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A RESILIENT EXPANSION OF ELECTRICAL NETWORK CONSIDERING PROTECTION COORDINATION BASED ON GEOREFERENCED INFORMATION

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Abstract

Electrical power systems are critical infrastructure within a modern society, the operation strategies are correlated with a satisfactory welfare and economic development. Consequently, overhead and underground distribution networks should be designed, constructed and operated withstand abnormal events. Thus, the implementation of remote-controlled switching equipment, novel and modern protective devices are key aspects to improve the operating grid's conditions during and after disturbances.

A resilient expansion of electrical network considering protection coordination based on georeferenced information is proposed in the present thesis. The aim of the research project is to determine the most suitable operating conditions for distribution network after facing abnormal events. This is achieved by an accurate resilient design, which considers the allocation of tie switch equipment that allows modifying the distribution grid by the implementation of a reconfiguration algorithm. Additionally, an automated protection coordination algorithm is executed based on the availability of electrical components. Both reconfiguration and protection coordination are implemented using a peer-to-peer communication between Matlab and PowerFactory.

The thesis deals with a resilient expansion of electrical network based on georeferenced data, consequently the optimal location of distribution transformers is determined based on minimal distances between them and customers. Furthermore, a heuristic model based on minimum spanning tree technique is applied to minimize the total distance of the medium voltage network. Improvements on planning algorithm for distribution networks are developed; consequently, a decision-making tool is elaborated to be used by engineers during planning and design tasks because the proposed model allows to obtain a pre-design based on geographical parameters (latitude and longitude) that meets all technical requirements.

The proposed resilient planning considers normally open points, which have been allocated by an optimization process. Then, the optimal allocation of switching equipment is accomplished by the optimal path considering the minimum distance to interconnect primary feeders, this will represent a considerable reduction on utilities budget. Set in this context, switching equipment has a prominent function during unusual events due to the fact that they sectionalize faulty branches using an automatic tool to reconfigure a network. Reconfiguration algorithm is implemented between a peer-to-peer communication, where Matlab executes an exhaustive search of possible network configurations, whilst PowerFactory per-

forms a power flow analysis. Several feasible solutions to recovery the electrical grid are determined, nevertheless, the best solution is selected based on technical constraints.

The automatic protection coordination is carried out after a topological reconfiguration has been achieved. As a result, the proposed iterative algorithm of protection coordination is executed based on communication peer-to-peer between Matlab and PowerFactory, which develops an adaptive calculation to determine the current setting and the time multiplier setting. The remarked algorithms could be developed and evaluated on different distribution networks, areas and locations.

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First and foremost, I have to express my sincere gratitude to my parents since none of this could have happened without them. All the love and support throughout my life is the greatest gift that I have received.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

Electricity demand is steadily increasing due to the fact that new and novel electric equipment is connected to the grid every day, such as factory's machinery, household devices, electric vehicles and new generation technologies. Consequently, the energy industry is moving into a new era based on reliability, efficiency, and resilience, that are essential requirements to manage the increasing complexity of an electrical network. A more efficient transmission of electricity, reduced peak demand, integration of renewable energies, better integration between costumers and utilities and a quicker restoration of electricity after power events are benefits associated to smart grids. Not only all the remarked aspects but also modern technology for power system components are vital to satisfy electrical demand with minimum outages and uninterrupted power supply.

therefore, not only primary equipment (power transformers, circuit breakers, disconnectors, etc.), but also protection, communication and control systems are needed to withstand unusual events or contingencies without supply interruption. Abnormal events are largely influenced by lightning discharges, insulation ageing, overvoltages, overloading, human error and natural disasters. The aforementioned events could cause a temporary or permanent outages, hazard to people, damage to faulted and unfaulted equipment; consequently, for the mentioned adverse effects is mandatory a suitable, reliable and resilient power system, which incorporates fast isolation and restoration capabilities for the entire network. As a result, control and protection systems are the most strategic ancillary services of the power system since it permits rapid recovery/reconstitution elsewhere on the system avoiding permanent loss of supply.

The grid resilience strategies adopted normally by electric utilities are focused to determine and identify the greatest risks to the power system and the economic impacts due to the mitigation and hardening actions to re-establish the electricity. The main resilience plans include implementation of tie-points, and reconfiguration capabilities, mobile transformers and substation deployment on critical locations, evaluation of risks, and energy storage devices deployment.

Protection and control capabilities are implemented on power systems using primary and backup protection at each point of the power network, then a properly coordinated protection will permit an automatic detection of abnormal conditions, and the subsequent operation of the associated circuit breakers. Additionally, protection systems must be operative after these disturbances, to prevent any future collapse. Hence, protection relays as well as instrument transformers, circuit breakers, battery supply and other devices must operate in conjunction to detect and isolate faults on automated feeders to minimize damage. The economic cost and the benefits of a resilient system is evaluated considering the importance of the rapid recovery and the consequences of a prolonged power outage. It is important to note that protection and control capabilities on resilience system will not avoid a failure or disaster, however it can limit the fault duration and minimize its consequences.

1.1 Nomenclature

Power system resilience is a novel and new research field consequently the topic is still not adequately defined, nevertheless, there are various research projects which are laying the foundations to analyze this topic on power systems. Over the years the term of resilience has been related with a variety of technical definitions, then a simple and universal interpretation has not been written. Therefore, it is important to point out that studies on resilience are associated with mitigation of unusual and catastrophic events which affect to the electricity network.

The most relevant terms related with power systems and resilience are listed from research articles (Gholami et al., 2018; Plotnek and Slay, 2019) and also from the glossary of terms used in NERC reliability Standards (North American Electric Reliability Corporation, 2008).

- **Power system definitions**:
  - **Utility**: A company in the electric power industry, which is a provider of generation, transmission, distribution services.
  - **Facility**: A set of electrical equipment that operates as a single bulk electric system element (e.g., a line, a generator, a shunt compensator, transformer, etc.)
  - **Transmission system**: An interconnected group of lines and associated equipment for the movement or transfer of electric energy between points of supply and points at which it is transformed for delivery to customers or is delivered to other electric systems.
  - **Distribution system**: A stage of the power system that is dedicated to delivering electric energy to an end-user.
  - **Ancillary service**: Those services that are necessary to support the generation, transmission and distribution of electricity and energy from resources to loads while maintaining reliable operation.
  - **Contingency**: The unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch or other electrical element.

- **Protection terms**:
  - **Protection system**: The term is related to protective relays which respond to electrical quantities,also Communications systems necessary for correct operation of protective functions.
  - **Protection coordination study**: An analysis to determine whether Protection systems operate in the intended sequence during faults.
  - **Fault**: An event occurring on an electric system such as a short circuit, a broken wire, or an intermittent connection.
  - **Outage**: The period during which a generating unit, transmission line, or other facility is out of service.
  - **Misoperation**: The failure of a composite protection system to operate as intended for protection purposes.
    - **Failure to trip – during fault**: A failure of a composite protection system to operate for a Fault condition for which it is designed.
    - **Failure to trip – other than fault**: A failure of a composite protection system to operate for a non-Fault condition for which it is designed, such as a power swing, undervoltage, overexcitation, or loss of excitation.
    - **Slow trip – during fault**: A composite protection system operation that is slower than required for a fault condition if the duration of its operating time resulted in the operation of at least one other element's composite protection system.
    - **Unnecessary trip – other than fault**: An unnecessary composite protection system operation for a non-Fault condition.
- **Resilience and reliability terms**:
  - **Reliability**: ability of a system to perform a required function under stated conditions, within a given scope, during a given period of time.
  - **Safety**: ability of a system not to cause danger to persons or equipment or the environment.
  - **Availability**: probability that a system or equipment will operate satisfactorily and effectively at any point of time.
  - **Cascading**: The uncontrolled successive loss of System Elements triggered by an incident at any location.
  - **Corrective Action Plan**: A list of actions and an associated timetable for implementation to remedy a specific problem.
  - **Special Protection Schemes (SPS) or Remedial Action Schemes (RAS)**: An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability.

- **Real-time Assessment**: An evaluation of system conditions using real-time data to assess existing (pre-Contingency) and potential (post-Contingency) operating conditions. The assessment shall reflect applicable inputs including, but not limited to: load, generation output levels, voltage levels ,transmission outages, distribution network outages, generator outages, and identified equipment limitations.
- **Blackstart Resource**: A generating unit and its associated set of equipment which has the ability to be started without support from the system or is designed to remain energized without connection to the remainder of the system.
- **Cyber Security Incident**: A malicious act or suspicious event that disrupts or attempts to disrupt the operation of the electrical power system.

1.2 Project Description

Electrical power systems represent a fundamental part of the society and their efficient operations are of vital importance for social and economic development. Power systems have been designed to withstand interruptions under already provided safety and quality principles, however, there are some extreme and not so frequent events that could represent inconveniences for the correct operation of the entire system.

The last years the term resilience, which serves to describe the capacity of a system to recover from an event that disturbs it, has been studied and analyzed on electrical networks. As a consequence of extraordinary events, usually overhead lines can bring down, or electric equipment like circuit breakers, distribution transformers, power substations can be affected, producing cascading events which eventually can lead to the formation of unplanned electric islands and then the collapse of the entire system (Espinoza et al., 2016; Oral and Dönmez, 2010; Amraee and Saberi, 2017; Panteli et al., 2016).

Power outages force to shut down business and factories, close schools and impede emergency services, resulting on high economic impacts due to the fact that lost output and wages, spoiled inventory, delayed production, inconvenience and damage to grid infrastructure (Kazmi et al., 2017; Espinoza et al., 2016). As a result of faulty sections, it is paramount task to re-establish the electricity supply as soon as possible in order to restore emergency services, hospitals, healthcare, and other critical infrastructure. Several restoration techniques and methods have been applied in different circumstances, which are normally based on three temporal stages: cleanup process system restoration and load restoration.

Within this background, resilience on electric network is associated with planning, resource allocation and routing problems. The project will be addressed to determine an optimal planning and routing to withstand abnormal events considering protection coordination, therefore, a variety of simulations will be performed using Matlab and PowerFactory [1].

The research contemplates an exhaustive and extensive review of literature associated with resilience on power systems, operation and protection coordination on distribution networks. Thus, three main stages can be defined as part of the project. The first stage is related with a practical methodology to develop a resilient planning of distribution networks considering georeferenced data, which exemplifies a real distribution network. As a consequence of a resilient planning, several remote-controlled switchgear equipment is allocated based on the optimization process, which are able to modify distribution network, improving the operating grid's conditions due to the enhancement of voltage profiles and reduction of power losses. These points will be capable of connecting tie lines and changing the distribution network topology, bringing different possible solutions to recovery the electrical grid taking into account technical and economic constraints. As a consequence of the topology's variation, protection schemes on distribution networks will be affected, then issues associated with reliability and selectivity could produce misoperation of protection relay. Finally, the first stage is focused to develop an algorithm for protection coordination, which is executed based on gathered data from power flows and short circuits analysis. The last part of the project develops an adaptive calculation to determine the current setting and the time multiplier setting of overcurrent relays. An adequate modification protection coordination of relay settings after network reconfiguration could avoid misoperation of circuit breakers, establishing a satisfactory protection coordination which can keep the network's operation during faults (Valenzuela et al., 2019a; Miloca et al., 2015; Raut and Mishra, 2018).

1.3 Outline of the Thesis

The contents of the thesis are briefly summarized in the following, in order to provide an overview of the work.

- **Chapter 2**: It introduces about resilience on power systems, the concept of resilience and its application in different engineering fields is stated. A world overview of resilience on power systems is analyzed and major contributions are studied. Regional and local aspects of resilience on power systems are carried out, where an extensive literature review is analyzed. Additionally, a relationship between resilience and protection principles and schemes are reviewed.

- **Chapter 3**: An extensive analysis of main topics are detailed; planning of electric networks is examined considering time horizon perspectives, main features and criteria for planning. Some automatic planning tools are listed, and fundamental concepts associated with overcurrent protection is stated.

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[1] PowerFactory is a leading power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. https://www.digsilent.de/en/powerfactory.html

- **Chapter 4**: This chapter is divided in three main parts: the first one depicts a resilient planning based on Minimum Spanning Tree (MST) techniques, while the second part focuses on the implementation of a Decision-making for planning, which is a very useful tool in educational and practical fields, since it could be used to obtain a quick and efficient pre-design based on georeferenced data. The last stage deals with operational aspects on distribution network, then reconfiguration and protection coordination algorithms based on a communication peer-to-peer between Matlab and PowerFactory are carried out. Consequently, a reliable and resilient network is developed based on georeferenced data.

- **Chapter 5**: It summarizes and comments the obtained results and proposes some future investigations about the discussed topic.

Chapter 2

Resilience on Power Systems

This chapter introduces fundamental aspects about resilience of power systems, then the concept of resilience and its application in different engineering fields is stated. A world overview of resilience on power systems is analyzed and major contributions are studied. Regional and local aspects of resilience on power systems are carried out, where an extensive literature review is scrutined. Additionally, a relationship between resilience and protection principles ans schemes are reviewed.

2.1 Resilience Aspects and Power Systems

Resilience is a general concept that can be applied to different events as it is related to the capacity to recover from complications. In engineering terms, resilience is the ability of any system or equipment to react to technical and untechnical contingencies and still offer the best possible service. Therefore, several studies have been conducted to diagram vulnerable territories, evaluating resilience indexes in different engineering topics such as transportation, electrical and water distribution networks, when they are exposed to natural or man-made disasters such as volcanic eruptions, hurricanes, storms or flooding (Wilson et al., 2014; New Zealand Lifelines Council, 2017).

2.1.1 World Aspects around Resilience and Power Systems

Natural disasters have increased research on risk management and disaster mitigation in cities. Therefore, some researchers have conducted studies to determine vulnerable territories, which normally are less resilient; consequently, these indicators permit to diagram maps and present the most vulnerable and unprotected areas on cities, where some methodologies should be applied to increase the capacity of withstand unusual contingencies (Bergstrand et al., 2015; van Zandt et al., 2012; Highfield et al., 2014). However, not only vulnerability, but also flexibility, robustness, stability, redundancy, resourcefulness, diversity, self-organization, and other geographical features can be used to assess the community resilience considering economic, social and organizational aspects to determine resilience's capacity

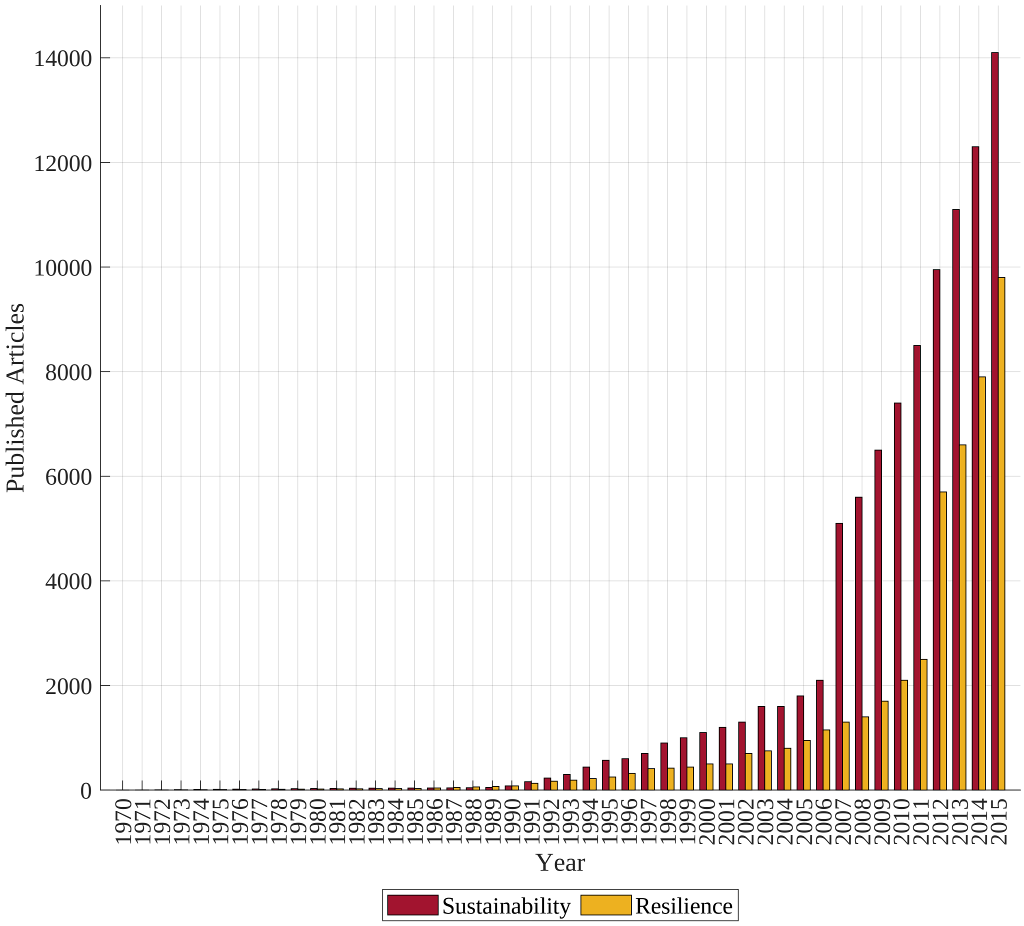

Figure 2.1: Relation between resilience and sustainability: number of research articles published in the Web of Science between 1970 and 2015.

indexes on populated areas such as Slovak and US areas (Sharifi and Yamagata, 2016; Cariolet et al., 2019; Hudec et al., 2018).

Mapping vulnerable areas permit to determine critical infrastructure affected by natural or human-induced hazards. Normally, locations and services, which are essential to ensure the functioning of the society guaranteeing well-being of citizens are denominated critical infrastructure such as water, transportation, gas and electric distribution networks, also hospitals, airports, emergency services and agricultural assets (Liu and Song, 2020; Shakou et al., 2019). Not only resilience and their critical infrastructure, but also sustainability has been examined considerably over the last decade as can be seen in Figure 2.1 and Figure 2.2, where the interest of researchers from North America, Europe and Asia about these topics is depicted. However, These two topics are correlated since it is not possible to reach sustainability without resilience (Loo and Leung, 2017).

After these considerations, resilience in transport network applied to real cases has been carried out assessing the impacts of unusual and disruptive events using simulations (Wang et al., 2019); other researches have studied the influence of high-

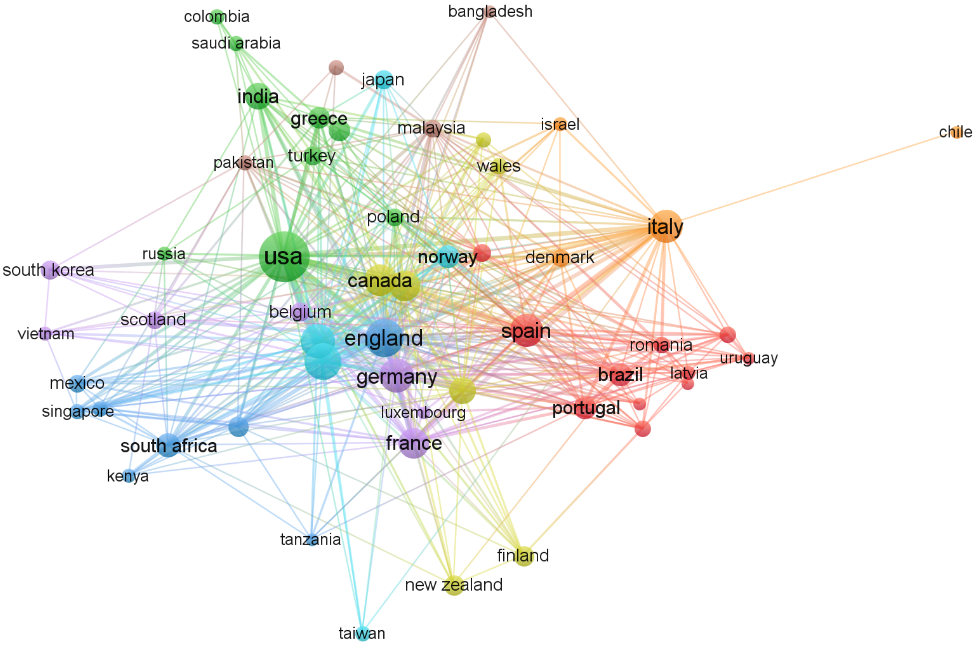

Figure 2.2: Map of main countries which are researching topics about resilience and sustainability. Data gathered from Web of Science.

speed rail networks and air network when they are affected by climate conditions and malicious attacks (Li and Rong, 2019). On the other hand, road transport has been investigated considering the user's response (Nogal and Honfi, 2019), and some researchers have focused their works on vulnerability of main highways which interconnect critical infrastructure, where results assist in decision process to improve resilience (Hsieh and Feng, 2018).

Water distribution networks play a highlighted role on society because they transport the liquid between reservoirs and domestic, industrial or municipal areas maintaining the health and safety of human lives. Planning and operation of water distribution networks based on vulnerability and risk management allows to identify system components which are more susceptible to fail; for example, Rodina (Rodina, 2019) proposed a resilient planning of water distribution network applied to a real case in Cape Town considering economic, social and environmental aspects. Operation and maintenance perspectives are addressed on the evaluation of internal and external hazards Qingdao (China); internal hazards are related to technical failures on components or buildings, sudden increment of water consumption, whilst external hazards are associated with droughts, earthquakes, heat waves or floods (Bi et al., 2019; Zimmermann et al., 2018). Other researches have combined water and electric networks on their studies since both are subject to abnormal disturbances, For example Voisin et al. (Voisin et al., 2019) focused on with a sustainable planning of water resilience network based on resilience factors in The United States on long term; whilst, Najafi et al. (Najafi et al., 2019, 2020) developed an investigation based on the integration of microgrids, which provide electricity to citizens and also the facility to access to clean water after hurricanes and floods.

It is important to note that the water and transport networks, hospitals and security services are critical assets, and they need electricity to face and work during and after any event, then an accurate and safe operation of power grid is a paramount task to maintain operative other critical infrastructures. The complexity and growth of transmission corridors have modified the operation procedures since local grids have been extended to regional or national grids, and currently it is extensively common to interconnect neighbouring countries by transmission lines at high voltage levels. Not only transmission grid, but also distribution networks have evolved from conventional networks constituted mainly radially to loop and mesh grids. Consequently novel equipment and electrical devices have been implemented in modern grids to meet technical requirements such as quality of supply, reliability and safety. As a consequence, large electricity systems are connecting wide areas, then some economic benefits and technical advantages can be achieved such as reduction in spinning and reserve capacity, reliability and stability enhancement, optimised use of power plants. However, under certain unusual conditions such as lighting discharges, insulation ageing and disasters, a failure in electricity network could cause a short or long-term loss of the electric power leading to a cascading outages causing a catastrophic impact on transmission and distribution system operations (Wang et al., 2016; Mitra et al., 2016; Bie et al., 2017).

2.1.2 Regional Aspects around Resilience and Power Systems

It is clear that disasters can be present in any part of the world, certainly, countries in America have face some issues related to natural disasters such as Hurricane Irma in Cuba on 2017, Hurricane Maria in Puerto Rico 2017, Mexico was hit by two earthquakes on 2017. Flood and landslides occurred on Peru on 2017, even Ecuador was hit by an earthquake on 2016 (French and Mechler, 2017; Venkateswaran et al., 2017; F Audefroy, 2018).

Natural disasters in South America have caused several fatalities and injuries, producing economical and social impacts as can be seen in Table 2.1, where the total amount of natural disaster occurred between 1900 and 2019 by country is depicted, including the fatalities, injured and affected people and the total damage expressed in monetary terms. Therefore, community resilience is a paramount topic, where strategies, methods and methodologies are established to face natural or man-made disaster. For example Aguilar-Barajas et al. (Aguilar-Barajas et al., 2019) analysed the infrastructure to improve resilience against floods; as a result, policies and politics are examined to enhance policies taking into account adaptive risk management. Floods and other disasters were reviewed by Chelleri (Chelleri et al., 2015) et al., who analyze the case of non-urban neighborhoods considering the improvement of resilience by decentralized water management us-

Table 2.1: Natural disaster statistics in South America between 1900 and 2019 (The International Disaster Database, www.emdat.be).

Country	**Occurrence** #	**Total deaths** #	**Injured** #	**Affected** #	**Homeless** #	**Total affected** #	**Total damage thousand of dollars**
Argentina	115	11547	36096	14483046	607654	15126796	14947410
Bolivia	81	1696	889	8692271	157575	8850835	3777718
Brazil	213	10297	15255	102181216	1360263	103566734	22538381
Chile	117	61472	77619	10701512	1702454	12481585	41178970
Colombia	179	33753	24596	17295077	844461	18164134	7060469
Ecuador	89	14174	7414	4760882	352305	5120601	5769245
Paraguay	47	250	202	4070255	102000	4172457	153557
Peru	168	86177	1985309	20304293	673724	22963326	6404750
Uruguay	31	42	262	268751	16800	285813	867000
Venezuela	50	31124	6276	888858	179358	1074492	3639426

ing spatial re-configuration and new infrastructure. Flooding events, and their impacts on urban areas has been examined in (Moura Rezende et al., 2019), where adaptive measures were proposed to absorb negative impacts of floods based on an strategic urban planning. Earthquakes, and tsunamis, volcanic eruption and landslides are typical disasters in South America, in fact, both Chile and Peru have registered numerous fatalities in last century. Consequently, several studies have been executed developing indicators for risk management for rural and urban areas of Chile (González et al., 2018; Villagra et al., 2014) by mapping or using geographical information systems.

Disasters are sudden, uncontrollable and mostly unexpected events which cause calamitous events such as lives lost, economic loss and disruptions on critical infrastructure. These sudden events lead to significant damages on power system equipment, even causing large interruptions which can affect over million people in various locations, and forcing to the collapse of the entire system (Deligne et al., 2017; Najafi et al., 2018). Additionally, important natural disaster effect on power systems are related to the damage of primary equipment and secondary components like telecommunication links, instrument transformers, circuit breakers, which cause the inoperability of control and protection system, and also the unexpected tripping of circuit breakers. On the other hand a man-made attack like hacking the grid, which could manipulate the SCADA system leading the disruption of power flows, and also transmit erroneous signals to operators.

Some researchers have carried out in South America on resilience on power systems, for example Contreras et al. (Contreras and Shaw, 2016) and Espinoza et al. (Espinoza et al., 2018) study resilience in Chilean power system. The first one focused on disaster management during natural disasters, whilst (Espinoza et al., 2018) considered the resilience assessment and adaptation of the power grid during seismic events, taking into account a classification of risks analyzing different simulations of earthquakes. Not only natural events, but also cascading failures could produce blackouts; consequently, (Carlotto and Grzybowski, 2015) studied the severity of blackouts when the power systems is running close to its operational limits. Colombian researchers Lopez et al. (López, 2014) worked on resilience from the point of view of flexibility of current power systems must have in order to face adequately during extreme meteorological conditions, focusing on technical, political and social improvements to have adequate corrective actions to return the system to a resilient state. An another researcher from Colombia performed an analysis improving resilience, reliability and efficiency of power grid after blackouts using island operation connecting distributed energy resources (Marín-Jiménez et al., 2019).

2.1.3 Local Aspects around Resilience and Power Systems

It has been observed that extreme events are present in any place around the world, and Ecuador has been affected by several kind of natural disasters like volcanic hazards, earthquakes and floods during last century, which cause several socio-economic impacts. Table 2.2 shows several natural disasters occurred between 1900 and 2019 in Ecuador, including the occurrence of each disaster, fatalities, injured and affected people and the total damage expressed in monetary terms.

Table 2.2: Natural disaster statistics in South America between 1900 and 2019 (The International Disaster Database,www.emdat.be).

