remark that the DER in the figure 3.9 is connected to the network through circuit breaker, this element could be a fuse but the circuit breaker ensures a fast disconnection in front of a fault.

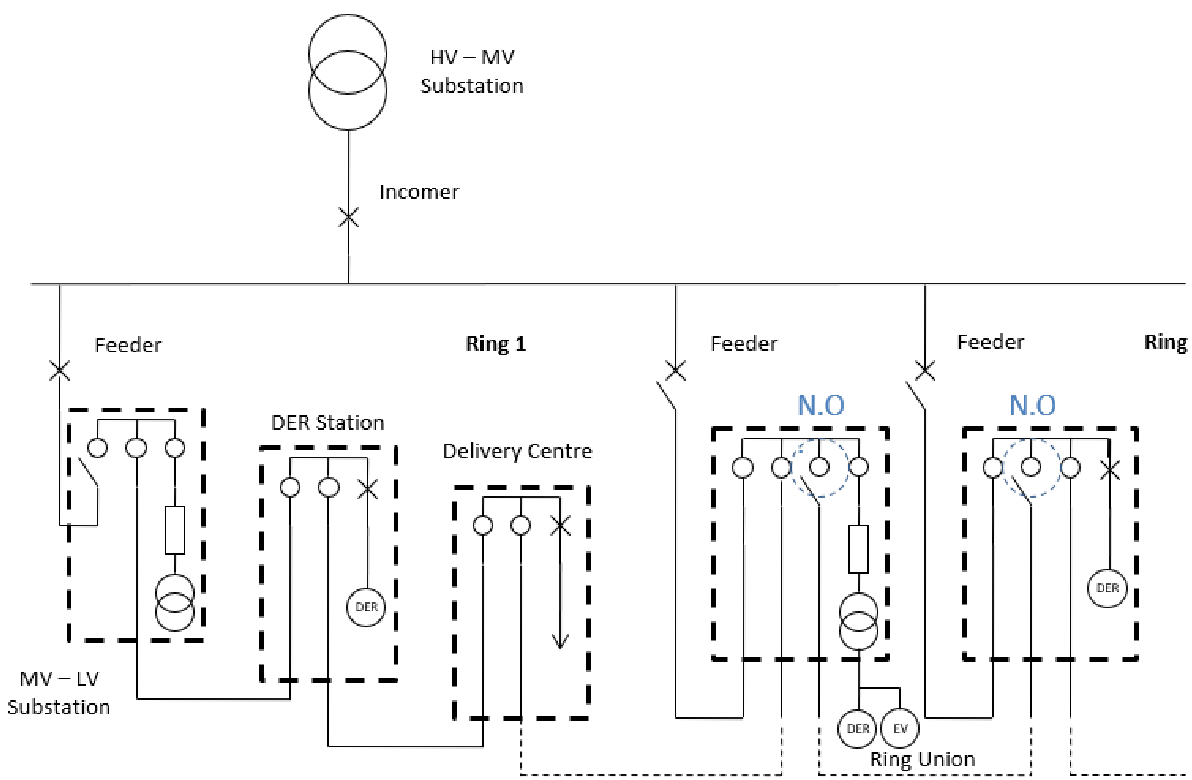


Figure 3.9 Mesh distribution network with DER and EV

In order to clarify better the LV distribution is interesting to see the figure 3.10 where a MV-LV substation is represented with the input and the output to the link and the output to the transformer where the LV distribution connect the common loads, DERs and EVs. In fact, the interconnections from the LV box will establish 12 lines in order to collect several monophasic elements.

Nowadays the network is evolving to this model with this news actor as mentioned before. If there is a combination between several DERs and EV in LV network and also in MV network with DERs and storage, the efficiency in the network could be increase considerably due to it will be possible transport the energy between several nodes reducing technical losses. It is important to remark that this kind of network will require new models to manage this area of the networks from the electric utility and also between users as commented in commercial quality section. Not only is the power control the new need to manage this new model of network besides the fault detection in several parts of the network will be a key part to avoid a small outage and consequently a black-out.

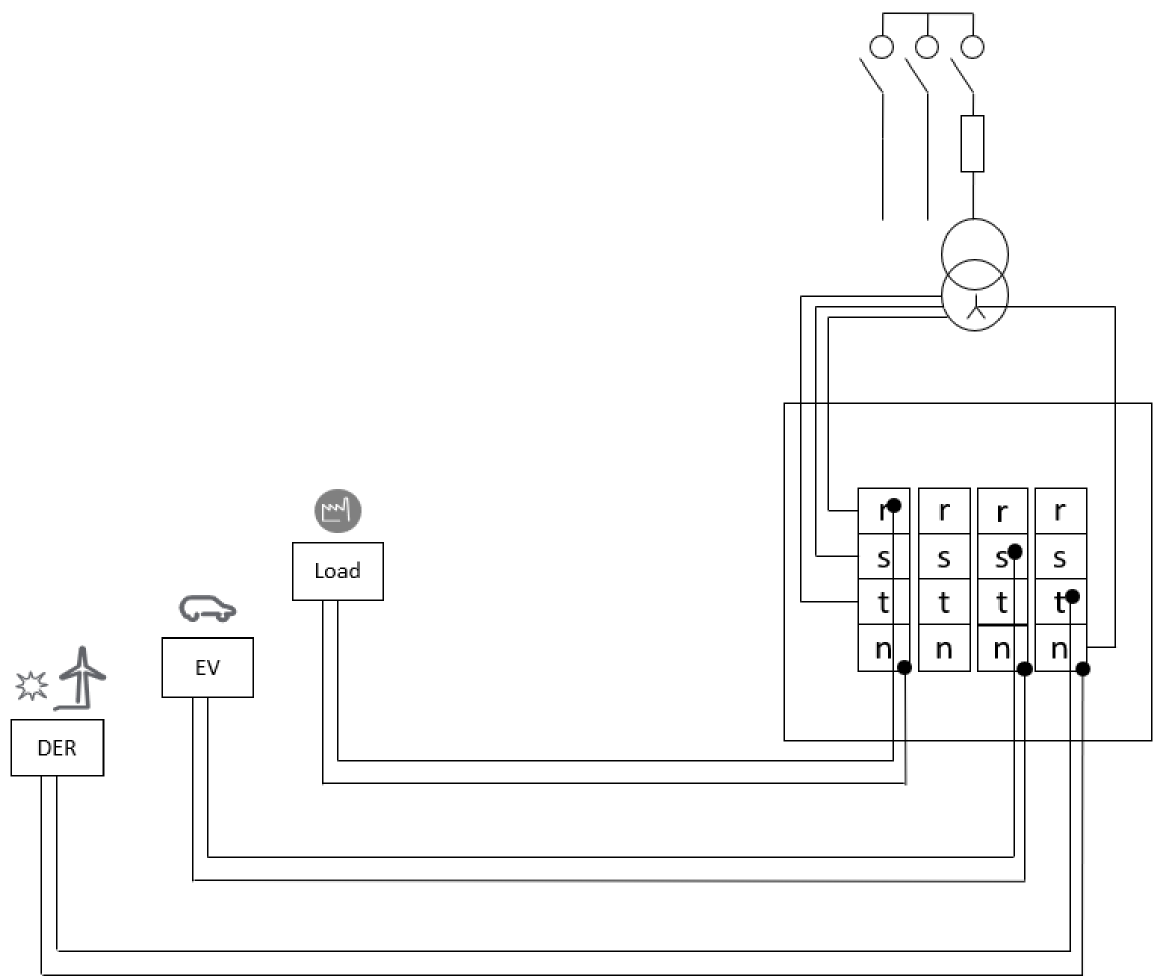
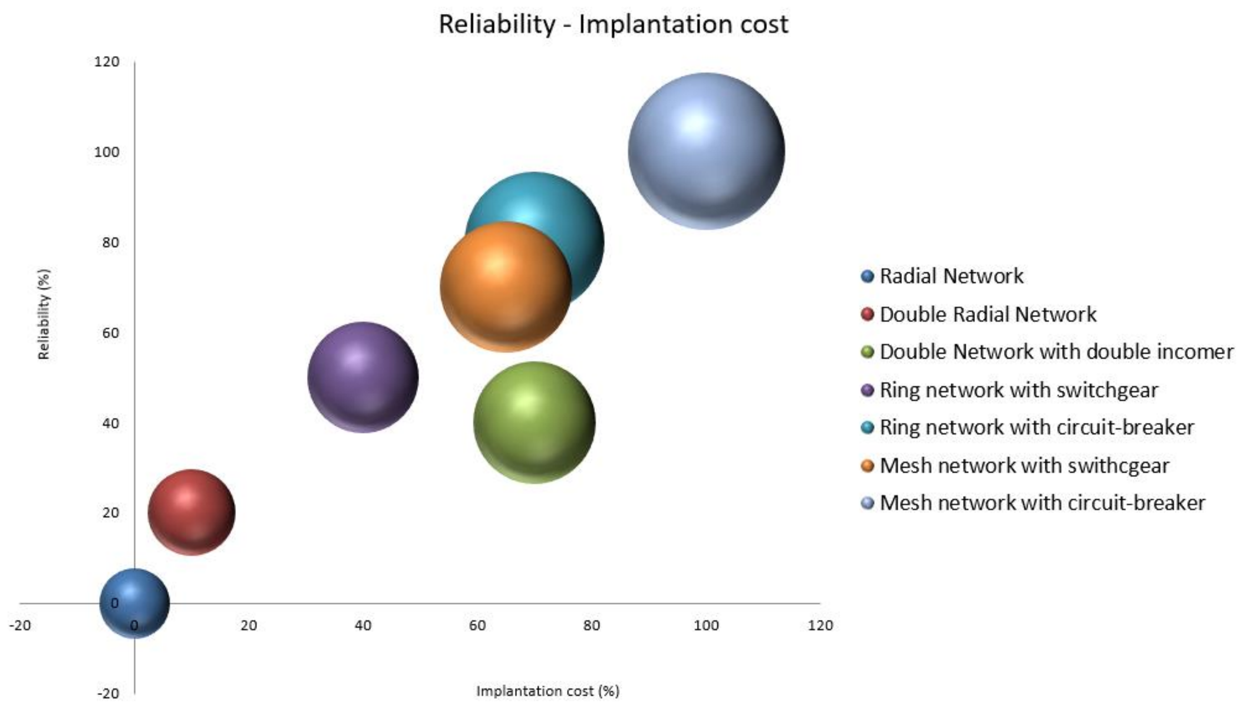


Figure 3.10 LV distribution network from MV-LV substation

3.2.5 Quality of supply according to network architecture

Regarding the previous showed architectures, some of them can provide better possibilities to restore than others, so taking into account that the simple architecture and the most economical is the radial distribution and the most expensive is the mesh distribution network, it is possible to establish a relationship between economic cost and restoration level.

The graph 3.1 shows different kinds of architecture which has been defined previously; it is a comparative between implantation cost and reliability. One of the variables used to define more architecture is the use of circuit breaker instead of switch-disconnector. The data of this figure has been extracted from the integration of several publication such as [39], [40] and [41].



Graph 3.1 Comparative between reliability and implantation cost in distribution networks

As the last figure shows a mesh network with circuit breaker contributes to increase the reliability of the network in front of isolation of a fault. However, the cost of this network is higher than not a ring network with switch-disconnector.

It is important do not forget that the architecture influences directly in the quality of service in the network, therefore a combination of architecture can improve the supply in an existing network according to the needs of the users. For example, there are distribution networks in rural areas where is difficult to establish a ring due to the distance and the orography, in these cases the best option will be to use a radial network because the total cost will be very high [42]. According to this publication several algorithms can be applied in order to decide where is the best position for each MV-LV substation. Therefore, it is important to highlight the differences between rural and urban world for an electrical system mainly the structure of the network in front of the investment plans. The rural network has a ramified structure and the urban network has a mesh or ring structure.

In other cases, such as [43] where the implantation area is an urban area other kind of structure exposed before as ring or mesh can be applied in order to give a high-quality service to the network. In urban areas there is a good possibility to invest in complete structure like mesh networks because the number of customer is high in comparison with other areas, so the return of investment is a short period and on the other hand the impact in the global quality of the network will be more effective. Regarding [43] it is necessary to establish an algorithm or procedure in order to define in urban areas the best solution to deploy the different nodes of the networks. The combination of several network structures with different technologies allow to find the best solution for every network.

3.3 Quality standard indices

In order to classify the quality of an electrical network there are a lot of indices to define it. These indices are classified regarding interruption and load according to the document IEEE Std. 1366™-2003 [44]. On the other hand, there are other indices which are focused to describe momentary situations. This fact shows that it is possible to establish two types of interruptions: sustainable and momentary. Although the most important indices as a world reference are SAIFI and SAIDI mentioned previously in the introduction of this thesis, which define the frequency and duration respectively [35].

3.3.1 Sustainable interruption indices

This set of indices has the main aim to evaluate the reliability of the network analysing it from the point of view of the user. The user in this case is the actor of the network who consumes energy. The calculation of these indices allows knowing the quality level of the electrical network although this quality not only depends on the supply continuity but also the wave quality and the commercial relationship between the customer and the electrical utility.

3.3.1.1 SAIFI

The SAIFI index has the aim to evaluate the frequency with which a user experiments a sustainable interruption during a predefined period of time. This index is a rate between the affected users by interruption and the total number of users of the network. The expression 3.1 there is the index mathematically expressed.

$$SAIFI = \frac{1}{N} \cdot \sum_{i=1}^{n} I_i \quad [3.1]$$

Where, I_i is the number of interruptions from user i and N is the total number of users.

3.3.1.2 SAIDI

The SAIDI index identifies the average duration of the interruptions from the users of the network during a period of time. The unit to quantify is the hour or minutes per year. Therefore, this index defines the relationship between the total duration of the interruptions and the total number of users. The expression 3.2 defines this index.

$$SAIDI = \frac{1}{N} \cdot \sum_{i=1}^{n} D_i \quad [3.2]$$

Where, D_i is the total duration of the user i and N is the total number of users.

3.3.1.3 CAIDI

The Customer Average Interruption Duration Index (CAIDI) sets the average time to restore the network. In fact, the indices SAIDI and SAIFI are implicit in this index which shows the restoration time of the network from the user view. The value of the index is lower than the restoration time due to during recover process some customers will recover the supply through other intermediate circuits. The expression 3.3 shows the relationship between duration and frequency.

$$CAIDI = \frac{SAIDI}{SAIFI} = \sum_{i=1}^{n} D_i \cdot \left(\sum_{i=1}^{n} I_i \right)^{-1} \quad [3.3]$$

3.3.1.4 CTAIDI

The Customer Total Average Interruption Duration Index (CTAIDI) shows the average total time in the information period. Unlike the CAIDI index, this index takes in account only one time the users which have had an outage, in other words, if a user has suffered several interruptions then the index will only count one time inside of total number of users with interruption. The expression 3.4 shows the mathematical expression of this index.

$$CTAIDI = \sum_{i=1}^{n} D_i \cdot \left(\sum_{j=1}^{n} U_j \right)^{-1} \quad [3.4]$$

Where, U_j takes the value 1 if the user j has suffered one or more interruptions or the value 0 if there has not suffered anything. Thus, the affected user is counted one time.

3.3.1.5 CAIFI

The Customer Average Interruption Frequency Index (CAIFI) has the goal to offer an average frequency of interruptions which is suffered by affected users. As previous index the user is counted one time. In the expression 3.5 there is this index.

$$CAIFI = \sum_{i=1}^{n} I_i \cdot \left(\sum_{j=1}^{n} U_j\right)^{-1} \qquad [3.5]$$

3.3.1.6 ASAI

The Average Service Availability Index (ASAI), analyses the time fraction that one user has received energy; in other words, by means of this index is it possible to analyse the average annual outage time. In the equation 3.6 is expressed mathematically the rate between number of availability hours and demand hours.

$$ASAI = \left(\sum_{i=1}^{n} 8760 \cdot N_i - \sum_{i=1}^{n} D_i\right) \cdot \left(\sum_{i=1}^{n} 8760 \cdot N_i\right)^{-1} \qquad [3.6]$$

Where the number of users of the system is N_i. Therefore, it can set the consideration of 8760 hours by year such as service supply hours although this quantity could be other according to the selected analysis period.

3.3.1.7 CEMI

The Customers Experiencing Multiple Interruption (CEMI), shows a customer rate where the users have suffered more than one interruption regarding the total number of customers. This index is defined mathematically by the expression 3.7 and it can offer a vision about the general status of the network, focusing in the location of the interruptions. In fact, this index is analysing the distribution of the interruptions in the network.

$$CEMI = \frac{1}{I} \cdot \left[\sum_{i=1}^{n} I_i\right]_m \qquad [3.7]$$

Where, I is the total number of interruptions and the suffix m expresses the set of users with more than m interruptions. The interest of this index is important due to know the reliability of the network in order to analyse the places with there are more interruptions. It is possible to set the index for any number of interruptions and thus to allow the interruption distribution analysis in the different customers.

3.3.2 Indices based on the load

3.3.2.1 ASIFI

The Average System Interruption Frequency Index (ASIFI) is based on the load instead of the affected customer. This index is used in order to measure the efficiency of the energy distribution in areas where there are few users but with a big consumption. These areas are such big industrial complex and commercials. In a system with a distributed homogeneous load, the index ASIFI would be equal to SAIFI. In the equation 3.8 there are the mathematical expression of this index.

$$ASIFI = \frac{1}{C_T} \cdot \sum_{i=1}^{n} C_i \qquad [3.8]$$

Where C_i is the interrupted load in the interruption i, on the other hand C_T is the total supplied load in the network. In Spain the distribution utilities use an equivalent called “Número de Interrupciones Equivalente de la Potencia Instalada” (NIEPI).

3.3.2.2 ASIDI

The Average System Interruption Duration Index (ASIDI) is based in load as the ASIFI index. Also, this index contributes in the analysis of efficiency of the network at partial level with few users but relatively greats. In the expression 3.9 it is possible to find the mathematical expression of this index.

$$ASIDI = \frac{1}{C_T} \cdot \sum_{i=1}^{n} Cs_i \qquad [3.9]$$

Where Cs_i is the interrupted load during the interruption i. In an electrical utility is difficult to know the supplied load during interruption than not the number of users without supply. On the other hand, this index is known in Spain as “Tiempo de Interrupción Equivalente de Potencia Instalada” (TIEPI), inside the MV Network environment. The TIEPI and NIEPI are analysed per provinces in Spain [45].

After the process in MV network to implant smart meters, the electrical utilities will know with a good accuracy the different outages of the users a long one year. In fact, it will know the consumption power from each user previously. This accuracy will allow analysing the reliability of the network with new parameters.

3.3.3 Other momentary indices

There are other indices which define momentary situations with the goal to analyse the momentary interruption effects under 5 minutes according to [44]. This index is interesting due to analyse a reliable network. Although an electrical network is reliable, it can have a lot of little interruptions. Therefore, there are a several indexes to analyse this issue. Probably this kind of situation can be found in urban areas where the substation's feeders have the reclose function.

3.3.3.1 MAIFI

The Momentary Average Interruption Frequency Index (MAIFI), shows the average frequency of the momentary interruptions in an electrical network. In the expression 3.10 there is the mathematical expression of this index.

$$MAIFI = \frac{1}{N} \cdot \left[\sum_{i=1}^{n} I_i \right]_m \qquad [3.10]$$

Where the suffix m is the number of momentary instantaneous interruptions of the users. As CEMI index it is possible to set this suffix in order to split different momentary interruptions of the users according to the time of the issue.

3.3.3.2 $MAIFI_E$

The Momentary Average Interruption Event Frequency Index ($MAIFI_E$), shows the average frequency of momentary interruptions events. This index excludes those interruptions the events immediately preceding a lockout.

$$MAIFI_E = \frac{1}{N} \cdot \left[\sum_{i=1}^{n} I_i \right]_{mE} \qquad [3.11]$$

The expression 3.11 shows the mathematically equation of the $MAIFI_E$ index; where the suffix mE is referred to the momentary events.

3.3.3.3 $CEMSMi_n$

The last showed index in this document is Customers Experiencing Multiple Sustained and Momentary Events ($CEMSMi_n$). The index shows the relation between individual users which experience more than n sustainable interruptions and m momentary interruption events regarding the rest of the users. In the equation 3.12 there are the mathematical expression of this index.

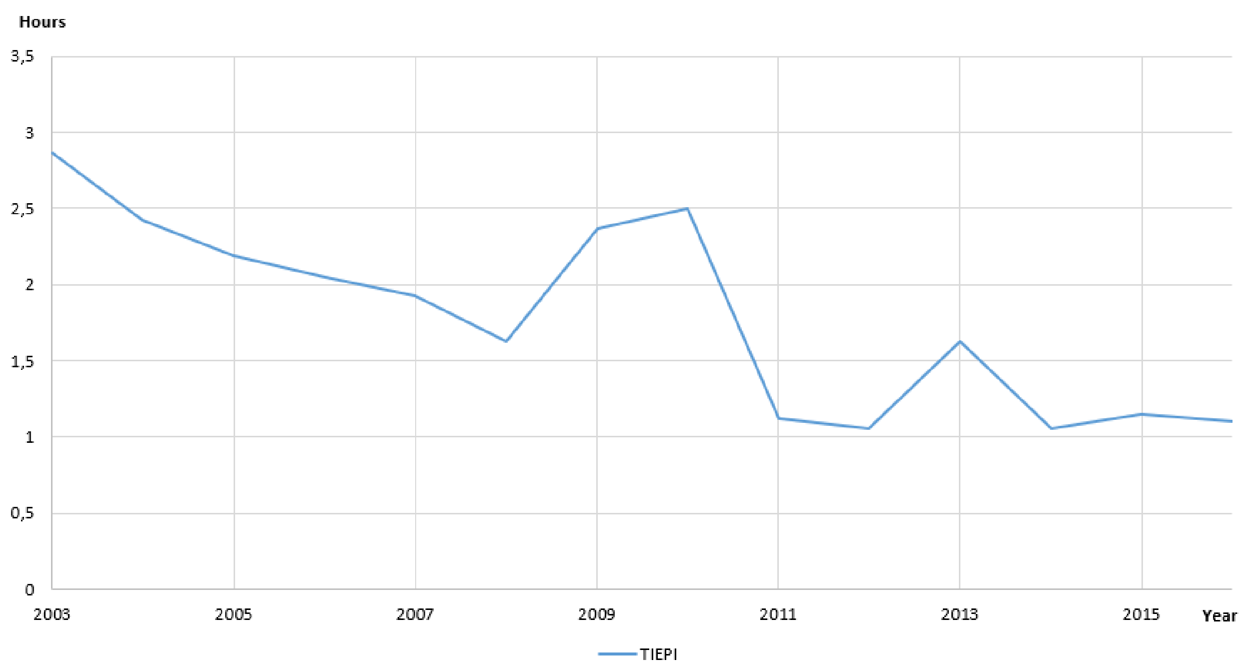
$$CEMSMi_n = \frac{1}{N} \cdot \left[\sum_{i=1}^{n} I_i \right]_{nm} \qquad [3.12]$$

This index has the goal to help to identify the issues in not observed customers. Sometimes it is difficult to detect this customer by means of some averages.

3.3.4 Implication of the automation in quality indices

In fact, it is possible to find more kind of indices and methods in order to analyse the quality of the network regarding availability according to [44] apart from the previously mentioned. Each country analyses these indices in different ways and apply different polices in order to enhance the network in their territories.

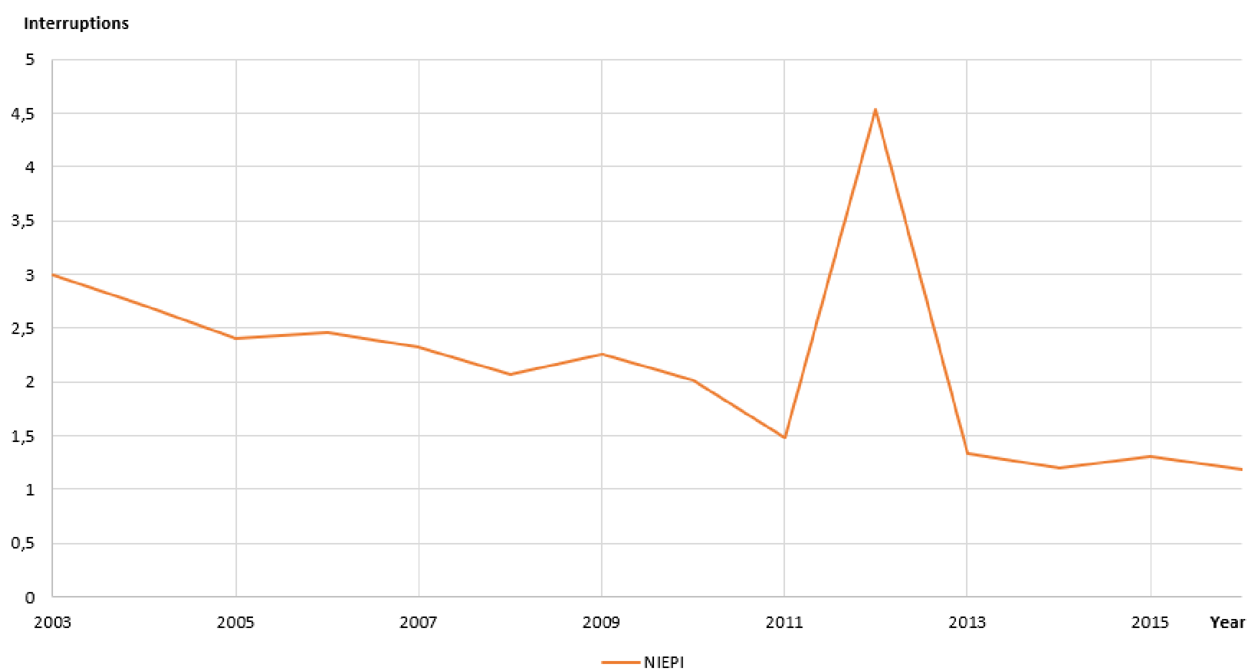
Nowadays it is important to highlight that the evolution of IT in last decades has contributed considerably in enhance these quality indices in electrical distribution networks. In fact, the trend of indices such as SAIDI and SAIFI is decreasing continuously year by year in several countries around the world according to [46] and [47]. This fact has been due to the deployment of automation in several points of the network, only with a roll out of telecontrol points in the network it is possible to reduce considerably SAIDI and SAIFI.



Graph 3.2 TIEPI in the period 2003-2016 in Spain, source from MINETAD

In the case of Spain, it is possible to analyse this reduction considerably during last decade. According to Ministerio de Energía, Turismo y Agenda Digital (MINETAD) sources [48], the graph 3.2 defines the evolution from 2003 until 2016 about the TIEPI and the graph 3.3 for NIEPI indices in the electrical distribution network. It is important to remark that the trend of TIEPI and NIEPI indices has decreased considerably during this period due to the telecontrol deployment. Although this deployment not only has been an installation plan of several devices in the electrical distribution, besides a several innovation projects developed and implanted for utilities and manufacturers such as [49], [50], [51] and [52] have contributed considerably to establish this positive trend. This kind of improvements will be analysed in following chapters of this thesis, where the feeder automation and high control systems can contribute considerably in this aspect.

Analysing the graph 3.3 the year 2012 there was an anomaly in NIEPI maybe an unusual issue in the network. According to [48] the problem was in a decentralized rural area, probably it is one of the sites where the investments are necessary to enhance the network in order to control the affected customers.



Graph 3.3 NIEPI in the period 2003-2016 in Spain, source from MINETAD

4. Electrical network simulation

After to analyse the different quality indices; the next step is to focus in the reliability of the network. Inside reliability study there are different methods based in analysis and simulation in order to define all possible network device problems. These problems could be a specific malfunctioning in a protection or detection device or even in a cut element such as switch-disconnector or circuit breaker and also in the wires after years of use.

Besides these methodologies it is important to think in the interruption causes to establish a model of the network in order to evaluate any algorithm. Knowing the causes of a fault can help to establish a test of some algorithm before test in real network.

In next chapters the high control system will be introduced through automation concept in the network although it is important to remark that in these systems it is possible to apply this simulation methods using all data collected such as an historical data base. The combination between this simulation with the historical data and other detection systems can help considerably to a fault detection and as consequence to enhance the quality indices showed before improving the electrical distribution network. Although it is not the goal of this thesis to deepen in electrical network simulation.

It is important to remark that the combination of several methodologies can provide a good detection of the fault in order to start a restore process. The current electrical networks have not reached a high automated level due to their dimensions therefore a fault detection could be based in probability methods joint other direct detections through the deployed devices in the network.

4.1 Interruption causes

As it has been mentioned in last section, the availability is one of the most important parameters of the quality in an electrical network although it can be caused by a lot of phenomena. The interruptions in the network are caused by different reasons. Among these causes can find equipment failures, animals, weather, trees and human factors. Probably this classification includes all possible causes although in front of a fault it is possible to find a combination of them.

An installed device in electrical network is prepared to do some functions and probably has several parts and overall is composed by several pieces. This fact means that there will be a probability of falling. This probability is related with the age of the devices although the chemical decomposition or the state of contamination can affect considerably.

Among these devices it is possible to find the transformers, the underground cable, the overhead lines, poles, circuit breakers, surge arresters, insulators and bushings, protection elements control elements, other communications networks independent from the network. These several elements of the network have a failure probability which composed between them define a general probability.

According to [16] several animals can establish the origin of a fault; it is possible to find examples such as squirrels, mice, rats, gophers, in fact different kind of rodents, birds, snakes and large animals. This classification can be change a lot regarding the fauna and habitat in each country or analysed area. There are several methods to avoid that the animals come into contact with electrical network, although it is difficult to avoid this problem overall in the case of the birds with overhead lines.

On the other hand, a severe weather can be a cause of interruption. Among these causes can find the extreme wind, tornados, hurricanes, vibrations, floods, rivers, overflow, lighting storms, ice storms, heat storms, earthquakes and fires. As in the case of animals this classification will be different in each country depending on climate conditions.

As it has mentioned before the trees are elements can origin a fault in the network and can contribute to do it with different ways. In instance can make a mechanical damage in a conductor, can allow to other animals to use them as a gateway to access to the electrical poles and can cause a fault when growing brunches push or fall above the overhead line.

Finally, the human factor is responsible for many interruptions in electrical network due to no controlled causes such as human error, vehicular accidents, excavations, vandalism and scheduled interruptions in order to modify configurations in the networks. Probably the last one although is controlled by utility sometimes in radial network it is impossible to avoid this situation. For this reason, in urban areas the ring distribution starts to be more used.

4.2 Analytic methods

The analytics methods represent the distribution system with mathematical equations in order to solve using reliability indices. These methods are between the results, the model and simulation methods in order to stimulate the random network behaviour approaching to the system restoration in front a perturbation [53].

A distribution system can be modelled as a set of connected components between them. The previous showed indices can be defined to capture the fault effects in each system component. The analytic methodology used to value the reliability provides the average performance of the system. In order to develop this method, it is possible to use some tools to evaluate the reliability distribution in the system. Some examples of these tools are state spaces, fault mode, event tree and fault tree.

The state space has the goal to represent a system defining all interest status which can be adopted by the system. This method uses the transition between fault states of components until normal or partial restoration status during adversities. The transition between statuses is modelled by Markov process which refines the problem; in fact, in Markov process it is possible to find finite statuses depending on the previous status.

In this process there are two variables: the fail rate and the repair rate. Through this process it is possible to establish probabilistic functions to define by example the availability of supply in a specific time moment [53]. In the expression 4.1 there is the supply probability in a time moment.

$$Prob\left(P(t)\right) = \frac{\mu}{\mu + \lambda} + \frac{\lambda^{e^{-(\lambda+\mu)t}}}{\lambda + \mu} \quad [4.1]$$

Where λ is the fail probability and μ is the repair probability. In order to define the fail rate, it will be necessary to know the fail and repair rate of each element of the network. After that the global rates λ and μ can be determined making a calculus by serial or parallel components.

There are other analytic methods such as the Failure Modes and Effects Analysis (FMEA), which identifies a fail status in a unique component. After this fail the component is repaired before other fail can appears. In this method, the fail statuses are registered with the number of affected customers and the event duration.

From the implementation of this method it is possible to use another tree analytic methods to describe possible fail scenarios in a distribution network. The most important point is to date this information to have a detailed description of the behaviour of the distribution system.

4.3 Simulation methods

The simulation methods give a modification in the distribution function showing the expected reliability. This methodology can be difficult to deal in procedures and process due to there is a lot of data. Although the evolution of the IT has been increasing last years and now it is possible to work with a lot of information. In fact, the data centres are a good tool in order to save this information to analyse after.

The methods commented previously do not use the variability in a distribution network. However, the simulation methods can be give this variability and additionally establish all scenarios and processes to estimate an interruption frequency for the complete system, estimate maintenance procedures, control interruption cost and show the uncertainty between fail and repair.

There are several methods to apply in a distribution network which are integrated in high systems software. One of them is Monte Carlo method which can simulate the fail, the repair and restoration of the system.

In Monte Carlo method, there are two kinds: sequential and no sequential. The first one is a dynamic simulation of the status, in other words, each component of the system is modelled in fail and repair terms. This information is stored such historical events and simulated random. This method gives information more accuracy than not the analytic methods which can be applied in electrical networks such as in [54].

The sequential method makes an artificial event list to determinate the reliability of the system. This list is based in the order of happened events. Although this method assumes that the happened contingencies in the system are exclusives and therefore the behaviour of the system does not depend on the last events.

5. Fault location in electrical distribution networks

The availability quality can be affected by different types of serious faults such as phase fault or earth faults, although also less serious faults are in the network such as bad quality of voltage which can allow drops and peaks and even oscillations on the waveform. In fact, these phenomena are present in power quality as it has been mentioned before.

Any transient phenomenon can affect considerably to the near users to the fault although an outage in a part of the network can affect considerably to the rest of the users. The transient oscillation phenomenon will affect to the voltage network quality although it will be able controllable from MV substation or by the user but a serious fault is not avoided easily and may cause an interruption.

Following these kinds of faults are classified regarding their network impact and duration. Those details which can affect considerably to the electrical network and may cause a large or small power outage will be detailed. In most cases the lack of supply is due to faults in electrical distribution network. In general terms 20% of this lack of supply is due to outages in transmission network according to the CAIDI index. In these cases, the restoration time is composed by the location time and by the restoration time. It highlights that these networks have a high automation level and for this reason in front of a fault the network can be restored quickly.

On the other hand, a 15% of the rest of the faults are originated in low voltage networks; in this case the restoration time can be elevated although the number of affected customers is lower than in other cases. In this kind of networks there is an important difficult to detect the location of the fault and to restore the network.

The distribution network in medium voltage is the part of the network which suffers most faults. The reason of it is due to this network has an automation grade lower than HV network although is greater than LV network, and besides in this kind of network there is a lot of users [55].

When a fault happens in the ring MV network a feeder from substation will open and isolate part of the network. The next step will be to locate where is the fault and after that to restore the network to offer availability defined by FLISR concept.

In fact, FLISR is based in three functions: the identification of the fault, the isolation of the section where the fault is and finally the service restoration. The FLISR can help to electrical system in the improvement of the power quality due to enhance of availability in the system [56]. This fact can bring back some of the lost revenue to the utilities when a fault appears in the network. At the end an improvement in power quality will improve the electrical utility’s benefits and thus to maintain a good availability to the users.

5.1 Fault typologies

As it has been explained before, an impact on the distribution network can be serious because there is a disablement, or on the other hand can be slight, although can be affect to the users. Therefore, the faults in the network can be classified as active or passive faults.

5.1.1 Fault classification

The active faults appear when the current flows from one conductor to another conductor or to the earth. The first is a phase fault and the second an earth fault, both faults can be an important impact in electrical distribution network regarding the magnitude of the current fault.

The current level of an active fault is important regarding a passive fault. Although it is important to note that an active fault can come back from an incipient fault. As an example, there is a partial discharge until there is an isolation fault and to reach a solid fault. Also, the pollution in insulators is other causes which can make an active fault. Therefore, is very interesting to detect these possible faults before to reach to be actives.

On the other hand, the passive faults are those are not serious, however can make a strange situation in the network. There are a several examples of passive faults such as overvoltage, undervoltage and frequency variation, harmonic distortion and imbalance as mentioned before in this document.

These passive faults can be derivate in an active fault and then there will be an immediate action to isolate this fault. The term fault in the network is for defects in the network which disables directly the supply function of the network.

The duration of the fault in the network establishes a classification in three terms: self-extinguished, fugitive and permanent [57]**.** Although it is important to note that this time it will depend on the reaction time of the components of the network, for safety reasons or total failure.

A self-extinguished fault is when the fault disappears before the reaction of the protection system. In fact, the protection system starts in the moment of the fault but the time is not enough to react in front of fault time. After few [ms] the fault disappears immediately.

The fugitive fault is not self-extinguished and then the system protection reacts quickly in front of the fault. When a fault appears, the protection system reacts and open the circuit where is the fault. After this reaction the system protection tries to reconnect the circuit to recover the supply in the network. The system will try this operation n-time and if it has been achieved, the fault will be fugitive. The feeder, main circuit breaker of MV network, has a protection system to detect a fault and open the circuit breaker and reconnect it after a fault in order to recover the network.

The permanent fault is a serious fault and appears when the feeder has tried to recover the network after n operations. This kind of fault requires an intervention to repair physically the network. An example of it is a broken overhead or underground conductor. In an overhead network a broken conductor is an important problem therefore is not good to think in a reconnection, the same situation is in the underground network for any defect.

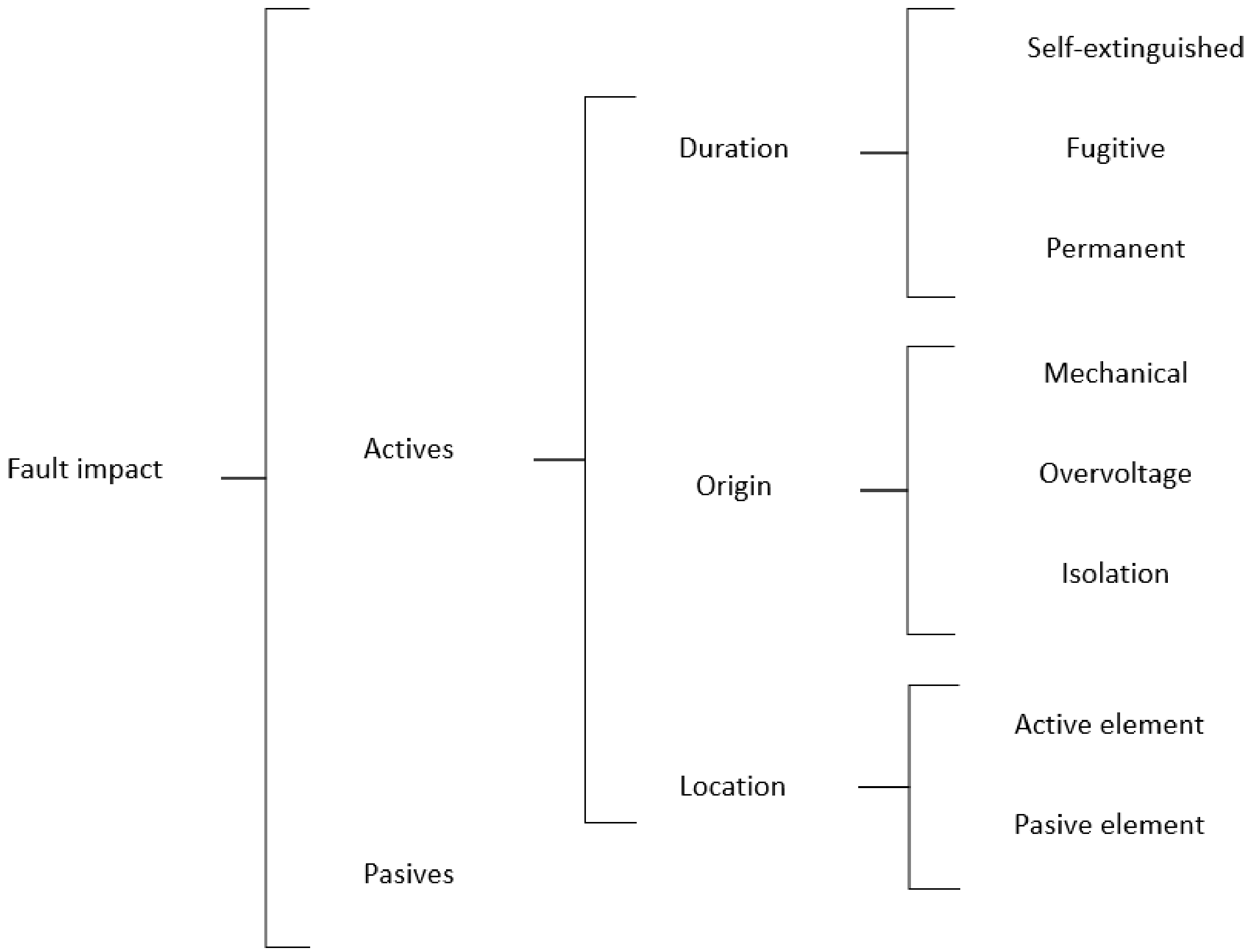


Table 5.1 Classification of electrical network faults

In overhead network the faults are normally fugitives and self-extinguished although sometimes it is possible to find a permanent fault but in underground network normally the fault is permanent because the environment is a conductor.

Another possible classification of the faults is due to the origin. The origin of the faults can be mechanicals, for an overvoltage or due to an isolation system [57]. As a mechanical fault it is possible to find the break of a conductor or the contact of the conductor with another element such a tree or animal. An overvoltage may be due an anomalous behaviour of the generation system. Finally, the origin of an isolation system in a conductor may be due for heat, humidity or corrosive environment.

The faults can appear in an element active or passive. An element active is a circuit breaker, a transformer, a recloser, a protection relay or any device with possibility to operate from the network manager. An example of passive element is the wires of the network. The table 5.1 shows all fault types according to the classifications mentioned previously.

5.1.2 Active faults

Previously the importance of active faults and their classifications according to the duration, origin and location has been commented before. Another possible classification of this kind of fault is the form of this fault regarding the contact between conductors or earth.

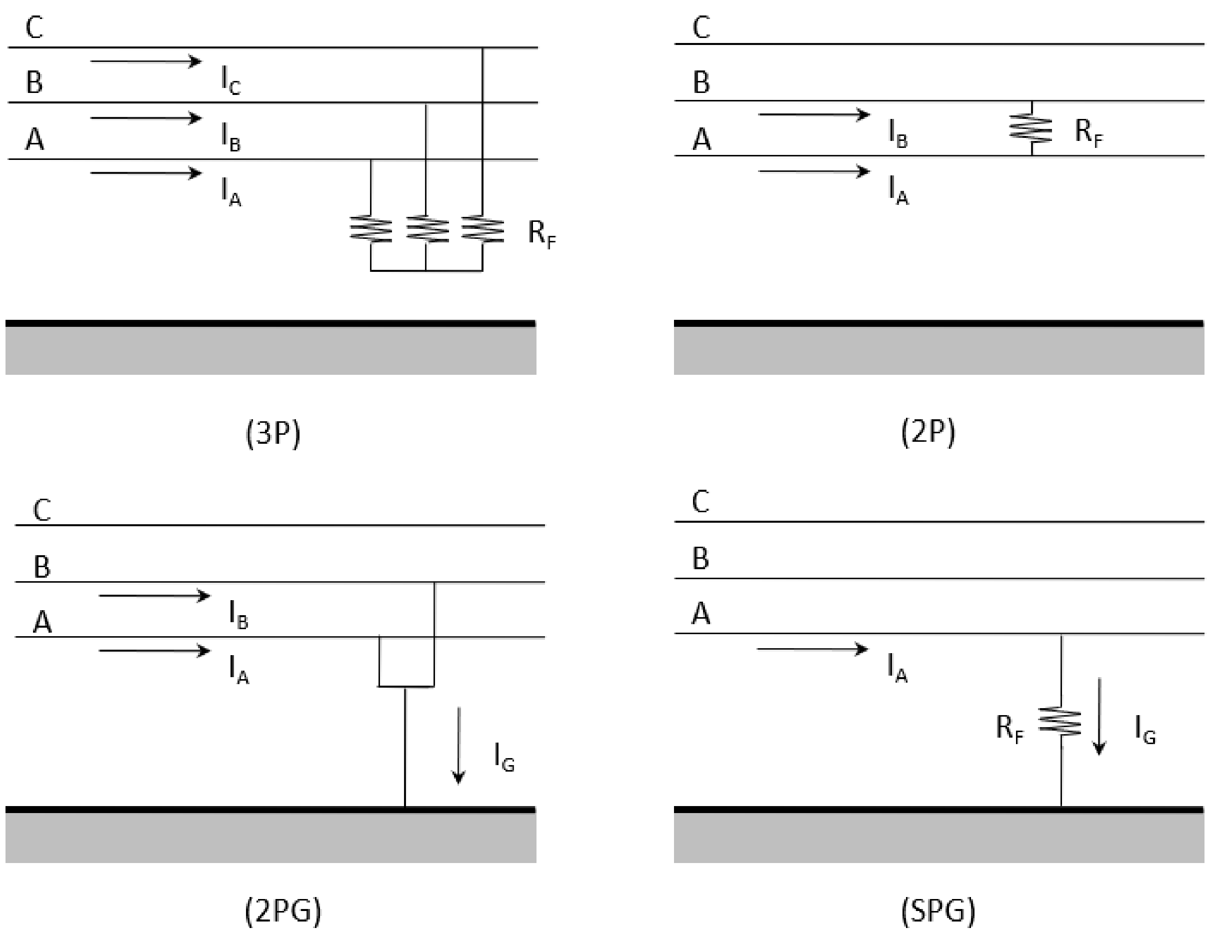


Figure 5.1 Types of short-circuits in network distribution

An active fault may be due a contact between phases or a contact between earth and phase. Therefore, it is possible to consider four types of short-circuits [58] in balanced three-phase system without neutral distribution. Next there is an explanation about this kind of short-circuits and in the figure 5.1 it is possible to find a graphic explanation about the flow of the current fault.

- **Three-Phase fault (3P)**. This fault appears when the three conductors meet in a common point.

- **Phase to Phase fault underground (2P)**. This fault appears when two conductors meet in a common point.

- **Phase to Phase Grounded fault (2PG)**. This is the same short-circuit that 2P but the common point is in earth.

- **Single Phase to Ground fault (SPG)**. This short-circuit appears when a phase establish contact with earth.

5.1.3 Active fault probability

According to the previous classification offered in [33], the 2PG fault has a low probability to appear in an electrical distribution network. In opposition to this fact it is possible to find a SPG fault with more frequency. The probability of these faults depends on several factors such as the configuration of the network, the height of the wires, earth system, isolation level, and the number of adversities. Probably in relation of kind of faults, the SPG fault represents the majority of fault events in distribution power networks [58]. According to different publications such as [33], [57], [59] it is possible to establish an approximately distribution about the kinds of short-circuits as the table 5.2 shows.

Active Fault	Probability
3P	5%
2P	15%
2PG	5%
SPG	75%

Table 5.2 Probability of active fault

The SPG fault is the fault with most possibilities to appear, this fact is due to the overhead network can establish contact with the environment through animals, trees, weather conditions. On the other hand, it is more difficult to establish contact between two phases.

5.1.4 Flow current in electrical distribution network

As a previous step to analyse the fault detection in distribution network it is interesting to analyse the behaviour of the electrical distribution network in front of a fault. As mentioned before it is possible to find the DG around the current electrical distribution networks therefore the behaviour of the fault can differ considerably in every kind of network topology mentioned before and also regarding the electrical earth system which is defined in the border between the HV and MV network. Therefore, in next points a phase fault and an earth fault will be analyse in order to understand the current flow and the DER affectation.

5.1.4.1 Phase fault

The phase fault in an electrical distribution network will have the direction of the current flow, basically from the substation HV-MV until to the point of the fault. In this kind of situation, the flow of the current is clearly identified by any market device prepared with several accessories to do this function. Although under a DG presence it could be appear a new flow in opposite direction to the main current flow of the network. This situation will difficult the detection of the fault and also the section of the network where it has appeared.

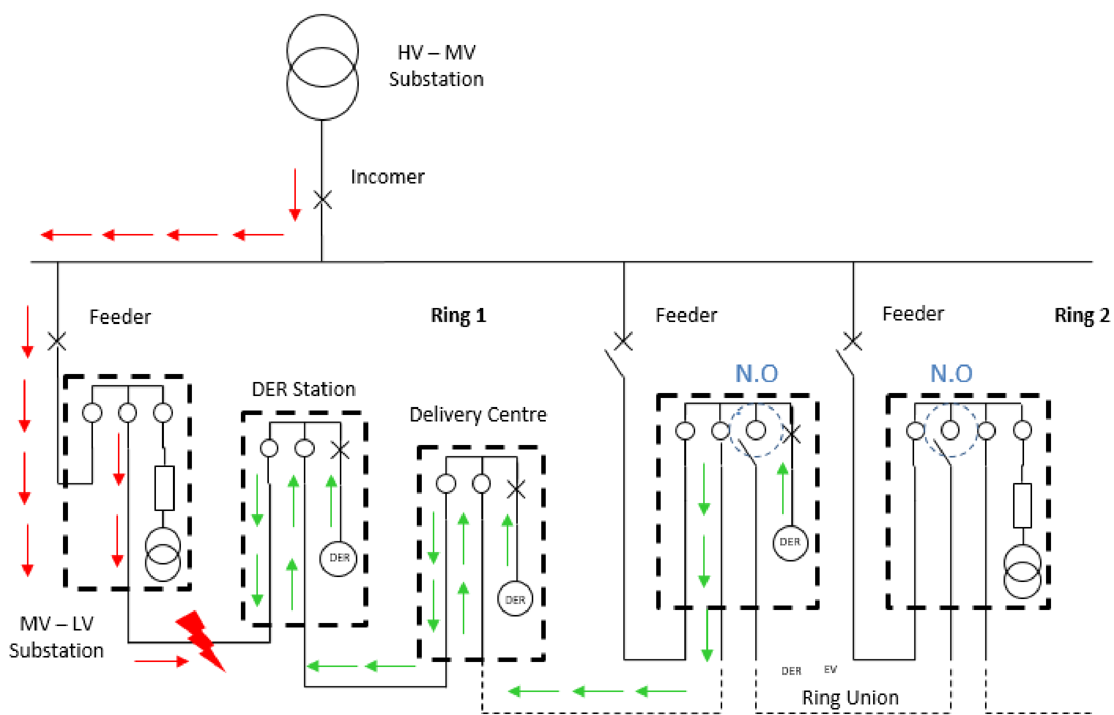


Figure 5.2 Current Flow in a meshed network with DERs under a phase fault

In a radial network, for instance, with several DERs the flow of the current can be different in some sections of the network but under a fault the flow in a part of the network it will be opposite to other part. The magnitude of the current will be very significantly different between these parts and there is other skill which can contribute considerably to detect the fault in this kind of network.

