



Dissertation

Master in Electrical and Electronic Engineering

***IMPACT OF DISTRIBUTED GENERATION AND
ENERGY STORAGE SYSTEMS IN ELECTRICAL
POWER DISTRIBUTION SYSTEMS***

PAUL ANDRES AUCAPIÑA AREVALO

Leiria, September 2017



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Dissertation developed under the supervision of Doctors Romeu Vitorino and Paula Vide, professors at the School of Technology and Management of the Polytechnic Institute of Leiria and co-supervision of Doctor Santiago Torres, professor at the Faculty of Engineering of the University of Cuenca.

Leiria, September 2017

Dedication

To my dear parents, José and Piedad and my girlfriend Marie, who always gave me the necessary support to finish my studies.

Acknowledgement

I want to thanks the SENESCYT, University of Cuenca and Polytechnic of Leiria for giving me the opportunity to study through the scholarship programs.

I would like to express my sincerest appreciation to my supervisors, Professor Paula Vide, Professor Romeu Vitorino and Professor Santiago Torres, who contributed their support and experience on the development on this thesis.

I am grateful to Sergio Zambrano who works for the electrical utility Empresa Eléctrica Regional Centro Sur C.A. (" CENTROSUR ") that provided the technical information about the electrical network of one sector of Cuenca needed for this work.

Resumo

Atualmente, a preocupação mundial sobre mudanças climáticas ou planeta é indiscutível. Um dos aspectos que influenciam os problemas ambientais é a geração de energia através de métodos convencionais. Devido a isso, os governos de todo o mundo, e particularmente o Equador, optaram pela implementação de energia renovável para o fornecimento de eletricidade. No caso equatoriano, por exemplo, o governo estabeleceu um programa chamado "para uma nova matriz de energia" e também regulamentos para promover o uso de fontes de energia renováveis para fins energéticos. Tendo em conta estas considerações e os possíveis desafios técnicos que a Distributed Generation (DG) poderia criar, é necessário estudar o comportamento das redes após a introdução de (DG). Nesta tese, o alimentador de distribuição de barra-ônibus padrão IEEE 13 e um alimentador de distribuição real foram escolhidos para realizar o modo de duas soluções, que são fluxo de energia de instantâneo e fluxo de energia Quasi- Static Time Series (QSTS). Essas redes foram modeladas e simuladas usando OpenDSS, um software usado em literatura científica para analisar o impacto da DG em sistemas de distribuição de energia elétrica. Para ônibus IEEE 13, foram definidos cinco cenários diferentes para avaliar características técnicas, como perdas, perfis de tensão e fluxo de energia reversa; apenas a geração de PV foi considerada para esta rede, enquanto para a rede CENTROSUR foi considerado três casos de estudo com cinco cenários cada um. Os casos de estudo para o CENTROSUR foram: i) apenas PV, ii) PVs integrados com BESS e iii) PVs integrados com BESS e fogões de indução. Para realizar simulações para a rede CENTROSUR, utilizou-se o perfil de demanda do transformador, o perfil do sistema de armazenamento, os perfis fotovoltaicos e os perfis de consumo de carga de 10 minutos de resolução.

Abstract

At present, the worldwide concern about climate changes on our planet is indisputable. One of the aspects that influences environmental problems is the generation of energy through conventional methods. Due to this, the governments all over the world, and particularly Ecuador, have opted for the implementation of renewable energy for the electricity supply. In the Ecuadorian case, for example, the government established a program called “towards a new energy matrix” and also regulations to promote the use of renewable energy sources for energy purposes. Taking into account these considerations, and the possible technical challenges that Distributed Generation (DG) could create, it is necessary to study the behavior of networks after the introduction of (DG). In this thesis, the standard IEEE 13 buses distribution feeder and a real distribution feeder were chosen in order to carry out two solution modes which are snapshot power flow and Quasi-Static Time Series (QSTS) power flow. These networks were modeled and simulated using OpenDSS, a software used in scientific literature to analyze the impact of DG in electrical power distribution systems. For IEEE 13 buses feeder, five different scenarios were defined to evaluate technical features such as losses, voltage profiles and reversed power flow; only PV generation was considered for this network while for CENTROSUR network it was considered three cases of study with five scenarios each one. The cases of study for CENTROSUR were: i) only PV, ii) PVs integrated with BESS and iii) PVs integrated with BESS and induction cookers. In order to carry out simulations for CENTROSUR network, the transformer demand profile, the storage system profile, the PV profiles and the load consumption profiles of 10 minutes of resolution were used.

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List of acronyms

AC	Alternating current
AFCs	Alkaline Fuel Cells
BESS	Battery energy storage system
CAES	Compressed air energy storage
CIGRE	International Council on Large Electric Systems
CS	Centralized storage
DS	Distributed storage
DC	Direct current
DG	Distributed Generation
DLC	Double layer capacitors
DR	Distributed Resource
EES	Electrical Energy Storage
E.E.R.C.S.	Empresa Eléctrica Regional Centro Sur (“CENTROSUR”)
ECs	Electro-chemical capacitors
EPS	Electric Power Systems
ESD	Energy Storage Device
FC	Fuel cell
FES	Flywheel energy storage
HRSG	Heat recovery steam generator
IEEE	Institute of Electrical and Electronics Engineers
LA	Lead acid battery

Li-ion	Lithium ion battery
LTC	Load Tap Changing
MPPT	Maximum power point tracking
MT	Micro-Turbine
NaS	Sodium sulphur battery
NiCd	Nickel cadmium
NiMH	Nickel metal
RE	Renewable Energy
OpenDSS	Open Distribution system simulator
PVs	Photovoltaic system
PVSS	Photovoltaic and storage system
uCHP	Micro combined heat and power
QSTS	Quasi Static Time Series
SMES	Superconducting magnetic energy storage

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1. INTRODUCTION

The worldwide concern about climate change on our planet is an indisputable fact. The energy sector is one of the main generators of greenhouse gases. The use of fossil-based energy resources causes a large emission of greenhouse gases, which contributes to environmental problems. Population growth increases day by day promoting the increase of electricity demand that leads to more contamination. In order to fulfill the need for more electricity, one of the solutions is to build large power plants. However, nowadays another solution can be the use of both renewable and non-renewable sources of energy as electric power generation within distribution networks or on the customer side of the network, which is known as Distributed Generation (DG).

In this context, in recent times there has been a strong impetus for the development and use of different technologies of small-scale generation, particularly those related to Renewable Energy (RE). DGs can be defined as the concept of small sizes electric power generation units (several kW to a few MW) connected to distribution network. The primary source of energy for these generators can be the traditional non-renewable sources, such as gas, or the renewable sources, such as wind, solar, hydro, and biomass. These generators can be connected either to the medium voltage or low voltage sections of the electric grid. Usually, they are connected near the load centers or the low voltage networks.

In addition to the integration of distributed generation points, storage systems are also being implemented, which together are causing traditional (passive) networks to evolve into active networks or smart-grids, in which the final consumer can be a generator or consumer. DG alternatives, such as wind and solar, depend on wind speed and solar radiation respectively, which makes the output power not always constant over time. Due to the fluctuation of the wind and the variability in the solar radiation, energy storage becomes necessary for storing electrical energy. Similarly, to conventional or renewable energy, an energy storage unit can be connected to the distribution, sub-transmission or transmission system.

Once stored, the energy can be used during periods of high demand or when DG's is null. All these changes require an effort from the electricity companies to solve problems that are related to the massive integration of DG, which means that the distribution networks are modified and have the flexibility to guarantee the continuity and quality of service.

The use of DG and storage systems helps solving some of the world's problems like shortage of energy. However, the implementation of these dispersed sources brings advantages and disadvantages, depending especially on the correct location and capacity of generation. Dispersed sources could change the normal operation of a common electrical power system, so the impact on planning, control, protection and operation of the distribution system is an important issue and should be analyzed.

This thesis discusses generally DG and the impacts of DG with energy storage on power distribution systems considering steady state conditions.

1.2. Background and study motivation

The introduction of DG and storage systems creates a set of technical and economic challenges in the power system. The motivation of this thesis is to study, analyze and contribute to the knowledge of the potential impact of this technology on distribution systems.

The introduction of DG and storage systems in the distribution system can significantly modify consumers' power flows and voltage levels, leading to important technical issues that must be considered when making these connections. Therefore, it is important to consider the random establishment of DG and storage systems in distribution systems, which could bring problems in the reliability, safety and quality of supply in the distribution network.

The Ecuadorian government, through the energy department, is implementing a program called "towards a new energy matrix" which consists of the implementation of new renewable technologies to produce electricity. This program considers incentive policies so that users can generate energy through renewable resources, for self-consumption or to injected into the grid for profit.

On the other hand, distribution networks were not designed to transport energy from the customer to the grid. Because of this, electricity distribution utilities are carrying out studies to find out what network parameters are affected when a customer decides to connect generation to the grid.

1.3. Objectives:

1.3.1. General objectives.

The general objectives of this thesis are the integration of DG and storage systems into power distribution systems and the analysis of the its impact on the behavior of the networks considering the characterization of different exploration scenarios.

1.3.2. Specific objectives

- ✓ Analysis of the behavior of a standard IEEE distribution system before and after the inclusion of DG and storage energy in steady state;
- ✓ Analysis of a real network of the CENTROSUR Utility - Ecuador;

1.4. Thesis Organization

This thesis is composed of five chapters:

- In Chapter 1, introduction, background and motivation are described. The objectives are also presented.
- Chapter 2 gives a brief overview of DG technologies. The literature review of modelling distribution systems and the impacts of DG into the grid are also presented.
- Chapter 3 gives a brief description of the software used in this thesis. The Modeling of utility distribution feeder and types of power flow analysis are also discussed.
- In Chapter 4, different scenarios of DG penetration along two feeders are proposed for both test systems. For both systems, voltage deviation and losses through the circuit are presented and discussed for each scenario and for two solution modes.
- Chapter 5, the last chapter provides the conclusions and recommendations in detail.

2 DISTRIBUTED GENERATION CONCEPT AND TECHNOLOGY

2.1. Introduction

In this chapter, definitions of DG as well as storage systems are given. Types of DG technology are presented.

2.2. Distributed Generation Concept

DG is a concept that existed years before. In the olden days, energy was provided by steam, hydraulics, direct heating and cooling and light and the energy was produced near the device. These happened until electricity was introduced as an alternative for the commercial purposes.

From the point of traditional view of planning and operation of distribution networks, the energy only flows from the transmission network, connecting generation sources across the state and country, through the distribution network and to the customer, as shown in Figure 2-1.

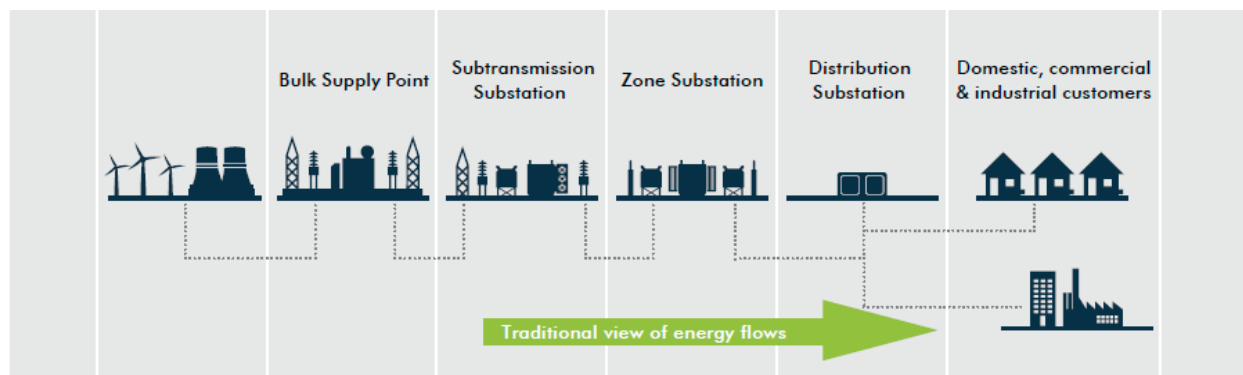


Figure 2-1: Traditional view of energy flows [1]

The increasing adoption of new generation technologies by the customers represents technical problems in the distribution network such as reverse energy flows. Figure 2-2 shows the emerging view of energy flows once DG is introduced in the distribution network.

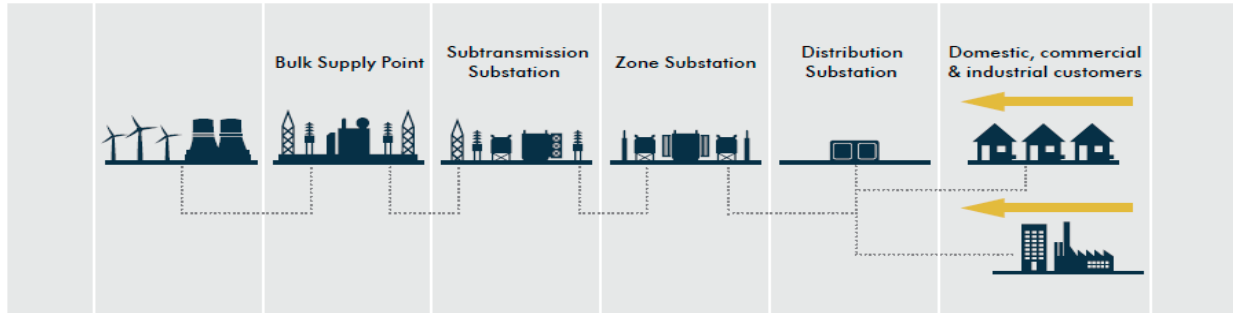


Figure 2-2: Emerging view of energy flows [1]

In this context, it is necessary to do a brief review of definitions, technologies, advantages and disadvantages of this technology.

2.2.1. Definitions

Actually, there is not only one definition for DG. In the literature it can be found a large number of terms and definitions associated to DG.

IEEE defines DG as the generation of the electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnections at nearly any point in a power system [2].

The Electric Power Research Institute defines DG as generation from "a few kW up to MW's" [3].

The International Council on Large Electric Systems (CIGRE) defines distributed generation as all generators with a maximum capacity between 50 MW and 100 MW connected to the electrical distribution system, which are not centrally designed or dispatched [4].

Gas Research Institute, contemplate that DG is " typically between 25 kW and 25 MW " [5].

2.3. Distributed Generation Classification

From a constructional and technological point of view, DGs can be classified as shown in Figure 2-3. Each one of these technologies are briefly described ahead.

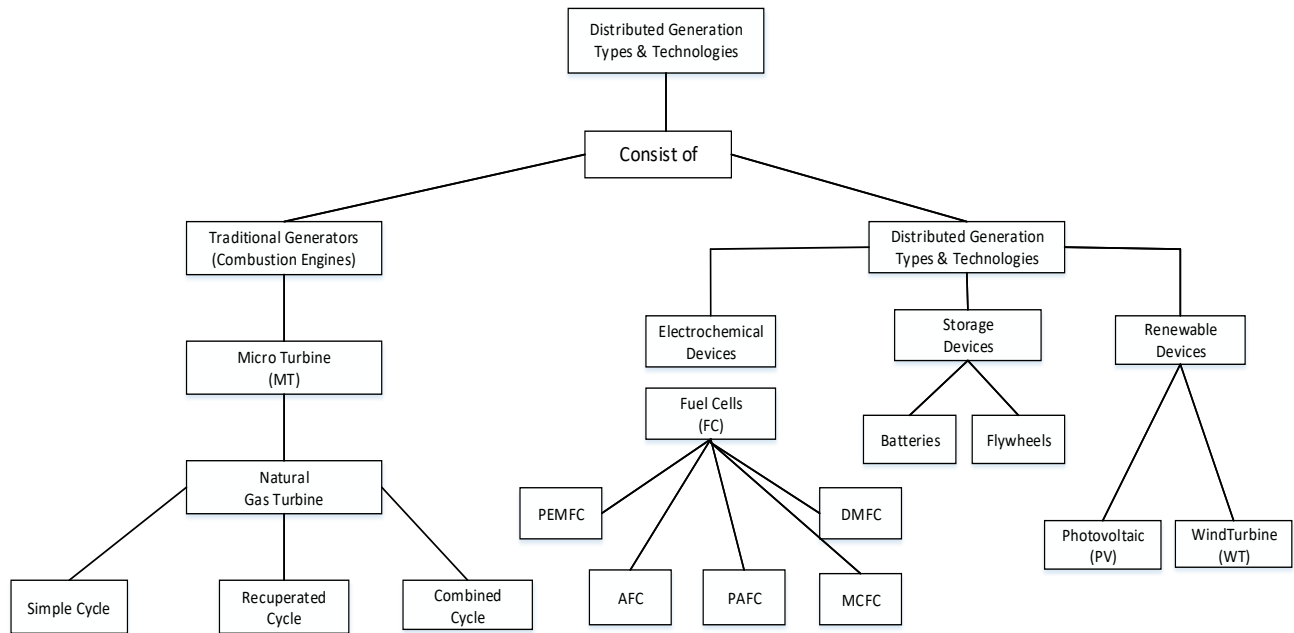


Figure 2-3: Distributed generation types and technologies [6].

2.3.1. Traditional combustion generators

2.3.1.1. Micro-Turbine

According to the type of operation, turbines can be classified as gas turbines and combustion turbines. Gas turbines are combustion turbines that produce high temperature and pressure gas. This high-pressure gas is used to rotate turbine shaft, which drives a compressor, an electric alternator and generator. They have a single shaft that rotates at a very high speed of over 40,000 rpm. A high-speed permanent magnet generator, air compressor and turbines are all mounted on the same shaft with air bearings [6], [7].

These kinds of turbines are small combustions turbines with power outputs from 25 kW to 500 kW. This kind of technology has advantages that includes lower emission, high efficiency and compact size. Therefore, it is expected them to have a bright future.

A typical power electronic convert used to convert electric energy from a micro turbine to a suitable voltage applied to the loads is shown in Figure 2-4. Firstly, the AC voltage generated by a micro-turbine is rectified, then the inverter will convert the DC voltage to a regulated AC voltage appropriate for the load and compatible with the grid. Micro-turbines respond slowly to a sudden change in power demand. The time constants for the changes in power output of micro-turbines can be from 5 ms to 5s, so it is necessary to install ESD coupled to the DC link to compensate for transient power demand which cannot be supplied by the micro-turbines. In Figure 2-4, it is shown how the ESD are coupled. The bi-directional power flow of the DC-DC converter is required to ensure that the ESD can be charged-up by the grid or the micro-turbine [8].

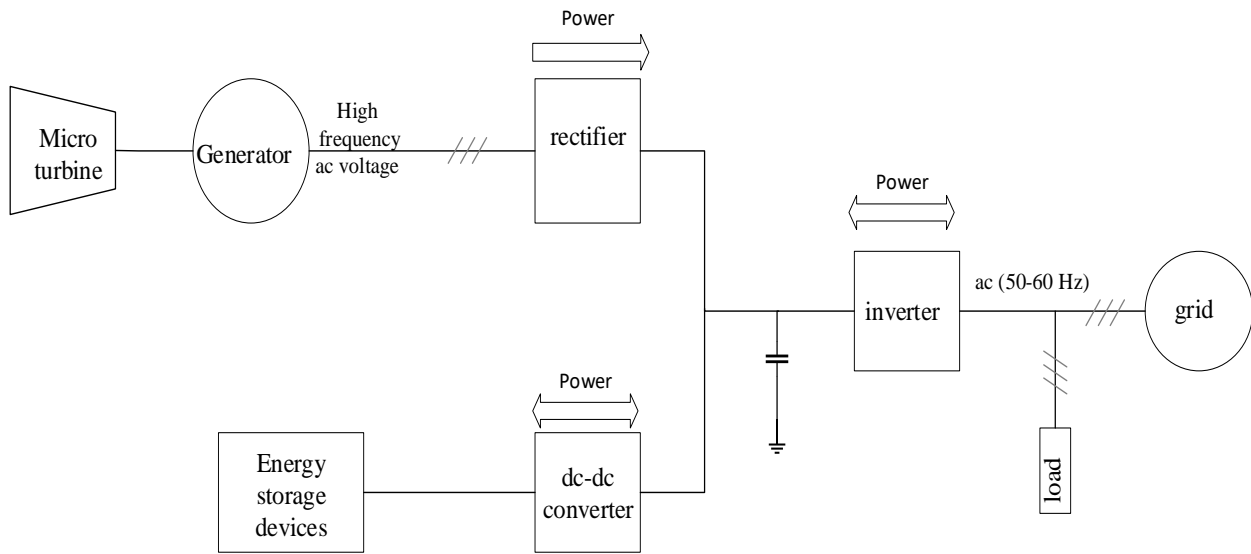


Figure 2-4: Power electronic converters for micro-turbine technology [8].

2.3.1.2. Simple-cycle gas turbines

Simple gas turbines can be either a single-shaft machine (with air compressor and power turbine (PT) on the same shaft) or a split-shaft machine. Also, they have a burner or combustor, and an electric generator rotated by power turbine [6].

2.3.1.3. Recuperated gas turbines

These turbines have a special heat exchanger (a recuperator), which uses the output exhaust thermal energy to preheat compressed air in its pass to the burner to increase the turbine electrical efficiency.

2.3.1.4. Combined cycle gas turbine

These turbines use the exhaust energy in a heat recovery steam generator (HRSG), based in the concept of that recovery, which may include a burner to increase the steam output. Figure 2-5 show how a steam turbine is driven by a steam from the HRSG. The steam from the HRSG generates power in addition to main power turbine to increase the total electric efficiency.

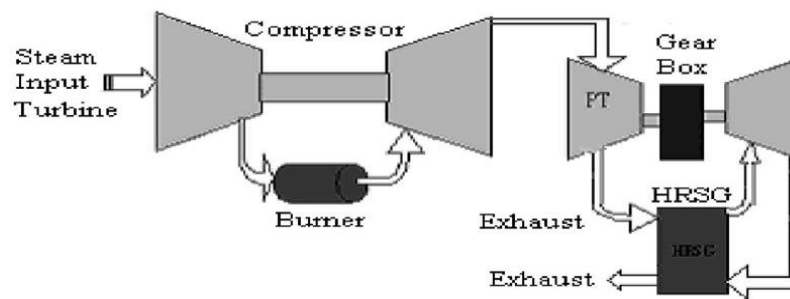


Figure 2-5: Combined cycle gas turbine[6]

Advantages of MTs.

- ✓ MTs can be installed in places where the space limitation be a problem;
- ✓ They have well-known technology and they can start-up easily, have good load tracking characteristics and simple design so they require less maintenance [7];
- ✓ They have a small number of moving parts with small inertia not like a large gas turbine with large inertia;
- ✓ They have lower emissions (less than 10 ppm NO_x) and more than 80% of efficiency, when compared with the large-scale ones [6];
- ✓ They have a modern electronic interface between the MT and the load or grid that increases the flexibility to be controlled efficiently [9].

2.3.2. Electrochemical devices: fuel cell (FC)

FCs are devices that use electrodes and electrolytic materials to accomplish the electrochemical production of electricity. They do not store chemical energy, but rather, convert the chemical energy of a fuel to electricity. Unlike batteries, FC does not need to be charged for the consumed materials during the electrochemical process since these materials are continuously supplied [10].

Figure 2-6 shows the basic components of a FC, which is integrated by an anode, a cathode, and an electrolyte. Fuel is supplied to the anode, and it is electrochemically oxidized while oxidant is electrochemically reduced on the cathode. Hydrogen, as a fuel, passes through the anode whereas Oxygen passes through cathode. FC technology is based on an electrochemical process in which hydrogen and oxygen are combined to produce electricity with no combustion. The catalyst splits the hydrogen atom into a proton and an electron. The proton passes through the electrolyte. However, electrons create a separate current that can be utilized before they return to the cathode to be demodulated with the hydrogen and oxygen in a molecule of water [10], [11].

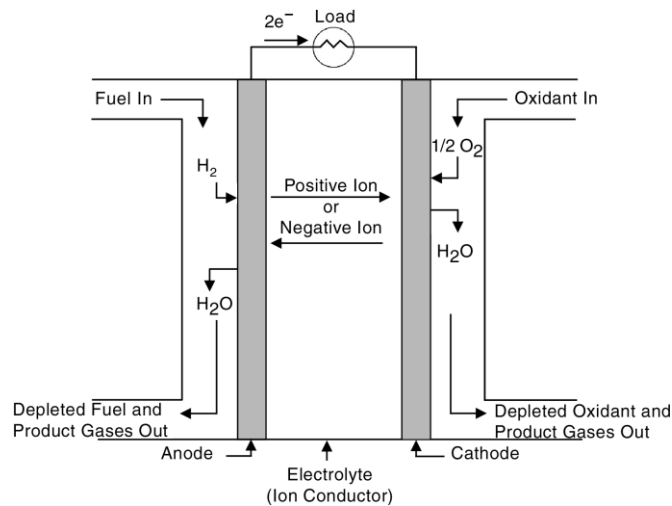


Figure 2-6: Fuel cell diagram [12]

The electrochemical process is shown in Figure 2-7. The stages of the process are direct current electric power, water heat, and some low emitted gases (like NO_x and CO_2). In order to convert the source fuel to a hydrogen-rich fuel stream, a fuel processor is used, which is needed for the electrochemical reaction.

A power electronic device (a power conditioner) is also necessary to convert the DC output to the AC output to be connected to the grid and control its voltage level according to the required application [10], [11]. The hydrogen used can be obtained by reformation of hydrocarbons or by electrolysis operation from water. The output products of the process by reformation are H_2 and CO_2 . Heating for the steam and the carbon is required for this chemical operation. The other process to produce H_2 is from electrolysis of water, which is not an economic process as it uses electric energy to do the process and cover its losses.