Disaster type	**Occurrence** #	**Total deaths** #	**Injured** #	**Affected** #	**Homeless** #	**Total affected** #	**Total damage** thousand of dollars
Drought	4	-	-	744665	-	744665	1700
Earthquake	20	12012	6880	566100	214867	787547	3535000
Flood	33	1011	331	1893924	130058	2024313	1571570
Landslide	15	1080	120	81306	180	81606	500000
Mass movement	1	60	-	-	-	-	-
Volcanic activity	13	6	13	1472212	7200	1479425	160975
Wildfire	3	5	70	2675	-	2745	-

Ecuador is a country with high risk due to volcanic hazards, where active volcanoes surround several cities and populated zones; consequently, volcanic ashfalls, pyroclastic flows and lahars could affect the normal operation of critical infrastructure. Therefore, several studies have been conducted by geologist about volcanoes in Ecuador. A complete investigation related with consequences of tephra fall deposited during the August 2006 Tungurahua eruption depicts a map with the representative grain-size of volcanic ash dispersed along the surrounded area of Tungurahua volcano (Eychenne et al., 2012). On the other hand, Gaunt et al. deals with reawakening on Cotopaxi volcano, where samples of ash are analyzed considering granulometic and petrological characteristics to gain a much clear understanding of volcanic events (Gaunt et al., 2016). Special research was carried out by Bernard et al. obtaining a real time volcanic hazard assessment based on high frequency sampling of ash applied to Cotopaxi Volcano (Bernard et al., 2016).

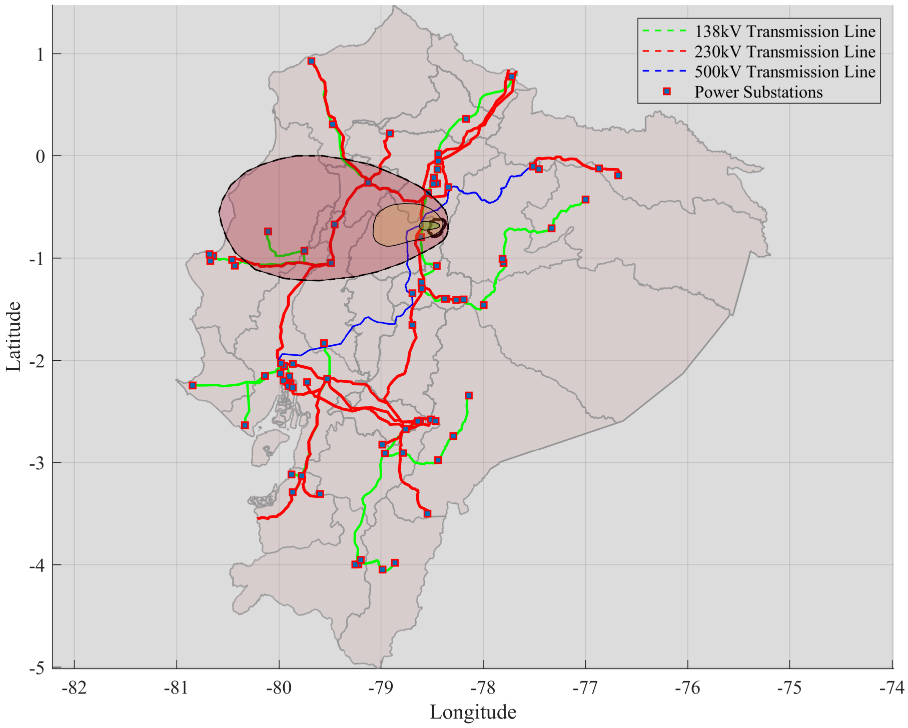

Figure 2.3: Ecuadorian electrical power system considering the hazards due to Cotopaxi eruption.

As it was highlighted, Ecuador has been involved in several natural events, subsequently, hazard maps, as it can be seen in Figure 2.3, have been developed by governmental institutions to prevent serious damage and deaths within vulnerable areas affected by hazards. It is depicted the estimated population, who is influenced not only by volcano hazards, but also by floods, landslide and other geological events. For example Encalada et al. (Encalada and Bernard, 2016) updated the volcanic hazard associated with Cotopaxi considering a numerical model for ash contamination according to wind direction and speed. However, not only research on volcanoes, but also other natural disaster have been investigated, for example in (Chunga et al., 2017) an extensive review of major destructive earthquakes and tsunamis occurred in the Northwest coast of Ecuador were well documented. Additional works related with landslides produced by a major earthquake is studied by Chunga et al. in (Chunga et al., 2019), where it was shown that a landslide inventory could be used to assess the vulnerability of physical environment such as critical infrastructure and public services including electrical power systems.

It is clear that researches on impacts and effects of natural disasters have been studied in Ecuador. However, topics related with resilience have not been widely investigated, for example Alatrista et al. (Alatrista-Salas et al., 2019) carried out a research focused on measuring the resilience on transport infrastructure in big cities like Quito and Lima. The results showed the most fragile and vulnerable points on transport paths. An interesting approach was examined in (Recalde and Meza, 2019), where a graph-based analysis was used in a citizen-oriented urban planning approach focused to improve resilience in two cities of Ecuador. On the other hand, an economic study was released about resilience after the 2016 earthquake, some economic policies taken by Ecuadorian government were analyzed, and also some new guidelines were articulated that could be put into practice on future events (Rosillo Suárez et al., 2019).

There are some critical infrastructures in countries, which should be evaluated to respond adequately during catastrophes. For example, Sword-Daniels et al. (Sword-Daniels et al., 2011) presented a report summarizing the affected zones by a Tungurahua volcano, where researchers investigated the direct and indirect effects of ashfall on critical infrastructure and public services including electrical and healthcare systems. Wardman et al. (Wardman et al., 2012) analyzed the potential impacts from tephra fall on hydro power plants, the study dealt with the relationship between the abrasion on turbines and blades and tephra fall. Lopez et al. showed the influence of volcanic ash over insulator chains on overhead lines based on a series of laboratory tests, which were conducted over insulators using volcanic ash from Cotopaxi and Tungurahua volcano. The results highlighted the imminent hazards to electrical equipment due to the volcanic ash contamination (Lopez et al., 2016). A comprehensive analysis of the influence of large hydro power generation plants on Ecuador was executed in (Carvajal et al., 2019), the author stated that it is possible to increment resilience in future as consequence of the implementation of renewable energy systems. An initial work was performed in (Villamarín-jácome and Ortiz-villalba, 2018), where the author pointed out the final damage cost of affected electrical equipment after the 2016 earthquake in Ecuador. Additionally, a generic three busbar system was evaluated by Monte Carlo simulations to quantify the impact of earthquake.

2.2 Relationship between Resilience and Protection Schemes

Modern power grids are implemented based on communication, control, protection and computing systems, and through the years it has been transformed in more sophisticated, complex and even vulnerable networks. An operating network, which is continuously running 24/7, is exposed to physical, cyber and personnel vulnerabilities which can influence on the grid's operation. Abnormal events and power outages are largely influenced by lightning strikes, insulation ageing, overvoltage, overloading, human errors and disasters, which can be produced by nature or man-made as can be seen in Figure 2.4. Natural disasters are associated with volcanic eruptions, landslides, earth-quakes, hurricanes, tsunamis, floods, etc. On the other hand, airplane crashes, nuclear power plant accidents, terrorism and war are examples of man-made disasters (Wardman et al., 2012; Xiang et al., 2018a).

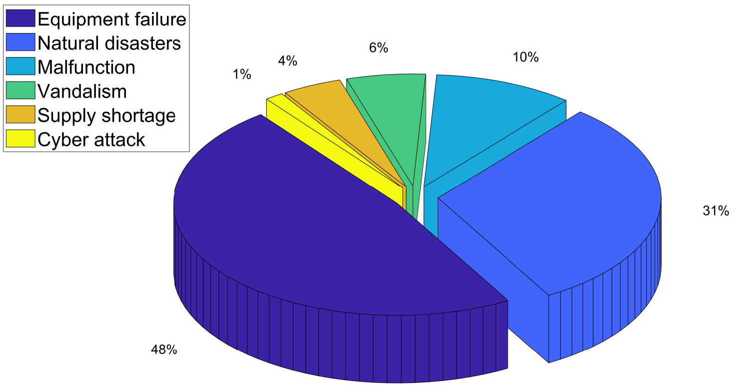

Figure 2.4: Power outages for 140 worldwide outage data from 1965 to 2012 (Bie et al., 2017).

The vulnerability related with the people who are running the electric power system is named personnel vulnerability, since they could produce inadvertently or intentionally disruptions in the operation of the power grid. On the other hand, physical vulnerability is associated with equipment's failure due to natural or man-made attacks, then power transformers, circuit breakers, transmission lines and primary feeders can be affected, where the destruction of substation, lattice towers could bring down the system due to cascade tripping. Another vulnerability can be associated with computing automation, and high-speed communications, *i.e.*, cyber vulnerability. (Xiang et al., 2018a,b; National Academies Press, 2012). Vulnerability of power grids and the critical points of power grids when it is attacked by terrorists was studied by (Wang et al., 2017), whereas vulnerability of power systems in interconnected grids in Nordic zones were studied in (Sperstad et al., 2020) due to extraordinary events.

After these considerations, it is clear that ancillary services like protection systems are mandatory on transmission and distribution grids, where protective systems are designed to ensure minimum loss of load; then it must take into account basic principles such as reliability, speed, selectivity, simplicity and cost (Saldarriaga-Zuluaga et al., 2021; Valenzuela et al., 2019b). Selectivity has been defined as the ability of the overall protection scheme to isolate the fault such that the minimum interruption occurs. The simplicity concept is associated with the minimum protective equipment and its circuitry to achieve the protection objectives. To achieve the required reliability levels, protection schemes are designed considering redundancy, dependability and security. The first one is achieved through duplication of the protection system or through remote back-up protections. Dependability is associated with the operation on the presence of a fault within its zone of protection, whilst security is the ability of the protection to refrain the tripping of the circuit breakers on the non-faulted parts of the protected zone when faults occur elsewhere on the protected zone. Consequently, reliability on power protections can be measured as the probability that the system will function correctly when it is required to act, *i.e.*, it must operate in the presence of a fault within its zone of protection and must restraint from operating at other times. The aforementioned concepts were applied in (Mehmed-hamza, 2019) where overcurrent protection relays were set for modern Medium Voltage (MV) distribution grids considering the inclusion of different generation sources.

Figure 2.5 shows the dependability and security concepts represented by logical gates (OR and AND), which are employed based on the functionality. For example, for busbar protection due to the large number of bays which are tripped when a busbar protection operates, it is more important the application of security concept. On the other hand, for feeder protection where the loss of a feeder can be compensated for other by parallel circuits, the dependability concept is more useful than security (Kiliçkiran et al., 2018; Cesar et al., 2019; Jain et al., 2019; Rizwan et al., 2020).

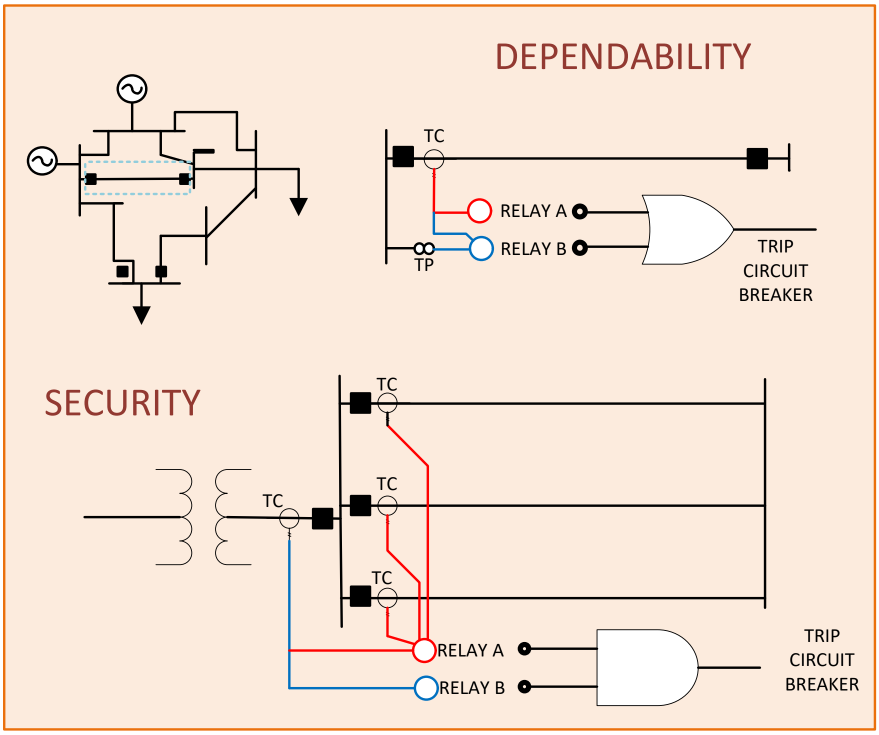

Figure 2.5: Dependability and security concepts for protection relays applied in power systems.

The aforementioned principles are practically impossible to satisfy completely and simultaneously on a protection system. Typically, the complexity increases due to reliability's enhancement and selectivity concept, consequently the protection system cannot be simple and straightforward, and therefore it converts on higher-cost protection. The optimum protection system is reached when the protection scheme offers the maximum protection at the lowest cost possible, and obviously at the minimum operating time to clear a fault in order to avoid equipment damage (Boaski et al., 2017; Sisitha and Hemapala, 2020).

Not only basic principles, but also advanced criteria such as protection zones, primary and back-up protections, or Special Protection Schemes (SPS) are used to avoid outages and damage in power systems (Arabzadeh et al., 2018). Protective zones are virtual divisions within the power system, which are protected and disconnected in the presence of a fault permitting that the rest of the power system operates normally (Chandraratne et al., 2020). Under these considerations, Ghorbani et al. modeled an electric protection system considering protective zones, and trip characteristics of distance relay, where a comparison with two different and specialized software were performed (Ghorbani et al., 2019). Approaches associated with primary and back-up protections were applied in (Sahoo and Samantaray, 2020; Sharafi et al., 2017), which stated the importance of installation of primary and back-up systems on power grids. The former are represented by relays within a given protection zone that detects a fault on power systems, whereas the back-up protection are installed to operate when the primary protection does not work. Consequently, the coordination of protection devices is performed to ensure that only the necessary faulty sections of the network are isolated. Usually a time-delay characteristic is used on back-up protection to guarantee that primary protection operates first. A more sophisticated design is the SPS which is implemented to preserve system stability after a large disturbance on important transmission lines or facilities. SPS is capable to avoid system's collapse using adequate matching between supply and load based on different methods such as load shedding, generator rejection (Canevese et al., 2016).

All the aforementioned protection principles and advanced schemes can be applied to resist, adapt, and recover from disruptions occasioned by events or disturbances. However, not only power protections, but also recommended practices taken by governments, advanced technologies and new strategies are useful to face such abnormal events. Currently, resilience and protection systems are highlighted topics since events could cause caused power outage for entire zones (Oral and Dönmez, 2010; Bie et al., 2017).

Chapter 3

Electric Power System

In this chapter, a brief and complete explanation associated with planning and protection coordination in power systems is achieved. Not only important components and structure of power systems, but also some planning concepts are covered, where boundaries between different studies and analysis used for planning problem are clarified. Additionally, Chapter 3 introduces some mathematical concepts, which are applied to the planning problem based on optimization process. Allocation and sizing of different main network components is done at minimal cost taking into account various technical constraints. On the other hand, the protection coordination of overcurrent relays is addressed taking into account the paramount concepts and equations.

3.1 Electric Power System Composition

Generation, transmission, and distribution are the main stages of power systems, where similar equipment and components are located in each stage. However voltage levels, equipment rating, operating conditions, management-maintenance and other technical aspects permit to differentiate appropriately each stage. Generation and transmission stages had been studied in detail, consequently, scientist and utilities had carried out outstanding advances on research due to the fact that the planning and operation of large interconnected systems had required more economical and technical resources. Nevertheless, during last years and considering the importance of residential, commercial and industrial customers, the analysis on distribution networks have changed, since the power distribution networks must be planned and later operating within its limits, meeting reliability, security and resilience indices (Kazmi et al., 2017; Miloca et al., 2015; Valenzuela et al., 2019a). The major power system components are detailed in Figure 3.1.

Power system planning is extremely important as it is linked to the economic development of industries, residential and commercial districts. Therefore, utilities invest technical and economical resources to have a safe and reliable supply of electricity based on adequate components, reliable equipment, system structures and modern devices. Under these considerations, not only reliable equipment is

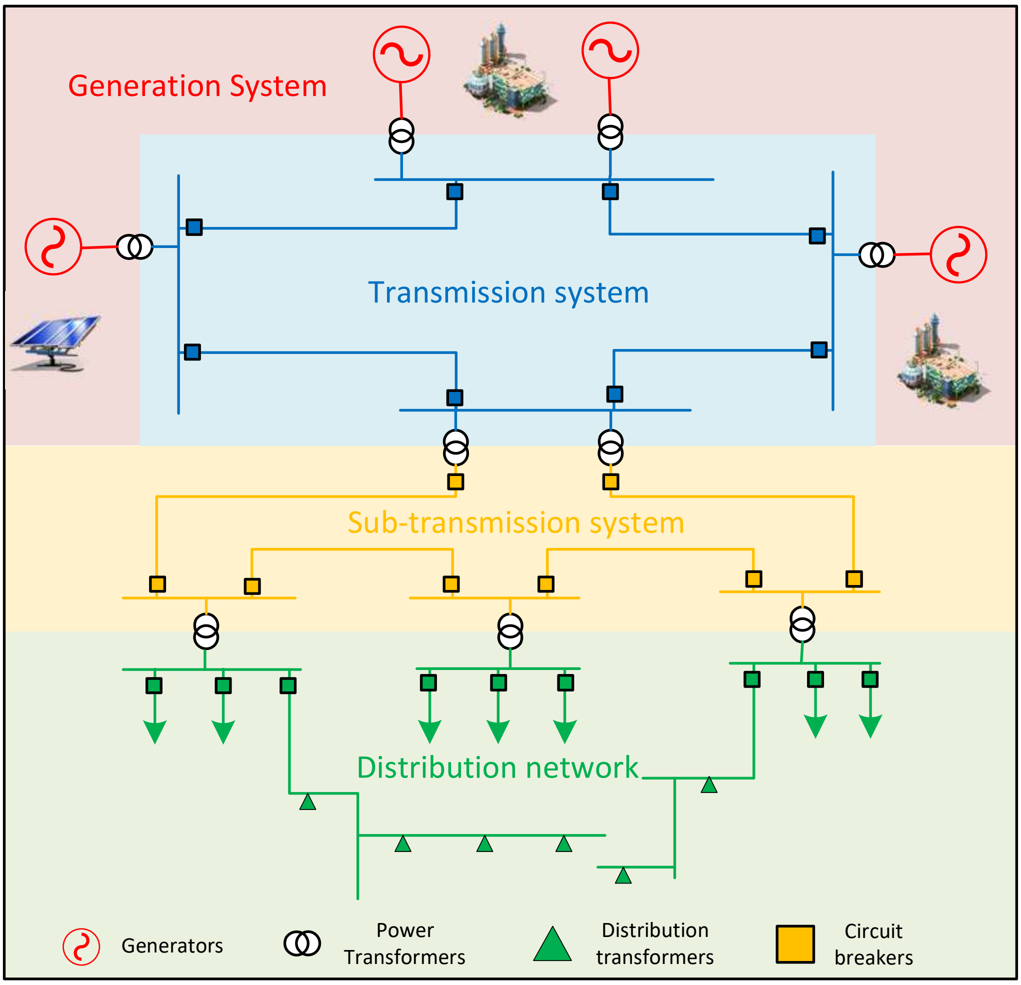

Figure 3.1: Major power system stages: generation, transmission and distribution.

needed in power systems, but also a competent use of international, regional and local standards and norms is necessary in order to fulfill all technical requirements and withstand any kind of fault limiting its effect on the electrical system. Additionally, several legal, social, political, environmental and financial restrictions are stated on laws for electrical power supply, regulations and guidelines, which have strong influence on planning tasks, construction and operation of electrical networks. Consequently, all the aforementioned restrictions generate an optimization problem, where it is needed to develop a electrical network which meet with technical requirements in the long and well as the short term (Schlabbach and Rofalski, 2014).

Normally, the connection of new customer to the electrical network, connection of new production plants or industrial users with requirement of additional power, large buildings such as commercial districts, office buildings, new residential areas, or connection of generation to the distribution network, are key factors to expand the electrical network taking into account technical and economic aspects (Grackova et al., 2017). Within this background, an accurate load forecasting is

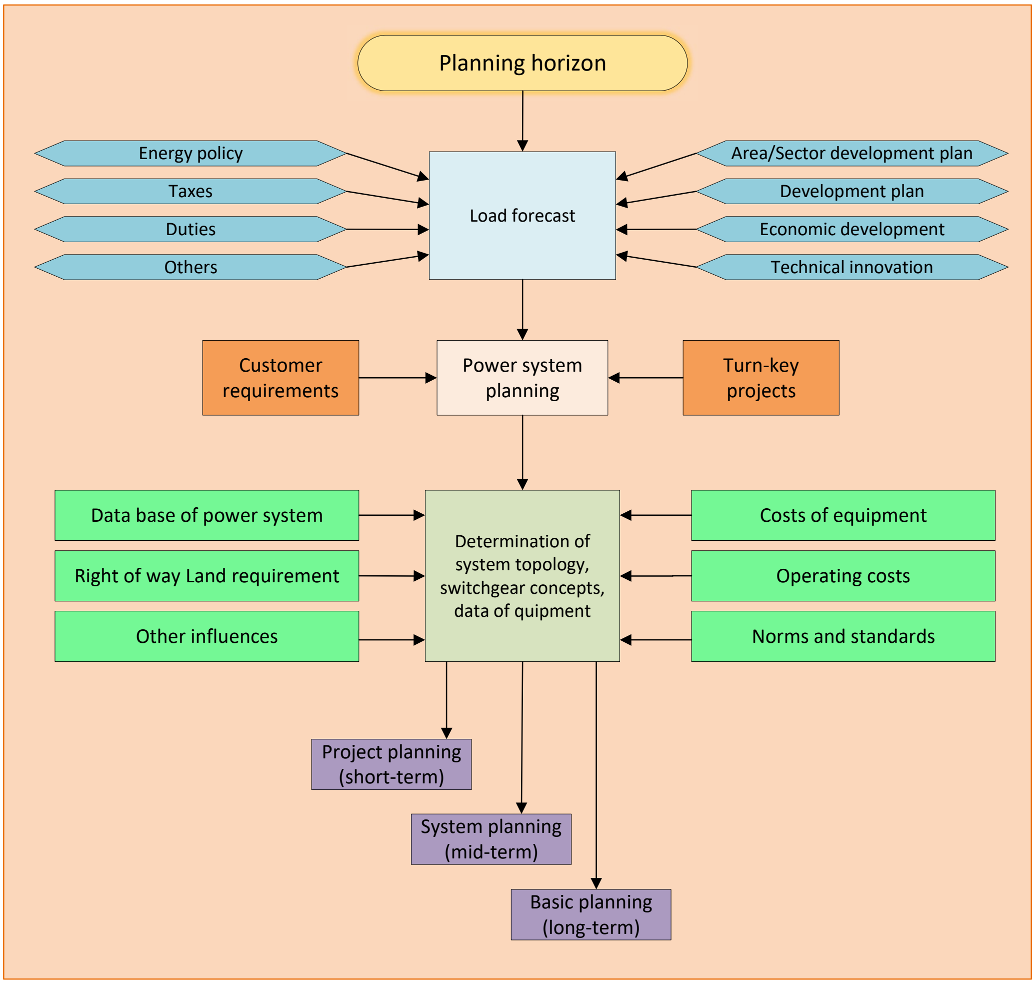

Figure 3.2: Major relations on planning of electric networks that include social, economical and technical requirements.

needed to measure the load increase due to customers, which is indeed affected by economic and social developments, fiscal incentives and regulations. Moreover, aspects related with data base such as geographical information, rights-of-way, investments and operational costs are fundamental in power system planning, as shown in Figure 3.2 (Huang et al., 2021; Kazmi et al., 2017).

3.2 A Time Horizon Perspective Planning Process

Within power systems there are several electrical studies that can be performed in time horizon. Operation of power system is normally executed with tasks with a duration between minutes - to one week, whilst power system planning is related with large time horizon between 1 year up to 20 years. Figure 3.3 shows a comprehensive time horizon, where it is depicted different kind of electrical studies that can be executed. Power system operation is related to electrical studies such as optimal power flow, economic dispatch and unit commitment, which are normally executed with a time frame of minutes to hours, or even up to one week. The time horizon between one week up to one year is called operational planning, where utilities analyze the possible scenarios of operation considering the availability of different components of the entire network based on its maintenance scheduling (Li et al., 2017; Khuntia et al., 2015).

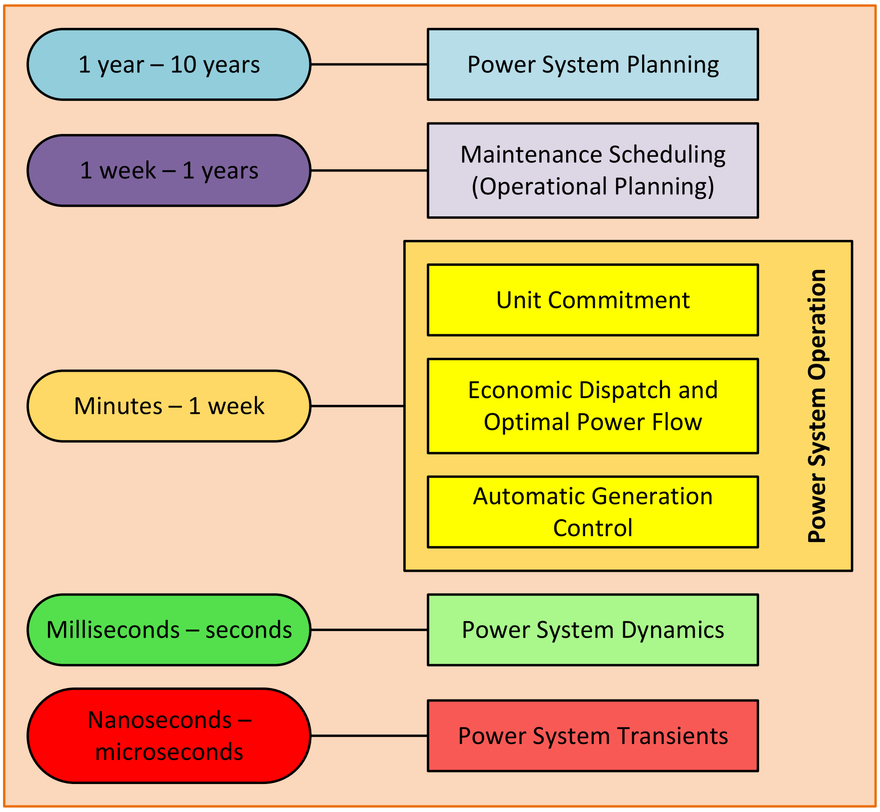

Figure 3.3: Time horizon of power systems studies (Seifi and Sadegh, 2011).