In the case of meshed distribution networks, the fault detection has a considerably difficult because the behaviour of the network will be different depending on the section where the fault is. In fact, if the main supply of the network is disconnected and there is a fault every DER will contribute to the fault and the current flow will different in each section and with different magnitudes depending on each kind of generation. The figure 5.2 shows a meshed network with several DERs where there is a fault and the current flow present an upstream and downstream direction. Depending on the configuration of the meshed network the current flow can change in an upstream or downstream direction regarding the position of the fault.

5.1.4.2 Earth fault

In the case of earth fault, the direction of the fault is not only conditioned by DERs in the network the earth fault system can contribute also in the flow direction. When there is an SPG in a balanced three-phase system not only there is an earth fault also there is a voltage fault.

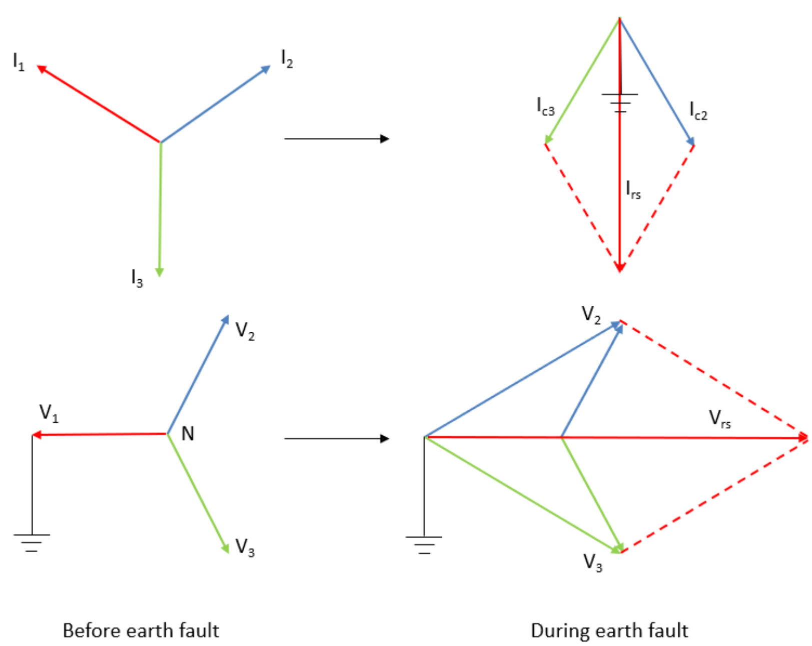


Figure 5.3 Current and voltage variation magnitudes in an earth fault

The simple voltages have suffered an unbalance due to one of them has been moved to the zero-voltage point or near it depending on the kind of contact of the phase with the earth. The figure 5.3 shows the earth fault and the voltage unbalanced where the first one makes a new phenomenon, the current earth fault or residual current, I_{rs}, and the second one, the neutral voltage displacement or residual voltage, V_{rs}.

Although the showed earth fault in the figure 5.3 is for isolated earth system due to all current during the fault is a totally capacitive current. In situations such as compensated or direct earth systems the I_{rs} can be an inductive or resistive current.

The selection of the earth fault system depends on several factors or conditions related with the management of the network or even by historical reasons in the utility or enterprise which is in charge to manage the system according to [39] and [41].

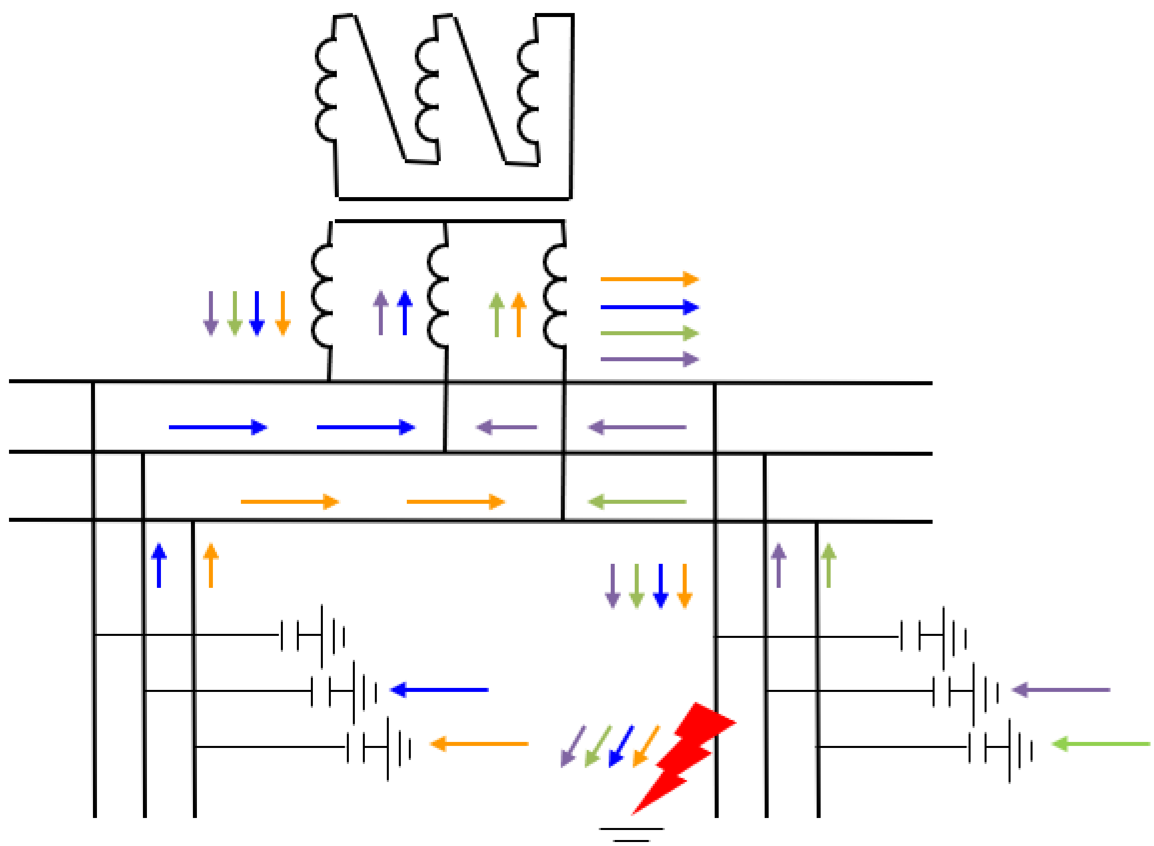


Figure 5.4 Current flow of an earth fault in isolated earth system

Although it is important to know the flow of the earth fault due to it will affect in other outgoings from the substation. In fact, an earth fault will still remain only in the voltage system where the earth system is connected, the fault will not pass to the other voltage levels. The figure 5.4 shows the current flow of the earth fault through the capacitor effect of the wires in an isolated earth system. The current flows through this wires until the last point of the HV-MV substation where the earth system is defined. It is important to remark that the capacitive current close the circuit for every outgoing of the substation where the earth system is defined so this situation can make a confusion regarding the position of the fault. In order to avoid this problem, the use of directional protections and directional detection can contribute positively in order to identify in which outgoing is the fault. Specially in the case of isolated earth system the magnitude of the current is very low due to the capacitive of the wires is also very low, the quantity of current is very limited. Under this phenomenon the module of each substation’s outgoing has a similar order, then there will be a problem to identify the correct position.

On the other hand, the figure 5.5 shows an earth fault but in a compensated earth fault. Independently of a resistance or impedance in the earth system of the HV-MV transformer there is a flow through the neutral point. In this case the level current which close the fault through the neutral point has an important module, then the outgoing with the earth fault can be identify easily.

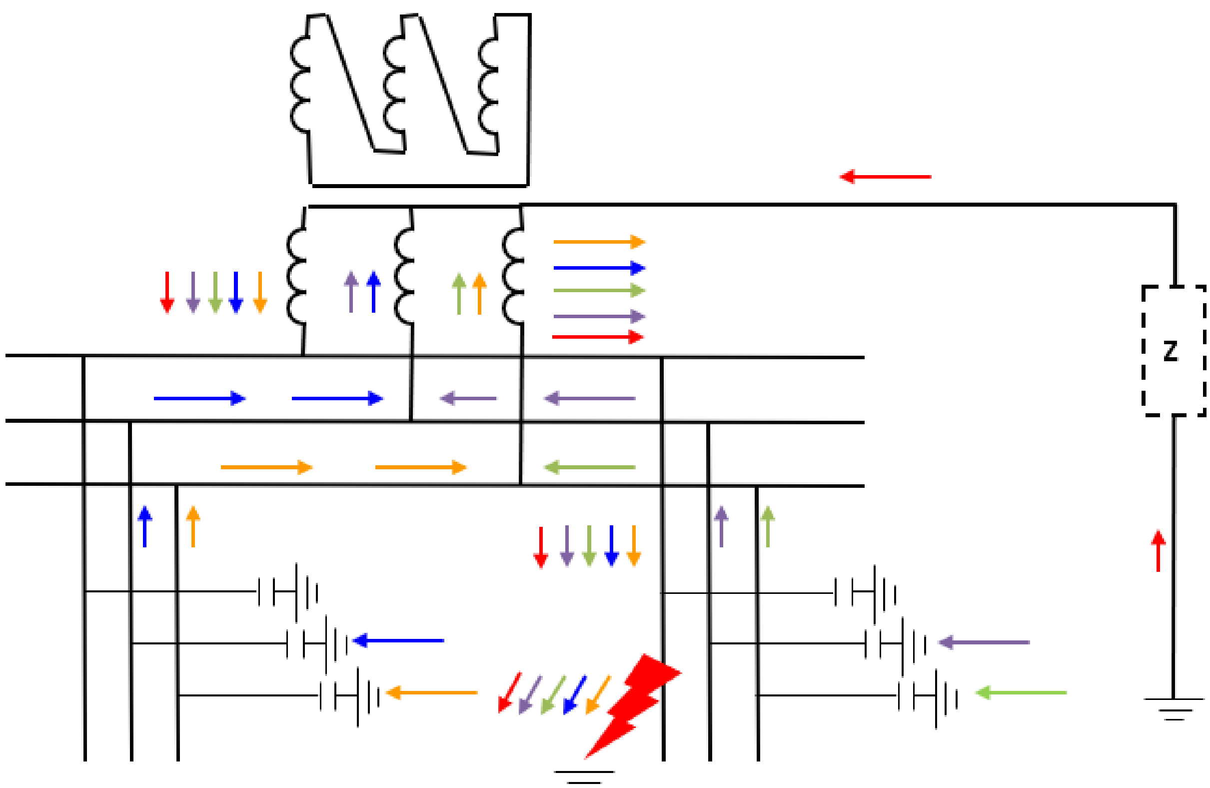


Figure 5.5 Current flow of an earth fault in compensated earth system

It is important to remark that the impedance can be regulated in order to minimize the earth fault. This is the case of meshed network where the capacitive current could be elevated. This kind of earth system is known as the Petersen coil [60] which is showed in figure 5.6. The inductive current I_L can compensate the capacitive currents I_{c2} and I_{c3} minimizing I_{rs}.

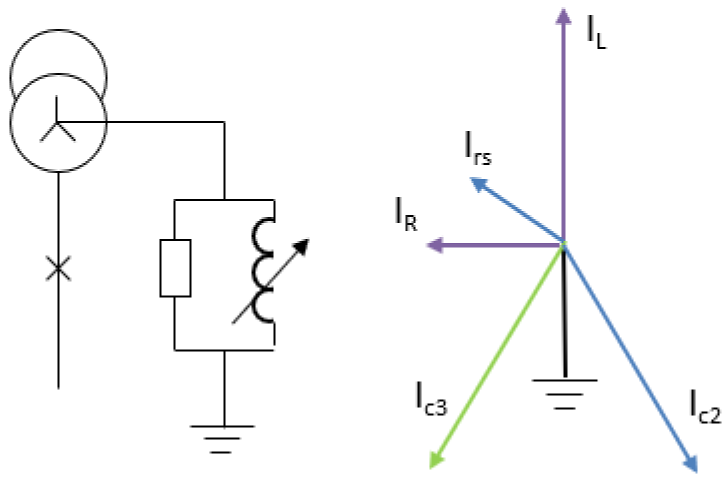


Figure 5.6 Current flow in a meshed network with DERs under an earth fault

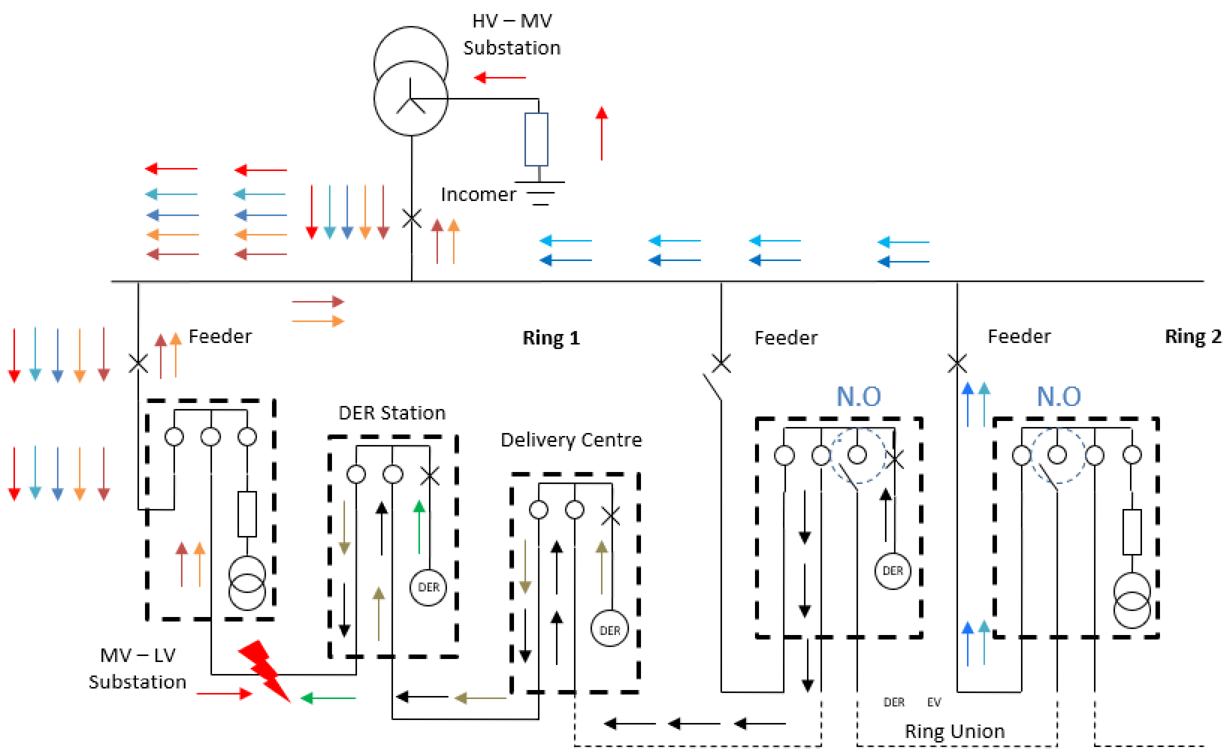


Figure 5.7 Current flow in a meshed network with DERs under an earth fault

As mentioned before in figure 5.4 and in 5.5 there is a current flow through the outgoing where the fault is not present. This situation makes a difficult detection depending on the kind of earth system. Then, in figure 5.7, where the HV-MV substation has a resistive earth system, the current flows from an earth fault are represented. It is important to remark that one of the outgoings of the substations is open, then the circulation of the capacitive fault will not close for this when the fault appears.

In the case of an earth fault for meshed network or even in radial network there are a current in every outgoing of the substation. The isolated earth system has a difficult detection in front of compensated earth system because the magnitude of the current is low and it is difficult to identify the outgoing where the fault is. Therefore, the only property to identify the position of the fault is to use the direction of the current in several points of the network. Following the directional protection will be exposed in combination with other technologies in order to detect the fault.

5.1.4.3 Directional protection. ANSI 67/67N

As mentioned before the directional protection is necessary in order to detect a fault in ring or meshed networks or even in a radial network to avoid false detection due to return capacitive current. This section describes the meaning of ANSI 67/67N protection and the potential of directional protection in 3-phase systems. Distribution line protection can use any of the following principles [61].

- **Directional overcurrent protection**. The overcurrent protection can be given directional features by adding directional element in the protection system. Directional overcurrent protection responds to an overcurrent for a particular direction flow.

- **Directional comparison protection**. Directional comparison protection can work with any high-speed, dedicated channel. Channel impairments may affect scheme dependability or security, depending upon the scheme logic (tripping or blocking logic).

- **Current differential protection**. Line current differential protection compares current information from the line terminals over the communications channel. Phase comparison protection only compares current phase angle information, which reduces the channel bandwidth requirements. Line current differential protection is secure and more dependable than other types of protection in response to the effects of unbalances, power swings, mutual coupling, and voltage inversion.

ANSI 67/67N protection has diverse applications like main protection of aerial lines and cables, of transformers of distribution, motors among many others. Usually it is also used as backup protection for power transformers and large generators and as emergency protection for distance protections and line differentials. In power transformers connected in parallel and in parallel lines fed by one end, overcurrent protections need the criterion of directionality to be selective. In these cases, the measurement of the voltages is required to determine the direction of the energy input to the fault. The trip is blocked with a fault current flow that is opposite to the set point and the directionality is represented in the protection schemes with an arrow indicating the direction of the current flow that will produce tripping. Equally to any another protection scheme in electrical systems, the main target is to detect the fault and to isolate the damaged part in a section as smallest as possible, respecting the selectivity term.

As shown in [62], the directional protection is necessary in the following conditions:

- there are several sources,
- there are closed rings or parallel cabled systems or mesh networks,
- there is an abnormal direction of flow of active or reactive power (generators),
- in isolated neutral systems for the return of capacitive currents.

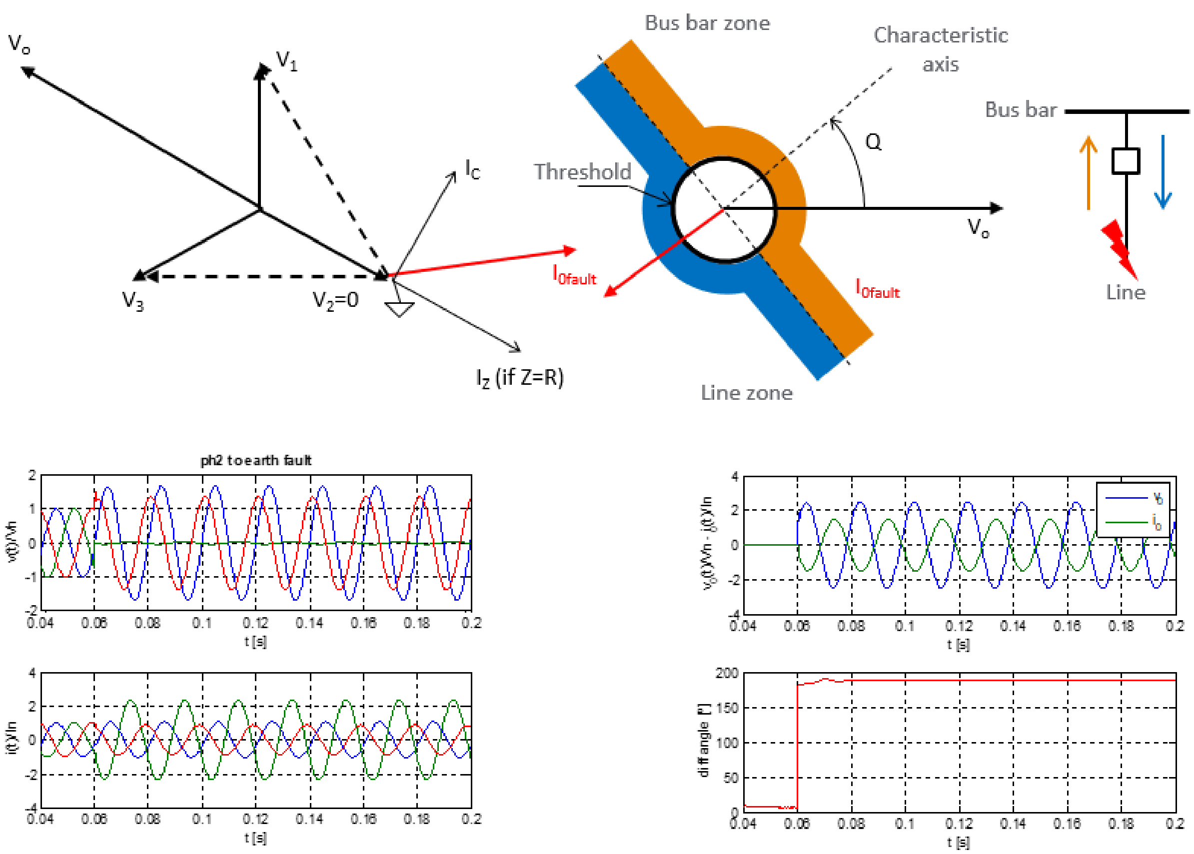


Figure 5.8 Earth fault detection and waveforms example

When facing new mesh networks with DERs it is necessary to know the current flow in order to detect a fault and isolate it. As mentioned before the main faults in an electrical mesh network and in fact in a radial network are the earth faults and after these, the phase faults [33]. Below, both protections, 67 and 67N are explained in order to show their functionalities in several cases such as open or close rings with DERs. These cases are presented in ring and in meshed networks, considered the future network trend in order to enhance the power quality in the electrical system.

ANSI 67N is the association of the protection against maximum currents and the element which measures the difference between the residual current and the polarization magnitude vectors. The directional earth fault protection, measures the direction of the fault current on a phase versus its polarization magnitude, as is shown in figure 5.8. Therefore, the protection trip occurs when the fault current is higher that a preset threshold and the differences between fault current and polarization magnitude, centered by the characteristic angle (Θ), which defines the zones trip. The angle Θ is formed by the normal vector to the half-plane of the trip with the magnitude of polarization.

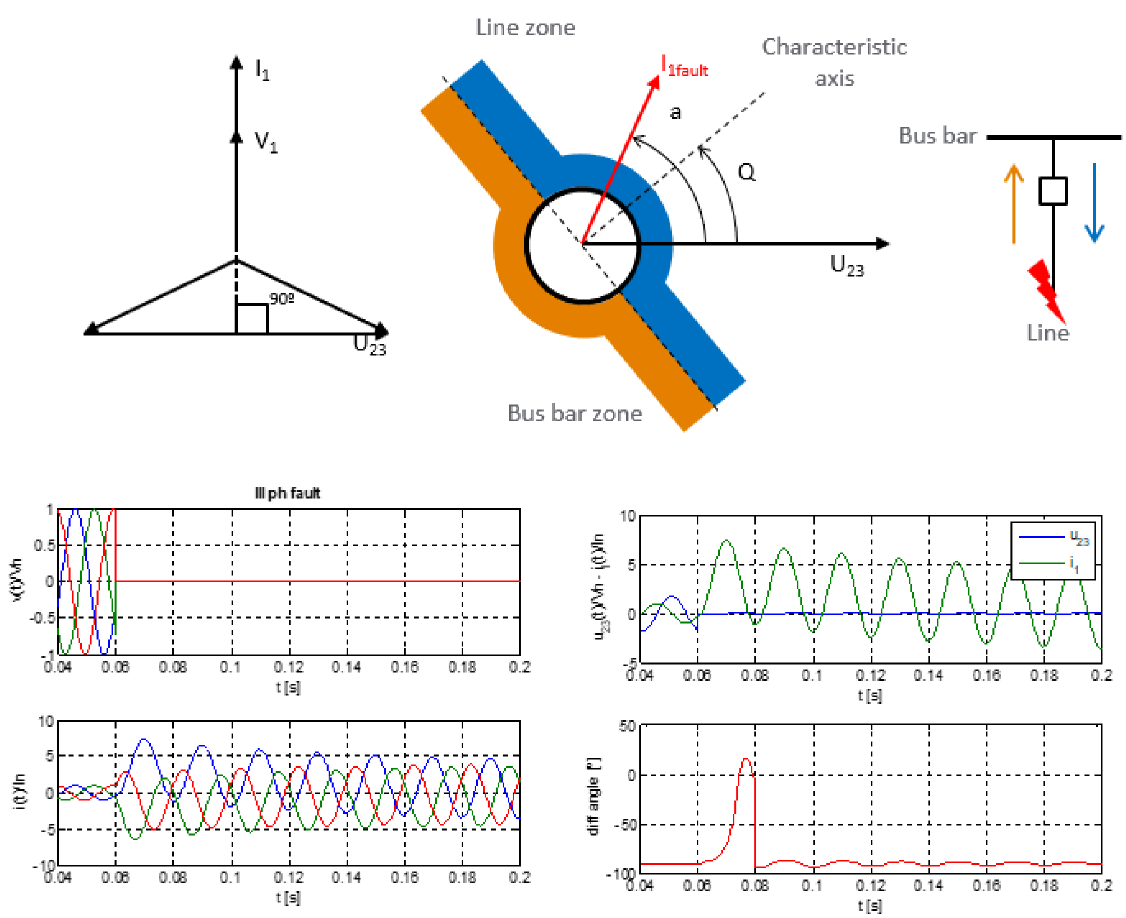


Figure 5.9 Phase fault detection and waveforms example

It is necessary to note that ANSI 67N protection is an extension of the ANSI 50N/51N [63] in which it only checks the earth fault current level versus a threshold. Figure 1 shows an example of waveforms in case of phase 2 earth fault in a 3-phase system. The fault occurs in the time 0.06 [s] where the voltage in phase 2 drops and the fault current flow in the same phase to earth, increasing to maximum value (the current and voltage values depend on the neutral system chosen, R/L relation and I-V angle in that instant). Also, the relation between the residuals current and voltage (polarization magnitude) and their angles difference is shown.

The directional phase protection, codified as ANSI 67, has a similar behavior as the protection above, and the protection trip is due to the same conditions, but in ANSI 67 protection, the simple voltage is not used due to the fact that in a phase fault it can change significantly. In this case, the polarization magnitude is the composite voltage of two phases. The protection analyses the direction of the fault current on a phase versus its polarization magnitude (in other words the derivation angle of the protection is 90°), as is shown in figure 5.9. Analogously to ANSI 67N, ANSI 67 is an extension of the ANSI 50/51 protection that only analyses the phase fault current level [63].

As in earth fault directional protection, the characteristic angle in a phase directional protection defines the orientation of the angular zone of the trip. The angle Θ is formed by the normal vector to the half-plane of the trip with the magnitude of polarization vector.

Figure 5.9 shows an example of waveforms in case of 3-phase fault. The fault occurs in the time 0.06 [s] where the voltages in all phases drop. The fault's currents increase to maximum values which depend on the switch power ratio and the system impedance. In this case, the relation between the phase 1 current and U23 voltage (polarization magnitude) and their angle difference is shown.

5.2 Fault location

Nowadays there are different techniques to detect faults in an electrical distribution network. The main goal of these techniques is to use the information which comes from the distributed intelligent devices in the network and complete with historical information of the system in order to detect and identify the fault. It is important to highlight that the information of these devices and also the historical information is collected and treated by high system control through several algorithms. In this chapter these algorithms are analysed in order to determinate the current state of the art of fault detection in electrical distribution networks.

5.2.1 Difference between HV and MV networks

First of all, to introduce the topic fault location it is interesting to remark the difference between of HV and MV networks. The fault location in HV is not an easy question but it is possible to use several functions such as line or distance protection in order to locate the fault due to the structure of the network. Unlike MV network, the structure of HV networks is a meshed network without deviations such as the figures 3.4, 3.5 or 3.6 shows. In other words, there is not any load or generation in a section between substations such as the figure 5.10 shows [64]. Therefore, in a MV network is more difficult to locate a fault than not in a HV due to the network's topology.

As mentioned before in a HV network generally the connection is point to point, thus the impedance is known with detail. Nevertheless, in a distribution network the impedance can be modified because there are several ramifications and even wire changes along the network. As there is not uniformity in the network it is very difficult to estimate correctly the impedance of the network.

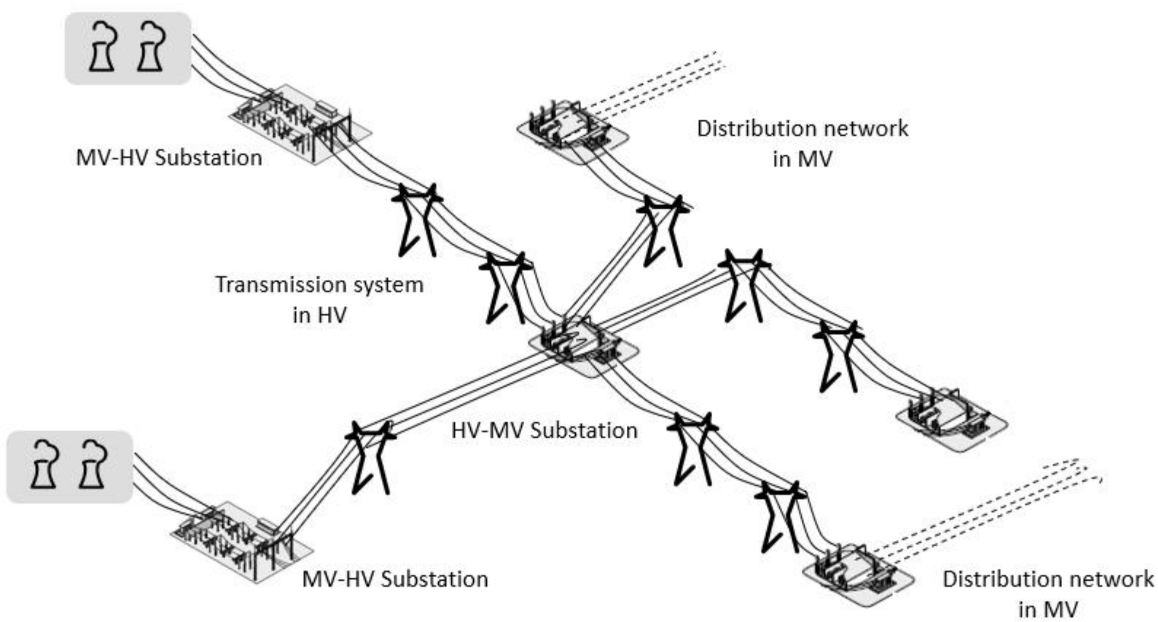


Figure 5.10 Traditional model of a transmission network

The HV-MV substations have protection devices with functions which can inform about the distance of the fault by means of the current and voltage magnitudes. It is important to take into account that the MV distribution networks have a great ramifications quantity from the same substation. A feeder from a HV-MV substation has different configurations depending on the distribution network downstream. This fact affects considerably to the detection regarding following points.

- **Multiple terminals**. There are feeders which have ramifications from one line, so in front of a fault there are several alternatives. As mentioned before in the case of HV networks there are not these multiple connections.

- **Intermediate loads**. In a feeder can be present loads and these can be located before or after a fault and it can suffer some variation in different moments of the year. This fact can difficult the location of the fault.

- **Mesh network**. In a meshed network the feeders can reach different topologies in front of different situations caused by fault, reconfiguration network for optimization or maintenance operation, for this reason the impedance can be different and it is very difficult to determinate the current value.

- **Wire topology**. As it has been commented before there is not homogeneity about the cord in the same path due to the construction of the feeder is in different phases when it is necessary to increase the electrical network [55]. The electrical network has been suffered a continuous evolution due to the population growth, migration movement and energy demand growth.

5.2.2 Detection and location fault devices

In the electrical distribution network, it is possible to find different devices which can offer us information about the kind of the fault and the location of it. These devices are associated to the network operation elements such as switch-disconnector or circuit breakers in overhead and in underground networks. Besides it is possible to find these devices over the conductors or in electrical towers.

This kind of devices are protection relay, known as Intelligent Electronic Device (IED), if the operation element is a circuit breaker or it is a Fault Passage Indicator (FPI) if the element is a switch-disconnector. The difference between these devices is that the IED is prepared to detect a fault and to react to give a signal to open the circuit breaker in order to isolate the fault. In opposition the FPI only detect the fault and its reaction is focused only to report the information. Therefore, the IED has other features to react quickly in front of a fault and other functions to complete the protection of the fault. In recent times the protection and detection algorithms of an IED and FPI are very similar and sharing a lot of features and besides there has been an evolution process in these kind of devices as it is mentioned in [65], [66] and [67].

The information from these devices is used as notification in order to know the different points where the fault has passed. With this information, the system can discriminate the section of the network where the issue has happened through an algorithm. Moreover, this information can be collected immediately after the fault or later to take some actions about the network.

Depending on the kind of the device can give to the system more information about the fault. For example, these devices can give the kind of the fault, its magnitude, its direction and besides to monitor these variables in a time window.

It is important to highlight that these devices have been evolving in last decades and have been acquiring new functionalities. Probably one of the most important evolutions has been to be a multifunction device. Besides another important change has been the communication mode. This improvement has been evolving in last time and it is possible to analyse the information in a high control system.

Thanks to this additional information can be calculating the fault impedance through the current measurement in several points, and thus it is possible to compare with the value obtained by calculus in a network model [55]. In fact, the fault impedance can be compared with the result of several short-circuit calculus modelling the system. After a fault in the network it is possible to compare the real impedance with the calculated impedance. In HV networks the knowledge of measurement of current and voltage due to the design of substations has incorporated the necessary elements to extract this information. Nevertheless, the MV network has not this information due to economic reasons. Under this situation the implementation of a fault location system like this has a high cost for this kind of network, although as mentioned before the evolution of the field devices has increased considerably in recent years and the sensors which are related with these devices. Now it is possible to have this information with some accuracy.

5.2.2.1 Intelligent Electronic Devices and the Fault Locator function

The IEDs is a general term but mainly are focusing to describe a protection relay which can include some functions in order to detect and trip when a fault is appearing. Besides these devices indicate to high system under a communication channel the distance to the fault and other information to establish the correct location.

The function of the IED is to trip and isolate the fault from the outgoing of the substation as it described before in structure network. Normally this is the position of the IED, controlling the circuit breakers of the feeders from HV – MV substations collaborating in the information collection to help in the fault location. These digital devices are multifunction and have protection functions to fulfil other ANSI and IEC normative such as voltage and frequency protection, therefore there are modules with several channels to collect digital inputs in order to implement automatisms. Another important point of these devices is the communication system, it is possible to integrate them through several communication media and with different protocols. In the electrical market due to this reason this kind of devices have started to be knows as Advanced Electronic Devices (AED).

As mentioned before the AEDs have the possibility to work with several functions. One of these functions is the Fault Locator (FL) which can indicate the distance to the fault from the position of the AED. Although this function is normally used in a high system [50], then it is necessary to analyse where is the best position to use this protection [51].

The FL function is described through ANSI 21FL, from the normative ANSI C37.2 [63]. This function is defined too through IEC in the normative 60617 as FLOC [68]. The function ANSI 21FL is present normally in some protection devices for the electrical network. It is important to remark that the function ANSI 21FL comes from ANSI 21, which is the distance fault function according to ANSI C37.2.

The protection distance 21 helps to locate a fault within a pre-set distance from its location in a long a transmission line or power cable. In HV systems, the ANSI 21 protection considers the resistance and reactance by kilometre in the line conforming a total impedance where the impedance is clearly known by the operator of the network. The IEDs use the voltage and current measures in real time and compare with the impedance of the line in order to identify the section of the fault. Through the algorithms of this protection, it is possible to calculate the fault distance to the fault [69]. Several manufacturers such as [70] and [71] have implemented the function 21FL in their AEDs. The cost of this function in an IED for HV-MV substation outgoing has not a big impact, although in other kind of devices such as FPI or telecontrol system for MV–LV substation the cost difference will be significative.

Nowadays there are several different algorithms that identifies the distance to the fault from one point of the network which is seeing the fault such as [72]. Through the fundamental Ohm's law and according to the feeder impedance by length unit can be developed the equation 5.1.

$$d = \frac{V}{I \cdot Z_l} \qquad [5.1]$$

Where V is the fault voltage in [V], I is the fault current in [A], Z_l is the line impedance in [Ω/length unit] and d is the length to the fault in [length unit]. As the current and voltage are complex values, the obtained result after applying the equation the result will be a real value near to the fault distance fault and another little complex component. In the cases when this result is not correct, the cause is mainly due to not have defined correctly the line impedance.

Although this implementation seems easy, the different faults have different impedances and besides there are compensations and the fault can be added an additional impedance depending on the kind of fault or the earth contact.

The AEDs and FPIs can identify correctly the kind of fault due to there are other kind of ANSI protections and other algorithms which allow a detection. Then it is possible to apply the equation 5.2 or 5.3 if the problem in the network is an earth fault or phase fault respectively. Where Z_0 and Z_1 are the zero and positive sequence impedance respectively.

$$V = V_a;\ I = I_a;\ Z = Z_s = \frac{(2 \cdot Z_1 + Z_0)}{3} \quad [5.2]$$

$$V = V_{ab};\ I = I_a - I_b;\ Z = Z_1 \quad [5.3]$$

The figure 5.11 shows different AED devices to include in a cabinet in order to install it above or near to the feeder circuit breaker cubicle. In the figure also is showed a set of substation outgoings with their protections. It highlights that these devices are connected to Current Transformers (CT) and Voltage Transformers (VT) which are inside the cubicles with a very reductive transformation constant. At the end it is an electronic device which works between 0 and 5 V. Also, in the picture there is the picture of internal cabinet with a wired AED to the circuit breaker and other loose AEDs.

Figure 5.11 AEDs devices in some substation outgoings, courtesy of Schneider Electric

In order to define the 21FL function accurately it will be necessary to establish an analysis between two important points. The network analysis and environmental the information influence directly to the calculus of this function [55].

- **Network analysis**. The fault signal has to be analysed in order to find the kind of fault and so the impedance from substation to fault point. The important detail is to get a signal which has been properly sampled in order to have an accuracy value. A field AED can provide this current and voltage signal with 12 samples per period. Although there are devices with more samples per period. The problem of this point is to send the information by communications. One option in front of this adversity is to make the analysis locally.

- **Environment information**. The impedance of the feeder and a possible fault will be identified from a model based in real network topology. The goal of this phase is to provide information to this model in order to simulate the fault and then to find the accurate location of the fault. Therefore, the model will take into account the previous load and the circuit breakers position of the network previous and after the fault.

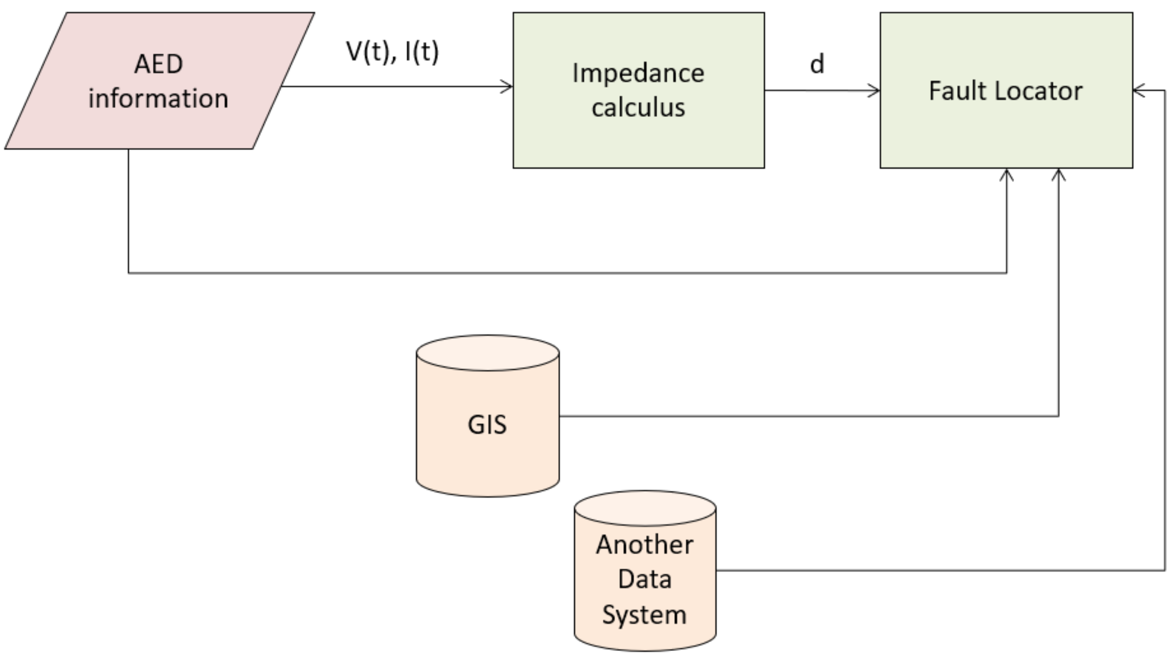


Figure 5.12 Data Flow to calculate the 21FL

The network model shows the current physical situation so this information is stored in a global system; this system is called Geographic Information System (GIS). In this system the information related with different nodes, wires and switch-disconnector is presented Therefore, each change in the network will make a different configuration of the GIS to establish new simulations.

The fault location can be established as a centralized or decentralized function. A centralized model can provide accuracy due to there is a lot of information about network status in this moment. Although to receive this information from different AEDs can slow down and the analysis result is not immediate. The figure 5.12 shows the centralized mode in a control centre where the field magnitudes such as voltage $V(t)$ and current $I(t)$ with their evolution on time are sending by communication channels by each AED with this function in order to calculate the impedance and define the distance to the fault. After this process the internal algorithm in the control centre with historical information from GIS and other historical data can contribute to establish the fault location.

In a decentralized model the AEDs make the analysis to fault distance and it is not necessary to send information and process after. Directly the AED can provide this information to the control centre although if the feeder has different ramifications it will be necessary to use another field information to discriminate the path of the fault.

5.2.2.2 Fault Passage Indicators

The FPI are normally installed in the underground and overhead electrical distribution network. The goal of these devices is to report the place where the fault has passed. This information can provide the part of the network where the fault has happened.

When a fault appears in the network the circuit breaker as an operation element of one of the substation's outgoing makes a trip in order to isolate the fault through an AED as mentioned before. The phase fault protections ANSI 50/51 or fault earth protections ANSI 50N/51N, or even directional versions ANSI 67 and ANSI 67N respectively [63], will analyse the fault and make the trip order.

After this moment the FPIs are in charge to indicate if the fault has passed through them or not. It highlights that the current flow from substation until the fault point. Therefore, the FPIs which are in this part of the network will see the fault. It is possible to suppose that a substation's outgoing has m FPIs, then n of them will see the fault and $m - n$ will not see it. Between the FPI number n and FPI number $m - n$ there will be the fault. The figure 5.13 shows a substation's outgoing where the current flows through the FPIs of one of its feeders. The FPI number n, in red colour, is the last fault's indication and the FPI number $m - n$, in green colour, is the first one that does not indicate a fault.

The disadvantage of this method consists in to reach the accuracy about the frame where the fault has been appeared; therefore, it is necessary to install a lot of FPIs in the distribution network. This fact requires a huge investment and therefore it is necessary to find a balance point to reduce the time fault avoiding a high cost [73]**.** Although as mentioned before in the case of network structures there are algorithms such as [74] and [75], which provide the best points of the network where establish a FPI unit to know the fault passage even with DG in the network.

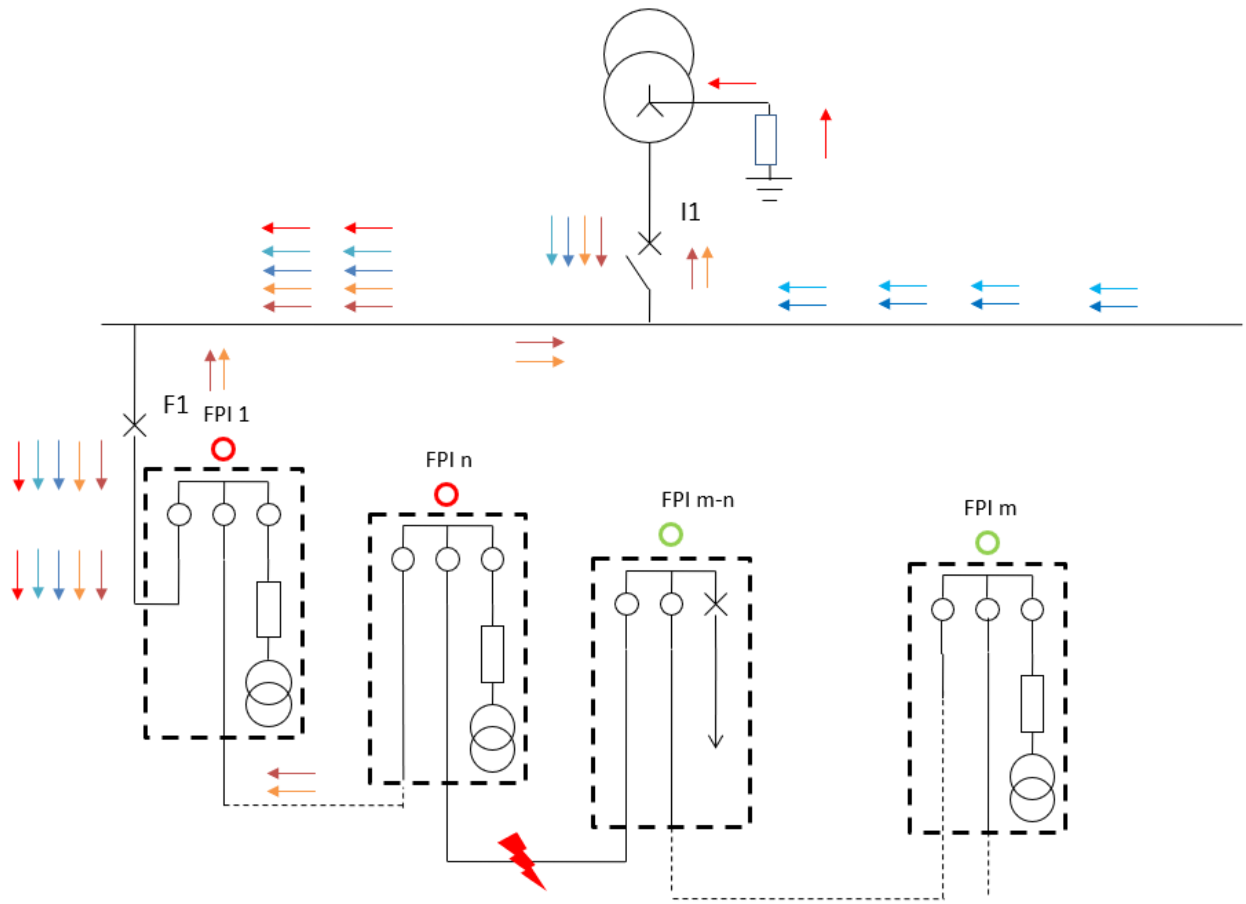


Figure 5.13 Fault detection through FPIs

The FPI can be found in individual devices with only this goal or in telecontrol devices. These last devices have the FPI functionality and the option to control overhead or underground switch-disconnectors which have motors inside to open and close the operation element.

5.2.2.2.1 Fault Passage Indicators as dedicated device

As it has been mentioned previously the FPIs are distributed in overhead network and underground network. There are different models about overhead FPI, someone can wrap the MV wire and others in the electrical tower without any contact with wires. The underground FPI can be installed in the MV-LV substation through CTs in the wire [76]. Following there is an explanation about the constructive features of the FPIs.

The current and voltage magnitude can be captured by overhead FPI with contact or not with the distribution overhead network. In case of contact the current measurement can be done by CTs such as toroidal which wraps the wire and the voltage magnitude can be detected through VTs.

Other economic possibility is to use the generated electromagnetic field by the wires in order to read these magnitudes. This last possibility can be done due to a coil which is excited by the electromagnetic field. The figure 5.14 shows the individual FPI by phase which allowing to know in which phase the fault has passed. This kind of devices is known as clip-on mounted or phase mounted and its installation is in the wire by means of a hook which allow to the operator a correct installation avoiding a direct contact with the wire.

Figure 5.14 Clip-on mounted or phase mounted FPI in MV cable, courtesy of Schneider Electric

There are other FPIs, known as pole mounted, which are prepared to install in an electrical pole or tower. These FPI receives the influence of the electromagnetic field analysing current and voltage although in these cases is not possible to know the phase where the fault is. Unlike to the clip-on mounted, this kind of FPI does not need a complex installation as it is showed in figure 5.15.

Both kinds of FPI have a small battery with long duration or the set battery and rectifier to load the battery through solar panel or auxiliary supply. Normally if the FPI has a small exclusive battery only indicates the pass of the fault locally, then DSO's patrol will travel the line to identify the information of every FPI. On the other hand, if there is a solar panel with rectifier the FPI will have the possibility to communicate with control centre. In this case the clip-on mounted FPI, several manufacturers have associated a local Remote Terminal Unit (RTU) in order to communicate the fault detection to the control centre according to [77] and [78].