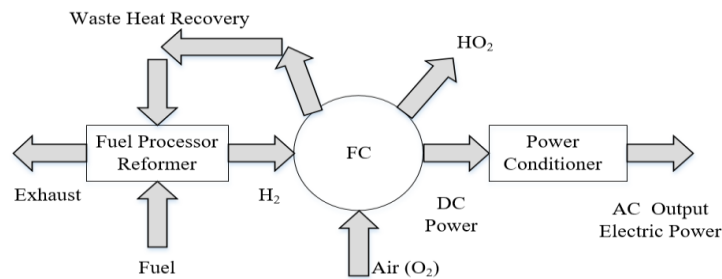


Figure 2-7: FC construction, operation, and products [6].

Advantages of FCs

- ✓ FCs transform the fuel chemical energy to electric power with a 60% efficiency;
- ✓ Due to slow prices and the output bi-product (electricity and heat), small size FCs are expected to be implemented as in commercial as residential buildings for the purpose of lighting and heating;
- ✓ The absence of big moving parts results in very low noise levels, relatively higher efficiencies and emits low pollution.

FC types and technologies. There are various fuel cell types depending on the electrolyte used such as: alkaline fuel cell (AFC), direct methanol fuel cell (MCFC), proton membrane fuel cell (PEMFC), and solid oxide fuel cell (SOFC).

2.3.3. Electrical Energy Storage

Electrical Energy Storage (EES) is a technology used to convert electrical energy to another energy form which can be used when it is required. This kind of technology is being used to achieve CO₂ reduction and as a smart grids complement. The main characteristics of EES are: ESS helps in reducing electricity costs by storing electricity at off-peak times when its price is lower. Secondly, EES could support customers when network failure occurs due to natural disasters. The third main characteristic is to solve problems of power fluctuation, voltage and frequency. Due to these considerations it is necessary to know their characteristics and types of storage systems.

Classification of EES systems

According to the form of energy, EES systems can be classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. This classification is shown below.

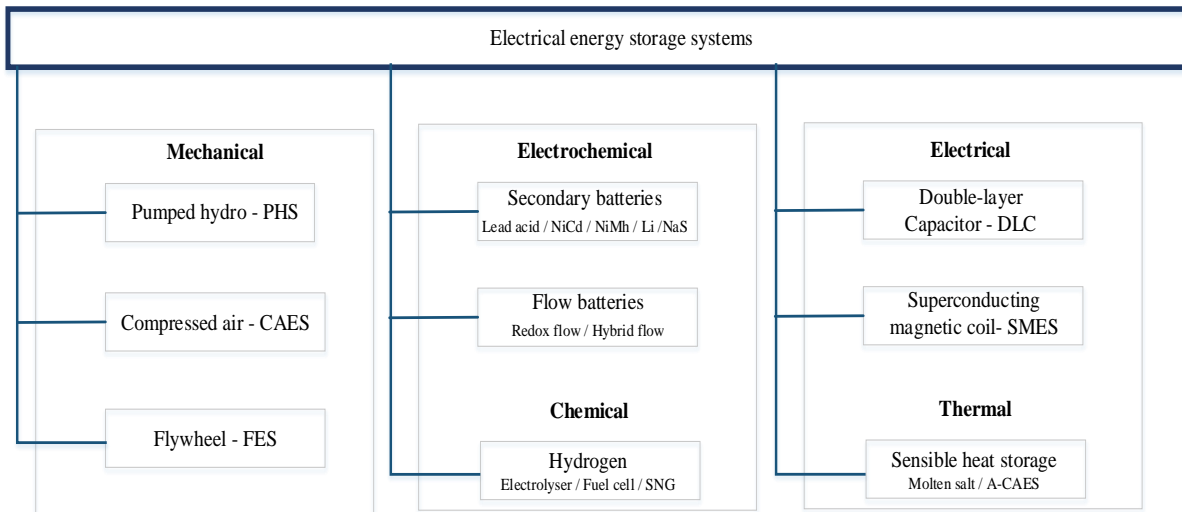


Figure 2-8: Classification of electrical energy storage systems according to energy form. [13]

2.3.3.1. Mechanical storage systems

The most common mechanical storage systems are pumped hydroelectric power plants (pumped hydro storage, PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).

Pumped hydro storage (PHS)

PHS is a type of hydroelectric energy storage which uses two water reservoirs at different altitude to pump water during off-peak hours from the lower to the upper reservoir (charging). When it is necessary the water flows back from the upper to the lower reservoir, powering a turbine to produce electricity (discharging).

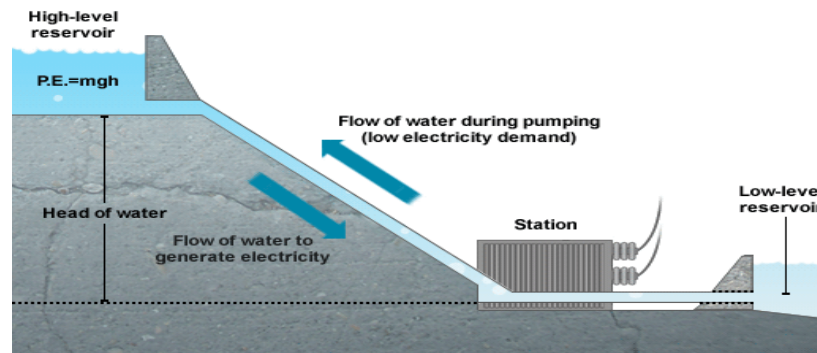


Figure 2-9: Pumped Hydro principle. [14]

Compressed air energy storage (CAES)

Compressed air energy storage is a technology which uses air as storage medium due to its availability. Electric energy is used to compress air. Then the air is injected into an underground structure or an above-ground system of vessels. Finally, a generator is fed by the air compressed during times when energy demand is the highest.

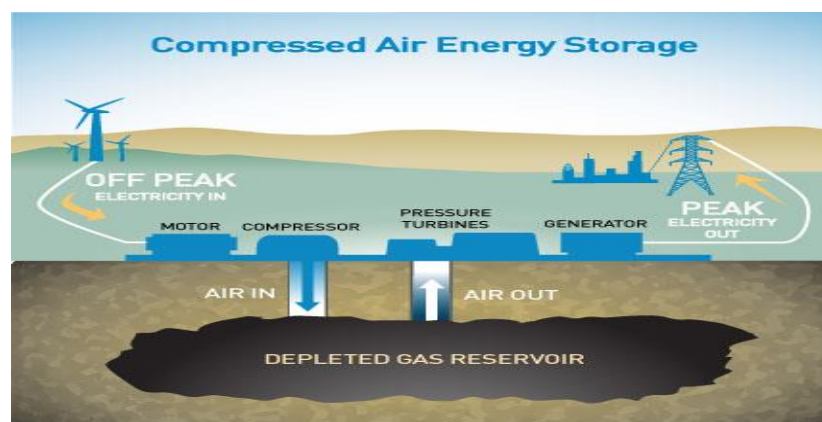


Figure 2-10: Underground CAES [15].

Flywheel energy storage (FES)

Flywheel energy storage system is a device which works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel [16].

2.3.3.2. Electrochemical storage systems

Nowadays the use of BESS has increased due the decrease of their costs and the improvement of their efficiency.

Lead acid battery (LA)

Lead acid batteries are the world's most used battery. These kind of batteries are used in stationary and mobile applications. Among its main applications are stand alone systems with PV, emergency power supply systems, battery systems for mitigation of output fluctuaction from wind power. Life service of LA is 6 to 15 years with a cycle life of 1500 cycles at 80% depth of discharge, and a effiience about 80 % to 90%.

Nickel cadmium and nickel metal hybride battery (NiCd, NiMH)

NiCd batteries are the only batteries capable of performing well at low temperatures in the range from -20 °C to -40 °C. These batteries have a higher power density and a slightly greater energy than LA batteries. However, one disadvantage of these batteries is their toxicity, so these have been prohibited for consumer user and only they are used for stationary application in Europe.

Lithium ion battery (Li-ion)

Lithium ion have become the most important storage technology in different areas of portable and mobile applications (e.g. laptop, cell phone, electric bicycle, electric car). One of the advantage of this batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. Another advantage is that to obtain the target voltage, the number of cells in series with the associated connections and electronics can be reduced due to high cells voltage levels of up to 3.7 V. For example, one lithium ion cell can replace three NiCd or NiMH

cells which have a cell voltage of only 1.2 Volts. The main drawback is the cost which is USD 600/kWh due to special packaging and internal overcharge protection circuits [13].

Sodium sulphur battery (NaS)

Sodium sulphur batteries consist of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode; the active materials are separated by a solid beta alumina ceramic electrolyte. The battery temperature is kept between 300 °C and 350 °C to keep the electrodes molten. These batteries have a discharge time of 6. hours to 7.2 hours, and a life cycles around 4500 cycles. Their efficiency is about 75% and commonly are used in combined power quality and time shift applications with energy density [13].

Flow batteries

A flow battery is a rechargeable battery that storage energy in one or more electroactive species which are dissolved in liquid electrolytes. The electrolytes are stored externally in tanks and pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the electrochemical cell whereas the energy depends on the size of the tanks. Although these batteries were developed by NASA in the 70s as EES for long term space flights, flow batteries are not commonly being used.

2.3.3.3. Electrical storage systems

Double – layer capacitors (DLC)

Electro-chemical capacitors (ECs) are known by different names as ultra-capacitors, DLC or super capacitor. All the name used before refer to a capacitor, which stores electrical energy in the interface between an electrolyte and a solid electrode. The advantages of this technology are durability, high reability, long lifetime, and operation over a wide temperature. Also, two of the main features are the possibility of very fast charges and discharges due to low inner resistance, and the really high capacitance value, typically in order of many thousand farads. DLC technology where a large number of short charge/ discharge used in applications with a large number being

required. Due to the investment costs, DLC are not suitable for the energy storage over long time periods.

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) systems work according to an electrodynamic principle. This systems storage energy in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. 100 years ago at the discovery of superconductivity a temperature of about 4 °K was needed. Much research and some luck has now produced superconducting materials with higher critical temperatures. Today materials are available which can function at around 100 °K. The main parts of this storage system are a coil made of superconducting material, power conditioning and a cryogenically cooled refrigerator. Due to high cost of superconducting wire and refrigeration requirements, SMES is only used for short duration energy storage.

2.3.3.4. Thermal storage systems

Thermal (energy) storage systems store available heat by different means in an insulated repository for later use in different industrial and residential applications, such as space heating or cooling, hot water production or electricity generation. Thermal storage systems are deployed to overcome the mismatch between demand and supply of thermal energy and thus they are important for the integration of renewable energy sources. Thermal storage can be subdivided into different technologies: storage of sensible heat, storage of latent heat, and thermo-chemical and absorption storage. The storage of sensible heat is one of the best-known and most widespread technologies, with the domestic hot water tank as an example. The storage medium may be a liquid such as water or thermo-oil, or a solid such as concrete or the ground. Thermal energy is stored solely through a change of temperature of the storage medium. The capacity of a storage system is defined by the specific heat capacity and the mass of the medium used [13].

2.3.4. Renewable devices

RE is energy generated from natural resources such as sunlight, wind and water. Some types of RE are discussed below.

2.3.4.1. Photovoltaic (PV)

The use of Photovoltaic Solar Energy is made through the direct transformation of solar energy into electrical energy by photovoltaic effect. This transformation is carried out by "solar cells" that are manufactured with semiconductor materials (for example, silicon) which generate electricity when solar radiation influence them. The photovoltaic effect consists of the production of an electrometry force by a luminous flux that influence on the surface of the cell. The most common photovoltaic cell consists of a thin sheet of a semiconductor material composed mainly of silicon of a certain degree of purity, which when exposed to sunlight absorbs photons of light with sufficient energy to cause the "electron hop", displacing them from its original position towards the illuminated surface (Figure 2-11).

When these electrons are released with their negative charge (n) they give rise to voids or gaps with positive charges (p). As the electrons tend to concentrate on the side of the plate where sunlight is incident, an electric field is generated with two well differentiated zones: the negative, the illuminated slide where the electrons are and the positive one on the opposite side where there are holes or gaps. If both zones are electrically connected by conductors attached to each of the slides of the plate the electric unbalance originates an electromotive force or potential difference, creating an electric current to equalize the charges. That current continuous is generated in a constant process while sunlight acts on the sensitive slide of the sheet.

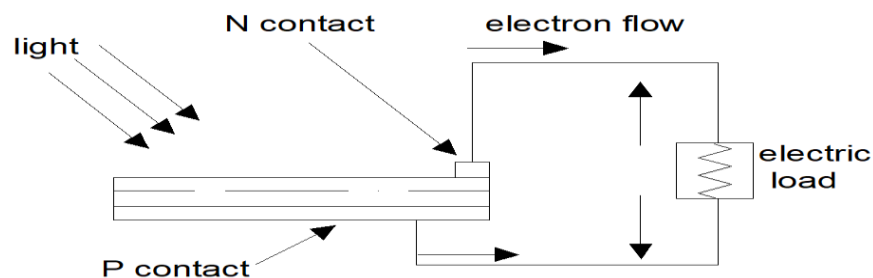


Figure 2-11: Photovoltaic panel [17]

2.3.4.2. Wind Turbines (WT)

WT is a device that converts the wind's kinetic energy into electrical power. They operate on a simple principle. The wind rotates the windmill-like blades, which in turn rotate their attached shaft. This shaft operates a pump or a generator that produces electricity [6].

Types of wind turbines

Wind turbines can be manufactured in two basic groups: the horizontal-axis and the vertical-axis design. A horizontal axis machine has its blades rotating on an axis parallel to the ground, while a vertical axis machine has its blades rotating on an axis perpendicular to the ground. There are several available designs for both and each type has certain advantages and disadvantages. However, compared with the horizontal axis type, very few vertical axis machines are available commercially. Figure 2-12 shows types of wind turbines.



Figure 2-12: Vertical and horizontal Axis Wind Turbines [18]

2.4. STATE OF ART

This section presents the state of art related to the impact of DG on electric power networks. In the current scientific literature, there are several published work concerning the integration of DG into distribution systems. However, the most representative works associated with each of the factors involved in formulating the problem and determining variables in the evaluation of the penetration of DG are described below.

2.4.1. Impacts of DG

Impacts of DG on electrical energy systems are inevitable, and therefore control requires the efforts of generation companies and users. The implementation of DG can be reflected in phenomena such as: bus voltage, harmonics, power losses, reliability, etc. Through the inclusion of DG, the power flow can be bidirectional and it can cause overvoltage on the distribution system. There are some interconnection guidelines in order to connect DG to the distribution network. In [19], rules for studying the impacts of interconnecting DG to a distribution feeder are defined. The IEEE 1547.7 standard [20] for distributed resource interconnection provides technical criterion and requirements for interconnecting DG resources to distribution systems.

2.4.2. Voltage Impact

In scientific literature, there are many studies which have analyzed the impact of DG on technical parameters such as voltages, losses, capacity, reliability and power quality. For example in [21], the impacts of utility scale PV-DG on power distribution systems is reviewed, particularly in terms of planning and operation in steady state and dynamic conditions. One of the conclusions of this study is the improvement of voltage profiles when DG is considered. In this study mitigation measures such as distributed storage are also presented with the purpose of reducing the magnitude of voltage fluctuation on the feeder analyzed [21]. In [22], a study of time series power flow analysis for distribution connected PV generation is carried out in three real feeders and over the IEEE 8500 node feeder. The main purpose of this study was to find out how analysis using Quasi-static time series (QSTS) simulation and high time resolution data can quantify the impacts and the mitigation strategies to address voltage regulation operation, and steady state voltage. In

reference [23] analyzed voltages problems due to DG penetration. The simulations were performed under the worst network condition (minimum demand and maximum DG output power). Monte Carlo method was used to allocate DG. Also in this study, was determined that a small amount of DG can produce voltage violations while very large amounts of DG allocated with adequate criterion do not affect the system operation. Reference [24] assesses the impact of low carbon technologies in LV distribution systems. Firstly, a realistic 5-minute time series daily profile is produced for photovoltaic panel, electric heat pump, electric vehicles and micro combined heat and power units. After that, a Monte Carlo simulation is carried out for 128 real UK LV feeders. Results for this study showed that photovoltaic (PV) panels technology produced problems in 47% of the feeders, EHPs produced problems in 53% of the feeders and EVs produced problems in 34% of the feeders. For uCHP no problems were found. In reference [25], the impacts of DG on voltage regulation by Load Tap Changing (LTC) transformer were studied. That study shows that if the LTC tap transformer control is not applied, problems of under voltages and over voltages can occur. In [26] energy storage is used for voltage support in low voltage grids when high photovoltaic penetration is added. Centralized storage (CS) and distributed storage (DS) are investigated. CS is implemented by adding a single storage unit on a feeder node while DS integrated a storage device together with PV at a feeder location.

2.4.3. Impact on Electric Losses

In [27], technical impacts of microgeneration on low voltage distribution networks are analyzed. Impact analysis on losses demonstrates that an adequate amount of PV generation (30% PV) decreased the daily total losses in the system while an inappropriate amount of PV (100%) generation increased losses. In reference [28], the impact of DG of a distribution network on voltage profile and energy losses are analyzed. The results obtained in this paper show that an adequate location and size of DG are essential for reducing power losses and voltage profile. In [29], a probabilistic technique for optimal allocation of PV based distributed generators to decrease system losses is developed. In that research work are presented six cases. For the base case, without DG, the annual energy loss is 540.967 MWh, while for case 6 when DG of 1590 kW is added the annual energy losses were reduced to 161.721 MWh, which represents an energy and economic saving.

2.5. IEEE standard 1547-7

In this section, it is presented a brief explanation of the main impact studies that should be developed according to IEEE standard 1547-7. The IEEE standard 1547-7 is a guide which describes criteria, scope, and extent for engineering studies of the impact on area electric power systems of a distributed resource (DR) or aggregate distributed resource interconnected to an area electric power distribution system [20].

In the following two tables, different conventional systems impact studies and their relationship to potential systems impacts on the Electric Power System (EPS) area are shown. In section 1.2 of chapter 1 it was established that the analysis of the distribution networks will be carried out in steady state. Under this consideration, the green area painted in each one of the tables would correspond to the proposed analysis in that section. According to this standard, the steady state study and the quasi-static study are briefly explained in this section.

2.5.1. Conventional distribution studies

According to this standard, a large Distributed Resource (DR) could cause voltage variations, overload, equipment misoperations, protection and coordination, and power quality issues in the (EPS) area. Once DR is connected to the grid and if it exceeds some criteria limits, the DR should be studied using conventional studies which are presented in Table 2-1.

According to each of these studies, the impacts of the DR on the EPS area might be within acceptable limits. They also indicate that mitigations or more complex studies should be carried out.

Table 2-1: Type of study vs potential impact on the EPS [20]

Study type Impact	Unintentional islanding	Area EPS equipment duty and operating ratings	Protection design, coordination and fault rating	Voltage regulation and reactive power management	Power quality
Steady state simulation		✓	✓	✓	
System protection studies	✓	✓	✓		✓
Short-circuit analysis	✓	✓	✓		✓
Protective device coordination	✓	✓	✓		✓
Automatic restoration coordination	✓		✓		✓
Area EPS power system grounding			✓		✓
Synchronization			✓		✓
Unintentional islanding	✓		✓		
Arc flash hazard study			✓		
Operational characteristic- loading, load shedding, etc.	✓	✓	✓	✓	

Steady state simulation

A steady state simulation tool, also known as power flow simulation, solves a snapshot of an EPS model at nominal frequency. In its most basic form, this tool solve voltages, currents, real and reactive power flows and losses throughout the Area EPS at a single point in time.

When these simulations are carried out, some types of problems can be identified from the results, such as:

- Excessive voltage rise. DR installation can cause a bus voltage exceeds acceptable limits due to reverse flow of power caused during light loading conditions. Therefore, generation impact, such as solar, should be analyzed under the lowest daylight loading conditions. The concept of power flow study should include the low voltage equivalent to understand the impacts on power quality at the equivalent customer terminals and to be able to analyze the performance of the DR connected to the low voltage circuits.

- Excessive voltage fluctuations. DR, such as wind and solar generation can cause voltage fluctuations which can be irritating to some customers. However, circuit voltage can be controlled through voltage regulators and capacitor banks.
- Improper operation. When DR is added, it can create reverse power, which causes improperly equipment operation. Voltage regulation equipment is designed to operate as through power flow in only one direction from the source to the customer. Nevertheless, the inclusion of DS could cause a reversal power flow from the customer to the source, and in this way the equipment can wrongly adjust the voltage. This condition commonly happens under light load condition.
- Incorrect situational awareness. If large DR is installed on a circuit, circuit metering may be analyzed to know if the reverse power flow would be identified in readings provided to the system operators. Metering equipment should be replaced in order to capture bidirectional flow.
- Equipment overloads. If the connection of DR is larger than the local load, an equipment overloads can be caused in the Area EPS. These overloads may occur at any time and not only at peak conditions.
- Unbalanced operation. When the DR is installed at the location of area EPS with significant phase imbalances can cause voltage imbalance on the generator terminals. Single phase DR installation can increase the imbalance, which in turn causes serious impact on other devices connected to the area EPS circuits. Through a three-phase power flow analysis tool, modeling single phase DR or three- phase DR on unbalanced circuits can recognize the complications that may occur on the circuit. Problems can be detected that occur in a circuit in which a single-phase DR or three-phase DR on unbalanced circuit have been modeled.

According to this standard, “if the conventional steady state simulation (“power flow” study) shows indications of equipment overloads, sustained overvoltage conditions, excessive voltage fluctuations, or equipment control problems, a quasi-static simulation should be considered to confirm the steady state results or to analyze corrective measures” [20].

2.5.2. Special system impact studies

In many cases, special studies are not necessary. However, a need could arise to perform special studies even after the DR has been interconnected. For example, technical issues experienced after the DR interconnection, customer complaints, or a new DR application on the feeder might trigger some of these special studies. Table 2-2 shows the type of study and its relationship with potential impacts on the EPS.

Table 2-2: Type of study vs potential impact on the EPS [20]

Study type Impact	Un-intentional islanding	Area EPS equipment duty and operating ratings	Protection design, coordination and fault rating	Voltage regulation and reactive power	Power quality
Quasi-static simulation	✓	✓	✓	✓	
Dinamic Simulation	✓		✓	✓	
Dynamic stability	✓		✓	✓	
System stability	✓		✓	✓	
Stability analysis interpretation	✓		✓	✓	
Voltage and frequency ride through		✓	✓	✓	
Electromagnetic transient simulation			✓		✓
Ferroresonanse			✓		
Interaction of diferent types of DR	✓	✓	✓	✓	✓
Temporary overvoltage		✓	✓	✓	✓
System Grounding			✓		✓
DC injection		✓			✓
Harmonics and flicker		✓			✓
Harmonic analysis		✓			✓
Harmonic problems		✓			✓
Harmonic resonance		✓			✓
Flicker					✓

Quasi-static simulation

In this simulation, a sequence of steady-state power flow is conducted at a time step of no less than 1 second. However, it can be conducted using another time step, such as from 5 minutes to one

hour. Applications such as energy and loss evaluation of generation and load profiles can be carried out under this solution mode.

As is known, solar and wind are variable resources by a quasi-static simulation, voltage fluctuation impacts due to variable DR output can be analyzed. The impact on voltage controls can be observed by quasi-static solution. Another advantage of this solution mode is that it can show the impact of DR on system equipment and customers.

3. METODOLOGY

3.1. Introduction

In this chapter, an explanation of the utility feeders model and its components is presented. The feeders were modeled using *OpenDSS* software. The main characteristics of lines, transformers and customer are given in this chapter. The procedure to evaluate the DG technical impacts is also described.

3.2. Software OpenDSS

OpenDSS is an electrical system simulation tool for electric utility distribution systems. It can be implemented as stand-alone executable program or by the COM server DLL. At the beginning, the program was originally developed to support DG analysis. However, it has been improved and designed to be expandable for the future needs.

Some of the applications that have used *OpenDSS* are:

- Distribution Planning and Analysis
- Analysis of Distributed Generation Interconnections
- Annual Load and Generation Simulations
- Risk based Distribution Planning Studies
- Probabilistic Planning Studies
- Solar PV System Simulation
- Wind Plant Simulations
- Protection System Simulation
- Storage Modeling
- EV Impacts Simulations
- Harmonic and Interharmonic Distortion Analysis
- Development of IEEE Test feeder cases

3.3. Methodology

According to Figure 3-1, the first step to analyze the DG impacts on the network is the model creation in *OpenDSS*. To represent the model, some files have been created. In each of these files, characteristics of the network are stored. In Appendix A, all configuration elements are present in detail.