Generally an electric planning considers three stages which can be defined as basic planning, development planning, and project planning, where each of one covers different horizon periods as can be seen in Figure 3.4. Basic planning states fundamental concepts and guidelines such as nominal voltages, basis of power system operation, standards and norms, which could be validate in a period of time up twenty years. The development planning or long-term planning is related with a time horizon of ten years, where detailed load forecasting and a variety of design alternatives are analyzed based on electric simulations and cost estimations. The highlighted parameters predict the system behaviour for these longer periods, normally long-term planning is associated with transmission networks. Finally, project planning stage or short-term planning is related with more precise and particular tasks like connection of new customers, evaluation, control and super-

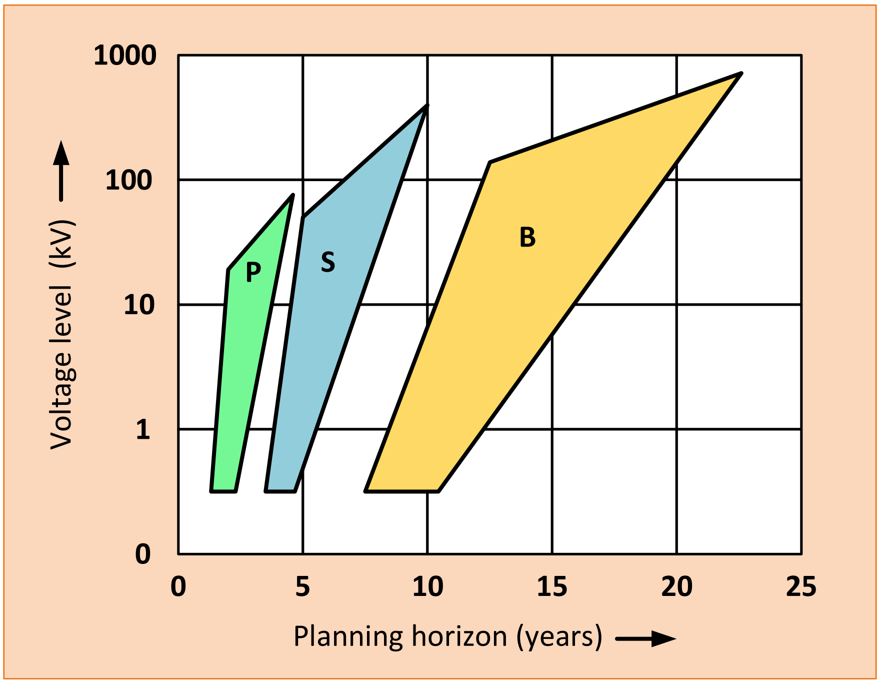

Figure 3.4: Different stages of planning at different voltage levels (Seifi and Sadegh, 2011).

vision of construction contracts predicting the system behaviour in a period of time between one to four years depending the complexity of works (Li et al., 2020; Gonzalez-Romero et al., 2020).

As it can be noted, the time horizon of planning is related to different tasks and stages in power systems, consequently a transmission planning is focused to provide electricity to local and regional customer loads considering voltages within operative limits. In addition, an adequate transmission planning should contemplate the capacity of withstand abnormal events and disturbances contributing to the overall system integrity, also avoiding overloading of transmission lines, power transformers or generators. On the other hand, distribution planning is oriented to meet customer demand by increasing electrical equipment such as distribution transformers, medium and low voltage networks; consequently it is needed to take into account an adequate load forecasting to estimate a value of energy consumption meeting power quality parameters like harmonic level, voltage dips, voltage unbalance, flicker, and also long duration interruptions (Li et al., 2017; Vai et al., 2021; Valenzuela et al., 2017).

3.3 Planning on Electrical Networks

Planning studies are performed considering future scenarios based on social, economic, technological and financial aspects; the objective is to provide the better supply service at the lowest cost meeting technical requirements such as quality of supply, reliability and safety. Reliability will be influenced not only by factors like the topology of the grid, equipment selection, maintenance schedule, and even qualification of employees, but also by the reduction of insulation strength on equipment, malfunction of control and protection systems, external and unusual events like floods, storms and even human influences.

3.3.1 Planning Principles

In general terms, power systems planning principles should consider at least the following aspects: (Valenzuela et al., 2019b; You et al., 2014; Müller et al., 2019).

- **Thermal loading of electric components**
  An excess of thermal loading in cables, transformers, or any other equipment could lead to a reduction of the insulation strength, consequently a probable reduction of life-time.

- **Generation, transmission and distribution capacity**
  The expected load should be covered by sufficient generation capacity in order to reduce outages, consequently, transmission and distribution network should be constructed to carry the generated electricity to the overall customers.

- **Voltage levels**
  Voltage level on power system must be within a permissible and tolerable bandwidth or voltage range, to avoid malfunction of households and industrial equipment in distribution systems.

- **Economical aspects and operational conditions**
  Selection of network's topology, equipment, and other technical factors are based on economic aspects, then a suitable and favorable operating cost should be considered taking into account flexibility for future expansion.

- **Frequency control and transient behaviour**
  In normal and steady-state conditions frequency, which is a global variable, is within a reduced range. During transients due to connection or disconnection of equipment, or abnormal events, power system frequency deviations are compensated by network operation, control and protection systems.

3.3.2 Planning Criteria

Planning criteria is established by electric utilities in order to define the level of service. Consequently engineers, planners and operating personnel use these guidelines in order to maintain electrical parameters within a tolerable range. Some important criteria that must be met when an electrical network is designed.

Voltage Criteria

Voltage on busbars and nodes in power systems must be within a tolerable and acceptable range depending on voltage level under normal and abnormal operating conditions. Set in this context, At high voltage levels such as medium or high voltage, voltage must be kept between -10% and + 10% in relation with the nominal voltage, whilst, the voltage level at the Point of Common Coupling (PCC), which is the point of connection of the customer to the utility, must be kept within a tolerance between of -5% and + 5% in relation with the nominal voltage. Nevertheless, this limits for medium and low voltage levels can be different depending on the utility's standards and norms (Valenzuela et al., 2019a; Miloca et al., 2015).

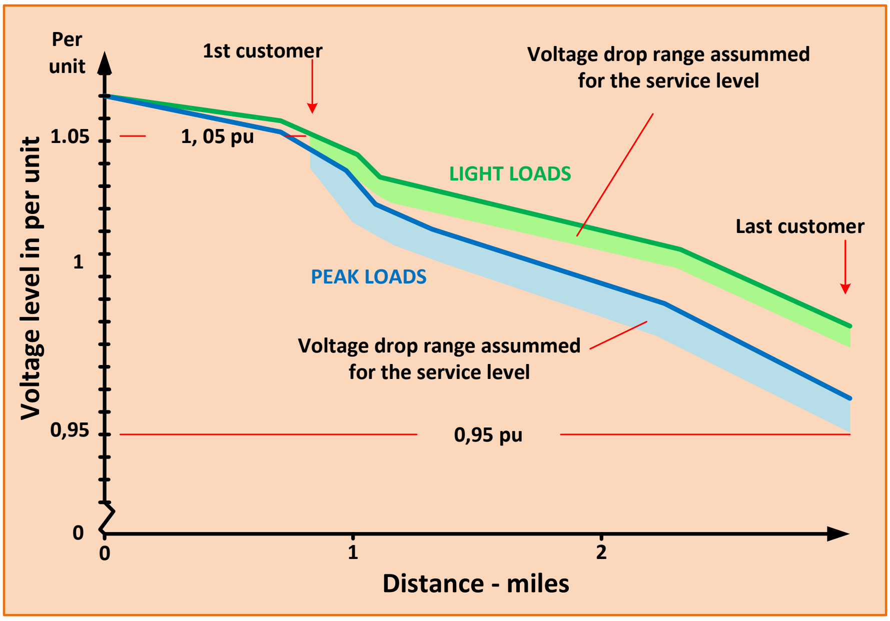

Figure 3.5: Voltage drop along a primary feeder on distribution network (Willis, 2004).

Figure 3.5 shows a voltage drop along a primary feeder; it is clear that voltage drops are inevitable on power grids due to cable impedance, then distribution network must be designed considering that the voltage at the beginning of electrical feeder and at the last part of the circuit is within voltage guidelines. Nevertheless, voltage drop will increase as load increase. Consequently, different technical solutions can be implemented to mitigate voltage drop, such as larger conductors, capacitor allocation, booster transformer allocation, tap changing transformers, however all these solutions implies an additional cost.

Loading Criteria

Loading is extremely related with permissible values of load that can be taken by electrical equipment that ensure their reliable performance without over-passing the values as defined in standards, norms and equipment specifications. However, special operating conditions during contingencies must be analyzed due to the fact that electrical equipment could overreach its nominal rating, thus reducing equipment's life expectancy.

3.4 Types of Electrical Network Design

Electrical networks are designed and constructed based on fundamental aspects such as type of load, customer's importance (hospital, military institutions, government buildings), reserve capability, consequently, radial, loop and mesh networks are predominant in power systems.

3.4.1 Radial Systems

The majority of power distribution networks on North and South America are based on this topology, where it is only one path to connect customers to the main grid. The predominance of this kind of network is not only related with its simplicity during planning, design and operation stages, but also is associated with its low planing expenditure and low investments cost. Figure 3.6 shows a radial system, which presents a simplicity of analysis because electrical parameters such as voltage, currents, and loading can be determined based on straightforward calculations, minimizing computer resources (Willis, 2004; Chen, 2017).

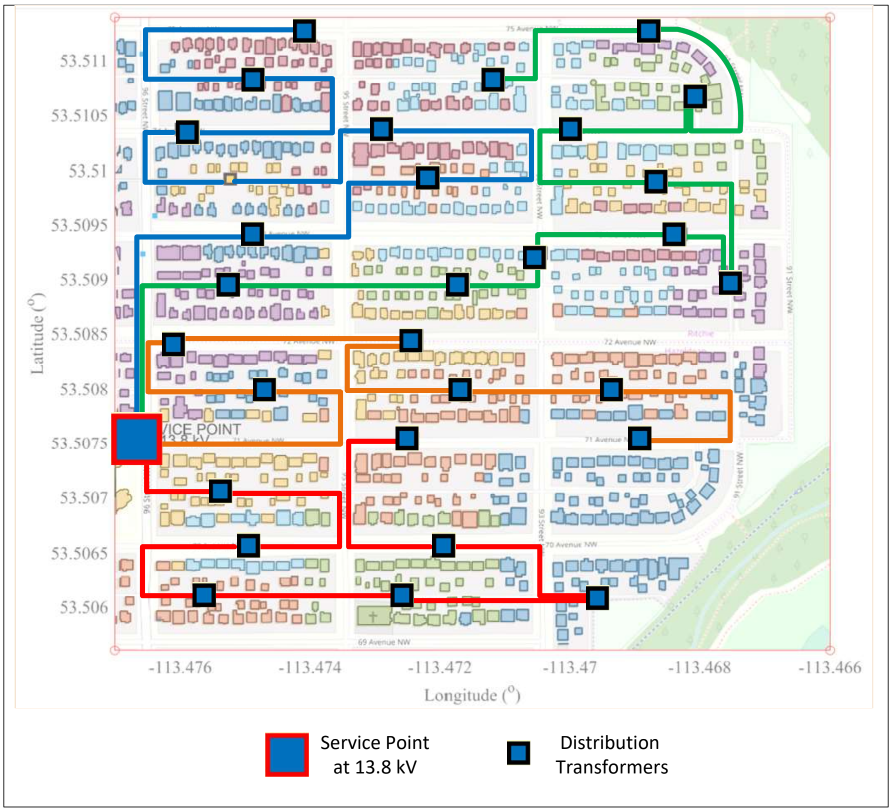

Figure 3.6: Topology of radial networks on georeferenced grids.

On the other side, a failure on this single path will result on a complete loss of supply; for this reason, radial systems are planned and constructed considering tie switches in open position, which are located in a predefined point on the network, to transfer interrupted customers onto another feeder, resulting in a electrically radial configuration.

3.4.2 Loop Systems

As it was remarked, a purely radial network can face some issues, which reduce noticeable its reliability, consequently, an accurate alternative is a loop system. This kind of network is specially designed and constructed by European utilities; the electric network can be operated in both operating conditions: radial or closed loop, due to the fact that equipment's rating is selected to be able to take the total load without overloading. Figure 3.7 depicts a loop system, which is installed in distribution and transmission networks due its reliability. As a result, electricity can be transported from two sides towards the middle point; subsequently, control and protection tasks are slightly more sophisticated than radial networks. A faulty segment of network can be isolated by circuit breakers or disconnectors reducing the interrupted area (Willis, 2004; Chen, 2017; Valenzuela et al., 2019a).

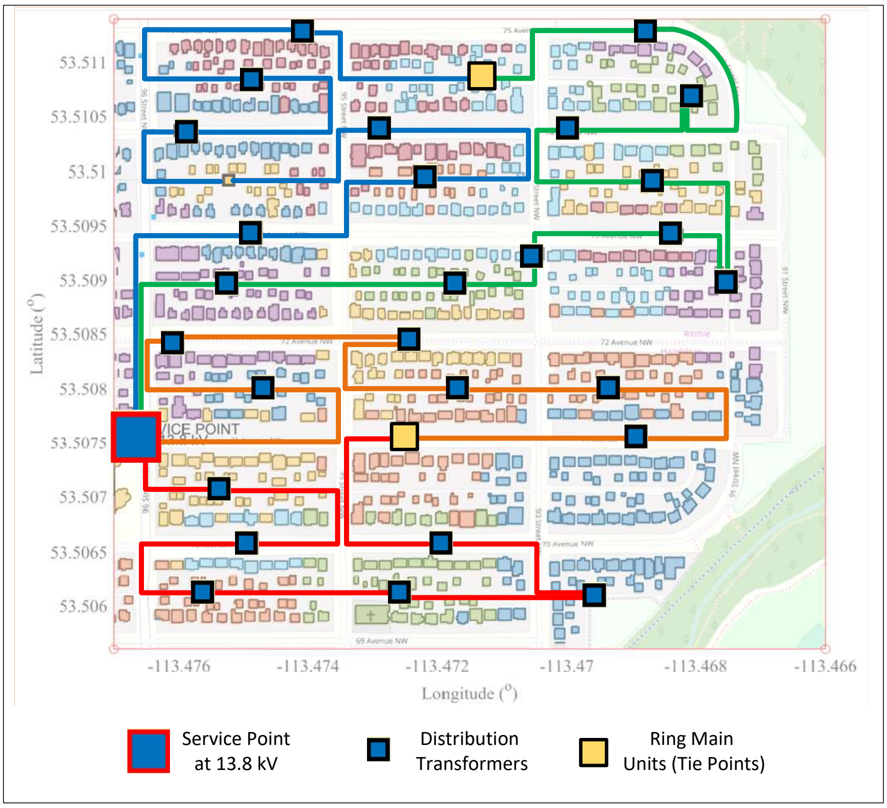

Figure 3.7: Topology of loop networks on georeferenced grids.

In contrast to radial networks, loop systems not only are more expensive, but also more complex on design, because electrical components are selected considering a higher capacity; then a more reliable, high quality, and secure network can be constructed to provide electricity to the end users.

3.4.3 Mesh Systems

A more complex and well designed topology on electrical networks is a mesh systems; aspects such as security, high quality and reliability are met due to the fact that if any event or fault occurs in one segment of the network, the network is capable to provide continuity of service based on its multiples paths to transport electricity to customers. Figure 3.8 highlights a grid mesh on georeferenced distribution networks (Willis, 2004; Vai et al., 2021).

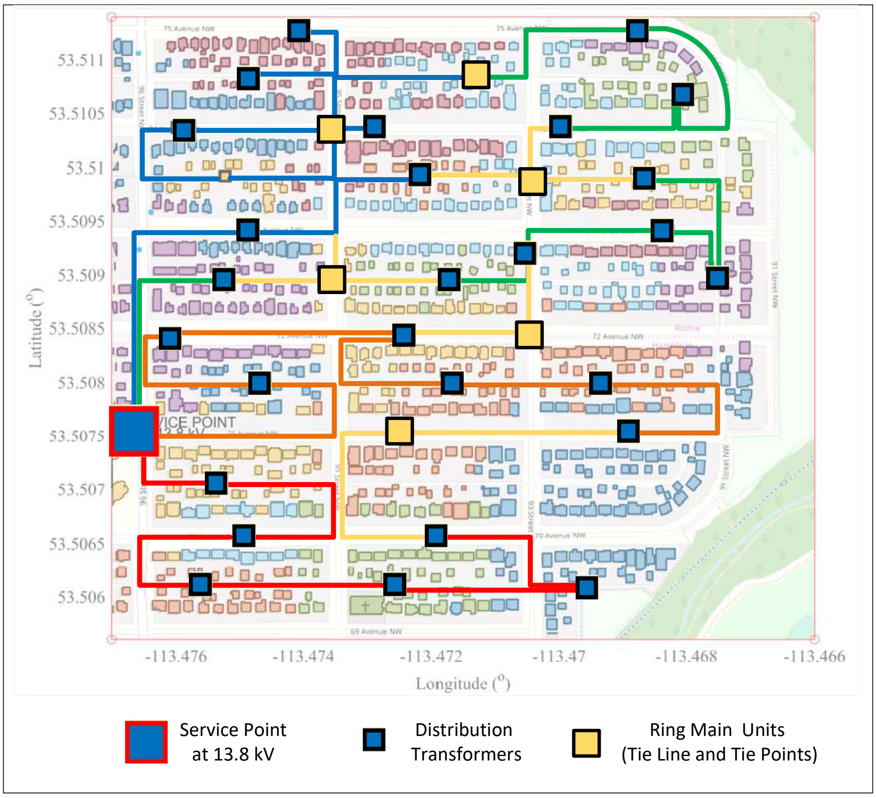

Figure 3.8: Topology of mesh networks on georeferenced grids.

Populated areas and financial districts are characterized by higher load density, where maintenance and repair tasks are difficult to develop due to congestion and traffic. Hence, underground and meshed networks are needed to connect service transformers to main grid. Under these considerations, meshed networks present more advantages than other kind of network because they keep an stable voltage profile, that means a minimal difference between the voltage at distribution substation and voltage at distribution transformers, which are known as service transformers as well. Furthermore, an increased level of flexibility during contingencies due to its control and protection systems, which permit to operate circuit breakers to isolate faults.

On the other hand, a meshed network implies a much complicate and complex network to assess due to the fact that power flow, fault analysis, and protection coordination should be performed using specialized software, and also personnel should develop more particular skills.

3.5 Automated Planning Tools

Different alternative and layouts can be contemplated during a design stage; Therefore, it is needed to use a decision support tool to analyze the outstanding design based on optimization.

As it was remarked above, not only planning process, but also optimization techniques are composed by three well defined steps like identification, evaluation and selection. Consequently, an optimization technique identifies all possible alternatives for solving a planning problem, then it evaluates them based on some constraints and finally the optimum solution is selected. Identification is focused on search through all feasible alternatives; thus, the chosen technique should be capable to produce all possible variations automatically based on the description of the planning problem. Evaluation is related to the assessment of each alternative determining if the analyzed alternatives meet with constraints. Finally, selection of the most favourable alternative is the last stage, which is chosen as the best solution based on the objective function and their constraints (Lin et al., 2018; Clack et al., 2014).

After these considerations, planning problems must be established considering variables, constraints functions and also objective functions. Decision variables are those variables which reach its maximum or minimum value, and then dependent variables can be determined based on those. Constraint functions are those limitations imposed by planning problem such as voltage above a defined value, load must not exceed capacity rating, or configuration must be radial. Not only technical constraints, but also economical, environmental can be defined on planning problems. An objective function is that function in terms of independent variables by which the planning problem finds its desirable solution (Lin et al., 2018; Seifi and Sadegh, 2011). The total cost or system losses are examples of objective functions.

$$\begin{gathered} Minimize \quad or \quad Maximize \quad C(x) \\ Subject \quad to \quad g(x) \leq b \end{gathered} \tag{3.1}$$

A generic optimization problem has the form of Eq. 3.1, where x represents the decision variable, $C(x)$ is the objective function and finally constraints are showed as $g(x) \leq b$

Consequently, optimization methodologies can be classified in different ways as can be seen in Figure 3.9, which reports deterministic, stochastic and heuristic and artificial methods. Deterministic methods involve mathematics on their algorithms, which could guarantee an optimal solution, which in some of cases that solutions does not reach a global optimum. Normally, a global optimum is guaranteed in some simple and special cases. On the other hand, heuristic and artificial intelligence methods are developed to solve complex and combinatorial problems, where a global optimum is reached in a reasonable time sacrificing optimality and precision (Lin et al., 2018; Clack et al., 2014).

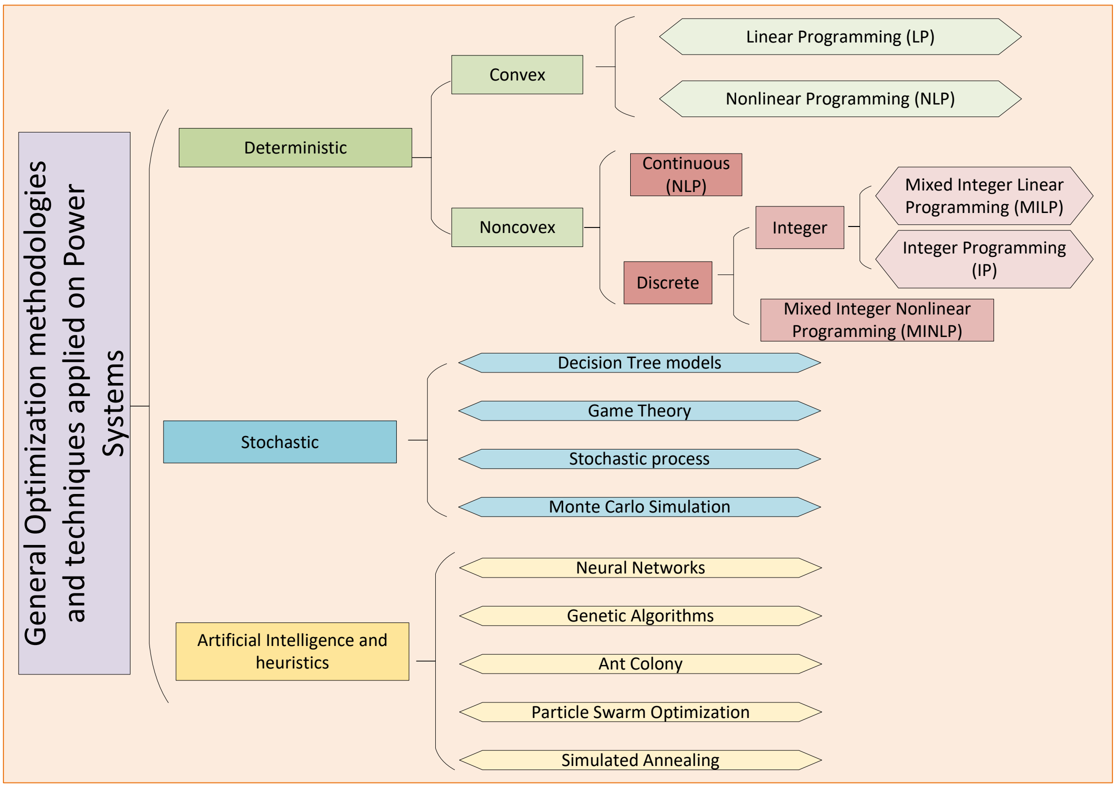

Figure 3.9: Traditional and modern planning aspects (Lin et al., 2018).

Table 3.1 summarizes some the most important optimization algorithms applied to different applications on power systems (Clack et al., 2014; Lee and Vlachogiannis, 2005; Soliman et al., 2004; Alrashidi et al., 2010; Lin et al., 2018; Solomonese et al., 2013).

Table 3.1: Several types of optimization methods applied on power systems.

Type	Algorithm	Description	Application
	Linear Programming	It is known as LP, where the objective function and constraints are linear functions	Power system planning and operation
	Integer Method	Decision variables considers only certain discrete values as possible solutions	Generation expansion

Mathematical Optimization	Mixed Integer Method	Method can handle variables that are continuous and integer. A Mixed Integer Non Linear Programming has been developed (MINLP) has been developed due to the problem nature	Demand forecasting, transmission expansion planning
	Dynamic Programming	Method used for multistage decision problems, in which a part of the problem is isolated and optimized, after that another part is evaluated up to entire problem has been analyzed	Generation dispatch and unit commitment
Heuristic Optimization	Adaptive Neural Networks	They are set using a feedback that causes them to change their coefficients in response to their results, consequently better solutions are achieved	Solar and wind forecasting
	Genetic Algorithms	Based on genetic and evolution process, subsequently, the objective function is used on a random by guided way to improve the likelihood of reaching better results close to the global optimum	Power system analysis and operation
	Simulated Annealing	Based on thermodynamic principles, which is used on combinatorial problems to find a global optimum. objective functions and constraints can be non differentiable, discontinuos and non convex functions	Harmonic estimation, long-term hydro scheduling problem
	Particle Swarm	Method based on natural behaviour of birds and fishes, where each individual coordinates its movements to the destination without collision among individuals. This method uses the fitness function value to guide the search for optimality avoiding derivative information	Economic power dispatch, reactive power compensation, power system operation

	Ant Colony	Method based on ants behave, where ants have the particularity to find the shortest distance between to points, even if there is an obstacle between points. The search area on this kind of methodology correspond to a discrete set of solutions	Active and reactive operational planning

3.6 Protection of Distribution Networks

Protection coordination of overcurrent relays is very useful to protect distribution networks, since they are designed to operate when current reaches high levels during an abnormal event. These elevated values of current are used to calculate the parameters for the adjustment of overcurrent relays. Overcurrent relays normally incorporate some operating characteristics, such as definite-current protection or instantaneous protection, which are implemented to protect power transformers due to the unique setting parameter is the current. Another type of relay is definite-time/current, which has the particularity to operate based on fixed steps of time. Finally, a more generalized kind of operating characteristic is based on an inverse-time overcurrent protection, which is employed to protect distribution networks. The three characteristics applied on electrical systems are depicted in Figure 3.10.

3.6.1 Inverse-Time Overcurrent Protection

As remarked above, a protection relay is a device that compares one or more signals to a reference value and emit an alarm when the input signals get higher than the preset value. The most used protection devices on distribution networks are inverse time overcurrent relays, which are activated by the increase of current levels, consequently it emits a signal that indicates to energize the circuit breaker, clearing the short-circuit (Vai et al., 2021).

The operation of this relay depends on its ability to detect a fault in its protection area, but it is limited because the current is the unique measured parameter, which is sensitive to the system's operating conditions and the topology presented towards the point of failure. Therefore, the operation of an overcurrent relay depends on the following setting parameters: the current setting (I_s) or pick-up current, which is the value the relay will start, and the Time Multiplier Setting (TMS) or time dial, which is an adjustment that permits to set the time delay before the relay operates whenever the fault current reaches a value greater than the current setting (Saldarriaga-Zuluaga et al., 2021; Sisitha and Hemapala, 2020).

Overcurrent of protection is considered as inherently non-selective, due to their immediate or delayed action when detecting a considerable increase in current,

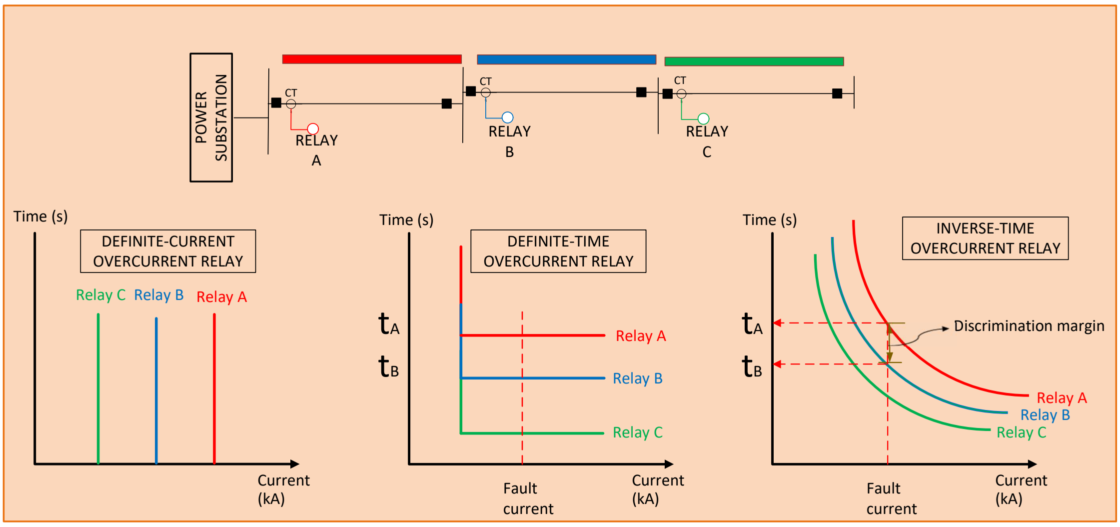

Figure 3.10: Time/current operating characteristics of overcurrent relays.

which causes them to act without considering protection zones. Nevertheless, this problem can be solved with a correct protection coordination taking into account a discrimination margin. Consequently, an adequate selection of pick up current and time multiplier setting permit to satisfy technical requirements such as selectivity, sensitivity and speed (Sisitha and Hemapala, 2020; Vai et al., 2021).