Figure 5.15 Pole mounted FPI with solar panel, courtesy of Schneider Electric

Another important skill of these devices is the possibility to identify if the fault is in the substation's outgoing where it is installed or is a capacitive current return to the substation. Then this kind of devices have the possibility to analyse the direction of the current in order to indicate correctly the position of the fault [76].

Figure 5.16 FPI in MV-LV substation, courtesy of Schneider Electric

The FPIs for underground network are in MV-LV substation, delivery centre or distribution centre mentioned before. This kind of FPI has associated a toroidal or CT to get the current measurement, regarding the voltage measure it is possible to use some capacitive or resistive sensors even a set of Low Power Voltage Transformer (LPVT).

As economic option, these FPIs have toroidals to wrap the wires of the MV cubicles. Normally it is used one per phase although there are combinations with two toroidals by phase and other to wrap the three cables to detect earth fault with accuracy adding the three phases. These toroidals are opened in order to install comfortably in the existing cubicles.

The figure 5.16 shows a FPI on the wall inside MV-LV substation. This FPI is connected with two phase toroidals and one zero sequence tore in a switchgear cubicle. The phase toroidals are wrapping the cables in the bushings and the earth fault tore is wrapping the three cables. Also, the capacitive sensors of the cubicle are linked to the FPI to indicate the absence or voltage presence. This indication can be done if the FPI receives an external supply from the MV-LV substation, in front of a fault if there is not supply in MV the FPI will not receive supply and then it will know the absence presence. Obviously, this kind of FPI will associate a rechargeable battery, which is supplied by the monophasic alternating current (AC) of the MV-LV substation, or simple battery. Others devices are self-supply and receive this energy from the toroidals joint to the measurement.

It is important to remark that the algorithm detection of this kind of devices is based in the comparison of magnitudes of current and voltage. In fact, when the current pass some set level in the FPI and there is an absence of voltage during a specific period of time, the device will send a signal by communication or by light local indication.

Other algorithms in this kind of detectors are based in rate of change of the current, $\frac{dI}{dt}$ by validation of absence voltage [76]. Some of these devices validate the indication of fault with these algorithm, verifying also the direction of the earth fault by means of residual and voltage current. In next chapter the directional protection and detection will be explained.

5.2.2.2.2 Telecontrol devices

As mentioned before the FPI functionalities can be defined in a telecontrol device. These telecontrol devices have as main function the operation of the cubicles in the MV-LV substation from the utility's control centre, although these devices can operate in overhead lines. It is important to highlight that in overhead network there are switch-disconnectors and circuit breakers therefore these devices can be associated a telecontrol device to operate these nodes.

One of the fundamental properties of these devices is the communication. Nowadays in the market there are different communication systems in different physical mediums such as radio, digital radio, General Packet Radio Service (GPRS), PLC and others. Besides this kind of device have other additional functionalities as the FPI because these devices have advanced electronic microprocessors to operate the cubicles, to measure and to do other algorithms for maintenance in order to enhance the global control in the MV-LV substations. Under this situation it is possible to implement the explained before algorithms and even to adapt to ANSI protections.

In order to control the MV-LV substations form the control centre the telecontrol device has three main skills; supply, communication and control. The supply module can provide power to the device to operate the motorizations of the cubicles; this operation can be done by means of a battery and a loader. In a MV-LV, distribution or delivery substation only an AC supply can be found, therefore the telecontrol device is supplied by this kind of current. Internally the supply module will convert the AC to Direct Current (DC). In front of a permanent fault the device will continue ready to control the cubicles [73].

Figure 5.17 Example of telecontrol device in a MV-LV substation, courtesy of Schneider Electric

The communication module is focused as an intermediary element among the control module of the telecontrol device and communication device which establish a physical medium to link with the control centre. This communication module is in charge to encrypt the information through different communication protocols for electric sector such as IEC 101 and IEC 104. Nowadays the IEC 61850 is also taking an important relevance to communicate with the control centre.

Finally, the control module establishes the management between physical outputs in order to operate the motorization of the cubicle and to collect signals of the substation. Also, the toroidals and capacitive sensors provide the current and voltage magnitude to the device. The figure 5.17 shows a telecontrol device in a MV-LV substation which operates several cubicles, also It is possible to see a loose device with battery and other toroidals and wires to connect to the cubicle.

5.2.2.2.3 Additional FPI features and trends

The FPI devices started with the goal to locate phase and earth faults in the network. The improvement of the IT technologies or evolution of electronic has provided new functionalities such as the communication or directional detection.

As mentioned previously it is important to know the indications of the FPIs in the control centre. Therefore, the communication in FPI is the key to report this indication. Nowadays the DSOs are installing this devices with communication option. Likewise, the FPI signalization can be done by different channels such as digital contact, lamp or led in order to do a physical exploration in the centre [73]**.**

Field devices	Protection	ANSI 21FL	Detection	Operation	Communication
AED	X	X	X	X	X
Overhead FPI			X		X
Underground FPI			X		X
Overhead Telecontrol			X	X	X
Underground Telecontrol			X	X	X

Table 5.3 Features of AEDs, FPIs and Telecontrol devices

Another functionality has been the directional detection of the fault due to the presence of DERs in the network and the high current capacitive in mesh networks as exposed before. If in a feeder there are several DERs along the electrical line, in a moment of the fault these DERs can contribute to the fault and the detection will be complex as it has been showed in figure 5.2 and 5.7. Therefore, the FPIs in the line will show the fault and the fault will not be identified properly. In fact, all FPI will identify the fault because the current flows from substation to the fault and from DERs to the fault.

Last decade some manufacturers have begun to develop their devices with directional feature in order to identify properly the site of the fault. Nowadays the FPI are very similar to AED regarding the functionalities although the economic cost is very different because an AED is prepared to make several protection functions and even to fulfil some conditions to trip in a short time because is working with an element which can sectionalize the network in front of a fault.

In order to establish a differentiation between these devices, the table 5.3 shows the functionalities about different devices in current market according to [77],[78],[79],[80],[81],[82] and [83]. It is important to highlight that the AED can make operate and communicate with auxiliary power supply. This fact supposes and additional cost in the installation. On the other hand, the AED can detect as FPI due to that the FPI's detection process is a simplification of the current protections.

5.3 Fault location algorithms

Previously it has been reviewed different ways to detect the fault in the distribution network through the information of magnitudes from field devices and through some detection functionalities in these devices. Following it will show several algorithms which combine this set of information in order to detect the fault. The validity of these algorithms depends on their evaluation in a real network although it can be validated in modelling software.

5.3.1 General classification

Nowadays there are a lot of algorithms to detect a fault in a transmission or in a distribution network although there is the possibility to classify them. As explained before these algorithms use the collected magnitudes from field devices or other generated information by themselves in the moment of the fault and the historical information collected by high system in other faults or issues.

The magnitudes such as current, voltage, frequency, etc.; from several devices and their indications are collected by a centre control. In this centre there will be an analysis in order to determinate where is the fault in the network. It is important to highlight that these data will be historical information for next faults so the operator of the network will be need to establish an Advanced Distributed Management System (ADMS) to manage this data and integrate the field devices. In following chapters, the concept of ADMS will be exposed.

Other publications such as [84] classifies these methods in centralized or decentralized methods. According to this classification it is possible to indicate two important differentiations about the data collected by the ADMS. If the high system uses the magnitude from AEDs and FPIs in order to locate the fault will establish a centralized algorithm but if use the partial information generated by the AEDs and

FPIs such as the result of 21FL or the status of several ANSI protection and other indications will establish a decentralized algorithm. This classification is according to implementation.

After this first classification, it highlights that there is another classification about the algorithms: methods focus in a network model and methods focus in acquire knowledge according to [85]. In fact, the centralized model could be separated between these kinds of methods due to the historical information is an acquire knowledge, nevertheless the decentralized algorithm is classified inside methods based in network model.

On the other hand, it is interesting to think in acquired knowledge by the system as an artificial intelligent system [86]. Thus, it is possible to use statistical tools comparing with other previous faults of which its kind and location are known in order to identify the current fault. The application of artificial intelligent can provide benefits due to the knowledge is growing or validating in every new event. According to [85] and [86] it is possible to determinate a global classification; there are methods based on impedance measurement, methods based on analysis of travelling waves and advanced systems based on the application neural networks. It is important to remark that there are technical reports in IEC such as [87] where the proposal is to find a mix between travelling waves and communications by IEC 61850.

Another classification is in function of network architecture. As mentioned previously in chapter 3, the architecture of the network is an important skill and then the algorithms are developed in base of the kind of the network.

Other important classification for fault location in electrical distribution is focusing in the way to analyse the network. As mentioned before the methodology can be based according to the model or through the acquired knowledge but this methodology could be applied for analyse the fault section location or to locate the substation outgoing where the fault is.

The algorithms based on to locate the fault can be direct, indirect or even practical. The direct methodology uses a matrix in order to describe the network structure and also uses the information from the network devices. Nevertheless, the indirect methods use an intelligent algorithm with the historical information applying an Artificial Neural Network (ANN). Finally, the practical methods are focusing in to use the direct report only from the field devices. This last method does not work properly in networks with DG and in meshed structure, it is necessary to implement and additional analysis in order to discriminate the information from field devices. This is important point in order to select an algorithm for current networks due to the DG is experimenting an important increase as mentioned before, then this selection is relevant.

On the other hand, the fault line selection methods use the steady and transient magnitudes in order to discriminate in which line is the fault. By means of the electrotechnical theory it is possible to use this information and to determinate in which outgoing from the substation is the fault. Besides, inside this fault line selection methods, there are other active selecting methods which act on the network in order to detect the fault.

In last decades a lot of algorithms have been developed in order to improve the electrical distribution network. As it has been commented before there are algorithms based on the model such [88], where there is a comparative between impedance and voltage. This kind of method based in the model is a good solution for transmission lines of distribution network, although is difficult to use in common lines for two reasons, there is not a good knowledge about the network and there is loads distributed along the line.

Therefore, with these partial indications according to different skills of the networks it is possible to establish a general classification about these methodologies. Following, in the table 5.4 there is a classification about these methodologies. It is important to highlight that an algorithm can be classified in more than one skill regarding its definition.

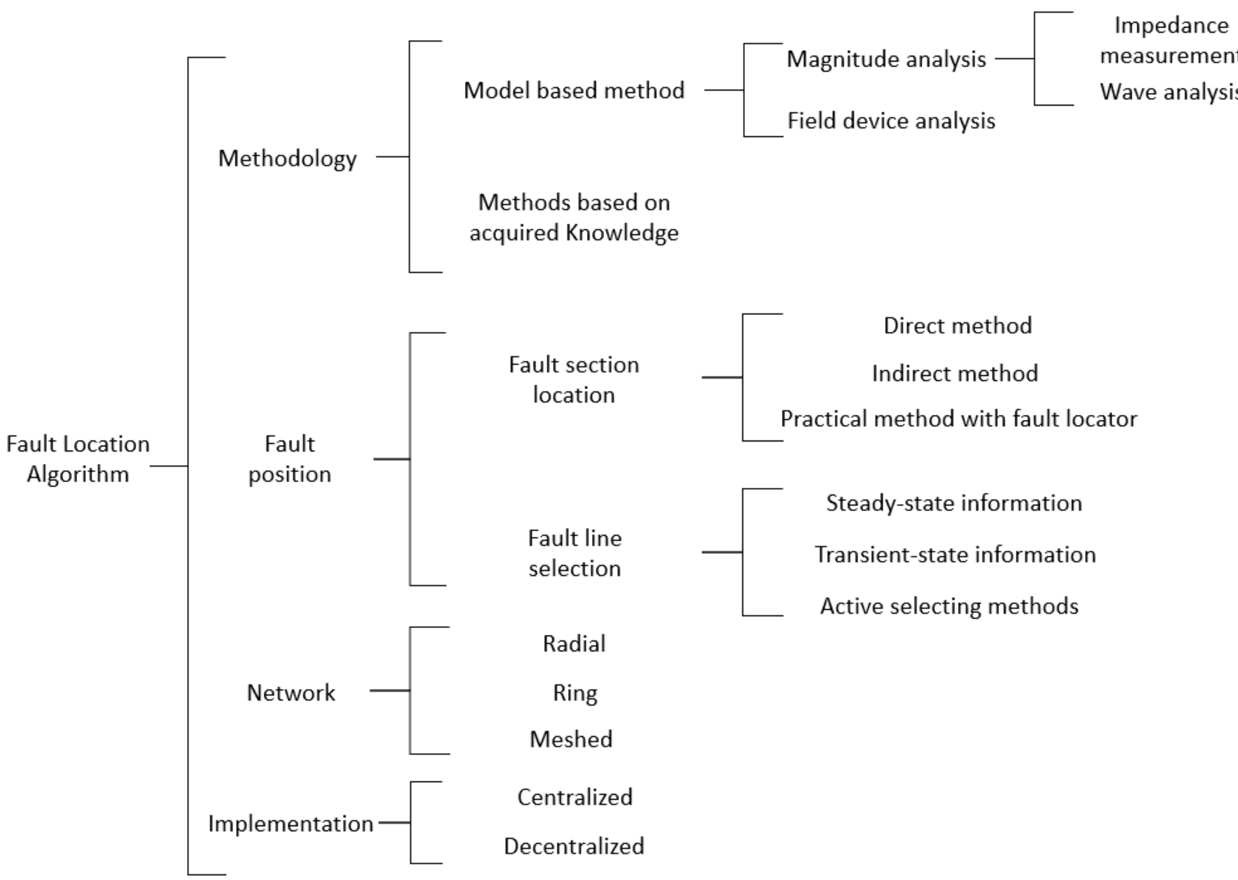


Table 5.4 Classification of fault locator algorithms

Although other authors establish this classification according to the methodology. Regarding to [89] there is another classification which considers that there are 5 kinds: Integrated methods and other similar methods such as [90], learning-based methods such as [91] and [92], travelling waves-based methods such as [58] and [93], impedance-based methods such as [94] and sparse measurement-based methods such as [95]. Therefore, the classification of this thesis from table 5.4 tries to identify the several skills and application fields from different fault location algorithms.

5.3.2 Fault location algorithms according to methodology

The first part of the classification analyses the fault according to methodology, in fact these methods have been the first methods that the network's managers have applied during years. It highlights that there are models through field devices collected information using the intrinsic functionality of these equipment and other methods acquire the magnitude from these devices and establish in a second term an analysis by impedance, using current and voltage or by means of wave analysis.

It is possible to try to combine the two methods, according to [86] it is possible to find an example about the combination of both principles. One of them is focused to define the distance to fault through the field device. The other method is focused in to analyse the wave to guess the distance to the fault.

The second part of the classification, the methods based in acquired knowledge, is a way where a lot of researches are working with Radial Basis Function Neural Network (RBFNN) [96], [97] and [98]. This neural network is an extension of ANN which can provide an establish solution to locate a fault.

5.3.2.1 Model based methods

According to last section the model-based methods establish a way to analyse the location of the fault by means only the real information recorded by field devices. In fact, this kind of methods is representing a model of the system and comparing it with the distance fault. It is important to establish a difference between the analysis of the information only with magnitudes from the devices and the analysis of the information from individual analysis of each field device.

Probably the analysis through magnitude analysis is more accurate than not the field devices analysis because the information is analysed globally [50] and in the other case each device can have a different way to locate the fault. Although it is possible to combine both methods; it will be shown later in this document.

5.3.2.1.1 Field devices analysis

As it has been explained above the field devices such as FPIs or IEDs can provide information about the fault's path and it is possible to combine this information in order to locate the fault. Previously the FPI and AEDs capabilities have been exposed; therefore, the combination of two elements is very important to locate the different kind of fault: self-extinguished, fugitive and permanents.

The field device analysis is probably the simplest analysis and until today one of the most resolute method. The most important advantage of this method is that it is not necessary to develop an algorithm in the control centre to find the fault. Probably only with the information from field devices, it will be possible to find the fault because it is possible to find the path of the fault. Likewise, other information such as 21FL information from the relay will be useful to identify the fault in the part of the line where is the fault. For this reason, is not necessary to cover all the distribution line with FPIs in each frame, just defining strategic points few FPIs have to be installed [73].

The FPIs have a proprietary algorithm from manufacturer to detect a current increase without voltage presence during a period of time. Nevertheless, it is possible to considerer the algorithm with voltage presence to detect a fugitive fault.

This kind of analysis is one of the most used historically because physical communication ways and communication mechanisms were not developed in advanced level such as current methods. In fact, the DSOs have been using these methods in rural areas where the radial network is often present.

Nowadays with information technologies this kind of method are in a second term because it is possible to establish a good detection system with other methods, although in long radial lines it is very interesting to use mobile FPIs as shown in figure 5.15 with direct communication to mobile phone or control centre in order to receive an indication of the fault.

5.3.2.1.2 Magnitude analysis

The magnitude analysis uses information gets from the field devices. Here there is a partial study about the pass of the fault using only the information of each device. However, a magnitude analysis uses all the information from all devices or a set of them to determinate a properly fault location.

The analysed magnitudes in this kind of method are the voltage and currents, basically the primary magnitudes of an electrical system. The most interest of the use of these magnitudes is in the capture of them before and during the fault [99]**.** Under this scope there are two algorithms, [100] and [101]**,** to detect the fault using this kind of methodology.

Although there are specific examples such as [102] which are using PLC. The idea of this kind of application is to calculate the distance to fault by means of different points where the fault is observed. The idea of this method is to establish a comparison between different data which has been captured in different points of the line. Through this data it is possible to calculate the impedance of each frame, from the device location to the fault. Thus, it is possible to establish an accurate measurement to calculate the distance of the fault.

A mentioned before example of this kind of system is [50] where there is distributed information in different devices along the line. In this example is important to take in account that it is very necessary to implant a supervisor system to collect this data and process after it. In order to improve this method, it will be interesting to cover some points of the line. These devices have to be able to capture several records to report to the supervisory system where the algorithm will be executed after the fault to locate the fault. This methodology has been presented in [103] and has been tested in a DSO in the northwest of Spain, EDP HC Energía. This method consists in the analysis of the waveform captured by an IED after the fault and so to calculate the distance to the fault. This information and the information of the distributed FPI in several parts of the overhead and underground line can identify the way to find the fault.

5.3.2.2 Methods based on acquired knowledge

This kind of methods are based on acquired information from different systems such as [104]; in this case the primary information comes from the three independent systems: customer trouble calls, Automatic Meter Reading (AMR), and distribution Supervisory Control and Data Acquisition (SCADA). These multiple information sources can increase the probability of conflicting because there is redundant data.

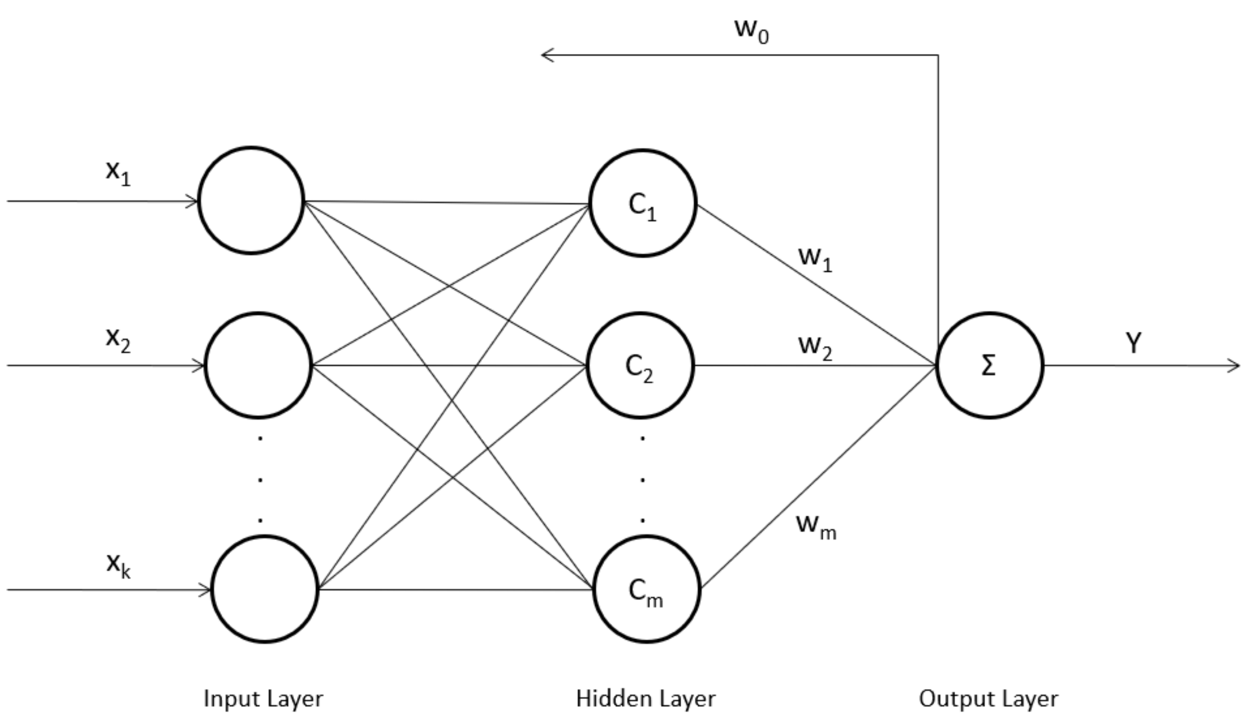


Figure 5.18 Architecture of the RBFNN

The ANN is an artificial intelligence technology to simulate receiving, transmission and processing information of human nervous system. The ANN consists of a large number of interconnected neurons which has behaviour as a parallel processor, and present similarities to the human brain because receives the knowledge from the external environment [105]. This kind of technique has started to use due to the presence of DER in the network. It highlights that in front of a fault the current flow has its direction from the generations to the fault. In this case the fault detection is complex because the flows in each part of the network have a different direction.

Nowadays the RBFNN is being used in order to locate a fault in several algorithms because is a feed-forward with a high convergence speed. The RBFNN is composed by three layers: input layer, hidden layer and output layer. The first layer feeds the values in every neuron in the hidden layer. This hidden layer is a set of neurons with radial basis activation functions which link with the output layer. This last layer is activation with a linear function. The figure 5.18 shows a generic architecture [96] of RBFNN with k inputs and m hidden neurons. In fact, this kind of system is an adaptive control. When the network receives a k dimensional input vector X, the network will compute a scalar value by means of the equation 5.4, where w_0 is the bias, w_i the weight parameter, m the number of nodes in the hidden layer and (D_i) is the RBF.

$$Y = f(X) = w_0 + \sum_{i=1}^{m} w_i \varphi\,(D_i) \qquad [5.4]$$

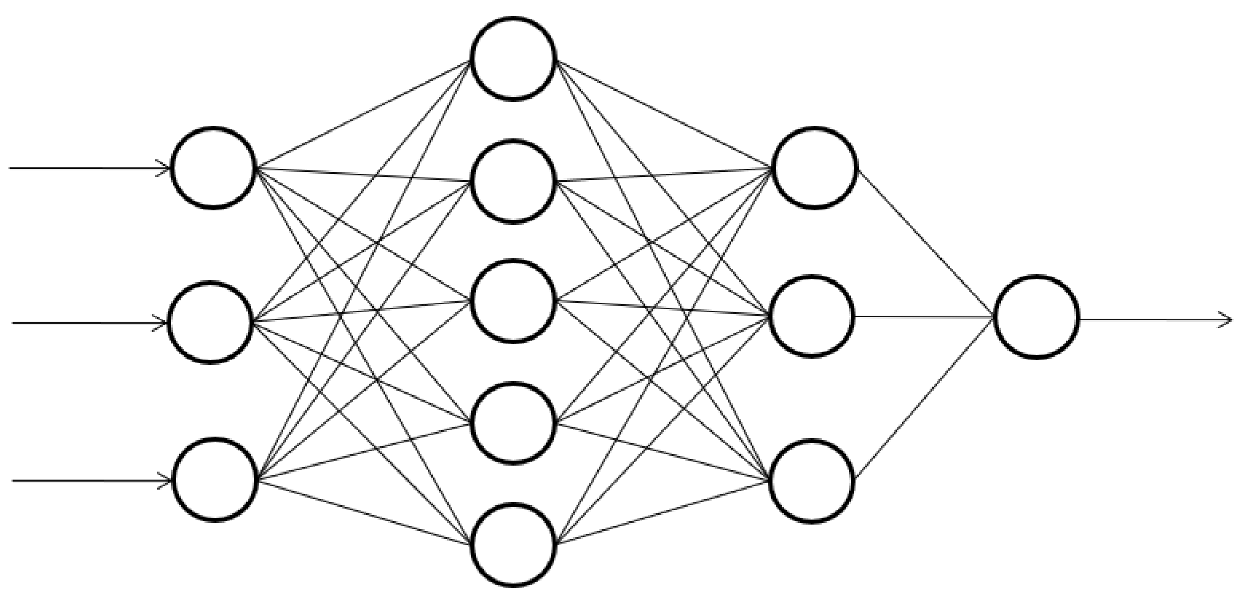


Figure 5.19 Architecture of the MLP with two hidden layers

The RBF is defined by a function such as Gaussian function [96] where this function is composed by the distance between the input vector X and the rest of data centres. In fact, this function will be different in each algorithm. It is important to highlight that the RBFNN are in a continuous training to find the location of the fault.

On the other hand, the implementation of this kind of system implies a definition of a process in order to apply the algorithm. According to [96],[97],[98],[105],[106],[107],[108],[109] and [110] there are different algorithms based in neuron systems. Although all these propositions establish three points: neuron model, complex-domain activation function and training algorithm. In these examples it is possible to find different hidden layer in the same algorithm although the vast majority have a single hidden layer.

According to [107] the algorithms with several hidden layers are known as Multilayer Perceptron Neural Networks (MLPNN). This kind of networks consists of several layers of neurons with one layer as output layer and other ones as hidden layers. In several technical and engineering problems MLPNN sometimes it is necessary to use more than one output in the algorithm as show in figure 5.19.

5.3.3 Fault location algorithms according to position

As mentioned before the analysis of the position of the fault according to the section of the network or even the substation outgoing where the fault has appeared is other possible classification which describes a fault location algorithm.

5.3.3.1 Fault section location

5.3.3.1.1 Direct method

The direct method defines a matrix in order to describe the network structure. These algorithms can be based in the structure shape or in base structure or even the overhead arc algorithm. This method is simple to implement but the complexity will depend on the network size. If the network expands the complexity of the computation will increase considerably, therefore several operations with matrix have to be avoided. Although nowadays the evolution of the Data Processing Centre (DPC) and in general terms the IT could increase the application of this kind of algorithms.

Several publications such as [111] and [112] depend on the structure of the network, so they are focused on networks with stable operation mode. This kind of algorithms use the known loads in the network to establish some calculus, but normally it is not easy to get the rated loads.

5.3.3.1.2 Indirect method

The indirect method defines a complex algorithm in order to detect the fault section of the network where is the fault. As mentioned before the use of ANN joint with GIS and historical network information can contribute specially in the location of a fault. This methodology has been classified in four main areas as described below:

- **Artificial Intelligence**. The use of ANN can contribute as mentioned before in the possibility to search the section where the fault is. As mentioned before the ANN is a connectionism of several artificial networks which simulate the empirical thinking mechanism. At the end, the ANN can produce reasonable outputs in order to detect a fault in distribution networks [113].

- **Optimization algorithms**. The optimization algorithms can build an evaluation function and convert the location of the fault in a minimum and maximum problem. Examples of this optimization problems are the genetic algorithms such as [114] or even the ant colony optimization such as [115].

- **Expert system**. As mentioned before a high system control can integrate this kind of algorithms which can use other auxiliary systems such as GIS and historical information. As mentioned in [116] and in [117] to share information and the use of GIS in a ADMS can contribute considerably in the fault location.

- **Rough set method**. This method is adequate for small-scale distribution network. In fact, the method proposes that when fault happens, the operator can detect the fault by means of the information from historical information with decision table in order to reduce the fault location. Algorithms such as [118] can reduce this operation time.

5.3.3.1.3 Practical method

The practical method uses the information from field devices in order to identify where is the fault. The use of FPIs or IEDs with communication to control centre or to local devices such as telephone mobile can give information to the operator in order to guess where the fault is. This method can combine with rough set method which has been explained before. The problem of this kind of methodology is focused mainly for radial distributions without DG.

5.3.3.2 Fault line selection

As mentioned before the fault line selection method has as goal to identify the outgoing of the substation where the fault is in a distribution network in order to avoid a bad recognition due to a weak fault current or unstable arc. The table 5.4 identifies three important methods inside this category which are based in steady state fault component, in transient state fault component and active selecting method.

5.3.3.2.1 Steady state information

This fault line selection methodology uses methods such as zero-sequence current magnitude and phase comparison method as it has been explained before with the flow current in electrical distribution networks. This method calculates each zero-sequence magnitude from each line and can compare the direction of the flow to determinate the line with the fault and also to discriminate is there is a fault in the busbar of the substation.

Also, this methodology uses other very similar technique such as fifth harmonic method which can compare the magnitude and phase of fifth harmonic current. The harmonic magnitude is much smaller that fundamental current. Then for a fault with large transient resistance it will be difficult to extract this information.

Other important method within steady state information is the active component method or zero-sequence admittance method which make a phase comparison in order to determinate in which line is the fault. These methodologies are very similar than the implemented algorithms in IED such as protection ANSI 67N, then it is possible to use this direct field device information to have more information to locate the fault.

5.3.3.2.2 Transient state information

These algorithms use the information during the fault in order to determinate the affected outgoing of the substation. One of the methods is the first half-wave, in this case the different zero-sequence transient states from each feeder are compared and the feeder with the fault will have the largest magnitude and also compare the phases and the different one is fault line. If the signals are the same the fault will be in the busbar of the substation. In fact, is a similar process to steady state zero sequence which has been described before.

Another efficient transient state information method is continuous wavelet transform. The application of this wavelet packet is more accurate that the signal analysis method due to the frequency band is divided into multilevel parts and the spectrum of the signal is matched then the resolution time-frequency is improved [119].

In this case it will be necessary to compare between feeders such as in last method but in this case the accuracy can contribute significantly in use it in several earth neutral systems. As mentioned before the isolated earth system has a lower zero-sequence current then to identify the feeder with the fault will be difficult in comparison with resistance earth system. This method can provide a better observation of transient variation instead of the Fourier transform, which is used by AEDs and FPIs in order to identify a fault.

5.3.3.2.3 Active selecting methods

The active selecting methods has the principle to modify the system doing several specific actions in order to locate correctly the fault. For example, the fact modifying the impedance in the Petersen coil or injecting some signal in the network.

A modification in the Petersen Coil makes a modification of the zero sequence and then it will help to detect the fault. Other modification could be to inject a signal to the neutral earth system and see the magnitude of the fault. Although this kind of method could be more interesting for an end user installation that not in a distribution network from utilities.

5.3.4 Fault location algorithms according to structure network

As mentioned before in this document the structure of the network has a relevant importance in the quality of the network but besides it will influence on the design of the algorithm. Nowadays these algorithms could be classified in radial, ring or meshed networks as in general terms. In fact, an algorithm focused on meshed network will be implanted in a ring and in a radial network.

It is important to highlight that developed algorithms such as [120], [90], [58], [121], [93] and [95] are focused in radial networks. However, this topology of networks, have evolved to networks with rings or even with a mix of rings, in last decades. Algorithms such as [88], [122] and [91] offer new solutions to detect a fault for this kind of networks. On the other hand, the presence of DER in electrical distribution radial networks have make necessary to create algorithms such as [105], [92] and [123]. In addition, algorithms such as [111], [112] and [94] are thought to be applied on radial and non-radial networks with DER presence.

During a fault the LV network is affected regarding the voltage level as mentioned before. The faults in MV produce a voltage unbalance in the LV side. According to [124] it is possible to find a relationship between direct voltage and indirect voltage in order to confirm a fault in MV.

5.3.5 Fault location algorithms according to implementation

As mentioned before the implementation of this kind of algorithms can be centralized or decentralized. This fact is not relevant in the efficiency of the algorithm but it can contribute significantly in the possibility to extend more and less in the distribution network. A centralized algorithm is present in a control centre where all signals are collected from several devices and all operations are making in this area. A decentralized algorithm also collects the information from several devices but the information has been treated previously by field devices. As an example, the information of FPI can be the magnitude and phase zero-sequence current in order to treat by centralized algorithm or directly can be the indication of fault presence which is saw by this device.

5.3.6 Algorithms examples

This part of the document introduces several examples about the fault location algorithms in order to illustrate the explanations about classification fault location algorithms. In mentioned reference is possible to find more details and examples about these examples. It is important to remark that the algorithms can be combined between them to reach a better result in an electrical distribution network.

5.3.6.1 Fault locator algorithm with ANSI21FL and FPI

A good way to get a correct location in the MV distribution network is to get ahead all tools of the network. A combination of FPIs and ANSI 21FL can provide additional information without to establish a great accuracy about the distance to fault. This algorithm can be classified as model-based method with field device analysis, within fault section location, which uses a practical method with fault location, radial and decentralized. Other important aspect is that this algorithm can be work with DG.

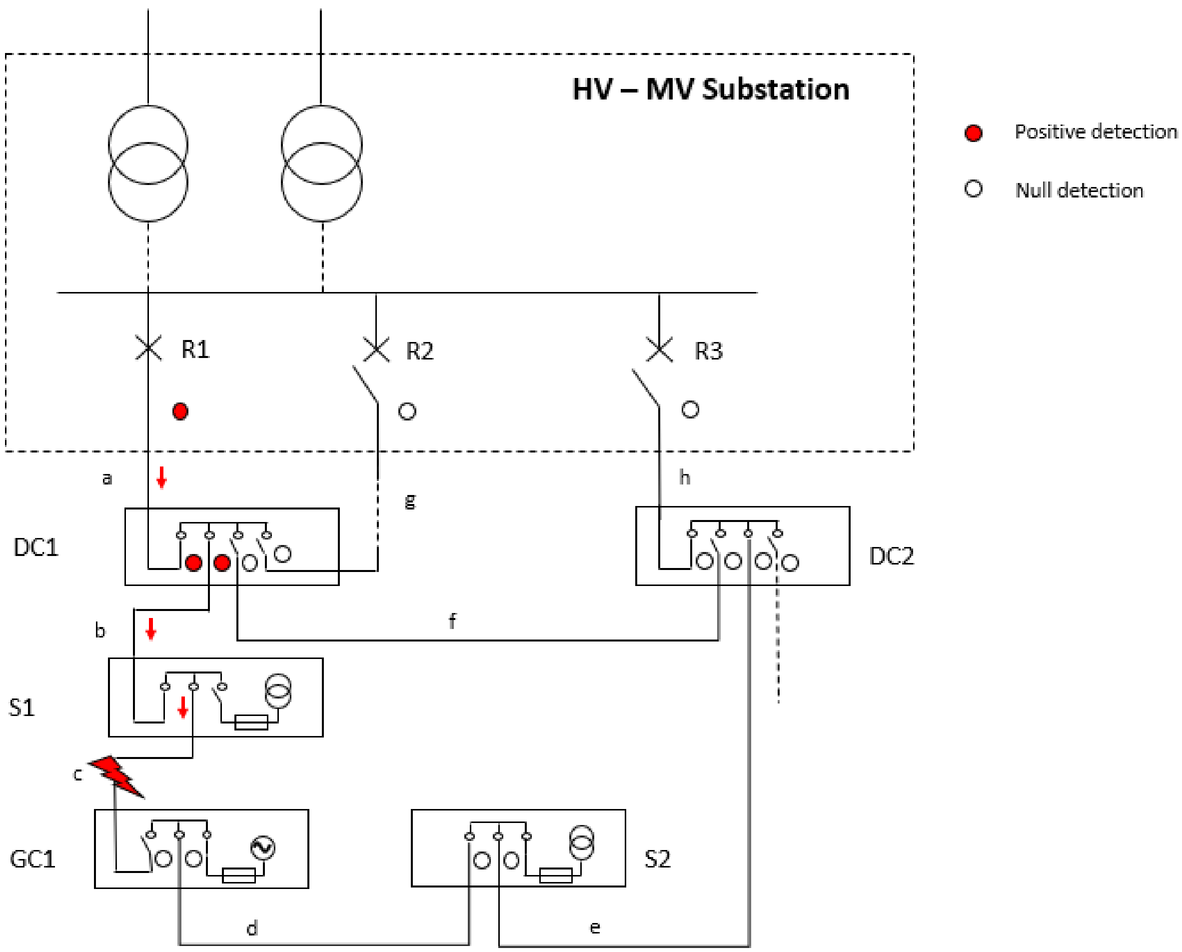


Figure 5.20 Detection with FPIs in a distribution network

In a feeder with different ramifications it is difficult to know where the fault is, with the information about 21FL function from the feeder. The FPI can contribute to know in which ramification there is the fault and with the 21FL distance it will be possible to identify the fame of the network where the fault is.

The figure 5.20 shows the combination between these functionalities with the ANSI 21FL in AEDs $R1$, $R2$ and $R3$ from substation and FPIs distributed in some substations. In the figure the frames are designed by the letters a, b, c, d, e, f, g and h and the centres by $DC1$, $DC2$, $S1$, $S2$, and $GC1$ where the terms DC, S and G are referencing to distribution centre, MV-LV Substation, and generation centre respectively. With this configuration it is not necessary to install FPIs in each distributed centre to detect the fault.

It highlights that the AEDs in the circuit breaker from the feeder makes protection functions and additionally the 21FL. The information from 21FL will not have a big accuracy due to there is not defined a model network although it is enough to locate the fault [125].

A network with FPIs in each node of the network can locate easily the point of the network. On the other hand, a partially automated network can be use this algorithm, it is not necessary to have a big automation deployment. The equation 5.5 expresses the position of the fault approximately and the frame where fault is [13].

$$f(\lambda, \mu_i, \varepsilon_{i,j}, \delta_{i,j}) = \sum_{1}^{n} \left[\mu_i \cdot \left[\sum_{1}^{m} \sqrt{\left(\left(\varepsilon_{i,j} - \lambda \right) \cdot \delta_{i,j} \right)} \right] \right] \qquad [5.5]$$

where:

- λ is the distance of the fault from the ANSI 21FL.
- μ_i is the indication form FPI i. The status of this variable can be 0, if the FPI does not active, 1, if the FPI is activated and the fault has positive direction or, -1 if the FPI is activated and has negative direction.
- $\varepsilon_{i,j}$ is the accumulative distance from substation outgoing until the frame j which follow the FPI i until the FPI $i+1$. It highlights that the distance between two FPI in the same centre is 0.
- $\delta_{i,j}$ is the variable with the connection between frame j until the frame of FPI i, which will not adopt any value.

By means of the expression 5.5 in a network such as the figure 5.20 it is possible to get several imaginary values and a real term. The imaginary part appears due to the cumulative distance until several sections $\varepsilon_{i,j}$ is lower than the distance to the fault λ and it can scorn due to it is uninformative.

On the other hand, the real term will be composed by a series of negative elements, due to difference between distances, except a positive term with the following showed form in equation 5.6, which will indicate the section where the fault has appeared, in this case between the FPIs p and s, and besides it will show the distance to the fault inside of the section.

$$\mu_p \cdot \sqrt{(\varepsilon_{p,s} - \lambda)} \cdot \sqrt{\delta_{p,s}} \quad [5.6]$$

This algorithm is valid for distribution networks in MV such as radial and with interconnected rings which work with switch-disconnector open in order to detect earth fault and phase fault. The advantage of this kind of solution is to know the fault section without know the exact distance to fault, it is not necessary an accuracy analysis. Later if the network has some automated part it will be able to start a restoration process immediately, if not a patrol of operators will go to the installation to know the exact place to isolate this part and repair it after.

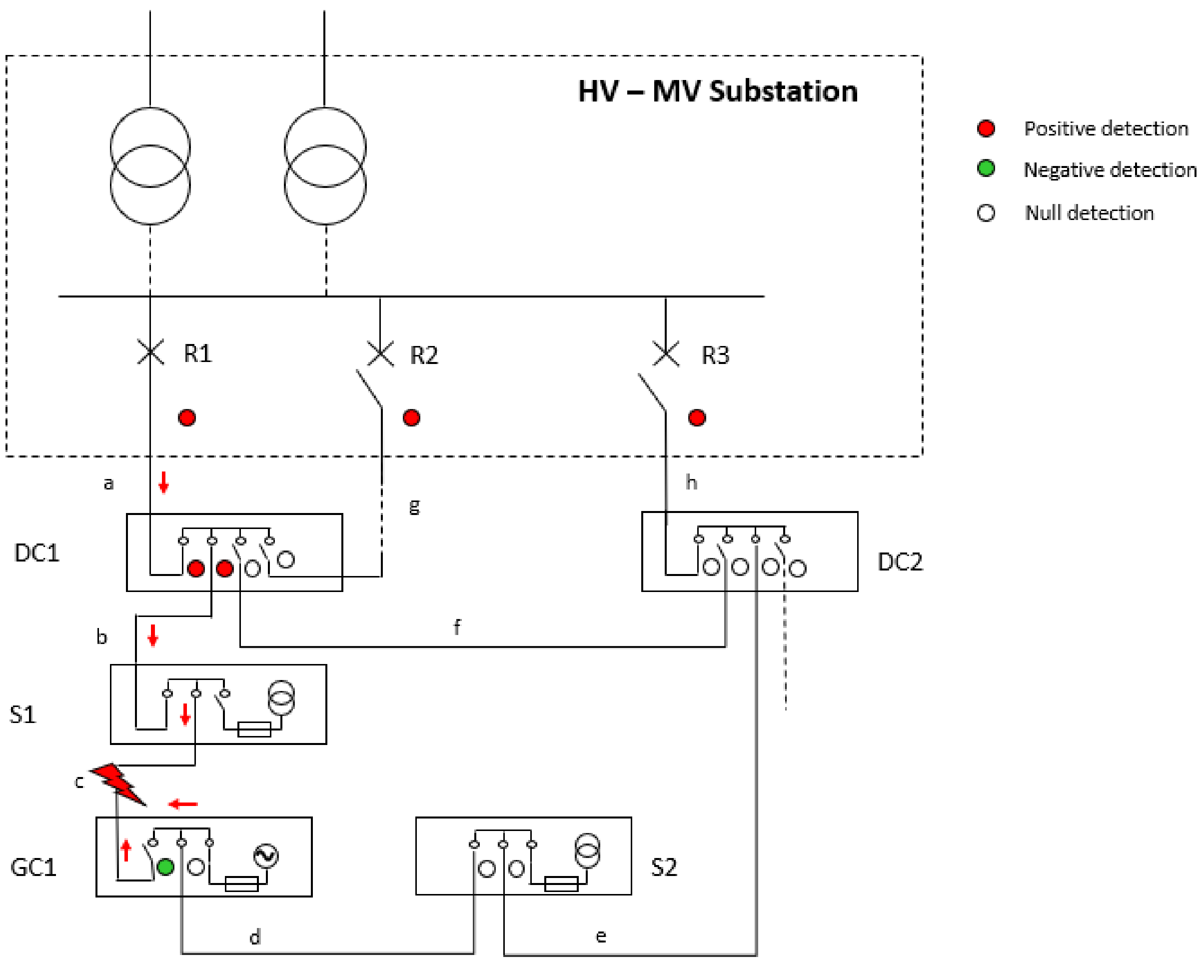


Figure 5.21 Detection with FPIs in a distribution network with DERs

Moreover, this algorithm can be used with directional FPIs to earth faults and phase faults. This last point is important due to in the current networks there is a lot of DERs. In front of a defect there will be a change in network frequency and the generators will disconnect although these devices will have ceded energy to the grid.

In this last case the distributed FPI in the network can report the fault due to the current flow is in both directions. The defined algorithm in the equation 5.5 can discriminate this situation thanks to use of the directional FPIs which can detect the direction of the fault. The figure 5.21 shows this fact where the current flows from one side of substation and also from the generation until the fault, enabling the FPIs with colour green or red according to the direction.

5.3.6.2 Fault location algorithm in a network with distributed generation

As it has been commented previously the DERs impact considerably in the electrical network. For this reason, in front of a fault these DER can be a tool to analyse the network while their behaviour is analysed. This algorithm is classified as model-based method with magnitude analysis under an impedance measurement and also as a fault line selection by steady-state information.

Additionally, this algorithm could be work in meshed networks in a centralized way, due to different devices will send the information to the control centre in order to apply several equations in high system control.

According to the algorithm [126] there is the possibility to detect three-phase fault detection using the behaviour of DER in the moment of the fault. A fault in a network without DER can be calculated by means of expressions 5.1, 5.2, 5.3 or 5.7. The last one expression can be extracted from the direct component from a generator in a network as it has been showed in figure 5.22 in this case R_f is zero.

$$d = \frac{V_d - I_{dm} \cdot Z_{td}}{I_{dm} \cdot Z_d} \quad [5.7]$$

Where d is the distance to the fault, V_d is the voltage in the generator, Z_{td} is the transformer impedance, Z_d is the line impedance and I_{dm} is the current in the circuit. This same situation happened in the figure 5.23 where the fault was fed from one point of the network. In order to analyse mathematically the circuit only it takes into account the left mesh.

In the case that there is more than one generator in the network there will be a different model for the distance function. As shown in figure 5.23 the fault current comes from two different points. Inside these generators there is LV-MV transformer, for this reason there is additional impedance.

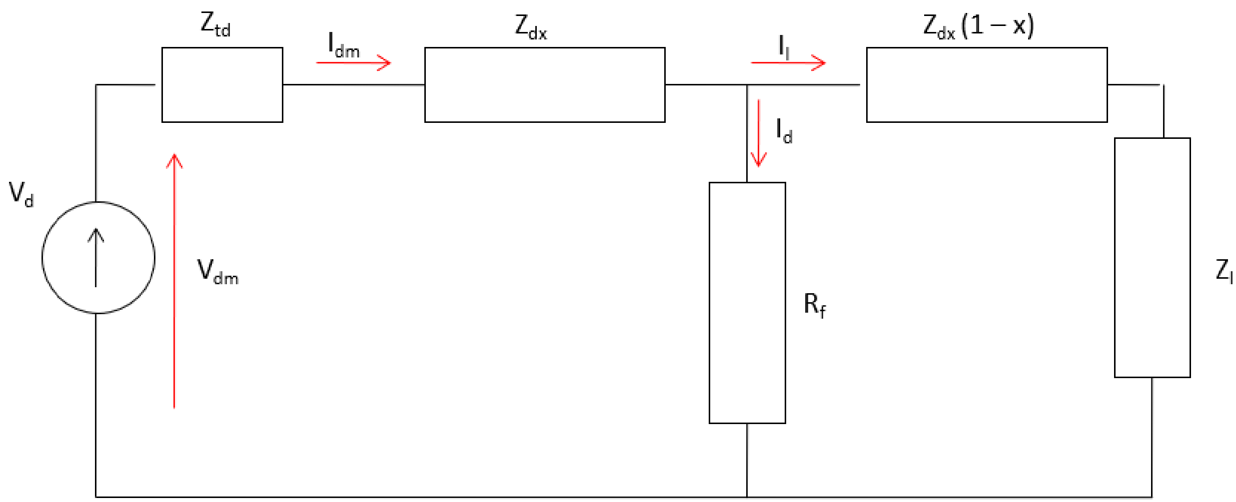


Figure 5.22 Direct representation of one circuit with generation

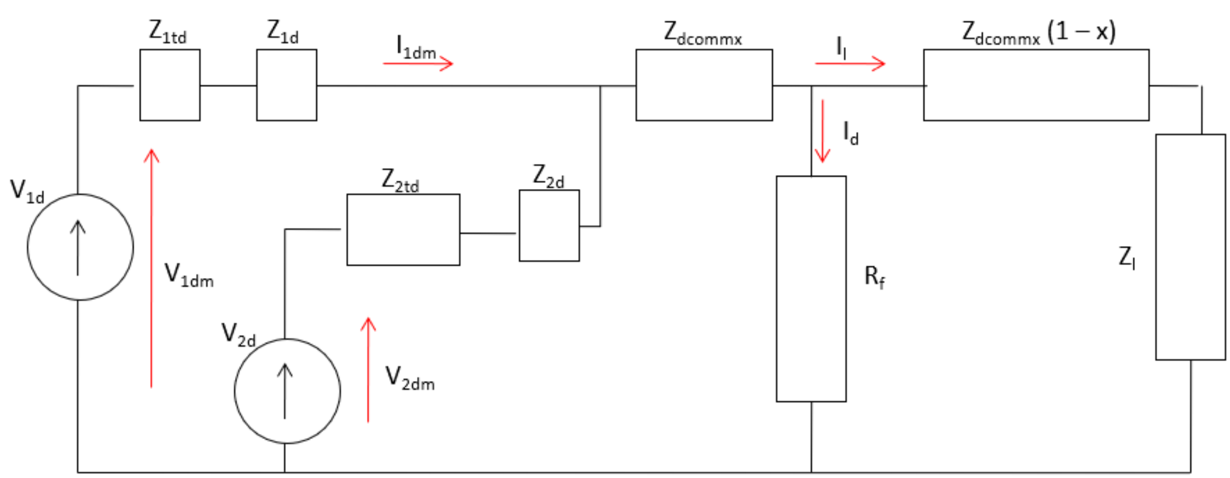


Figure 5.23 Direct representation of one circuit with two generations

Through the representation in figure 5.23 a system of equations has to be established in the expression 5.8, where the fault resistance R_f is zero again. In this expression are defined the impedances in base a generator 1 and 2; then the Z_{dcomm} is a common impedance of these generators.

$$V_{1d} = I_{1dm} \cdot (Z_{1td} + Z_{1d}) + (I_{1dm} + I_{2dm}) \cdot Z_{dcommx} + I_d \cdot R_f$$

$$R_f = 0 \qquad [5.8]$$

$$Z_{2td} = Z_{DG} + Z'_d + Z_{transform} \cdot d$$

From this system and through identical generation [126], it is possible to consider the equation 5.9 which define the impedance provided by generator 1.

$$Z_{f1} = \left(\frac{V_{1d}}{I_{1dm}}\right) = (Z_{1td} + Z_{1d}) + \frac{Z_{1td} + Z_{1d} + Z_{2t} + Z_{2d}}{Z_{2td} + Z_{2d}} \cdot Z_{dcommx} \qquad [5.9]$$

The previous expression represents the impedance for one generator. If there would be a number n of generators in the feeder can be establish a generic expression to integrate all possible generators. The system 5.10 defines the impedance Z_{fi} seen from the source when i generators are distributed and connected in the way of the fault.

$$Z_{fi} = Z_{fi-1} + (1 + \sum_{k=1}^{k=i} \frac{Z_{fk-1}}{Z_{DGk}}) \cdot Z_{dcommx} \qquad [5.10]$$

$$Z_{f0} = \frac{Z_{1td} + Z_{1d}}{Z_{2td} + Z_{2d}}$$

In order to establish this algorithm, it is necessary to have the information of distribution network to offer the impedance data in the fault calculation. This algorithm has been validated without and with distributed generation in a network with five generations and concentrated load as shown the figure 5.24. Also, the algorithm has been validated with ten equal loads [126].