- Linecodes.dss
- Substation.dss
- Lines.dss
- Load.dss
- Capacitors.dss
- Transformer_sub.dss
- Transformer.dss
- Regulator.dss
- Switches.dss
- Voltage.dss

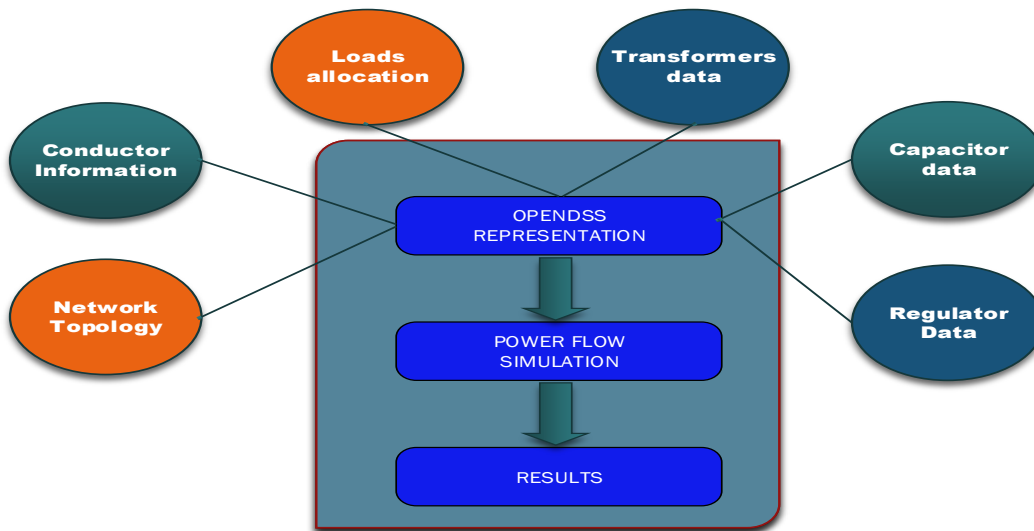


Figure 3-1: Input information for network modeling in OpenDSS

3.3.1. Overview

To carry out an analysis of the impact of DG in the distribution network, it is necessary to make comparisons with different DG penetration levels. The first step consists of analyzing a base case without DG. After that, the procedure continues with the connection of certain amount of DG penetration in a particular location of the network. Finally, the impacts of different penetration levels are analyzed. Losses and voltages of the grid are particularly evaluated and compared with the base case. An IEEE test feeder and a real network are analyzed. For each case study, two methods to evaluate the impacts of DG are used; these methods are static and Quasi-Static Time Series Analysis.

3.4. LOW VOLTAGE MODELS AND CREATING LOAD PROFILES

Distribution System

Electric power distribution is the portion of the power delivery infrastructure that takes the electricity from the highly meshed, high-voltage transmission circuits and delivers it to customers [30]. This distribution system typically starts with the substation that feeds one or more sub transmission lines. In some cases, the distribution substation is fed directly from a high-voltage transmission line in which case, most likely, there is not a sub-transmission system. Feeders are radial with a rare exception [31].

3.4.1. IEEE 13-Buses Test Feeder

One of the advantages of using OpenDSS is that it includes some test distribution feeder in a folder when it is installed. To carry out snap shot and QSTS analysis in the base case all the documentation found in OpenDSS is used in the original form. This feeder is shown in Figure 3-2 and the main characteristics are presented in Table 3-1.

Table 3-1: Main characteristics of the IEEE-13 Buses Test Feeder

Characteristic	Value
Nominal distribution voltage	4.16 kV
Number of buses	13
Number of loads	9
Load classes	Residential and Commercial
Voltage at loads	4.16 kV
Types of loads	Aggregated, spot
Electrical model of loads	Constant PQ, Constant current, Constant impedance
Loading	Relatively highly loaded
Voltage regulator	Single voltage regulator at the substation
Types of lines	Overhead and underground lines

The IEEE 13 buses test feeder is one four standard distribution model developed IEEE Power Engineering Society’s Power Systems Analysis, Computing and Economics Committee. This test feeder is small and it is used to test the features of distribution analysis software. The voltage operation of this system is 4.16 kV. This system has also a shunt capacitor, a 4.16/0.416 kV transformer, three-phase and one phase loads connected. All characteristics of this feeder can be found in Appendix B.

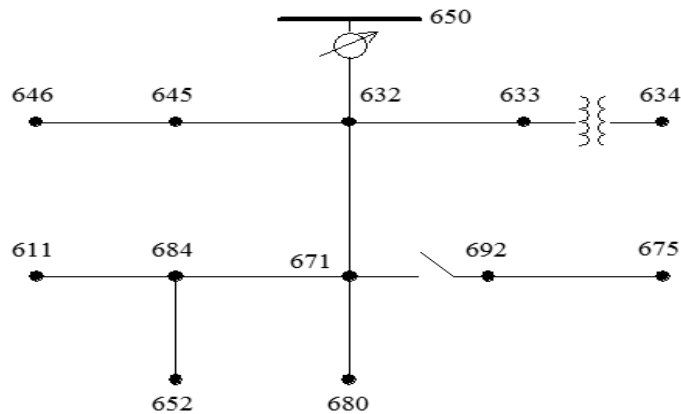


Figure 3-2: IEEE 13 Buses Test Feeder configuration [32].

3.4.2. Real Distribution Test System (CENTROSUR)

CENTROSUR low voltage system supplies energy to residential, commercial, small industrial customers and public lighting. The level voltage is 120/240 for single phase systems, 120/208 V and 127/220 V for three phases systems.

It is possible to analyze the behavior of the network in different operating scenarios through the secondary circuit model. Transformers, lines, loads, and structures models are presented below.

3.4.2.1. Three-Phase Transformer Models

The model three phase transformer can be seen in Figure 3-3. The network analyzed has a three-phase conventional transformer of 50 kVA. It has a connection delta-wye.

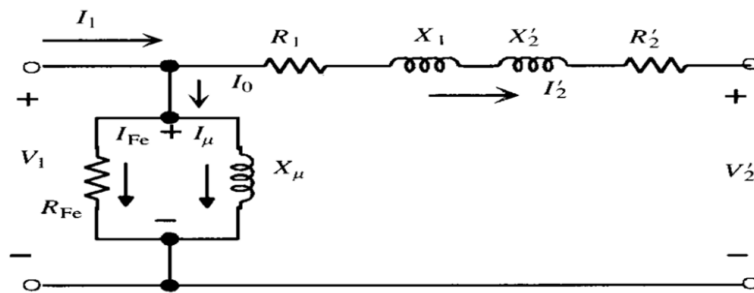


Figure 3-3: Equivalent circuit of a transformer referred to primary side [31].

Where:

R_1 : Primary winding resistance

X_1 : Primary winding reactance

R_2 : Secondary winding resistance referred to the primary side

I_{Fe} : Current in p.u. unit of resistive branch shut

I_{μ} : Magnetization current

3.4.2.2. Distribution System Line models

The modeling of distribution overhead and underground line segments is a critical step in the analysis of a distribution feeder. It is important in the line modeling to include the actual phasing of the line and the correct spacing between conductors [31]. The exact three-phases, two phases, or single phase line model is shown in Figure 3-4.

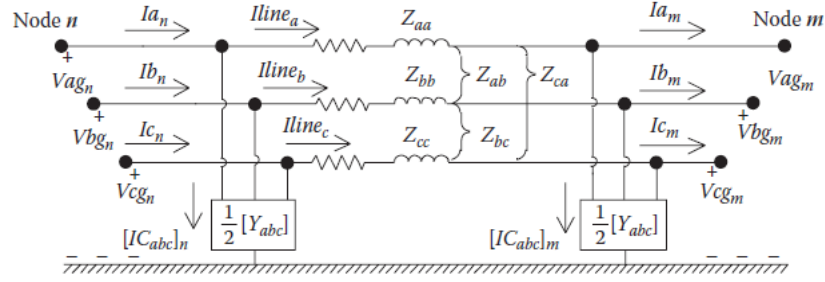


Figure 3-4: Three-phase line segment model [31].

In some situations, lines are of small length as it is the case of the distribution lines; the parallel admittance can be neglected due to its very small length, having only the series impedance as seen in Figure 3-5. This model is known as the modified line model.

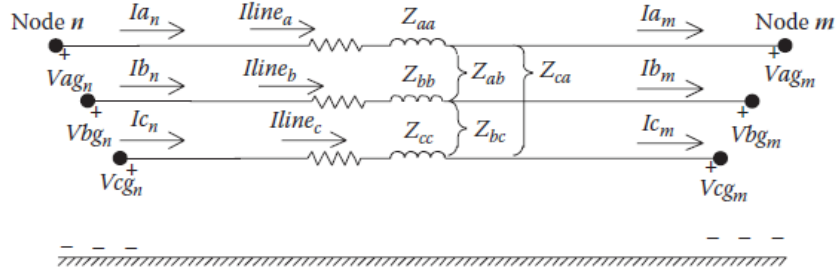


Figure 3-5: Modified line segment model [31].

Considering 60 Hz as nominal frequency and the earth resistivity $100 \Omega / m$, the following modified Carson equations are obtained.

$$z_{ii} = r_i + 0.05922 + j0.07541 \left(\ln \frac{1}{RMG_i} + 6.746 \right) \quad \Omega/km \quad (1)$$

$$z_{ij} = 0.05922 + j0.07541 \left(\ln \frac{1}{D_{ij}} + 6.746 \right) \quad \Omega/km \quad (2)$$

Where:

r_i : resistance wire Ω/km

RMG_i : Geometric medium radius in meters

D_{ij} : Distance in meters between wire i and wire j

Through Eq.1 and Eq.2 it is possible to calculate the primitive impedance matrix of the line.

3.4.2.3. Load Models

Loads on the distribution system are specified by the consumed complex power. The specified load will be the “maximum diversified demand”. This demand can be specified as kVA and power factor, kW and power factor, or kW and kVAr.

Loads on distribution systems can be modeled as wye connected or delta connected. The load models can be classified in static load model, ZIP models, and exponential models.

The exponential model of constant power was used in this work. For this model, active and reactive power are presented by the following equations.

$$P = P_0 \left(\frac{V}{V_0} \right)^\alpha \quad (3)$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^\beta \quad (4)$$

Where P_0 y Q_0 are active power and reactive power with nominal voltage.

V_0 is the nominal voltage; α and β are exponential load parameters.

3.4.2.4. Conductors and cables database

The Electric Distribution Utility CENTROSUR has an equipment database which contains characteristics of all conductors and cables used in low voltage. The most used conductors are ACSR #2, 4, and 1/0. The cable gauge used in the connection from the secondary circuit to the customer are multiplex conductors such as 2x6, 3x6, 4x6. The main characteristics of these conductors are presented in Table 3-2.

Table 3-2: Conductors Characteristics used in low voltage networks

Type	Resistance (R) 50° C [Ω /km]	Reactance (X) 50° C [Ω /km]	I_{max} [A]
ACSR.2	1.0092	0.9519	184
ASCR.4	1.5702	1.0081	140
ASCR.1/0	0.6562	0.9344	242
MUL.AL.2X6	2.8751	0.9902	80
MUL.AL.3X6	2.4844	0.9898	76
MUL.AL.4X6	2.8751	0.9902	76

3.4.2.5. Structure types

The configuration and distances between conductors is necessary to create the lines distribution model. Once the geometric configuration of the lines is known, it is possible to calculate RMG and through Ec. 1 and 2 calculating the mutual and self-impedance of each configuration.

There are three kinds of structures used by CENTROSUR in distribution networks. These structures are shown in Figure 3-6.

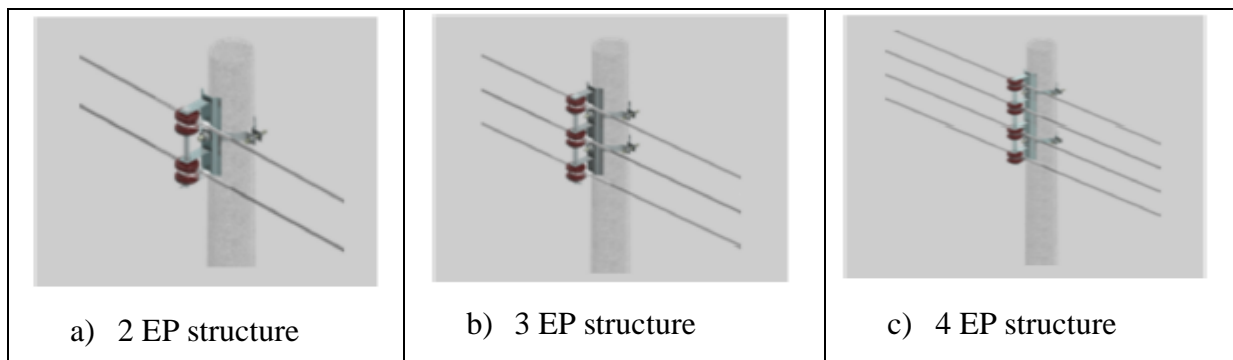


Figure 3-6: Main structures used in low voltage networks [33].

Once the components have been modeled, these have been included in OpenDSS.

3.4.2.6. Network localization

In Figure 3-7, a real distribution system located in the parish of Totoracochoa, Cuenca, Ecuador, is shown. The analyzed network belongs to feeder 0325. This feeds a three-phase transformer (ID number 63991). This transformer supplies 44 residential and 2 commercial customers and 26 lights.



Figure 3-7: Network location

The maximum length of this real system from transformer to the last customer is 262 meters. Blue lines represents aerial lines while red represents underground lines. The main characteristics are presented in Table 3-3.

Table 3-3: Main characteristics of the real system CENTROSUR

Connection type	Value
Nominal distribution voltage	22 kV
Number of buses	66
Number of loads	46 loads, 26 lights
Load classes	Residential and Commercial
Voltage at loads	0.220 kV
Types of loads	Spot
Electrical model of loads	Constant PQ
Loading	Unbalanced
Types of lines	Overhead and underground lines

3.5. TYPES OF ANALYSIS

3.5.1. Single Power Flow Analysis

Power flow analysis is one of the most important tools to assess the state of the system in a particular situation or in a specific point. However, this kind of study is limited to snapshots such as peak and minimum load points. With this analysis only the magnitude of the impact of DG could be evaluated at one instant in time.

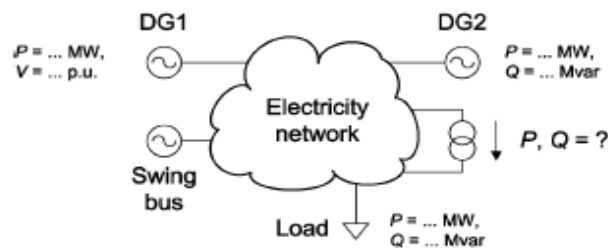


Figure 3-8: Typical steady-state power flow problem [34].

3.5.2. QSTS Time-Series Power Flow Analysis

To carry out better DG impact analysis, QSTS simulations are performed. They produce power flow solutions sequentially in steady state, where the first state of an iteration is used as the beginning of the next state. To apply QSTS simulations, it is necessary time varying load and time varying DG output data (also known as load-shapes). Figure 3-9 shows that DGs and the load are time function so the output solution should also be time function.

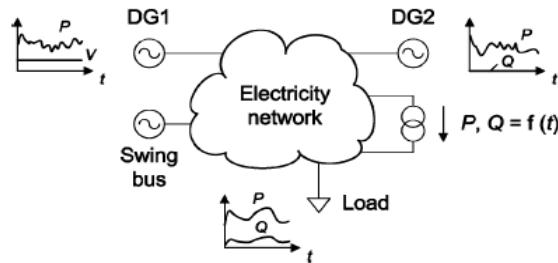


Figure 3-9: Time series applied to the power flow problem [34].

3.6. TIME-SERIES DATASETS

More complex data for power flow simulation is necessary when a QSTS simulation is carried out. This data is divided into three categories: model data, load data, and DG data.

3.6.1. Load Curves

For the IEEE 13 buses test feeder, load curves were chosen from [35]. It can be shown in Figure 3-10. As it can be seen, the maximum demand for residential loads occurs at 21:00 while for the industrial loads the maximum demand occurs at 12:00.

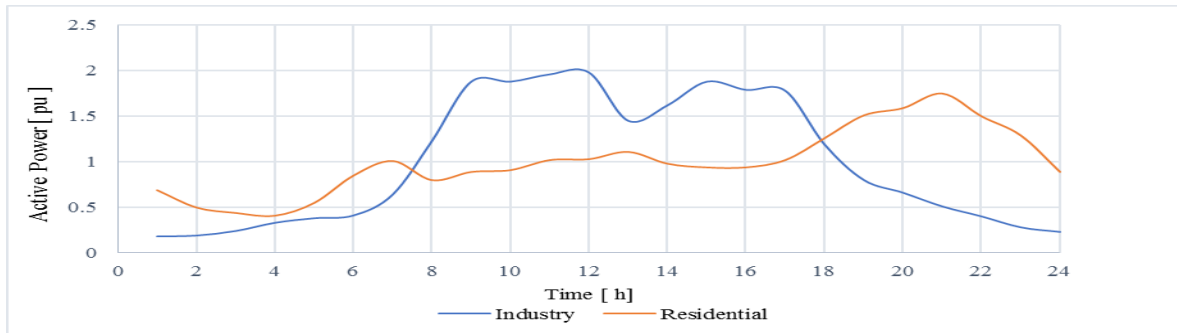


Figure 3-10: Load profiles [35].

For CENTROSUR network, load curves were built using 10 minutes resolution. Figure 3-11 shows the considered load curves for each one of the 46 customer.

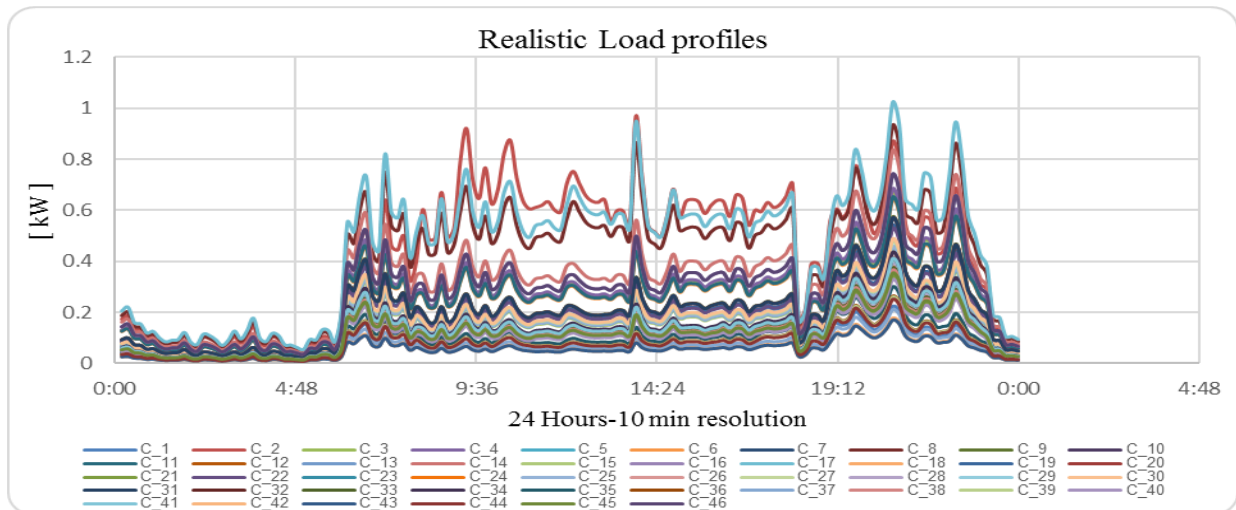


Figure 3-11: Load profiles of each customer.

3.6.2. Irradiance Curves

In general, to model solar generation, time series of irradiance are necessary. The irradiance curves used in this work for IEEE 13 buses test feeder have been taken from [36], [35].

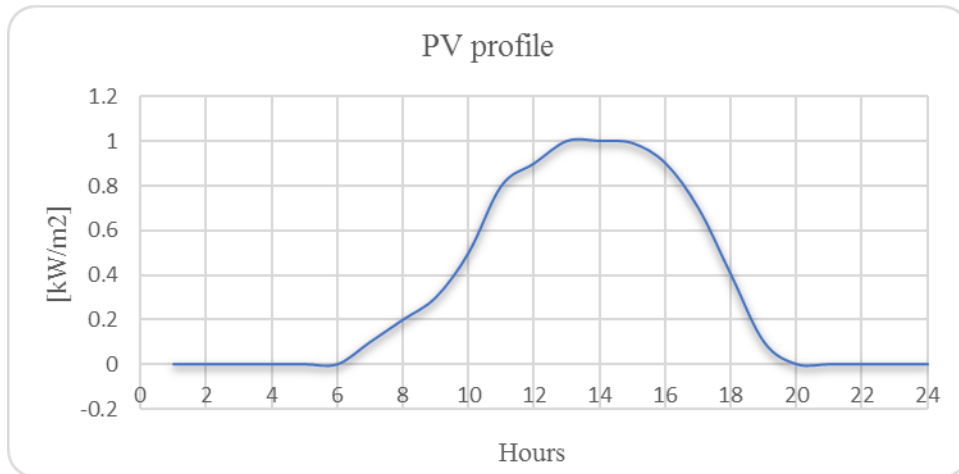


Figure 3-12: Radiation PV profile [37].

For the low voltage system real, data was provided by CENTROSUR for April 3, 2017. This radiation data is also presented with 10-minute resolution.

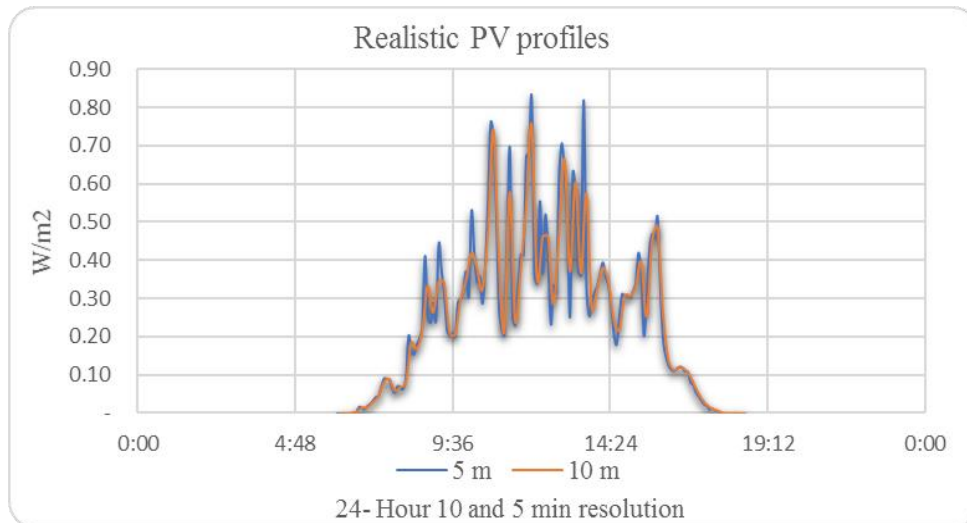


Figure 3-13: Realistic PV profiles

3.7. PV SYSTEM MODEL

PV system in OpenDSS is shown in Figure 3-14. This model combines a model of the PV array and the PV inverter into one model which is used for evaluate impacts of DG. In the model, it is assumed that the inverter is able to find the maximum power point tracking (MPPT) of the panel quickly. The model injects active power, $P_{out}(t)$, into the grid which is a function of the irradiance, temperature (T), inverter efficiency and the rated power at the maximum power point, P_{mpp} defined for a selected temperature (usually 25° C) and base irradiation of $1 \text{ kW}/\text{m}^2$ [38].

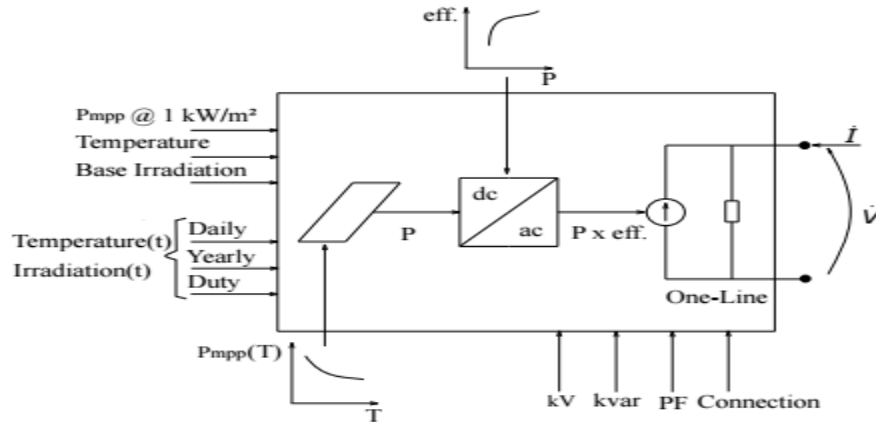


Figure 3-14: PV system model [37].

Figure 3-14 shows the block diagram and Equation 5 provides $P_{out}(t)$ [38].

$$P_{out}(t) = P(t) * eff(P(t)) \quad (5)$$

Where

$$P(t) = P_{mpp} \left(1 \text{ kW}/\text{m}^2 \right) * irra(t) * P_{mpp}(T(t)) \quad (6)$$

$P(t)$: output power of PV at specific time, t.

$P_{mpp} \left(1 \text{ kW}/\text{m}^2 \right)$: Rated power at the maximum power point and selected temperature.

$irra(t)$: Per unit irradiation value at t.

$irradBase$: Base irradiation value for shape multipliers

$P_{mpp}(T(t))$: P_{mpp} correction factor as function of the temperature.

$eff(P(t))$: Inverter efficiency for a given $P(t)$

At this point, it is necessary to mention that PV system model from OpenDSS was used for the QSTS analysis in the IEEE 13 buses test system, while PV system was modeled as simplified model of a negative load.

3.8. Storage element

The storage element in OpenDSS is basically a generator which can be dispatched to produce power or consume power. The model for storage was developed from the generator element model. Thus, it has inherited some of the features such as a built-in energy meter and an interface to user-written DLLs [36].