The main property of these overcurrent relays is its capacity to operate in a time that it is inversely proportional to the fault current. Therefore, the activation of an inverse time overcurrent relay is characterized by a curve that defines the operating time of the protection device for various current magnitudes. Therefore this curve allows the relay to operate slowly at low overcurrent values and as the current increases, the action time decreases. There are several types of inverse time curves, which are mathematically modeled under the IEC, ANSI / IEEE standards and manufacturer policies. Table 3.2 shows the parameters that are used for different manufactures for overcurrent relays (Gers, 2011). For this work, an standard inverse IEC curve will be used to carry out the automatic coordination of overcurrent protections. In particular, Eq. (3.2) shows the mathematical models of the inverse time curves:

$$t = \frac{TMS * \beta}{(I/I_s)^{\alpha} - 1} + L \tag{3.2}$$

where:

t is the operating time in seconds
TMS is the time dial or time multiplier setting
I is the fault current level at the secondary side of current transformer
I_s is the current setting expressed at the secondary side of current transformer
L, α, β, are constants defined according to the standard considered, as summarised in Table 3.2

Table 3.2: ANSI/IEEE and IEC constants for overcurrent relays.

Curve Description	Standard	α	β	L
Moderately inverse	IEEE	0.02	0.0515	0.114
Very inverse	IEEE	2	19.61	0.491
Extremely inverse	IEEE	2	28.2	0.1217
Inverse	CO8	2	5.95	0.18
Short-time inverse	CO2	0.02	0.0239	0.0169
Standard inverse	IEC	0.02	0.14	0
Very inverse	IEC	1	0.0515	0
Extremely inverse	IEC	2	80	0
Long-time inverse	UK	1	120	0

3.6.2 Coordination Protection

As remarked above, there are two basic parameters to set an overcurrent relay. Those parameters are the TMS and pick up current, which allow to adjust the characteristic curve in order to be activated for a given value of time and current. Before calculating these parameters, a short-circuit analysis must be carried out to know the value of the short-circuit current at the most critical point of the relay protection zone, which is associated with the furthest point of protection. The pick-up current is the most essential parameter, which is the value that will trip activate the protection, thus allowing the change of state in the relay. The pick-up current is expressed as:

$$I_s = \frac{I'_s}{CTR} \tag{3.3}$$

where:
CTR is the Current Transformer Ratio
I'_s is the current value expressed at the secondary side of current transformer
I_s is the current setting expressed at the secondary side of current transformer

A protection coordination is a process in which the operating times of the overcurrent protections are defined in order to allow a prioritized trip based on the activation order, minimizing the tripping times and guaranteeing selectivity. Consequently, it is possible to have an appropriate graduation in the operating times of all relays that are part of the protection system. The TMS of an inverse time overcurrent relay is a parameter that allows the characteristic curve of a relay to be adjusted to a predetermined tripping time of a specific current. An important aspect to be considered is the discrimination margin, which is a margin time used between two successive time/current characteristics. Common values of discrimination margin are between 200ms to 400 ms, which avoid losing selectivity due to excessive breaker opening times, variation in fault level, and error in current transformers (Sisitha and Hemapala, 2020; Barra et al., 2020).

As remarked above, an overcurrent protection is a valuable device during a restoration procedure due to the fact that the overcurrent protection relays detect faults or abnormal operating conditions caused by the presence of an overcurrent in the system. Therefore, the adjustment and coordination must be characterized by its sensitivity, speed and selectivity. Sensitivity is a characteristic that allows the detection of abnormal conditions no matter how incipient they may be, allowing the protection to distinguish between normal and abnormal operation of the distribution system. The other requirement is the speed, associated with the operating time of the relay, which must clear the fault in the shortest time. Finally, selectivity requires an adequate adjustment to detect all the faults in the respective protection zones that are assigned to each relay. Within this background, a protection coordination of overcurrent relays is based on the determination of the operating conditions of the system in order to define the thermal limit of different electrical components, ensuring that current not overpass its nominal value in normal operating conditions.

Considering the network's configuration, it is needed to execute a fault analysis in the furthest busbar in order to determine and adequate value of current setting and time multiplier setting. It also requires a very coordinated action, in order to disconnect the affected zones while maintaining the supply of energy in unaffected areas. Consequently, it can be stated that the main objective of the adjustment of protection coordination problem consists of achieving a total selectivity with the maximum sensitivity and speed. Nevertheless, it is worth noting that these parameters are not independent, as two of them are more likely to decrease when the other one increases (Saldarriaga-Zuluaga et al., 2021; Vai et al., 2021; Nascimento et al., 2020).

Chapter 4

Simulations and Results

The present chapter is divided in three main sections, which report simulations and results related to the expansion of electrical networks considering protection coordination. The first section deals with a practical methodology to develop a resilient planning distribution network based on real georeferenced data. Information of customers' demand and their location represent fundamental data to determine the optimal allocation of distribution transformers, where the minimal construction cost is achieved due to the reduced distance of low and medium voltage networks. The second section proposes the implementation of an intelligent decision-making tool, that carries out the design of network distribution system considering electrical company standards. It is exploited to have a clear and quick initial overview of the configuration that an electricity network should have in response to an increasing demand, considering not only the coverage and capacity of the transformers but also voltage drop along the conductors. Finally, the third section is focused on the implementation of a topological reconfiguration tool, which is centered to change the structure of primary feeders based on changing the status of switchgears. After the distribution network is reconfigured, an algorithm of protection coordination is executed based on communication peer-to-peer between Matlab and PowerFactory [1], which develops an adaptive calculation to determine the current setting and the time multiplier setting. The reconfiguration and coordination protection algorithms could be developed and evaluated on different distribution networks,areas and locations.

4.1 Planning of a Resilient Distribution Network

The complexity and growth of power systems have modified the operation procedures since local grids have been extended to regional or national grids, and currently it is extensively common to interconnect neighbouring countries by transmission lines at high voltage levels. According to ANSI C84.1-2020 [2] voltages from

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[1] web page: https://www.digsilent.de/en/powerfactory.html

[2] American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz)

69 kV to 1100 kV are referred as high voltage and extra high voltage, whereas medium voltage refers to voltages between 0.6 kV to 69 kV; finally voltages from 0.6 kV and below are referred as low voltage. Not only a transmission grid, which operates at high voltage levels, but also distribution networks have been evolved to loop and mesh grids from conventional networks constituted mainly radial. Consequently novel equipment and electrical devices have been enabled in modern grids to meet technical requirements such as quality of supply, reliability and safety (Figueroa-Candia et al., 2018). However, under certain unusual conditions such as lighting discharges, insulation ageing and disasters, a failure in electricity network could cause a short- or long-term loss of the electric power, leading to a cascading outages and causing a catastrophic impact on transmission and distribution system operations (Amraee and Saberi, 2017).

After these considerations, distribution networks are exposed to uncontrollable and mostly unexpected events; therefore, planning, design and implementation of distribution grids considering tie points and switch equipment in radial networks, deployment and allocation of Distributed Generation (DG), mobile power transformers and feeder's reconfiguration are valid techniques and strategies to provide a rapid restoration avoiding unintentional load shedding. The connection of generators to the grid will have an impact on the operation of the network. Positive benefits of DG are related with enhancing the reliability, resilience and integrity of the network, nevertheless, some difficulties and problems could give rise with DG deployment. Generator fault level contributions can surpass the rating of electrical equipment, steady-state rise in network voltage levels is an issue if the amount of the generated power exceeds the local demand. Voltage flicker and harmonic pollution could be produced by static power conversion equipment used to couple photovoltaic systems to the network (Li et al., 2014).

4.1.1 Network Planning Based on Theory Graphs

Distribution network planning is not only associated with newly-built districts where public facilities, residential and commercial areas are growing, but also with existing regions which have a deficient level of efficiency and insufficient capacity. Therefore, Distribution network operators have the responsibility to design and plan novel and modern grids, based on sophisticated communication, control and automation capabilities, which allow the flexibility of power grids to be enhanced. Electric network transformation is mainly caused by the incessant growing of electric demand, integration of intermittent renewable sources and electric vehicles (Valenzuela et al., 2017). These new requirements could exceed the capacity of distribution equipment since current distribution networks were planned considering generic profiles of domestic, commercial and industrial customers. Consequently, the planning, design and reinforcement of power distribution networks face economical and technical challenges. Technical challenges are associated with operative constraints such as adequate voltage profile, accurate selectivity on protection system, and quality of supply. Whilst economical aspects are related with short-term and long-term investment considering minimum cost.

Distribution grids generally are developed in radial topology, where a unique path between the source and end users is built using overhead lines or underground cables. This topology is the cheapest and is widely used in urban and rural areas. Additionally, any disaster in the grid will interrupt the power flow, consequently it will result in complete loss of power to the customer. Normally open points (tie points) installed in strategic locations within primary feeders are used to transform a radial grid into loop or mesh systems. The last aforementioned topology is more complex to analyse, nevertheless those systems provide better continuity of service than the common topology (radial system). Subsequently, the operation of tie switches will provide operational flexibility and it will reduce the number of supply interruptions caused by natural disasters, faults or scheduled maintenance. Therefore, graph theory has been studied as a tool for planning and reconfiguration in distribution networks, where the reconfiguration is determined by opening and closing switching devices, whilst planning and design deal with optimal location of the distribution transformers and tie points considering the end user positions (Mosbah et al., 2017).

Planning and sizing of distribution systems are required in order to develop an efficient, reliable and secure grid, therefore, this stage allows to minimize the construction costs and reduce utility's budget based on the optimal allocation of technical resources such as distribution transformers, conductors and switching devices. Generally, a power distribution grid is comprised by several distribution substations, which are located near to main loads, additionally each substation is composed by a variety of primary feeders, which typically are operating in a radial configuration. Nevertheless open ties are taken into account to reconfigure the initial topology reducing downtimes (Li et al., 2016; Xie et al., 2018).

Within this background, the topology of distribution can be modified and reinforced after a construction in order to increase resilience, reliability and security. However, this part of the project is focused on planning stage, where there are no existing facilities and solely georeferenced data is available, then an accurate design should meet the requirement imposed by the expected load in future. Future end customers are normally clustered in different categories considering the electricity usage and their associated used equipment (residential, commercial and industrial). Nevertheless, some utilities have divided residential customers in categories based on the load profile and electricity consumption, hence, large populations are represented by a strata with similar electricity consumption pattern (Raeisi-Gahrooei et al., 2018).

Distribution networks constitute a local infrastructure that is comprised by several substations near to a populated area, which operates at primary voltage levels (46 kV to 132 kV). The power substation is not only comprised of switching and protection equipment, but also it has a control and energy management system. The control system permits the automatic connection and disconnection of three-phase primary outgoing feeders which are linked at the low voltage side of the power transformer (6.3 kV to 33 kV). Primary feeders are distributed in the surroundings of the power substations, and they are the physical medium to transport electricity to loads via a number of overhead lines or underground cables. Underground schemes are used not only in densely populated urban areas, but also in zones where high levels of reliability and resilience are required since underground cables eliminates susceptibility to wind damage, lightning, ice and wind storms and vegetation contact. The customer's load cannot be supplied at medium voltage levels, so distribution transformers are used to provide the final voltage level at 220 V phase-to-phase.

After these considerations, a MV underground network is composed by several padmounted distribution transformers, which meet the calculated demand design and voltage regulation requirements. In addition, Ring Main Units (RMU) are employed to provide connections to transformer and possible isolation points along the primary feeder. RMUs represent an equipment completely sealed and used indoors or outdoors, which comprise switching devices that can be either circuit breakers, disconnectors, fuses and bays for transformers. These elements are extensively used in underground grid in distribution systems because they provide continuity of service, allowing network reconfiguration, and ensuring reliability for the grid and security for operators during operations in place and remote operation during abnormal conditions. On the other hand, the Low Voltage (LV) underground network is characterized by a radial topology due to the fact that a disturbance in LV grid has a minimum impact on the grid's operation since a reduced number of end customers are affected during a contingency. Universally, these end users are connected to the low voltage grid in the nearest junction box, which are placed in range between 30 and 50 m, and also they are located near street intersections (Santos et al., 2017).

Distribution network planning is mainly related with a tree-topology, then graph theory can be applied to solve the planning problem, which is considered as NP-complete problem [3] due to its combinatorial nature (Zhai et al., 2018; Bajpai et al., 2016). Additionally, clustering algorithms, like k-medoids or k-means, are focused to break the dataset up into groups, minimising the distance between the center of the cluster and each corresponding nodes. The aforementioned algorithms are used to subdivide dataset of n objects building into k clusters (primary feeders), therefore nodes are represented as distribution transformers. Contrastingly, minimum spanning tree algorithm such as Kruskal[4] and Prim [5] can be used to find the primary feeder route which connects each distribution transformer considering the shortest path (Mosbah et al., 2017; Moradijoz et al., 2018). Spanning tree problems not only are used to solve electrical problems, but also they are applicable in other sciences such as computer and communication networks, wiring connections and circuit design (Valenzuela et al., 2019a). Prim's algorithm finds a minimum spanning tree for weighted undirected graph, where the spanning tree

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[3] It is any of a class of computational problems for which no efficient solution algorithm has been found. Many significant computer-science problems belong to this class—e.g., the traveling salesman problem, satisfiability problems, and graph-covering problem, routing problem

[4] Kruskal's algorithm finds a minimum spanning forest of an undirected edge-weighted graph. If the graph is connected, it finds a minimum spanning tree.

[5] Prim's algorithm is a greedy algorithm that finds a minimum spanning tree for a weighted undirected graph

is connected one vertex at time, consequently, at each step the nearest vertex is added to the tree (Wang et al., 2014).

For the present part of the project,the medium voltage network is designed considering a modified Prim algorithm, the aforementioned algorithm is based on prim algorithm, however, modifications permit to find the minimal path in less time. The modified Prim needs a graph G = (V,E) of order n and size m, then spanning tree T of G is defined as a connected graph spanning all the vertices of the vertex set V with exactly n-1 edges belonging to the edge set E, considering there are not loops formed. Set in this context, modified Prim algorithm find the minimal tree cost taking into account that the created tree has a subset of edges, where every node is included in each step assuring the minimal cost (Mosbah et al., 2017; Moradijoz et al., 2018; Wang et al., 2014). Not only the MV grid but also the distribution transformers location are based on modified Prim algorithm, where transformers are placed and sized in a georeferenced map using the end user demand and the minimal distance between end user and manholes. The manholes are commonly located in the sidewalks on main streets, and they are used as point of connection from the main grid to the consumer premises. The placement of distribution transformers is based on the equivalent loading gravity center where the load demand of customers is used to find the equivalent location of the total demand within each small area by Eqs. 4.1 and 4.2. The procedure guarantees that the transformer is located near to the most loaded nodes.

$$Lo_{dt} = \frac{\sum_{i=1}^{n}(Lo_i * S_i)}{\sum_{i=1}^{n}(S_i)} \tag{4.1}$$

$$La_{dt} = \frac{\sum_{i=1}^{n}(La_i * S_i)}{\sum_{i=1}^{n}(S_i)} \tag{4.2}$$

where S_i represent the load demand associated in each manhole i at location expressed in latitude and longitude (Lo_i, La_i). Consequently, the coordinates of each transformer is calculated as Lo_{dt} and La_{dt}, respectively (Chuang et al., 2014).

4.1.2 Problem Formulation

Underground network planning considering a resilience approach is a combinatorial problem defined as NP-complete, where the connection between customers and the main grid on a georeferenced scenario is dealt using a heuristic model based on MST techniques. The project deals with the optimal location of distribution transformers using a modified Prim algorithm based on the minimal cost of low voltage network between transformers and end customers. Secondly, clustering algorithms are used to break the data set (number of distribution transformers) up into groups, then k-medoids algorithm [6] determines the a defined number of clusters, which can be used as primary feeders. The next stage deals with the built up the medium voltage network based on modified Prim to determine the

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[6] The k-medoids problem is a clustering problem, which attempts to minimize the distance between points labeled to be in a cluster and a point designated as the center of that cluster.

Table 4.1: Parameters and variables.

Nomenclature	**Description**
X_{st}, Y_{st}	Street point positions (Latitude and Longitude)
X_s, Y_s	Residential customers' locations (Latitude and Longitude)
X_{box}, Y_{box}	Manhole's position (Latitude and Longitude)
X_{tra}, Y_{tra}	Transformer's position (Latitude and Longitude)
X_{rec}, Y_{rec}	RMUs positions (Latitude and Longitude)
$dist_{box}, dist_{ub}$	Distance matrix (variable dimension) for LV network
$dist_{tra}, dist_{MV}, dist_{rec}$	Distance matrix (variable dimension) for MV network
$G1, G2$	Connectivity matrix
kl, km, kn, kp, kj	Variables for loop control
$tmp, sum_{tmp}, k1_{tmp}, k2_{tmp}$	Temporary variables
$[user\ ibu]$	Residential customers connected to the nearest manhole
dem_{us}	Residential customer' demand
D_{boxes}	Associated manhole demand
n	Number of residential customers
m	Capacity Restriction
$primary$	Number of primary feeders
$path1, path2$	Connectivity route for medium Voltage grid and tie-lines
d_{mbox}, d_{mMV}	Route selection criteria
$loc, flag, rpos, cpos, z$	Complementary variables

lowest path between main substation and distribution transformers on a georeferenced path. The improvement of resilience is handled by the optimal location of tie points in medium voltage network, consequently, the operation of RMUs will provide operational security and flexibility reducing downtimes due to abnormal events. Finally, power system simulations are executed on PowerFactory to determine the functionality of the proposed methodology. Variables and parameters are summarized in Table 4.1.

Algorithm 1 is used to develop the planning of a resilient distribution network. In addition, the second step considers the connection between end users and low voltage grid in the nearest manhole, and consequently a manhole's demand is calculated by the connected end user's demand. The third step determines the location of distribution transformers considering the manholes' position and their demand. Subsequently, different scenarios can be simulated and analysed, where the position and the kVA rating of distribution transformers are determined based on maximum length of low voltage grid within a voltage drop restriction.

Algorithm 1 Planning of a Resilient Distribution Network

```
$Step\ 1\ :\ Manhole\ Allocation$
$U_{st} = [X_{st}\ Y_{st}]$
$dist_{box}\ \leftarrow\ haversine\ [U_{st}\ U_{st}]$
for $kl \rightarrow 1 : dist_{box}$ do
    $sum_{tmp} = dist_{box}\ (kl) + dist_{box}\ (kl+1)$
    if $sum_{tmp}\ \geq\ d_{mbox}$ then
        $find\ [X_{box}\ Y_{box}]$
    else
        $next$
    end if
end for
$Step\ 2\ :\ Network\ Operator's\ Service\ Cable\ Allocation$
$U_s = [X_s\ Y_s];\ n = length\ [U_s]$
$U_{box} = [X_{box}\ Y_{box}]$
$dist_{ub}\ \leftarrow\ haversine\ [U_s\ U_{box}]$
for $km \rightarrow 1 : length\ (U_{box})$ do
    $k1_{tmp}\ \rightarrow\ (min(min(dist_{ub})))$
    if $length\ (k1_{tmp})\ \neq\ 0$ then
        $[user\ ibu] = find(dist_{ub} == min(min(dist_{ub})))$
    end if
end for
for $kn \rightarrow 1 : length\ (ibu)$ do
    $D_{boxes} = sum(dem_{us}(dist_{ub}))$
end for
$Step\ 3\ :\ Distribution\ Transformer\ Allocation$
$dist_{tra}\ \leftarrow\ haversine\ [U_{box}\ U_{box}]$
while $loc\ \leftarrow\ 1$ do
    $flag = 1$
    while $flag\ \leq\ m$ do
        for $kp \rightarrow 1 : length\ (X_{box})$ do
            $k2_{tmp}\ \rightarrow\ (min(min(dist_{tra})))$
            if $length\ (k2_{tmp})\ \neq\ 0$ then
                $[rpos\ cpos] = find(dist == min(min(dist_{tra})))$
                $loc = [loc\ U_{box}(kp)]$
                $next$
            else
                $flag == 0$
            end if
            if $length\ (loc)\ \geq m$ then
                $flag\ \leftarrow\ 0$
            end if
        end for
    end while
end while
$tmp \leftarrow loc$
while $z\ \leq\ length\ (X_{box})$ do
    $G1\ (tmp\ ,\ tmp) = 1$
    $z = z + length\ (tmp)$
end while
$X_{tra}\ \leftarrow\ sum(D_{boxes}) * X_{box}/sum(D_{boxes})$
$Y_{tra}\ \leftarrow\ sum(D_{boxes}) * Y_{box}/sum(D_{boxes})$
$Algorithm\ 2 : Routing\ of\ MV\ network\ and\ Switching\ Equipment\ Allocation$
$Output : U_{rec} = [X_{rec}\ Y_{rec}]$
```

Algorithm 2 develops an adequate route for MV grid connecting all distribution transformers. The first stage is to establish the number of primary feeders, then a clustering methodology is used to divide the total transformers in to groups. The second stage deals with the optimal routing based on street topology and manhole location. Finally, the switching equipment allocation is accomplished taken into account the nearest points between primary feeders, where the optimal placement is obtained based on the minimal distance between tie-points. As a consequence, tie-lines between primary feeders are established improving reliability and resilience.

Algorithm 2 Routing of MV network and Switching Equipment Allocation

```
$Routing\ in\ Underground\ Medium\ Voltage\ Network$
$primary = 3$
$U_{tra} = [X_{tra}\ Y_{tra}]$
$kmedoids(U_{tra}, primary)$
for $kj \to 1 : primary)$ do
    $dist_{MV} \leftarrow haversine\ [U_{tra}\ U_{tra}]$
    $G2(dist_{MV} \leq d_{mMV}) = 1$
    $path1 \leftarrow prim(sparse(G2))$
    $U_{trap} = [X_{trap}\ Y_{trap}]$
end for
$Switching\ Equipment\ Allocation$
$dist_{rec} \leftarrow haversine\ [U_{trap}\ U_{trap}]$
$[X_{rec}\ Y_{rec}] = find(dist == min(min(dist_{rec})))$
$path2 = find(prim([X_{rec}\ Y_{rec}]))$
$[X_{rec}\ Y_{rec}] = find(min(path2))$
$U_{rec} = [X_{rec}\ Y_{rec}]$
```

4.1.3 Case Study

The planning of a distribution network represents an important task for distribution operators, where the appropriate location of power substation, and distribution transformers are accomplished considering technical constraints such as voltage drop, power quality and security at the minimum capital cost. The financial strategy in distribution infrastructure is extremely related with the length of primary feeders (MV networks), secondary grids (LV network) and investments on major components such as distribution transformers, switchgear equipment (RMU) and protection systems.

For the present, the case study is characterised as a residential and commercial sector, where a vast amount of lucrative business will run in conjunction with apartment buildings. In addition leisure spaces, shopping centres and government institutions are located in this zone. As a consequence of the high urban density, more than one power feeder is used to serve this area. The case study has been designed considering 1155 residential and commercial end users, which are provided of electricity via a three primary feeders connected to the main power substation, which is located in a practical and feasible area within the case study. For simulation proposes, voltage levels and primary equipment was selected based on technical requirements, consequently an indoor substation was chosen, which operates at a primary voltage level of 66 kV. The power substation is not only comprised of switching and protection equipment, but also it has a control and energy management system. The control system permits the automatic connection and disconnection of three-phase primary outgoing feeders which are linked at the low voltage side of the transformer (11 kV).

Table 4.2: Case Study parameters and planning criteria.

Item	Parameter	Value
Medium Voltage network	Primary feeders	3
	Voltage level	11 kV
	Installation Type	Underground Network
	Network Configuration	Radial with tie points using RMU
	Conductor size and type	Cross-linked polyethylene (XLPE) cable 3x95 $\text{mm}^2 15kV$
	RMU	1 to 4 switchgear cubicles
Low Voltage network	Distribution Transformers	Oil Immersed distribution Transformers 11/0.22 kV
	Distribution Transformers Rating	kVA {30, 50, 75, 100, 160, 250, 350, 500, 750, 1000}
	Voltage level	0.22 kV
	Installation Type	Underground Network
	Network Configuration	Radial
	Conductor size and type	XLPE insulated power cable 2 kV
Deployment features	end users information	1155 closed-features from OSM
	Total demand	13.029 MW
	Associated junction boxes per transformer	# {5, 10, 15,20}
	Coverage LV network	100 %
	Coverage MV network	100 %

The geographic information used for planning and routing is obtained from Open Street Map (OSM) files, which contain georeferenced features that can be mapped (roads, avenues, buildings). The gathered information is hierarchically structured and it can be divided in nodes, ways and relations. The geographical coordinates (latitude and longitude) are showed as points named nodes, whilst ways is an ordered list of nodes which can form a closed features (buildings) and none-closed features such as roads, avenues. In particular, the case study is composed by 1155 closed features, which are represented as end users, additionally roads, avenues and streets are represented as 88 non-closed features. Both closed and non-closed features are the basis for planning and routing, where the electrical demand of customers is extremely associated with the area of the closed features, whereas the design and configuration of the network is based on street topology. Consequently, the extracted data from OSM defines the planning and routing of the distribution networks, therefore any outdated, erroneous and incomplete collected information could lead to an erroneous planning. Table 4.2 shows the case study parameters and planning criteria used for the present analysis, where the features of different primary equipment and ancillary services are reported.

The load forecasting is an important feature for a proper decision in planning and operation of electric energy system, which is permanently affected by uncertain nature since there are several factors such as population, economy (income per capita), lifestyle and socio-demographic factors, weather and acquisition of new electric appliances. In this work, a relation between the customer's demand and gross floor area is calculated using proportional demand based on ecuadorian standards *i.e.*, a bigger floor area consumes more electricity than a small building due to the fact that the number of electric appliances in residences and commercial markets.

4.1.4 Results

This section depicts the results obtained from Matlab and PowerFactory by performing a planning and routing a real distribution grid from georeferenced data from OSM. Distribution utilities have used electrical studies such as power flow, fault and harmonic analysis to determine planning expansions, upgrades, refurbishments and investments. The present project is focused in planning, consequently, power flow analysis is mandatory to determine voltage levels, voltage drops, losses and loading of cables and transformers when the grid is running on normal conditions. Furthermore, unusual conditions are simulated when a partial section of a primary feeder is out of service and normally open ties (RMU) are connecting the grid in order to minimise the outages.

The secondary network transports electricity between each distribution transformer to end customers, who are connected to the LV grid in the nearest junction box at 220 V. Figure 4.1 depicts 4 possible scenarios contemplating location of distribution transformers due to the increment of length in low voltage grids. The length of LV grids is extremely related with conductor size because the cross-sectional area of the conductor determines its resistance and therefore voltage drops. Some scenarios have been analysed considering the average length of the LV network, scenario A shows an average length of 100 m between between the final customer and its distribution transformer, then this scenario is formed by 5 manholes. Similarly, scenarios B, C and D consider an average length of secondary network of 200 m, 300 m and 400 m, respectively. Distribution transformers in each scenario have been situated considering based on the equivalent loading gravity center using the end customer's load demand.

The insulated conductors used on underground networks can be buried directly in the ground or installed in ducts buried in the ground. These aspects should be considered in design and planning process, due to the fact that installation condition will affect the power cable's performance. Therefore, it has been selected different power cables for low and medium voltage network which meet the imposed requirements of length with a drop voltage lower than 3% in each scenario. Additionally, as can be seen in Table 4.3, it is depicted the average length between distribution transformer and the most distant end customer for each scenario providing electricity to the 100% of customers. Consequently, scenario A is formed by 82 distribution transformers located in 3 primary feeders with a total length of MV voltage grid grid of 7.484 km, whilst scenario D comprises 43 distribution transformers placed into 5.862 km of MV voltage grid.