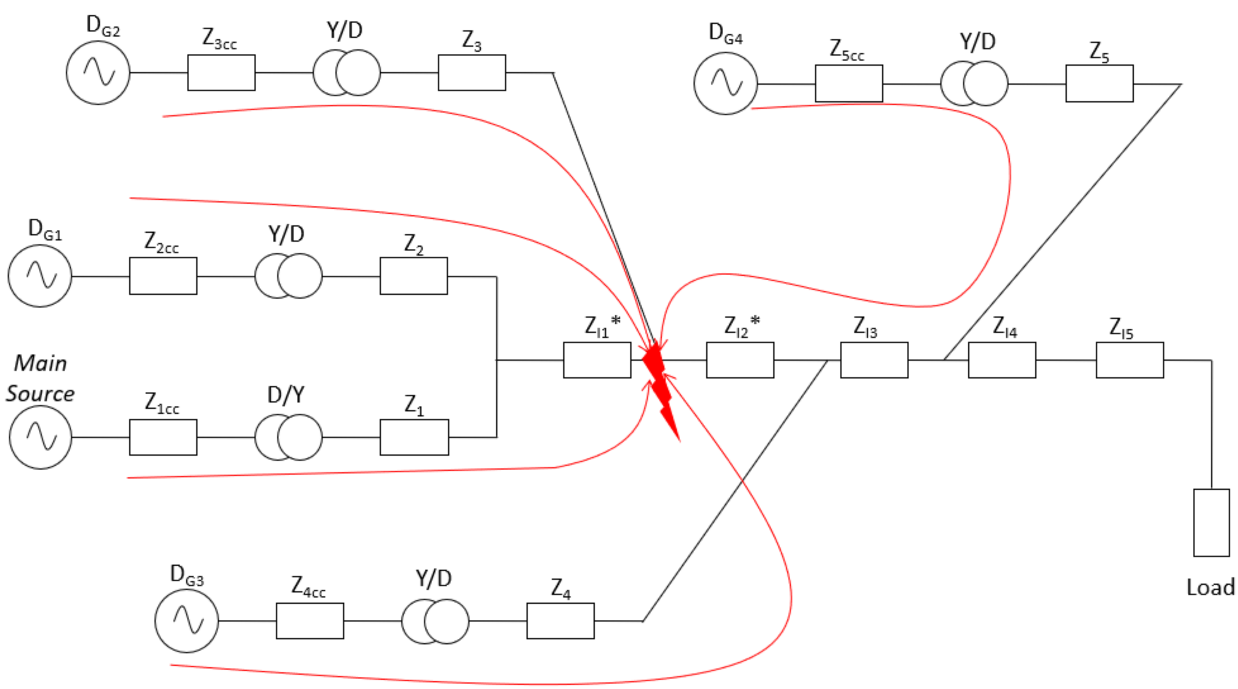


Figure 5.24 Validation of the three-phase fault location algorithm

5.3.6.3 Ratan Das fault location algorithm

An interesting algorithm in order to locate faults in distribution electrical networks is the Ratan Das algorithm. This algorithm estimates the location of the fault through the voltage and current phasors in the fault instant [101]. In this algorithm is estimated a filter for the phasor's value and after that there is an analysis about the fault location. This algorithm can be classified in model-based method with magnitude analysis under a wave analysis, as fault line selection as steady-state information, for radial networks and as centralized algorithm.

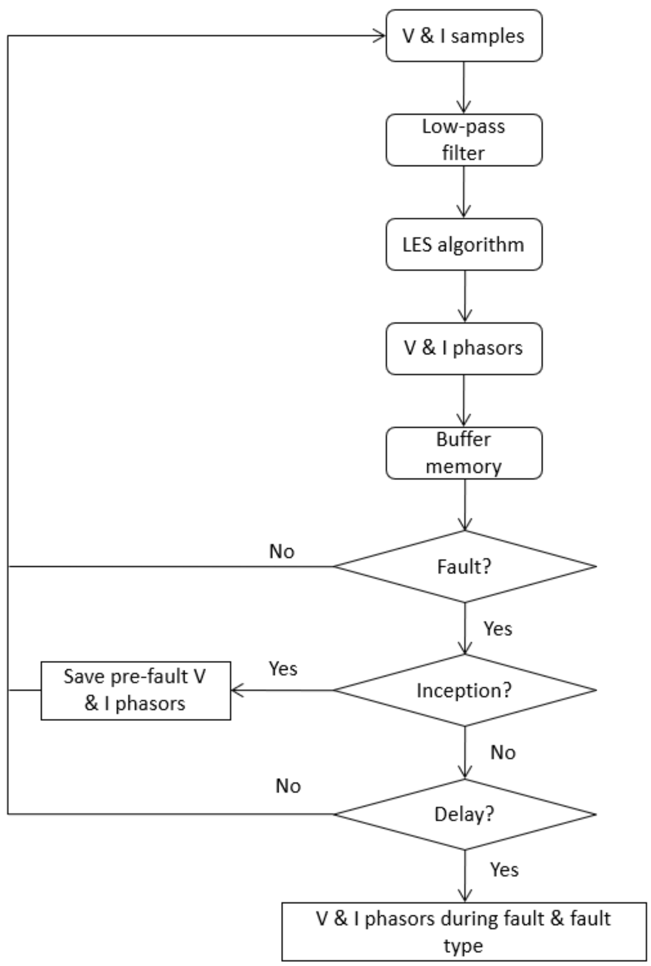


Figure 5.25 Ratan Das algorithm

The Ratan Das algorithm analyses the voltage and current in different nodes. Previously the algorithm studies the frame where the fault is in order to use the current information and voltage from the nodes which surrounded the fault. The first step is to estimate the position of the fault knowing the distance between nodes, before that there will be a comparison with the voltages and currents in the nodes between the fault and the line terminals. Several iterations will be done until a convergence is achieved.

Although it is not necessary to have a network model to make these comparisons. This method has been tested in different situations and offer good results when there is not a good knowledge about the network [99].

According to [101] the algorithm has been proposed for radial networks although it is possible to apply in ring configuration with some modifications. As it has been explained before there are two important processes: identify the voltage, V, and current, I, phasors with the kind of fault and estimating the location of the fault. The figure 5.25 shows the block diagram with both processes. The first diagram is the data acquisition process and the second one is the estimating fault location very similar to [50].

The first step is to acquire the data through the fundamental frequency component of the pre-fault voltage and current phasors in the first node in the line. In a second step this information can be used to estimate the location of the fault. As in previous algorithms this estimation can be done through the information of the network. The fault section can be estimated through the information of the line the fault between node n and the next one $n + 1$.

In a third step, the load model must be done with dependency on voltage. All loads up to node n are independently and the loads beyond the fault are assumed to be consolidated with the load and remote end. The load constants describe the voltage-admittance relationship are computed from the pre-fault load voltage and currents.

In a fourth step, there is an estimating about the sequence voltage and current at the fault and at the remote end. The sequence voltage and current at node n during the fault are computed thanks to use the voltage dependent load model. The sequence voltage at remote end is calculated through distance function from the fault to node n.

Finally, the estimation of the distance of the fault from node n is the last step. Appropriate sequence voltage-current relationships at the fault note are used to estimate the distance of the fault from node n. Now an iterative process starts until to reach a convergence.

Moreover, there are more modalities in order to estimate the distance to the fault such as reactive component, Srinviasan's method, Girgi's method, Zhu's method, Aggarwal's method, Novosel's method, Yang's method, Saha's method, Choi's methods which are mentioned in [85].

5.3.6.4 Fault Distance Artificial Neural Network

The next algorithm [110] is an example about methods based on acquired knowledge. This technique contains two stages. The first one is the determination of type of the fault and the second one is to estimate the fault location, from substation to the fault. This algorithm could be classified as centralized and as indirect method.

In the first stage if one current is more than the threshold of substation the algorithm assumes that a fault has occurred. The magnitude of the zero sequence current increases when there is an earth fault. In this case an increase of this magnitude can be an earth fault of one or two phases to ground.

In the second stage a multilayer feed forward, neural network is adopted a trained for fault location analysis. This method is known as fault distance to the substation estimation, with the name Fault Distance Artificial Neural Network (FDANN). The figure 5.26 shows the method proposed.

The important point of this algorithm is the simulation study, then the FDANN has been applied in IEEE 34 bus test feeder. This test consists in radial network with 34 nodes, 32 lines, 6 spots loads, 19 distributed loads and 2 shunt capacitors [127]. It is important to take into account this test has been realized with unbalanced loads and non-homogeneity lines.

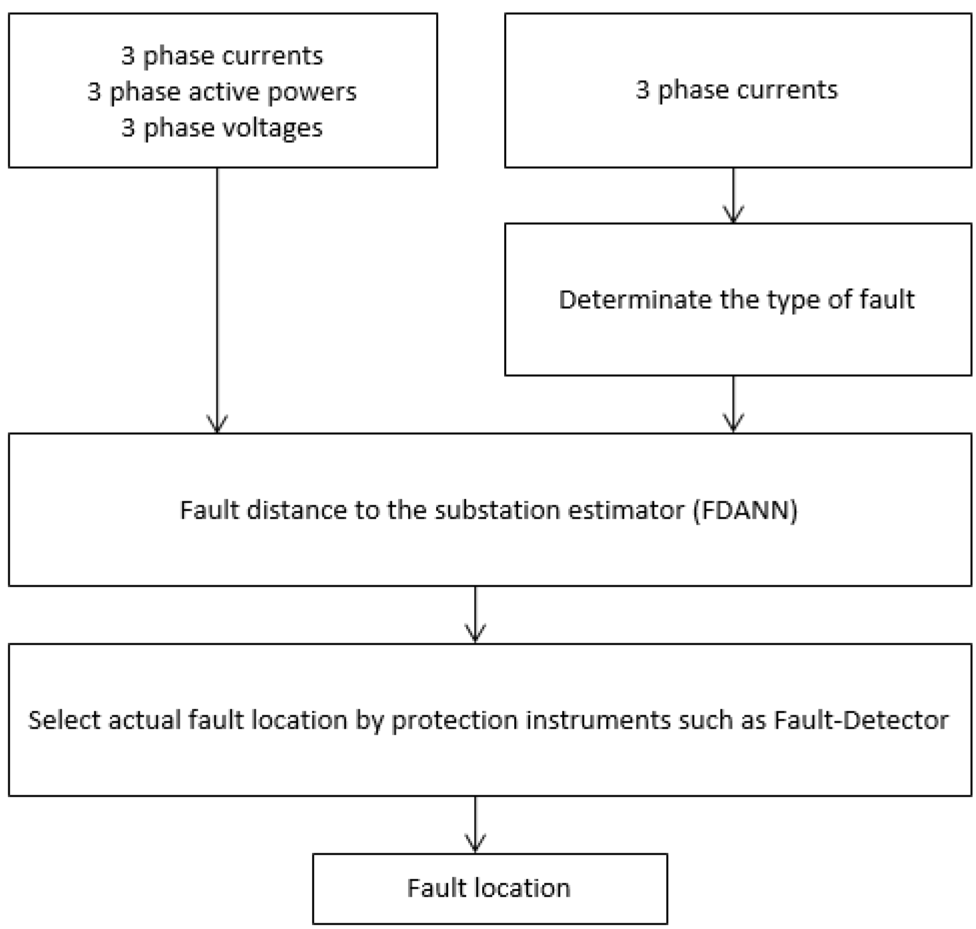


Figure 5.26 FDANN flowchart

In this algorithm it is important to highlight that the accuracy of the input data is a key point to locate the fault. For this reason, the field devices elements such as protection relays with their CTs and VTs must have a good accuracy, although to install these devices in the will increase the cost.

5.3.7 Fault location algorithm for meshed distribution networks with DERs

The proposed algorithm below is based on a model such as the used in [120] but adapting it to mesh networks. It is also covered in the publications [111] and [112] but the proposed algorithm is also independent of the topology of the network and its current configuration. The algorithm uses only the indications from the Directional Fault Passage Indicators (DFPI) and from IEDs and also the information about fault distance. In this algorithm it is not necessary to know the status of the circuit breakers and switch-disconnectors. The method uses only the relation between FPIs.

This algorithm can be classified as model-based method with field device analysis and direct method for fault section location. As mentioned before the algorithm can be work in meshed distribution networks as decentralized way.

The algorithm is focused in detection phase faults and earth faults, using the information available in the placed DFPIs in the electrical distribution systems and the fault's type and its distances, available in the installed IEDs in the main substation feeders. The combination of this information in the algorithm can provide an estimation of the exact position of the fault. It is important to highlight that the DFPIs could have the functionality 21FL as in the case of IEDs, then it is possible to use an IED instead of DFPI. Although this last proposition will increase the cost of the solution.

This novel algorithm is based on field device analysis because it is contemplating the field information of the network. As the 21FL feature is used as a tool to identify the fault [128] it is possible to consider that this algorithm has a methodology based on the model shown at [85].

The goal of this algorithm is to help to locate the fault; the section where the fault has happened and the location of it inside it. For this reason, the algorithm is composed of two important parts: the Fault Location Brick (FLB) and the Distance Brick (DB). This algorithm is known by name Automatic Fault Location (AFL) algorithm.

The FLB module has the mission to locate the fault between fault passage indicators in the network. After that the DB will detect the accurately distance inside this identified section. This algorithm is prepared to work in meshed distribution networks working in open or close ring configuration without any variation. The main benefit is that this algorithm can work with different flow direction in an electrical distribution network.

5.3.7.1 Fault Location Brick

As mentioned before one of the parts of the algorithm is the FLB. This part identifies the section of the network where the fault happened by analyzing the information from the installed DFPIs. The provided information by the DFPI or IED is characterized by two variables: the proper function b_i and the value of the direction of the fault detection, d_i, where i is the identification number of the device. If one of these devices is not working properly it will be necessary to extract it from the algorithm. It is important to remark that these devices can identify the kind of fault then the algorithm it must replied for earth and phase fault.

Each device identifies one of the points of a network section, the beginning or the ending. In order to define the network, it is necessary to previously define all the nodes from the analysed network. A node in the network is a part of the network where different lines come together such as a MV-LV substation, an overhead switch-disconnector, etc. In fact, these nodes link different sections of the network.

Figure 5.27 shows a network's node which corresponds to a MV-LV substation with one input and two outputs. The first input and the first output are to link the MV-LV substation with the distribution MV ring. The third output can link this substation to another ring such as happen in a mesh network [37]. Likewise, the MV-LV substation could have more additional switch-disconnectors to connect this substation with other distribution rings. The fourth output in figure 5.27 is for a load or for a DER.

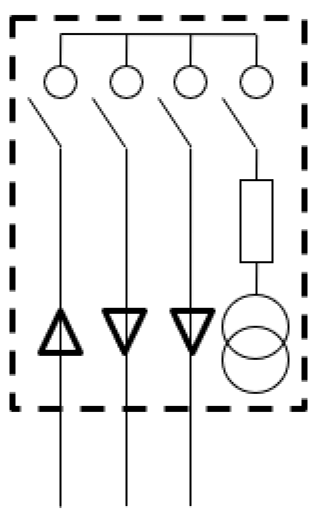


Figure 5.27 Example of a MV-LV substation topology

The current electrical networks have DERs and the future trend is to install circuit breakers and directional relay in the network in order to isolate the fault directly. This new trend allows working with a mesh network closing all the switch-disconnectors in the network. However, as mentioned before, the current electrical distribution networks are composed by switch-disconnectors without possibility to open directly in front of a fault and also with DERs. Therefore, it is possible to find a bidirectional flow current in front of a fault. In this case in a node with different brunches there will be current as an input or as an output. For this reason, it is very important to know the direction of the current flow in every node. This situation forces to establish a criterion in order to define the flow's direction.

After this analysis it will be necessary to define each node as a box with α inputs and β outputs with different directions. According to [129] if the current flow enters in the node the criterion is positive and if the current flow comes out of the node the criterion is negative. Figure 5.28 shows the node n_i of the network where the sign criterion mentioned before is applied with the contiguous nodes.

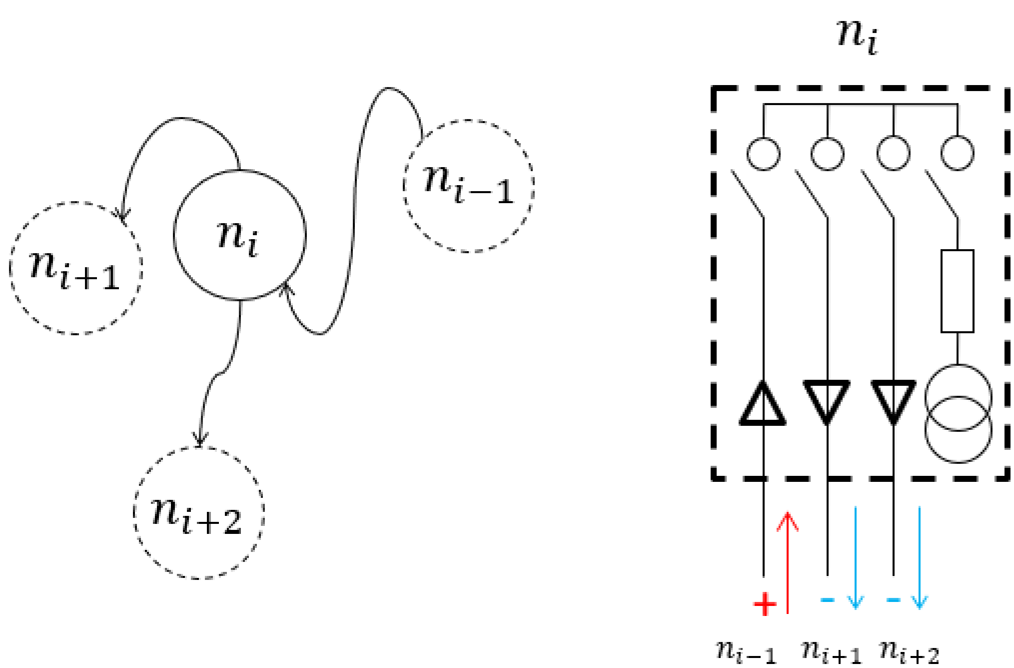


Figure 5.28 Sign criterion

In these nodes there will be a device which will identify the direction of the fault in each input and output. The chosen sign criterion has been used in the figure 5.28 in order to define the direction of the fault in a node.

Another important information is the structure of the network. This part defines the relationship between different nodes in the network in order to help about the location fault. In this algorithm it is only necessary to establish the relationships between DFPIs or IEDs then the result of the algorithm identifies the device more near to the fault. Hereinafter the devices in MV-LV substation will considerer only DFPIs.

These relationships between these DFPIs could be establish in a matrix with dimension $[n, n]$ where a_{ij} defines the relationship between DFPIs where i and j are two DFPIs. The relationship is established with DFPIs between nodes, but never between DFPIs within a node. The value a_{ij} can adopt two possible values:

- Value 0: when there is not relationship between i and j DFPI.
- Value 1: when there is a relationship between i and j DFPI, or when the term is in the diagonal of the matrix, in fact when i is equal to j.

Another important point is the status of the DFPI because is the key in order to have a proper relationship between these devices. For this reason, each value has to be multiply by the status of the relationship DFPI and by himself. Thus, the value a_{ij} will be affected by status b_i as it is shown in the expression 5.11.

$$c_{ij} = b_i \cdot b_j \cdot a_{ij} \qquad [5.11]$$

Therefore, b_i can assume the next values:

- Value 0: when the DFPI is broken.
- Value 1: when the DFPI is working properly.

In fact, it is possible to define a vector with the status of the DFPI in 5.12

$$B = |b_1 \quad b_2 \quad \dots \quad b_n| \qquad [5.12]$$

If one of this DFPI has the status b_i as broken it will be necessary to extract it from the system, and after that to set again the value c_{ij}, as mentioned before. Therefore, it will be necessary to develop a new relationship between affected DFPIs.

The relationship between DFPIs happens when these elements are followed without other DFPIs between them. In order to establish the relationship, it will not be necessary a flow of current between both DFPIs out of the node, the algorithm can work in open ring or close ring independently. Therefore, the connection matrix C is as follow in 5.13

$$C = \begin{vmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \dots & \dots & \dots & \dots \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{vmatrix} \qquad [5.13]$$

One of the properties of this matrix is its symmetry and the other one is that the elements of their diagonal are equal to 1, in exception when the quality status of one of the DFPIs is 0. In this case, it will be necessary to establish a new matrix C' without this DFPI. It is important to highlight that only it is necessary to eliminate the row and column of the FPI with quality status equal to 0.

This definition establishes a part of the algorithm where the network is represented. In a second part it will be necessary to define a vector D where there are the values of different DFPI of the network as follow in 5.14.

$$D = |d_1 \quad d_2 \quad \dots \quad d_n| \qquad [5.14]$$

The elements of this vector can adopt several values. Therefore, d_i can assume following values regarding the last criterion:

- Value 1: when the flow of the current in the DFPI i is an input of the node.
- Value -1: when the flow of the current in the DFPI i is an output of the node by means of the sign criterion defined in the figure 5.28.

It is important to take into account the status of the DFPIs. Then it will be necessary to multiply the status of the DFPI with his value. Then e_i will be the value d_i multiplied by b_i in each DFPI as described in 5.15.

$$e_i = d_i \cdot b_i \qquad [5.15]$$

Then it is possible can get the vector E in 5.16.

$$E = |e_1 \quad e_2 \quad \dots \quad e_n| \qquad [5.16]$$

Therefore, through C and E it will be possible to get a vector with a result about the location of the fault. This operation offers the vector F in 5.17.

$$C \cdot E = F = |f_1 \quad f_2 \quad \dots \quad f_n| \qquad [5.17]$$

The information of this vector includes the section of the way where the fault has happened. The element of the vector f_i can assume following values.

- Value -2: There is a fault in the section where there is the DFPI i. In this case the value is due to there is a close ring in the network. The current arrives to the fault in both directions.
- Value -1: There is a fault in the path where there is the DFPI i. In this case the value is due to there is an open ring in the network. The current arrives to the fault for one direction.
- Value 0: when there is not any fault in the path where there is the DFPI i.

If all values of the vector F are 0 then it is possible that there is not any fault or the fault is in the busbar from one node. For this reason, it will be necessary to establish a second analysis where this situation will be determined.

The vector G represents a result which identifies if the fault is in the node as it is shown in expression 5.18.

$$G = |g_1 \quad g_2 \quad \dots \quad g_n| \qquad [5.18]$$

Where each component is defined as follow in expression 5.19.

$$g_i = \left| f_i + \left(\left(1 + \prod_{1}^{y} e_k \right) \cdot \left(\left| \prod_{1}^{y} b_k \cdot e_k \right| \right) \right) \right| \qquad [5.19]$$

Where k is one of the DFPI from the node x. The DFPI i is a member of the node x, so y is the member number of the DFPI of node x. In instance if the node x has z DFPI then y will be equal to z. Therefore x is a set of DFPI where DFPI i will be inside as described 5.20.

$$k \epsilon x | \exists! i = k; \quad 1 \leq k \leq n \qquad [5.20]$$

The components of the vector G can adopt several values as following:

- Value 0: There is not a fault in the node where DFPI belongs.
- Value 1: There is a fault in the path where is DFPI i in an open ring.
- Value 2: There is a fault in the node where DFPI i belongs, when all values from G are equal to 0. Additionally, when there is a fault in a frame where is the DFPI i.

In the table 5.5, there are possible values which can adopt the result of components of the vector F and the vector G.

f_i	g_i	**Kind of fault**
-1	1	Fault in line section where is DFPI i in Open ring
-2	2	Fault in line section where is DFPI i in Close ring
0	2	Fault in the node where is the DFPI i

Table 5.5 Fault detection values of the components of the vector F and G

After this table it is possible to define ε in 5.21 as a vector to keep the information from vector F and the vector G. Therefore, the vector ε takes its value regarding next function when f_i and g_i are different to 0.

$$\varepsilon = \begin{vmatrix} \varepsilon_1 & \varepsilon_2 & \dots & \varepsilon_n \end{vmatrix} \qquad [5.21]$$

Where each ε_i component is as follow in 5.22.

$$\varepsilon_i = \frac{2 \cdot g_i + f_i}{2^{g_i} + f_i} \qquad [5.22]$$

Where ε takes the value 1 when f_i and g_i have taken the value combination of the table. It is important to indicate that all showed vectors before have natural numbers in their components, then (B, D, E, F, G and $\varepsilon \in \mathbb{N}$).

5.3.7.2 Distance Brick

As mentioned before the brick locator has been able to detect the section where the fault is. In order to define better the position of the fault it will be need to have more references about the fault. In fact, if the distance between DFPIs is short, probably only with Locator Brick it will be enough to detect the fault exactly visually in the field. Nevertheless, if the distance between DFPI is long then it will be necessary to have information about the distance of the fault. There are several devices which can enable the function 21FL in outgoings from DERs or from substations HV-MV. As mentioned before the use of this kind of function has not good accuracy due to there are a lot of changes in a distribution network because the wires have different features and the network has suffered several changes during the development. Therefore, it is very difficult to know the impedance of each part of the network.

Using 21FL it is possible to increase the accuracy of the fault detection in the network [125]. In order to extract good information about the 21FL distance it will be necessary to build a matrix to define the topology of the network. The size of this matrix is $[n, m]$, where n is the number of DFPIs of the network and m the DFPIs with 21FL function implemented. The elements of this matrix are h_{ij} as it is defined in 5.23.

$$H = \begin{vmatrix} h_{11} & h_{12} & \dots & h_{1m} \\ h_{21} & h_{22} & \dots & h_{2m} \\ \dots & \dots & \dots & \dots \\ h_{n1} & h_{n2} & \dots & h_{nm} \end{vmatrix} \qquad [5.23]$$

The elements of the matrix H will adopt the distance between the DFPI i, with 21FL function, to the rest of the DFPIs. Defining the DFPI i as an output, this DFPI will see the rest of DFPIs until to reach the last DFPI before to connect with the node where is this DFPI i. The distance h_{ij} defines a section between consecutive FPIs, therefore the first FPI of the path takes value 0 in h_{ij} and second takes a distance value between first DFPI and second DFPI and so on. It is necessary to highlight that it is important to establish the difference between DFPIs from HV-MV substation, which have a connection with main network, and DFPIs from DER. The DFPIs with 21FL in a node network will connect the possible ways to others DFPIs until other DERs in exception of the last section to close the ring. The DFPIs from DER will establish possible ways until main network or other DERs, in this case the way stopped when arrive to one of these sites. If one of the DFPIs is broken it is necessary to extract the correspondent row of the matrix H. On the other hand, if the DFPI has a 21FL skill, then it will be necessary to eliminate the correspondent row and column.

In fact, the 21FL only can give information when the fault is out of the centre. If the fault is an input in the centre this FPI with 21FL will not give information about the fault distance. It is important to remark that the current flows from every DER to the fault although it will not pass for all part of the network and besides in front of a fault the current will separate in different ways depending on the impedance of every brunch. As mentioned before the function 21FL only will be in several DFPIs but not in all of them. Then, through the answers of the DFPIs, it will possible to make a mix of information from different distance fault.

Therefore, it is necessary to establish a second matrix, L, with the same size that H which will determinate if the different sections will be part of the current flow from the DFPI i as it is mentioned in 5.24.

$$L = \begin{vmatrix} L_{11} & L_{12} & \dots & L_{1m} \\ L_{21} & L_{22} & \dots & L_{2m} \\ \dots & \dots & \dots & \dots \\ L_{n1} & L_{n2} & \dots & L_{nm} \end{vmatrix} \quad [5.24]$$

To fill this matrix, it will be necessary to know the value of the DFPIs defined in vectors E and ε. Therefore, each element of the matrix will be following values as showed in 5.25.

$$L_{ij} = \left(\frac{(1 + e_i)|e_i|}{2} + |\varepsilon_i| \, (1 - |e_i|) \right) \cdot h_{ij} \quad [5.25]$$

After to obtain matrix L it will be possible to simplify in one vector where there are the accumulated distances. In fact, the vector M is the result of the sum of columns from matrix L expressed in 5.26.

$$M = |m_1 \quad m_2 \quad \dots \quad m_m| \quad [5.26]$$

Where each component of the vector is as follow in 5.27.

$$m_j = (1 - \varepsilon_j) \cdot \sum_{i=1}^{n} L_{ij} \quad [5.27]$$

After this operation it will be necessary to establish the difference between M and the distance vector from 21FL result. Then N is the vector with distance from 21FL function as follow in 5.28.

$$N = |n_1 \quad n_2 \quad \dots \quad n_m| \quad [5.28]$$

Then it will be necessary to avoid DFPIs with 21FL which does not participate in the location. For this reason, it will be necessary to introduce a new vector, O, to avoid this part as shown in 5.29.

$$O = |o_1 \quad o_2 \quad \dots \quad o_m| \quad [5.29]$$

Where o_j is described in 5.30.

$$o_j = |e_j| \cdot \left|\frac{(e_j-1)}{2}\right| \cdot (p_j \cdot q_j) \qquad [5.30]$$

Where terms p_j and q_j are defined in 5.31 as follow.

$$p_j = \begin{cases} 0, m_j = 0 \\ 1, m_j > 0 \end{cases}; \qquad q_j = \begin{cases} 0, n_j = 0 \\ 1, n_j > 0 \end{cases}; \qquad j \in 1, \dots, m \qquad [5.31]$$

The algorithm only takes into account the distance detected for the DFPI i when the fault is out of the centre, in other words, when e_i is equal to -1. After to find this term it will be possible to define the difference between distances in vector R as follow in 5.32.

$$R = |r_1 \quad r_2 \quad \dots \quad r_m| \qquad [5.32]$$

Where r_j is as follow in 5.33.

$$r_j = |(m_j - n_j) \cdot o_j| \qquad [5.33]$$

After this operation the vector R provides the difference of distance inside the section where the fault is. As mentioned before this section has been located for the Brick Locator. Although the reference of r_j can come from different edges from the section. Therefore, it will be necessary to define a good position of the distance inside the section.

In order to define the good position, it will be necessary to take into account the number of DFPI which have been activated in the track of the fault from each IED with 21FL. Then it will be necessary to considerer the matrix S which is described in 5.34.

$$\begin{vmatrix} s_{11} & s_{12} & \dots & s_{1m} \\ s_{21} & s_{22} & \dots & s_{2m} \\ \dots & \dots & \dots & \dots \\ s_{n1} & s_{n2} & \dots & s_{nm} \end{vmatrix} \qquad [5.34]$$

Each element of this matrix will be defined as follows in 5.35.

$$s_{ij} = \begin{cases} 0, h_{ij} = 0 \\ \dfrac{L_{ij}}{h_{ij}}, h_{ij} \neq 0 \end{cases} \qquad [5.35]$$

After to know the value of matrix S, it is possible to extract the vector T which is defined in 5.36.

$$T = |t_1 \quad t_2 \quad \dots \quad t_m| \qquad [5.36]$$

Where t_j is as follows in 5.37.

$$t_j = \sum_{i=1}^{i=n} s_{ij} \qquad [5.37]$$

Finally, it will be necessary to establish the correct distance inside the section. To do this operation it will be necessary to take into account if the value of the components of vector T is even or odd. Therefore, the vector U will be define this situation as it is showed in 5.38.

$$U = |u_1 \quad u_2 \quad \dots \quad u_m| \qquad [5.38]$$

Where u_j is as follows in 5.39.

$$u_j = \begin{cases} 0;\ tj \in 2k;\ k \in \mathbb{N} \\ 1;\ \ tj \in 2k+1;\ k \in \mathbb{N} \end{cases} \qquad [5.39]$$

After this operation, it will be necessary to define a vector which contents the distance of every section. In fact, the value of the section will be assigned in the first DFPI. The first DFPI is considered according to the natural flow of the current. This vector V is expressed in 5.40.

$$V = |v_1 \quad v_2 \quad \dots \quad v_n| \qquad [5.40]$$

With this vector V is possible to define another vector W which shows the value of the section where the fault is shown in 5.41.

$$W = |w_1 \quad w_2 \quad \dots \quad w_n| \qquad [5.41]$$

Where w_i is as follow in 5.42.

$$w_i = \varepsilon_i \cdot v_i \qquad [5.42]$$

The sum of the w_i components will give the value x of the distance of the section such it is showed in 5.43.

$$x = \sum_{1}^{n} w_j \qquad [5.43]$$

Finally, the vector Y will provide the distance from the end of the patch of every DFPI which have gave the value of the distance through 21FL as it is showed in 5.44.

$$Y = |y_1 \quad y_2 \quad \dots \quad y_n| \qquad [5.44]$$

Where y_i is as follow in 5.45.

$$y_j = \begin{cases} r_j \cdot o_j, u_j = 0 \\ (x - r_j) \cdot o_j, u_j = 1 \end{cases} \qquad [5.45]$$

This vector provides the fault distance from the end of the section. After this step it will be possible to sum the different distances and to get a final distance. Therefore, average distance μ as follows in 5.46 through the sum of the values of the vector Y can be established

$$\mu = \frac{1}{z} \cdot \sum_{1}^{m} y_j \qquad [5.46]$$

Where z is the number of DFPI with 21FL which have been participated in the moment of the fault, such it is showed in 5.47.

$$z = \sum_{1}^{m} o_j \qquad [5.47]$$

5.3.7.3 Simulation

This algorithm has been simulated through MATLAB [130] and also through EXCEL as shown after by the author of this thesis in order to verify the expressions compressed between 5.11 and 5.47. The idea of this simulation has been to test as mathematical method the mentioned algorithm. Therefore, several matrix and vectors will create in order to define the final result.

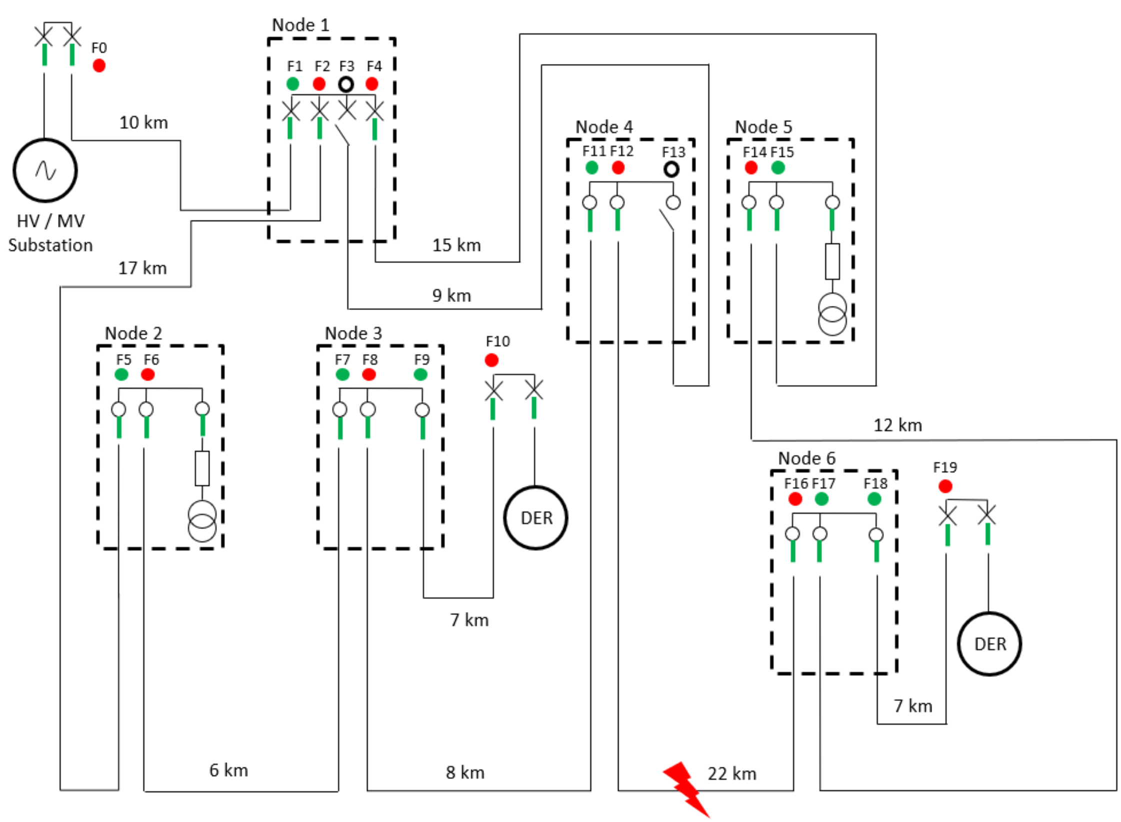


Figure 5.29 Meshed distribution network with DERs to test the algorithm

During the simulations has been tested with several kinds of networks. Following a complete test will be showed with an example of network with mesh distribution network as show the figure 5.29, in [130] other tests has been exposed.

The figure 5.29 shows a distribution network with a fault between DFPIs 12 and 16. The switch-disconnector 3 and 13 are opened, the rest of the switch-disconnectors are closed forming a meshed network. Also, this figure shows the status of the FPI in colour red when the fault is an output for the node and in colour green when it is an input. The DFPIs with colour white have not seen any fault. The fault can be a phase fault or an earth fault due to the behaviour of the directional fault detection in the DFPIs is the same for both faults.

As mentioned before the matrix C for this algorithm is defined as follow in 5.48, which defines the relationships between all DFPIs. The dimension of the matrix is [0,19].

$$C = \begin{vmatrix}
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1
\end{vmatrix} \qquad [5.48]$$

On the other hand, there is the vector E with the status of the different DFPIs and their value in 5.49. It is important to remark that the value of values b_i are equal to 1 due to all DFPIs is running correctly.

$$E = \begin{vmatrix} -1 & 1 & -1 & 0 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & -1 & 1 & -1 & 1 & 1 & -1 \end{vmatrix} \qquad [5.49]$$

According to 5.17 the result of the vector F is showed in 5.50.

$$F = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 \end{vmatrix} \qquad [5.50]$$

The F vector is not a null vector therefore G vector will be the same but with positive values. On the other hand, the ε vector will identify the section where the fault is such as it is shown in 5.51. The fault in this case is between DFPI 12 and 16.

$$\varepsilon = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0| \qquad [5.51]$$

As mentioned before once known the section of the fault it will be possible to detect the position of it using the information from 21FL which is in the DFPI with number 2, 3, 4, 7, 8, 16 and 17. First of all it will be necessary to define the topology distance matrix H of the network as it is showed in 5.52.

$$H = \begin{vmatrix} 10 & 10 & 10 & 10 & 10 & 10 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 17 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9 & 9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 15 \\ 17 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 6 & 6 & 6 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8 & 8 & 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 7 & 7 & 0 & 0 & 7 & 0 \\ 8 & 0 & 0 & 0 & 8 & 0 & 0 \\ 0 & 0 & 22 & 0 & 0 & 22 & 0 \\ 0 & 9 & 0 & 0 & 0 & 0 & 0 \\ 12 & 12 & 0 & 0 & 0 & 0 & 12 \\ 0 & 0 & 15 & 0 & 0 & 0 & 0 \\ 22 & 22 & 0 & 0 & 22 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 7 & 7 & 0 & 7 & 0 & 0 \end{vmatrix} \qquad [5.52]$$

After to establish the topology definition the matrix L is defined after according to 5.24 in 5.53, where there is the global distance from different sections defined by participation of different DFPI.

$$L = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 17 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & 0 & 0 & 8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 15 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \qquad [5.53]$$

After this step the M vector collects the accumulated distance of DFPIs in 5.54 which are in the way of the fault. The N vector shows the distances from the DFPIs with function 21FL in 5.55.

$$M = |31 \quad 0 \quad 27 \quad 0 \quad 8 \quad 0 \quad 0| \qquad [5.54]$$

$$N = |34{,}7 \quad 0 \quad 44{,}1 \quad 0 \quad 8{,}7 \quad 17{,}2 \quad 0| \qquad [5.55]$$

In order to avoid DFPIs with 21FL which does not participate in the location it will be necessary to establish the O vector as it is showed in [5.56].

$$O = |1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0| \qquad [5.56]$$

According to 5.32 the R vector will establish in 5.57 the difference between M and N using the O vector in order to take into account the correct measurements.

$$R = |3{,}7 \quad 0 \quad 17{,}1 \quad 0 \quad 0{,}7 \quad 17{,}2 \quad 0| \qquad [5.57]$$

After to know the distance R vector, it will be necessary to adapt the distance of each of its components to the end of the section. Therefore, the matrix S is showed in 5.58.

$$S = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \qquad [5.58]$$

After to know the value of matrix S it will be possible to extract the vector T which is defined in 5.59.

$$T = |3 \quad 0 \quad 2 \quad 0 \quad 1 \quad 0 \quad 0| \qquad [5.59]$$

Although it will be necessary to know the distance of the section where the fault is. It is obvious that the fault is between DFPI 12 and 16 and then the distance is 22 km but the goal is to define it automatically. Therefore, the vector V contains the distance of each section taking into account that the initial point has the value of the distance and the final point the 0 value as it is showed in 5.60. After that the vector W defines the section with fault and x the distance as is showed in 5.61 and 5.62 respectively.

$$V = |10 \quad 0 \quad 17 \quad 9 \quad 15 \quad 0 \quad 6 \quad 0 \quad 8 \quad 0 \quad 7 \quad 0 \quad 22 \quad 0 \quad 12 \quad 0 \quad 0 \quad 0 \quad 0 \quad 7| \qquad [5.61]$$

$$W = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 22 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0| \qquad [5.62]$$

$$x = 22 \qquad [5.63]$$

Finally, the vector Y will provide in 5.64 the distance from the end of the section of each DFPI with 21FL.

$$Y = |18{,}3 \quad 0 \quad 17{,}1 \quad 0 \quad 21{,}3 \quad 17{,}2 \quad 0| \qquad [5.64]$$

As last step the z value will define the total IEDs which are reporting a distance and the value μ will define the average distance as it showed in 5.65 and 5.66 respectively.

$$z = 4 \qquad [5.65]$$

$$\mu = 18{,}48 \qquad [5.66]$$

The distance μ is taking into account the final position of the section. In this case as the fault has been between DFPIs 12 and 16 the distance 18,48 km has been from the DFPI 16 position. In next tables, the algorithm simulation in EXCEL from mentioned network in figure 5.29 is showed.

System Definition (Relationship between DFPIs)																					DFPI Value		
C																					B	D	E
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	FPI Status	FPI Value	FPI Vector
0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
2	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1
3	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	-1	-1
5	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
6	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1
7	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
8	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	-1	-1
9	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1
10	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	-1	-1
11	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	-1	-1
13	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	-1	-1
15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
16	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	-1	-1
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	1
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	-1	-1

Table 5.6 Algorithm simulation in EXCEL; matrix C and vectors B, D and E

Fault detection			
F	G	ξ	Final result
Operation	FIS		Kind of Fault
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
0	0	0	
-2	2	1	P Fault close ring
0	0	0	
0	0	0	
0	0	0	
-2	2	1	P Fault close ring
0	0	0	
0	0	0	
0	0	0	
-4			

Table 5.7 Algorithm simulation in EXCEL; vectors F, G and ξ and the fault section identification

H										
	P2	P3	P4	P7	P8	P16	P17	ξ	V	W
0	10	10	10	10	10	10	10	0	10	0
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	17	0	0	0	0	17	0
3	0	0	0	0	9	9	0	0	9	0
4	0	0	0	0	0	0	15	0	15	0
5	17	0	0	0	0	0	0	0	0	0
6	0	6	6	6	0	0	0	0	6	0
7	6	0	0	0	0	0	0	0	0	0
8	0	8	8	0	0	8	0	0	8	0
9	0	0	0	0	0	0	0	0	0	0
10	7	7	7	0	0	7	0	0	7	0
11	8	0	0	0	8	0	0	0	0	0
12	0	0	22	0	0	22	0	1	22	22
13	0	9	0	0	0	0	0	0	0	0
14	12	12	0	0	0	0	12	0	12	0
15	0	0	15	0	0	0	0	0	0	0
16	22	22	0	0	22	0	0	1	0	0
17	0	0	12	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0
19	7	7	7	0	7	0	0	0	7	0

Table 5.8 Algorithm simulation in EXCEL; matrix H and vectors ξ, V and W

L							
FPI Value	P2	P3	P4	P7	P8	P16	P17
-1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
1	17	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
1	6	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
1	8	0	0	0	8	0	0
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
1	0	0	15	0	0	0	0
-1	0	0	0	0	0	0	0
1	0	0	12	0	0	0	0
1	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
M	31	0	27	0	8	0	0
O	1	0	1	0	1	1	0

Table 5.9 Algorithm simulation in EXCEL; matrix L and vectors M and O

	S						
	FPI 2	FPI 3	FPI 4	FPI 7	FPI 8	FPI 16	FPI 17
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	1	0	0	0	1	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	1	0	0	0	0
	0	0	0	0	0	0	0
	0	0	1	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
T	3	0	2	0	1	0	0

Table 5.10 Algorithm simulation in EXCEL; matrix S and vector T

N	**34,7**	**0**	**44,1**	**0**	**8,7**	**17,2**	**0**		**x**	22
R	3,7	0	17,1	0	0,7	17,2	0			
U	1	0	0	0	1	0	0			
Y	18,3	0	17,1	0	21,3	17,2	0	**µ**	**18,475**	

Table 5.11 Algorithm simulation in EXCEL; vectors N, R, U, Y and values x and μ

The yellow values in table 5.6 and table 5.11 are the necessary values to introduce in the algorithm in order to identify the section with fault and after that to identify correctly the average distance to the fault inside this section.

5.3.7.4 Conclusions about AFL algorithm for meshed distribution networks with DERs

This algorithm detects the section and the approximately position where a phase to phase or a phase to earth fault appears in a distribution meshed network with DERs. As mentioned before this algorithm has been evaluated in platforms such as EXCEL and MATLAB using the matrix systems and establishing a network with a main generation and several DERs.

Taking into account this background, this chapter has been focused on an advanced algorithm to detect a phase to phase fault or phase to earth fault in an electrical distribution network with DER penetration. Notwithstanding, although it focused in a specific network with DERs, this algorithm is suitable for all kind of electrical networks, both radial or meshed ones and even working in open or close ring. The proposed algorithm is validated on a specific distribution network with DERs.

The algorithm can help to the utility or end user installations to detect a fault with current technology which is used in common real installations. Therefore, the implementation of this algorithm it is not suppose an expensive cost to implement in high control system in the utility or end user installation.

On the other hand, another research line can consist in to establish a redundant method in case of DFPI error. Therefore, this future implementation will take into account the possible errors of the DFPI, a malfunctioning or a false indication, in the moment to analyse the location of the fault.

The current algorithm can only use the field information from DFPI but it can be combined with other systems such as GIS or other transversal systems. In next chapters there will be an analysis about the possibilities to implement the algorithm in systems such as IEC 61850 or using technology for integrate in Low Power Wide Area Network (LPWAN) in order to work in IoT world after the explanation of this new Smart Grid trends.

6. Feeder Automation

The Feeder Automation concept establishes the link between the global management of the electrical distribution network with the field. This chapter aims to show the main control functionalities and the communication protocols as vehicles to work in these electrical distribution networks.

The shown algorithms to locate faults have to be implemented in a high system in order to help the management of the network. These systems can guide to the network operator in the fault detection and in the subsequent restoration.

As mentioned before another important point in the electrical distribution networks is the way to communicate the elements in the network with these high systems control. Therefore, the traditional protocols such as IEC 101 or IEC 104 with technologies such as GPRS or PLC have had a relevant importance in order to establish the new Smart Grid trend. Although the new standards such as IEC 61850 and the use of LPWAN are starting to establish several deployments in this electrical distribution networks.

6.1 Automation functions in the electrical distribution networks

The previous algorithms and devices such as AEDs or DFPIs contribute in the automation for electrical distribution networks. Although it is important to highlight that this automation can be described in four main missions as follow.

- **Reconfiguration**. This function consists in to minimize loses, to optimize the voltage profile and to load profile keeping the network distribution architecture. The main goal is to search the efficiency in the network analysing previously new possible configuration scenarios.

- **Restoration**. In front of a fault in the distribution network, the restoration can guarantee the electrical supply and thus to enhance the quality of service. In this case the goal is to give an answer in front of an outage to recover the supply to the customers.

- **Quality supply**. This concept covers all related anomalies with the voltage, current and frequency variation after fault or in normal operation. Therefore, the quality supply tries to analyse all of the problem in the network in order to define new actions by DSO.

- **Fault analysis**. This function encompasses a set of algorithms in order to analyse a fault in the network and locate it in order to establish new actions such as restore the network. In previous sections the fault location algorithms have been developed.

This automation process in a network distribution is performed through AEDs, DFPIs, telecontrol devices and other field devices which are governed by a high system where the fault location algorithms are implemented. Nowadays the automation is a centralized process although there is a trend in order to define a decentralised process among the field devices. Therefore, it is possible to define to types of automation, the centralized and the decentralised automation.

6.2 Centralized automation

In a centralised automation system, the intelligent system which controls all these devices is a Distribution Management System (DMS) [53] or as mentioned before ADMS. It is very difficult to mention all functions that a high system such as ADMS can do but it is possible to establish the main functions in following points.