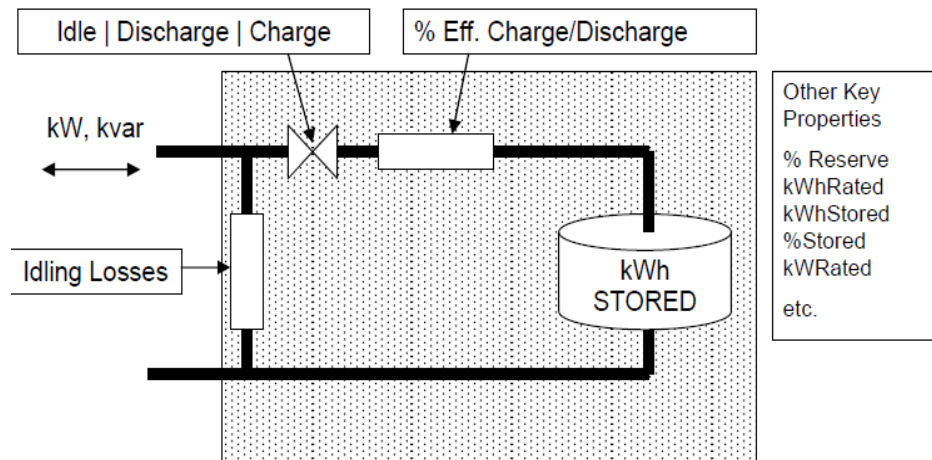


Figure 3-15: Basic concept of the Storage Element [39].

There are some modes to dispatch the stored energy in this element and they are: default, follow, external, loadlevel, and price mode. For this work was used the Follow mode. In this mode the kW and kvar output of the STORAGE element follows the active loadshape. The loadshape used in this work is shown in Figure 4-15 of section 4.5.

3.9. LOAD ALLOCATION

Active power load allocation

In order to carry out the QSTS power flow in a real low voltage system it is necessary to know the demand value of each customer, in other words the active and reactive power. Commonly, P and Q are values not known, while the average monthly energy consumption is known. CENTROSUR, through a study called “*Investigacion y Caracterizacion de la carga*”, determines by a linear regression technique the relation between maximum non-coincident demand (P_{\max_noinc}) of a customer in kW and the average monthly energy consumption of this customer in kWh ($E_{\text{average_monthly}}$). Figure 3-15 shows the relation between maximum demand and the average monthly energy consumption.

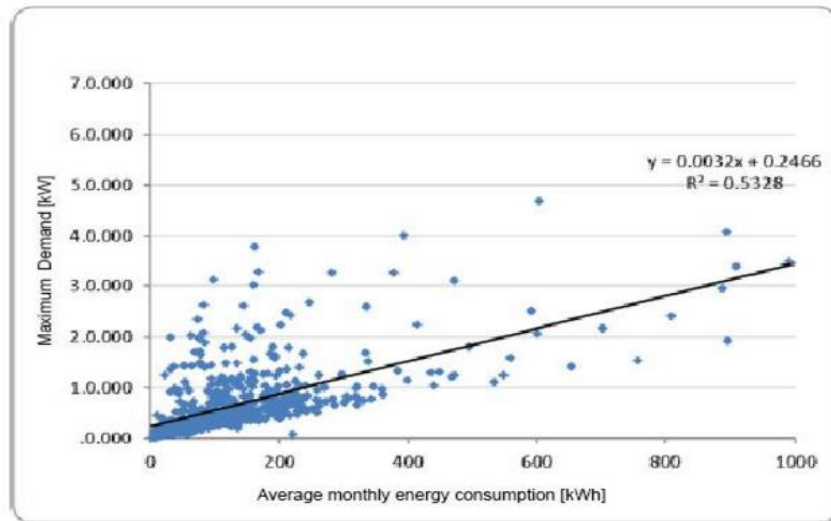


Figure 3-16: Dispersion diagram representing monthly energy consumption with respect to the maximum demand [40].

According to the study [40] the relation between maximum demand and the average monthly energy consumption is given by the following equation:

$$P_{\max_nocoïn} = 0.2466 + 0.0032 * (E_{\text{promedio}_{mes}}) [kW] \quad (7)$$

For example, if a residential customer has an average monthly consumption of 407.5 kWh, their non-coincident demand will be:

$$P_{\max_necoin} = 0.2466 + 0.0032 * 407.5$$

$$P_{\max_necoin} = 1.5506 \text{ kW}$$

To know the initial demand of a customer, it is necessary to know to which extent of consumption the customer belongs. CENTROSUR by [40] presents unitary load profiles for each consumption extract. Table 3.4 shows load classification by consumption group and extract.

Table 3-4: Load classification by customer class and consumption extract

Consumption Group	Consumption Extract Kwh/mes
Residential	0<Consumption≤60
Residential	60 < Consumption≤ 110
Residential	110<Consumption≤180
Residential	180<Consumption≤310
Residential	Superior to 310
Comercial	0<Consumption≤290
Comercial	290<Consumption≤1235
Comercial	Superior to 1235
Industrial	0<Consumption≤410
Industrial	410<Consumption≤2520
industrial	Superior to 2520
Other	0<Consumption≤405
Other	405<Consumption≤1820
Other	Higher to 1820
Luminary	Power W
Double-level power luminaire	100
Double-level power luminaire	150
Double-level power luminaire	250
Double-level power luminaire	400

The demand factor (F_d) is defined as the relation between maximum demand system and the total load connected. This factor gives an indication of the percentage of electrical devices that are on when the maximum demand occurs [31].

$$F_d = \frac{P_{\max-sist}}{P_{\text{tot-connected}}} \quad (8)$$

To obtain the initial estimated demand or base of a consumer in a specific time, it is necessary to multiply the maximum non coincident demand by the demand factor corresponding to that time, depending on the consumption extract in which it belongs.

$$P_{base-n} = F_{d-h} * P_{max_nocoïn-n} \quad (9)$$

Where:

P_{base-n} : Customer base power n, at hour h.

F_{d-h} : Demand factor which depends on consumption extract of each customer and specific hour.

$P_{max_nocoïn-n}$: Maximum noncoincident power of a customer n.

The Electric Distribution Utility “CENTROSUR” has measurements of active and reactive power at the secondary transformers each hour, so it is possible to assign demand to the customers depending on the performed measurements in transformers.

Load are classified as fixed loads (luminaire) and variable loads (customers) in order to carry out load allocation. The nominal power of fixed loads is known, so it is not necessary to make load allocation, while for variable loads load allocation is necessary.

The distributed power to the customers, in each measurement interval (each hour), has to satisfy the following equation:

$$P_{dist} = P_{Total} - P_{fixed} - P_{losses} \quad (10)$$

Where

P_{dist} : Active power to be distributed in the customers (value to be calculated)

P_{Total} : Active power measured in a specific hour at the secondary of the transformer

P_{fixed} : Fixed active power, which correspond to the luminaires power in a specific hour

P_{losses} : Power corresponding to the losses in the lines (This value is calculated by OpenDSS)

The power assigned to each customer is the power to be distributed by the power ratio that corresponds to each customer. Following equation is used to assign demand to a client n.

$$P_{assi-n} = P_{dis} * \frac{P_{base-n}}{\sum P_{base-n}} \quad (11)$$

Where:

P_{assi-n} : Assigned demand to a customer n in a specified hour.

Load allocation example

An example, given below, consists of a transformer which has a measurement of active power at 21:00 of 6.5 kW with four costumers and two luminaires of 0.150 kW each one. The base power for their customers are presented below.

$$P_{base-1} = 0.9kW$$

$$P_{base-2} = 0.8kW$$

$$P_{base-3} = 0.75kW$$

$$P_{base-4} = 0.67kW$$

$$P_{base-5} = 0.45kW$$

$$\sum P_{bases} = 3.57kW$$

Iteration 1

$$P_{tot} = 6.5kW$$

$$P_{fixed} = 0.3kW$$

$$P_{loss} = 0$$

$$P_{dis} = 6.5 - 0.3 - 0 = 6.2kW$$

Through Eq. 11 P_{assi-n} is determined:

$$P_{assi-n} = 6.2kW * \frac{0.76}{3.57} = 1.32kW$$

Iteration 2:

$$P_{tot} = 6.5kW$$

$$P_{fixed} = 0.3kW$$

$$P_{loss} = 0.1kW$$

$$P_{dis} = 6.5 - 0.3 - 0.1 = 6.2kW$$

Through Equation 9 it is possible to calculate new power value bases

$$P_{base-1} = 1.56kW$$

$$P_{base-2} = 1.39kW$$

$$P_{base-3} = 1.3kW$$

$$P_{base-4} = 1.16kW$$

$$P_{base-5} = 0.783kW$$

Applying this procedure, the demand is assigned to all customers.

It is necessary to mention that the procedure used to perform reactive power allocation is similar to the procedure performed for the active power.

In the next figure, the demand profile curves of the transformer 18053 are compared. It can be seen that the curves are almost the same. The first curve in (Figure 3-17 (a)) is the measured load profile while the curve in Figure 3-17 (b) is the obtained profile by the procedure of allocated load.

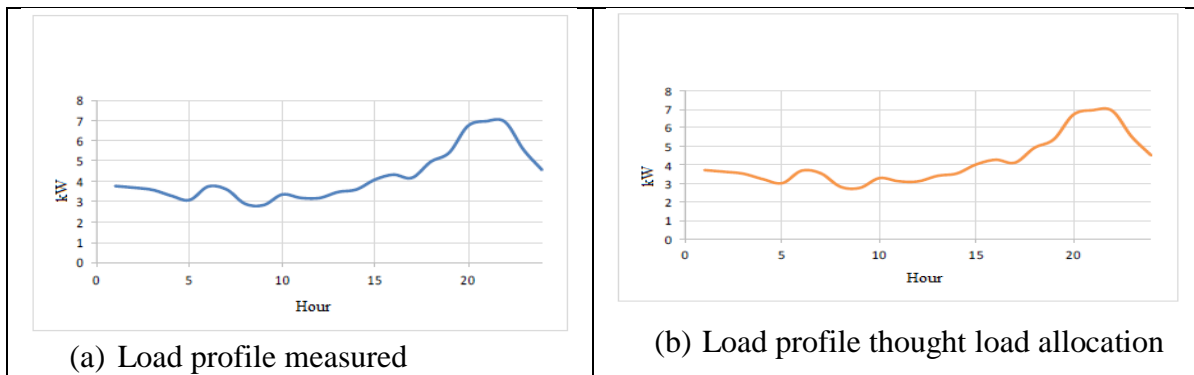


Figure 3-17: Load profiles got through measurements and by allocation load.

4. SIMULATIONS AND TEST RESULTS

4.2. IEEE 13 BUSES SNAPSHOT SIMULATION

Five different scenarios have been defined in order to evaluate technical features such as losses and voltages profiles after the integration of DG in this network. In these scenarios, it was considered different penetration scenarios of DG. Each scenario was considered according to the penetration percentage which, is defined by the following equation.

$$\%Penetration = \frac{Peak\ Power\ DG}{Peak\ Load\ [kw]} \quad (12)$$

- The first scenario (Scenario base) is the scenario that does not include DG.
- Scenario 2 represents the effect of including a 10 % of DG penetration. In this scenario, DG was distributed proportionally to the load in all buses by an OpenDSS command.
- In scenario 3, 10% of DG penetration is distributed at 675 and 680 buses.
- In scenario 4, 20% of the total load DG penetration is distributed at 675 and 680 buses.
- Finally, scenario 5, 50% of the total load DG penetration is added at the same nodes considered previously.

Scenario 1: Base Case

In scenario 1, the system is analyzed without DG. The results of the power flow analysis, bus voltage profiles and system losses are presented in Table 4-1 and Figure 4.1. A summary of the power flow solution for the IEEE test network can be seen in Table 4.1. It is demonstrated that the lower voltage occurs on bus 611 with a value of 0.96 pu and the maximal value is 1.056 pu on bus where the regulator is connected.

Table 4-1: Summary of power flow results for the IEEE 13-buses test feeder [35].

Status	SOLVED
Solution mode	Snap
Load multiplier	1
Devices	39
Buses	13
Nodes	41
Max pu, voltage	1.0562
Min pu, voltage	0.96101
Total Active Power	3567.08 kW
Total Reactive Power	1736.38 kvar
Total Active Losses	112.109 kW (3.143%)
Total Reactive Losses	327.71 kvar

In Figure 4.1 the voltage in some phases of the buses is 0 because there is only one phase in those buses.

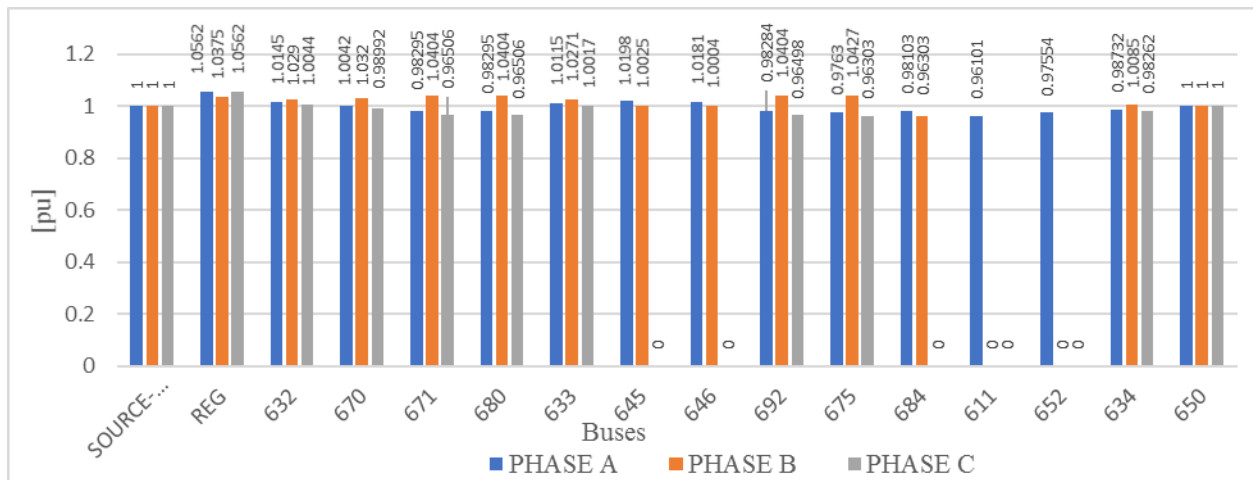


Figure 4-1: Voltage results of IEEE 13-buses test feeder (Base Case).

4.2.1. Impacts of DG on IEEE 13-buses voltages

In this study, a snapshot solution with different penetration scenarios is considered. Figure 4-2, 4-3 and Figure 4-4, represents different voltages variation in all system buses. It can be observed that when DG is added, all bus voltages improved in all scenarios. This means that voltage decreased their values in some buses approaching to 1 p.u. while in other buses the voltages increased their value approaching the nominal voltage of 1 p.u. Comparing scenario 2 and 3 when the same value of DG is added to the system it can be said that better results are obtained when DG is distributed in a specific buses as it is on 675 and 680 buses and not at all buses.

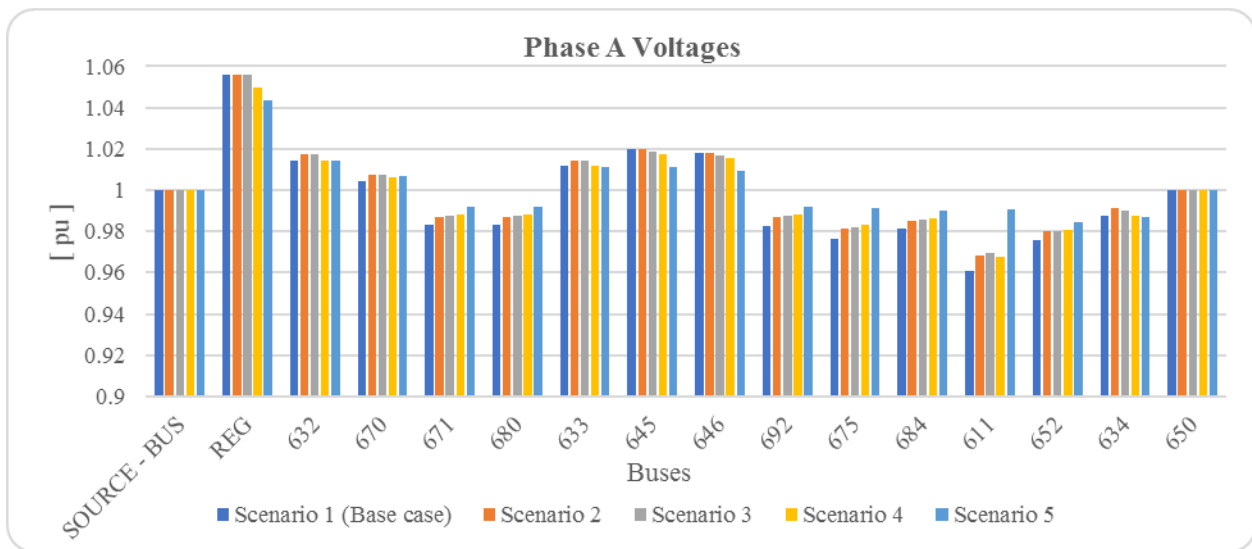


Figure 4-2: Phase A Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

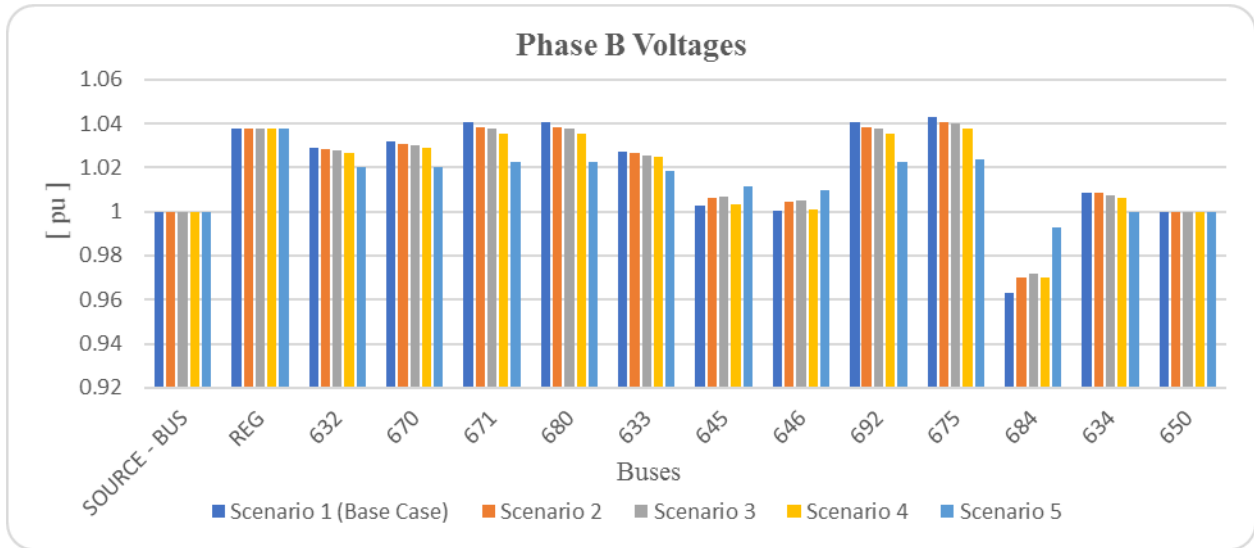


Figure 4-3: Phase B Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

Some loads have only two phases, due to these the voltage on phase C is 0 and they are not presented in Figure 4-4.

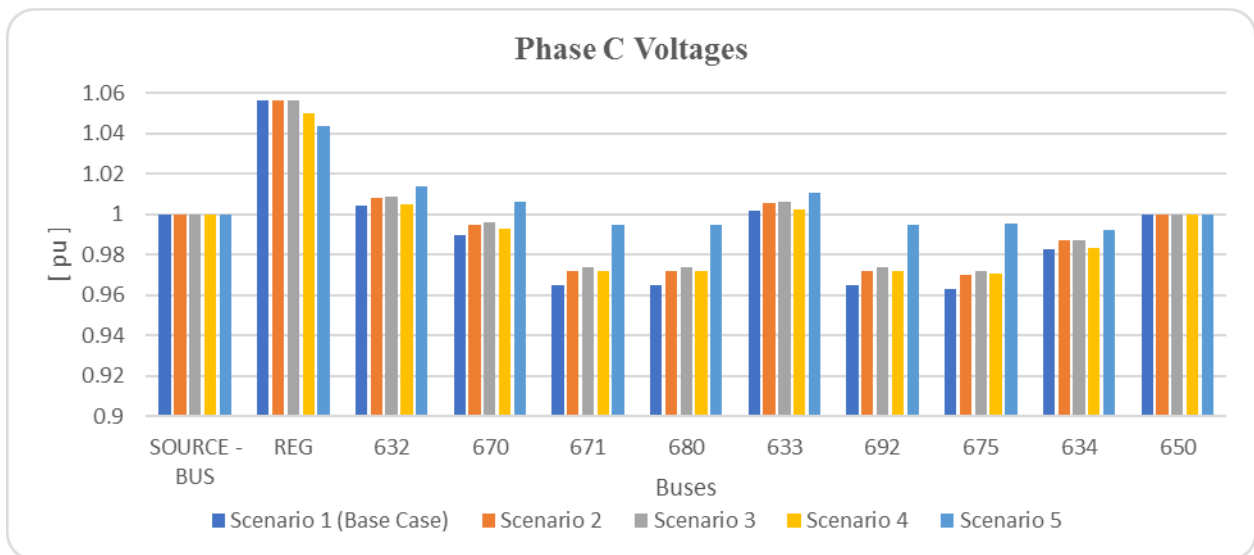


Figure 4-4: Phase C Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

4.2.2. Impacts of DG on IEEE 13 buses losses

Another analyzed feature in this work is the system losses when DG is connected. Table 4.2 summarizes the results considering five different scenarios. As it can be seen lower losses take place in scenario 5 where a 50% of DG has been considered.

Table 4-2: Summary results of IEEE 13-buses feeder for different scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total Active Power [kW]	3567.08	3206.37	3204.96	2842.28	1773.86
Total Reactive Power [kvar]	1736.38	1677.43	1671.18	1623.14	1503.22
Total Active Losses [kW]	112.109	93.09	91.84	76.112	39.47
Total Reactive Losses [kvar]	327.71	271.4	266.385	218.15	106.95
Max. pu, voltage	1.0562	1.0562	1.562	1.05	1.0437
Min. pu, voltage	0.96101	0.96827	0.96957	0.9678	0.98443

A simple conclusion that can be taken from this study: there is a decrease in system losses and the voltage profile significantly improves. However, to have an accurate analysis of DG impact, another approach must be adopted. This approach uses time series power flow analysis. By this approach it is intended to identify the behavior of the network throughout the day (at any time), particularly in hours where high demand or a large amount of DG exists.

4.3. IEEE 13-BUSES QSTS SIMULATION

4.1. Introduction

This chapter presents simulation scenarios and results of the two test systems. Two solution modes, a snapshot power flow and Quasi-Static time series power flow are carried out in each system. Technical problems such as losses, voltages profiles, and reversed power flow are analyzed. For the CENTROSUR network one more case is presented, in which induction cookers are added.

4.1.1. Impacts of DG on IEEE 13-buses voltages

The QSTS results for IEEE 13-Buses feeder are presented in Figure 4-5, Figure 4-6 and Figure 4-7. The QSTS simulation is calculated for a 24-hour period. The same 5 scenarios considered in the previous section 4.2 are used to evaluate the network behavior when DG is added. The type of DG used for analyzing this network was PV generation. For QSTS solution, it was necessary to assign a radiation curve to PV systems and a load shape to the customers.

For the QSTS simulations the voltage profile can be evaluated for all system buses. Nevertheless, to have a better criterion of the impact of DG, these voltages are analyzed at the point (bus) of connection of the DG, in which it is expected to have large voltage variations.

As can be seen in Figure 4-5 to Figure 4-7, voltages are presented at the connection point, in this case the 675 bus. The impact of the PV system on the network can be seen from 08:00 am where solar generation starts to 18:00 pm when it ends. The voltage profiles at the other connection point (680 bus) are presented in Appendix B.

Voltage profiles in Figure 4-5, Figure 4-6, and Figure 4-7 depicts that voltages in all phases improved at the period that the PV systems begin to produce electricity, so no voltage violation occur when PV generation is added.