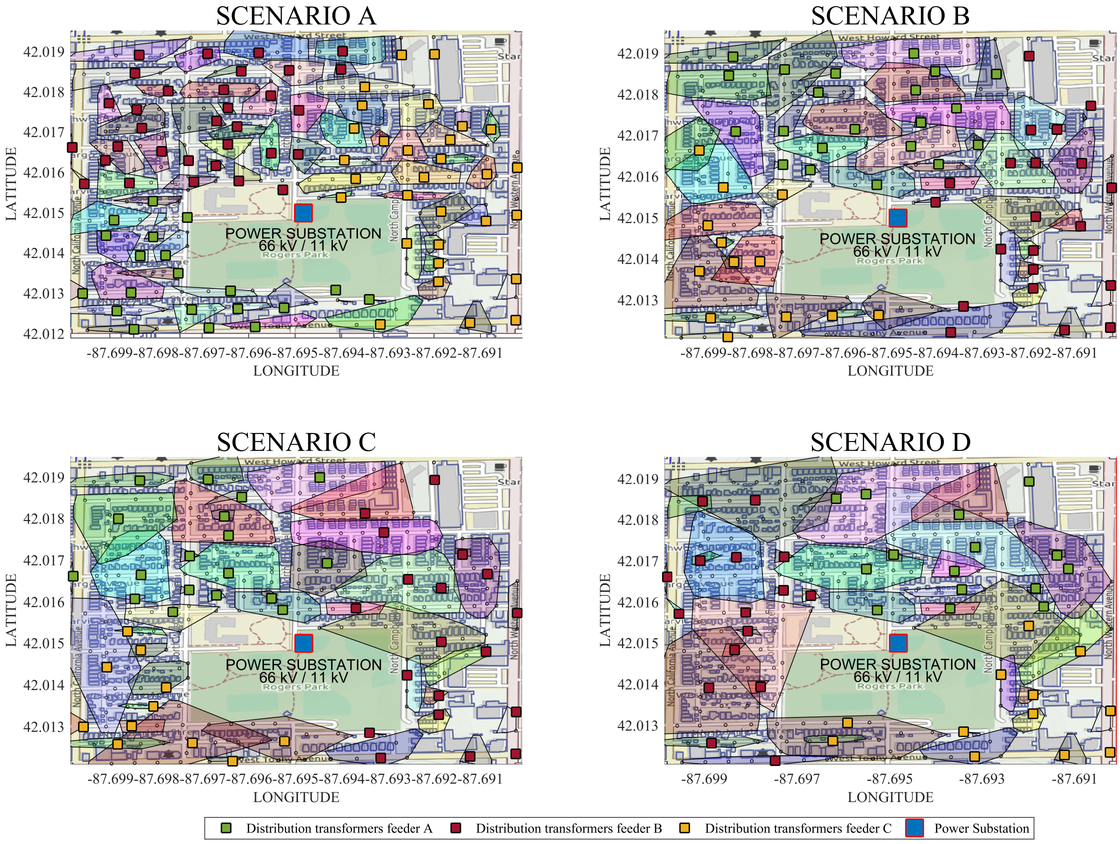


Figure 4.1: LV network for 4 scenarios.

Figure 4.2 shows the rating capacity of selected distribution transformer by each scenario, where it is clear that the number of transformers employed to feed residential and commercial customers decrease in function of the LV network's length. 7 different kVA rating values have been selected for planning process. In particular, the smallest capacity is 30 kVA to supply to reduced number of customers, whilst the bigger transformers have a nominal capacity of 1000 kVA, which are used solely in special conditions where the LV network has an average distance of 400 m. After these considerations, scenario B and C present the most effective features due to the fact that the LV network has an average length of 200 m and 300 m, respectively. Additionally, 55 and 48 distribution transformers along

3 primary feeders (scenario B and scenario C) are needed to supply electricity to end customers, which have mainly a lower capacity than other scenarios; which represents an important aspect since small transformers are more economical than large distribution transformers.

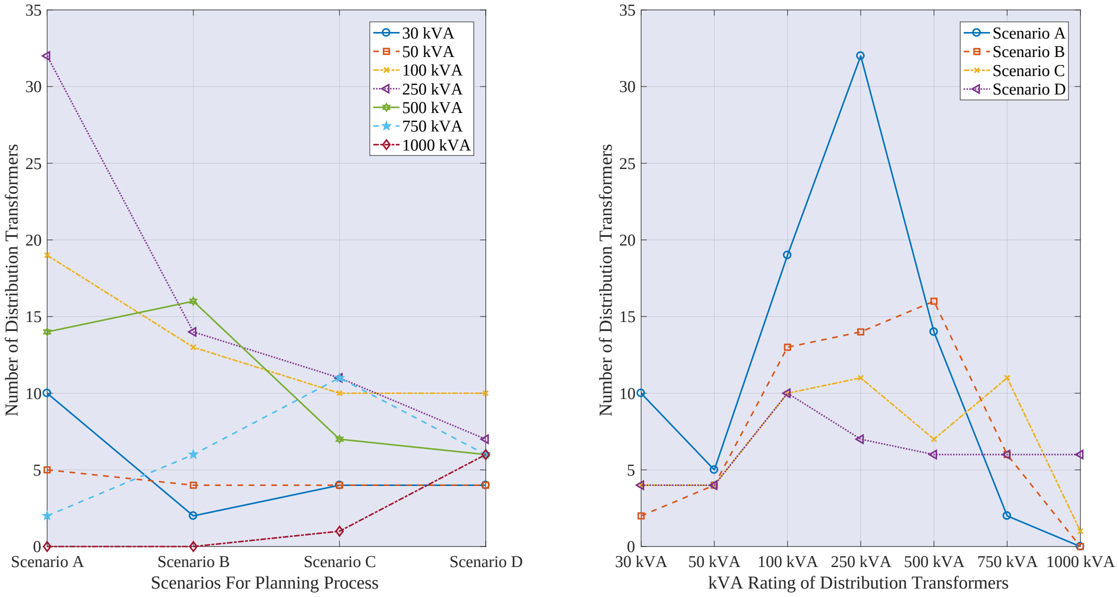


Figure 4.2: Distribution transformer rating per scenario.

Table 4.3: MV and LV network results.

Scenario per cluster #	Primary feeder Description	Distance Transformer to end user Average	Coverage LV %	Distribution Transformer #	End users per primary feeder #	MV grid Length km	MV grid voltage drop %
SCENARIO A	PRIMARY FEEDER A	100	100	32	466	2.524	< 1.2
	PRIMARY FEEDER B	100	100	30	452	2.94	< 1.2
	PRIMARY FEEDER C	100	100	20	237	2.04	< 1.2
	TOTAL	100	100	82	1155	7.484	< 1.2
SCENARIO B	PRIMARY FEEDER A	200	100	22	318	2.572	< 1.2
	PRIMARY FEEDER B	200	100	13	306	1.799	< 1.2
	PRIMARY FEEDER C	200	100	20	531	2.234	< 1.2
	TOTAL	200	100	55	1155	6.605	< 1.2
SCENARIO C	PRIMARY FEEDER A	300	100	19	444	2.568	< 1.2
	PRIMARY FEEDER B	300	100	11	245	1.507	< 1.2
	PRIMARY FEEDER C	300	100	18	466	2.039	< 1.2
	TOTAL	300	100	48	1155	6.114	< 1.2
SCENARIO D	PRIMARY FEEDER A	400	100	16	422	2.038	< 1.2
	PRIMARY FEEDER B	400	100	12	249	2.032	< 1.2
	PRIMARY FEEDER C	400	100	15	484	1.792	< 1.2
	TOTAL	400	100	43	1155	5.862	< 1.2

Figure 4.3 depicts the medium voltage network in each scenario, where the primary feeders connects the totality of distribution transformers. Primary feeders A, B and C are represented by green, red and yellow colours respectively for each scenario. The routing of MV network is based on MST techniques considering the lowest path between distribution transformers and power substation. As can be seen in Table 4.3, the length of MV network is intensely associated with the

amount of distribution transformers. Therefore, scenario A shows the longest MV network, whereas, scenarios C and D show the lowest length of MV grid.

The topology of the underground primary feeders is based on radial configuration with external interconnections (tie-lines), which have enough capacity to connect and transfer end-customers between primary feeders. Circuit breakers on auxiliary interconnections are normally open, but they allow various configurations when are tripped by emergency conditions. The operation of switching equipment can be achieved by remote control from a utility control centre. These strategies and features provide higher service reliability and flexibility under unusual circumstances, due to the fact that customers' loads are taken by another primary feeder in order to minimise interruption times, as highlighted in Figure 4.4.

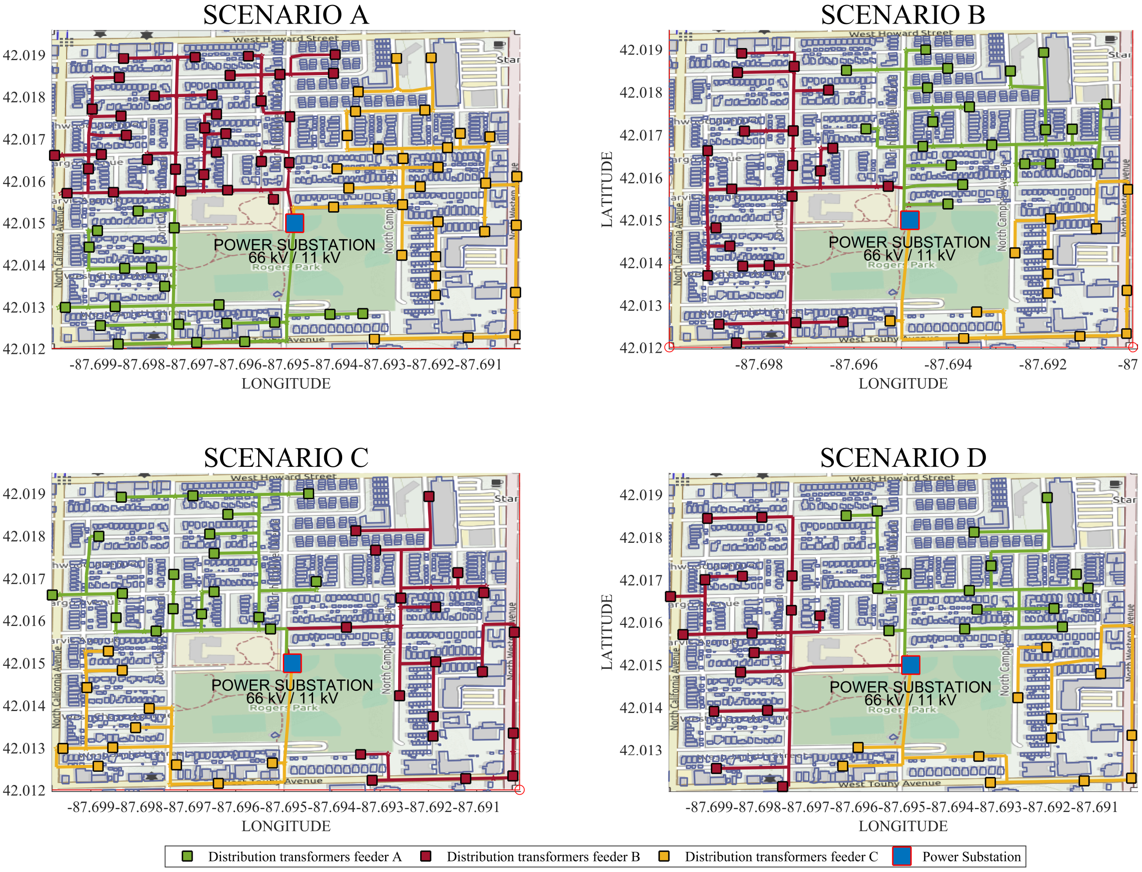


Figure 4.3: Routing of primary feeders using MST techniques for each scenario.

The optimal allocation of switching equipment and tie lines is accomplished in three stages. The first of these consists of determining the feasible positions to allocate RMU equipment, which are defined considering the nearest points between primary feeders. Candidate positions for normally opened automatic circuit breakers are suggested considering points where distribution equipment already exists, like distribution transformers. The second step is to enumerate the possible paths to connect the candidate RMU equipment in each primary feeder. Underground tie-lines between primary feeders must be placed along public streets and roads. Therefore, the optimal path is selected considering the minimal distance, which will represent a reduction on excavation cost, installation and material cost. The third stage is addressed to select adequate and optimal positions for switching equipment based on the two aforementioned criteria as can be seen in Figure 4.4. All scenarios have been evaluated considering at least one possible tie-line between primary feeders. In fact, this principle will improve reliability and resilience while reducing downtime during contingency events.

Figure 4.4: Ring Main Units (RMU) allocation and tie lines for scenario C.

Figure 4.4 depicts the normal operating conditions of a distribution network, where the grid is not subjected to unusual events. Nevertheless, any failure in a distribution system interferes with the normal system operations, which are commonly caused by insulation failure, flashover, physical damage or human error. Faults on power systems could involve all the phases in a symmetrical manner, or may be asymmetrical where only one or two phases are on short. Nevertheless, open-circuit faults are present on distribution grids due to conductors of primary feeders are broken, or circuit breakers operate only on one or two phases, leaving others connected. The aforementioned kind of fault is usually due to extreme events, where sections of the grid can be affected; consequently, power outages involve end customers, producing extensive damage to private and public property, affecting utilities and their infrastructures.

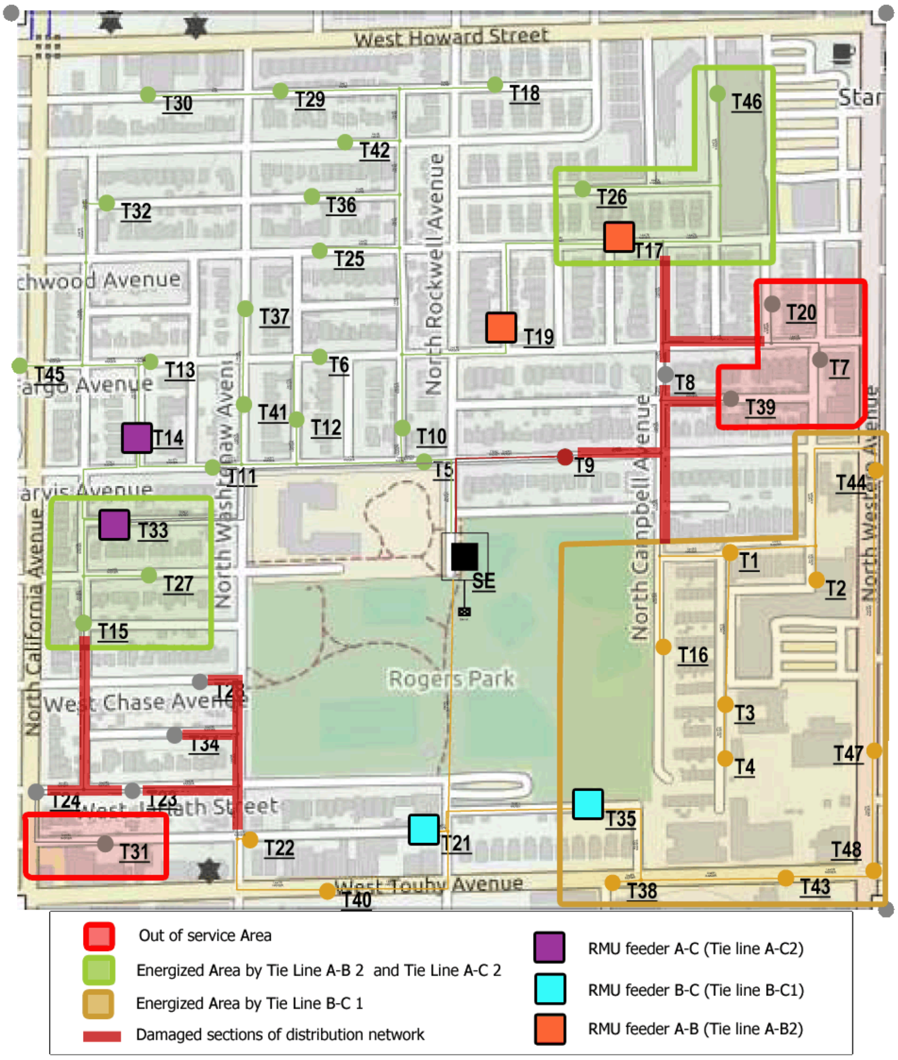
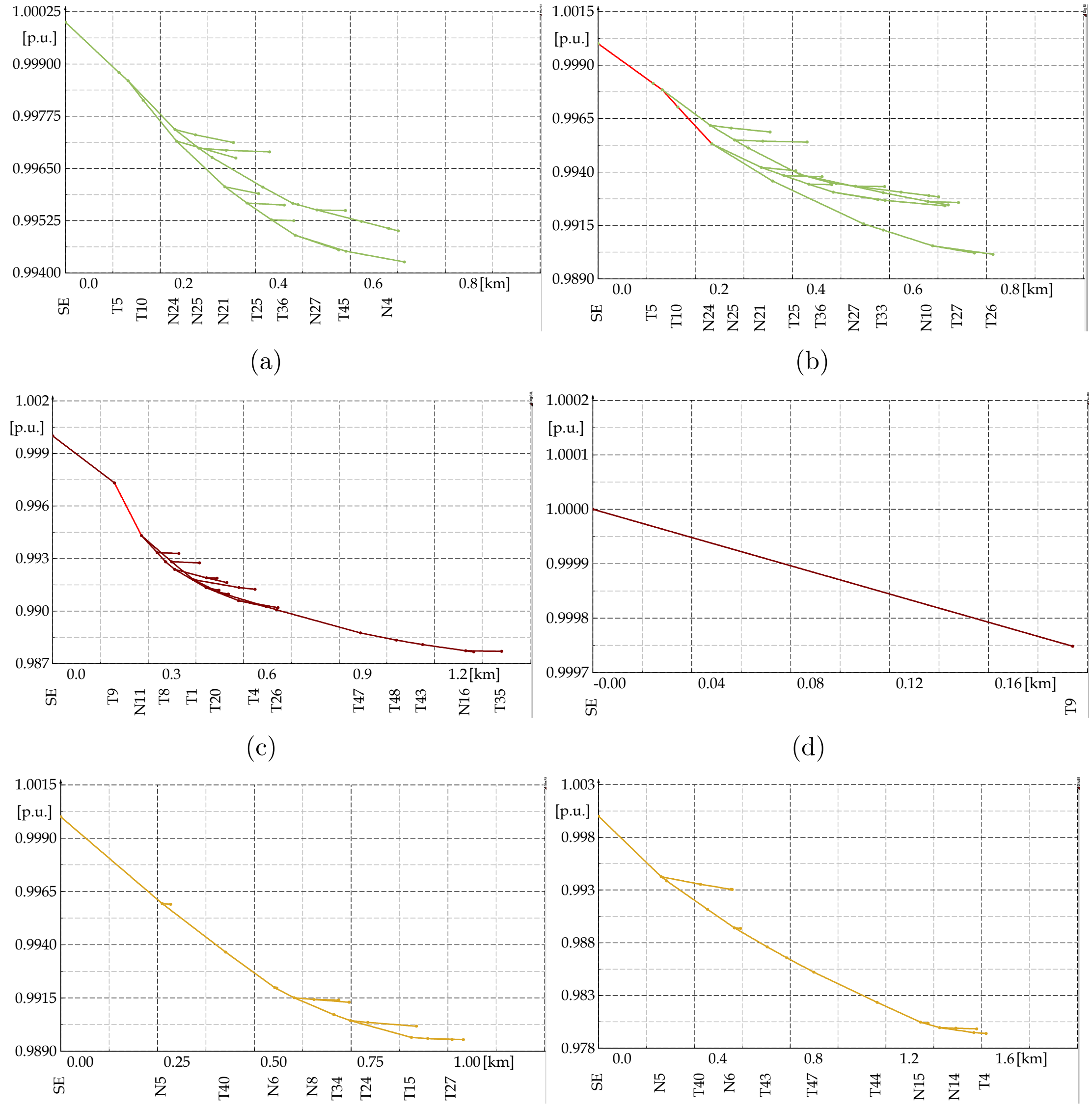


Figure 4.5: Reconfiguration of distribution network (scenario C).

After these considerations, switching equipment has a prominent function during unusual events due to the fact that they sectionalize faulted branches, as can be seen in Figure 4.5. In this work, it has been supposed an event that induces open-circuit faults on the distribution grid (highlighted in red) can be detected by utility's monitoring system. The monitoring system has the capacity to order the RMU operation, changing the topology of the distribution network. Subsequently, the feeder topological infrastructure is reconfigured altering the close/open status of tie switching equipment, thus improving reliability and resilience.



(a) (b) (c) (d) (e) (f)

Figure 4.6: (a) voltage profile of distribution feeder A under normal conditions (b) voltage profile of distribution feeder B under normal conditions, (c) voltage profile of distribution feeder C under normal conditions, (d) voltage profile of distribution feeder A after a feeder's reconfiguration, (e) voltage profile of distribution feeder B after a feeder's reconfiguration and (f) voltage profile of distribution feeder C after a feeder's reconfiguration.

Figure 4.5 shows the areas and energised branches taken by the nearest primary feeders after an abnormal event. The normally open switches that have been operated are connecting tie-lines A-B2, A-C2 and B-C1, which reconfigure the network, minimising out of service areas (box highlighted in red). During abnormal operating conditions feeder A takes the end user's load from feeder B and feeder C due to faulted branches. Additionally, primary feeder C supplies the yellow area which has been out of service due to faulted lines on primary B. The aforementioned study allows to determine the functionality of the proposed algorithm, where an example of an external event is simulated on PowerFactory, considering the operation of tie-switches to reduce power outages.

Electrical analysis for both, normal and unusual operating conditions has been developed on PowerFactory, defining an external equivalent grid which is the point of connection between the sub-transmission system and the power substation. Additionally power transformer, underground power cables and distribution transformers are considered for simulation purposes. Voltage drop analysis is showed in Figure 4.6, where a voltage profile depicts the behaviour of the distribution network during normal conditions. It is clear that voltage drop is kept within standard limits that are imposed by utility policies. Figure 4.6 is composed by six subplots, where subplots (a), (c) and (e) represent the profile voltage per feeder in normal conditions, *i.e.*, primary feeders are connected with their maximum demand. Whilst subplots (b), (d) and (f) depict the voltage profile when the grid is operating during abnormal conditions.

4.2 A Decision-Making Tool for Planning

Currently, within the electrical sector there is an infinity of simulation programs that allow to know in detail all the characteristics of a distribution system; however, the electricity market at professional and educational level, does not have an intelligent decision tool which allows to implement a design solution for the layout of that distribution network. It is for this reason that, due to the lack of a tool that covers a network design necessity, the decision has been made to create an adaptable and flexible program which allows an optimal future distribution network layout in any georeferenced scenario. It is evident that, as a consequence of the exponential advance of the economy, there is a parallel growth in the number of users that are connected to the electricity grid, which in turn leads to a considerable increase in the system's installed load. Thus, the importance of having suitable planning that allows an expansion of the electrical system is mandatory (Li et al., 2017; You et al., 2014). Expansion and planning of electrical networks involve the first and most important topic, which is distribution system. This system could become one of the most complex and important, mainly because it is related to the connection of the electrical system with the end users (Marcos et al., 2017; Valenzuela et al., 2017; Raut and Mishra, 2018; Cadenovic et al., 2018).

The planning of electrical networks is facing new and more complicated challenges due to evolution of demand, insertion of unbalanced demands and change of direction of the electric flow due to the presence of distributed generation. It is for this reason that the planning and selection of an appropriate topology is extremely important for the proper operation of the system, as well as for the contribution to improve the performance and user experience (Abeysinghe et al., 2018; Girbau-Llistuella et al., 2018). An efficient distribution system needs to be provided with the best possible topological configuration in order to provide and supply the increase in power and demand and in order to ensure minimum requirements demanded by the local distribution company, such as the voltage drop (Li et al., 2017; Marcos et al., 2017; Müller et al., 2019). In the same way, considering the expansion of the system is as important as planning, because in this way the optimum levels of service can be maintained and can ensure that the coverage area of the distribution network will include all desired users and thus provide them with electrical service (Pavón et al., 2019; Valenzuela et al., 2019a).

4.2.1 Distribution Network Utility Criteria

Electricity distribution utilities are private or government-owned, however both have the same responsibilities, challenges and opportunities. Duties and tasks are focused to provide electricity to customers, considering technical requirements such as quality of supply, reliability and safety, whilst challenges and opportunities include cost-effective planning and the construction of distribution grids considering advanced devices in protection, control and communication technologies which facilitate a grid's operation, increasing efficiency and security.

In recent years, some studies have been carried out on electricity distribution network planning, for example, (Georgilakis and Hatziargyriou, 2015) provided a complete analysis of a variety of research articles, which deal with perspectives, models and methodologies applied to design power distribution networks in recent years. Both, Kazmi et al. (Kazmi et al., 2017) and Li et al. (Li et al., 2017) provided an extensive and comprehensive report about planning problems of distribution networks; both reviews deal with optimization techniques, models and methods and also they propose concepts relates with future/smart grids. On the other hand, some researchers proposed an elemental idea of how the decision tool could be developed; to this end, they proposed several optimization methods that could be useful for the implementation of the design, but they do not execute it (Grond et al., 2013; Zhang, 2018). Other authors even described several decision algorithms for the optimal location of some elements along the distribution system, but the location of these components is based on a previously established or designed distribution systems made by a person (Martinez et al., 2011). Moreover, there is additional information where optimal planning tools were mentioned, but here the fundamental considerations for a design of distribution lines were carried out by the use of simulation programs (Liu et al., 2013; Kasim et al., 1997; Ge et al., 2010). Related to power distribution systems, some studies focused on the improvement of resilience in distribution grids by graph theory or integrating distributed generation to the main grid (Valenzuela et al., 2019a; Pavón et al., 2019), using georeferenced information as the initial stage.

In contrast, the present work integrates all the basic considerations used by utilities to obtain the optimal deployment of a distribution network; as is known, MV grid extension is one of the most performed activities that a distribution utility implements daily; consequently, power grid construction projects need an extensive amount of budget to face labor costs and material cost. Therefore, as can be seen in Figure 4.7, the proposed algorithm has been implemented to display the best distribution of the electrical components such as optimal allocation of technical resources such as power cables, distribution transformers and switching equipment. They are evaluated based on effectiveness cost analysis considering the minimal investment on construction projects supplying to the maximum number of customers and considering technical constraints like voltage drops and commercial ratings for cables and transformers on georeferenced planes. Additionally, the proposed tool can be used in any real situations and not only as a theoretical simulation; consequently, the decision-making tool could be used for academic and field purposes.

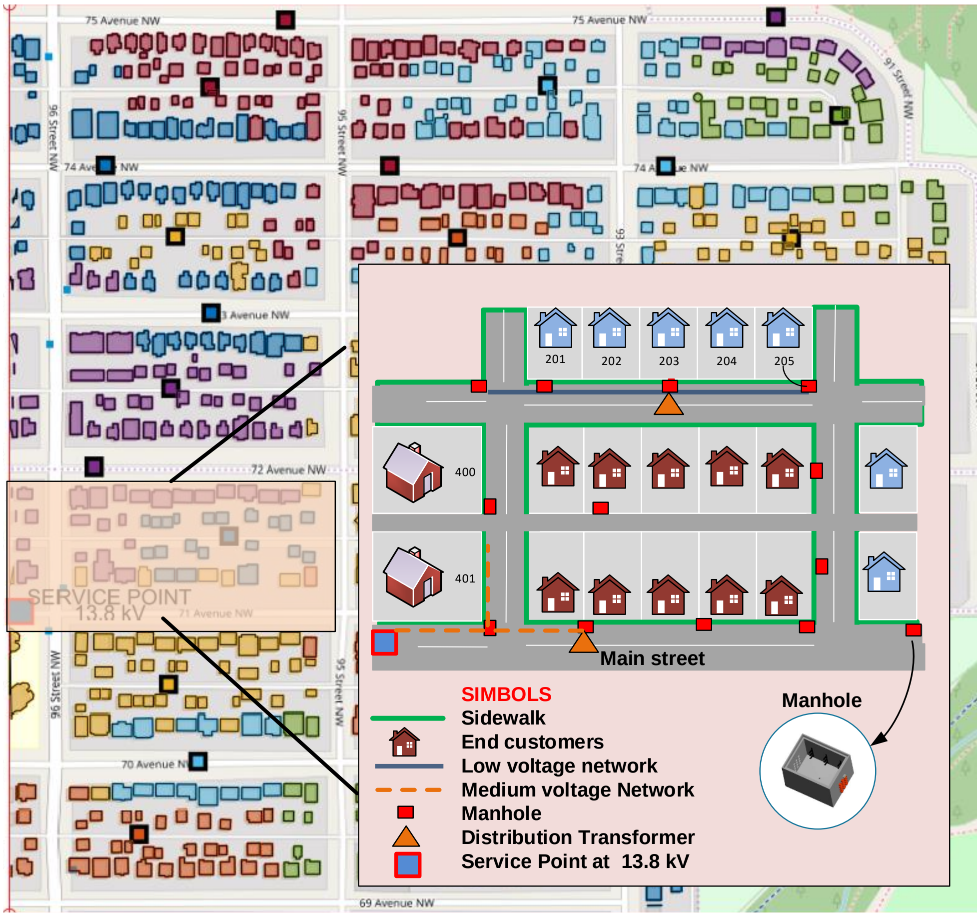


Figure 4.7: A schematic overview of the distribution network and its main components.