- **Report**. Collect all the information from all field devices in the distribution network. This collection is not only the indication about trips or faults from these devices, also it is possible to collect current information in order to establish future maintenance analysis.

- **Represent – Control**. Monitor all information, or more recently, as intelligible way for an operator thus to ease the access to the control of all elements of the system.

- **Storage**. In order to analyse past events or faults this function consists in to storage all events. It can provide the possibility to establish report analysis.

- **Analyse – Simulate**. To provide analytic functions in order to help to the operator about to understand the information and help in the decision making. Thanks to the capability of this high system and the current IT technologies it is possible to establish simulations in fault case or in network restoration.

- **Link**. Other high systems can be linked to the DMS in order to share information. Examples of these systems are a Customer Information System (CIS), GIS or Weather Information System (WIS).

6.3 Advanced Distribution Management System

6.3.1 ADMS description

Nowadays the DMS concept has been extended to the ADMS, due to the new functionalities such as management energy, demand response where it is possible to find algorithms based in knowledge acquired [131]**.** In fact, the ADMS is composed by different layers which are defined briefly and showed in figure 6.1.

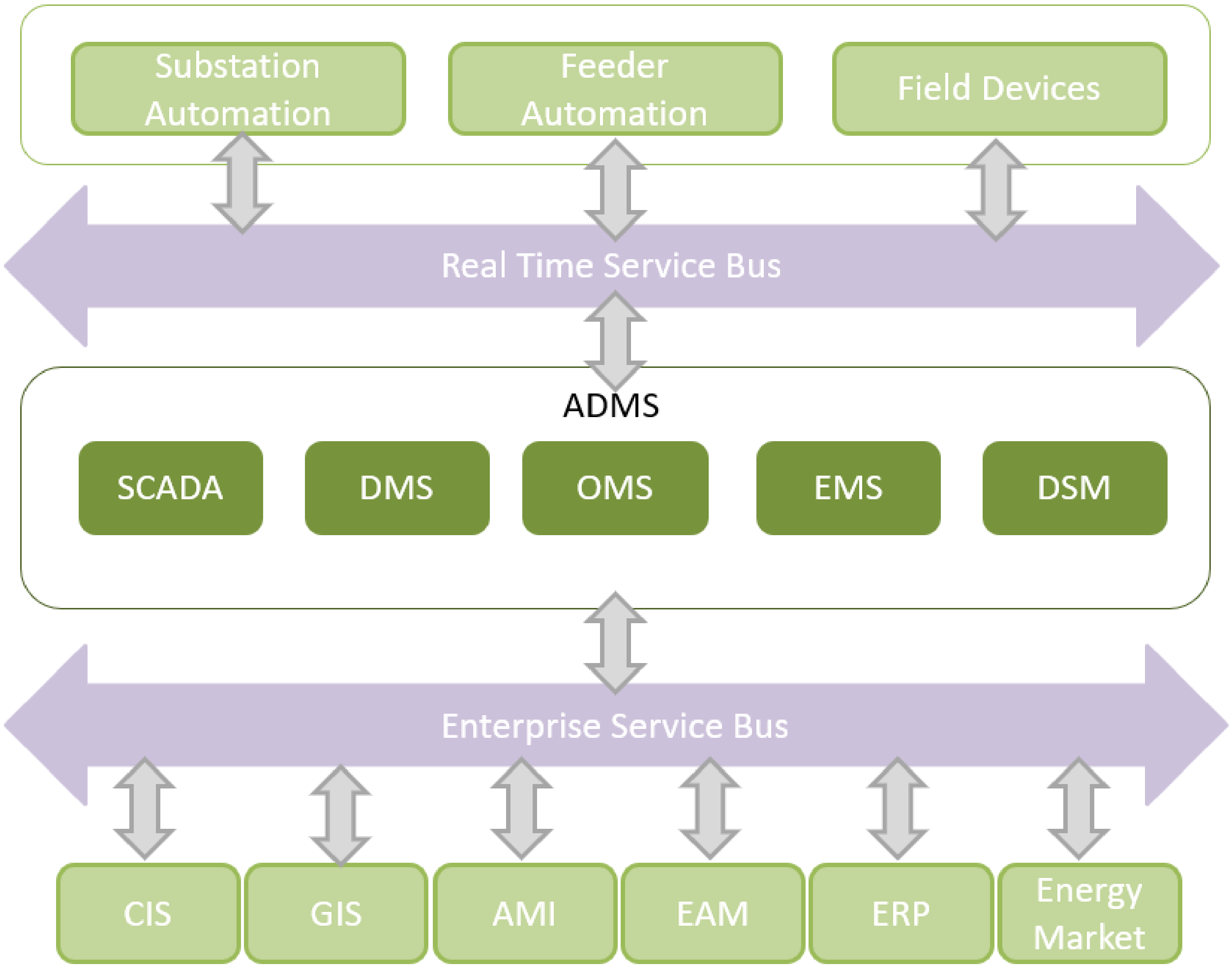


Figure 6.1 ADMS layers in a distribution network

- **SCADA**. General management about all information, alarms, events, from the field devices and the control over them. This part of the ADMS will be able to open and close the switch-disconnectors and circuit breakers to do the mentioned functions such as reconfiguration and restoration.

- **DMS**. The DMS analyses and treat about the collected information by SCADA. Among its main functions are the mentioned algorithms before and other functions in order to block some functions or operations by safety reasons. In fact, the DMS is the intelligence of the SCADA layer and save all the information about the network. For this reason, the ADMS can be considered a big data base with all information from the electrical distribution network.

- **Energy Management System (EMS)**. This part of the ADMS is in charge to manage the information of field devices in order to know the consumption trends of the users. This function analyses the technical and not technical losses and establish an energetic balance.

- **Outage Management System (OMS)**. The OMS controls the system to avoid an outage. This module in front of a fault can manage the restoration of the system. The OMS will be linked with SCADA to do the necessary orders to open and close several devices in order to restore the network.

- **Demand Side Management (DSM)**. This ADMS module establishes a network reconfiguration in order to optimize the energy distribution, providing an answer to demand. This module proposes several combinations of the switch-disconnectors and circuit breakers in the network in order to establish an efficient flow energy distribution. Depending on number of operations the DSO will execute one of them or not in order to optimize the energy consumption in the system.

The ADMS is a modular system where there is a relationship between field devices in the substations and along the feeder by means of concepts Substation Automation and Feeder Automation, respectively. This kind of system establishes a relationship with other high software systems which are linked to the system manager such as CIS, GIS, Advanced Metering Infrastructure (AMI), Enterprise Asset Management (EAM), Enterprise Resource Planning (ERP) and even a relationship with Energy Market [132].

It is important to remark that the ADMS can provide an intelligence to the utility and DSO in order to take future decisions in new investments or even to establish a training through several simulations to the network operators.

6.3.2 SCADA, the interaction between ADMS and field devices

The interaction between the ADMS and field devices such as IEDs and FPIs is the SCADA. Probably the SCADA is the most important module of the ADMS which links the information of field devices with DMS. This application helps to the system operator in the management in real time. The SCADA is a platform with basic functionalities to classify and management events, process alarms and measurable limits about the quality energies.

This application has a data base about the process, a Man Machine Interface (MMI), and a software application. The MMI interface represents the information about the process data base in a graphic environment where there is an electric single-diagram which represents the distribution network.

Nowadays this diagram is represented with the orography and other urban elements. In fact, the SCADA is a source of information about the network and its environment.

There are different SCADA structures according to different utilities but a representative example is showed in the figure 6.2 which is based in [55] and is analysed under the point of view of distribution network. It is important to take in account that this platform represents part of the transmissions system. In several situations the SCADA will integrate al transmission network if the utility controls all electrical network. In a great majority of countries there is a TSO and DSO then each of one will have an independent ADMS platform.

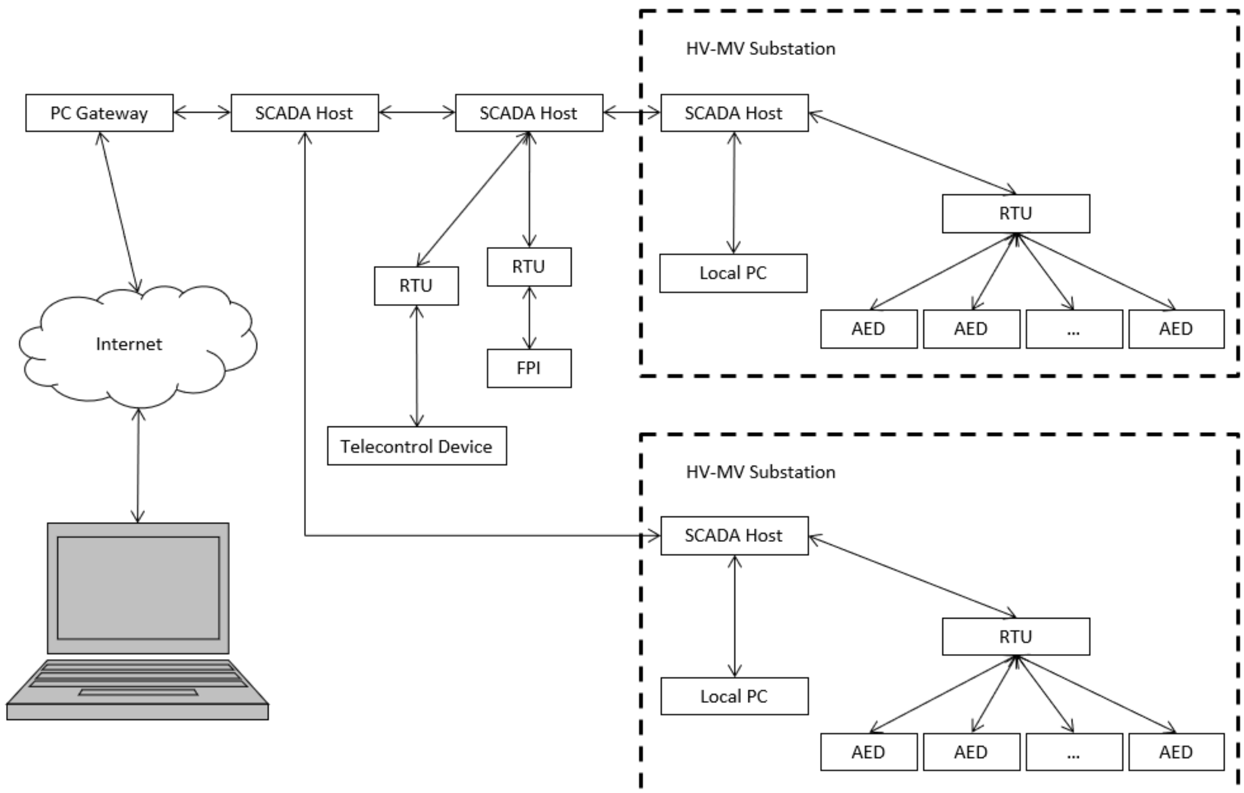


Figure 6.2 SCADA system for a distribution network

The figure 6.2 shows the SCADA Host as an intermediate platform connected to the network, besides this platform uses services of the network. On the other hand, the RTU will collect all the information in a substation HV-MV or in a MV-LV substation with telecontrol or in a FPI. This figure is showing a traditional architecture for communicate with devices in electrical distribution networks but there are other possible architectures.

The RTU manages the information previous to the communication layer with the function to collect all the information in a network node. A node can be a substation, a telecontrol device, an FPI or any device which can communicate and link with the SCADA Host. In fact, the RTU is the border between communication network and field functionality.

Finally, through different terminals or gateways, protocol conversers, it is possible to get the access of the SCADA. The SCADA is a hosted platform software in a server, which can be access by other servers. Sometimes these systems are redundant in order to have a good answer in front of a problem. The general functions of SCADA system are the next ones.

- **Acquisition**. The acquisition of data from the field devices through the RTUs in MV-LV and HV-MV substations.

- **Control**. The control and the possibility to set over the field devices through their respective RTU. This is an important point because the high system can interact with the physical system and then the restoration process can be done.

- **Record**. The SCADA can record all events in the network and all actions from the system and from the operator and other devices. The accuracy of timestamp is 1 millisecond due the faults and other issues are lower than 1 s.

- **Representation**. MMI shows the current situation in the network to the operator and can help to take several decisions through a graphic and dynamic interface.

These functions are linked with the fault location algorithms in the DMS. Therefore, the FLISR can be improved a lot thanks to the system can offer a fast restoration. The SCADA function links with other modules of ADMS in order to provide information.

6.4 Communication protocols in electrical distribution network

A high system software such as ADMS have different protocols in order to communicate with different elements in field. It is important to highlight that the communication world is evolving considerably and consolidating new physical mediums and different communication languages.

This situation can be unsustainable for a distribution network with several decades. In this network there will be devices with different communication protocols, for this reason the ADMS have to integrate several old protocols and new protocols in order to adapt the different life phases of the distribution network.

Previously to this scenario with systems such as ADMS the DSOs have been used a lot of kind proprietary protocols from different manufacturers in order to communicate different elements of the electrical distribution network. Examples of these protocols inside substation have been Modbus serial, Profibus, DNP3 serial and IEC 103. On the other hand, to communicate from RTU to the control centre the IEC 101 has been one of the most important.

Nowadays the current protocols use in the electrical distribution network for new devices are mainly the IEC 104 and DNP 3.0 to communicate the devices in the field. The first one is more used in Europe and the second one in USA and South America. Both protocols can have different profiles depending on the DSO.

On the other hand, there is the IEC 61850 standard focused in the automation and communication at the same time for electrical networks in general. This protocol has been started to be an important reference at substation level although there are several applications for the distribution network and other sectors. The IEC 61850 standard protocol provides a decentralized automation.

As mentioned before there is another kind of protocol for LPWAN such as LoRa, Sigfox or NB-IoT which can help to the DPFI’s communication of the network with a low cost. This kind of protocols can transmit and receive few digital information with a small power supply.

Maybe the use of each protocol is conditioned by the final application of the network. For this reason, is very important to know the application in the electrical distribution network. In instance a communication with a substation will be interesting to use IEC 104 or even IEC 61850 but, in the case, to communicate with a DFPI it could be better to establish a LPWAN as it will explain after.

6.4.1 IEC 61850. The new standard for the automation of electrical networks

IEC 61850 is a data model and communication architecture standard that allows the interoperation in automation systems in power systems from International Electrotechnical Commission (IEC). The IEC 61850 standard is becoming the most common communication solution in Electrical Energy Systems (EES) of many countries. The standard provides the features and services needed to make this standard the tool for devices’ communication and automation.

The strengths of IEC 61850 are standard modelling object-oriented equipment belonging to the EES and communication services it offers [133]. This communication services offers a dialog both between IED devices, known as the horizontal communication, and between IED devices and the Supervision and Control platforms, known as vertical communication.

As mentioned before the IEC 61850 is a revolutionary standard in electric sector which can provide a new way to automate the substations [134] and the network. This standard can open the traditional concept about centralised network automation because it has three services very significant among others:

Manufacturing Message Specification (MMS), the Generic Object Oriented Substation Event (GOOSE) and the Sampled Values Protocol (SVP).

The standard IEC 61850 defines the communication standard between the IED in electrical substations and related systems. This is developed in fourteen parts, which is divided in ten principal themes. The definition of standardized information and the standardized models make possible to archive the interoperability between different kinds of devices regardless of manufacturer as shown in [135] and in [136]. It is important that IEC 61850 is focused in several fields of the electrical sector such as Power Quality [137], in fact the IEC 61850 is being extended to other sectors such as EV where there are descriptions to apply in it.

6.4.1.1 Evolution of the IEC 61850

Before to describe the three important aspects of this standard, it should be mentioned the evolution of different communication standards until the arrival of the IEC61850. It is important to establish a differentiation between the American and European evolution. In the American region the Manufacturing Message Format Specification (MMFS) appeared for industrial sector in 1984 and after several years this protocol was transformed to MMS. From this kind of services in 1991 the Electric Power Research Institute (EPRI), and IEEE, defined communication architecture for electrical utilities. This architecture was known as Utility Communication Architecture (UCA). The initial goal of this standard was the communication between control centres and substations.

In 1994 EPRI and IEEE began to work in next UCA phase the UCA 2.0 focusing in bus communication from the substation between local SCADA and IEDs. In parallel in 1996 the IEC started to work in the normative IEC 60870 with a similar goal [138]**.** The European vision came from a lot of proprietary protocols although it derivates in IEC 60870 and in Distributed Network Protocol (DNP) in DNP3 Series protocol which was transformed to DNP3 Ethernet.

Then in 1997 both groups, EPRI/IEEE and IEC, agreed to work in an international standard in order to define a common international normative. This standard received the name IEC 61850 which was established as a first version in 2003 with the first ideas to how to use IEC 61850 in protection and automation [139].

6.4.1.2 Goals of the IEC 61850 and main features

The IEC 61850 was conceived with one important goal, to establish a common communication protocol for all intelligent devices in a substation reaching the interoperability. The standard was extended to all devices such as switch-disconnectors, CTs, VTs, circuit breakers, etc. Therefore, the IEC 61850 models the reality through a virtualization of the devices [137]**.** As the figure 6.3 shows there is a virtualization of the real world to the virtual world where the minimum represented unit is a Logical Node (LN). This logical node represents the ANSI protections, the circuit breaker, the CTs and VTs each element of the substation.

Therefore, the IEC 61850 is focused in to establish automation with distributed intelligent defining a semantic according to electrical networks.

Probably there are three important features in IEC 61850 very different to other standards. The first one is the object-oriented data model as mentioned before, a second one is the configuration language and the last one the communication technology [138].

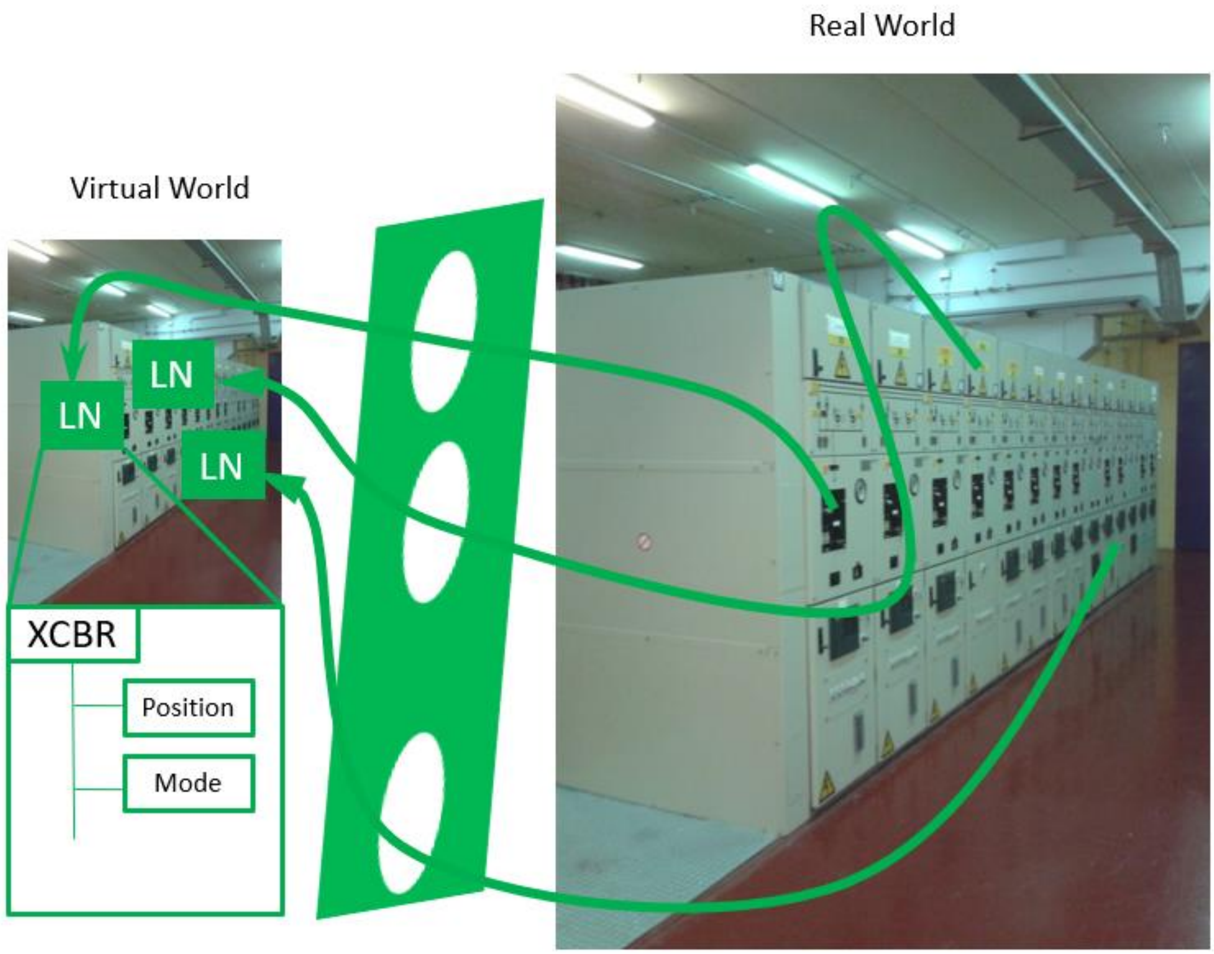


Figure 6.3 Virtualization of the real world through IEC 61850, courtesy of Schneider Electric

6.4.1.2.1 Data model

The object-oriented data model is the composition of Logical Device (LD) by LNs. These LNs are composed by Data Objects (DO) and Data Attributes (DA) which have the real information. These data model provides the self-description to be understood by another application. In fact, this data model is establishing the semantic. As an example, a LD can be a circuit breaker and the LN is the same circuit breaker. Although it is possible to find other examples such an AED or IED, on that case physically the LD is the entire relay although the LNs are the internal functions such as protection, measurement… or even the circuit breaker.

Thus, it is possible to establish different propositions of LD with different LN. The standard allows to integrate any device. The figure 6.4 shows the object-oriented data model in a graphical way with this kind of description. The LD can contain as LN the circuit breaker with the semantic, XCBR, and position attributes such the figure shows. It is important to highlight that the semantic is univocal.

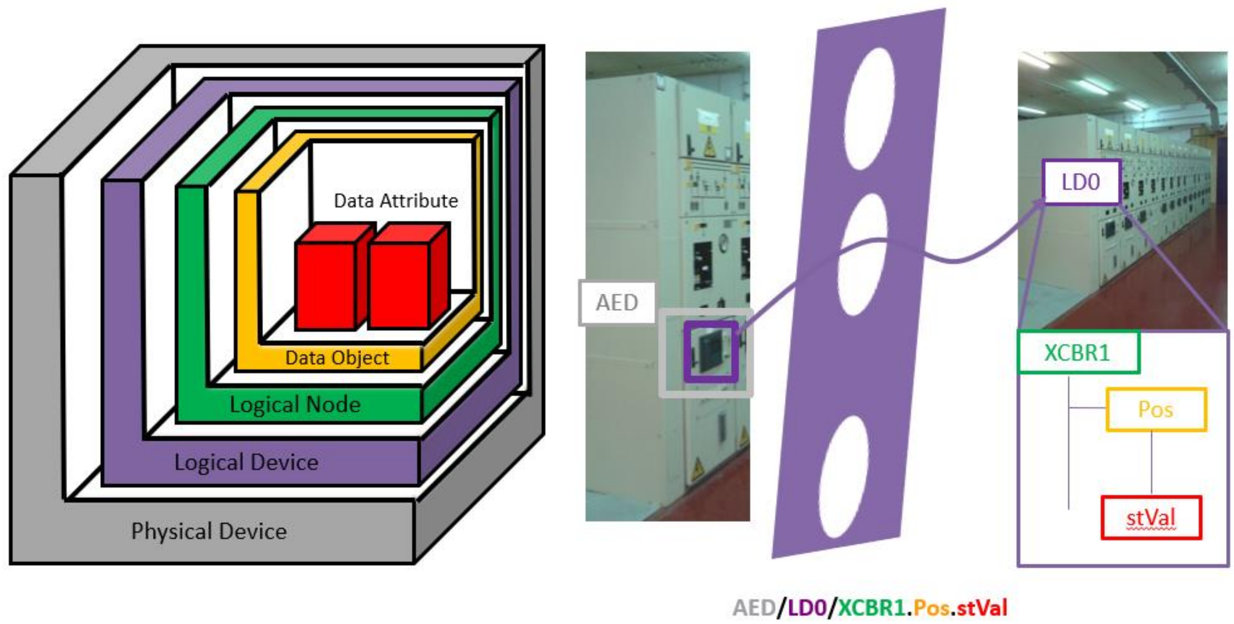


Figure 6.4 Object oriented data model of the IEC 61850

On the last figure it is possible to see the string to identify one of the data attribute of the system. In fact, with this description is easy to identify the definition of the data. This is one of the most important features of the IEC 61850 the interoperability. Devices from different manufactures will have a similar description and it will be understood for different SCADA, ADMS, etc.; to integrate comfortably.

IEC 61850-7-4 part of the IEC 61850 standard describes this data model hierarchy. Its target is to virtualize the IED devices in a common object-oriented based model. It defines a hierarchy that is based on a decomposition of the information contained in the devices, through assemblies and subassemblies, to reach the smallest information unit. As mentioned before the set of information that represent the hardware is named LD and the LDs are subsets of LD, represent physical or functional parts of the device. As another possible example of the LN is MMXU which is related with measurement and it contains all the variables measured on the device. Within the LN, there is the DO that includes all data forming the LN.

Analogously, the DOs in the LN MMXU are VPP for phase-phase voltage, PHV for phase-neutral voltage, [A] for intensity, [Hz] for frequency and others DOs. Finally, DO ends in the structure of the DA. DAs in MMXU are, for example, the value of the above magnitudes of DO ([V], [A] or [Hz] respectively), q for the quality bit which represents that the value measured is valid or within the defined ranges, and the t for time stamp which represents the moment in which the measures have been realized.

The standard defines the common structure of LD, LN, DO and DA for all devices in the market, but keeps free the grouping of different LN into groups and subgroups according to functionalities of equipment, such as Measures, Protection, Control, States… Figure 6.5 shows the virtualization and data model of a MV cabin and its IED device where the MMXU LN is showed.

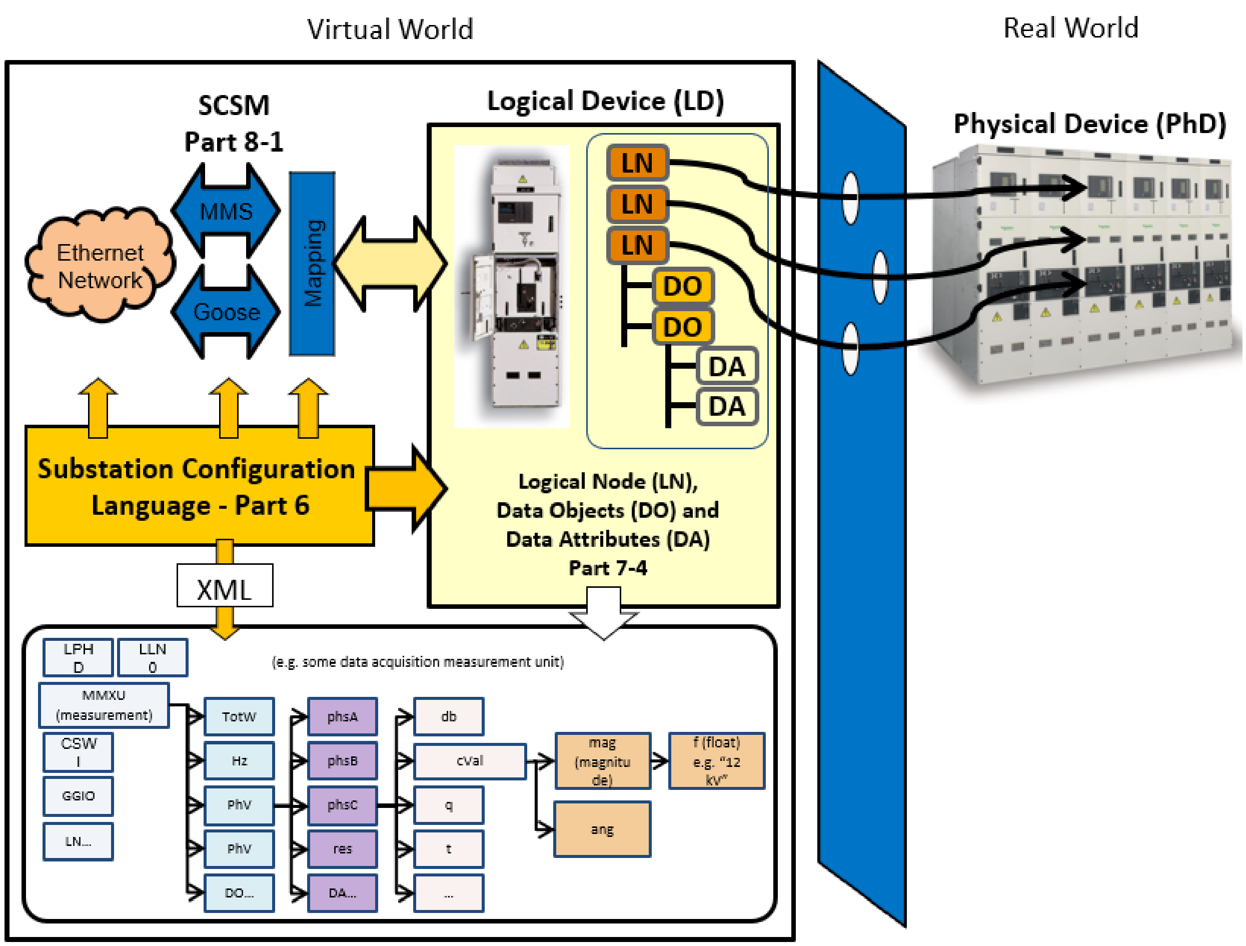


Figure 6.5 Data model of MV cubicle and its protection relay

The configuration language of the IEC 61850 is known as Substation Configuration Language (SCL), which is an eXtensible Mark up Language (XML) based file format. This file is a good tool to exchange configuration information between design and engineering tools. The result of this file is a description with the object-oriented data model in each LD and the relationships between them.

Thank to this kind of file there is not a description map with different address the file is the map with all information and can be integrated easily by different systems. Besides the IEC 61850 standard includes a mention to File Transfer Protocol (FTP). This service provides an easy configuration of the devices for modify the XML file.

Finally, the other important point is the communication technology. With regard to it, IEC 61850 strictly separates the application from the communication. The Abstract Communication Service Interface (ACSI), defines the abstract services available for the application. The mapping for client-server is different for critical time, this is the big different between MMS and GOOSE/SVP.

Also, this standard can work over ETHERNET network in physical medium such as cooper, Fibre Optic (FO) and in other physical mediums such as 3G, 4G or PLC. This standard can share the same network that other devices which communicate with other protocols.

6.4.1.2.2 Abstracts models and communication services

IEC 61850-8 and 9 standard parts describe the set of communication models and services in order to allow the exchange of the data model information between different IED in electrical power systems. The goal is the deployment of automation of the electrical system by sending data groups of different IED LNs. Figure 6.6 shows the abstract models and communication services defined in the standard. Finally, they are mapped or encapsulated over an Ethernet network frame.

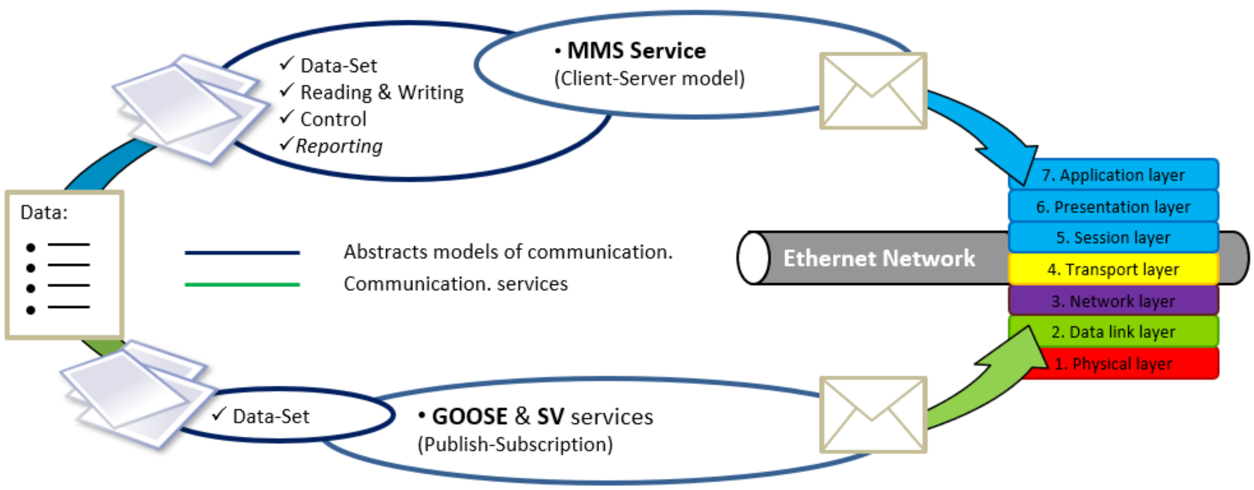


Figure 6.6. Abstracts models and communication and services

The first three models are based on a client-server model. The server is the device which contains the information while the client accesses it. Reading and writing models are used to access data and their attributes. The control model is a specialization writing service, which allows management of attributes that are defined in this class, and it allows action on the device. The reporting model is used to exchange a set of event-oriented information, which is transmitted spontaneously when the data value is modified.

Today, all these models are mapped over MMS Ethernet protocol in the Open System Interconnection (OSI) layer 7.

The other services are based on a publish-subscribe model. In IEC 61850, the term peer-to-peer communication is introduced to emphasize that communication between the publisher and the subscriber involves communication between devices. These communications services are used for the exchange of critical information. The device, which is the source of information, publishes it, and any other equipment that needs this information can receive it by subscribing to it. The GOOSE service is a fast transmission of event information to multiple devices. Instead of using a communication service with receipt confirmation, the information exchanged is repetitively sent for ensuring the arrival to the subscriber. SVP transmission service, is used when is needed to transmit analogue field signals, such as current, voltage or any of its derivatives, using digital communications. The analogue signals are sampled and transmitted. Both the GOOSE and SV services are encapsulated in OSI layer 2 Ethernet.

On the other hand, the standard allows for an evolution in communications technology, because their models and information exchange services are abstract and uncoupled from the protocols that implement them (MMS, Transmission Control Protocol / Internet Protocol (TCP/IP), etc.), which helps to improve communications technology without affecting the standard model and services. An example of this is that the standard is working to provide the mapping of client-server model in Web Services, replacing the MMS.

The MMS service defines the communication between client and server. In the IEC 61850 there is not the concept master-slave although there is the possibility to establish some rules between IEC 61850 SCADA and other devices. As LN is the minimum structure of definition in the oriented object data model, the Data Set (DS) is the minimum package of information to send.

The DS can be content different information about the data objects from different LNs. In the moment to establish a communication between a SCADA and different field devices there are several mechanisms in order to help and to optimize the communicated information. One of these mechanisms is the Report Control Block (RCB), which can take the information from one of the DS and can send this information in different situations.

The RCB send all the information of the DS when there is a change of one data attribute, a change in the attribute quality, an update of defined value in a data attribute, periodically, spontaneously under some conditions or by General Interrogation (GI), from the server.

On the other hand, this RCB can be Buffered (BRCB) or Un-buffered (URCB). In the case of a problem in the communication network the BRCB sends the changes of the DS and saves this DS in order to recover after. In the case of URCB the data will lose.

The standard IEC 61850 can help to optimize the management for collect data from different devices with RCB. Besides the IEC 61850 has as a control model the traditional system as in other protocols. This is a direct control where the high system sends the order and the device confirms the reception of the other and sends after the confirmation with the final execution. There is also another mechanism with an intermediate confirmation, Select Before Operate (SBO), which confirms the first order with a question to the high system. This kind of orders can open and close circuit breakers or change some parameters in the AEDS.

It is important to remark that regarding to records there is a special mechanism to do it, the Logging. This mechanism collects the data and storages in a buffer to recover from SCADA. In fact, this Logging can collect information from different DS. Internally the mechanism uses a First In First Out (FIFO) in order to save these data.

6.4.1.2.3 GOOSE service

Conceptually the GOOSE service is implemented to substitute the traditional signal wiring in the control systems, and to add new functionalities. GOOSE provides several advantages over traditional wires:

- traditional wiring is substituted by a medium only for communication,
- a GOOSE can carry more information that a simple cable,
- protection, supervision and control applications use the same physical medium,
- Virtual Local Area Network (VLAN) and Quality of Service (QoS) implementation capabilities.

As it was mentioned before, a GOOSE message is based on publish-subscribe pattern. Publishers send GOOSE messages to multicast Media Access Control (MAC) addresses across the Local Area Network (LAN), and subscribers just listen to what information is in the network and pick the GOOSE messages to which they are subscribed. IEC 61850-8-1 specifies a retransmission scheme to achieve a highly dependable level of message delivery. Figure 6.7 shows the mechanism of retransmission of GOOSE messages. According to [140], once started, GOOSE messages are published constantly, containing a collection of information called a data set. During configuration, each GOOSE message a max time parameter (T_0-seconds) is given between message publications. The messages are published each time one of the data set elements changes or if the maximum time expires. After a data set element changes, the time of transmission between messages is very short, and a minimum time parameter (T_1-[ms]) is defined in the GOOSE message. Consequently, the messages are sent very often to increase the likelihood that all subscribers will receive them across the nondeterministic Ethernet. After the initial fast publications, the time of transmission grows longer (T_2, T_3, T_x) until it reaches maximum time again.

The time mechanism explained before is showed in figure 6.7 where the event appears in a specific moment. The GOOSE message is always sending in a time T_0. The time T_0 is a big time, for instance 2 seconds and the other times T_i depends of the equation 6.1.

$$T_n = t_0 + \left(t_{conf} \cdot 2^n\right) \quad [6.1]$$

Where t_0 is equal to 0, and t_{conf} is equal to 8 [ms] and then T_n is equal to 0, 8, 24, 56, 120, ... 2050 [ms].

Also, in GOOSE message a VLAN can be defined, in order to segregate the paths where the GOOSE is transmitted on the LAN, and a priority tag QoS can be also specified, to add high priority to the GOOSE message over other frames in the LAN and avoiding potential delays of this critical message in saturated networks.

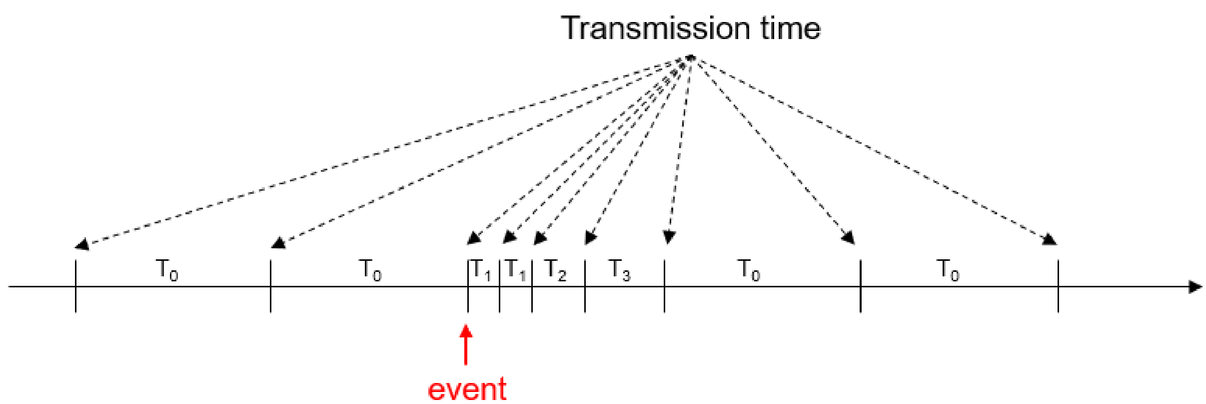


Figure 6.7 Example of changing time between message publications

The use of IEC 61850 GOOSE service, instead of traditional wiring in the ANSI protection system for logic discrimination, offers an optimization of the installation cost, better performance of the system and more options of distributed automation in the ring main topology systems. Several publications such as [141] and [142] consider that the usage of GOOSE can reduce considerably the installation costs taking into account that only one Ethernet network is required for the whole system. It increases the possibilities to establish any combination of variables using the same network. Therefore, the GOOSE has a great relevance as usage for directional protection.

As mentioned before the main feature of GOOSE service is to send fast messages between different elements in a communication network. This service is used in order to send critical data between AEDs in order to establish a logical discrimination, although there are multiple options to do with it, the load shedding, setting modifications and other critical operations in an electrical substation or even in industrial sector. As it will show in next chapter the GOOSE message can help to the electrical sector in several applications [143].

One important aspect of the GOOSE message is that use a high priority, therefore if the communication network is overload the GOOSE message will able arrive to the subscribed AED across different switch and points of the network. Although the GOOSE cannot cross a router, nowadays several manufacturers and committees are working in a Routed GOOSE (R-GOOSE) [144].

The application of GOOSE service provides several benefits to the electrical system not only for the protection system but also at the global level of the project. Therefore, some of the benefits of logic discrimination using IEC 61850 GOOSE service are highlighted in table 6.1.

Table 6.1 compares the difference between both discrimination systems and defines approximately obtained benefits through field experience of the author and analysed references on this document in part 7.2.2.

After to use this kind of system in several projects it is important to remark that the savings has been approximately in 90% because the dedicated signal between IED has been replaced by GOOSE configuration in IEDs. Additionally, it is possible to find an installation cost reduction about 30%. Although the total cost reduction is emphasized when there is a distance between bus bar nodes more than 100–150 meters and they are not in the same area.

Discrimination with Traditional Wiring	Discrimination with IEC 61850 GOOSE	Obtained Benefits/Improvements
Dedicated wire for each signal	Using the communication network in the system	Cost reduction about 90%
Only one automation possibility	Multiple automation possibilities	Increase of the system flexibility
Expensive installation costs	Reducing installation costs	Installation cost reduction about 30%
Long time between latching	Reducing time between latching through GOOSE service	Latching time reduction about 70%
Unknown due to lack of confirmation or possible error	Safety system in front of a problem in a part of communication network	Increase of the system security

Table 6.1 Comparative analysis between IEC 61850 and traditional wiring

The emission times of GOOSE messages are in the range of 2 [ms] to 4 [ms]. Even the Ethernet network is non-deterministic, using nowadays redundancy network protocols such as Parallel Redundancy Protocol

(PRP) or Hot Standby Router Protocol (HSRP) with 0 [s] [145] of recovering time, the transmission time of the GOOSE in the networks is taken as deterministic over the configuration time. Nevertheless, a digital contact in a IED has a contact time about 4 [ms] and if there is a long distance, as mentioned before, it will be necessary to use another kind of conversion hardware to send the binary signal between relays, and then the time will increase considerably over 20 [ms]. For this reason, the inter-locking signals which have been exposed before will have a reduced time, about 70%, in comparison with traditional wiring in a global large installation. The substitution of traditional wiring for this communication experiments a sustainable reduction in cost as it is mentioned in [7] and in [146]; although it will be an increase of other communication elements such as switch which will be needed for other applications [147].

In general terms, the use of IEC 61850 in this kind of installations can help in system cost reduction during the engineering process of the project as mentioned in [7] or during the maintenance of the ownership in [148]. The configuration tools contribute considerably in these processes reducing the time and obviously due to the different vendors' devices provide the same objects hierarchy description. However, all these advantages require basic communication knowledge from engineers, integrators and maintenance workers, versus the easier wired systems.

6.4.1.2.4 General architecture

Finally, it should be mentioned the SVP service. This service provides a protocol to sample the value of the measurements of current and voltage in order to send this information through the network until different AEDs. The SVP can send 94 samples by signal period among CTs and VTs to several AEDs is to send information a control bay or another intermediate process or test in a substation.

The figure 6.8 represents the three-important service of IEC 61850: MMS, GOOSE and SVP in a communication architecture in HV-MV substation. As the figure shows there are the different field devices and control devices and also the process bus and station bus. The first bus is between field devices and control devices and the second one is among all set of bays and the high-level system such a local SCADA or ADMS in the control.

It is important to highlight that the SVP is a service between control devices and field devices, in exception of the circuit breaker. In fact, is a vertical communication as the MMS communication from SCADA to the control devices and field devices, although it is more common to communicate with control devices. Nevertheless, the GOOSE service is a horizontal communication between control devices in order to establish the interlocking conditions described before.

This kind of architecture provides both important points the scalability on time and on technology. In spite of new expansions of the installations and also new device development the architecture can still remain in front of this changes.

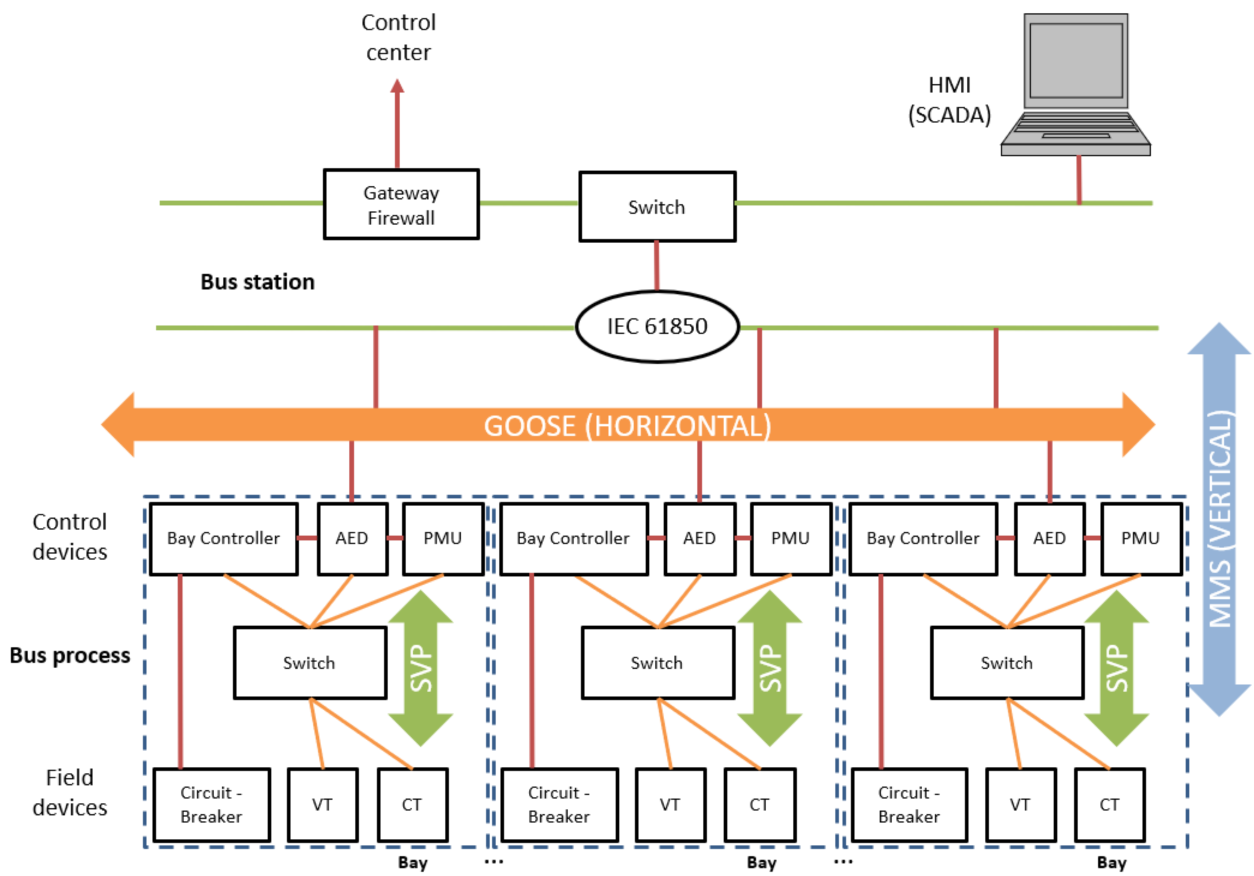


Figure 6.8 IEC 61850 Services in a HV–MV substation architecture

6.4.1.3 Related work on IEC 61850 for protection communication and DER integration

As mentioned before there is an important relationship between IEC 61850 and new actors in the electrical distribution network such as DERs. It is important to remark that the application of GOOSE service has been verified in publications such as [149], [150], [151] and [152] in which this kind of IEC 61850 message is used to make a logic discrimination, transfer application and modify settings between protection relays, IEDs as in [153], [154] and in [155].

GOOSE service has been proposed as an important tool in order to carry out new enhanced automation in electrical network. For example, reference [149] defines a Virtual Power Plant (VPP) model in which IEC 61850 can be used to enhance the interaction with DER, contributing to seamless integration of the DER data to a VPP and facilitating the integration to market applications. Moreover, references [150], [151] and [152] present different studies about how GOOSE enable fast horizontal peer-to-peer communication between several IEDs. For example, reference [150] stated that this technology provides very low latency (4–5 [ms]) allowing to deploy decentralized functions, such as distributed and autonomous microgrid protection. A fast FLISR algorithm based on IEC 61850 GOOSE messaging was proposed in [151] to reduce service outage time. However, the algorithm is quite generic it was considered as a starting point for the definition of the algorithm presented in this document. The advantages of IEC 61850 GOOSE service were also analysed in [152], highlighting the replacement of complex network of hardwired connection with an Ethernet network for inter-IED communication at the station level.

Furthermore, reference [153] analysed the usage of IEC 61850 for managing Distribution Automation Systems (DAS) and proposed GOOSE messages as an appropriate technology to transmit time-critical information from one source to multiple receivers. The article also analysed on the configuration requirements and proposed a configuration solution for a DAS case study. Previous work in [154] and in [155] also studied the advantages of GOOSE messages for operating MV protection at substation, instead of the more complex and expensive hard-wired schemes. However, they do not present a detailed explanation of GOOSE configuration and the required LNs.