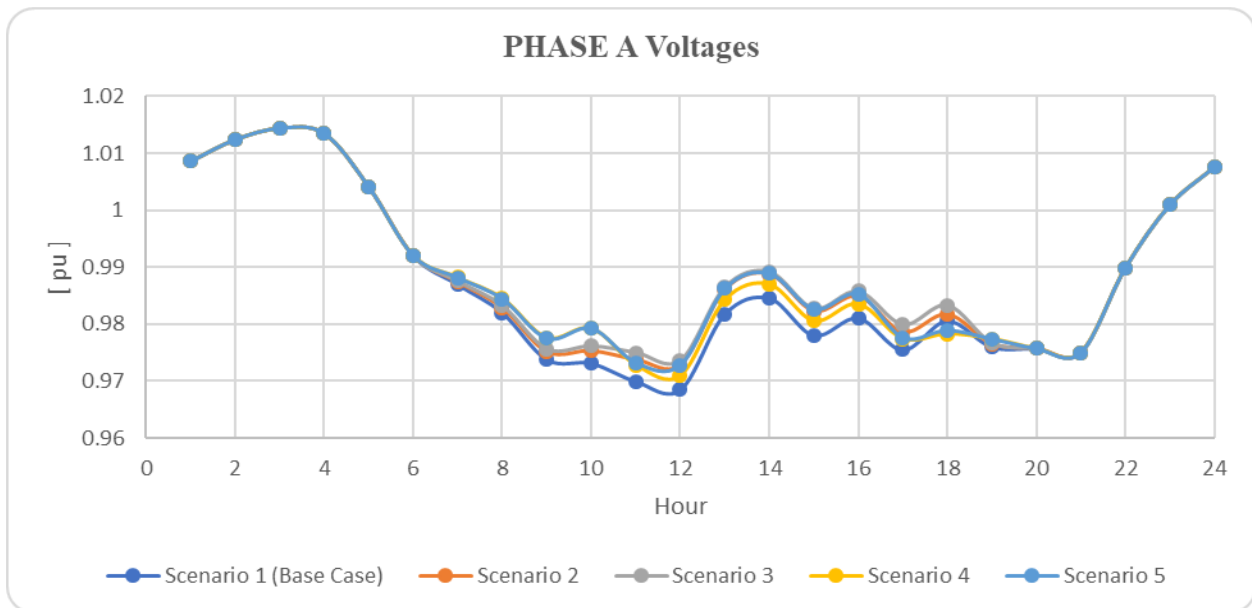


Figure 4-5: Phase A Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

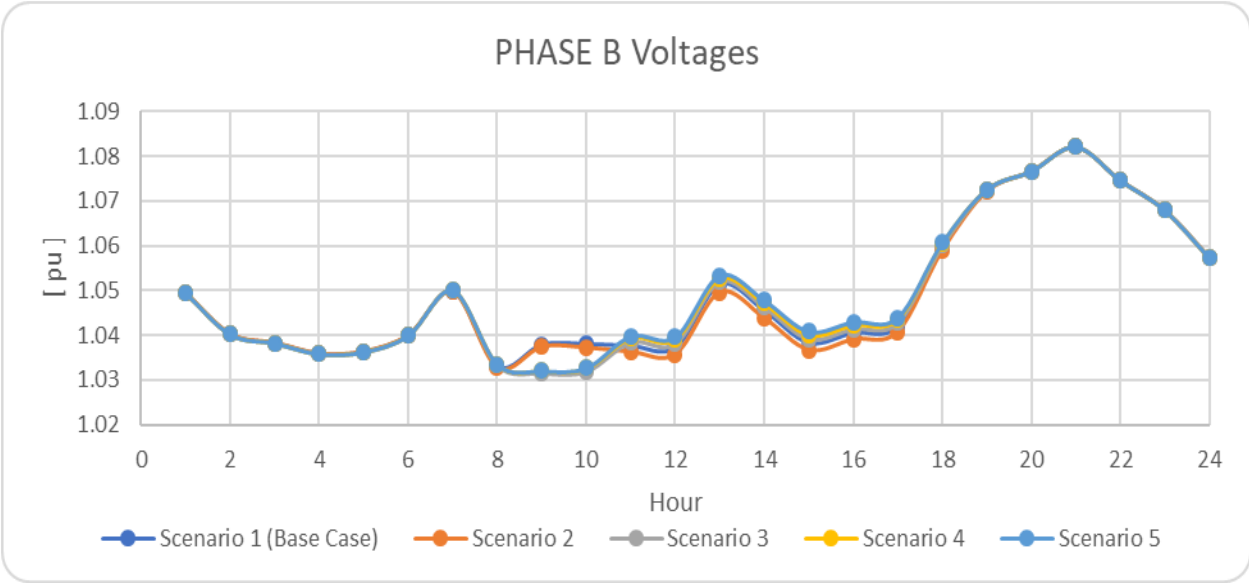


Figure 4-6: Phase B Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

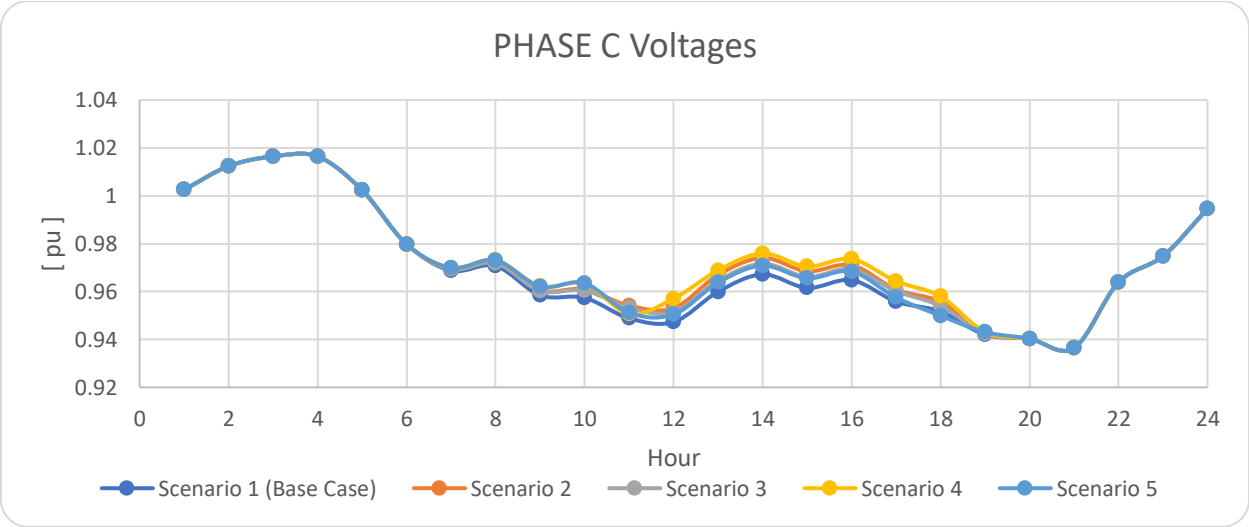


Figure 4-7: Phase C Voltage profile for different DG penetration scenarios (IEEE 13-buses test feeder).

4.1.2. Impacts of DG on IEEE 13 buses losses

Below, in Figure 4-8 and 4-9 active and reactive power at the substation are shown. For scenario 1 the substation only provides energy to the loads. In the other scenarios, the power given by the substation is lower than in the base case. This is because PV systems start working. In all cases only active power change as power factor is considered unitary.

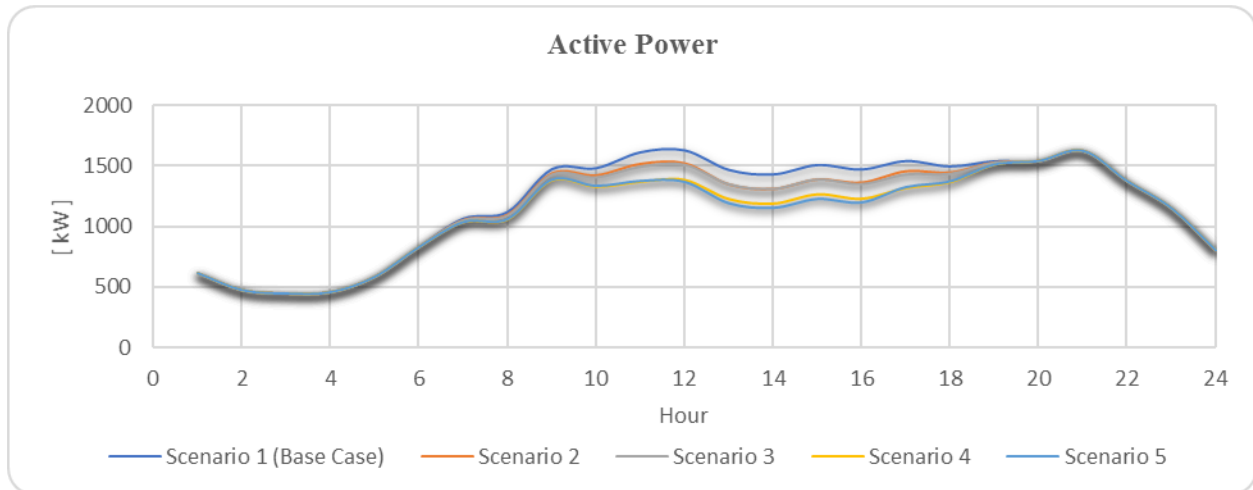


Figure 4-8: Active power supplied by the substation (IEEE 13-buses test feeder).

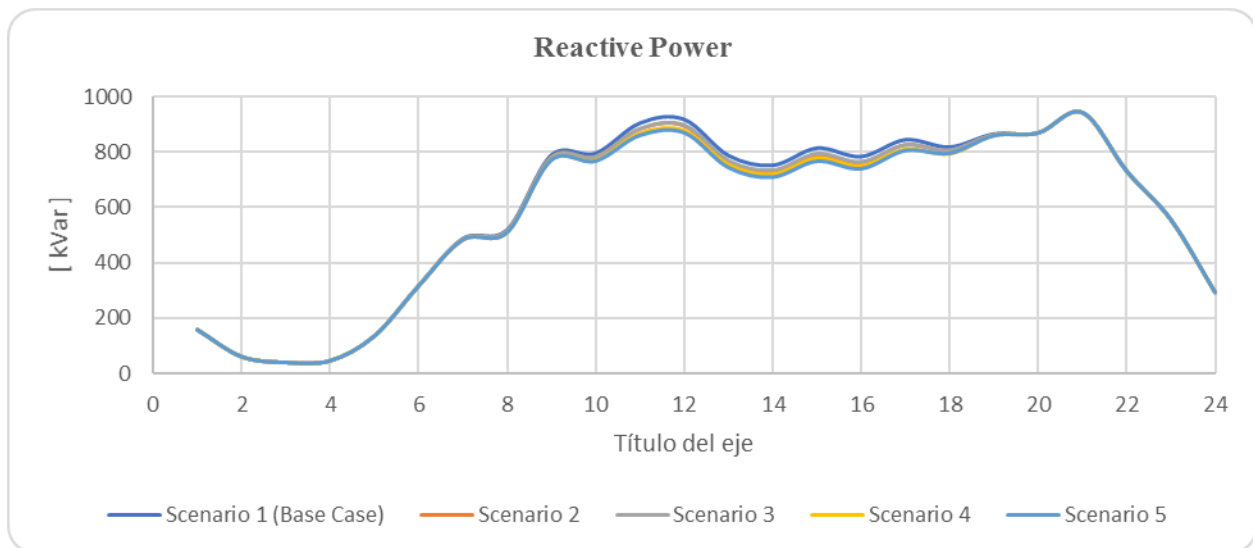


Figure 4-9: Reactive power supplied by the substation (IEEE 13-buses test feeder).

Table 4-3 summarizes the losses in the circuit. These results correspond to 12:00 pm where there is a large energy demand. According to Table 4-3 lower losses are obtained in scenario 5 where the losses percentage is reduced from 4.25% (Base case) to 3.72%.

Table 4-3: Summary results of IEEE 13-buses feeder

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total Active Power [kW]	4880.88	4518.73	4555.04	4143.59	3265.34
Total Reactive Power [kvar]	2756.49	2695.33	2687.21	2634.29	2527.11
Total Active Losses [kW]	207.6(4.25%)	183.39(4.07%)	184.26(4.04%)	162.21(3.92%)	121.37(3.72%)
Total Reactive Losses [kvar]	630.79	569.88	560.72	514.78	409.9
Max. pu, voltage	1.07	1.07	1.07	1.07	1.06
Min. pu, voltage	0.942	0.946	0.948	0.952	0.95

4.2. CENTROSUR REAL SYSTEM (SNAPSHOT SIMULATION)

As it is known, many utility systems are not designed to allow the inclusion of DG. A distribution network from Electric Distribution Utility “CENTROSUR” has been chosen to study the technical impacts when DG is incorporated to their networks.

Five scenarios are considered to study the behavior of this network after the inclusion of solar PV. Table 4-4 shows the simulation scenarios.

Table 4-4: Simulation scenarios

Scenario	Total Customers with PV	% of total Customers with PV
1	2	4%
2	5	11%
3	9	20%
4	23	50%
5	46	100%

In each scenario, a percentage of the total of 46 customers is considered, including PV generation. For example, in scenario 1 it is considered that 4% of 46 customers add PV generation. In order to carry out simulations it was considered that each customer adds 2 kW of PV generation with a power factor of 0.98.

Scenario 0: Base Case

This scenario represents the case prior to the introduction of PV generation and will be considered the base case used as reference to make comparisons with the other scenarios. The results for this scenario such as power flows, bus voltages and system losses are presented on Table 4-5. Table 4-5 also presents a summary of the power flow solution for the test network.

Table 4-5: Summary of power flow results for the CENTROSUR network.

Status	SOLVED
Solution mode	Snap
Load multiplier	1
Devices	139
Buses	66
Nodes	184
Max pu, voltage	1
Min pu, voltage	0.975
Total Active Power	22.45 kW
Total Reactive Power	6.23 kvar
Total Active Losses	0.50 kW (2.263%)
Total Reactive Losses	0.35 kvar

Figure 4-10 shows a distribution power flow, once the network is solved in OpenDSS. In each line of the diagram it is possible to know parameters such as voltages and power flows.

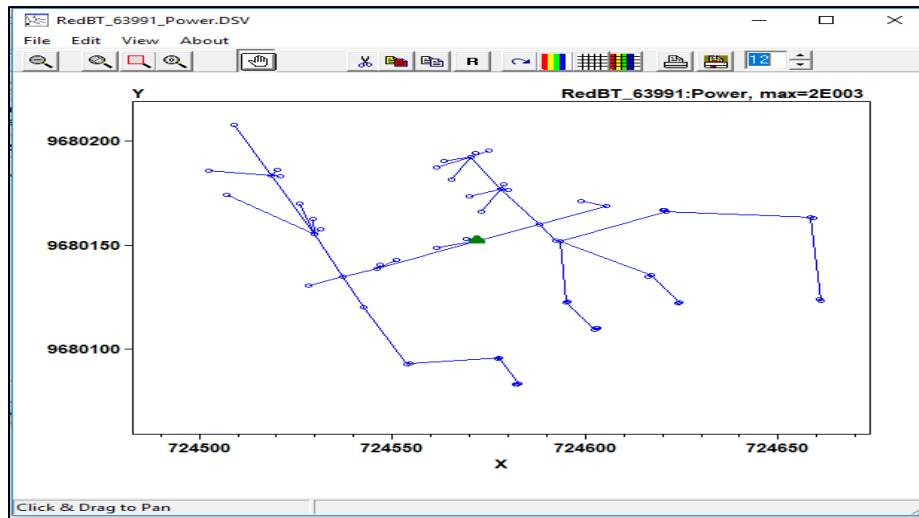


Figure 4-10: Circuit plotting in OpenDSS

Some buses have two phases so in Figure 4-11 some phases voltages are 0.

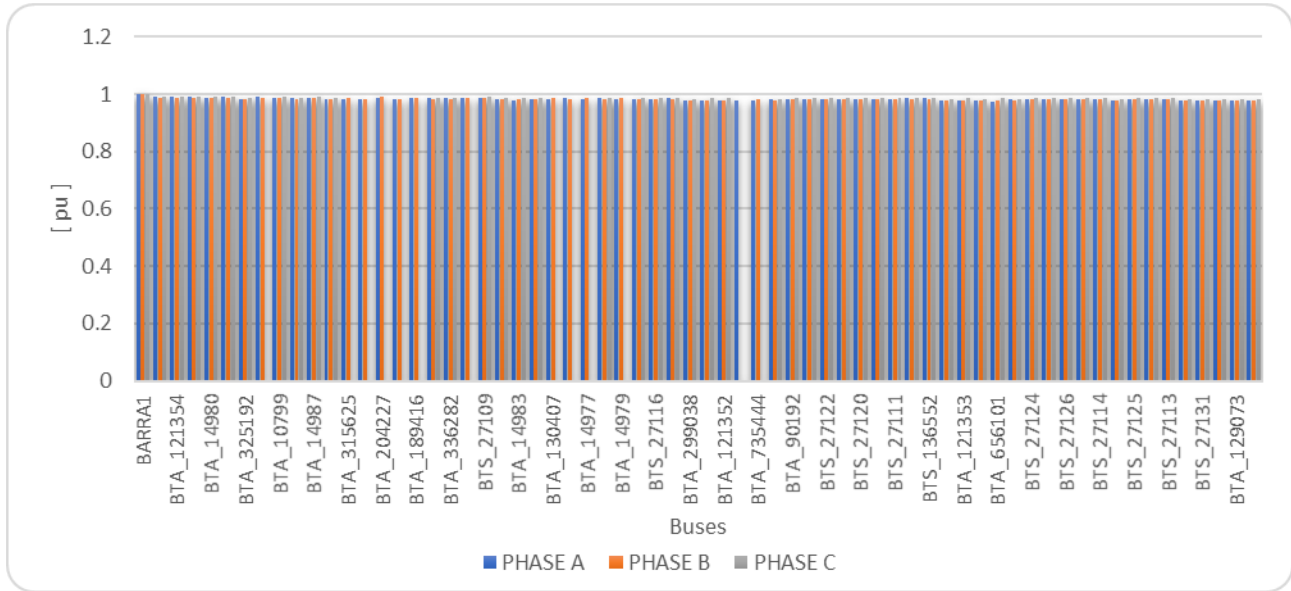


Figure 4-11: Voltage result for the CENTROSUR network (Base Case)

4.2.1. Impacts of DG on CENTROSUR network voltages

In the following figures, all bus voltages of the real network are shown. It can be seen voltages profiles improved for scenario 2 and 3. In those scenarios, it can be seen that the voltage profile approaches to 1 p.u. However, in the scenario 5 a voltage violation occurs in some buses of the phase A as this phase has a higher load. According to Figure 4-12 it is possible to determine that the maximum percentage allowed of PV generation must be 50 % (scenario 4). If this percentage is higher problems in the voltage profile can be seen as it can be seen in scenario 5 where it is considered that all 46 customers have added PV generation. Most of the violation of voltage limits occurs in the some buses, as it can be demonstrated in Figure 4-12.

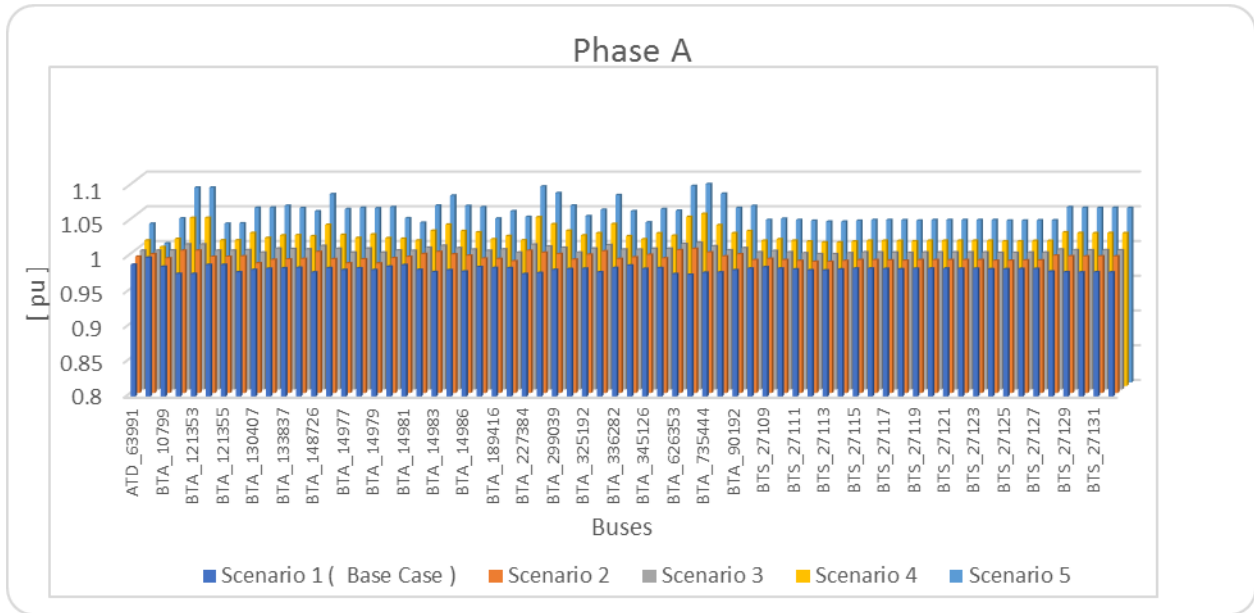


Figure 4-12: Phase A Voltage profile for different DG penetration scenarios (CENTROSUR network).

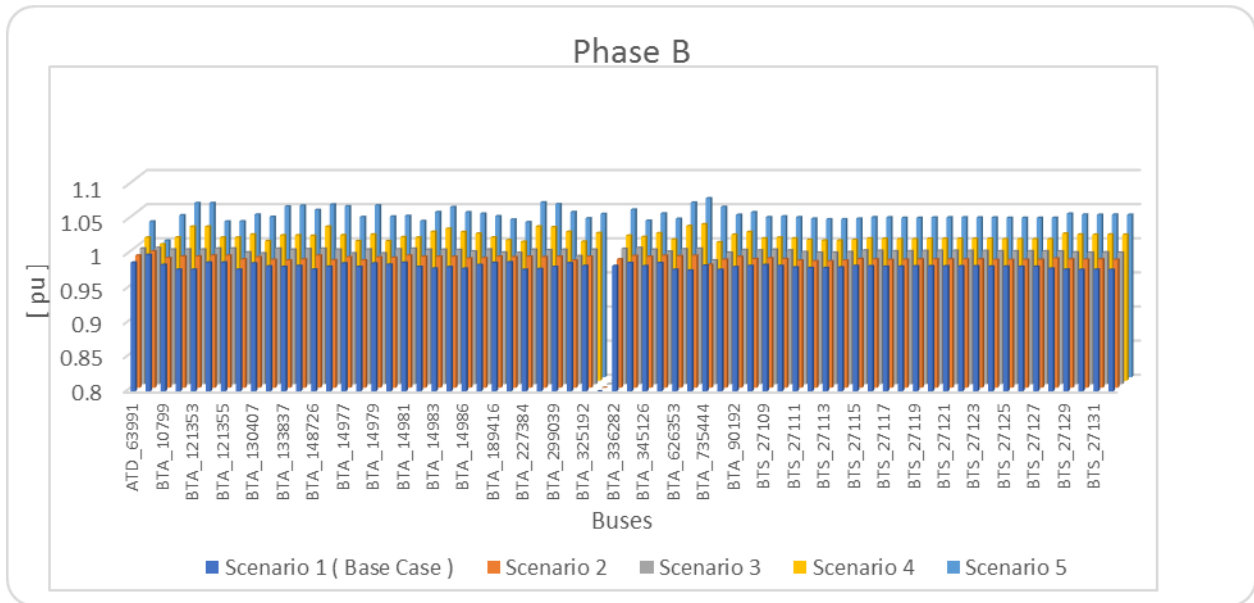


Figure 4-13: Phase B Voltage profile for different DG penetration scenarios (CENTROSUR network).

In figure 4-14 some buses voltages are 0 because on these buses there are only two phases A and B.

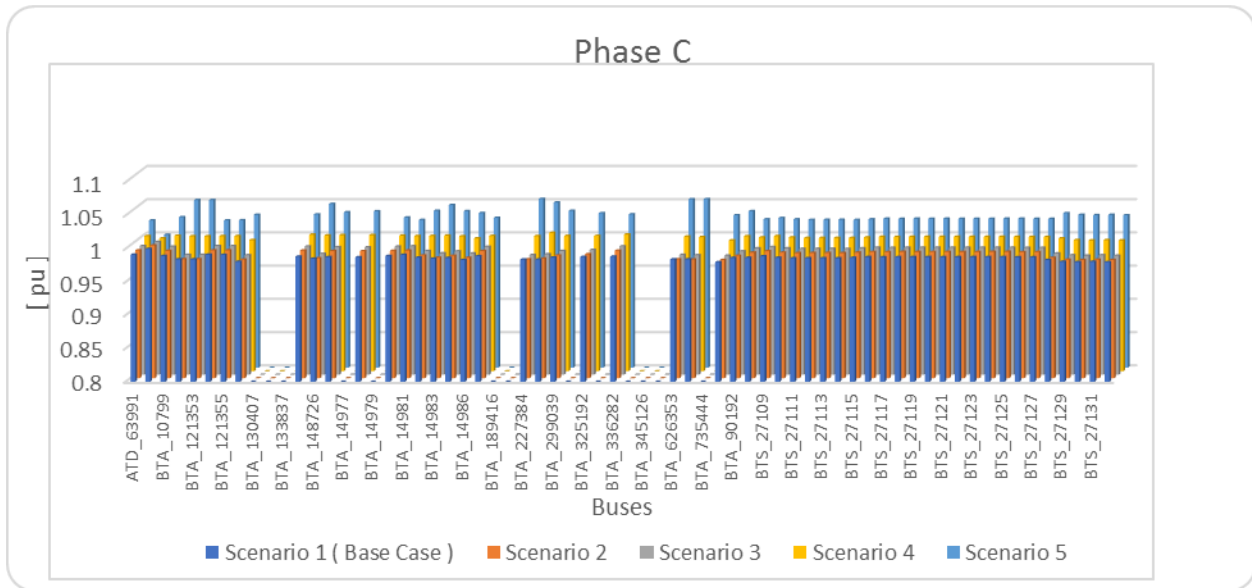


Figure 4-14: Phase C Voltage profile for different DG penetration scenarios (CENTROSUR network).

4.2.2. Impact of DG on CENTROSUR network losses

Table 4-6 summarizes the results considering six different scenarios. Results shows that in the four first scenarios there are no problems with a reverse power flow. However, in scenario 4 and 5 it can be seen that there is a reverse power flow which mean that the power flow is bidirectional.