To start the design process, there are several considerations that must be taken into account to have an optimal and adequate design, which will define and identify minimum and maximum values, and the capacities and locations of equipment, among other things. Depending on the considerations described above, a final decision may be taken to have an adequate arrangement of the distribution network, as well as the characteristics of all the elements that are part of that network (Xie et al., 2018; Raeisi-Gahrooei et al., 2018). Furthermore, basic criteria and elements are described based on the local electricity company standards; these conditions are considered by the design tool in order to plan the distribution electricity networks. These conditions are: consumer classification, factors for the calculation of the maximum diversified demand, design demand, acceptable voltage drops, circuit configuration, connection schemes and the location and nominal capacity of the equipment and cable selection (EEQ, 2014).

Table 4.4: Consumer classification by energy consumption.

Consumer Classification	**Energy Consumption (kWh/month/customer)**
E	0–100
D	101–150
C	151–250
B	251–350
A	351–500
A1	501–900

As can be seen in Table 4.4, consumers are segmented according to the level of energy consumption that each of them has per month. Residential clients are classified as B of the consumer classification, since this is one of the most common along an urban area:

$$DMD = (FactorM \cdot FactorN) \tag{4.3}$$

The second parameter that must be analyzed for an accurate design of a distribution network is the Maximum Diversified Demand (DMD) in Eq. 4.3, which could be specified as the maximum load connected to the distribution system. This index is directly proportional to the value obtained by the multiplication of the M and N factors, which are known as the coincidence factor and the consumption factor, respectively. The first one depends on the number of customers that can be connected to the system at the same time, while the second one relates to the maximum amount of energy the customer can consume in a period of one month. Both values are already specified in tables within the regulations of the local electricity company.

The Design Demand (DD) and the maximum design demand are closely related, since the first one is calculated from the second one, as indicated in the following equation:

$$DD = \frac{DMD + DAP + DPT}{FP} \tag{4.4}$$

where:
DD is the Design demand
DMD is the Maximum design demand
DAP is the Public lighting demand
DPT is the Demand for resistive technical losses
FP is Power Factor

It should be clarified that the demand for street lighting is particular for each project; also in many cases the demand for lighting is minimal compared to the total maximum demand of the circuit; and usually the demand for street lighting can be negligible. In addition to this, the demand for resistive technical losses is calculated by multiplying the DMD by a percentage of technical losses commonly established at 3.6% [7]. This value already includes 1% of the technical losses that appear in the feeder which connects the transformer and the electrical control board of the final consumer. Finally, a power factor of 0.95 [8] has been established for the whole system.

There are several considerations that must be taken into account for the design of distribution networks, but there is no doubt that voltage drop is one of the most important technical parameters. Consequently, the distribution networks must be designed in such a way that the farthest point of the power supply network, with the design demand already established and expressed as a percentage of the system's nominal voltage (phase–ground), should not exceed the recommended values for urban areas of 3.0% and 3.5% for rural areas Maximum voltage drop established by the local electricity company standard. However, it is important to note that the consumer who is connected to the network and whose location is the closest to the source does not exceed the maximum tolerable voltage values, but at the same time this must not compromise that the furthest consumer of the electrical source has voltage ranges below the minimum percentage allowed.

The characteristics and type of installation which are planned to be implemented must be based on the standards previously established by the local electricity company and the corresponding regulatory organization; all this depending on the location of the project and the characteristics of the area to be interfered in. There are several alternatives depending on the type of installation (overhead or underground cable) and the configuration of the distribution networks (radial, loop or mesh).

4.2.2 Application of Graph Theory to Electrical Networks

Graph theory is a widely used study technique not only to deal with engineering-related problems but it can also be applied to multiple aspects and problems of several fields of study (Ni et al., 2015; Bajpai et al., 2016; Inga et al., 2017). Graph theory bases its operation on mathematical principles in which can be

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[7] Technical losses established by the local electricity company standard

[8] Power factor established for residential customers by the local electricity company standard

found several elements commonly known as vertices, nodes or points and a set of edges, lines or sides. These elements can be oriented as a result of the restrictions adopted. Therefore, a direct relationship between electric distribution lines and graph theory can be made due to its combinatorial nature. Thus the nodes or points mentioned previously can be considered as coordinates that indicate the location of a substation and the transformation or a user, while the set of edges and lines are the conductors that physically connect substations with the transformers and these in turn with the users (Li et al., 2016; Mosbah et al., 2017).

Most design methods and tools use mathematical models based on heuristics as the base for solving planning problems, since this allows finding a first approach that is very close to the optimal solution. In the present case study, these mathematical models focusing on a heuristic have been used in order to reduce the number of distribution transformers using voltage drops as a constraint by implementing a controlled process that allows the growth of the distribution network. This controlled growth is carried out based on previously established values and data, which were explained previously, such as design demand, nominal power of transformers, locations of sources and energy consumers and characteristics of cables (Bajpai et al., 2016). The distribution network planning is related to the tree topology, where it is intended to find the shortest path from the source to all users who are included in the projected electricity system. Algorithms that are frequently used in graph theory are Kruskal or Prim (Kruskal, 1956); both are focused on optimizing a process by minimizing the distances between the nodes. In addition, Prim's algorithm finds a minimum spanning tree for weighted undirected graphs, where the spanning tree is connected one vertex at time; consequently, at each step the nearest vertex is added to the tree (Wang et al., 2014; Mosbah et al., 2017; Moradijoz et al., 2018).

The decision-making tool was designed based on a modified Prim algorithm, which uses the basis of a Prim algorithm. Nevertheless, changes and modifications are thought to find the minimal path between distribution transformers and the service point in less time. The proposed modified Prim requires a graph G = (V,E) of order n and size m; consequently, the vertex set V with exactly $n - 1$ edges, which belongs to the edge set E, permits to construct a spanning tree T of G joining all the vertices without loop or mesh topologies (Valenzuela et al., 2019a; Gnana Swathika and Hemamalini, 2016; Moradijoz et al., 2018; Wang et al., 2014). Under these assumptions, not only the MV network but also the location of distribution transformers have been determined based on the modified Prim algorithm, due to the fact that the minimal tree ensures the minimal cost of the total grid. The decision-making tool uses geographic information, which is gathered from OSM files that normally contain data of highways and buildings. The geographical coordinates (latitude and longitude) are shown as points used to represent closed and non-closed features such as buildings and highways, respectively. Both closed and non-closed features are the basis for the decision-making process, where closed features permit to determine the amount of end users available in a specific area, whereas street topology and its geographical location are used to determine the best routing of medium voltage and low voltage networks joining manholes and distribution transformers. Distribution transformers are located under sidewalks on main streets and they are placed using the equivalent loading gravity center shown in following equations. The aforementioned process ensures the lowest voltages drops, since transformers are located near the most loaded manholes (Chuang et al., 2014).

4.2.3 Case Studies

The preparation of an electrical demand study considering the incidence of demographic, technical and technological variables will allow performing an adequate expansion planning of the distribution network in order to ensure the supply of electrical energy.

Table 4.5: Case study parameters and decision-making criteria.

Item	**Parameter**	**Value**
Case study 1	Number of end customers	926
Case study 2	Number of end customers	666
Medium Voltage Network	Connection point to main supply	1 service point
	Voltage level	13.8 kV
	Installation Type	Underground Network
	Network configuration	Radial
	Conductor size and type	XLPE insulated power cable 3 × 70 mm^2 15 kV
Low Voltage Network	Distribution Transformers	Oil Immersed distribution Transformers
	Voltage level	13.8/0.22 kV
	Network Configuration	Underground Network
	Installation Type	Underground Network
	Network Configuration	Radial
	Conductor type	XLPE insulated power cable 2 kV
Deployment features	Georeferenced data	Closed features and non-closed features from OSM
	Strata	Type B
	Low voltage Cable	(6 AWG, 4 AWG, 2 AWG, 1/0 AWG, 2/0 AWG
	Conductor size	3/0 AWG, 4/0 AWG, 250 MCM, 300MCM)
	Distribution transformer rating	kVA (50, 75, 100, 125, 250)

The study of the planning of an electricity distribution network must be based on the evolution of the users and their behavior of electricity consumption, based on the fact that, if there is an error in the projection of demand, a generation deficit could occur. The assessment of the demand is essential in order to obtain a decision of the possible routing alternatives of the distribution line and therefore the proper path to reach each user with the electricity supply. Likewise, it should be clear that appropriate planning according to demand can be very useful for the preparation of an optimal budget, to carry out a study that allows the reduction of losses in the system and especially for sizing and proper location of the equipment to be used.

Table 4.6: Parameters and variables.

Nomenclature	**Description**
X, Y	Vector data with georeferenced information (latitude and longitude)
X_{st}, Y_{st}	Street point positions (latitude and longitude)
X_s, Y_s	Residential customers' locations (latitude and longitude)
X_{box_1}, Y_{box_1}	Manhole's position (latitude and longitude)
X_{tra_1}, Y_{tra_1}	Transformer's position (latitude and longitude)
$dist_{min}$	Route selection criteria
$dist_{i,j}, dist_{man}, dist_{sg}, dist_{MV}$	Distance matrix (variable dimension)
$G1, G2$	Connectivity matrix
ki, kh, km, kn, kp, kq	Variables for loop control
fm, fn	Maximum divirsified demand factors
X_{box_2}, Y_{box_2}	Residential customers connected to the nearest manhole
D_{box_2}	Residential manhole's demand
$path_1, path_2, path_{MV}$	Connectivity routes for low and medium voltage networks
$Prim_{mst_{mod}}$	Prim-modified AV algorithm
cap_{cond}, cap_{trans}	Cable and transformer thermal ratings
dV	Iterative voltage drop
D_{tra_1}	Low voltage demand per group of manholes
kte	Public lighting and network losses factor
$cond$	Different cable rating
kVA_{rating}	kVA rating per group of manholes
$Loc_1, Loc_2, flag, used, Ind$	Temporal and complementary variables

Both case studies are a representation of an urban district, which are primarily characterized by residential customers. As a consequence, they can be categorized as urban residential strata based on local electrical company standards, where the electricity consumption is determined based on land usage and socio-economic factors. Case study 1 and case study 2 contemplate 926 and 666 urban residential end users, respectively. The gathered information is obtained from geospatial vector data in the shape of files from Openstreetmap[9], where latitude and longitude provide all geographical parameters to define a pre-design based on the decision-making algorithm. The case study parameters employed and the technical network requirements are reported in Table 4.5.

Underground network projects involve two main components: MV and LV distribution grids. Both of them are complex systems, which are defined as combinatorial problems considered as NP-complete, which are mainly dealt with MST techniques based on the minimal path of the power grid extension. Parameters and variables are summarised in Table 4.6 for the proposed methodology.

As remarked before, the reduction of labor costs and materials is an important task for engineers during the planning and execution of an underground project, where the objective function is to maximize the number of customers connected to the grid which is subjected to several technical constraints such as voltage drops, rating of transformers and cable size considering the most economical budget. In this work, the distribution network design is based on local electrical company standards, where distribution transformers are located using a modified Prim algorithm considering the maximum amount of customers, which can be connected to the grid using an adequate underground cable that meets with a technical constraint that allows a permissible voltage drop up to 3%. The objective function and its constraints are presented in Eqs. (4.5)–(4.8).

$$dV = \sum_{km=1}^{n3} max \sum_{kn=1}^{n4} (D_{box_2}) * (dist_{sg}) * (path_1(km)) * (cond(kn)) \tag{4.5}$$

subject to:

$$\sum_{s,k \in n} (s-1) = n, \forall s, k, \in n; \forall n \in A(n) \tag{4.6}$$

$$X = \sum_{r_{i,j} \in r_{ds}} r_{tm} < dist_m in, \forall X \in A(n) \tag{4.7}$$

$$D_{tra_1} = \sum_{kp=1}^{n1} D_{box_2}(kp) \tag{4.8}$$

As a consequence, a minimal amount of the distribution of the transformers is located on the greenfield, reducing the amount of investment in transformer acquisition. The other important component of underground projects is related with MV grid extension, which is dealt by a modified Prim algorithm to find the minimal path between distribution transformers and the Point Of Connection (POC) to the electricity distribution system:

$$Path_{MV} = \sum_{kq=1}^{n2} dist_{MV} * cap_{cond} \tag{4.9}$$

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[9] web page: https://www.openstreetmap.org/map=7/-1.783/-78.132

Algorithm 3 Planning of a resilient distribution network.

```
Step: 1 Variables
$X, Y, z, fm, fn, cond, dV, kte, cap_{trans}, used, Ind, Loc_1, Loc_2, X_{box_2}, Y_{box_2}$
Step: 2 Manhole Allocation
$used \leftarrow Prim(X, Y);$
$Ind \leftarrow find(sum(used) == 1);$
$X_{box_1} \leftarrow X_{st}(Ind);$
$Y_{box_1} \leftarrow Y_{st}(Ind);$
Step: 3 Network Operator's Cable Allocation
$Loc_1 \leftarrow [X_s Y_s];$
$Loc_2 \leftarrow [X_{box_1} Y_{box_1}];$
for $ki \rightarrow 1 : length(X_s)$ do
    for $kj \rightarrow 1 : length(X_{box_1})$ do
        $dist_{i,j} \leftarrow norm(Loc_1, Loc_2);$
        $z \leftarrow find(dist_{i,j} == min(min(dist_{i,j})));$
    end for
end for
$X_{box_2} \leftarrow Loc_2(z, 1);$
$Y_{box_2} \leftarrow Loc_2(z, 2);$
$D_{box_2} \leftarrow Loc_1(f_m * f_n);$
Step: 4 Manhole Associated by distances
$X \leftarrow [X_{box_2}];$
$Y \leftarrow [Y_{box_2}];$
for $kh \rightarrow 1 : length(X)$ do
    $dist_{man} = norm(X, Y);$
    $G1(dist_{man} <= dist_{min}) \leftarrow 1;$
    $path_2 \leftarrow Prim_{mst_{mod}}(sparse(G1));$
end for
$path_1 \leftarrow path_2(kh);$
Step: 5 Calculation of Voltage Drop
$X_{box_2} \leftarrow X_{box_1}(path_1);$
$Y_{box_2} \leftarrow Y_{box_1}(path_1);$
for $km \rightarrow 1 : length(path_1)$ do
    for $kn \rightarrow 1 : length(cap_{cond})$ do
        $dV \leftarrow D_{box_2} * dist_{sg}(path_1(km)) * cond(kn);$
        if $dV \leq 5\%$ then
            $X_{tra_1} \leftarrow sum(D_{box_2}) * X_{box_2}/sum(D_{box_2});$
            $Y_{tra_1} \leftarrow sum(D_{box_2}) * Y_{box_2}/sum(D_{box_2});$
            for $kp \rightarrow 1 : length(cap\_trans)$ do
                $D_{tra_1} \leftarrow D_{box_2}(path_1(kp)));$
                if $D_{tra_1} \leq cap_{trans}$ then
                    $kVA_{rating} \leftarrow D_{tra_1} * kte;$
                else
                    return to step 4;
```

```
                end if
            end for
        else
            return to step 4;
        end if
    end for
end for
Step: 6 Routing of MV network
$X \leftarrow [X_{tra_1}]$;
$Y \leftarrow [Y_{tra_1}]$;
for $kq \rightarrow 1 : length(X)$ do
    $dist_{MV} = norm(X, Y)$;
    $G2(dist_{MV} <= dist_{min}) \leftarrow 1$;
    $path_{MV} \leftarrow Prim_{mst_{mod}}(sparse(G2))$;
end for
```

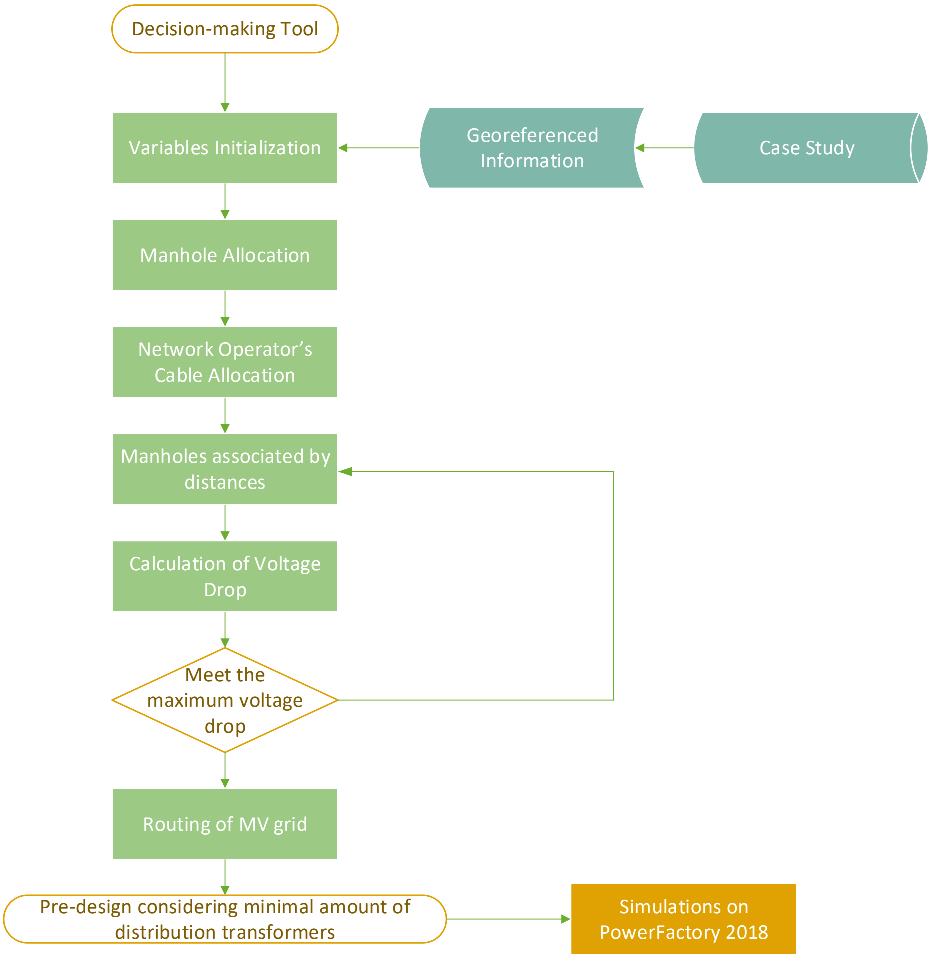


Figure 4.8: Flowchart to determine a pre-design of a distribution network considering a minimal amount of transformers.

The present decision-making tool for underground distribution expansions can be explained in *Algorithm 3*, which can be divided into two main sections. The first part of the algorithm uses georeferenced information to allocate manholes or cable chambers along streets, which are placed in range the of 30 to 40 m. Then, residential customers, who are identified as buildings in georeferenced data, are connected to the nearest manhole reducing service entrance drops. Distribution transformers are allocated based on the size of the LV grid; consequently, the optimal size of the LV network is calculated by an iterative method, which maximizes the number of manholes connected by a feasible and commercial underground cable that meets with a voltage drop constraint. Finally, transformer ratings are determined based on local electrical company standards, considering the number of customers connected to the LV grid. The second part is focused on establishing the minimal path of the MV grid that links the totality of distribution transformers with the point of connection of the main system. A MV network is routed based on the street topology and the manhole's location; as a consequence, the minimal construction cost and reduction of a utility's budget is achieved. The decision-making tool applied for planning and routing of underground distribution networks is performed in Matlab and is contrasted with simulations in PowerFactory to test the functionality of algorithms.

The aforementioned algorithm can be depicted on an explanatory flowchart in Figure 4.8, which shows the most decisive steps to determine a pre-design of distribution networks considering the connection of the minimal amount of distribution transformers which feed to the totality of end customers. Finally, simulations are executed in PowerFactory to evaluate and verify the proposed methodology in two different case studies based on the georeferenced information and electrical parameters.

4.2.4 Results

This stage depicts the results obtained from Matlab where the decision-making criteria is applied to different real scenarios from georeferenced data from OSM. Planning expansion, refurbishment and investments are typical actions done by distribution utilities in order to provide electricity to the end customers, meeting technical and economical requirements. All the aforementioned actions are performed taking time and following a specific process; however, the proposed decision-making criteria reduces time design producing a successful outcome.

The secondary network or LV grid has the objective of connecting each distribution transformer to end customers who are connected to the grid throughout the nearest manhole. Figure 4.9 shows a possible LV grid for case 1, where a possible cluster of manholes, which are connected with the nearest end users, is depicted. Additionally, the distribution transformer is also presented considering the loading gravity center that ensures the best position of the distribution transformer in electricity networks. For aesthetic purposes, it has been depicted with solely one distribution transformer and its two secondary LV circuits that connect it with end users.

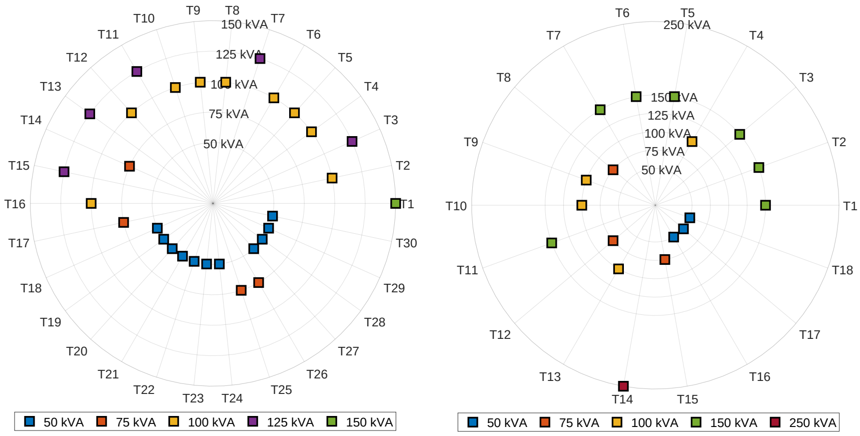
Figure 4.9: Case study 1: Low voltage distribution network, where distribution transformers and end users are represented with different colors depending on the cluster.

Case study 2 represents another urban residential area as can be seen in Figure 4.10, where distribution LV grid is designed considering the minimal number of distribution transformers; each transformer and its end customers are colored depending on the cluster. The service point, which represents the existing MV grid, is depicted as blue square at the bottom right corner.

The basic requirements needed for planning of an electrical distribution network have been analyzed in detail, where sizing and allocation of elements that are part of the system should be executed. Sizing the transformer properly is extremely important in order to avoid future problems related to energy efficiency, such as system losses. It is for this reason that, knowing the voltage in the primary and secondary side, the type of transformer, the type of assembly and in particular the nominal capacity of the transformer are decisive when a design is taking place. Several rating (50, 75, 100, 125 ,150 and 250 kVA) are taken into account, which are the nominal powers of the most used transformers at distribution level to supply energy to several users in residential areas. As can be seen, the decision-making tool provides a rapid estimation of the number of transformers and in this way minimizes the budget required to construct an underground project in order to supply electricity to the totality of customers.

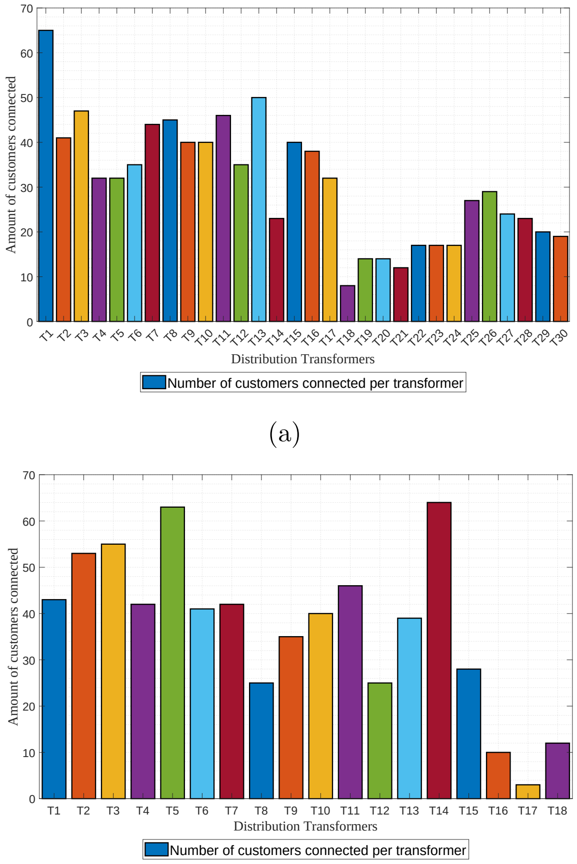
Figure 4.10: Case study 2: Low voltage distribution networks, where distribution transformers and end users are represented with different colors depending on the cluster.

As a result, the amount of distribution transformers can be determined for both case studies and they are illustrated in Figure 4.11. Six different kVA ratings have been selected for the planning process; the smallest capacity is 50 kVA to supply to a reduced number of customers, whilst the biggest transformer has a nominal capacity of 250 kVA, and is used solely in special conditions where the LV network is large and meets with its technical requirement of 3% voltage drop. The aforementioned kVA ratings are selected from commercial transformers by local electrical company standard. Moreover.it is assumed that the selection of the optimal capacity of distribution transformers must consider all associated factors such as public lighting, low voltage losses and load growth.



(a) (b)

Figure 4.11: (a) kVA distribution transformers of case study 1; (b) kVA distribution transformers of case study 2.



(a)

(b)

Figure 4.12: (a) Number of end users connected to distribution transformer of case study 1; (b) Number of end users connected to distribution transformer of case study 2.

Figure 4.12 shows the amount of end customers connected to distribution transformers in both case studies, where the analysis considers B customer load classification, since load are located in urban areas. Therefore, load is permanently affected by uncertain nature since there are several factors such as population, economy (income per capita), lifestyle and socio-demographic factors, weather and acquisition of new electric appliances.

Figure 4.13 depicts the MV network for case study 1, where the service point, which is the available connection point to the main, feeds electricity to the totality of distribution transformers. The extension of a primary feeder at 13.8 kV is represented in black. The routing of the MV network is based on MST techniques considering the lowest path between distribution transformers and the service point.

Figure 4.13: Routing of primary feeder using MST techniques for case study 1.

Figure 4.14 shows a MV grid proposed as the solution for case 2, which is entirely modelled and performed using PowerFactory based on MST techniques. MST techniques permit to obtain the optimal path along public streets and roads considering the minimal distance, which represents a reduction in excavation, installation and material costs during the planning and extension of distribution networks.