Taking into account that the usage of IEC 61850 GOOSE service is a growing trend in recent literature, it was considered that the specific case presented in this document provides some outputs and conclusions that can be helpful for other researchers of the field in the future. Moreover, the authors identified also an increasing industrial need for the implementation of adaptive protection algorithms, such as the one presented in the following section. Therefore, the solution presented details configuration schemes (including GOOSE messages and IEDs), processes and the control algorithm in order to efficiently manage protection systems in scenarios with DER.

6.4.1.4 Orientation of IEC 61850 towards Smart Grid

The concept of Smart Grids has been considered in the last years as the appropriate answer to address the new challenges in the energy domain: network reliability, energy efficiency, distributed renewable energy sources and the increasing network complexity. However, multiple barriers appear in the road to realize these achievements. Proactive operation of the grid, efficient integration of demand and renewable generation into grid operation, or the integration of Smart Grids with other energy networks still need additional resources to get applicable solutions.

Moreover, the increasing penetration of DERs demands the evolution of the traditional control and protection schemes of electrical energy systems. Traditional protection schemes are evolving in new functionalities thanks to the emergence of standards such as IEC 61850 and the usage of Ethernet-based communication capabilities. They are necessaries to success in new electrical energy system topologies that are coming with the increasing penetration of renewal energy sources distributed around the Smart Grid.

The protection relays’ evolution to the current IEDs, which include measurement, protection, control, fault recording and reporting, allows fast and efficient system management. That is possible because of their capability for providing and communicating more data and increasing the Smart Grid distributed automation versus the traditional centralized nodes.

Research work has been presented in [156] proposing the application of IEDs and their communications capabilities on traditional protection schemes. Indeed, there is a research trend focused in the evolution of FLIRS applications and adaptive protection schemes as a part of the automation in the future smart grids and micro-grids. Several research articles such as [157], [158], [159] and [160] have revealed projects developing self-healing functionality in mesh grids after a fault location using IEC 61850 services in directional protection schemes. All these functions are included in Advanced Distributed Automation (ADA) systems, which are necessaries to cover the increasing penetration of DER in the grids.

6.4.1.4.1 IEC 61850 towards Software-Defined Utility

Several researches have worked on the analysis of different communications options for efficient and flexible deployment of novel Smart Grid services at the distribution level towards the Software-Defined Utility (SDU) concept [161], with the objective of obtaining a higher software-based and automated management of the grid and reducing its operational cost. As stated in [161], SDU strategies send messages with stringent reliability demands between different points of the electrical distribution network with delay requirements of a few [ms], which force the communication network to react in a similar response time in case of failure. Thus, many of the SDU services have stringent requirements in terms of availability and delay as it is mentioned in [161] and [162]. For example, in the European project FINESCE, SDU claims are not always considering their extension to the power distribution network and thus they were confined to the primary substation. This was mostly due to the difficulties arisen from the distributed, complex and partly buried nature of the distribution network in addition to its partially meshed physical topology. To bridge this challenging gap, distribution network requirements has been defined according to the analysis performed on IEC 61850 among others.

From the main master lines of the SDU developments, the authors stress on coping with the stringent Smart Grid Information Communication Technology (ICT) requirements and allowing the easy deployment of distributed applications over the grid by following existing standards as much as possible. An example of the SDU paradigm pursues to extend the primary substation protocols to its surrounding distribution area by creating an IEC 61850 centric system that allows to consider the defined area as a virtual substation from the communications point of view. Following this line of thought, the approach proposed in [162] for communications over the distribution network is to focus on the development of a novel and flexible ICT infrastructure based on a mix of heterogeneous Ethernet link layer technologies.

Previous articles [161] and [162] have disclosed that intelligent electronic devices operating with the IEC 61850 protocol and that any other protocols for accessing data are translated to the mentioned protocol before storing the data in the repositories. The enablement of GOOSE messages defined in the IEC 61850 standard in the whole domain is also relevant, even outside of the Primary Substation. In [162], it was highlighted that the low latency and very high reliability needed for active protection functions can be difficult to achieve with the GOOSE protocol. However, it also remarked the high reliability needed for command and regulations, and monitoring and analysis functional classes, which are not easy to achieve in practice in a distribution grid environment over Ethernet protocol. In summary, although there are some publications such as [163], which presented a method that can communicate several nodes in a microgrid by means of IEEE Time Sensitive Networking and GOOSE messages, the demonstration of GOOSE capabilities in these concerns is still an uncompleted scientific study regarding the communication in a SDU paradigm.

Taking into account this background, a part of this thesis focuses on validating and evaluating the usage of IEC 61850 in the configuration and deployment of phase directional protection and earth fault directional protection cases, respectively called 67 and 67N in ANSI codes. Notwithstanding, although it focused in these specific cases, it also represents a very valuable study for the SDU deployment, exploring how IEC 61850 GOOSE service can be configured and applied to different protection cases, but also provides a proof-of-concept of how other SDU applications could be adapted for running with a communications layer directly over Ethernet.

As mentioned before the IEC 61850 is a standard focused for substations although the particularities of the services such as GOOSE or SVP are defining a new way. As mentioned before the combination between IEC 61850 and PLC is a good opportunity to develop a new control system in the electrical network.

Several papers, such as [164], [165], [166] have proposed new communication architecture for distribution automation network where the IEC 61850 takes an important role for system protection and fault locator. A good example a direct application of IEC 61850 over the distribution network is [167], where there is an application about logic discrimination and IEC 61850. This example uses GOOSES such as [129] and [168].

Other publications such as [169] provides a self-healing system in a distribution network in order to recover a system. Therefore, the IEC 61850 has a lot of possibilities to apply in a distribution network where the self-healing is a new step in order to enhance the power quality. A good example of a self-healing where there is an important automatic application is showed in [170].

This kind of automatic systems with an application of IEC 61850 can provide a good reaction time to the network. Due to the IEC 61850 can model the real world through a virtual world where each device has a common semantic structure and univocal description, the automation can reach a new level. The current problem is in the physical medium to communicate the distribution network devices between them with this protocol in order to use as SDU.

6.4.1.4.2 IEC 61850 in a protection system remote laboratory

Laboratories are useful in education and research, since they let users the opportunity to experience with physical systems or systems related with the material of study in a safe and reliable way [171]. Remote laboratories are a learning tool that allows carrying out remote tutorials. Such sort of platforms can be useful to complete some subjects. Timetables flexibility is the main advantage of remote laboratories for both students and teachers, since these laboratories are in operation 24 hours per day without any human assistance. The actuation of electrical protection can save a lot of human lives and save money by avoiding the destruction of equipment. So much people do not know the function of these devices.

Following an e-laboratory of electrical protections will be presented which emulates the structure and conditions of a medium voltage grid. Such laboratory is used to realise practical activities in degree and master subjects and professional courses of electrical protections and communications in IEC 61850 [172].

The construction of such laboratories was started in mid 90s [173]. This construction involves time, money and energy. So, if it is used by some students, the cost per student will be reduced. Due to its remote feature, accessibility is much higher, reducing this way its cost [174]. The control engineering experience gained by the student is pedagogically the same as the traditional laboratory experience in [175] and in [176].

The restructuration of electrical systems and the promotion of renewable energies have encouraged the need for education about this technology to non-engineers [177]. Some kinds of laboratories exist in the field of electrical engineering, mainly in the fields of automation, control and supply quality as it mentioned in [178], [179], [180] and in [181].

Electrical energy currently plays a very important role in our lives. It is used in industries to carry out complex processes, as well as in daily life [182]. Such energy is very efficient; however, it involves risks, reduced or removed by protection systems.

Therefore, the usefulness of protection systems in electrical grids is to protect from such risks. Their role is focused on maintaining stability and service continuity, avoiding damages in equipment and protecting adjacent premises. In order to carry out the previous objectives, the selected devices have to work quickly and reliably and, also to guarantee selectivity.

Different kinds of protections are used depending on the grid. Complex protections are applied in transport grids, since they have to detect the current direction due to its meshed structure, as well as to support high voltage and intensities. Distribution grid is radial; consequently, protections are not so complex, although they have to resist high voltage and intensities as well. Protections assigned to users are the simplest, normally not programmable, they are easy installable and inexpensive.

The power grid is increasingly automated, which aim is to increase supply security, as well as to provide a distance control and visualization. Its automation is carried out based on communications and SCADA systems. As mentioned before the standard IEC 61850 is defined as: communications grids and substations systems with different applications, that is, a communication standard between the different protections, control and measure devices inside a power substation, without considering the manufacturer of the different devices. This standard definition was created in 90s [183], starting with power substation, but currently wind turbines, hydroelectric plants or distribution and high voltage grids are also included.

There are some remote platforms for electric systems, but there is not specifically in the electrical protections because is difficult to dispose the equipment used in the distribution system, and the medium voltage given its cost and danger. The platform has been made consists in electrical protection remote laboratory of distribution grid.

According to [172] the purpose of the laboratory is to improve teach quality in the electrical protection and distribution grid fields, increase the practice of studies and applies new technologies. Complementing the existent practices in the electric systems area. Specifically, the electrical protection used in the electrical distribution networks. This experience shows the possibilities to use IEC 61850 as local SCADA and to integrate the IEC 61850 with other elements such as Programmable Logic Controller (PLC), out of the electrical SCOPE.

The students will be provided with the possibility of studying the protection of electrical systems, automation, supervision and remote-control technologies. The versatility of laboratory permits to use different kind of people, people who is initiates in the protection systems or users who has a lot of experience with these systems.

This platform emulates an electrical distribution grid. It consists of a radial network with three loads; each one has a protection device. For added flexibility has a ring upon failure to reconfigure the platform. The operator can simulate two kinds of failures, overcurrent and short circuit.

The network topology is reconfigured with contactors that allows opening and closing the power circuit, through a PLC. This ring incorporates a protection relay; it has selectivity with the relays protection loads. Actually, the platform incorporates three kinds of loads; each load has his protection relay, in case of fault, this send a signal to circuit breaker to open the circuit and stops the current circular.

Each load can emulate two kinds of faults, overcurrent and short circuit, together with a nominal state. The PLC is the controller of the loads, the user can choose the type of defect to emulate. The physical loads are lights, it was chosen because facilities the remote visualization of the platform and for his low cost compared to alternatives. To emulate the overcurrent fault are added three lights over the circuit, doubling the current. For emulate a short circuit, the intensity is trebled respectively the nominal power, this is achieved by adding six lights to the rated load. The figure 6.9 shows the panel where several contacts, relays and PLC are connected between them in order to simulate a reality. This idea contributed in the definition of another panel which will show in next chapter 7.

Figure 6.9 Remote laboratory structure for distribution electrical protection, courtesy of UPC

The automation system is carrying out by PLC, TSX Micro model, it allows the interaction with the laboratory, with the data receptions, the contactors control, the inputs in dark green and outputs with light green. This automation allows the control of all contactors in the laboratory; the user can change the laboratory configurations with controlling the ring.

In the laboratory, has been implant the norm IEC 61850. There are two protection relays whom are exchanging the data with the Modbus protocol to a gateway, and it has been transformed to the IEC 61850 edition 1. It permits the configuration, visualization and the access to protection relays through the Internet, whether as assign the restriction levels account for each user. The other two protection relays incorporate IEC 61850 directly using GOOSE message between them. The product use for this function is Sepam from Schneider Electric and it will describe before.

The kind of protections defined in the IEDs are overloads and short circuits. In case of the grid value was superior of the settings defines; the protection relay will send a signal to the circuit breaker that will allow the circuit open as mentioned in previous chapters. Then, this laboratory platform could help to the user in ring control, monitoring and control of IEDs and circuit breakers, monitoring faults, ring restoration, load shedding…

The electrical protection remote laboratory of distribution grid allows for great variability of usage, as well as for analysing different areas in the electrical world; able to study the field of electrical protection, communication between protection relays using the standard IEC 61850 as well as to implement a complete automation of platform by programmable PLC.

6.4.1.4.3 IEC 61850 into the industry world

As mentioned previously IEC 61850 has started to work in several new worlds out of the electrical distribution network. One of these examples has been mentioned before through the PLC. The PLC is one of the maximum exponents of the industry world, in fact it is the established element to control several processes in the industry in a low level and in high level.

Nowadays several manufacturers such as [184] and [185] have adopted the IEC 61850 in their traditional products for the industry. This action provides the possibility to combine the benefits of IEC 61850 such as GOOSE message for instance in the industrial processes. It is important to take into account that IEC 61850 can provide several benefits in order to combine with other protocols by obviously reason; the explained services before can work properly in Ethernet network. Nowadays the Ethernet network is taking account a relevant importance and it is expanding in several industrial processes because is an open habitat where several TCP/IP protocols can work simultaneously. The figure 6.10 shows a possible architecture which integrates the electrical world in LV distribution joint the process areas [186].

In one only architecture, the electrical control together the process control is integrated through the PLC. It is important to remark that the LV distribution process is independent to the process areas but both are in the same control network but with different protocols. Although IEC 61850 can provide fast actions from the process areas to the electrical distribution in instance by means of GOOSE message. This fact provides to the process control the possibility to interact in the MV and LV electrical distribution directly [187]. For instance, it could be interesting a load shedding regarding the current situation in every process area. An event in the process area could be generate a GOOSE in the PLC and then the LV IEDs of this area and the MV IEDs joint the general PLC will subscribe to this GOOSE. Thus, a load shedding process could be start in order to optimize the process.

This last example is one of the options that IEC 61850 can provides in architecture like this because the rest of the control and monitoring can be developed by traditional protocols in the electrical and industrial sector such as MODBUS, Ethernet IP or even PROFINET. Therefore, the possibility to use the IEC 61850 to distribute the intelligence in the industry world as open way can provide big benefits.

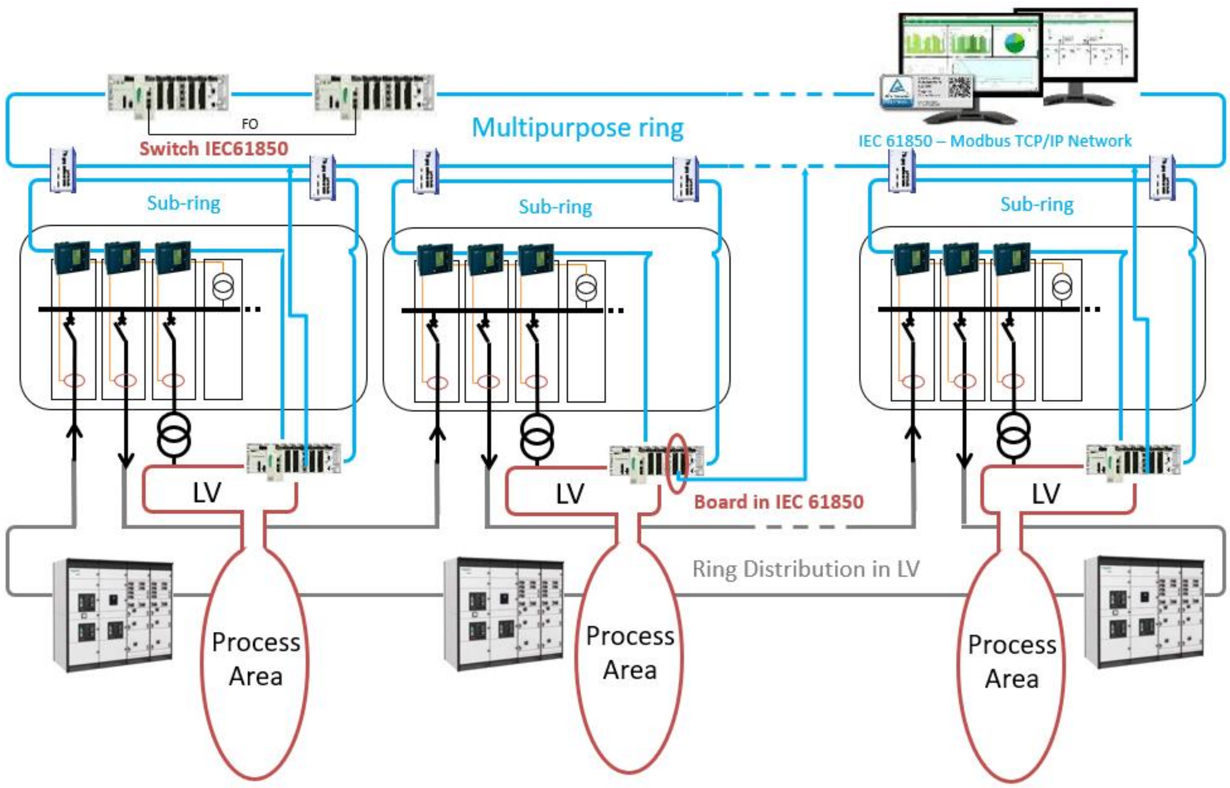


Figure 6.10 Architecture for industrial sector with IEC 61850, courtesy of Schneider Electric

6.4.1.5 AFL algorithm in IEC 61850

According to the relevance of the IEC 61850 in the electrical sector, the AFL algorithm presented before in chapter 5 can be implemented in this standard in order to integrate with future systems. In fact, there are systems in the market where FPI have been implemented natively with IEC 61850 [157]. Therefore, in this case it will be necessary to indicate the variables in order to integrate this algorithm in a high control system as follow.

- Number of nodes (z)
- Number of DFPIs (i)
- DFPIs position in nodes ($i \in z$)
- Relationship between DFPIs (a_{ij})
- Distances between DFPIs (h_{ij})

Several inputs will be necessaries to define the last matrix and vectors in order to define the system. As mentioned in chapter 5 the relationship is present only between DFPIs although it will be necessary to know where the DFPIs are. This number of parameter can define the electrical system where AFL algorithm will analyse the fault when it happens. All these parameters can provide a good definition of the network in order to apply the defined algorithm. Although the algorithm needs to collect the value of three variables in order to locate the fault as follow.

- Detection value of the DFPI (d_i)
- Status of the DFPI (b_i)
- Distance from DFPI with 21FL (n_j)

These are the necessary variables and parameters in order to detect a fault in a network with the AFL algorithm. Therefore, these variables and parameters have to be implemented in a high control system with the rest of systems.

According to [188], there is the proposition to introduce DFPI in reclosers and switch-disconnectors inside different nodes of the electrical system. For this reason, this algorithm can define their variable by link with IEC 61850. It will be necessary to include the last variables in a logical node of these DFPIs with the possibility to define DS to launch RCB and GOOSE Control Block (GCB).

One possible option is to create a new DFPI as LD in order to define specific LN. As show next table in figure 6.11 there is a possible structure of a DFPI with several logical nodes in order to collect the information from control centre.

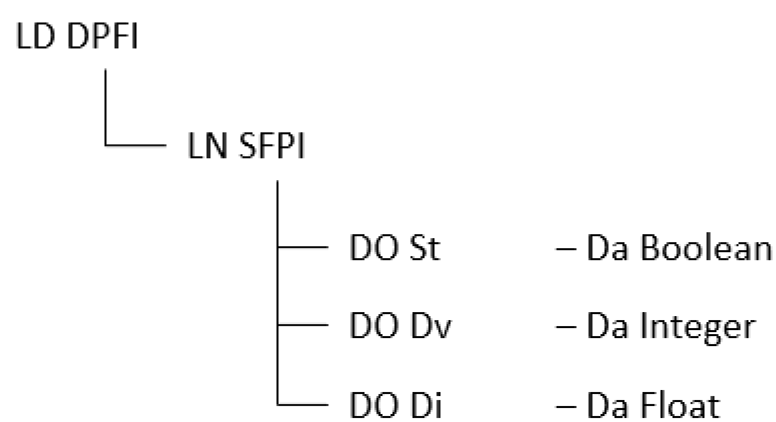


Figure 6.11 Logical Device DFPI

Where St is an attribute which is in charge of to report the status of the DFPI (b_i), Dv is the value of the detection from DFPI (d_i) and finally Di is the value of the detected distance in DFPI (n_i) with this function.

6.4.2 LPWAN. Technologies for electrical distribution networks in IoT world

In chapter 5 an algorithm for meshed distribution networks with DERs has been presented. Although it is necessary to develop a system to collect this information previously in order to apply the algorithm in the control centre. Using the traditional communication which has been explained in chapter 6 it is very difficult to deploy it and even the cost is very expensive due to these communication systems require a considerable infrastructure in order to establish the communication.

The IoT concept is based on the collection of data from distributed devices in an environment towards a high system in order to make some actions in them. This recent trend has several application fields such as Smart Home, Smart Health, Smart Factory and even Smart Cities in urban areas [189]. The IoT has been developed in the industry sector initially where it has been received the name Industrial IoT (IIoT) [190]. The figure 6.12 shows the architecture in IIoT where several devices known as the name as "things" are linked to LAN networks and after that Wide Area Networks (WAN) which communicate directly with data centre which will make some actions to the things.

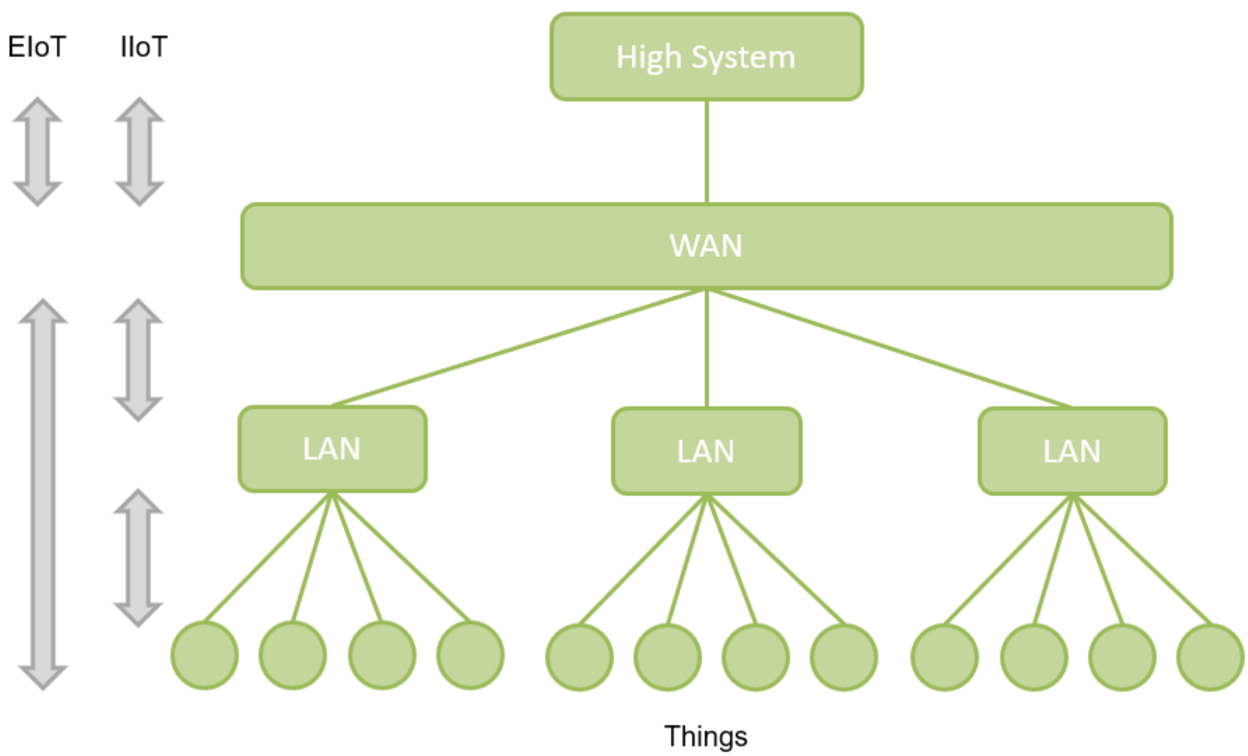


Figure 6.12 EIoT and IIoT architecture

The application of IoT in the electrical distribution network consists in the connection of the "things" directly to a high system control in order to analyse the data or to make some control through WAN networks to collect the field information. This application is taking an important relevance in the electrical sector [191]. In the electrical distribution network, the field devices exposed before such as IEDs or telecontrol devices is using the IEC standards to communicate with control centre through WAN networks but the DFPIs can be considered "things" and use another kind of WAN networks. The IoT for the Electrical sector can be defined such as Energy Internet of Things (EIoT).

As mentioned before a modelling of the algorithm through IEC 61850 could be a good option to establish this kind of algorithms but it can suppose an expensive cost. Nowadays a new technology has appeared in the market and it could help to reduce the deployment cost. These new technology is the LPWAN.

LPWAN is a type of wireless telecommunication WAN which has been designed to allow long range communications for a low bit rate. The focus of this technology is for devices such as sensors or elements with battery. This kind of network works in a range from 0.3 kbps to 50 kbps per channel [192]. Therefore, these networks can be used to deploy devices in a private network although this kind of service can be offered by a third party. The main interesting point of this technology that it is not necessary to invest in gateway technology, then LPWAN is a complement to the cellular mobile network and short-range technologies.

These kinds of networks are the key way to deploy the IoT concept in electrical distribution network in order to fulfil the following features from IoT concept [193].

- **Intelligence**. Data generation and collection in order to transform in knowledge.
- **Architecture**. Heterogeneous event and infrastructure managed by time. Some sensors can take information continuously or in a discrete time when event happens.
- **Complex system**. The number of devices can be huge. The capabilities of the objects can variety considerably between them therefore the network have to be prepared to adapt different objects.
- **Size considerations**. The network growth can increase considerably then the network has to be support for scalability process.
- **Time considerations**. Real time consideration is a key point of the network, overall for EIoT system.
- **Space considerations**. The area of work is considerably therefore the architecture can be prepared to assume the information from different areas with different environments.

- **Everything as a service**. This backend is a cloud computing platform which has to be scalable and versatile in order to integrate new future services.

Following, several LPWANs will be analysed in order to apply the best option to apply in described algorithms in chapter 5. As LPWAN it is possible to find Long Range Wide Area Network (LoRaWAN™), Sigfox and Narrowband IoT (NB-IoT) among others [194].

6.4.2.1 LPWAN technologies

6.4.2.1.1 LoRaWAN™

LoRaWAN™ is a LPWAN specification intended for wireless battery-operated devices in several network areas such as regional, national or global [195]. In fact, LoRaWAN™ provides a bidirectional communication, mobility and localization services avoiding complex local installations. By this way the communication of several devices will be comfortably with control centre.

The LoRa architecture is a star topology where the end devices communicate with several gateways which communicate with network server system. In fact, this kind of network is covering little areas with local gateways to change the protocol and physical medium in order to connect with servers in the backend by means of Internet Protocols (IP). In fact, the gateways have to be connected to the network server through IP connections, nevertheless end terminals use single hop wireless communication to one or many gateways. This feature can allow a bi-directional communication although it supports operation such as multicast enabling software upgrade or other mass distribution messages. One of the important aspects of LoRa is the possibility to support software upgrades and mass distribution messages.

The communication among end-devices and gateways is by means of different frequency channels and data rates. The selection of the data rate depends on the communication range and message duration. LoRa can communicate with different data rates and it will not interfere with others and create a set of virtual channels. This fact is due to the spread spectrum technology [196] which increases the capacity of the gateway. As mentioned before the data rate is under the limits of a LPWAN communication, this is not a big speed communication in the channel but can help to optimize the battery life of the end-devices and the network capacity. Although the server is in charge of to manage the data rate and radio frequency output for each device.

LoRaWAN™ can operate devices in a regional, national or global network and besides this technology has the possibility to establish bi-directional communication, mobility and localization services. There are several conditions in order to fulfil a robust communication in everywhere with few information. These conditions are indicated as follow.

- Long battery life.
- Wide area connectivity characteristics, allowing for out of the box connected solutions.
- Low cost chipsets and networks.

This set of requirements provides to end user and business developer a ready technology to enabling the roll out of IoT due to the cost and integration devices in a LoRaWAN™ network is easy in comparison with other kind of networks. In fact, there are several classes of end-point devices to establish different solutions as follow.

- **Class A**. Bi-directional end-devices. Tis devices are prepared for bi-directional communication whereby each equipment has an uplink transmission which is followed by two short downlinks receive windows. These devices need a low consumption due to require downlink communication from the server after to send an uplink transmission.

- **Class B**. This kind of device opens extra receive windows at scheduled times. This fact will allow the server to know when the end-device is listening in the channel.

- **Class C**. In this case the device is opened only it will be closed when the device transmits some information through the channel.

As an example, regarding to the AFL algorithm presented previously the best communication skill should be the class A because the consumption is lower than other classes and maybe it will be used properly in overhead DFPIs. As mentioned before this kind of DFPIs can be supplied by a small battery. According to [197] it is not necessary to establish an important infrastructure in order to deploy a device with LoRa capability to communicate. Additionally, it is important to remark that LoRa can manage several millions of devices with few data per day [198] and cover an important extension of territory [199]. It is enough for DFPIs applications, although the temperature can affect considerately to the signal [200].

Nowadays one important aspect of this network is the cybersecurity. Previously LoRaWAN™ has several encryption layers such as unique network key (EUI64) to ensure security on network level, unique application key (EUI64) in order to ensure end to end security on application level and device specific key (EUI128) [195].

6.4.2.1.2 Sigfox

Unlike LoRa, Sigfox is not a standard, it is a French IoT provider. Its network is a backend where the different devices launch the data and it manages the message transference by means of a http request to a presetting backend.

This situation provides to the sensors developers the possibility to integrate comfortably the radio module in these devices. The Sigfox network is based on star topology which requires a mobile operator to carry the generated traffic. The signal can also be used to easily cover large areas and to reach underground objects. This is a technology Ultra-NB-IoT which works with radio bands between 868 MHz in European region and 902 MHz in USA.

Sigfox transmits data by means of a standard radio transmission method called Binary Phase-Shift Keying (BPSK). The modulation of this standard is very slow due to the speed is 300 bps. Although this modulation rate can allow to get a great range using few base stations. As an example, it is important to remark that in USA this system modulates at a higher rate due to in the normative FCC part 15 the maximum time a transmission can be on the air is 0.4 seconds [201]. It is important to remark that Sigfox has developed the cybersecurity concept in their solutions through IT security, secure software and architecture [202] as in the case of LoRa.

6.4.2.1.3 NB-IoT

NB-IoT is a LPWAN radio technology standard designed for the IoT which has been developed to link several devices and services to be connected through cellular telecommunications bands. NB-IoT has been released by 3rd Generation Partnership Project (3GPP) in order to provide extended coverage and low energy consumption for low cost devices [203]. This development has only required a low-cost hardware update in the Long Term Evolution (LTE) devices in order to reduce the battery consumption and minimize the signalling. It is important to remark that NB-IoT has a fast connection and can send 12 bytes per day.

Nowadays the NB-IoT deployment is quickly increasing then this technology is dominating the LPWAN [204]. This kind of networks can support the firmware and software transmission and other functions such as task updates or commands towards an important number of devices due to its optimised data transfer.

As in the case of LoRa and Sigfox, NB-IoT has been thought for use as a low power consumption which can be deployed into existing cellular network architecture in an indoor and outdoor range supporting more than 100,000 connections per cell. NB-IoT supports security by two-way authentication and strong interface encryption. The possibility to use the established network 4G or 5G and its future evolutions will provide a robustness network in order to deploy IoT devices around the networks such as the electrical system.

6.4.2.2 AFL algorithm in LPWAN

In last chapter, there are a lot of algorithms which combine different technics to help to fault location. In this point is presented the deployment of the AFL algorithm in a LPWAN in order to find an alternative to IEC 61850.

First of all, to define the AFL algorithm in a LPWAN, it will be necessary to evaluate all several possibilities about to establish the communication of different DFPIs. In fact, there are a lot of possible communication protocols such as IEC 104 or IEC 101 from family IEC 60780-5 although this kind of protocol requires about a special infrastructure with significative consumption in order to collect the information from these devices. For this reason, one of the possibilities is to establish a communication system which will be based on LPWAN. As mentioned before this kind of network provide us an easy communication although the information quantity is with low density.

As it has been described in AFL algorithm, it is important to remark that the different DFPIs and IEDs will have different communication needs. In instance an IED in a substation will have the possibility to communicate the fault detection through ANSI protections and even the distance fault through the HV-MV substation communication system. As an example, this communication can be in IEC 61850 inside substation and in IEC 104 towards the control centre.

On the other hand, the DFPI in MV-LV substation can communicate in similar protocol such in HV-MV substation, due to there is auxiliary power supply such as UPS. Besides in this case it is necessary to open and close switch-disconnector then there will be a considerably power supply system to avoid any problem. It is important to remark that it is possible to find MV-LV substations without an auxiliary power supply. In this case, it will be managed as overhead position in the network.

Finally, in the DFPI in overhead MV points of the network where it is difficult to give an auxiliary power supply it could be establish a power supply by small battery as it has been defined in 5.2.2.2. In this case where the device could be self-supply or with small battery the LPWANs can contribute considerably in to collect the information to apply the algorithm in ADMS.

6.4.2.2.1 Implementation

The implementation of the AFL algorithm in order to deploy in an electrical distribution network needs a device which is based in two principles: the easy roll out and the and the easy implementation in control centre of the utility. Additionally, the algorithm has to be focused in the fault location with certain accuracy, therefore the first point is to find the section of the network where the fault is but proposing a distance inside this section.

The DFPIs are a good solution in order to deploy it along the network such is showed in [205]. One of the possibilities is to think directly in communication networks such as Global System for Mobile (GSM) to communicate with the control centre as it is mentioned in [206], but the problem is in the integration of this kind of FPI due to the use of GSM Subscriber Identify Module (SIM) card in the GSM modem.

According to [192] LPWANs can capture up to 55% market share using battery-powered devices with an operating time of 10 years and covering a distance of tens of kilometres. These technologies can help to establish a link between several FPIs and a back panel in order to collect the information and after that to send to control centre this information to locate the position of the fault and to report it to other employees.

As mentioned before in 6.4.1 and according to [207], the IEC 61850 can help considerably to the implementation of this systems. The combination between functionality and communication can provide a lot of possibilities to enhance the functioning in the electrical system in whole scale. The extension of this standard out of the substation can help to establish a lot of relationships between substation, although nowadays it is difficult to apply in DFPIs because it is necessary to have an important infrastructure. Although the platform of the AFL algorithm there will be combine several protocols depending on the situation of each device on the network as described before. Then the following kind of devices will be implementing as follow and also is indicated in figure 6.13.

- **IED**. This device will communicate inside HV-MV substation by IEC 61850 in a local network towards RTU.

- **RTU**. The RTU of the HV-MV or MV-LV substation with telecontrol could be communicate in IEC 61850 or IEC 104 as a standard protocol towards control centre.

- **DFPI**. These devices will communicate as a device A in LoRaWAN™ standard towards a backend which will integrate in the control centre. Other option will be NB-IoT, according to [208] and [209] the NB-IoT and LoRaWAN™ are the best option in comparison with GPRS and Sigfox. Although at the end it will be depend on the environment where the network is. The idea will be combine both standards.

On the other hand, the implementation of the algorithm should cover and ensure several skills of service in order to fulfil its the main objectives. Below there are different inputs which expose these important features.

- **Collect information**. Ensure the data collection of all DFPIs of the network when a fault appears. This information is composed by the status of DFPI and also the direction of the fault according to the type of fault. In the case of IEDs it will be necessary to collect also the distance fault.

- **Treatment**. After the data collection from the IEDs and DFPIs it will be necessary to execute the algorithm in order to locate the position of the fault.

- **Results**. At the end it will be necessary to indicate the section where the fault is and the distance to the fault from the initial point of the section in order to repair or take some actions in this area of the network.

It is important to remark that the algorithm application could be launch messages to the patrols or technical area managers based on different areas of the utility. Additionally, the information from the DFPIs could be transmitted directly to these employee by means of some application in mobile phone in order to start the repair procedure.

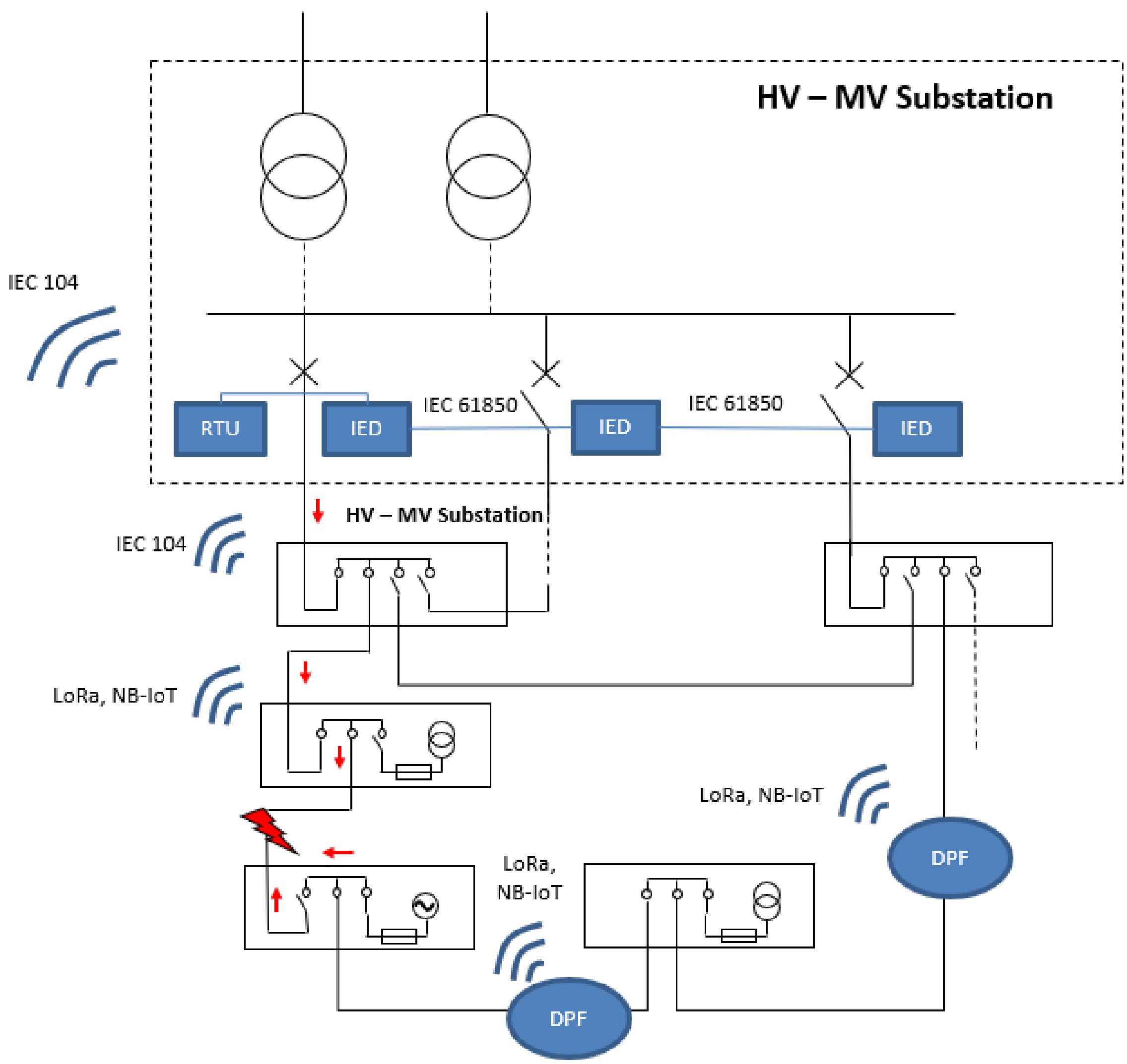


Figure 6.13 Applied communication standards in the AFL algorithm

6.4.2.2.2 Feasibility. AFL algorithm implementation cost

This section establishes a feasibility evaluation about the implementation of the AFL algorithm in comparison with traditional communication technology such is GSM or GPRS in front of LPWAN. Also, this is an analysis about the implementation of the algorithm; it is also focused in to analyse how can enhance the performance of the network regarding the fault time detection, in other words, how can affect the algorithm in several kinds of network such as urban network or rural network.

First of all, it is important to take into account that the DFPI in overhead networks could be communicate through GPRS or GSM in protocols such as IEC 104 or IEC 61850. As mentioned in chapter 5 this fact requires an electronic device with an UPS and infrastructure, composed by solar panel, battery and loader, which increase the cost of the solution. According to pole mounted overhead DFPI such as [79] and [210] and the cost of communicated device in IEC 104, IEC 61850 or DNP3 explained before the total cost is higher than use a LPWAN protocol. Nowadays in the market the cost of the traditional solution is the double that the LPWANs [211], comparing the global system; under device comparison it is possible to find more cost difference. Maybe this difference will be reduced in time because the power electronic of the converter and the solar panel will decrease.

On the other hand, it is highlighting to remark that the cost in HV-MV and MV-LV substations where there are IEDs will be the same for traditional solution as for the new solution because these devices will use the traditional communication in both scenarios. Then the difference will be in the overhead solution and in MV-LV substation without telecontrol where the power supply will be not necessary. As mentioned in chapter 5 these underground devices can be self-supplied, then they are good candidates in order to apply the recent LPWAN communication.

After these previous considerations it is possible to establish a simple indication regarding the cost. In the table 6.2 there is an analysis about the example of the figure 5.29. It is important to remark that this analysis has two important considerations as follow.

- The MV-LV substation without generation has DFPIs with trend technology LPWAN.
- The cost of the devices and infrastructure for overhead and underground DFPI has a 50% reduction for trend technology LPWAN.
- The cost of IED in a HV-MV substation is the triple that DFPI overhead technology.
- Each 2 km there is an overhead DFPI in order to locate with accuracy the fault. In total in the network there is 45 possible devices as overhead devices.
- λ is the unit cost to analyse the system. The back panel has been considered with a weight about 7λ.

As the table 6.2 shows the difference between these technologies is about 45% of reduction if the new LPWANs are selected. This is a possible scenario when there are several overhead DFPIs in the network. Therefore, if the network is an overhead network, such as rural networks, the cost impact will be considerably due to the number of overhead DFPI is important. In the case of underground network, such as urban network, the LPWAN communication will not impact considerably.

	Traditional Communication			**LPWAN Communication**		
Elements	**Relative Cost**	**Numer of Units**	**Total**	**Relative Cost**	**Numer of Units**	**Total**
IEDs - Telecontrol	3λ	13	39λ	3λ	13	39λ
Overhead DFPI	2λ	45	90λ	λ	45	45λ
Underground DFPI	2λ	6	12λ	λ	6	6λ
Back panel Integration	7λ	1	7λ	7λ	1	7λ
Total Cost			**148λ**			**97λ**

Table 6.2 Comparison between traditional and LPWAN communication

The AFL algorithm with LPWAN technology has a significative difference in cost in rural network in comparison with the traditional communication. Unlike this fact, the algorithm can reduce the indices SAIFI and SAIDI due to it can detect the section and position of the fault. In the urban networks there is not the possibility to introduce DFPIs in the cable in order to know with more accuracy the exactly position.

7. Distribution network restoration

The electrical distribution networks can be restored under several changes in open switch-disconnectors. Feeder Automation methods have been developed to minimize losses. Although after a fault in the network the most important need is to recover the system as soon as possible. This is the reason to establish an algorithm after the FLISR application.

Due to the exponential growth of distribution networks in last decades and the incorporation of DERs the complexity of quality service in the network has increased. This fact has contributed in the research in the distribution network automation thanks to the resources of information technologies [212]**.**

From the union between electrical technology and IT is when the Smart Grid concept appears. This intelligent part has been evolving during last decades. The evolution has been linked to two ways; one of them has been the information transmission, through physical mediums, and a second one in the information management, through different communication protocols.

The evolution of these physical mediums has modified the quality of the distribution network restoration. These changes have established an exponential improvement in the time to manage a network. It is important to highlight that this evolution is limited in this moment due to the data exchange between network controllers. As mentioned before the IEC 61850 standard can provide a distributed communication between AEDs, FPIs and telecontrol devices in order to help in the restoration process [12].

On the other hand, in the physical mediums has been appeared the PLC as mentioned before. This kind of communication was focused initially in applications such as AMI or Home Area Network (HAN) [213]**.** The evolution of this communication to broadband has stimulated the launch of new applications to trend a decentralized automation in the electrical network. Today this kind of communication is known as Broadband Power Line Communication (BPLC).

7.1 Smart distribution network

This new kind of network knows as Smart Grid is being implemented in several distribution networks through the IT. This evolution is in a slow process over the current installations due to it is not possible to establish a complete change due to the cost.

The Smart Grid definition is according to [214]**:** “A Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety". Therefore, the Smart Grid is a concept which provides flexibility to the network and potential benefits for all the chain. This chain is formed by DSOs, TSOs, users and other intermediates. Thus, the Smart Grid could work in the network with flexibility; through the collect data the system will take decisions in order to optimize the demand versus the generation, in other words, to reach the demand response efficiently [215].

The goals of the Smart Grid are focused in optimize the distribution, in supply quality, in the management of the network, in the integration of renewable energies, in implantation of the self-consumption and in to reach to the goals 20-20-20 which have been fixed by European Commission. Maybe this last goal is under review because there has been an important change in last five years regarding geopolitical actions.

Another interesting vision according to [216] defines five fundamentals technologies to reach a Smart Grid. These technologies are the integrated communications, measurement technology, advanced components such super conductor or storage, advanced control methods and improvement of the support interfaces in order to help the operators of the system.

The Smart Grid implantation can provide a lot of benefits to the electrical distribution network. According to [215] there are several points such as comfortable renewable energy integration, new incentives for the customers, reduction of the outages, infrastructures optimization, electric vehicle implantation and global optimizations of energetic sources.

One of the benefits is the reduction of the outages frequency. As mentioned before this fact affects to improve the quality of the network. Therefore, the Smart Grid is a good tool to enhance the network behaviour.

7.2 Decentralized automation

As mentioned before the current management of the electrical distribution network is centralized. The different nodes of the network are linked to control centre with ADMS where the intelligence is inside. The new physical medium such BPLC are impacting in the kind of control network. This technology can transfer information by broadband carrier wave with high frequency in the power wire.

The current communication between MV-LV substation and control centre is by GPRS, Digital Radio, Asymmetric Digital Subscriber Line (ADSL) and others. This kind of communication needs other external network to exchange the information; the BPLC can use the same electrical distribution network to transfer this information. In fact, the control architecture can be decentralised with this technology and after a fault, the different field devices will communicate between them and there will be a fast process restoration. According to [217] there are utilities that are using the BLPC to communicate field devices with the ADMS.

The distributed intelligence deployment does not imply the substitution of centralised automation; in fact, this automation can continue present in order to establish general reconfigurations and other analysis as mentioned before. Both automations can be living together to improve the quality service because the distributed intelligence provides a quicker answer in front of the traditional automation [129]**.** Therefore, following an example of decentralized automation will showed using the IEC 61850 GOOSE service in order to adapt the ANSI protections in a ring system with DERs [218].

7.2.1 Adaptive protection in ring systems with DERs

In order to reduce losses and increase the availability in electrical system, ring main distribution topologies are implemented. Basically, there are two types of electrical rings as it was mentioned before in previous chapters, based in circuit breaker (CB) and in switch-disconnectors.

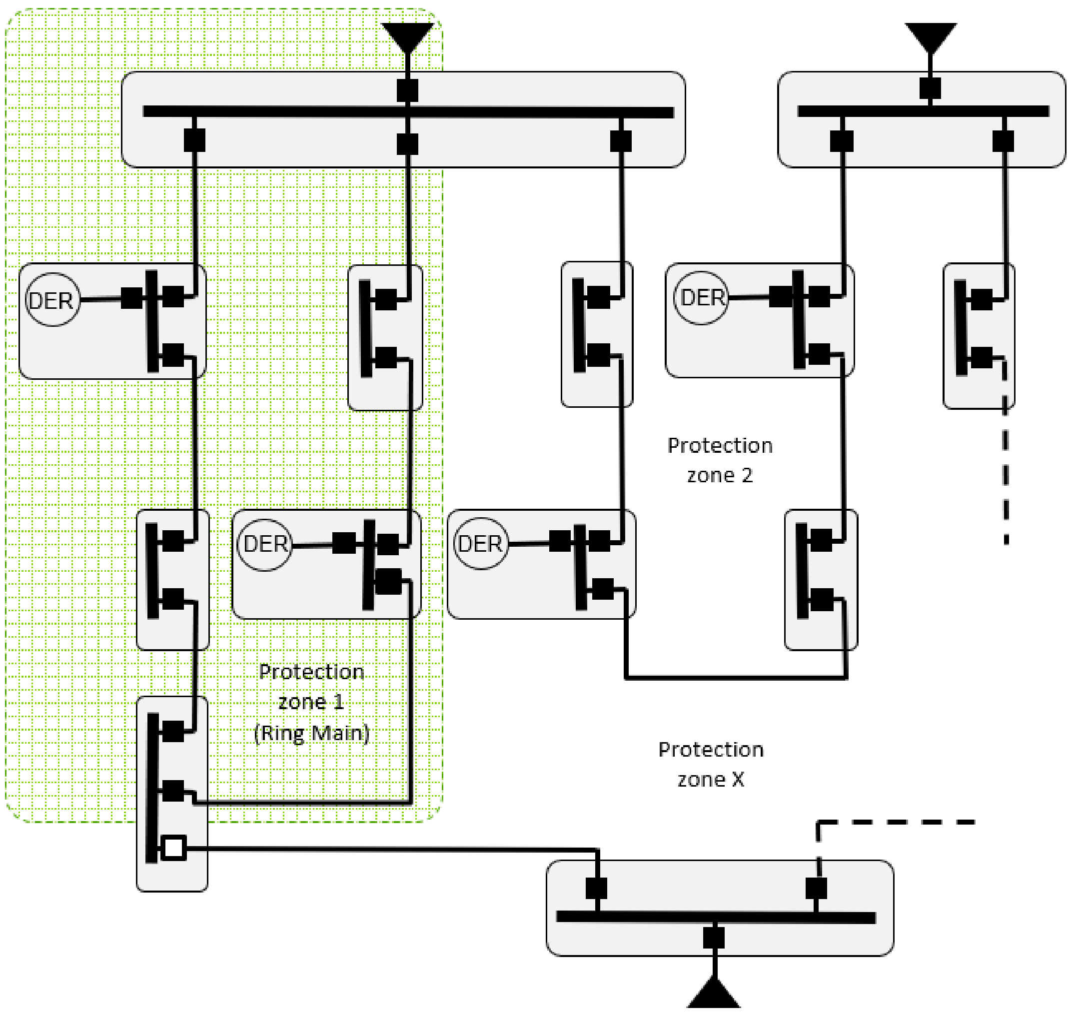


Figure 7.1 Electrical distribution network with DER presence

This subsection focuses on three phase balanced networks and medium size ring networks (e.g., industrial, utility, isolated…) with automatic CB topology, which represent a good option for critical power supply systems, target of future installations and distribution grids. Moreover, it is also considering DER integration plants in which the type of the DER and its protection point of interconnection are not considered.