Table 4-6: Summary results of CENTROSUR system

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total Active Power [kW]	22.45	18.35	12.28	4.2	-20.8	-66.4
Total Reactive Power [kvar]	6.23	5.3	3.9	2.3	-23.5	-9.4
Total Active Losses [kW]	0.5(2.26%)	0.40(2.22%)	0.34(2.77%)	0.28(6.84%)	0.7(-3.53%)	3.3(-5.098%)
Total Reactive Losses [kvar]	0.35	0.23	0.14	0.078	0.44	3.2
Max. pu, volt	1	1	1.007	1.01	1.047	1.08
Min. pu, volt	0.975	0.978	0.977	0.979	0.996	1

4.3. CENTROSUR NETWORK QSTS SOLUTION

For this solution mode, three case studies have been selected. For each case, the same scenarios considered for mode snapshot in Table 4-4 are taken. In figure 4-15 load shapes of PV generation, storage systems, induction cookers and transformer demands are shown.

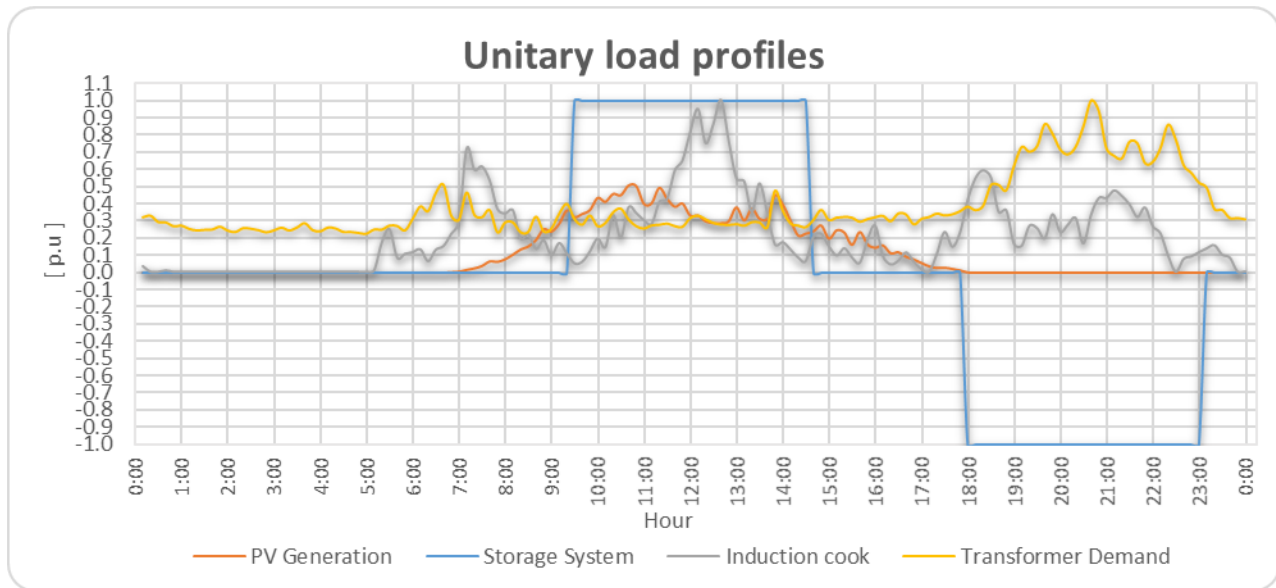


Figure 4-15: Unitary load profiles

4.3.1. CASE 1: PV

4.3.1.1. Impacts of DG on CENTROSUR network losses

This case considers the PV generation inclusion for each customer according to the scenarios shown in Table 4-4. The QSTS power flow results for this case are presented below in Figure 4-16.

Once carried out simulations, it can be shown that the maximum demand occurs at 20:00 pm for scenario 1, where PV generation is not included. As the customers start to add PV generation simulated in the different scenarios, it will be required a lower energy demand from the grid. Simulation results shows that there are no problems with the first three scenarios. On the other hand, results show a reversal of active power flow from customers back to the substation with 50% (scenario 5) accumulated PV connection during the day. From Figure 4-15 it can be seen that PV

generation can only be harnessed from 07:00 am to 18:00, so the energy produced by them could not be used to help reduce the demand peak at night.

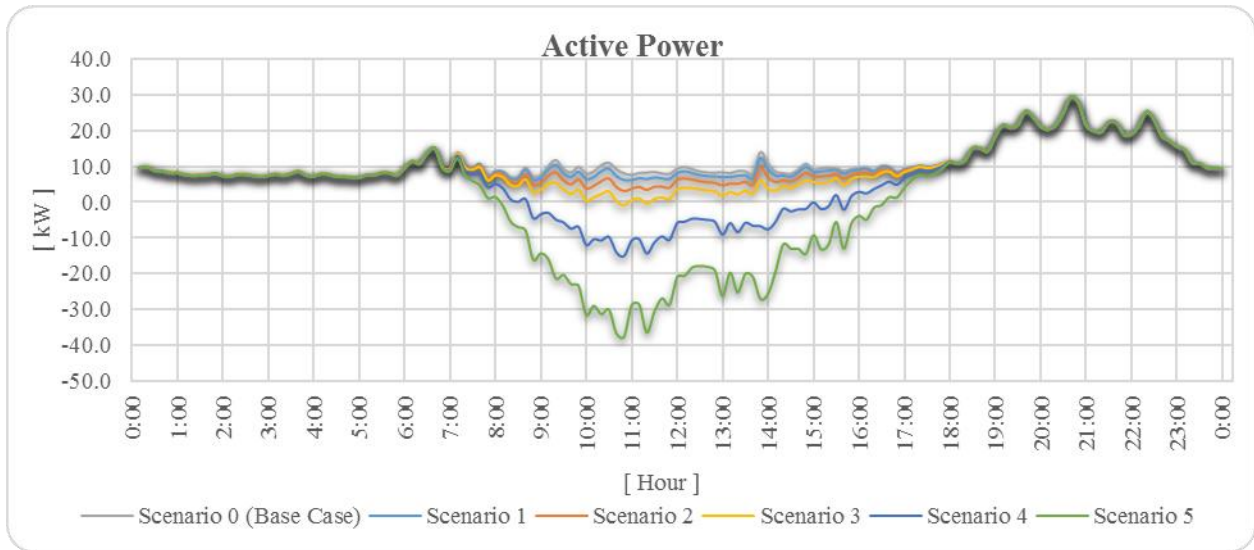


Figure 4-16: Active Power for different DG penetration scenarios (CENTROSUR network). [kW]

From the reactive power curve in Figure 4-17, it can be seen that the reactive power is decreasing in each scenario due to PV generation contributing with reactive power to the grid.

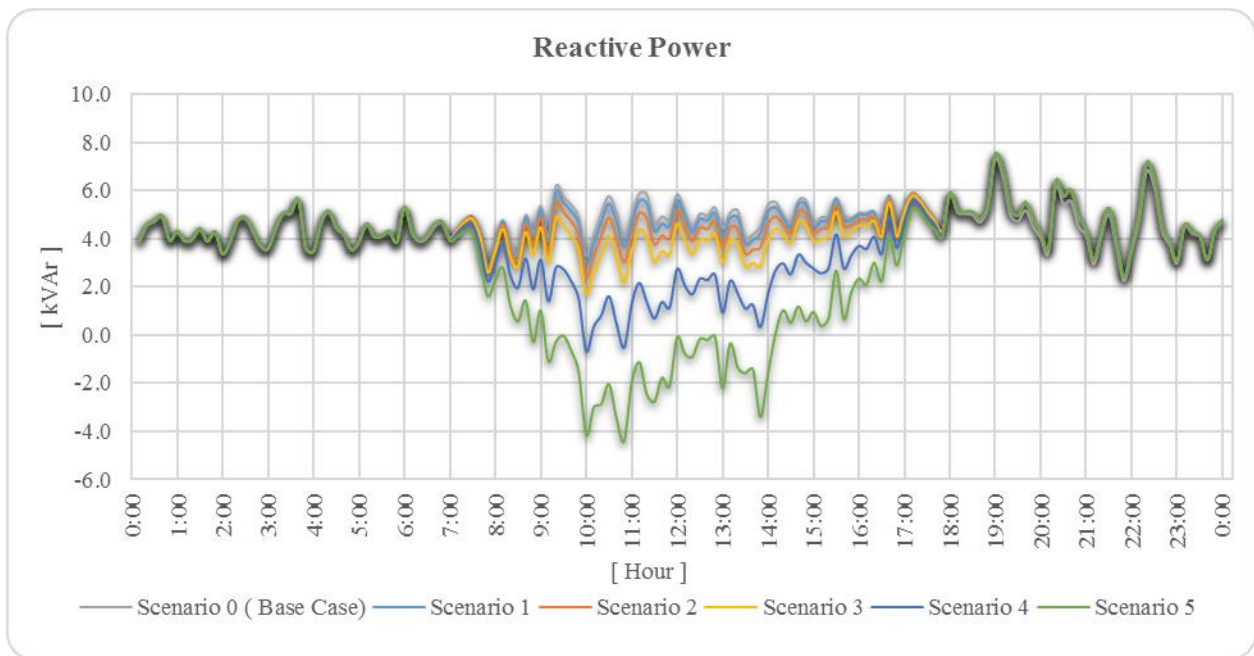


Figure 4-17: Reactive Power for different DG penetration scenarios (CENTROSUR network). [kVAr]

Figure 4-18 shows the daily system losses. High losses take place due to the reversed power flow when the levels of radiation are high. The maximum loss value is 1156 W and it occurs in scenario 5 at 10:40 am.

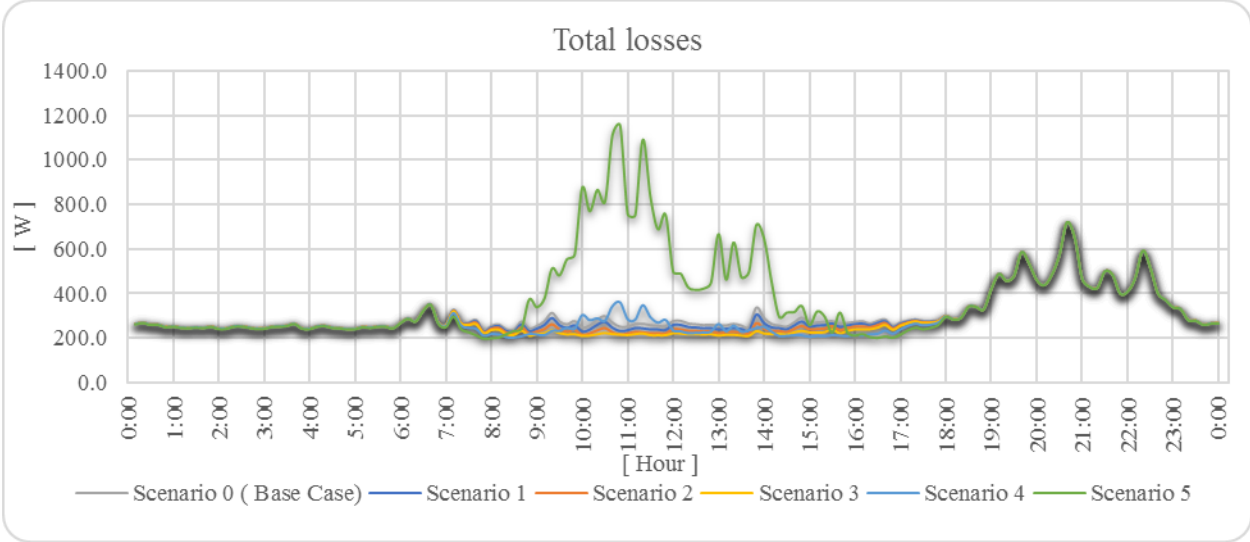


Figure 4-18: Total active losses for different DG penetration scenarios (CENTROSUR network). [W]

4.3.1.2. Impacts of DG on CENTROSUR network voltage

The voltage profile across the whole system for scenarios 0 and scenario 5 are shown in Figure 4-19 and 4-20 respectively. The voltage values represent the voltage along the feeder. Through these two figures it is possible to see that for scenario 0 the voltage drop is 0.965 pu with respect to nominal voltage and it occurs in bus bta_656101 which is located 174 meters from the transformer.

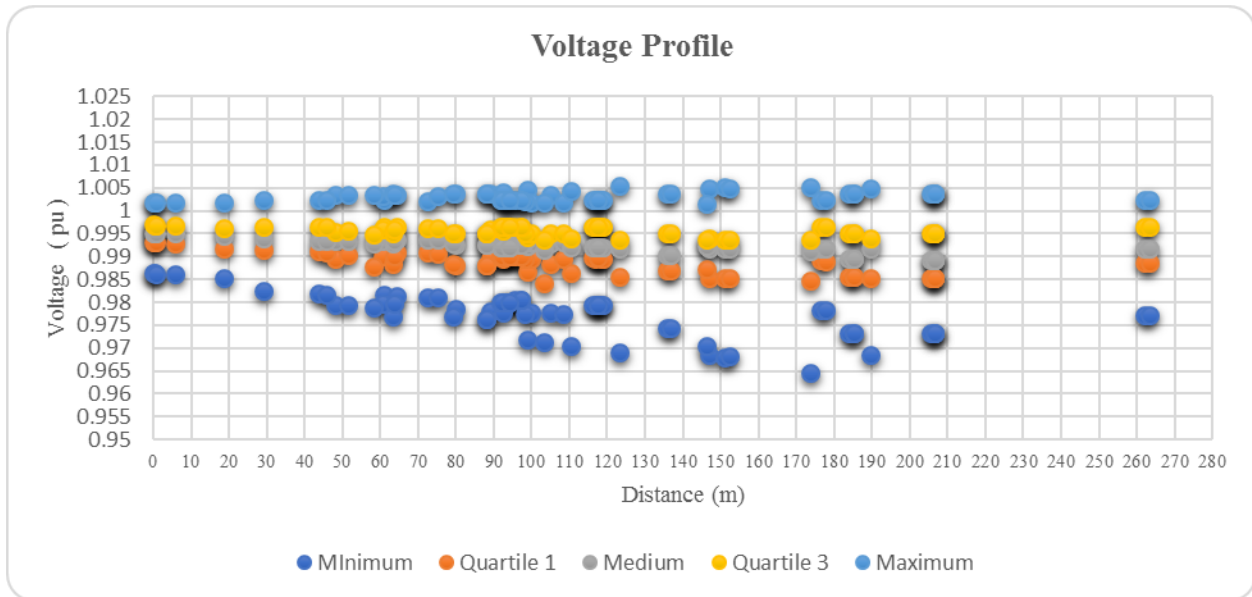


Figure 4-19: Voltage profile for scenario zero (CENTROSUR network).

In scenario 5 it can be seen that the voltage increase is 1.046 pu with respect to nominal voltage. The increase on the voltage happens due to generation being located near the customers.

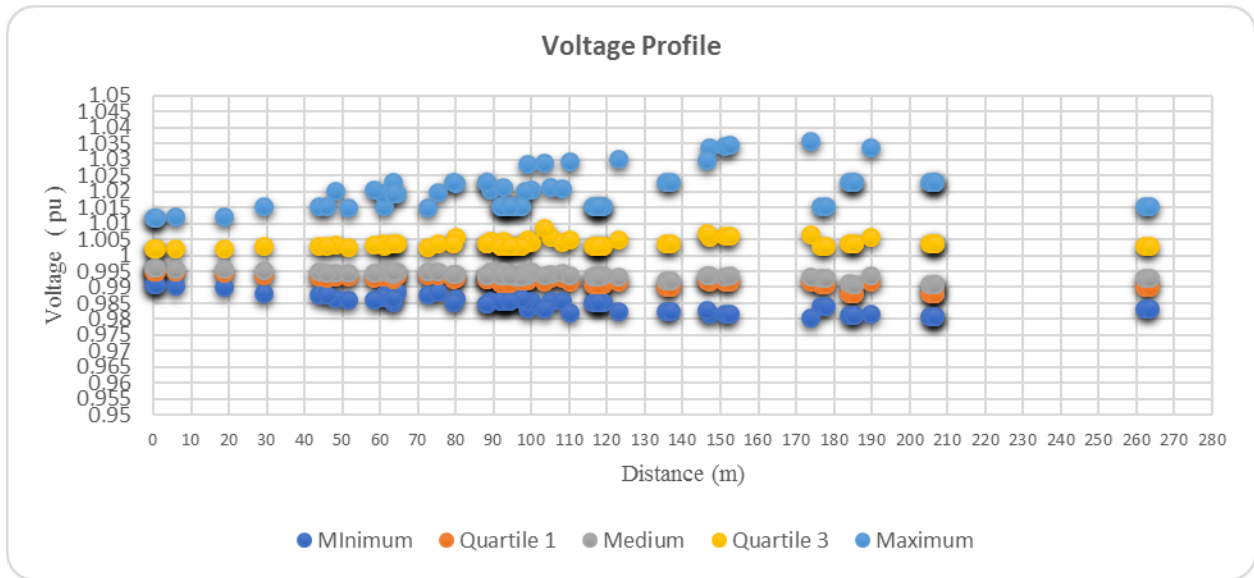


Figure 4-20: Voltage profile for scenario 5 (CENTROSUR network).

In the following Figures 4-21 to 4-23, voltage profiles for bus bta_656101 throughout the day are presented. As it is evident from these figures, voltage variations happen in all phases. However, this variation is between the allowed voltage ranges.

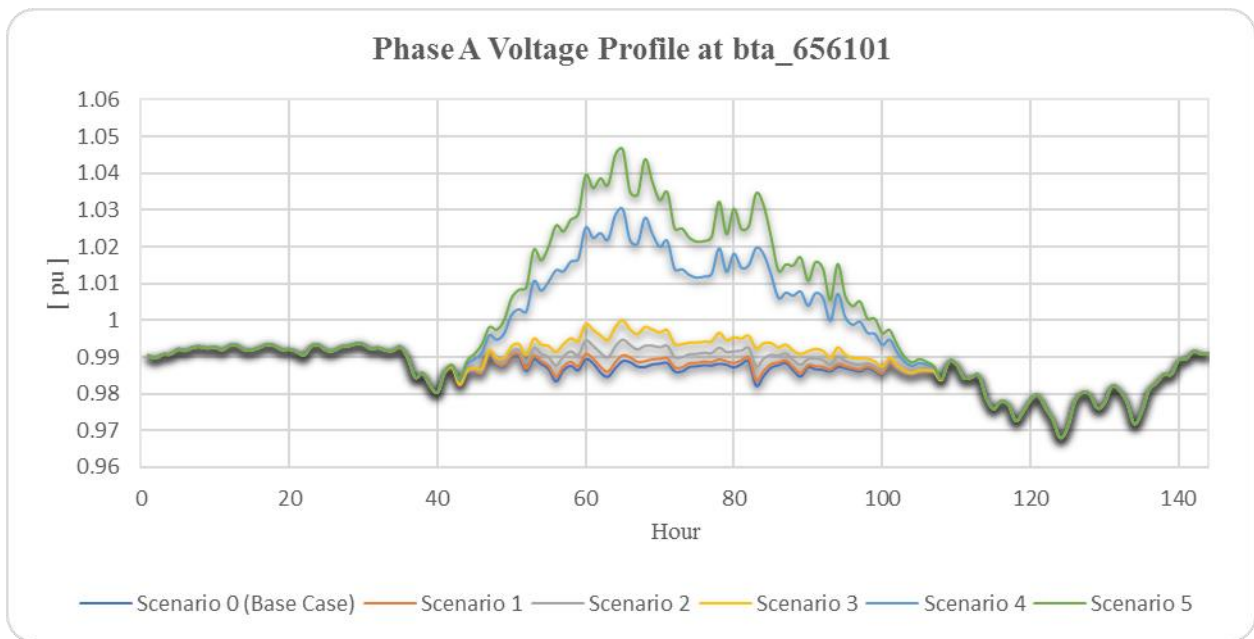


Figure 4-21: Phase A Voltage profile for different DG penetration scenarios (CENTROSUR network).

From the previous figure, a simple conclusion is that PV generation power added by each customer should not be higher than 2 kW in order to guarantee no voltage violations.

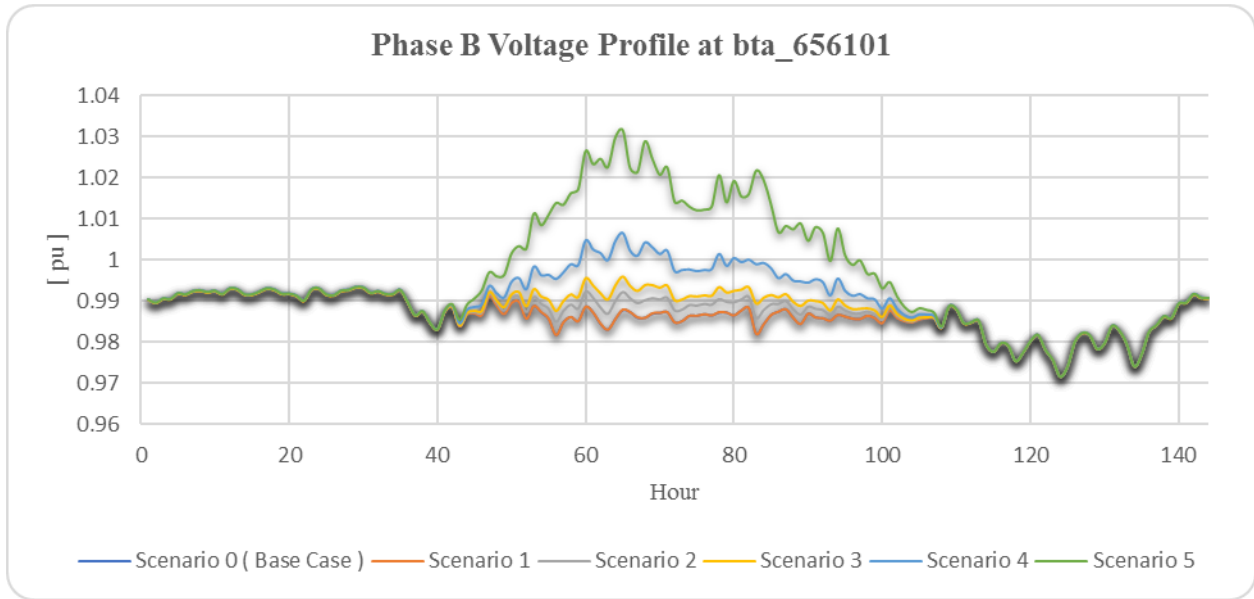


Figure 4-22: Phase B Voltage profile for different DG penetration scenarios (CENTROSUR network)..

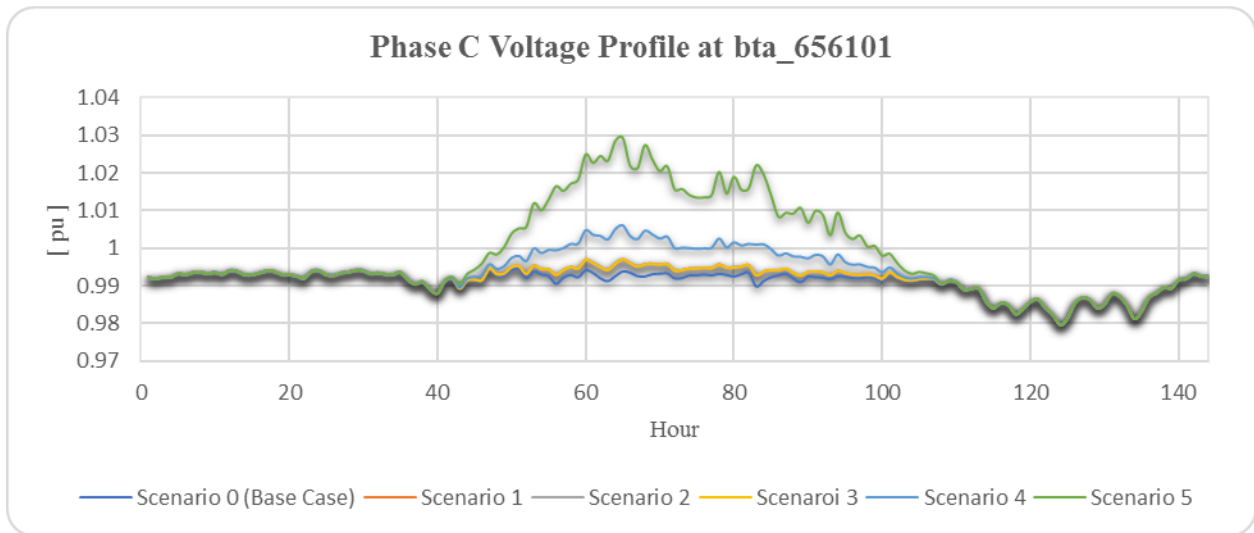


Figure 4-23: Phase C Voltage profile for different DG penetration scenario (CENTROSUR networks).

4.3.2. CASE 2: PVs integrated with Storage systems (BESS)

4.3.2.1. Impacts of DG on CENTROSUR network losses

As it is known, battery storage systems are being used to help integrate PV generation into the grid. The storage system was modeled as a load curve which is charged from 09:30 am for a time

of 5 hours and is discharged from 6 pm when there is no solar radiation (according to Figure 4-15). For this case, it was considered that in all scenarios each customer adds the same 2 kW of PV generation and a power of 200W of storage. If scenario 5 is compared in case 1 and 2, it is possible to conclude that when storage systems are integrated with PVs a reduction of reverse power flow of 39 kW to 29 kW is obtained. It can be also appreciated that the load peak at 21:00 is reduced due to the storage systems being added.