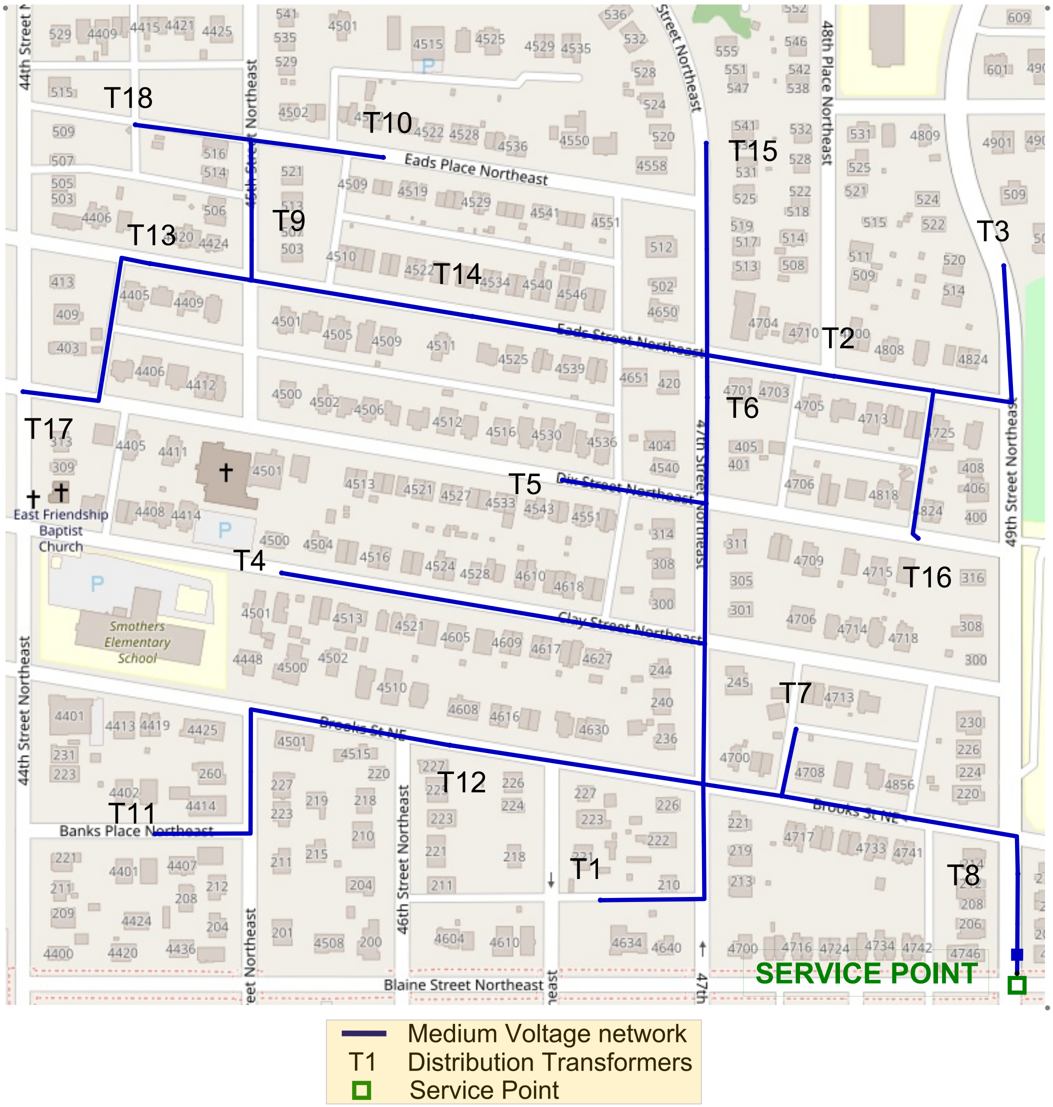


Figure 4.14: Routing of primary feeder using MST techniques for case study 2 performed on PowerFactory.

Operating conditions of the underground primary feeder extension are evaluated by simulations on specialized software, where an external equivalent grid is used as the point to the main grid at a voltage level of 0.97 pu. This voltage level represents a realistic value due to the fact that normal distribution grids have technical losses and voltage drops along the primary feeder. For simulation purposes, underground power cables for MV and distribution transformers and their expected loads are modelled. Aggregated customer loads consider a utilization factor closer to 60%, which represents the maximum estimated amount of energy that could be used divided by the maximum available capacity to be used.

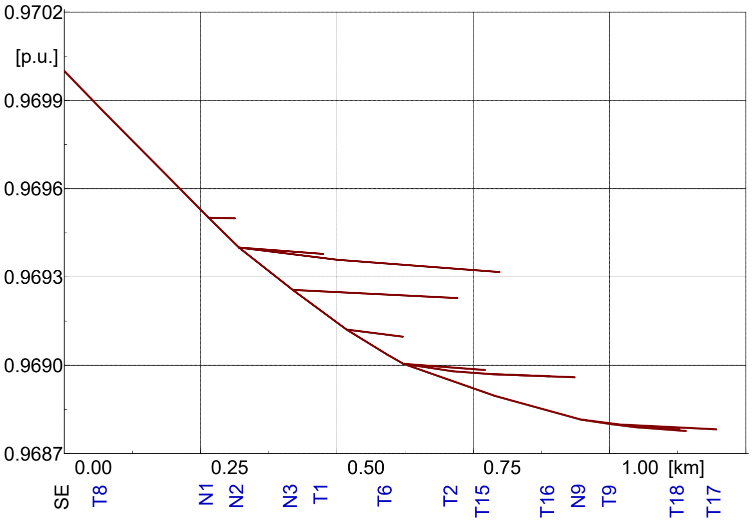


Figure 4.15: Voltage drop calculated on the feeder-extension for case study 2 performed on PowerFactory.

Voltage drop analysis is shown in Figure 4.15, where a voltage profile depicts the behavior of the distribution network during normal conditions. It is clear that a voltage drop meets the standard limits that are imposed by utility policies; this was already expected, since the length of distribution networks reduced.

4.3 Network Reconfiguration & Protection Coordination

As described in the previous sections, electrical power systems are a fundamental part of the society and its efficient operation are of vital importance for social and economic development. Power systems have been designed to withstand interruptions under already provided safety and quality principles, however, there are some extreme and not so frequent events that could represent inconveniences for the correct operation of the entire system (Bie et al., 2017). For this reason in the last years the term resilience, which serves to describe the capacity of a system to recover from an unwanted event. It has been analyzed on planning, operation and remedial actions (Valenzuela et al., 2019a; Wang et al., 2016; Espinoza et al., 2016; Gholami et al., 2018) .

Within power systems, distribution network has the function of supplying the energy that is carried from power substations via primary feeders to distribution transformers and finally connect to end users. Distribution system is mainly composed by overhead lines or power cables that build the primary feeders, distribution transformers and also include protection devices such as circuit breakers, reclosers, fuses and overcurrent relays (Valenzuela et al., 2019a; Wang et al., 2016; Espinoza et al., 2016; Gholami et al., 2018) . Due to this complexity, distribution network is exposed to multiple factors or events (such as natural disasters) that can put its operation at risk. Consequently, it is particularly important to have a distribution network correctly protected in order to guarantee the adequate operation of the entire system meeting technical requirements such as quality of the service and the effective continuity of supply (Mosbah et al., 2017; Cadenovic et al., 2018).

Contingencies or continuous failures on different system components can affect quality of service, especially if they cannot be solved in acceptable time frames, which may lead to users to have no access to the service for long periods of time. In this regard, fast and effective service restoration procedures become significantly important, especially in those loads considered critical due to their high productivity or relevance; the main goal of these procedures is to keep the largest possible portion of its service area energized when failures occur (Zhai et al., 2018; Zhang, 2018). Distribution system may be affected by several kind of disturbances such as short-circuits, undervoltages or overvoltages, as well as lightning strikes. Consequently, protection devices activate the circuit breakers in order to isolate faulty sections, keeping the rest of the system under normal operating conditions. However, due to this isolation strategy and the network topology, some healthy sections can be left disconnected. One of the objectives of a resilient operation is to maintain the greatest amount of loads connected to the distribution network with acceptable levels of power quality, and those non-fault zones are the main ones involved when performing network reconfigurations (Kumar and Singh, 2015; Raut and Mishra, 2018).

A very valuable tool to operate distribution networks is the topological reconfiguration, whose objectives include most commonly the reduction of losses, improvement of voltage levels and the increase of reliability levels. The reconfiguration problem cannot be optimally solved without considering first an adequate modelling of all the distribution network components, including loads, distribution transformers, power cables or overhead lines and protective and switchgear equipment. Restoration process is associated with robust algorithms, which are responsible for managing the status of switchgear equipment, consequently the network's topology. Commonly, power-flow analysis is carried out to obtain the system's electrical variables and parameters that are relevant to determine the best solution as part of the optimization problem; which is based on the implementation of the objective functions and technical and economic constraints (Agrawal et al., 2020; Silva et al., 2021). To this end, reconfiguration of a distribution network must be carried out with the necessary speed and precision, consequently, it is a paramount task the automation of the electrical networks, considering all the elements involved such as control and protection equipment improving communication capabilities (Kamble et al., 2019; Li et al., 2016).

4.3.1 Problem Formulation

Network reconfiguration and protection coordination are critical procedures, which are aimed to change the topological structure of primary feeders based on changing the status of switchgear equipment, where tie lines are closed. Consequently, overcurrent relays are coordinated based on new operating conditions to face any abnormal event (Raut and Mishra, 2018; Ali et al., 2021). For the present analysis, the network has been designed considering the availability of different tie lines and tie points with remote switching, which are placed in each feeder of the distribution systems. Subsequently, several network's configurations are possible, which are able to deal with contingencies occurring at any point in the network. Under the previous assumptions, reconfiguration of electrical systems and the co-ordination of protection systems are valid options to improve the resilience and the reconstitution of distribution networks. To this end, an important index will be analyzed, the Expected Energy Not Supplied (EENS) (Xiang et al., 2018a), which indicates the energy not delivered to the users during a period of time. It is expressed mathematically with the following relation:

$$EENS = \sum_{i=1}^{k} (La_i * U_i) \tag{4.10}$$

where:
La_i is the average load at busbar i
U_i is the duration of the energy not supplied
k is the number of faulty busbars

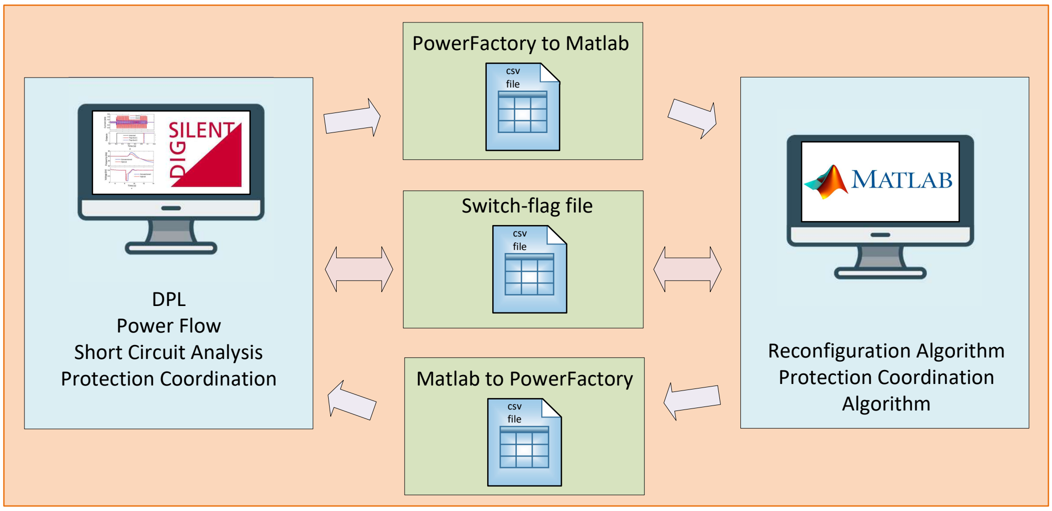


Figure 4.16: Peer-to-peer communication between Matlab and PowerFactory.

Reconfiguration and protection coordination are performed on both PowerFactory and Matlab tools running at same time. DIgSILENT Programming Languahe (DPL) [10] is utilized to performs automated tasks such as power-flow, short-circuit analysis and protection coordination on PowerFactory. On the other hand, Matlab, which is a versatile mathematical tool, provide all the parameters, circuit breakers status, operating conditions due to of algorithm's execution. Figure 4.16 depicts a Peer-to-Peer scheme between Matlab and PowerFactory, where various Comma Separated Values (CSV) files are used to transfer data from PowerFactory

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[10] web page: https://www.digsilent.de/en/scripting-and-automation.html

to Matlab, and viceversa. Information transfer between simulators is achieved by Switch-Flag file, which permit to couple both tools.

The reconfiguration process is implemented to improve customer's satisfaction, especially after an outage, when service restoration process must energize all available areas as possible, isolating the faulty section. Consequently, as can be seen in Eq. 4.11 the objective function aims to maximize the amount of restored loads. The possible solutions must be within operative constraints such as maximum and minimum voltage level per busbars as can be seen in Eq. 4.12. Moreover, also the restored load must not be greater than feeder capacity as showed in Eq. 4.13. Finally, Eq. 4.14 indicates that the topology of the system should remain radial.

$$max \sum_{i=1}^{LD} S_i, i \in LD_a \tag{4.11}$$

Subject to:

$$|V_k^{min}| \leq |V_k| \leq |V_k^{max}|, k \in B_a \tag{4.12}$$

$$\sum_{i=1}^{LD} P_i \leq P_f^{max}; \sum_{i=1}^{LD} \leq Q_f^{max}, i \in LD_a \tag{4.13}$$

$$\Psi = 0 \tag{4.14}$$

where:
S_i is the apparent power consumed by load i
V_k is the voltage at bus k
V_k^{min} is the minimum voltage at bus k
V_k^{max} is the maximum voltage at bus k
P_i is the active power consumed by load i
P_f^{max} is the limit of active power at the feeder
Q_i is the reactive power consumed by load i
Q_f^{max} is the limit of reactive power at the feeder
LD_a is the set of active loads
B_a is the set of active busbars
Ψ is 0 when the system remains radial (variable control)

The algorithm of the topological reconfiguration of distribution networks is depicted as flow diagram in Figure 4.17, where the key features in the Matlab and PowerFactory environments used to develop a load restoration are showed. Variables and parameters are listed to determine the maximum restored load. The main parameters of distribution network (loads, busbars, voltages) are gathered in a initial step sent data from PowerFactory to Matlab. Consequently, Matlab performs an analysis that finds all loads which are disconnected (out of service). After that, all circuit breakers are evaluated, checking which one has changed from its predefined status. This procedure is used to generate generate a different switch combinations, which are sent from Matlab to PowerFactory to execute a power-flow analysis, where all variables such as voltage on each busbar, cable loading and circuit breaker status are sent to Matlab to determine the best restoration process, which meets all technical requirements.

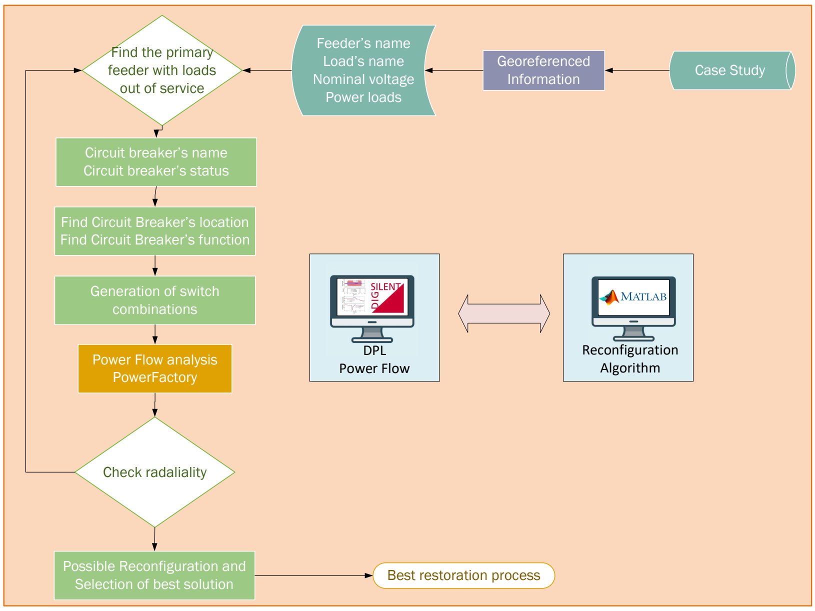


Figure 4.17: The flowchart used to determine the best topological restoration based on a peer-to-peer communication between Matlab and PowerFactory.

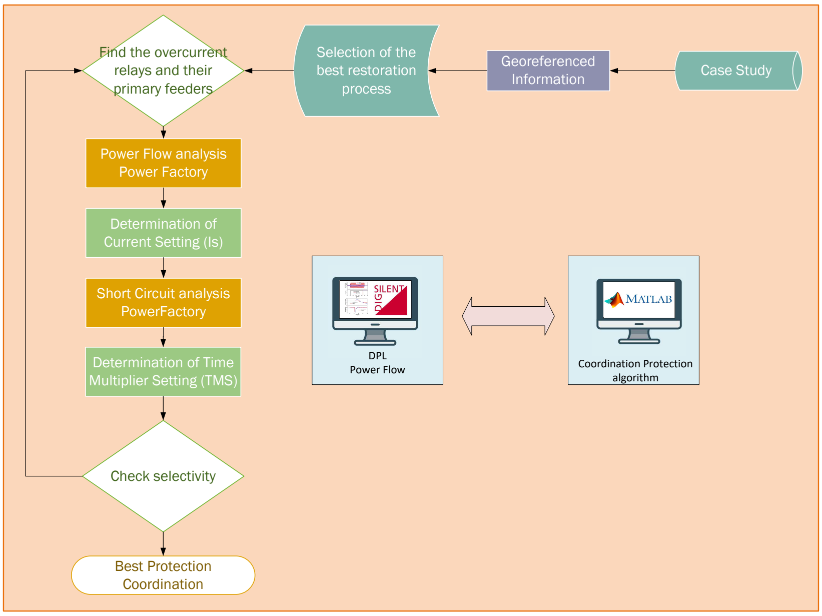


Figure 4.18: The flowchart used to determine an adaptive overcurrent protection coordination based on a peer-to-peer communication between Matlab and PowerFactory.

The algorithm of protection coordination is applied after a topological reconfiguration has been achieved. In particular, Figure 4.18 shows the development of the main steps and the adaptive calculation of overcurrent protection. The power-flow analysis is executed on PowerFactory in order to determine the current that is circulating along the feeder, and the current setting is calculated on Matlab. Short-circuit analysis in executed on each busbar, to determine the TMS. Both parameters, I_s and TMS are fundamental to analyze selectivity, where a fault along a feeder is cleared. As already remarked, selectivity, sensitivity and speed are important requirement on protection systems in order to achieve an adequate correct protection coordination on distribution networks. Consequently, the protection system should clear faults considering a minimum of load disconnection. As an example, Figure 4.19 depicts a protection coordination, where the fault could be cleared by the relay A or the relay B. However, the protection's algorithm should be implemented in such a way the relay B operates first, clearing the fault and keeping maximum continuity of service.

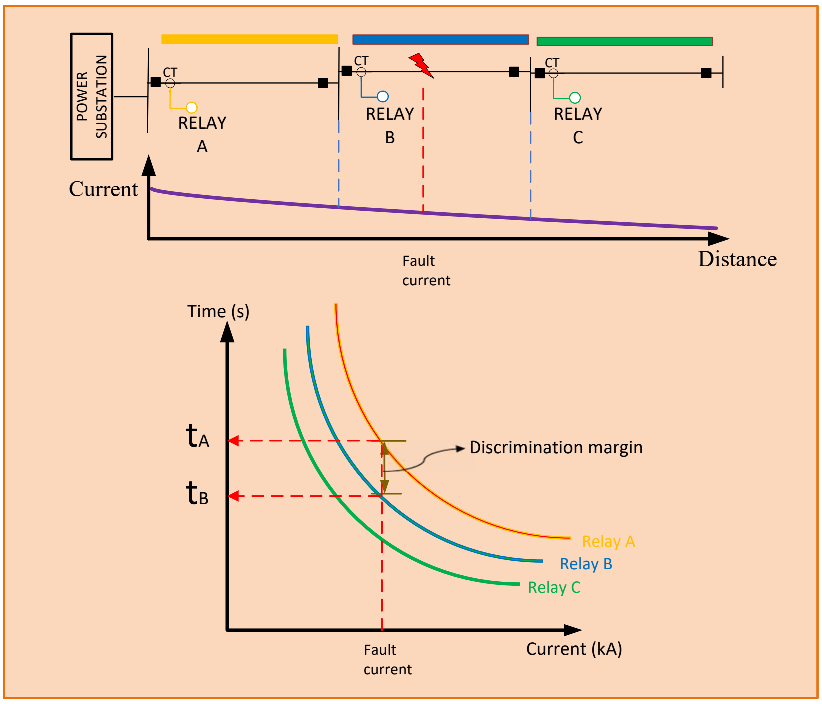


Figure 4.19: An detailed example of overcurrent coordination within a radial distribution network.

4.3.2 Case Study

The service restoration on electrical networks is a crucial task for distribution network operators due to the fact that a rapid and effective connection to the main grid ensure high levels of continuity of service by switching operations of tie lines. The proposed restoration strategy has been applied to a predefined case study, which was designed considering a resilient planning for a residential and commercial sector, as depicted in Figure 4.20. The proposed case study considers three different primary feeders, which feed several distribution transformers, also RMUs with control, protection and communication capabilities are considered. Table 4.7 shows the features and the parameters of the proposed case study.

Table 4.7: Case study parameters and variables.

Item	Parameter	Value
Medium Voltage Network	Primary feeders	3
	Installation Type	Underground Network
	Network Configuration	Radial with tie points using RMU
	Conductor size and type	XLPE insulated power cable 3x95 mm^{2}15kV
	RMU	1 to 4 switchgear cubicles
	Feeder A (Maroon Color)	19 distribution transformers
	Feeder B (Yellow Color)	11 distribution transformers
	Feeder C (Green Color)	18 distribution transformers
Tie Points	Feeder A and Feeder B	2 (Light Blue Color)
	Feeder B and Feeder C	2 (Purple Color)
	Feeder C and Feeder A	2 (Orange Color)
Protection System	Relays	12 Time-Inverse overcurrent relays
	Current Transformers Ratio	100/1

Table 4.8: Status of connection of different switchgear equipment on normal operating conditions.

Ring Main Units	Operating Condition	Status	Feeder
NC-11	Closed Position switch	1	A
NC-21	Closed Position switch	1	B
NC-31	Closed Position switch	1	C
NC-111	Closed Position switch	1	A
NC-211	Closed Position switch	1	B
NC-311	Closed Position switch	1	C
NO-121	Open Position switch	0	A and B
NO-122	Open Position switch	0	A and B
NO-311	Open Position switch	0	C and A
NO-312	Open Position switch	0	C and A
NO-231	Open Position switch	0	B and C
NO-232	Open Position switch	0	B and C

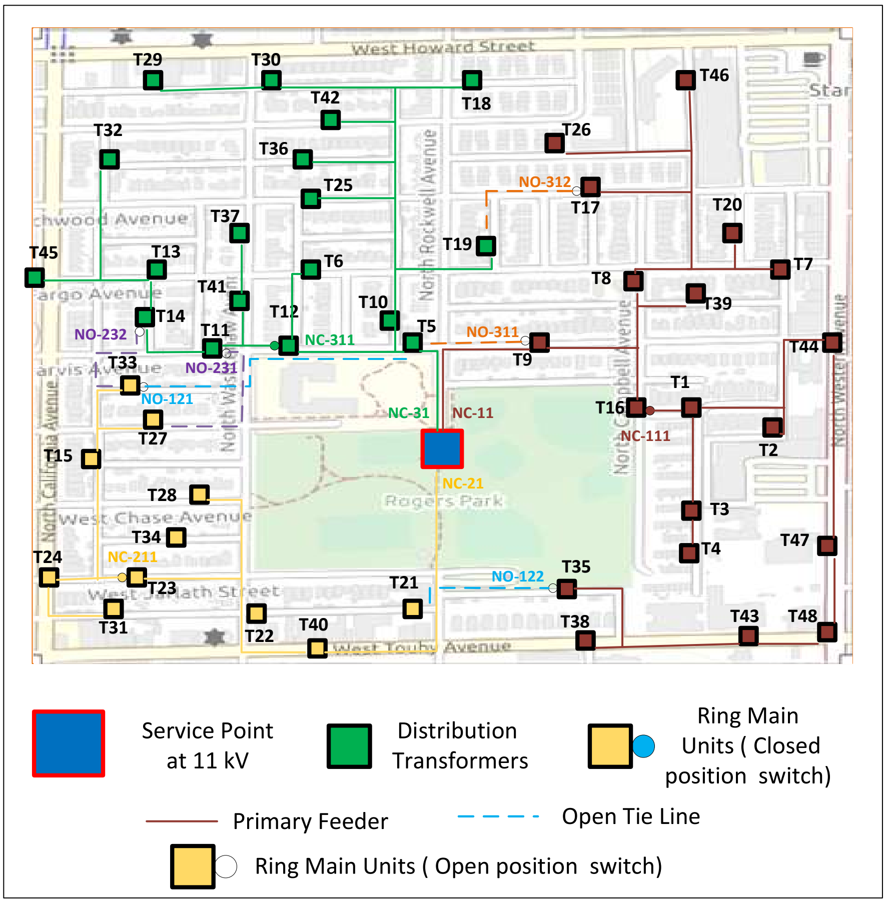
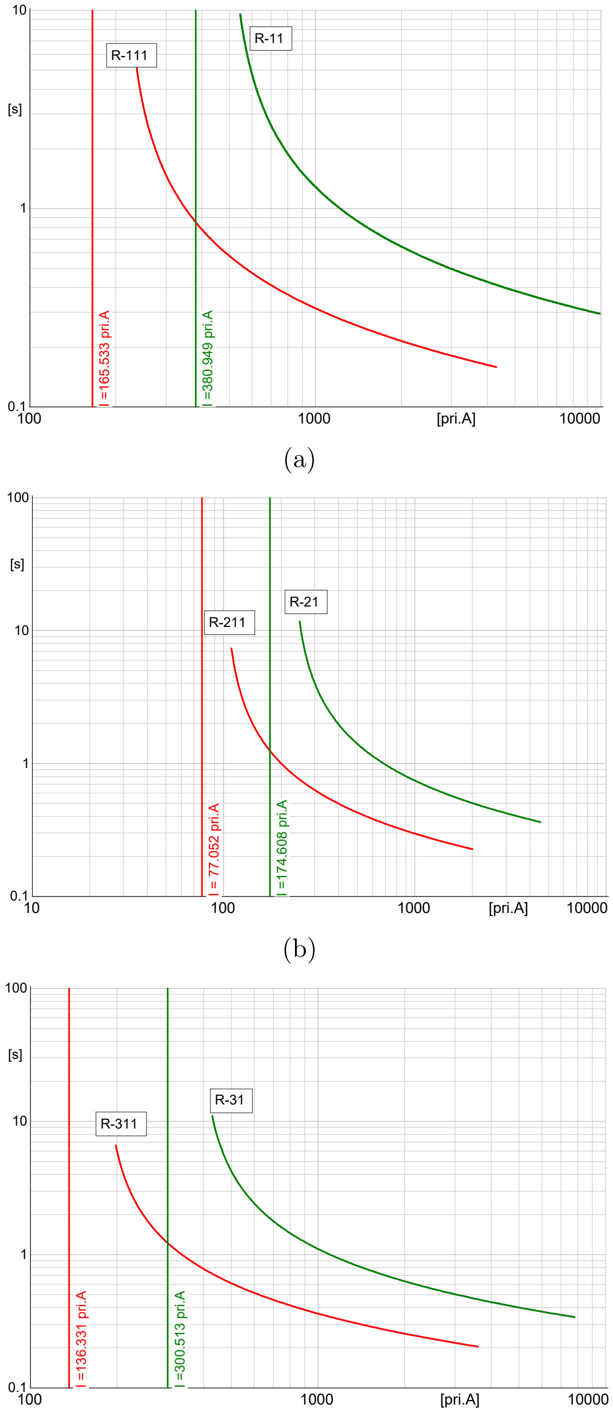


Figure 4.20: Distribution network on normal operating conditions.