To carry out the protection in a CB-based ring, in closed or opened operation mode, it is necessary to set a protection system that allows a proper selectivity between the CBs included in the ring. All of them will have the same pick-up and setting time, so it will be necessary to implement logic discrimination block signals.

The DER penetration in distribution network can affect mainly to three network aspects: the voltage quality, the current quality and the stability of the system [219]. As mentioned before, one of the objectives of this thesis is to find an adaptive network protection for current faults. Therefore, some modification may be necessary regarding the number of DERs that are working in each possible scenario, as shown in Figure 7.1. According to [220], it will be necessary to introduce a new current setting, a new time setting or even to enable or disable directional protection when a DER is present in the electrical bus. More concretely, the scope of the study is the protection zone 1 shown in Figure 7.1.

7.2.1.1 Ring main in closed operation

The equipment configuration of this topology is based in automatic CBs around the ring. It is an expensive solution but it allows a maximum availability because it avoids a zero voltage drop in the system in case of an electrical fault. When a fault occurs in this topology, every IED activates the pick-up level because the fault current flows from the source to the fault location for both paths. In addition, the two IEDs that are closest to the fault activate the pick-up, but each of them senses the current fault in opposite directions, as it is shown in Figure 7.2.

In order to implement a priority and to allow the fault isolation only from the closest IEDs to the fault point, it establishes an automatic sequence by ANSI 67/67N protections called logic discrimination. In case of a fault, this sequence sends a temporary block signal (block indication) from each IED to their adjacent, in the opposite direction where the fault current comes from. These signals allow a temporary blocking of every IED, except of the closest IEDs (non-blocking ones, because they are not blocked by other), which they are going to trip themselves and to execute a fault fast path isolation in the minimum setting time (typically between 50–100 [ms]).

It is important to highlight that in Figure 7.2 there are no indicated voltage transformers for voltage measure but these devices are mandatory in order to the properly function of 67/67N protection as explained before.

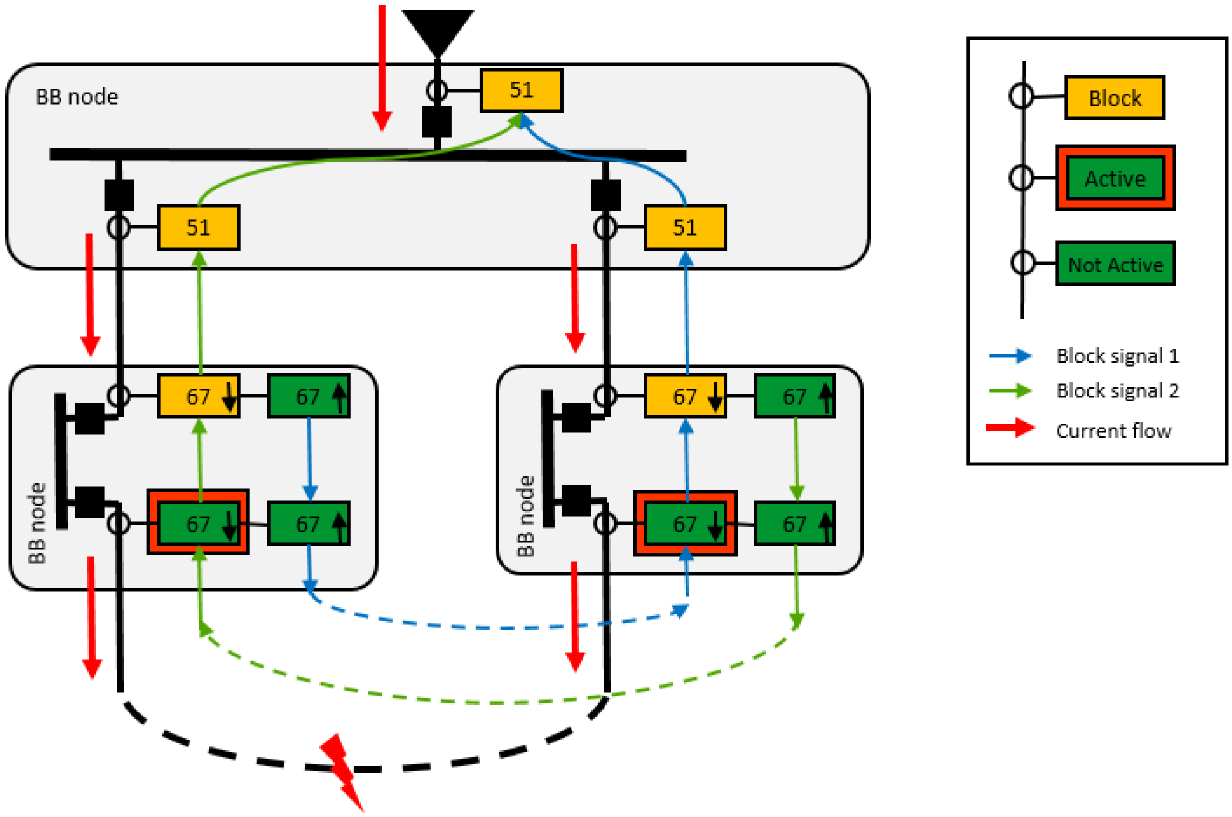


Figure 7.2 Ring main system based in automatic circuit breakers

In case of CB open failure, considering the blocking signals are temporal, after the logic waiting time (typically 200 [ms]) the adjacent IED is still sensing the current fault and trips the CB. If the ring is managed in open mode due to system operation, when fault occurs, the current will circulate only for one path from the source to the fault location. In this case, the sequence will be the same way as the one in closed operation, but just on the IEDs that sense the fault current. It is shown in figure 7.3.

In the feeders of the busbar in which there is an incomer fed by a source, the selected protections in the feeder (also in the incomer) are ANSI 50/51 and 50N/51N, unlike the rest of the feeder protections of the ring. This option is selected because the ANSI 67/67N will not work properly in this case, when there is a three-phase fault in the busbar and the voltage reference can be lost.

It is important to remark the relevance of the closed ring where the availability exposes in chapter 3 in this kind of systems based on CB can provide to the network a fast answer to isolate a fault directly. Therefore, a close ring is a good solution for critical installations such as industrial complex, power plants, airports… where the availability is a key needed. Although it is important does not forget that it can be extended to other kind of network such as electrical distribution network.

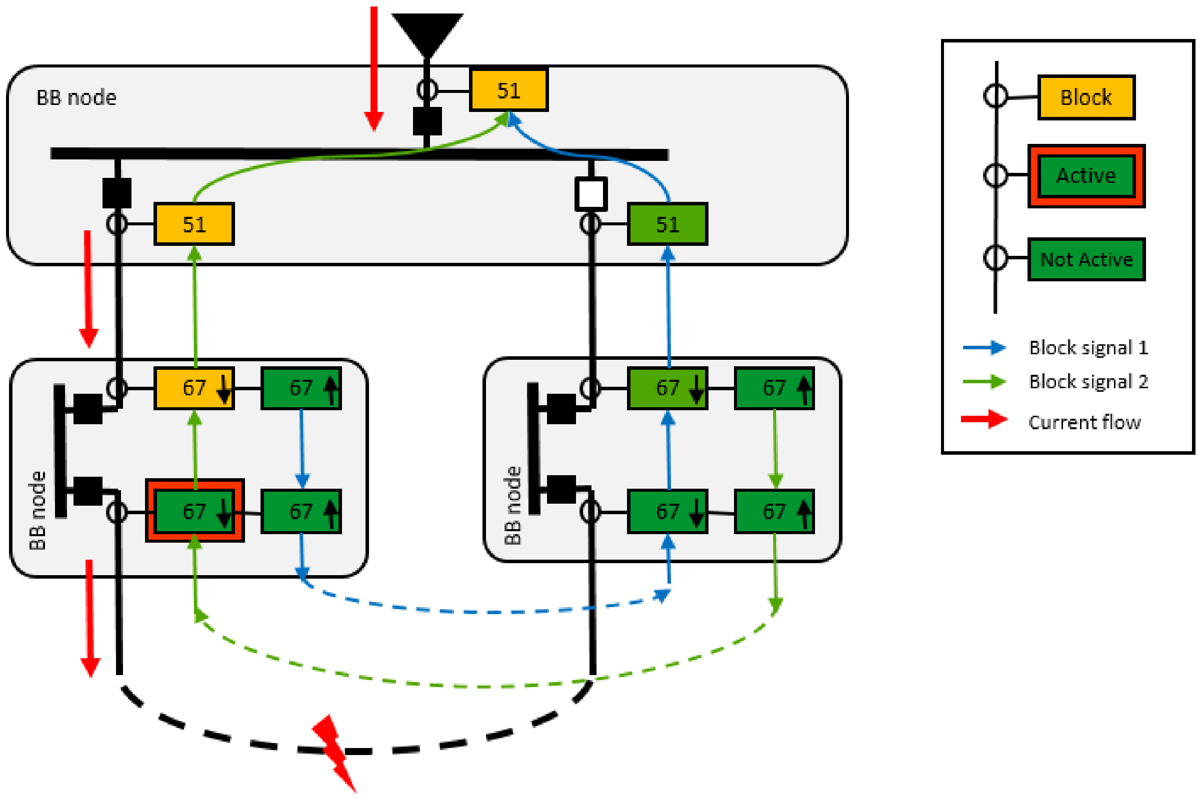


Figure 7.3 Electrical ring main system based in automatic circuit breakers in open mode

7.2.1.2 Ring Main operation with DER Sources

In the case that there are several DERs in the main ring, the fault current level can be significantly different, especially in the islanded mode. This operation mode can affect directly the fault detection because of some sources (distributed generators) will provide current to the fault until their limits, but it can be lower than the fault current in non-islanded mode, when the fault current contribution level reaches the short circuit power of the grid. For this reason, using the same protection setting as the non-islanded mode, the IEDs will not detect the fault and it will not activate any of its over-current protections.

Therefore, in these cases where DERs are present, it is necessary to take in account the islanding mode detection [221] and the currents contribution of DER in the ring faults in order to establish appropriated protection settings. In the migration of the system to an isolated mode, several protections are enabled and others are disabled. As it was comment before, and shown in Figure 7.4, the ANSI 51/51N protection will be enabled in the IEDs feeders of each busbar where there is a DER, and the ANSI 67/67N protection will be enabled in the rest of IEDs.

Consequently, it will be necessary to know if these DERs are contributing to the fault level, and how it will be this contribution depending on the typology of the DER [222]. Also, the presence of each DER at the time of the fault can establish a different level of contribution in the current fault, and it can be different in each segment of the network.

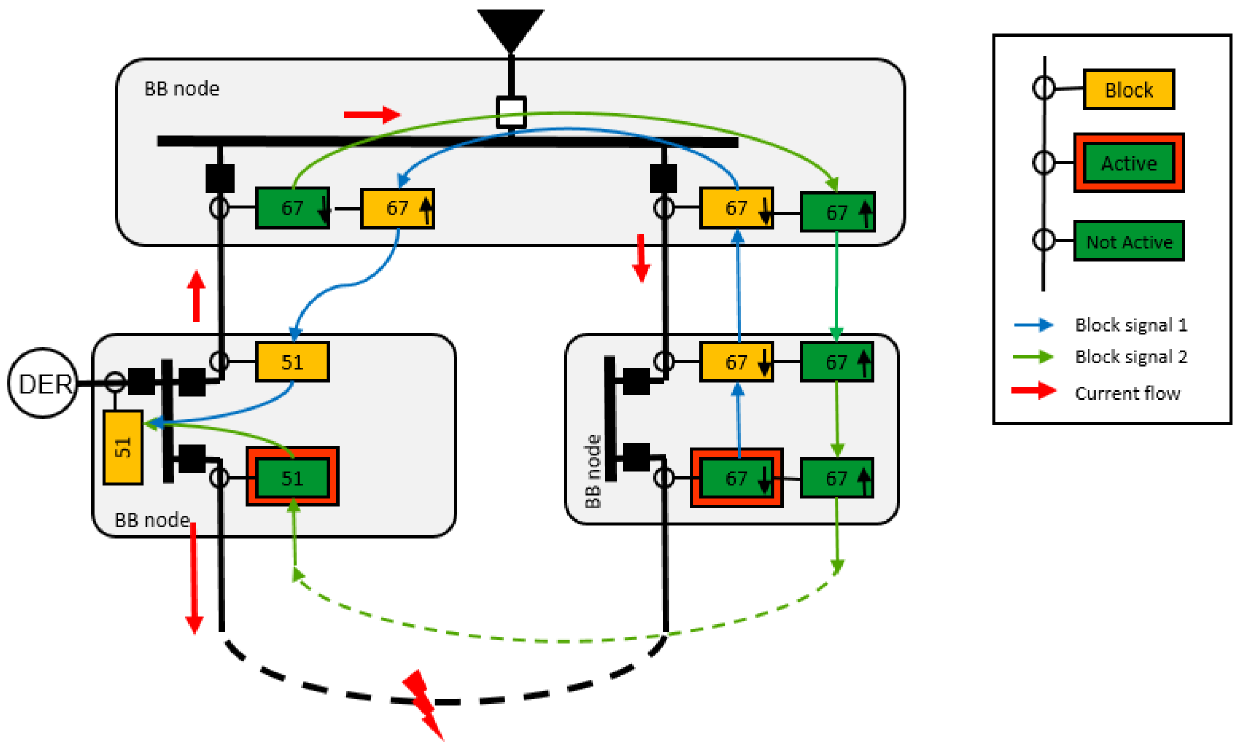


Figure 7.4 Electrical ring main system with DER in islanded mode

7.2.2 Implementation of adaptive protection through IEC 61850 GOOSE service

This section shows an example of how to implement the 67/67N protection using IEC 61850 GOOSE service communication. For this purpose, and as an example for facilitating its configuration, the Sepam S82 IED [223] from Schneider Electric is used, which integrate both protections, and his IEC 61850 integration tool.

However, it must be said that this section focuses on the IEC 61850 integration and does not cover the overall protection configuration. In order to define the parameters of these function protections it will be necessary to develop a discrimination study where the short circuits currents should be analysed such as in example [224], where several settings are defined according to different scenarios.

CET850 [225] is the IEC 61850 integration tool for Sepam protection relay of Schneider Electric. Figure 7.5 shows an extract of the data model of Sepam S82 where it is possible to define the IEC 61850 hierarchy and the Time Over Current Protection logical nodes for ANSI 67/67N protections (LN A67_PTOC and LN A67N_PTOC). The number 1 or 2 is referred to the two possible directions of the fault current. The Over Current protection trip condition logical node (LN PTRC1) contains the Block Indication 1 and 2 DO (BlkInd1 and BlkInd2) and its DA in order to implement the blocking signal in the application of the ring protection such how it was introduced above. Also, it is possible to see in the figure 7.5 the DO and DA of the protection operation.

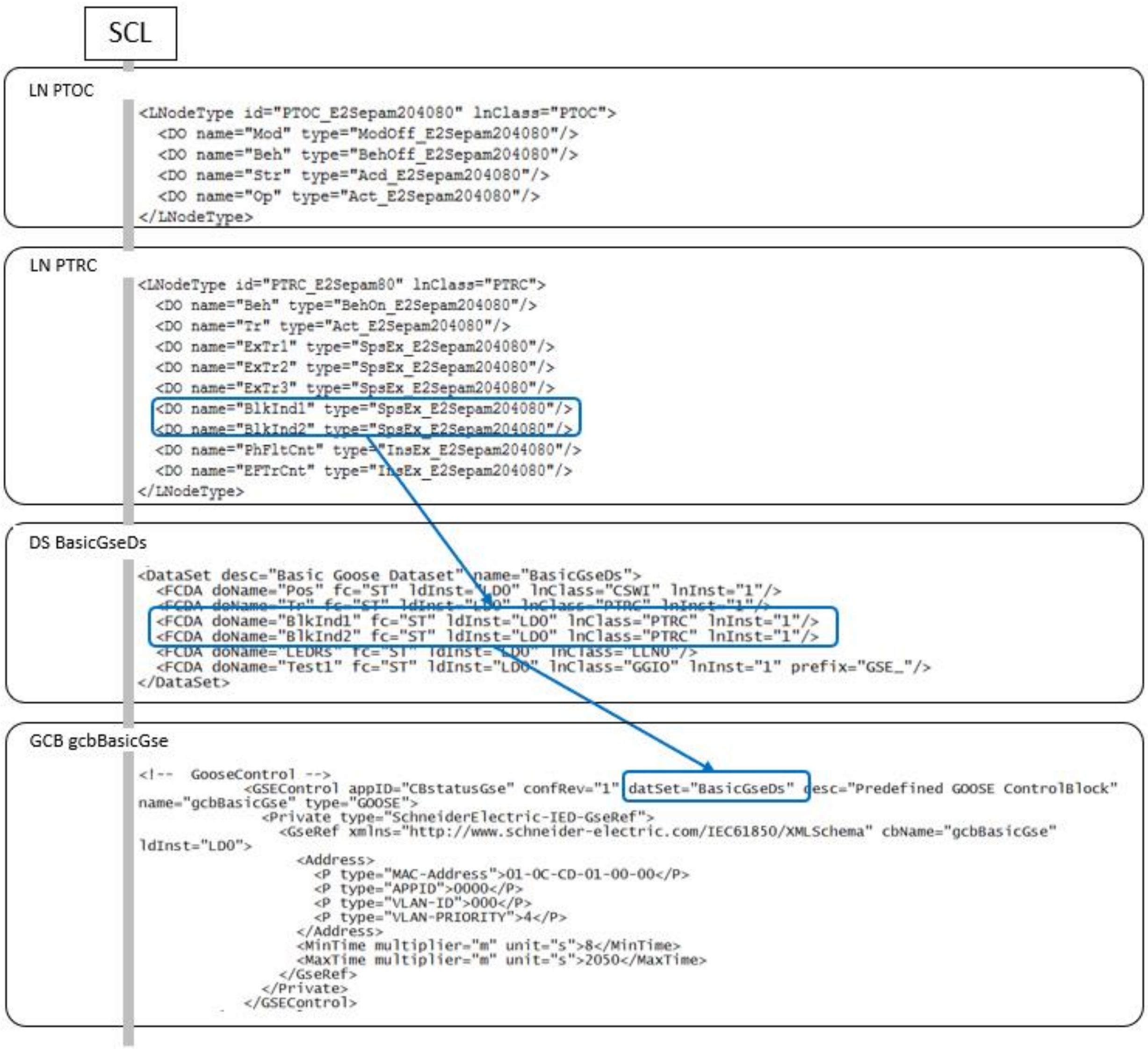


Figure 7.5 Sepam S82 implementation data model

The Over Current protection trip condition logical node (LN PTRC1) contains the Block Indication 1 and 2 DO (BlkInd1 and BlkInd2) and its DA in order to implement the blocking signal in the application of the ring protection such how it was introduced above. Also, the figure 7.5 shows both DO and DA in the IEC 61850 hierarchy.

In order to use the Block Indication information in any IEC 61850 service, it must be included in a DS. In Sepam S82 this DS is implemented and it is called BasicGseDs. The DS and how it is setting in the GCB are showed in figure 7.5. Also, in the GCB is possible to set the GOOSE ID, and the minimum and maximum times.

Once the ANSI 67/67N protection is implemented via GOOSE, it will be necessary the implementation of the algorithm that allows the correct protection of the ring main operation in the particular case where there are DERs as sources and the ring is operating in islanded mode as it was introduced before. There are many solutions but the proposal in this thesis follows a modular solution and an interoperable solution which allows different vendor devices to be part of this solution.

Regarding these ideas, the solution is focused in the use of the standard IEC 61850 and its ability to create distributed automation as a part of the new adaptive network protection needs. The proposal for the automation is to change the protection settings of the IEDs according to the ring operation mode and the number of the DER units connected to the ring at each moment. Therefore, parameters such islanded mode and DERs presence should be known at each bus bar node.

As mentioned previously, the DERs presence in the network will vary the fault level in island mode (also in network connected, but in this case, the variation is insignificant compared to the fault current contribution of the grid). Its means the settings for detection and trip will be modify according to it. Also, the DERs presence, change the electrical configuration of the system from the sources point of view, so it will be necessary to change from ANSI 67/67N to ANSI 50/51 and 50N/51N respectively.

Normally the protection settings of ANSI 67N and 51N have to be modified due to there is a change in earth neutral system when the system changes to island mode. The earth neutral system of the main grid can be different to the earth neutral system of the DERs. This change it will be independent on the number of connected DER in the system.

To carry out the adaptive network, the figure 7.6 proposes an algorithm to establish this real-time adaptive protection system. It is important to highlight the algorithm have to be implemented only in ring IEDs. The first part of the algorithm analyses if the system is in island mode and the type of the ring IED. This ring IED can be a part of a busbar node feed by source or not. After this first treatment, the algorithm decides which protections must be activated.

In order to apply this algorithm in a system it will be necessary to establish a discrimination study as explained before, to contemplate all the scenarios of the network and to establish in each moment the correct setting.

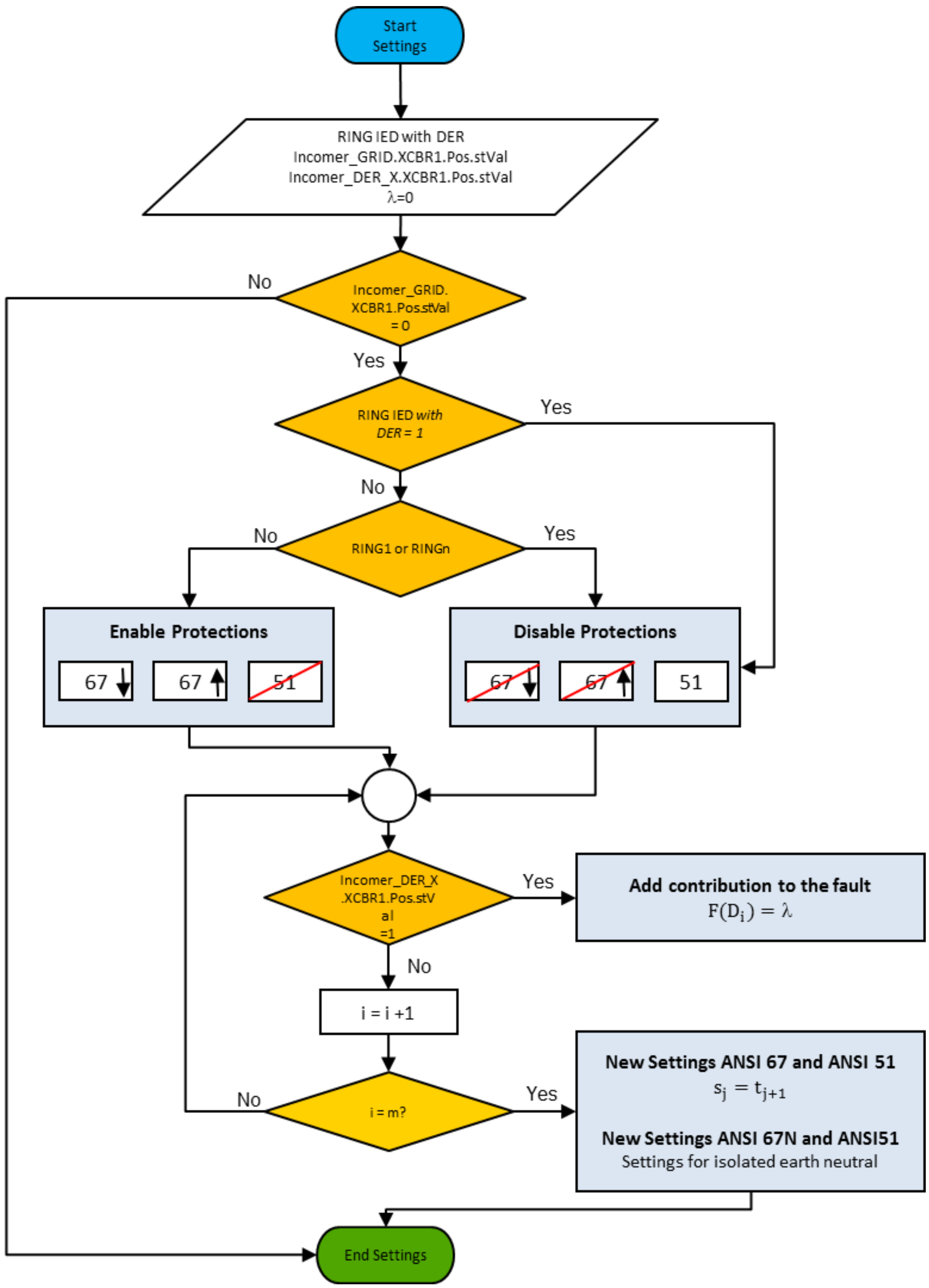


Figure 7.6 Adaptive protection real time algorithm

Once the protection configuration system has been decided it will be necessary to adapt the new protection settings. In order to do this adaptation, each connected DER to the system will contribute in different way to the fault level. So, these possible DER combinations are in following truth table 7.1, where λ is a $\mathbb{N}$ number which indicates a fault level in the ring and D_i is the value of the DA

Incomer_DER_X.XCBR1.Pos.stVal from each incomer DER. In fact, λ is the result of a function whose variables are the presence of each incomer DER as indicate equation 7.1. A low value of λ will indicate a low contribution fault, for this reason it is be important to sort the truth table according to DER combination in the system. Therefore, every combination has to be simulated to know the fault impact in the system in order to assign the correct value of λ.

$$F\ (D_1, D_2, \dots, D_m) = \ \lambda \in \{1, \dots, n\} \qquad [7.1]$$

$$i\ \in \{1, \dots, m\}$$

D_1	D_2	...	D_i	...	D_{m-1}	D_m	λ
0	0	...	0	...	0	0	0
1	0	...	0	...	0	0	1
0	1	...	0	...	0	0	2
...	...	...	...	...	...	...	...
1	1	...	1	...	1	1	n

Table 7.1 DER combination truth table

After assigning a contribution level λ λin each combination, the new settings can be selected in each IED. Due to possible limitations settings in each IED for protections ANSI 67 and ANSI 51 protections it will be necessary to establish some levels. The setting level s_j is defined according to Equation 7.2 where r_j is a parameter which establishes the difference between every level, t_j is the value of setting in [A] and p pis the number of settings to establish in each ANSI protections. The λ value obtained before will help to select the appropriate setting for each protection.

$$s_j = t_{j+1};\ r_j \leq \lambda < r_{j+1}$$

$$j\ \in \{1, \dots, p\} \qquad [7.2]$$

$$r_j\ \in \{0, \dots, g\}$$

To carry out the association of different $\lambda\lambda$ value and number of settings will be necessary to simulate the short-circuit capabilities for every DER combination. It is important to remark that the first protection setting will be t_2 in order to avoid a blank setting in the protection in the case that λ is 0 where the phase fault will be 0 due to there is not generation. In fact, $t_1\mathrm{t}_1$ is a blank value.

As mentioned before, there are different IEDs in each bus bar node such as ring, DER and main grid IEDs. The table 7.2 shows the data information associated in the DS which will be published through GOOSEs according to each IED. It does not only show the information necessary to modify the settings in each ring IED besides, also it shows the GOOSEs and the data for the blocking signal protection system explained before. In the example proposed in this thesis, the letter X represents what DER source is connected from in the incomer IED, or the position of the CB in the ring IED (used for the correct logic discrimination protection implementation).

IED	DATA SET	DATA	GOOSE
Incomer_GRID	DS_Island_Mode	Incomer_GRID.XCBR1.Pos.stVal	GRID_STATUS
Incomer_DER_X	DS_Connection	Incomer_DER_X.XCBR1.Pos.stVal	DER_STATUS
IED_X_RING	DS_Protection	IED_X_RING.PTRC.BlkInd1.stVal IED_X_RING.PTRC.BlkInd2.stVal	RING_PROTECTION

Table 7.2 DS information for each IED

Figure 7.7 shows a conceptual representation of the GOOSE messages that are published (Gp) by the different IEDs to the communication network and the subscription receivers (Gs) of these GOOSE messages by the other IEDs, in order to implement the automation algorithm.

The ring IEDs will subscribe to GOOSE messages in order to modify settings and besides execute the logic discrimination in the system protection. It is important to remark that the incomer GRID and incomer DER IEDs will only publish to GOOSE messages in island mode.

The GRID_STATUS GOOSE provides information to the other IEDs about the operating mode. On the other hand, DER_STATUS GOOSE provides the information about the presence of the incomer DER_X in the ring. This information will get to the Gs of each ring IED and it will change the protection configuration and settings.

Figure 7.8 shows a part of the GOOSE publication and subscription between several IEDs of the ring. In fact, the incomer IED publishes the status of its circuit breaker through a GOOSE in order to enable or disable the directional protection in ring IEDs 1 and 2. On the other hand, the DER incomers publish a

GOOSE message in order to modify the settings of several PTOC protections of ring IEDs mentioned before. Finally, the discrimination system protection is running properly thanks to the GOOSE service that publishes the blocking signal between ring IEDs and the DER incomers. Similar propositions like this is presented in [226] and in [227].

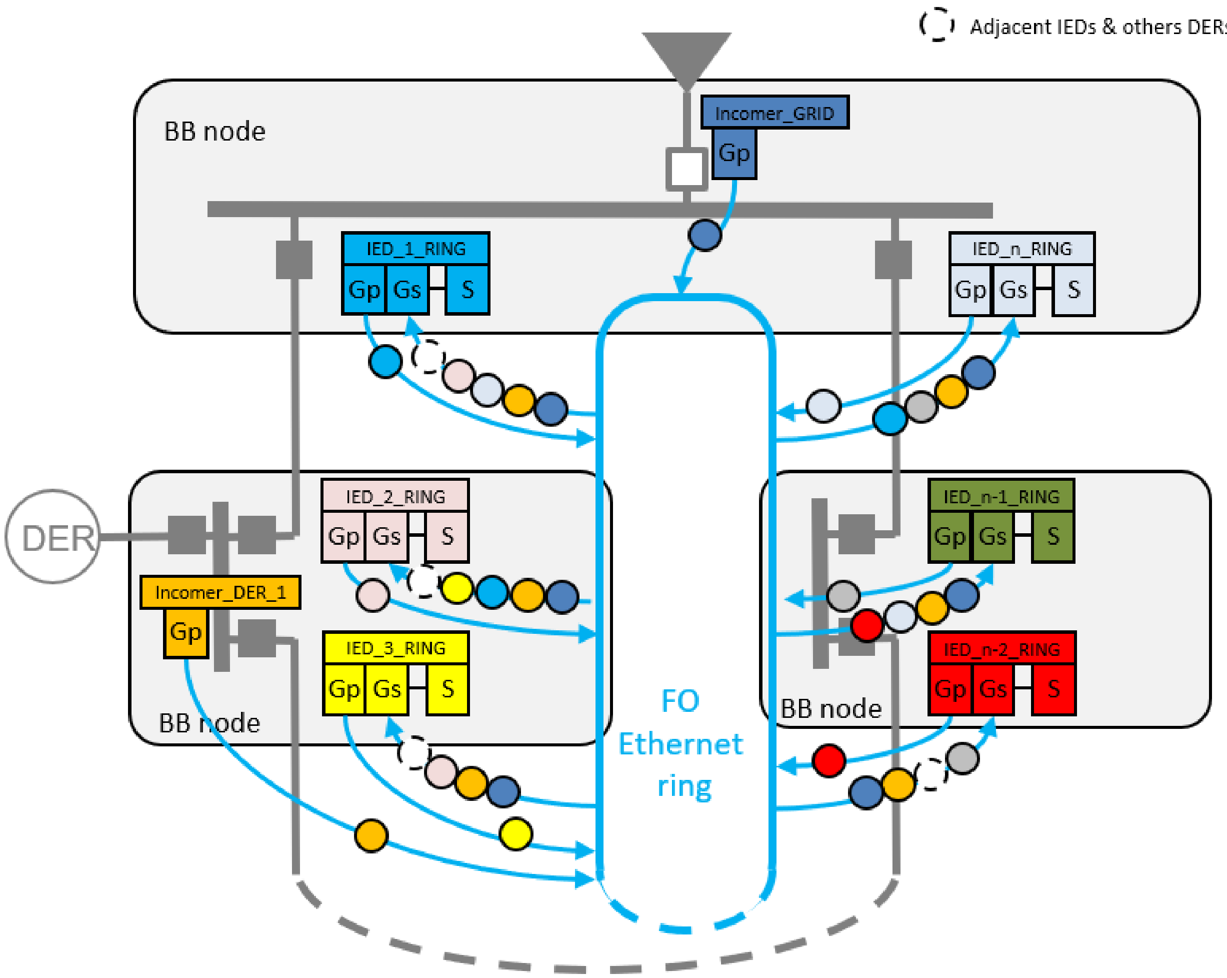
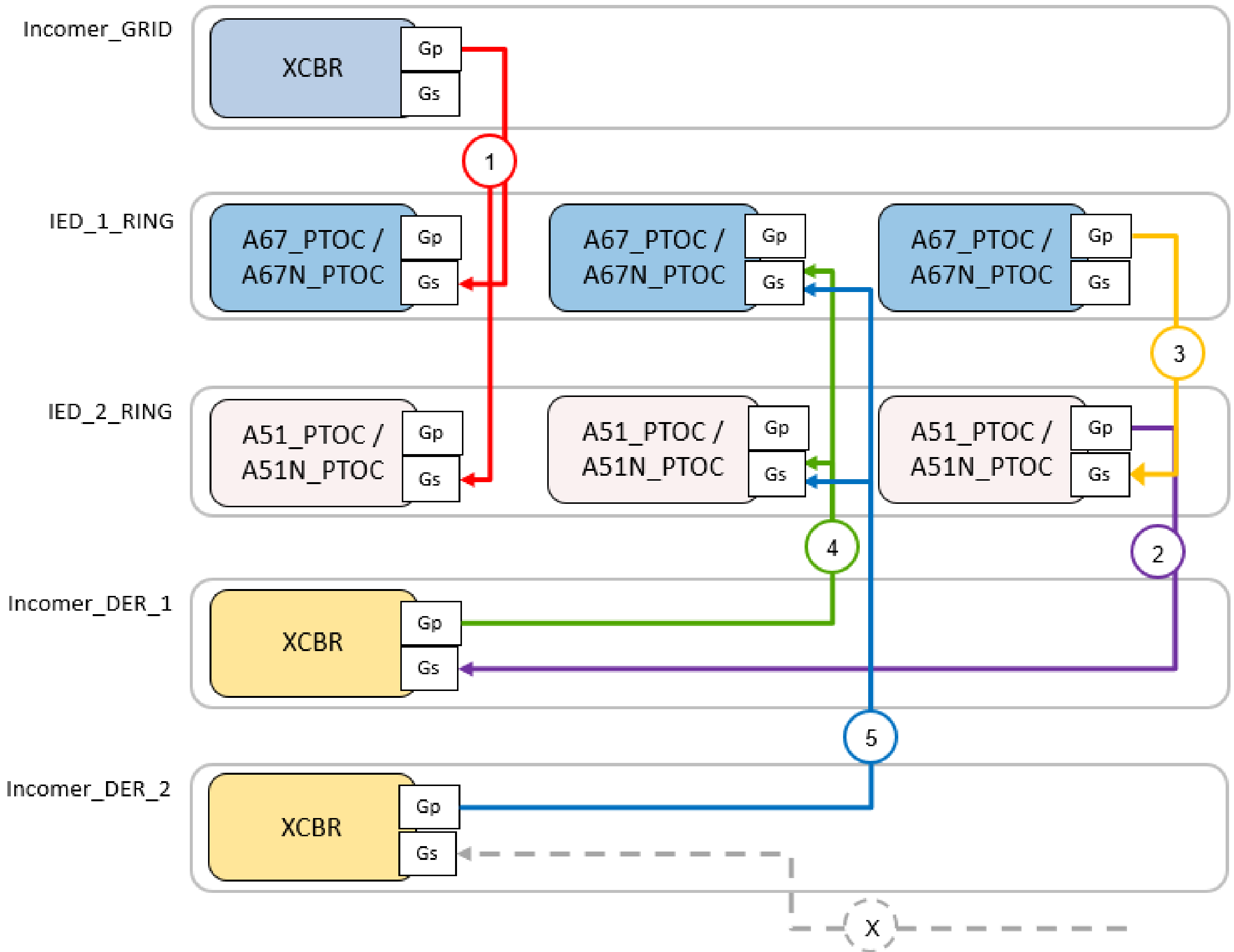


Figure 7.7 GOOSE flow in the communication network

It is important to remark the power of the GOOSE in order to establish a distributed automation between several distributed devices in an electrical distribution network. In fact, this is the main mission of the IEC 61850 regarding the automation of this kind of system. Although it is important to take into account that there is a limit due to the maximum number of publications and subscriptions of the GOOSE message, it will depend on the every each IED. Then, in order to define a system like this it is very important to analyse the capabilities of the IEDS which will define the installation. Not all devices have the same capabilities due to its digital inputs and outputs and also its electronic definition are different in each model.



GOOSE sequence:

1. (goID)GRID_STATUS	IED_GRID/LLN0GOGRID_STATUS	(DS)CBpos	(DA)XCBR1.Pos	= open
2. (goID)RING_PROT	IED_2_RING/LLN0GORING_PROT	(DS)BlockSignal	(DA)PTRC.BlkInd2	= active
3. (goID)RING_PROT	IED_1_RING/LLN0GORING_PROT	(DS)BlockSignal	(DA)PTRC.BlkInd2	= active
4. (goID)DER_STATUS	IED_DER_1/LLN0GODER_STATUS	(DS)CBpos	(DA)XCBR1.Pos	= close
5. (goID)DER_STATUS	IED_DER_2/LLN0GODER_STATUS	(DS)CBpos	(DA)XCBR1.Pos	= open
X. (goID)RING_PROT	IED_X_RING/LLN0GORING_PROT	(DS)BlockSignal	(DA)PTRC.BlkInd2	= active

Figure 7.8 GOOSE publication and subscription between several IEDs

A laboratory mock-up in the Schneider-Electric Spain Headquarters (Barcelona, Spain), shown in figure 7.9, emulates real client installations and was used in early states in other to design and validate the directional protection before its implementation in the field. This environment helped to identify the research need and proposed solution in ring main with DER, detecting incorrect fault detection issues in the emulation of real cases, in example: low fault current levels in the case of islanding operation of the ring main with DER. However, the results presented in document are mainly based on simulations for two reasons. First, is that due to privacy issues the data used in the laboratory coming from real scenarios had legal limitations. Second factor is that simulation method used for this section of the document can be reproduced by other researchers of the field and allows comparison with future improvements and the obtained results.

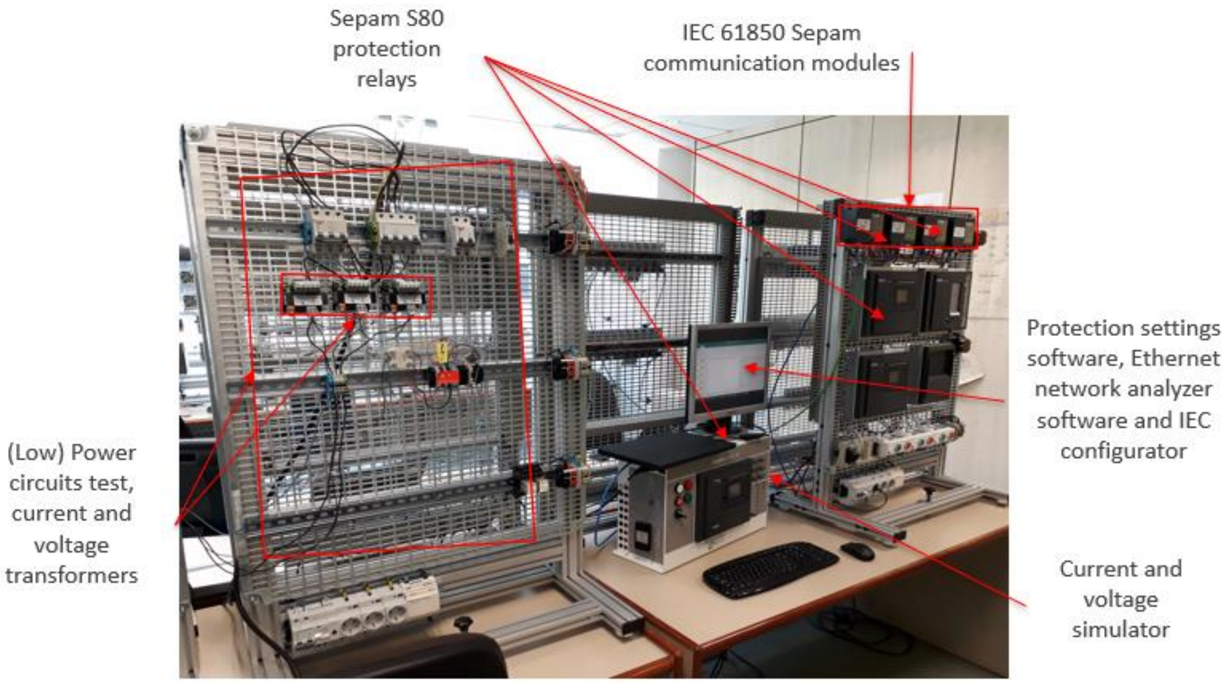


Figure 7.9 Laboratory mock-up, courtesy of Schneider Electric

This mock-up has been prepared for other projects and solutions in order to test an application before to launch to market or to install in a real installation. This platform is evolving continuously and adapting news devices from different manufacturers in order to test interoperable solutions.

As it has been told before the mock-up has an important property due is working in order to test protocols such as MODBUS TCP/IP with other PLC platforms. In this laboratory there is an ETHERNET network in FO in order to work properly in IEC 61850 simultaneously due to the AEDs. It is an important point because it will be possible to establish a good scalability in the mock-up to connect new devices. In the mock-up there are several AEDs in order to simulate different faults. This behaviour can be controlled by injection demo cases or other devices to simulate these faults.

As mentioned before the IEC 61850 can admit other devices in this standard to integrate new functionalities. An example of it is presented in figure 7.10 where an INGETEAM and VAMP devices are integrated in the mock-up. These devices have been developed from different research centres and the interoperability using GOOSE service has been totally, this is an important point in order to promote and use IEC 61850 as an automation reference for electrical distribution networks.

Figure 7.10 Interoperability between devices, courtesy of Schneider Electric

This platform is located in Schneider Electric Spain Headquarters in Barcelona as indicated before, although it is a mobile mock-up to show in events or in order to integrate in real platform in order to test as the figure 7.11 shows.

Figure 7.11 Mobile mock-up, courtesy of Schneider Electric

It is necessary to highlight that the adaptive protection system and its automation presented in this application is developed in the station level of the installation and the communication between IEDs (horizontal communication). It means that the protective system is a decentralized logic (islanded from the design) system, which is independent from superior logical entities or control centres. It works autonomously between the IEDs defined for that target, regardless of the electrical power configuration. When the number of IED participating in the protection system and the algorithm are defined, the different cases of islanding are studied and it is determined the finite number of scenarios taking into account in the implementation of the solution. In addition, it is necessary to add that the target of this part of this thesis is to study the microgrids, where the distribution system is based in ring main. The protections and settings used in the test have been extracted from a real critical protection installation. A short-circuit discrimination study has been done for this end-user installation.

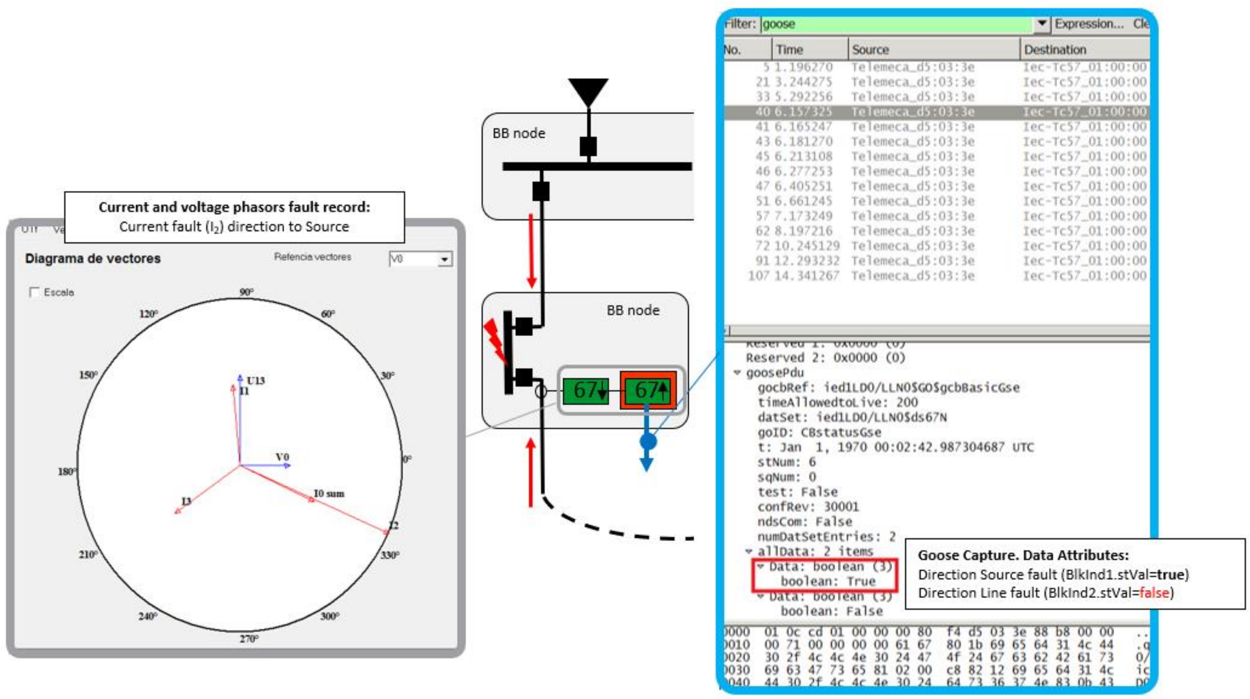


Figure 7.12 Line direction phase fault

Moreover, the protective system is based in an Ethernet communication network. It means that it is necessary to consider, as in every Ethernet implementation in the industrial environment in a critical power system, the redundancy and back-up power supply for all the devices of the system (IEDs, CB motor supply, switches, and others control and protection equipment) to ensure the reliability of the system. Ethernet redundancy protocols are also used in order to avoid the failures in the communication network. As mentioned before it is possible to find several redundancy protocols such as Rapid Spanning Tree

Protocol (RSTP), PRP and HSRP. Thus, to fully understand the application of the ANSI 67/67N using GOOSE service several tests were realized and results are shown as follows. Figure 7.12 shows a simulation of a phase fault in the phase 2 of a power system. The tested Sepam senses the fault current direction to line and it sends to the opposite direction the blocking indication 1 (BlkInd1) to block the action of adjacent IED. After the setting time, the CB associate in order to isolate the fault relays opened. By means of an Ethernet conventional network analyser software, it was captured that the blocking indication 1 (BlkInd1) is activated and it triggers a set of GOOSE.

Figure 7.13 shows the same phase fault but in this case the tested Sepam senses the fault's current direction to source. Now, it sends to the opposite direction a blocking indication 2 (BlkInd2) to block the action of the adjacent IED.

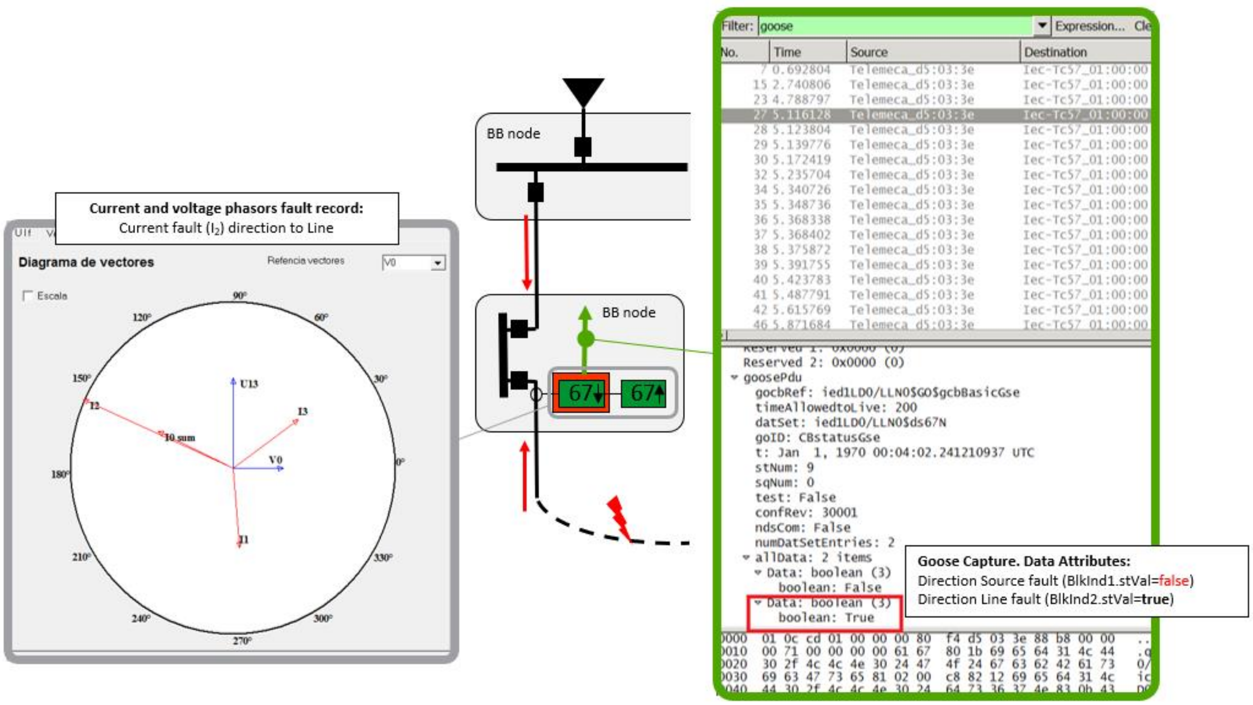


Figure 7.13 Source direction phase fault

Also, after the setting time, Sepam opened the CB fault. This time, the Ethernet network analyser capture shows that it is activated the blocking indication 2 (BlkInd2) and it triggers another set of GOOSEs, while the blocking indication 1 keeps false. In addition, it was checked that both block indications return to the inactive state after blocking time of its activation. It allows that in case the CB down is not operating, the next one is ready to trip after this time. Figure 7.14 shows the sequence in the case of CB (CB2) open failure and the action of the adjacent CB (CB1), according to IED algorithm in [228].