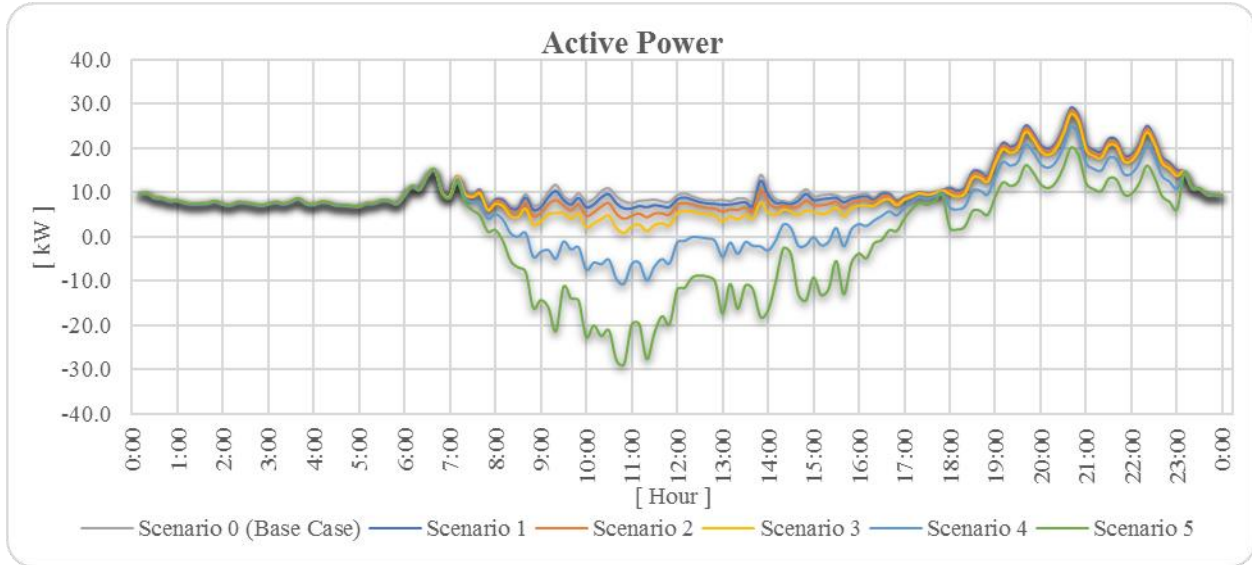


Figure 4-24: Active Power for different DG penetration scenarios (CENTROSUR network). [kW]

Reactive power also presents a reduction in all scenarios. Mainly in scenario 5 where reactive power changes from 4.2 kVAr to 3 kVAr as it can be seen in Figure 4-25.

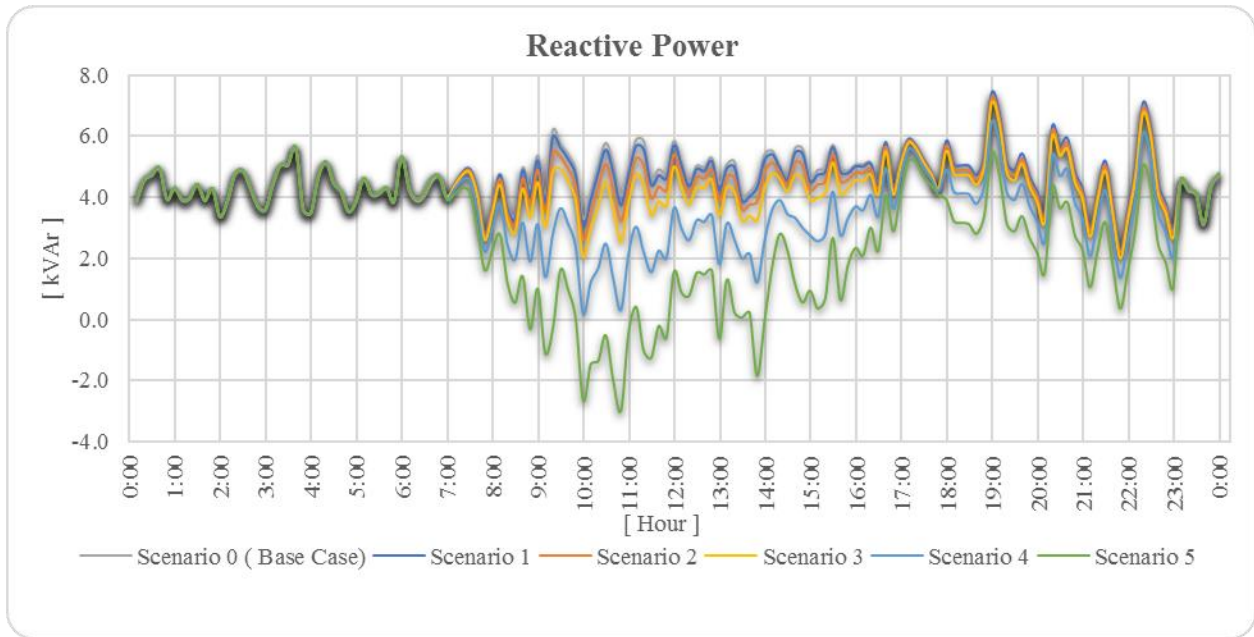


Figure 4-25: Reactive Power for different DG penetration scenarios (CENTROSUR network). [kVAr]

Figure 4-26 shows daily system losses. The maximum peak loss value is 761.7W and it occurs in scenario 5 at 10:40 am. In this case it represents a reduction of 1.5% of losses with respect to case 1.

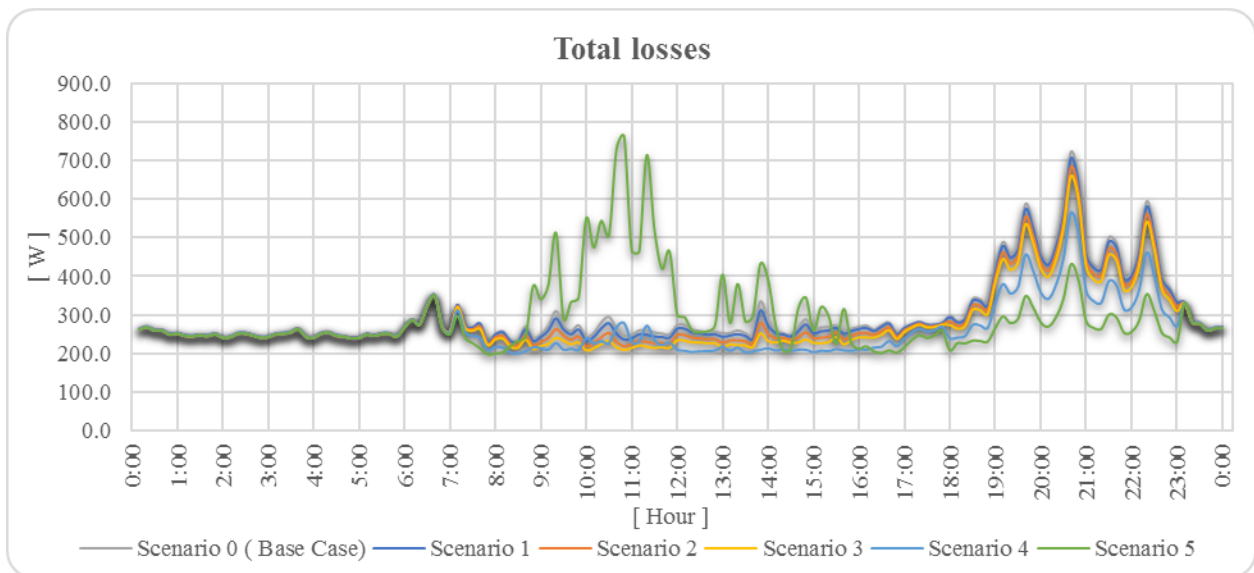


Figure 4-26: Total losses for different DG penetration scenarios (CENTROSUR network). [W]

4.3.2.2. Impacts of DG on CENTROSUR network voltage

The voltage profile when PVs and storage systems are considered together is shown in Figure 4-27. The maximum voltage value is 1.0357 pu with respect to the base voltage.

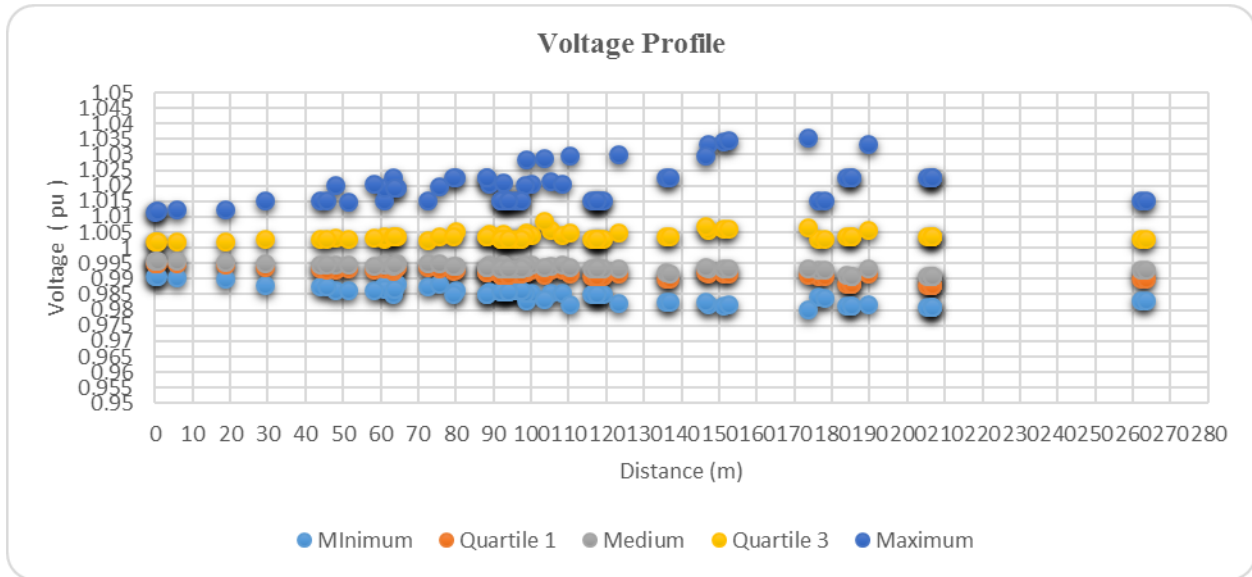


Figure 4-27: Voltage profile for scenario 5 (CENTROSUR network).

The voltage profile throughout the day is presented in the figures below. It can be seen a reduction in the voltage increase happens for all phases. For this case, no voltage violations occurs.

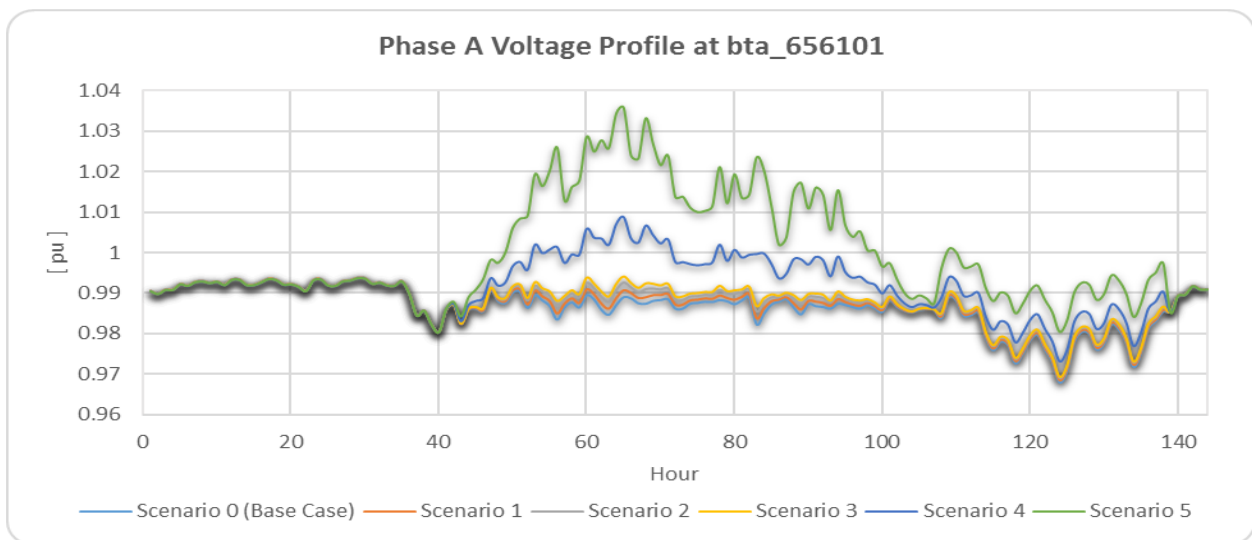


Figure 4-28: Phase A Voltage profile for different DG penetration scenarios (CENTROSUR network).

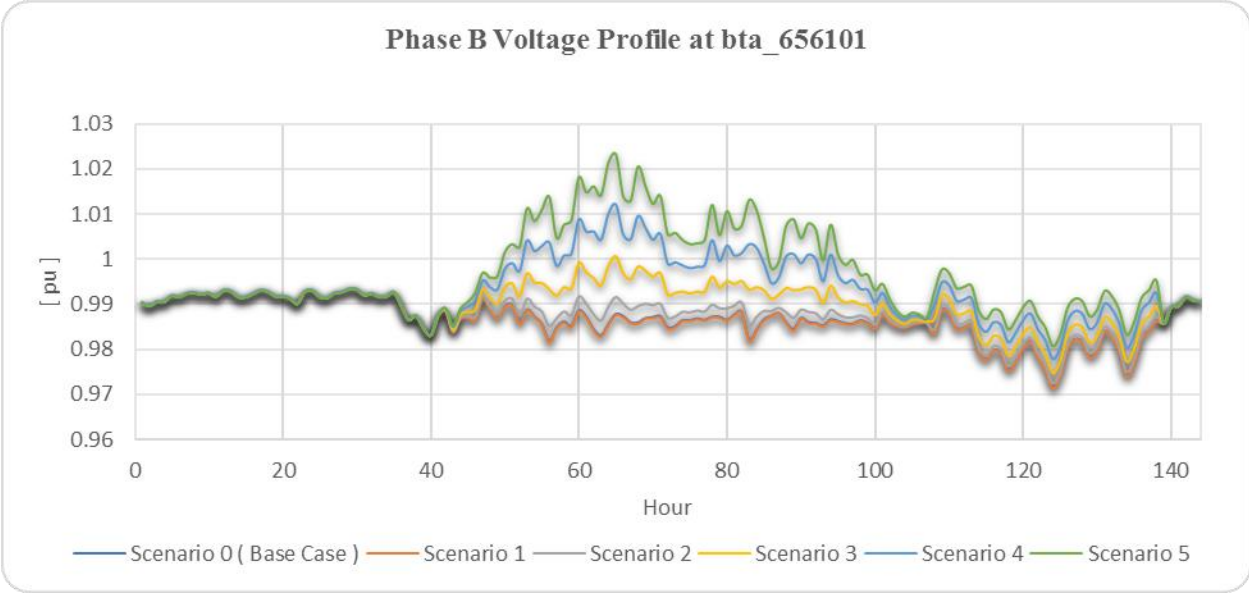


Figure 4-29: Phase B Voltage profile for different DG penetration scenarios (CENTROSUR network).

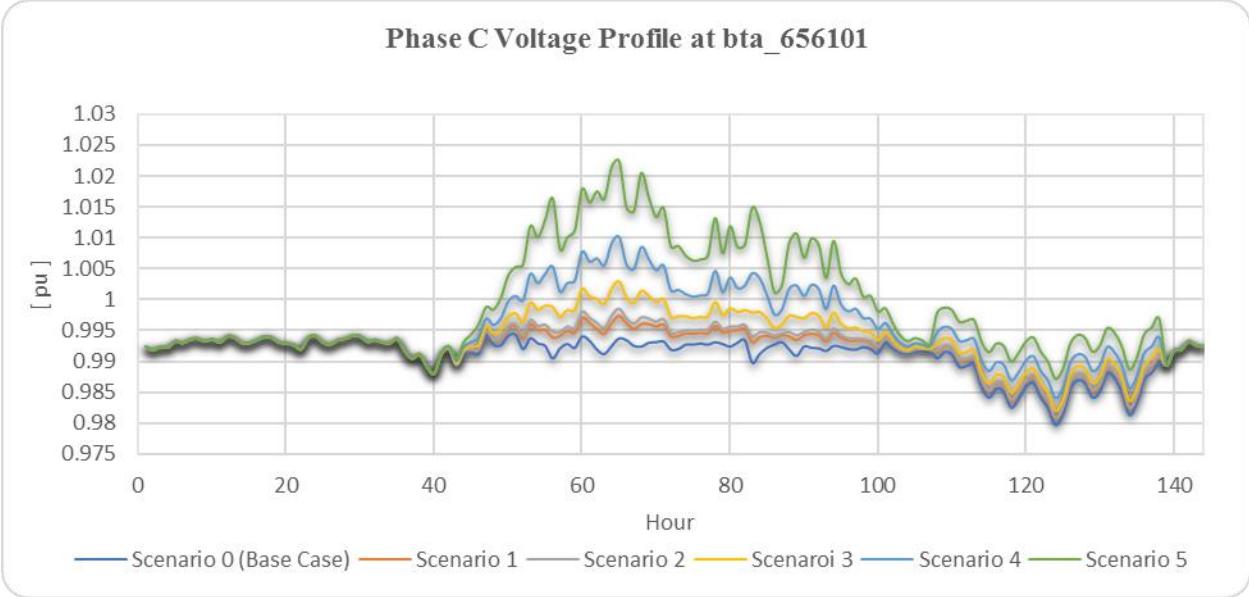


Figure 4-30: Phase C Voltage profile for different DG penetration scenarios (CENTROSUR network).

4.3.3. CASE 3: PVs Integrated with storage system and induction cookers

4.3.3.1. Impacts of DG on CENTROSUR network losses

Another case is presented to study the behavior of the network when induction cookers are added to the distribution systems. As it is known, the Ecuadorian government is changing its energy matrix, and within this program is included the replacement of liquefied petroleum gas (GLP) with electricity for cooking and water heating, using renewable energy.

In the previous figure 4-15 the load curve for an induction cooker was presented. This load curve has a resolution of 10 minutes. As is shown, the peaks of this curve correspond to the three meals of the day: breakfast, lunch and dinner.

The power of induction cookers used for this analysis is 3.105 kW with a PF=0.98 capacitive.

For this analysis, the same scenarios shown in Table 4-4 are considered. For example, in scenario 1 it is considered that 2 customers add PV generation, storage systems and induction cookers.

The active power in the primary side of the transformer for this case and for all its scenarios are presented in figure 4-31.

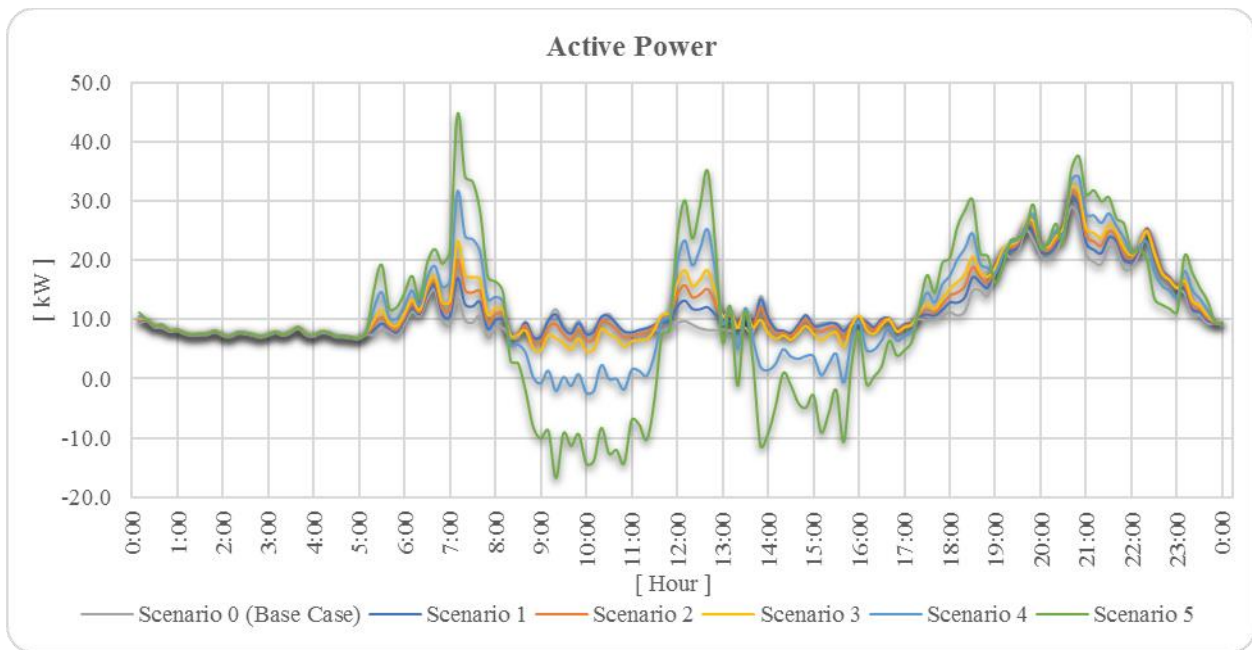


Figure 4-31: Active Power for different DG penetration scenarios (CENTROSUR network). [kW]

From the previous figure it can be observed that in the base case the peak power occurs at 21 hours. However, when induction cookers are added, the maximum peak occurs at 07:00 am. This probably happens as people are using the induction cookers more intensively in the morning period. Another characteristic of this figure is the reduction of reverse power flow in the period between 08:00 am and 12 am, and for the period between 13 and 16 hours. The main reason for that is because the generation has to supply a greater demand with the inclusion of induction cookers.

The results in Figure 4-32 below show the reactive power curve for all the considered scenarios. This figure shows that reactive power is decreasing in all scenarios due to induction cookers contributing with reactive power to the grid.

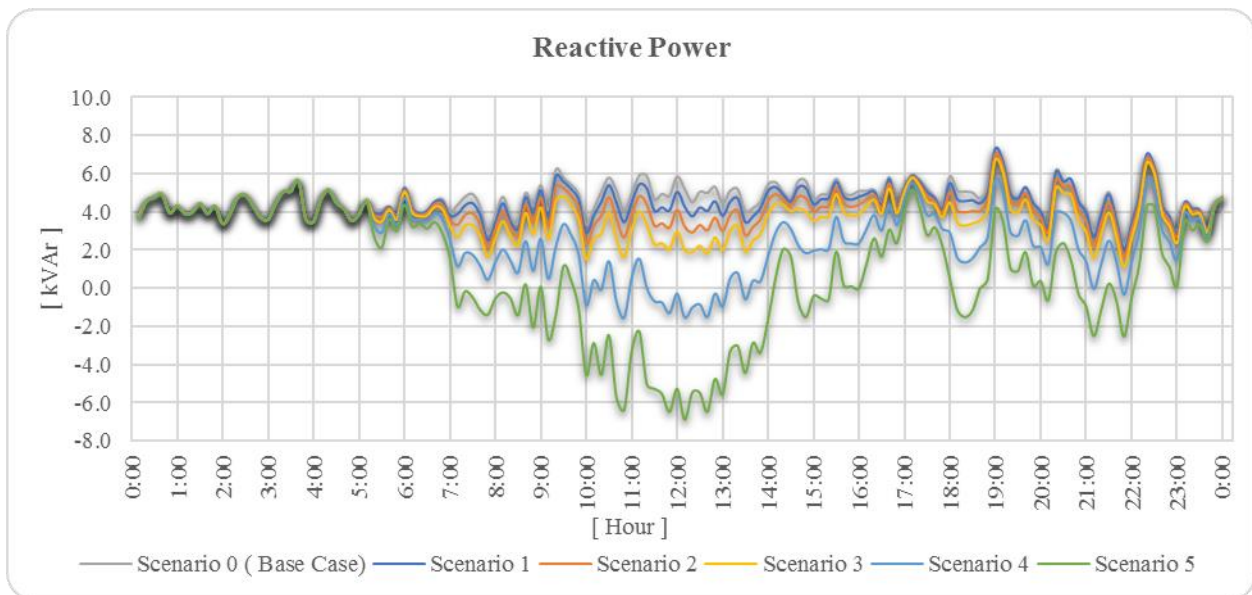


Figure 4-32: Reactive Power for different DG penetration scenarios (CENTROSUR network). [kVAR]

Figure 4-33 shows daily system losses. The maximum loss value is 1434.6 W and it occurs in scenario 5 at 07:00 am. Comparing this case with case 1 and 2, it can be observed that higher losses occur due to the high load of the induction cookers.