Table 4.9: I_s and TMS parameters on overcurrent relays at different switchgear equipment on normal operating conditions.

Overcurrent Relay	Current Setting	TMS	Feeder
R-11	4.95	0.13	A
R-21	2.27	0.16	B
R-31	3.90	0.15	C
R-111	2.15	0.07	A
R-211	1.00	0.10	B
R-311	1.8	0.09	C
RX-121	-	-	A and B
RX-122	-	-	A and B
RX-311	-	-	C and A
RX-312	-	-	C and A
RX-231	-	-	B and C
RX-232	-	-	B and C



(a)

(b)

(c)

Figure 4.21: (a) Protection coordination of overcurrent relays on feeder A; (b) Protection coordination of overcurrent relays on feeder B; (c) Protection coordination of overcurrent relays on feeder C.

The three underground primary feeders are based on a radial configuration with external interconnections (tie-lines), which have enough capacity to connect and transfer end-customers between primary feeders. Circuit breakers on auxiliary interconnections are normally open, but they allow various configurations when are tripped by emergency conditions. For this case, overcurrent relays have been located on specific positions such as tie lines, and also in the middle of the primary feeder, as sketched in Figure 4.20. Additionally, Table 4.8 shows the initial switching status of the ring main units which have a overcurrent relays.

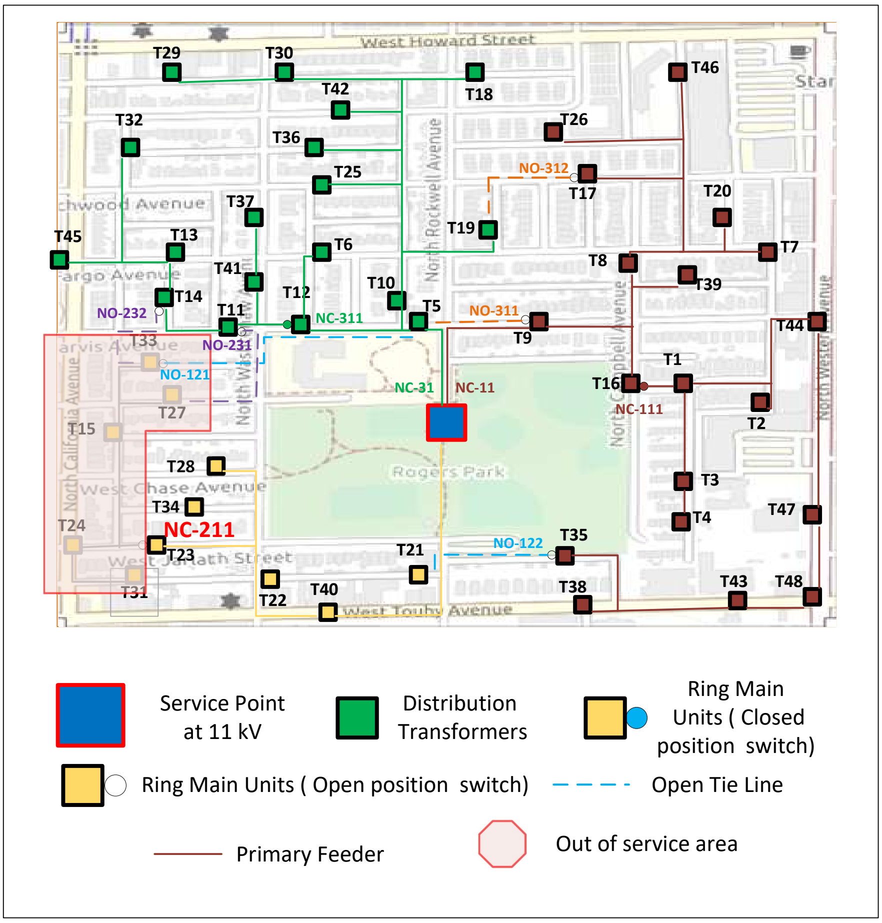


Figure 4.22: Distribution network under abnormal operating conditions, activation of switchgear equipment NC-211 and trip of overcurrent relay R-211.

As mentioned before, protection coordination can be associated with a network's resilience because protective equipment allows rapid recovery of a power network, and also permits to face any disturbance or anomalous event after a grid reconfiguration. Consequently, all switching equipment and overcurrent relays can be operated and configured by remote control from a utility control center. These strategies and features provide higher service reliability and flexibility under unusual circumstances, due to the fact that customers' loads are taken by another primary feeder in order to minimize interruption times. The principle of selectivity has been considered on protection coordination of inverse time overcurrent relays as highlighted in Figure 4.21, where I_s and TMS for initial operating conditions are reported in Table 4.9 for each of one of the primary feeder. Figure 4.21 shows a proper coordination of overcurrent relays located on feeder A, B and C, respectively. For initial conditions, each of one the primary feeders is protected by two overcurrent relays which are located at the beginning and the middle of the feeder, and they are displayed as red and green color, respectively. For the present analysis, a three phase short-circuit has been considered in protection coordination, as it represents the most severe event in a distribution network.

4.3.3 Results

This section reports the results achieved from a peer-to-peer communication between Matlab and PowerFactory to develop a service restoration after a outage in a distribution network, and also it shows an adequate protection coordination on distribution network. Figure 4.22 shows a particular case, where an out of service zone is highlighted in red due to the detection and operation of protective and switchgear equipment of ring main units. The tripping of circuit breaker is produced in case of anomalous events in primary feeders due to temporary or permanent faults provoked by flashover, insulation failure and open-circuit faults.

Table 4.10: Status of connection of different switchgear equipment under different reconfiguration cases.

RMU	**Case initial**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
NC-11	1	1	1	1	1	1	1	1	1
NC-21	1	0	0	1	1	1	1	0	1
NC-31	1	1	1	1	1	1	1	1	1
NC-111	1	1	1	1	1	1	1	1	1
NC-211	0	0	0	0	0	0	0	0	0
NC-311	1	1	1	1	1	1	1	1	1
NO-121	0	1	0	0	0	1	0	0	0
NO-122	0	0	0	0	1	0	0	0	0
NO-311	0	0	0	0	0	0	0	0	0
NO-312	0	0	0	0	0	0	0	0	0
NO-231	0	0	0	0	0	0	0	1	1
NO-232	0	0	1	0	0	0	1	0	0

The reconfiguration algorithm is applied to the distribution network as a consequence the detection of unusual operating conditions by the utility's monitoring system. The communication peer-to-peer between Matlab and PowerFactory has generated 8 possible reconfiguration methodologies, each of one meets the technical requirements of voltage level and radiality. Table 4.10 shows the status of each switchgear equipment in each of one reconfiguration cases. Furthermore, Figure 4.23 depicts the number of distribution transformers connected to the main grid by the restoration process,where only three cases feed the complete load of the power substation, *i.e.*, 48 distribution transformers are connected to primary feeders.

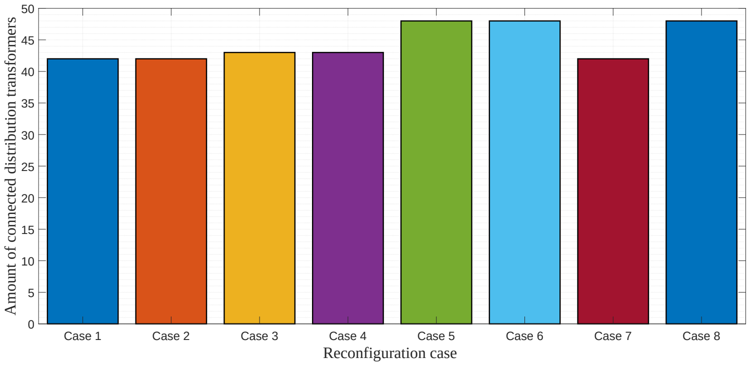


Figure 4.23: Number of distribution transformers connected to the main grid for the different reconfiguration cases of the distribution network under abnormal operating conditions, *i.e* activation of switchgear equipment NC-211 and tripping of overcurrent relay R-211.

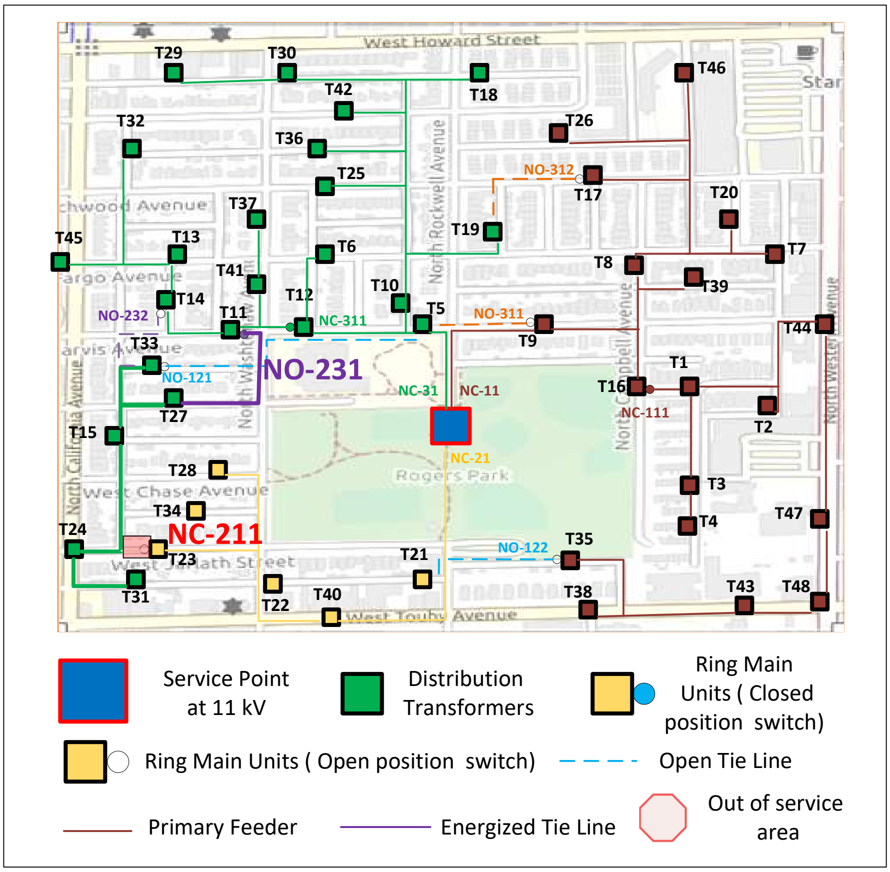


Figure 4.24: Distribution network under the new operating conditions, *i.e* switchgear NC-211 is in open position and NO-231 has changed to closed position due to the reconfiguration process.

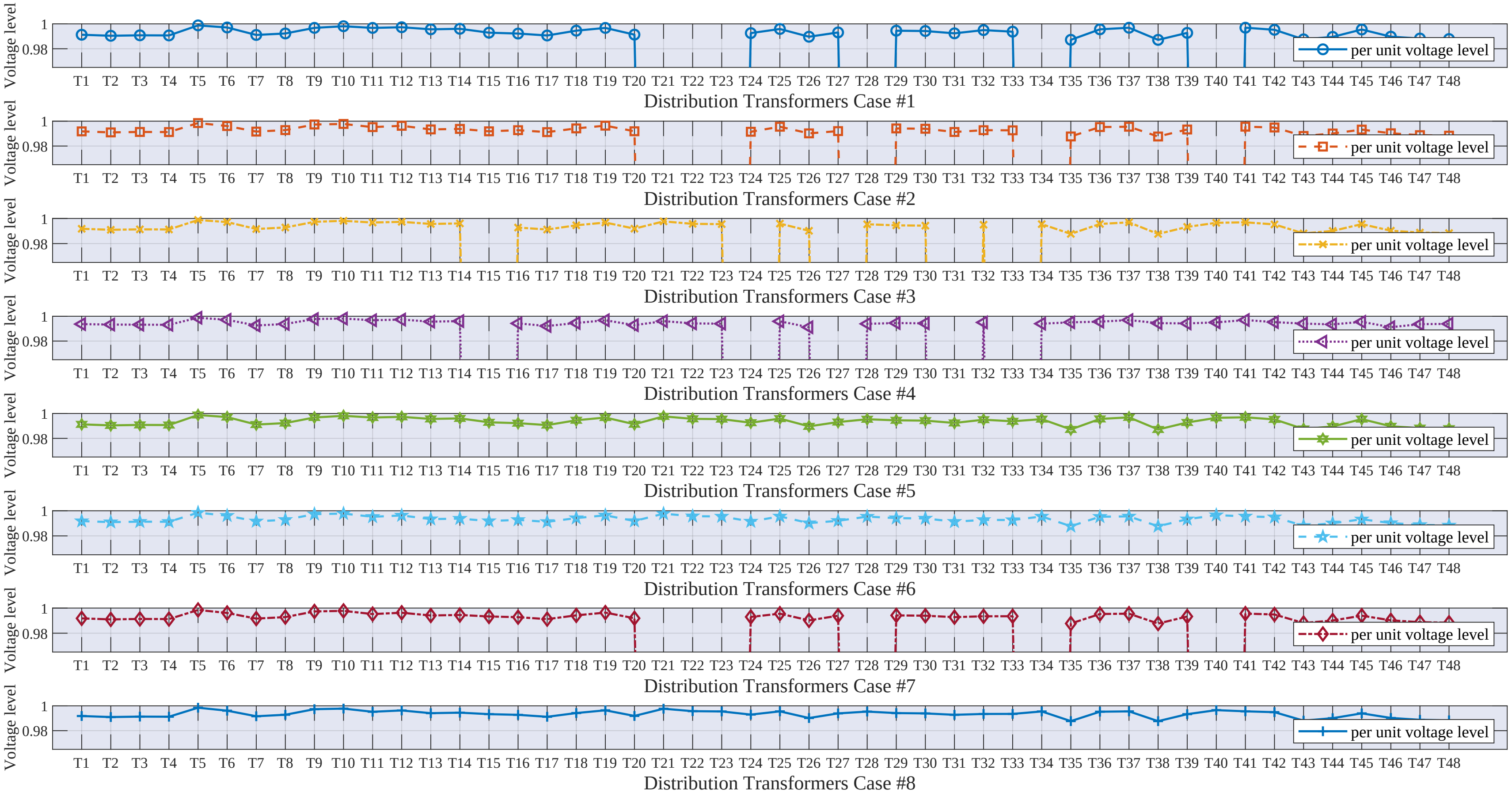
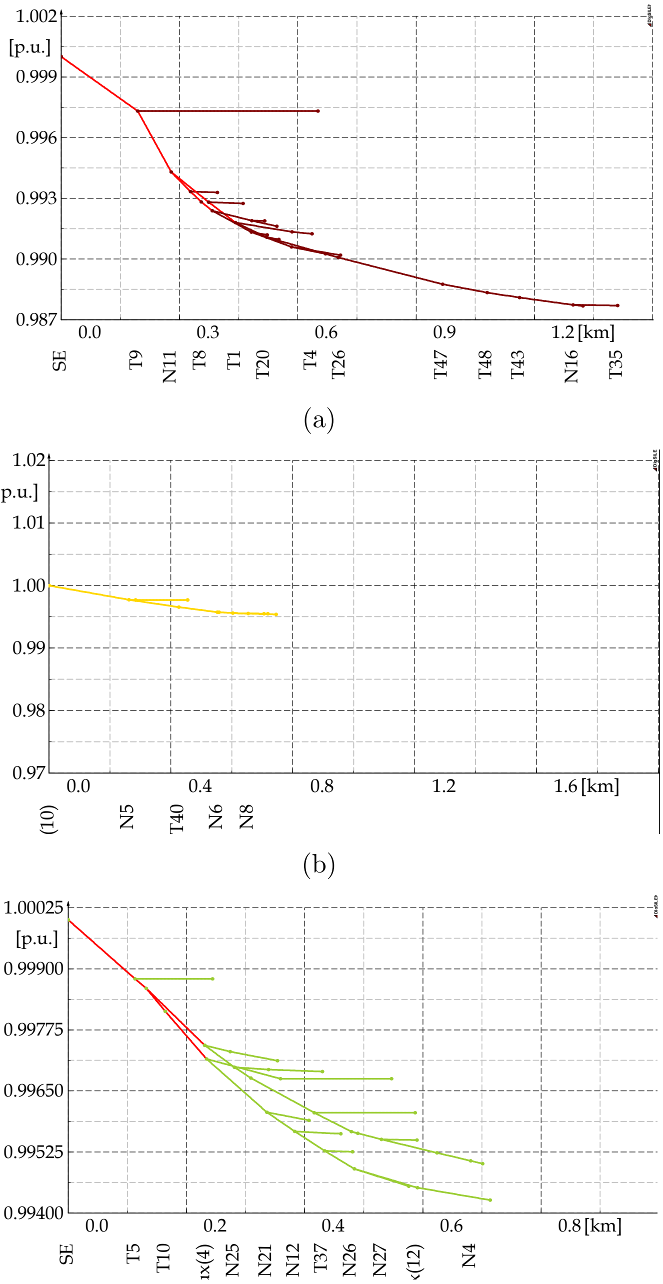


Figure 4.25: Voltage levels of the different busbars with reference to possible reconfiguration solutions of the distribution network under abnormal operating conditions,*i.e* activation of switchgear equipment NC-211 and tripping of overcurrent relay R-211.



(a)

(b)

(c)

Figure 4.26: (a) Voltage profile of distribution feeder A after a feeder's reconfiguration; (b) Voltage profile of distribution feeder B after a feeder's reconfiguration; (c) Voltage profile of distribution feeder C after a feeder's reconfiguration.

As already remarked, the reconfiguration process is solved as an optimization problem, where the objective function aims to maximize the restored load subject to technical constraints such voltage levels and radiality. For this case study, three suitable options satisfy the the objective function and its constraints. Therefore, not only the case 5, case 6 and case 8, but also the other restoration cases are evaluated to determine the best reconfiguration solution based on voltage levels, as reported in Figure 4.25.

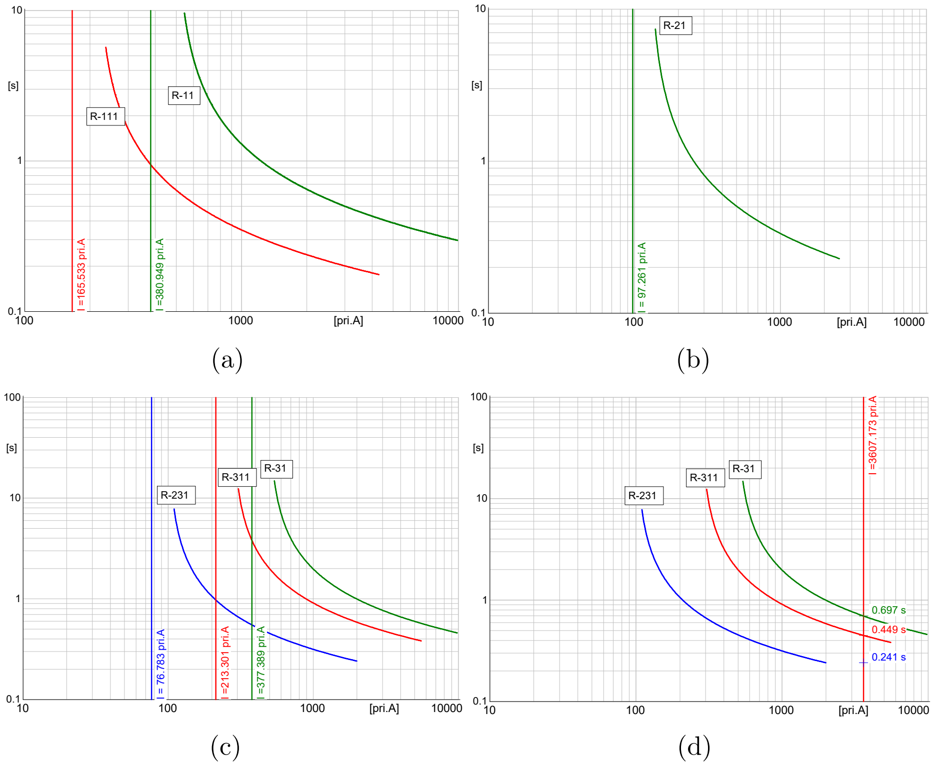
Figure 4.24 shows the distribution network under the new operating conditions, where switchgear equipment NC-211 is in open position, and NO-231 has changed to closed position. As a result of this switch operation the network has been reconfigured; consequently the amount of restored load is maximized, *i.e* minimizing out of service areas (box highlighted in red). The new operation condition indicates that some distribution transformers has been connected to feeder C (green feeder) due to the faulty section on primary feeder A. Figure 4.24 permits to display the functionality of the proposed algorithm using communication peer-to-peer between Matlab and PowerFactory, and it can be applied to different distribution networks.

The voltage drop analysis is depicted in Figure 4.26 where a voltage profile highlights the behavior of the distribution network after operation of switchgear equipment, *i.e* reconfigured network. It should be clear that the voltage drop is kept within standard limits that are imposed by utility policies. Figure 4.26 shows the voltage profile in feeder A, feeder B and feeder C during the new operating conditions,respectively.

Table 4.11: Parameters of I_s and TMS on overcurrent relays at different switchgear equipment after reconfiguration process.

Overcurrent Relay	Current Setting	TMS	Feeder
R-11	4.95	0.13	A
R-21	1.26	0.10	B
R-31	4.90	0.20	C
R-111	2.15	0.07	A
R-211	-	-	-
R-311	2.77	0.16	C
RX-121	-	-	A and B
RX-122	-	-	A and B
RX-311	-	-	C and A
RX-312	-	-	C and A
RX-231	0.99	0.10	C
RX-232	-	-	B and C

When reconfiguration process is completed, the remaining phase of the algorithm is applied to the new operating conditions. Therefore, a communication peer-to-peer between Matlab and PowerFactory is executed to determine the electrical parameters such TMS and I_s. Current setting or pick-up current is evaluated on the basis of the load current circulating along the feeder, which it is provided by the power-flow analysis. On the other hand, the TMS is determined on the basis of Eq. 3.2 of inverse overcurrent characteristic, which utilizes short-circuit analysis to determine the most remote point of protection, assuring selectivity. Table 4.11 shows the new calculated parameters (TMS and I_s) for overcurrent protection, whilst Figure 4.27 consists of 44 subplots, each of one showing the protection coordination in feeder A, feeder B and feeder C after reconfiguration process. In particular, Figure 4.27 (a) shows the protection coordination of two overcurrent relays connected in feeder A, Figure 4.27 (b) depicts only one overcurrent relay in feeder B due to the fact that the other one is disconnected because it associated to the faulty section, while Figure 4.27 (c) shows the coordination of three overcurrent relays because this feeder took the restored load. Finally Figure 4.27 (d) shows the behavior of overcurrent relays in feeder C when this feeder is affected by a short-circuit. Figure 4.27 highlights the case of a proper protection coordination for a distribution network, where selectivity is achieved.



(a) (b)

(c) (d)

Figure 4.27: (a) Protection coordination of overcurrent relays on feeder A; (b) Protection coordination of overcurrent relays on feeder B; (c) Protection coordination of overcurrent relays on feeder C; (d) Protection coordination of overcurrent relays on feeder C during a short-circuit on feeder C.

Chapter 5

Conclusions and Further Investigations

Simulations, experiments and results achieved for resilient expansion of electrical network considering protection coordination based on georeferenced information, reported in Chapter 4 lead to several considerations.

This thesis was focused to develop a resilient expansion of electrical network based on georeferenced information obtained from OSM files, which normally is hierarchically structured. However, the gathered information is not always following a specific order, thus, georeferenced information must be processed in order to divide information in closed and non-closed features, which were used for planning and routing electrical networks based on technical requirements. Improvement in a decision-making tool for electric distribution network planning was developed, where clustering techniques were used to divide secondary low voltage networks enhancing low voltage levels. A resilient planning was associated with reconfiguration capacity, consequently, a peer-to-peer communication between Matlab and PowerFactory was implemented to develop a reconfiguration algorithm which was focused to restore distribution network when it faces abnormal events. As a consequence, of this topology's change, an automated protection coordination was determined based on the available electrical components.

The first part of the thesis proposed a powerful and innovative methodology to design, plan and route a resilient distribution network considering geographical information from public available data, minimising the total load shedding due to tie-switches allocation, including construction costs and reduction the utility's budget. The proposed model was based on georeferenced data such as roads, avenues and land for construction, which was used to forecast the electrical demand customers, which was needed to determine the optimal location of distribution transformers contemplating the minimal distance between distribution transformers and end users. The routing problem was addressed throughout MST techniques which connected distribution transformers and power substation using a medium voltage underground network, which is sited along public streets and roads, minimising the total distance. The proposed model can be applied to different areas and location considering an increment of customers and their demand, therefore the heuristic model was exploited to develop a flexible power distribution networks based on different georeferenced maps. For this problem, not only the end customer's demand and location but also the feeder network constraints were required to test the proposed methodology. Satisfactory results were achieved, where there are no scenarios exceeding prescribed limits associated with voltage drop (lower than 1.2%), and cable loading for both normal and abnormal operating conditions. Subsequently, the model represented a feasible solution for planning procedure. providing a coverage of 100% since it is mandatory to supply electricity to the totality of customers.

Improvements on planning algorithm for distribution networks is achieved, which is based on a modified Prim algorithm to determine a feasible distribution network extension, adequately locating distribution transformers and medium voltage and low voltage power cables. Consequently, the proposed methodology can be seen as a decision-making tool to be used by utilities' engineers during planning and design tasks. In fact, the proposed model allowed to obtain a pre-design based on geographical parameters (latitude and longitude) that met with all technical requirements with a high time response. A suitable pre-design was obtained considering the minimal amount of distribution transformers, which fed to 100% of end users, by the maximization of manholes connected by a commercial low voltage cable that meets with a drop voltage constraint of 3%. The proposed methodology was performed based on local utility guidelines for the planning of distribution networks. However, the decision-making criteria could be adapted to different utility guidelines and also could be applied to different scenarios around the world based on georeferenced information. The only requirement was associated with available georeferenced parameters, which allowed the execution of the aforementioned algorithm; subsequently, any outdated, erroneous or incomplete gathered geographical information could lead erroneous grid extension.

To this end, considering a resilient planning, normally open points (tie-points) were allocated in strategic locations within the distribution network. Candidate tie points were suggested based on possible paths to connect primary feeders; however, the optimal allocation was defined by the minimal distance between them. As a result, at least one and two possible tie-lines between primary feeders were contemplated; consequently, the proposed methodology was focused on altering the close/open status of tie switching equipment, improving reliability and resilience reducing downtime during contingency events by reconfiguration capacity. Moreover, a peer-to-peer communication between Matlab and PowerFactory was implemented to develop a reconfiguration algorithm which was focused to restore distribution network when it faces abnormal events. As a consequence of this topology's change, an automated protection coordination was determined based on the available electrical components.

A faulty section was used to test the reconfiguration algorithm, which was based on a peer-to-peer communication between Matlab and PowerFactory. In particular, Matlab organized, processed and developed an exhaustive search of possible combinations of close/open status maximizing the amount of distribution transformers connected to primary feeders. On the other hand, PowerFactory allowed to model and simulate the distribution network, where power-flows were executed and sent to Matlab to be processed. Optimization process represented the best option of restoration considering technical requirements such as voltage levels and radiality, and therefore, the best option was evaluated in order determine the new order of protection coordination. In fact, a new topology involves, new overcurrent relays in the primary feeder. Both parameters, current setting and time multiplier setting were calculated on Matlab based on short-circuit analysis performed by PowerFactory. The achieved results highlighted an accurate protection coordination assuring selectivity for the proposed case. The reconfiguration and coordination protection algorithms can be developed in different areas, locations and distribution networks.

Future research will be focused on different methodologies for service restoration and protection coordination by the use of the environments of PowerFactory and Python.

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