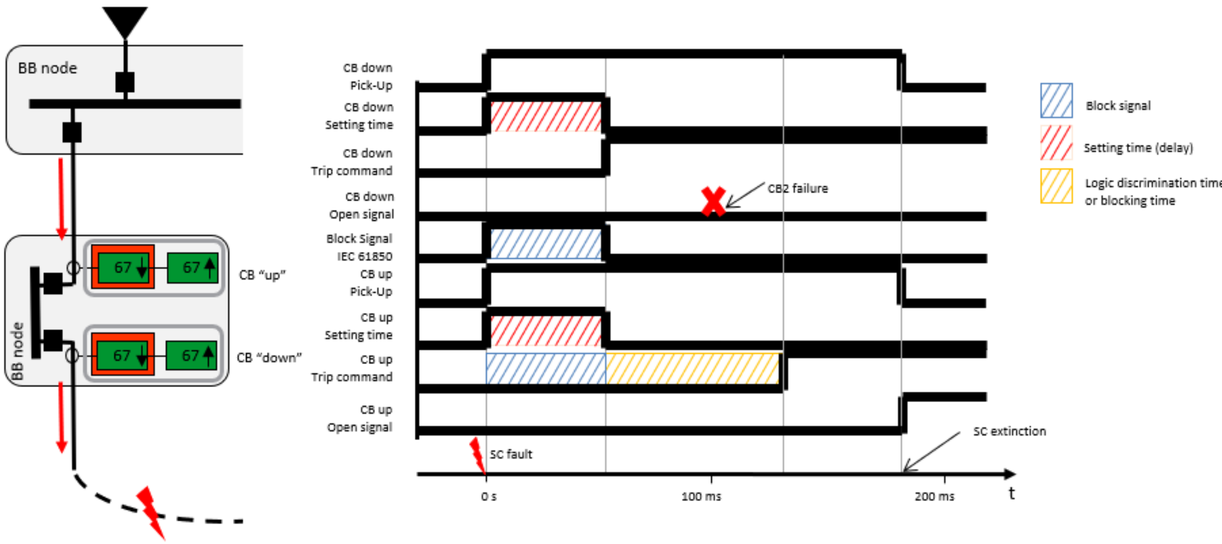


Figure 7.14 CB failure in ring main distribution system

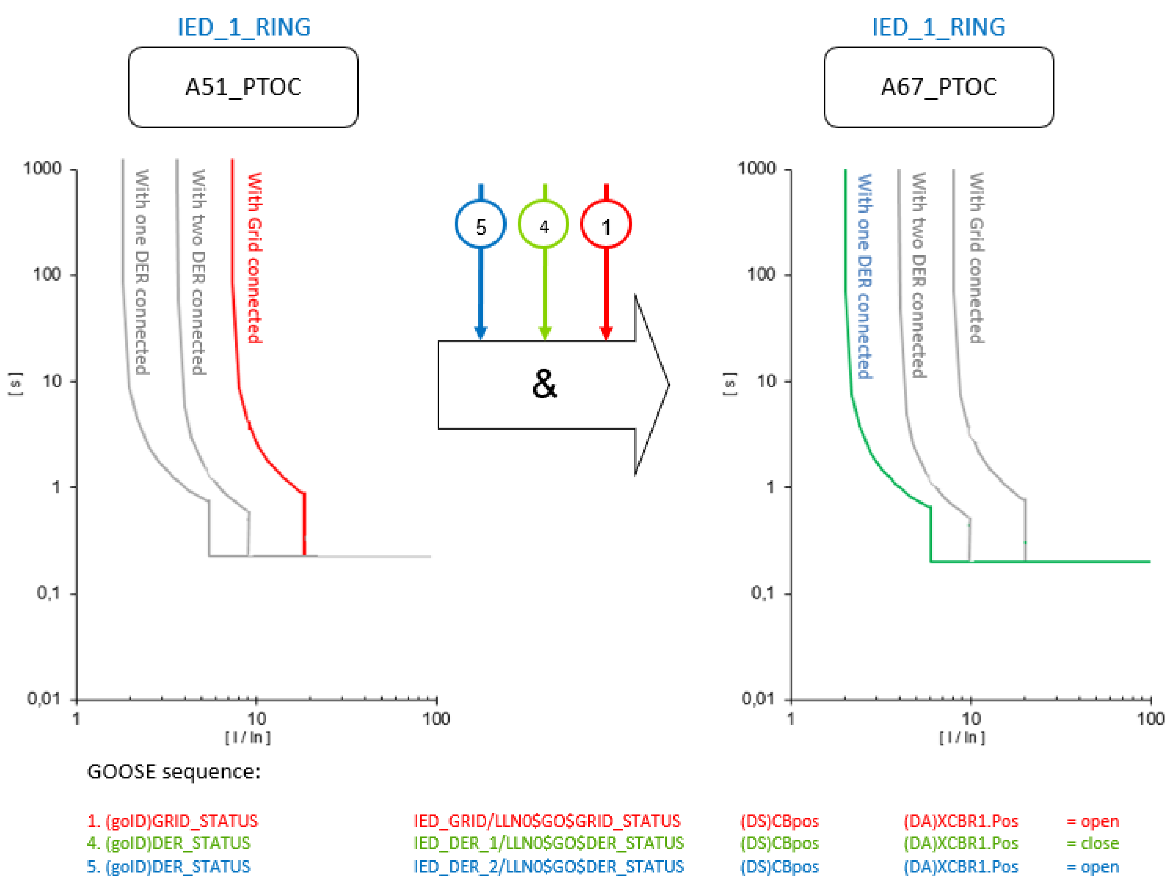


Figure 7.15 Change of protection setting after GOOSE messages reception

In this example, the status of the circuit breaker of the Incomer Grid is opened and then the network is on islanding mode, being the DER 1 connected to the network and DER 2 is disconnected. Therefore, this status provides a change in overcurrent level ANSI 51 from 400A to 100A and in short circuit level ANSI 50 from 1000A to 300A. It is necessary to remark that the kind of protection has also changed from directional protection ANSI 67. Obviously, another kind of protection have been implemented, such as voltage protection ANSI 27 or frequency protection ANSI 81, but it has not been linked with this algorithm. The values have been extracted from real end user installation where the algorithm has been implemented although for reasons of confidentiality is not possible to mention the name of this installation.

As mentioned before, the process explained before has been implemented in a real end user installation where more than 80 IEDs are connected in an Ethernet communication network using the standard IEC 61850. Specifically, 20 of these IEDs are using the GOOSE service in order to establish the exposed protection system before. It is important to remark that this algorithm could be extended to microgrid networks where it is necessary to define an adaptation protective system such as [229].

7.3 Restoration procedures

The restoration in an electrical network is not a simple neither immediate process, because it is necessary to know the current status before to do the restoration. Therefore, in front of fast network restoration it is important to do a previous communication validation in order to launch the restoration automatisms.

In this automated procedure it is important that the control can be taken by the operator system [230]. The figure 7.16 shows a diagram which defines the verification in real time. The real time concept can be take different time intervals but normally it is possible considerer the interval around 1 to 12 seconds in order to do these operations.

In figure 7.16 there is a step where there is the decision about an automatic restoration. After this point the possible events are communicated to the operator. When the restoration is not automatic; the ADMS would offer a set of suggestions in order to restore the network comfortably and in the shortest possible time [231].

Whether restoration procedure is centralized or decentralized the operator system has to receive suggestions from the ADMS. These suggestions have the goal to help to the operator about the past or future events during process. Although this kind of automation is disappearing due to the control systems are doing some of these operations without human supervision. Maybe in a future the re-configuration of the electrical networks will do as an autonomous task due to the evolution of intelligence in computational systems.

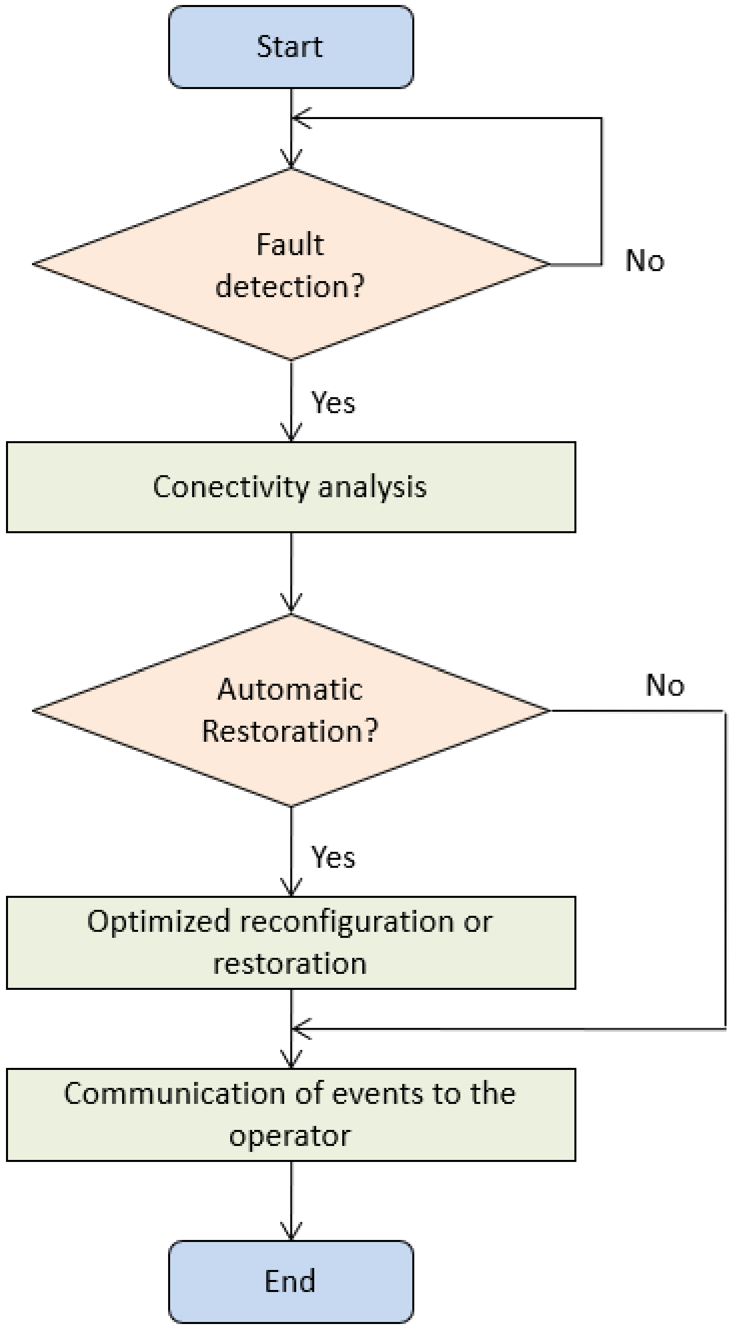


Figure 7.16 Connectivity algorithm in real time

7.3.1 Centralized restoration in the ADMS

As mentioned before the ADMS is a high system which can include different applications. In fact, the DMS should to include an application about the restoration after fault analysis in combination with SCADA. The figure 7.17 shows the general diagram about ADMS architecture in order to establish a restoration according to [212].

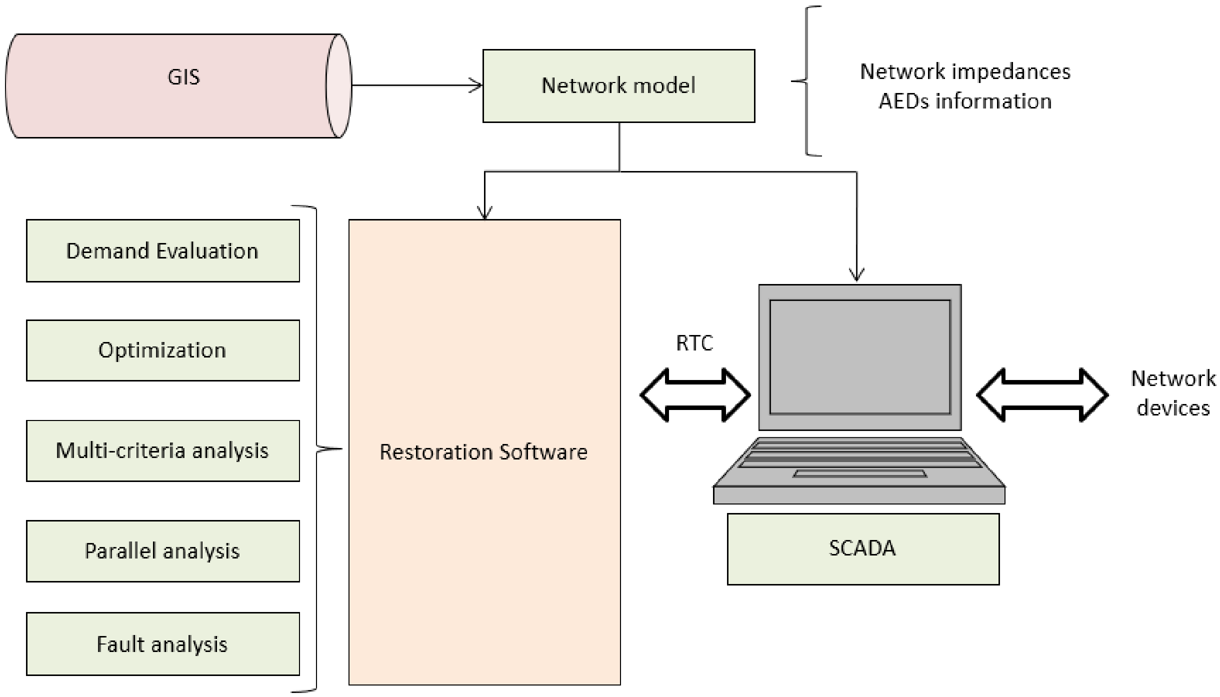


Figure 7.17 ADMS architecture for automatic restoration

The centralized restoration in an ADMS establishes different criterion to avoid problems during the process. This architecture is very similar to the figure 5.12 although without restoration process. Previous to restoration process there are other analyses such as parallel in order to determinate the system reliability and to enable the possible changes. On the other hand, the multi-criteria analysis which establishes an analysis about possible ways, in other words, in the case with more than one option to restore the system this analysis is in charge to select the most economic and safety way.

7.3.1.1 Optimization methodology

The optimization methodology is a network restoration to establish optimum services conditions. This process is not applicable after a fault due to the restrictions will be conditioned by the location of the fault.

The proposed methodology is based in [232] and takes into account DERs in the network. This methodology is based in one first step which evaluates the demand after that the distributed generation profile and finally proposes a restoration process. The steps of the process are showed following.

- **Demand evaluation**. The first step determines when a change it is necessary in the current configuration. This situation avoids changes with a little optimization. The used strategy in this methodology is based in current demand, although it can use the future forecasts.

- **Distributed generation profile**. At moment to establish a network restoration it is necessary to take into account the connected generations. It is important to confirm if the generation could to assume the demand in the network.

- **Reconfiguration heuristic technique**. This technique uses the potential of DERs. The optimization function is based in the minimization of SAIFI and ASIFI index and the lost energy which receive a specific weight. The method in order to determinate the weight criteria will be defined by Analytic Hierarchic Process (AHP). It is important to highlight that this optimize function is defined by restraint of current, voltage and power in order to keep a network stability.

The reconfiguration process is divided in two modules; one of them will analyse the connections between feeders without distributed generations. In this case is interesting to work with ring open due to the voltage level in each feeder can be different, although both feeders are in the same substations the transformers can be different.

This methodology has been experimented according to [232] in a network with five feeders in two substations, three generation power plants: hydraulic, photovoltaic and wind, and a total of twelve mobile links between feeders.

7.3.1.2 Restoration methodology after a fault

Previously a methodology to optimize the consumption in the network has been showed although in the case of a fault it will be necessary to establish another kind of methodology. This process will start after the fault detection.

According to [231] after a fault, all switch-disconnectors will be open in the de-energized area. These switch-disconnectors will be connected at least to one feeder of the energized area. After this moment it will be necessary to establish a calculus in the restoration algorithm to evaluate the switch-disconnectors which will isolate the fault. In a second process it will establish a list with switch-disconnectors without telecontrol in order to improve after by means of a patrol the isolation.

The goal of this restoration consists in to establish a way between the energized and de-energized area. Therefore, it will search a point between areas in order to link them with a path. The method is to simulate all the switch-disconnectors in close mode and then those which have an energized part and other de-energized will be the limits. After that it is possible to establish a path between these switch-disconnectors.

According to [231] it is interesting to include in the path some circuit breaker in order to restore the network with load if it is necessary.

7.3.2 Decentralized restoration with field devices

A centralized restoration through ADMS has been presented before. This kind of solution provides a fast answer although it is possible to reach a much faster fault location and restoration. The decentralized automation can provide solutions in order to improve the quality system with technology such as BPLC and IEC 61850. There are propositions such as [129] where the GOOSE service is used in order to restore the network. The combination of these technologies in order to reach a good FLISR is known as self-healing.

7.3.2.1 Self-healing system for distribution network

A self-healing algorithm has the goal to establish a link between adjacent devices from a feeder or a ring [8]. The information about the fault location will flow between devices and after that the restoration orders too, establishing a distributed intelligence. Likewise, this information will transfer at the same time to the ADMS [129]**.**

In order to develop this type of algorithms it is possible to use two technologies: BPLC and IEC 61850. The first one is related with physical medium. This technology can operate in high frequency from 2 to 7 MHz or from 8 to 18 MHz [12] through the power wire reaching a latency of 10 [ms] between devices. The important point is that it is independent is there is energy on the network or not, the carrier wave flow between devices in high frequency.

The second technology is the standard IEC 61850, this standard has been thought to do automation and communication at the same time. As mentioned before the standard was created by international committee TC57 from IEC in the 90s although from working group 10 the standard has been modified in order to adapt to other electrical sector applications [234]**.** As mentioned before this standard can provide to the automation multiple possibilities with its GOOSE message. These messages are being sent always in a period of time, when an event appears the message will be sent very quickly in a blast with exponential distribution. The standard guarantees the need reliability to send to other devices in a few periods of time. The combination of this standard with BPLC can help to reduce the operation time in a centralized automation system. In this case the information will flow between devices.

The communication architecture for a self-healing is showed in the figure 7.18 in a MV-LV substation. It is important to highlight that this architecture will be valid also for each network node such as MV-LV substation, overhead switch-disconnectors or any element which can change the flow of Energy [129]**.** The architecture of each node is composed by AED with directional protection ANSI 67/67N and current and voltage transformers due to the presence of distributed generation. Besides there is a BPLC communication with sensors and gateways. On the other hand, it is possible to find a modem GPRS, ADSL, etc.; in order to communicate with ADMS in protocols such as IEC 104 or IEC 101. It is important to establish an intermediate element such as switch to send the information in both ways, to ADMS and between AEDs.

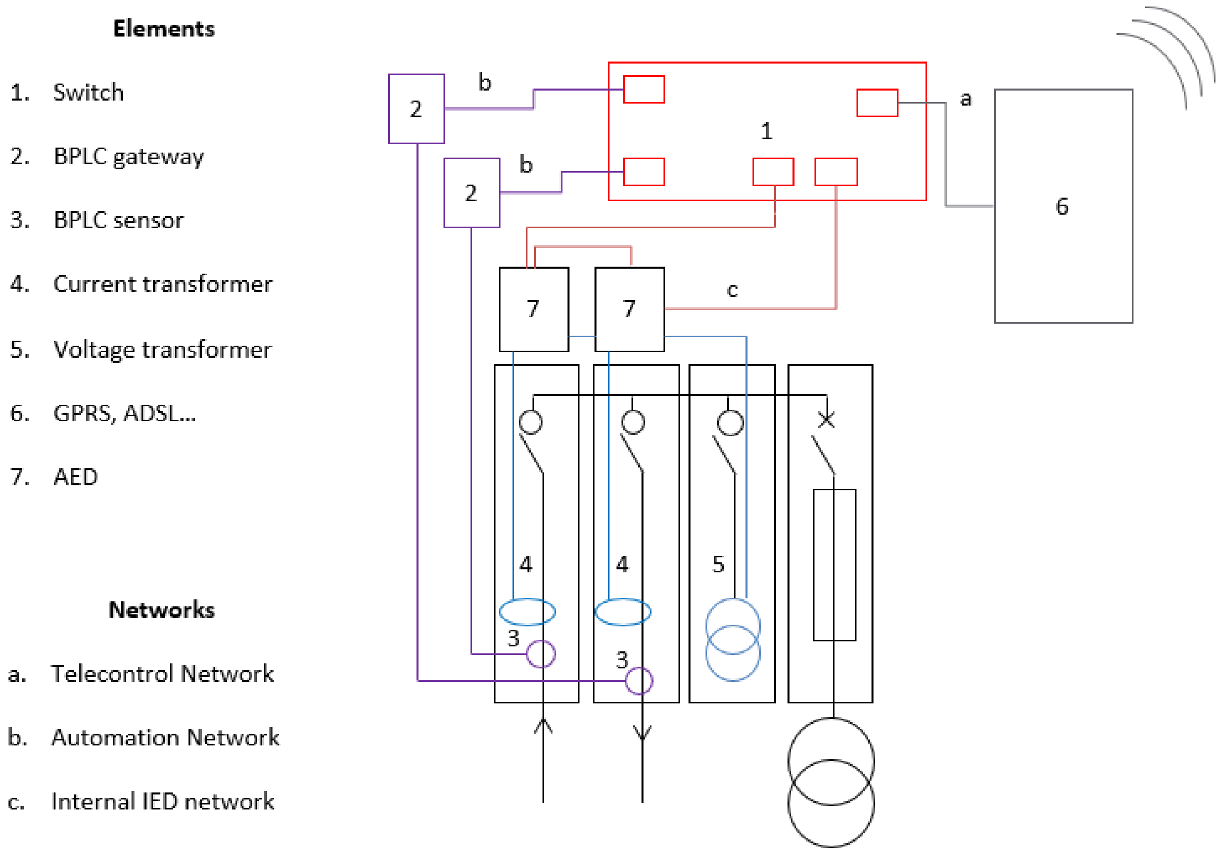


Figure 7.18 Communication architecture in a network node

7.3.2.2 Self-healing algorithm description

After the system description, in order to establish a self-healing in an electrical distribution network it will be necessary that in the moment of fault each node knows the direction and distance to the defect. The first information will be used to send a notification to the adjacent nodes with the goal to start the procedure. The second information is important for ADMS in order to determinate the exact fault position in the network. Each node has an input and an output, although these inputs or outputs can change to other ways or another feeder due to a restoration system. In the figure 5.29 there are different nodes which can establish a ring although they can link with others from others rings. The figure also shows the structure of one node where there are the cutting elements.

The signs which represent the fault passage by input and by output. The criterion has established a sign positive in the input and a sign negative in the output, in fact positive in clockwise and negative in counter clockwise. The equation 7.3 shows the algorithm f in order to detect if a fault has passed in each node, according to[129], this is a first version of the AFL algorithm.

$$f(\lambda_{i,j}, \mu_{i,j}, \varepsilon_{i,j}, \delta_{i,j}) = \left[\frac{\sum_{j=1}^{n} \lambda_{i,j} \cdot j \cdot \mu_{i,j}}{\left(\sum_{j=1}^{n} j \cdot \varepsilon_{i,j}\right) - 2}\right] \cdot (\delta_{i,o} \quad \dots \quad \delta_{i,n}) \cdot \begin{pmatrix} \varepsilon_{i,0} \\ \vdots \\ \varepsilon_{i,n} \end{pmatrix} \qquad [7.3]$$

Where λ_{ij} is the distance to the fault which is provided by ANSI 21FL from the cutting element (AED) j from node i. This variable is expressed in km.

$\mu_{i,j}$ is the fault detection sign of the cutting element j from node i. The possible values for this variable, 0, if the AED does not active, 1 or -1 according to the direction of the fault.

$\varepsilon_{i,j}$ is the status of the fault of the cutting element j from the node i. The value of this variable is 0 or 1.

$\delta_{i,j}$ is the cutting element j from the node i. This parameter identifies an output or an input from a node.

This algorithm has to be implemented in AED devices from each node. In fact, these devices can exchange information through IEC 61850 because both are in an internal network inside the node although there will be nodes with one AED.

After this detection with distributed intelligence, a procedure to restore the network will start. Therefore, it is possible to consider a network with m nodes with n cutting elements each of them in ring architecture. After a fault the intelligent cutting element δ_k from node n_i which knows the direction of fault will send a GOOSE message to the node n_{i+1} which will be connected with the cutting element δ_j through the cutting element δ_k from the node n_i. The information will be the activation of the fault and the type of the fault, earth or phases. Besides another GOOSE will be send to the cutting element δ_k from node n_{i-1} which communicate with noden_i through the cutting element δ_j.

Finally, when the cutting element δ_j from node n_{i+1} receives the GOOSE message and detect an activation of fault through cutting element δ_k and does not receive any GOOSE from cutting element δ_j from node n_{i+2}, then the fault will between n_{i+1} and n_{i+2}.

After fault detection the node n_{i+1} will start the restoration process operating over the cutting element δ_k. After the node n_{i+1} reports to n_{i+2} the opening and it will operate over the cutting element δ_j. The node n_{i+2} will send a message in order to restore through the rest of the nodes until to arrive to n_{i+m} where there is an opened cutting element δ_p to connect to another available network.

Entire restoration must be done without voltage in order to follow the automatic procedure from ADMS with safety. Previous to this restoration the cutting elements must wait to the possible reclosing from substations. On the other hand, it is possible to use this kind of automatism to adapt among reclosing in the moment of the fault.

Finally, the table 7.3 shows the procedure to isolate the fault in a point of the network. After this first step the procedure to restore the network using the IEC 61850 standard with GOOSE messages is showed in table 7.4.

Node	Detected Fault?	Cutting Elements	Direction	GOOSE fault node	Operation
...	...	...	...	...	...
n_{i-1}	Yes	δ_j & δ_k	+	n_{i-2} & n_i	No
n_i	Yes	δ_j & δ_k	+	n_{i-1} & n_{i+1}	No
n_{i+1}	Yes	δ_j & δ_k	+	n_i & n_{i+2}	No
...	...	...	...	...	...
n_{i+m-1}	Yes	δ_j & δ_k	+	n_{i+m-2} & n_{i+m}	Opening δ_k
n_{i+m}	No	0	0	n_{i+m-1}	Opening δ_j

Table 7.3 Fault and isolation detection

Node	Available cutting elements	Reception restoration GOOSE	Emission restoration GOOSE	Operation
...	...	...	...	...
n_{i+m}	δ_j	No	Yes	No
n_{i+m+1}	δ_j & δ_k	Yes	Yes	No
...	...	...	...	...
n_{i+m+n}	δ_j	Yes	No	δ_p

Table 7.4 Restoration procedure through nodes

8. Conclusions, contributions and future research

8.1 Conclusions

This doctoral thesis has tried to collect information about the fault location and automatic restoration in order to develop some contribution in this area. As mentioned before the quality is one of the priorities in the electrical networks therefore any improvement in fault location can enhance its power quality.

The problem formulation of the power quality has been analysed in this document when a fault appears in the network. A not located fault in the network can contribute in a significant increase of the SAIDI or SAIFI indices, in the Spanish case the relevant indices are TIEPI and NIEPI. This situation is a clear reduction of network power quality. Therefore, a fast isolation and location of the fault is a key point to keep a good level of quality in the network.

In order to enhance the current system there is the possibility to introduce DFPIs devices in distribution overhead and underground networks to find information about the passage of the fault. It is important to take into account the new communication standards presents in IoT world which can help to deploy sensors in the network with a not expensive cost.

In fact, the combination of a fault locator with a fast restoration can reduce considerably the outage time for the user. Although it is important to remember that the quality has three important features: wave quality, commercial quality and availability, the last one is the most important due to it is necessary in order to evaluate the others.

The fault location is implementing nowadays using the artificial neural network. This is important tool for search a good definition model of the network, although sometimes it is possible to complete this model through the traditional methods based in the information from field devices. Probably a combination of different tools can provide a good solution.

On the other hand, the restoration network is reaching a lot of importance in order to improve the quality network. This quick restoration is focusing in self-healing because an automation process in a low network level can contribute in fast restoration. For this reason, protocols such as IEC 61850 and physical mediums such as 4G, 5G or BPLC can contribute in a fast coordination between devices which take decisions regarding the information of the rest.

The fast development of the Smart Grid over the current network has been contributed to test and implement new communication techniques. Probably the trend to enhance the FLISR will consist in the gathering of fault location techniques and new communication developments as a unique element. In near future there will not a clear trend in network automation nevertheless there is an idea which has taken relevance: "Establish a high system control to supervise the network and a low system control among the AEDs to restore the network". Although this situation is not only applicable to electrical distribution networks if not also in industrial world.

8.2 Thesis contribution

This thesis has contributed lightly in three main important points as mentioned below.

- AFL algorithm to detect earth and phase faults in electrical distribution networks with DERs for any topology such as radial, ring or mesh with any status of the switch-disconnectors.
- An adaptive algorithm to change settings in ring systems in front of different scenarios with DERs by means of GOOSE service from IEC 61850.
- A self-healing restoration procedure for electrical distribution networks through IEC 61850 using GOOSE service.

The AFL algorithm detects the section and the approximately position within it when a phase and earth fault appears in a distribution meshed network with DERs. This algorithm has been evaluated in platforms such as EXCEL and MATLAB using the matrix systems and establishing a network with a main generation and several DERs.

AFL algorithm can help to the utility or end user installations to detect a fault with current technology as DFPIs which are used in common real installations and functions ANSI such as 21FL. Therefore, the implementation of this algorithm it is not suppose an expensive cost to implement in high control system in the utility or end user installation.

Through the second algorithm has been introduced the detection basics of ANSI 67/67N protection and its use in a ring main system based on automatic circuit breakers. It is combined with the implementation of GOOSE service in ANSI 67/67N and adaptive protection solution was designed, detailing its configuration settings and testing and validating its deployment in different cases.

For this purpose, laboratory tests and real installations emulation were deployed. In those tests all the system design and configuration details were specified in order to help to understand how IEC 61850 GOOSE service can be configured to simplify the integration with electric protection systems and provide more flexible and adaptive solutions. Moreover, a control algorithm is defined showing how to set the blocking indication DAs triggers in GOOSEs in order to implement the directional blocking signals in the IEDs of the system. In summary, the obtained results in the simulation of the proposed solution show the benefits of using IEC 61850 instead of the hard-wired network connections in terms of the cost of the infrastructure, outage time reduction and the system flexibility, and the thesis validates and evaluates a use case example of the IEC 61850 GOOSE service for facilitating an adaptive 67/67N protection configuration.

Finally, last contribution is the restoration process. The self-healing automatism can provide a distributed intelligence detecting faults and restoring the network. The combination of technologies such as BPLC and GOOSE service from IEC 61850 can enhance the restoration time considerably. This procedure has to be implemented in several IEDs of the network out of the ADMS of the electrical network, this fact provides a new autonomy of the network avoiding a centralized control.

The GOOSE latency between nodes in the network is very low. Thanks to this time all nodes know the status of their adjacent then it is possible to make the network restoration in a safe and automatic way. This algorithm has been exemplified for electrical distribution networks although these networks can be presents in networks for airports, large factories, hospitals…, in fact, in large end users.

8.3 Future research

As a future research of the contributions of this thesis may be the following.

- Implementing the algorithm AFL to detect earth and phase fault in a real scenario. In this case it is possible to enhance the IEC 61850 definition for DFPI in order to implement the algorithm in IEC 61850 systems or use LPWANs for overhead DPFIs.
- Another research line could be to establish an analysis to study the contribution quantitatively of this algorithm. Also, the current algorithm could use the field information from DFPI only but it can be combined with other systems such as GIS or other systems.
- Regarding the adaptive algorithm although the use case is specific for this scenario, this research continues the study and analysis of the data transmission possibilities for building up novel communication paradigms and architectures in the Smart Grid.
- Another possibility could be to continue the AFL and adaptive algorithm for applications in WAN instead of LAN using R-GOOSE and R-SV for Wide Area Monitoring Protection and Control (WAMPAC) systems. Even to study the usage of these algorithms with IoT communications such as LoRa, Sifgox or NB-IoT in order to analyse the viability of it for rural and overhead networks where establish a communication is difficult.

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Appendix A. Publications and academic curriculum vitae

This appendix presents several publications related to the specific topics of this thesis where the author has contributed to such as journal papers, conferences, articles in technical magazines and even papers under development. Additionally, there have had points which have contributed indirectly in this thesis such as meetings and contributions in technical committees and project following in several universities as well as presentations in several gatherings, participation in exhibition congresses and training courses where is indicated the duration of participation related with the topic of this thesis.

A.1 Papers

A.1.1 Journal paper

- Silos, A.; Señis, A.; Martín de Pozuelo, R.; Zaballos, A., "Using IEC 61850 GOOSE Service for Adaptive ANSI 67/67N Protection in Ring Main Systems with Distributed Energy Resources", MDPI, Energies, Barcelona, Spain, October 2017.

A.1.2 Presentation paper at international conferences

- Silos, A., "Special Algorithm for fault location in Smart Grid Medium Voltage networks", Jornadas Internacionales de Equipos Eléctricos, Bilbao, Spain, 26-27 October 2011.

A.1.3 Presentation paper at local conferences

- Silos, A., "Sistemas Self-Healing para la regeneración de redes de distribución de Media Tensión", II Congreso de Smart Grid, Madrid, Spain, 27-28 October 2014.

A.1.4 Paper under development

- Silos, A.; Lloret, P.; Villafáfila, R., "Novel fault location algorithm for meshed distribution networks with DERs".

A.1.5 Other paper contributions

- Pérez-Martínez, R.; Villafáfila-Robles, R.; Lloret-Gallego, P.; Egea-Alvarez, A.; Sumper, A.; Silos-Sanchez, A., "Protection System Remote Laboratory", International Conference IEEE EPQU, Lisbon, Portugal, 17-18 October 2011.
- Silos, A., "Beneficios de la localización de defectos con Feeder Automantion para una red eléctrica Smart Grid de distribución en Media Tensión", I Congreso Smart Grids, Madrid, Spain, 22-23 October 2012.

A.2 Other publications

- Silos, A., "IEC 61850: la clave para la automatización de la subestación eléctrica", Automática e Instrumentación, no. 411, Barcelona, Spain, October 2009.
- Silos, A., "La importancia del telecontrol y la telesupervisión en la red de Media Tensión", Elektroprofesional, no. 174, Madrid, Spain, October 2010.
- Silos, A.; Lamarca, J., "Smart Grid: De la red eléctrica a la vivienda", ADIME, no. 33, July 2011.
- Silos, A., "Smart grid: el paso inicial para la integración del vehicula eléctrico en la red", Automática e Instrumentación, no. 434, Barcelona, Spain, November 2011.
- Silos, A. "La red inteligente, antesala de la ciudad inteligente", Distrelec, January-February 2012.
- Silos, A., "Avances técnicos para la localización de faltas en redes inteligentes de media tensión", Energética XXI, no. 119, April 2012.
- Silos, A., "Smart Grid. Presente y futuro de la gestión inteligente de la energía", Electra, no. 177, February 2013.
- Silos, A., "Inteligencia Distribuida en la Red Eléctricas: Solución Self-Healing", Energética, XXI, http://www.energetica21.com, May 2013.
- Silos, A., "The four tentacles of the smart grid: From telecontrol towards intelligent self-healing", Energetica International, no. 134, July - August 2013.
- Silos, A., "The Smart Grid wraps the city of the future", Energetica International, no. 4, March 2014.
- Silos, A., "Nuevas técnicas de monitorización y gestión, oportunidades de las redes eléctricas", Enertic, http://www.enertic.org, 8th July 2014.
- Silos, A., "Monitorización y gestión, oportunidades de las redes eléctricas en la Smart City", IndustriaAmbiente, no. 6, July-September 2014.
- Silos, A., "Microgrid Quality and Management. From the Traditional Grid to Microgrid", FuturEnergy, http://futurenergyweb.es, October 2014.
- Silos, A., "Gestión y calidad de las microrredes. De la red tradicional a la microrred", Automática e Instrumentación, no. 469, January 2015.
- Silos, A., "Soluciones de la Smart Grid para la red eléctrica", Energía de hoy, no. 11, July 2015.
- Silos, A., "IEC 61850, pieza clave de la Smart Grid", Energía de hoy, no. 12, October 2015.
- Silos, A., "Gestión y calidad de las microrredes", El Instalador, no. 535, December 2015.
- Silos, A., "Comunicación y automatización en equipos de Alta Tensión. El IEC 61850 como herramienta de la Smart Grid", Energetica XXI, no. 160, September 2016.

A.3 Conferences

- Silos, A., “Seminario de protecciones para instalaciones de alta tensión” in Colexio Oficial de Enxeñeiros Técnicos Industriais (COETI), Ferrol, A Coruña, Santiago de Compostela, Spain, 28-30 October 2008.
- Jarrega, M.; Silos, A., “Sistemas de protección en subestaciones de media tensión. Impacto en la mejora del mantenimiento” in I Feria Operación y Mantenimiento de Energías Renovables, Valladolid, Spain, 2nd December 2009.
- Silos, A., Presentation of “Smart Grid: Calidad y Respuesta” in Ecostruxure Innovation Tour, Barcelona, Spain, 3rd February 2011.
- Silos, A., Presentation of “Smart Grid: Smart Operation y Smart Metering” in Simposio de Eficiencia Energética y Empresas de Servicios Energéticos, Colegio Oficial de Ingenieros Industriales de Madrid (COIIM), Madrid, Spain, 1-2 February 2012.
- Silos, A., Presentation of “Smart Grid: Una nueva puerta para la Ingeniería Eléctrica” in Escola Universitaria d’Enginyeria Tècnica Industrial de Barcelona (EUETIB), Barcelona, Spain, 29th May 2009.
- Silos, A., Presentation of “Eficiencia en la red de distribución de Media Tensión” in Fomento de San Sebastián, San Sebastián, Spain, 3rd October 2012.
- Silos, A., Presentation of “Gestión Inteligente de la Energía. Del telecontrol de la red a la Smart Grid” in I Congreso de la Ingeniería Industrial, Colegio Oficial y Asociación de Ingenieros Industriales (COAIN), Madrid, Spain, 23rd October 2012.
- Silos, A., Presentation of “Gestión Inteligente de la Energía. Gestión inteligente de la integración de la Generación de Energía Renovable” in Genera 2013, Madrid, Spain, 28th February 2013.
- Wild, J.; Silos, A., Presentation of “Integris Developments. Schneider Electric” in Integris Workshop, Barcelona, Spain, 9th May 2013.
- Silos, A., “Inteligencia distribuida en la red eléctrica. Soluciones Self-Healing” in Smart Grids, las redes del future, organized by Energetica XXI, Madrid, Spain, 29th May 2013.
- Silos, A., “Smart Grid: La gestión de las redes inteligentes. Los cuatro tentáculos de la Smart Grid” in Electro Forum 2013, Barcelona, Spain, 3rd October 2013.
- Silos, A., “The four Smart Grid tentacles wrap the city of the future” in Smart City Expo World Congress, Barcelona, Spain, 21st November 2013.
- Silos, A., “Gestió i qualitat de las microxarxes” in Jornada mongràfica sobre Smart Grids, Col·legi Oficial d’Enginyers Industrials de Catalunya (COEIC), Barcelona, Spain, 23rd Maig 2014.
- Silos, A.; Jarrega, M., “Smart Grid y Servicios Avanzados para redes de distribución eléctrica” in Congreso CIDE 2014, Toledo, Spain, 13th June 2014.

- Silos, A., “Autoconsum, DER i vehicle elèctric per medi de microxarxes a Catalunya” in 2n Congrés d’Energia de Catalunya, Barcelona, Spain, 17th September 2014.
- Silos, A., “Aplicacions de Smart Grid per a la Industria” in Col·legi d’Enginyers Tècnics de Barcelona, 5th June 2014.
- Silos, A., “Smart Grid. La nueva concepción de la red eléctrica” in Voltium Webinar, https://www.voltimum.es/, Barcelona, Spain, 24th September 2014.
- Silos, A., “Smart Grid Monographic, How can the Smart Grid help to energy dilemma?” in IESE Business School, University of Navarra, Barcelona, Spain, 27th February 2015.
- Silos, A., “Energías Sostenibles. De la Smart Grid a la Microgrid” in Saló Internacional de la Logística 2015, Barcelona, Spain, 10th June 2015.
- Silos, A., “What does the Energy Future hold? Enhancing our world and meeting the demands of the future” in IESE Business School, University of Navarra, Barcelona, Spain, 11th November 2015.
- Silos, A., “Smat Grid. L’evolució intelligent de la xarxa eléctrica” in Innova Barcelona, Barcelona, Spain, 4th May 2016.

A.4 Training

- Congress. “International Electrical Equipment Conference 2011”, organising body: Tecnalia, duration: 14 hours, Bilbao, Spain, 26-27 October 2011.
- Conference. “Redes inteligentes de energía, Smart Grids, Regulación y Tecnología”, organising body: Comisión Nacional de Energía (CNE), duration: 5 hours, Madrid, Spain, 26th March 2012.
- Conference. “Jornada Smart Grid”, organising body: Col·legi Oficial d’Enginyers Industrials de Catalunya (COEIC), duration: 4 hours, Barcelona, Spain, 25th May 2012.
- Congress. “I Congreso Smart Grid”, organising body: Tecmared, duration: 14 hours, Madrid, Spain, 22-23 October 2012.
- Exhibition. “Smart City World Congress & Exhibition”, organising body: Fira Barcelona, duration: 6 hours, Barcelona, Spain, 13-15 November 2012.
- Exhibition. “Smart City World Congress & Exhibition”, organising body: Fira Barcelona, duration: 6 hours, Barcelona, Spain, 19-21 November 2013.
- Technical Worksop. “Broadband over Powerline (BPL), technologies for Smart Grid Applications”, organising body: Corinex, duration: 4 hours, Madrid, Spain, 26th May 2014.
- Subject. “Electrical Power Systems”, organising body: ETSEIB, duration: 5 ECTs course Barcelona, Spain. Start date: September 2014. End date: January 2015.
- Congress. “II Congreso Smart Grid”, organising body: Tecmared, duration: 14 hours, Madrid, Spain, 27-28 October 2014.

- Exhibition. “Smart City World Congress & Exhibition”, organising body: Fira Barcelona, duration: 6 hours, Barcelona, Spain, 18-20 November 2014.
- Conference. “Power Electronics in the Grid: HVDC and FACTS”, organising body: CITCEA, duration: 4 hours, Barcelona, Spain, 28th November 2014.
- Conference. “Jornada monogràfica sobre Smart Grids”, organising body: COEIC, duration: 4 hours, Barcelona, Spain, 23rd Maig 2014.
- Symposium. “Symposium on Smart Rural Grid”, organising body: CITCEA - ETSEIB, duration: 4 hours, Barcelona, Spain, 9th June 2015.
- Workshop. “Rapid prototyping for Smart Grids”, organising body: IMDEA, duration: 5 hours, Móstoles, Spain, 26th April 2016.
- Exhibition. “Internet of Things Solutions World Congress”, organising body: Fira Barcelona, duration: 5 hours, Barcelona, Spain, 26-28 October 2016.
- Exhibition. “Electric Utility Week”, organising: Clairon Events, duration: 6 hours, Barcelona, Spain, 15-17 November 2016.
- Workshop. “Cybersecurity & Digital Substation ACS”, organising body: Schneider Electric, duration: 18 hours, Lattes, France, 30th January - 3rd February 2017.
- Seminar. “Mendeley Avançat”, organising: UPC, duration: 1,5 hours, Barcelona, Spain, 28th March 2017.
- Demo Workshop. “Smart Rural Grid Demo Workshop”, organising body: Smart Rural Grid, duration: 5 hours, Granollers, Spain, 23rd May 2017.
- Symposium. “International Symposium on Energy Innovation. The transition to a flexible electricity market”, organising body: Càtedra Endesa d’innovació energètica, duration: 4 hours, Barcelona, Spain, 11th July 2017.
- Workshop. “Product Application Engineer Training”, organising body: Schneider Electric, duration: 18 hours, Grenoble, France, 17-20 October 2017.

A.5 Teaching

A.5.1 Classes

- Workshop. “Comunicacions en el sector electric. Norma IEC 61850”, organising body: CITCEA, participation: 2 hours in several sessions in 2008, 2010, 2011 and 2012, Barcelona, Spain.
- Workshop. “Centros de Transformación”, organising body: IIR, participation: 3 hours in several sessions in 2008, 2009, 2010, 2011, Madrid, Spain.
- Master. “Màster en Enertrònica”, organising body: CITCEA, participation: 3 hours in several sessions in 2012, 2013, 2014, 2015, 2016 and 2018.

- Degree. “Enginyeria Tècnica Elèctrica, Grau d’Enginyeria Elèctrica”, organising body: UPC, participation 2 hours in several sessions in 2012, 2013, 2014, 2015, 2016 and 2018
- Master. “Máster en Tecnologías para las Smart Cities y Smart Grids”, organising body: La Salle, participation: 9 hours in several sessions in 2013, 2014, 2015, 2016 and 2017, Barcelona, Spain.
- Master. “Màster de Mobilitat de la UPC”, organising body: UPC, participation: 2 hours in several sessions in 2013, 2014, 2015, 2017 and 2018, Barcelona Spain.

A.5.2 Follow-up projects

- Elbaile, A.; Ruíz, C., “Aplicaciones IEC61850 en el sector eléctrico y en la industria”, professors: Martin de Pozuelo, R.; Silos, A., in “Máster en Tecnologías para las Smart Cities y Smart Grids”, organising body: La Salle, Barcelona, Spain, 2014-2015.
- González, J., “Aplicación de la norma IEC 61850 en Smart Cities. Propuestas para Vehículo Eléctrico y Smart Lighting”, professors: Martin de Pozuelo, R.; Silos, A., in “Máster en Tecnologías para las Smart Cities y Smart Grids”, organising body: La Salle, Barcelona, Spain, 2014-2015.
- Toapanta, J. C., “Reposición de suministros en redes de distribución”, Trabajo Fin de Grado, Grado en Ingeniería Eléctrica, UPC, Barcelona, Spain, May 2017.
- Monsalve, M., Noboa, Y., Puig, A., “IEC 61850 en las Smart Cities: Propuesta para el Vehículo Eléctrico”, professors: Martin de Pozuelo, R.; Silos, A., in “Máster en Tecnologías para las Smart Cities y Smart Grids”, organising body: La Salle, Barcelona, Spain, 2016-2017.
- Bañon, J. M.; Sánchez, J. G., “Aplicación del estándar IEC 61850 para el control de REDs en el sistema eléctrico”, professors: Martin de Pozuelo, R.; Silos, A.; Señis, A., in “Máster en Tecnologías para las Smart Cities y Smart Grids”, organising body: La Salle, Barcelona, Spain, 2016-2017.

A.6 Committees

- SC 57-205A AENOR, “TC 57 Mirror committee. Power System Management and Associated Information Exchange”, committee member since 2011.
- SC 94-95 AENOR, “TC 94-95 Mirror committee. Electrical Relays”, committee member since 2011.
- CTN178 AENOR, “Ciudades inteligentes”, committee member since 2013 until 2015.
- T&D Europe, “Transmission and Distribution Europe. Association of manufacturers”, committee member since 2015 in working group Smart Grid and Microgrid.

A.7 Research projects

- Participation in INTEGRIS, “INTelligent Electrical Grid Sensor communications”, organising body: Enel Energy Europe, supervised by: FP7-ICT, main research: Corbeira, L., participation in the pilot project in Barcelona 2012-2013.

- Participation in ESTORELOT, “Eines per a la gestionabilitat de les plantes de generació elèctrica amb fonts renovables”, organising body: EMELCAT, supervised by RIS3CAT, main research: Mata, M., participation in the project in period 2017-on going.

A.8 Short biography

Ángel Silos Sánchez was born in Barcelona, Spain on April, 30th 1981. He received his M.Sc. in Industrial Engineering from the Polytechnic University of Catalonia in 2006. Additionally, he received his M.Sc. in Marketing in 2010. In 2014 he started as a Ph.D. student at Polytechnic University of Catalonia.

Until 2006 he joined SIEMENS in Barcelona, Spain, where he was involved in industrial automation commercial area. In 2007 he joined Schneider Electric starting as product technician developing support functions to the Protection and Telecontrol Medium Voltage. In 2009 he started as Protection and Telecontrol in Medium Voltage manager, working with end users and utilities in their electrical distribution networks. From 2013 he also worked as Energy Architect for Smart Grid solutions giving support to several solutions in this area. During this period in Schneider Electric, he has contributed with several posts in Schneider Electric’s Blog. In 2018 he has started a new position in Schneider Electric as business developer manager for field services in energy systems.