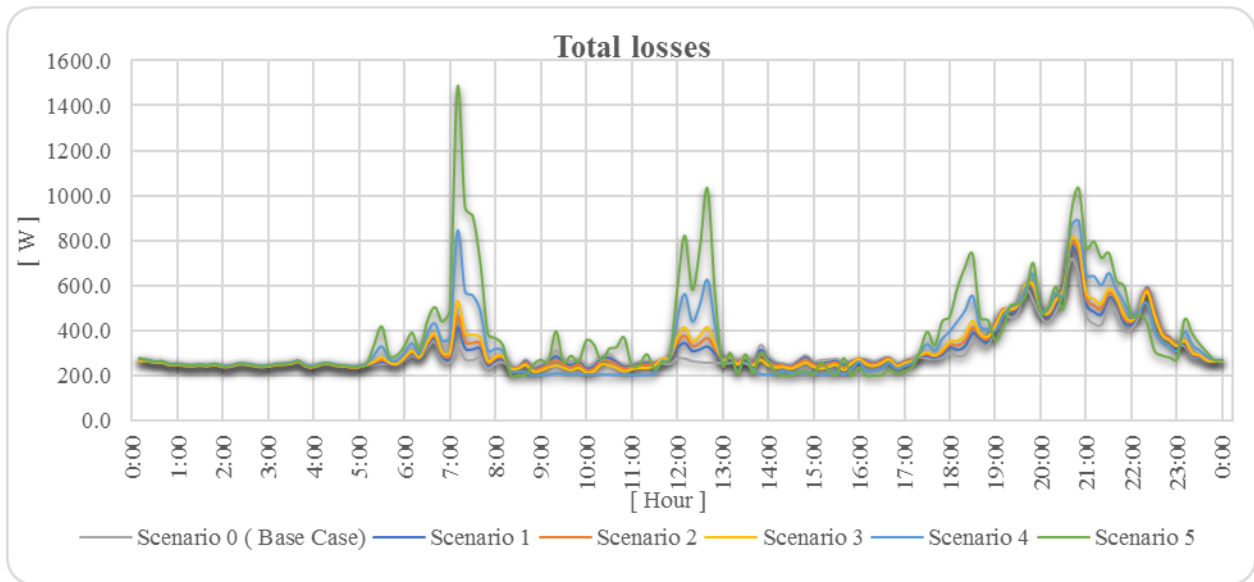


Figure 4-33: Total losses for different DG penetration scenarios (CENTROSUR network). [W]

4.3.3.2. Impacts of DG on CENTROSUR network voltage

The voltage profile when PVs, storage systems and induction cookers are considered together is shown in Figure 4-34. The maximum voltage value is 1.024 p.u. with respect the base voltage. As shown in the next figure voltage profiles presents a reduction in all scenarios due the significant load of the induction cookers.

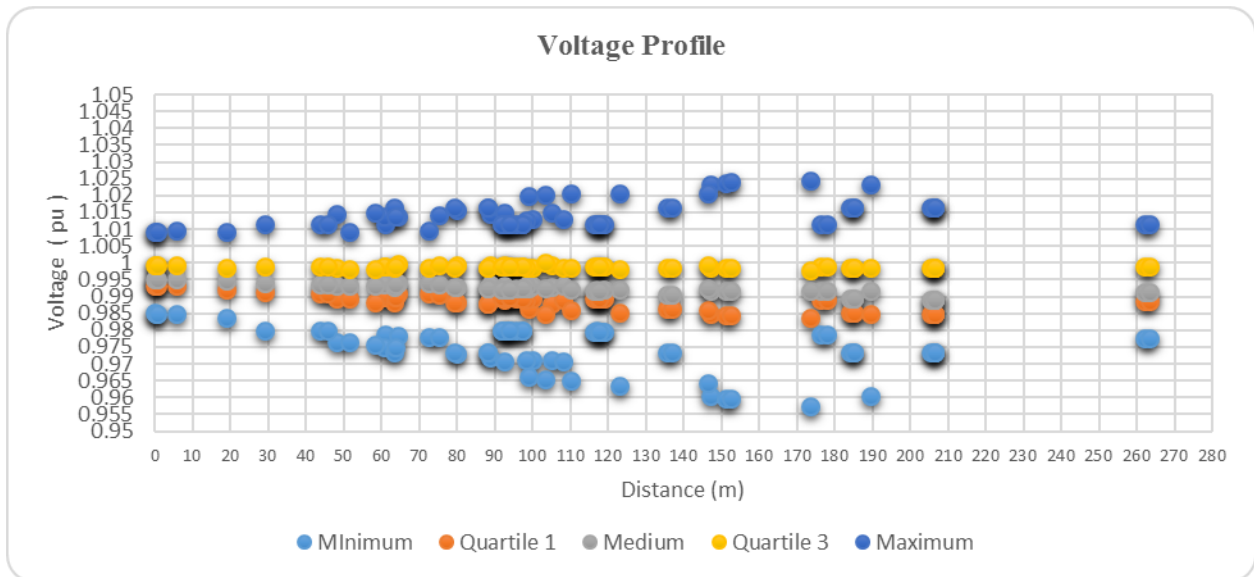


Figure 4-34: Voltage profile for scenario 5 (CENTROSUR network)

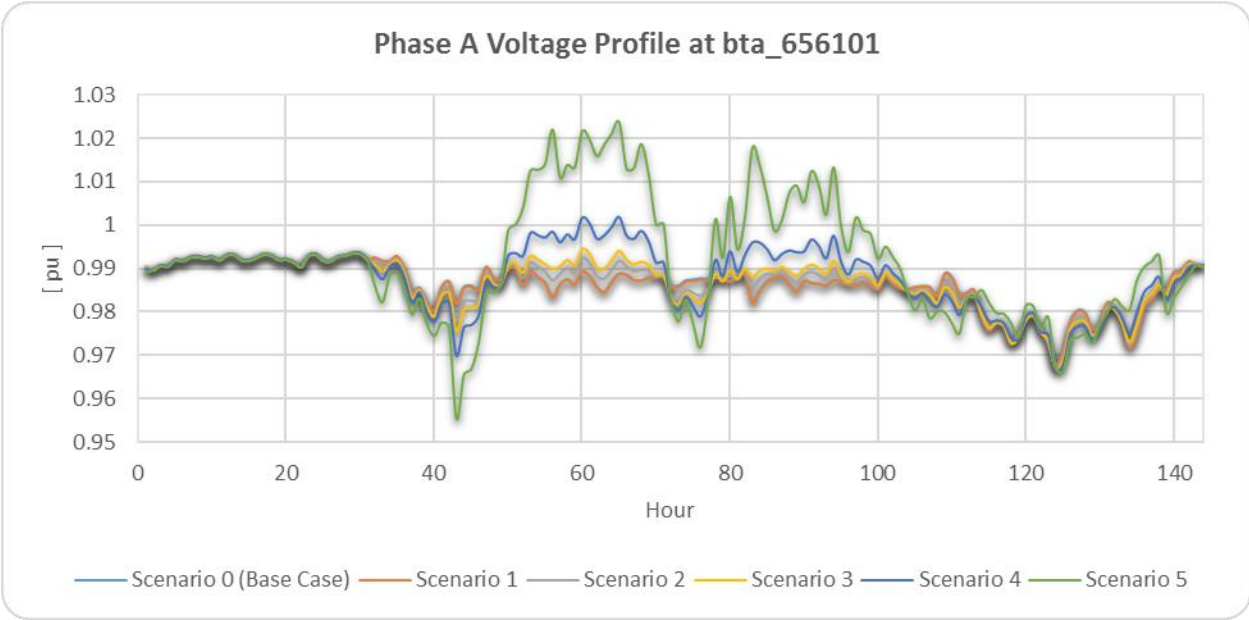


Figure 4-35: Phase A Voltage profile for different DG penetration scenarios (CENTROSUR network)..

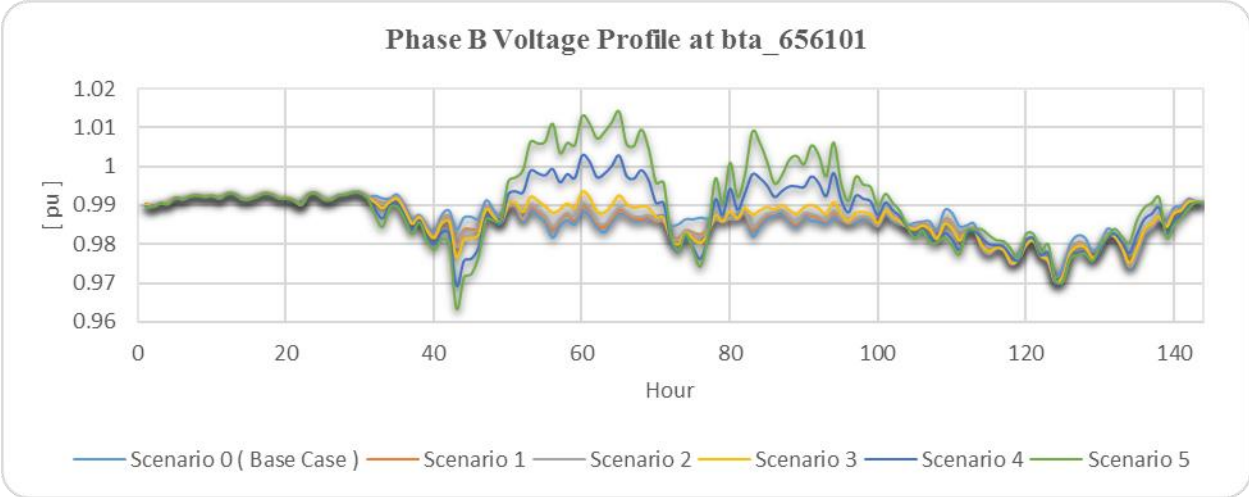


Figure 4-36: Phase B Voltage profile for different DG penetration scenarios (CENTROSUR network).

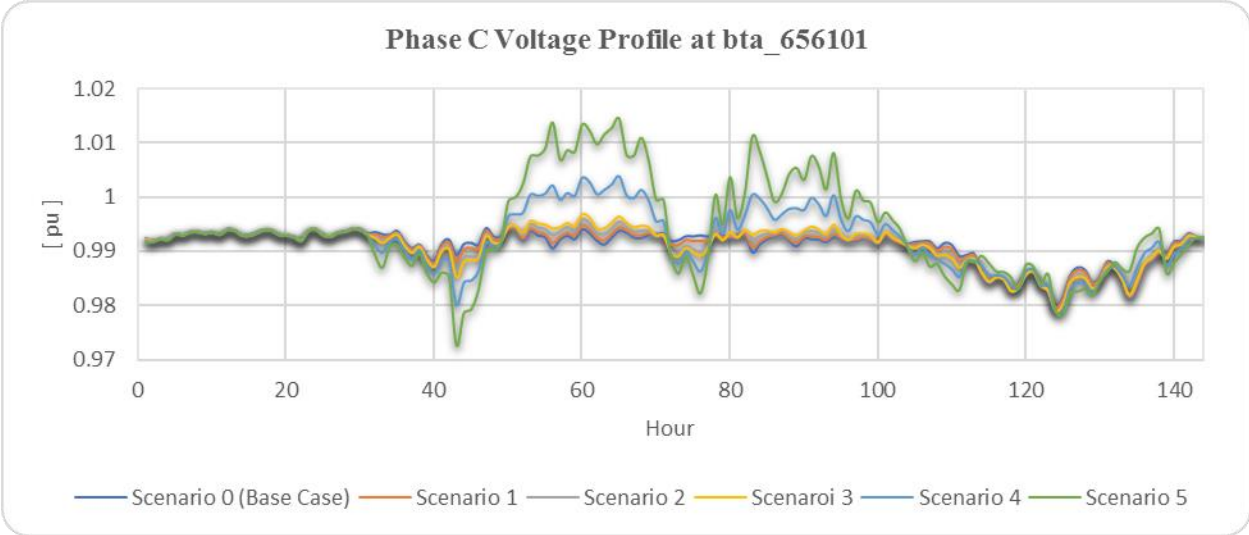


Figure 4-37: Phase C Voltage profile for different DG penetration scenarios (CENTROSUR network).

5. CONCLUSIONS:

Today with the increasing installation of PV with energy storage systems, electricity distribution utilities are carrying out analysis to know the affected grid parameters when a customer decides to connect DG to the grid. This analysis focus into many areas such as voltage regulation, grid stability, fault detection, dynamic control, power quality, etc. However, this thesis focused on, studying the effect of grid-connected PV generation with storage and also with induction cookers on technical parameter such as losses, voltage profile and reverse power. As for the most important conclusions obtained, it can be said that:

For IEEE 13 buses feeder, simulation results showed that better result in the voltage profile and losses are obtained when the same amount of DG is connected to specific buses where the load is highly, and no at all buses. Another approach called QSTS was adopted due to this analysis it is possible to determine technical characteristics of the network along one day, one month, or one year, particularly when a large amount of PV generation is added in hours where the demand is light. However, once this simulation mode is carried out, a little bit improvement could be seen in profile voltage along the day, particularly in hours where there is solar radiation.

The QSTS results for CENTROSUR network showed that there are no reversed power flow problems for the three scenarios when only PV generation is considered. On the other hand, results show a reversal of active power flow from the customer back to the transformer with 50% (scenario 4) accumulated PV connection during a day. High losses take place due to this reversed power flow. The maximum loss value is 1156.35W, and it occurs in scenario 5. If scenario 0 and 5 are compared, it can be shown that losses increased a value of 434.32W.

With the purpose of reducing losses and the reverse power flow another study case is presented. In this case, battery storage systems were integrated with PV generation. The results show that if scenario 5 is compared in case 1 (only PV) and case 2 (PV+BESS) a reduction of reverse power flow of 39 kW to 29 kW is obtained. It can also be appreciated that the load peak is reduced in all scenarios due to the storage systems being added. For this case, the maximum losses value is 761.7 W, which represents an increase of 39.64 W with respect to base case where losses are 722.02 W

For the analysis of the real network it was considered that each customer adds a maximum power of 2 kW. Above this limit, there would be violations on the voltage levels. Another reason considered to simulate with a power of 2kW is due to the space that would be needed for the installation of by each client.

In terms of software it can be said that OpenDSS presents obvious advantages. Its software allows to carry out solutions such as snapshot type and quasi-static time series. One of the high points of OpenDSS is that it can be handled by programs like Microsoft VBA allowing this way for example to perform programs for optimization. On the other hand OpenDSS has an unfriendly graphical environment which makes learning a little difficult.

FUTURE WORKS

- In this work, only the impacts of PV generation and storage systems in the distribution network was analyzed. As a future work it should be analyzed the impact of new technologies and distributed resources such as electric vehicles, wind turbines, electric heat pumps, etc. In the case of electric vehicles, they could be used as a storage source for PV generation and can be used to supply energy when solar radiation being null.
- Another interesting work it would be to work with hundreds of circuits to have more generalized conclusions and with more confidence.
- In the literature review there are very few studies that perform transient analysis in distribution networks so an interesting analysis would be to carry out the transient analysis of the impact of DG in electrical distribution network.

PUBLICATIONS

Title: IMPACT OF DISTRIBUTED GENERATION AND ENERGY STORAGE SYSTEMS IN ELECTRICAL POWER DISTRIBUTION SYSTEMS

Event: II Congreso I+D+Ingeniería, Universidad de Cuenca

Status: Accepted

● IDI 2017 notification for paper 5 ★

● **IDI 2017** <idi2017@easychair.org>

📧 ago 18 a las 3:09 P.M. ★

Para Paul Aucapiña

Estimado/a Paul

El Comité de Programa IDI 2017, tiene el gusto de informarle que su resumen extendido "Impact of Distributed Generation and Energy Storage Systems on Electrical Power Distribution Systems" ha sido aceptado. Por favor, tomar en cuenta las recomendaciones de los revisores y enviar el artículo completo hasta el día 25 de agosto (actualizar el archivo en easychair). El artículo debe ser presentado en formato MASKANA (<https://publicaciones.ucuenca.edu.ec/ojs/index.php/maskana/information/authors>), le recordamos que al menos uno de los autores debe registrarse al congreso y presentar el artículo, para que éste sea publicado en la revista.

Agradecemos por el interés presentado en el Congreso IDI 2017 y por pensar en nosotros para divulgar sus resultados de investigación. Esperamos contar con su presencia en Cuenca.

A continuación los resultados de la evaluación:

----- REVIEW 1 -----

PAPER: 5

TITLE: Impact of Distributed Generation and Energy Storage Systems on Electrical Power Distribution Systems

AUTHORS: Paul Aucapiña, Santiago Torres, Romeu Vitorino and Paula Vide

Evaluación general: 2 (accept)

----- Evaluación general -----

The topic is interesting for presenting at the congress. The authors should be asked for the complete paper

----- REVIEW 2 -----

PAPER: 5

TITLE: Impact of Distributed Generation and Energy Storage Systems on Electrical Power Distribution Systems

AUTHORS: Paul Aucapiña, Santiago Torres, Romeu Vitorino and Paula Vide

Evaluación general: 3 (strong accept)

----- Evaluación general -----

1.- Bastante interesante, con muy buenas ideas y muy útil en temas de investigación.

2.- Se describe correctamente el estudio con literatura actual.

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APPENDIX A

OpenDSS structure

OpenDSS is a command line based program, configured basically as shown in Figure A-1. The scripts that define the circuits can be provided by the user, from text file or from external programs through the COM. OpenDSS can be controlled through programs like Matlab, Python or Visual Basic (VBA).

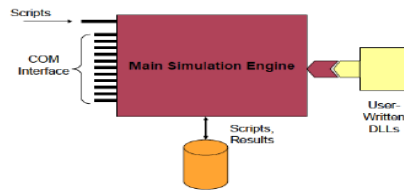


Figure 0-1: OpenDSS structure [37]

Basics elements in OpenDSS

The OpenDSS consist of a model of the electrical power distribution system in the rms steady state, in other words it is a tool of algebraic calculation in the phasorial domain. The basic elements for the construction of a circuit are “Power Delivery” and “Power conversion”. The OpenDSS object structure is shown in the next figure.

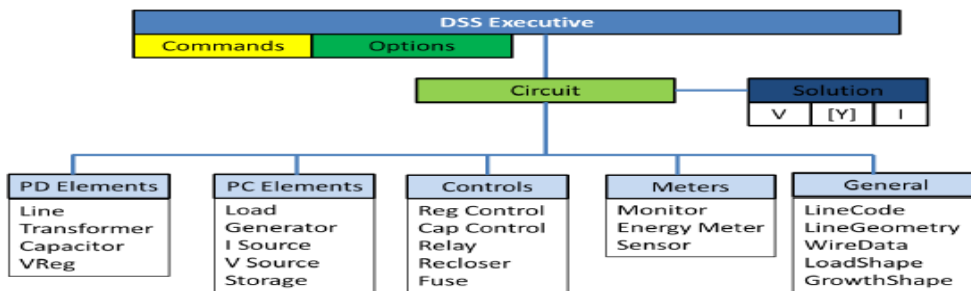


Figure A-2: OpenDSS object structure [37]

Buses

A bus is a circuit element having $[1 \dots N]$ nodes as shown in Figure A-3. Buses are the connection point for all circuit elements. Each node has a voltage with respect to the zero node which is a reference node.



Figure A-3: Bus Definition [37]

Terminal

In OpenDSS electrical elements has one or more terminals that can has more than one conductors.

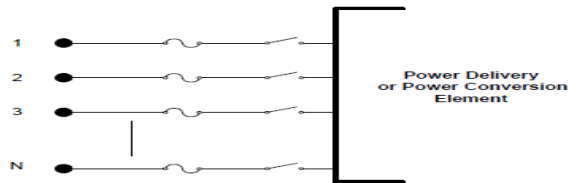


Figure A-4: Terminal definition [37]

Power Delivery (PD) Elements

The elements more common are, transformers, capacitor and reactors. PD elements usually consist of two or more terminals. The principal function of the PD is the energy transportation between one point to other.

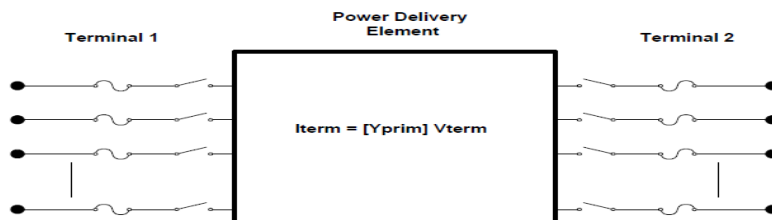


Figure A-5: Power Delivery Element Definition

Power Conversion (PC) Elements

PC elements convert electric energy in other form or vice versa. Some PD elements can temporarily store energy. These elements are commonly generators, loads, energy accumulators, and others. PC elements have one terminal with N Connectors, it is shown in the Figure: A-6

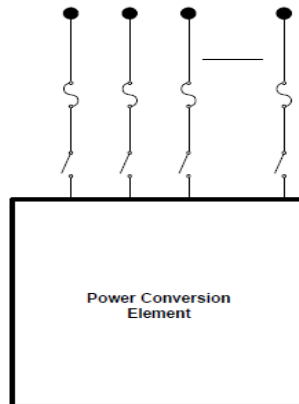


Figure A-6: Power Conversion Element Definition

Support elements

This element provides the possibility of facilitating the parameters definition of the PD and PC elements. By supporting elements is possible monitoring, provide data and results to carry out and temporary analysis. The common elements of this kind are:

- **LineCode:** Stores and defines basic information of a specific line
- **LineGeometry, LineSpacing, WireData:** Define the positions of the conductors
- **LoadShape:** Commonly is used in time simulations. A LoadShape object consists of a series of multipliers which are applied to the kW values of the load to denote how is the load variation respect to the time.
- **EnergyMeter:** It is an intelligent meter connected to a terminal of a circuit that simulates the behavior of an actual energy meter. It can measure power, energy, losses and overload values in a defined area of the circuit.
- **Monitor:** It works like a real power monitor. It could record values of current, voltage and power in a specific phase or at all phases.

- **RegControl and CapControl:** These objects emulate a standard utility voltage regulator or LTC control.

OpenDSS Circuit Solution Technique

OpenDSS uses the creation of the matrix (Y_{pri}) to build the system model. Figure A-7 is shown the solution algorithm. The normal circuit solution technique in the EPRI OpenDSS program may be concisely written as a simple fixed-point iterative method:

$$V_{n+1} = [Y_{system}]^{-1} I_{PC}(V_n) \quad (1)$$

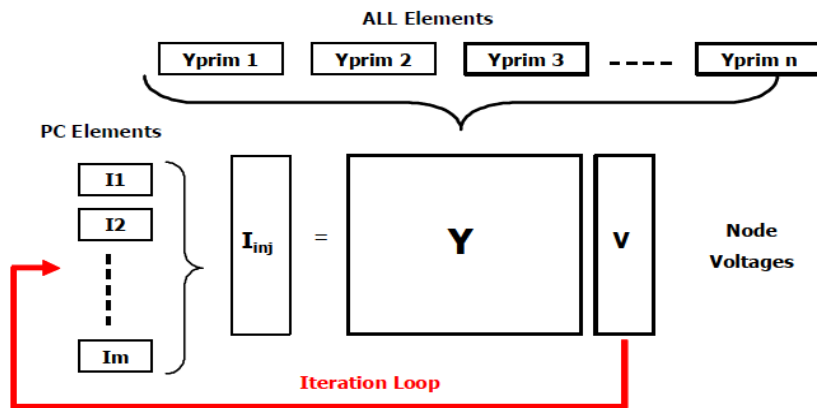


Figure A-7: OpenDSS Solution Loop [37]

Once building Y_{system} , the process starts with a guess at the system voltage vector, V_0 , and computes the compensation currents from each power conversion (PC) element to populate the IPC vector. Using a sparse matrix solver, the new estimate of V_{n+1} is computed as shown. This process is repeated until a convergence criterion is met. For distribution systems, convergence is typically achieved in 4-10 iterations for the initial power flow solution and 2-3 iterations for subsequent solutions in a time series [1].

Once defined some program characteristics, it is possible to say that OpenDSS is a good tool to analyses some studies that have relation with smart grids. One of the capabilities of the program is that algorithms can be done externally and link it with OpenDSS though the COM interface. On the other hand, one of the weaknesses of OpenDSS is that it does not have a graphic interface.

ANEXO B

13 BUSES TEST SYSTEM

Lines Configuration

IEEE 13 nodes consist of overhead and underground lines. Tables B-1 and B-2 presents the configurations of the arrangements for these kinds of lines.

Table B-1: Overhead lines configuration [32]

Config.	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Table B-2: Underground Cable Configurations [32]

Config.	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Once known the characteristics and information of the lines, it is possible to calculate the impedance matrices and the capacitance matrix according to (Kersting). Due to Kron, the neutral is not shown in the matrices.

- 601 Configuration

$$Z = \begin{bmatrix} 0.2153 + j0.6325 & 0.0969 + j0.3117 & 0.0982 + j0.2632 \\ 0.0969 + j0.3117 & 0.2097 + j0.6511 & 0.0654 + j0.2392 \\ 0.0982 + j0.2632 & 0.0954 + j0.2392 & 0.2121 + j0.6430 \end{bmatrix}$$

$$C = \begin{bmatrix} 10.3833 & -3.2894 & -2.0759 \\ -3.2894 & 9.8228 & -1.225 \\ -2.0759 & -1.2225 & 9.2936 \end{bmatrix}$$

- 602 Configuration

$$Z = \begin{bmatrix} 0.4673 + j.7341 & 0.0982 + j0.2632 & 0.0969 + j0.3177 \\ 0.0982 + j0.2632 & 0.4645 + j0.7446 & 0.0954 + j0.2392 \\ 0.969 + j0.3117 & 0.0954 + j0.2392 & 0.4621 + j0.7526 \end{bmatrix}$$

$$C = \begin{bmatrix} 9.3931 & -1.7828 & -2.7862 \\ -1.7828 & 8.5369 & -1.0859 \\ -2.7862 & -1.089 & 8.9508 \end{bmatrix}$$

- 603 Configuration

$$Z = \begin{bmatrix} 0.8261 + j0.8370 & 0.1284 + j0.2853 \\ 0.1284 + j0.2853 & 0.8226 + j0.8431 \end{bmatrix}$$

$$C = \begin{bmatrix} 7.7626 & -1.4833 \\ -1.4833 & 7.6902 \end{bmatrix}$$

- 604 Configuration

$$Z = \begin{bmatrix} 0.8226 + j0.8431 & 0.1284 + j0.2853 \\ 0.1284 + j0.2853 & 0.8226 + j0.8370 \end{bmatrix}$$

$$C = \begin{bmatrix} 7.6902 & -1.4833 \\ -1.4833 & 7.7626 \end{bmatrix}$$

- 605 Configuration

$$Z = [0.8259 + j0.8373]$$

$$C = [7.4488]$$

- 606 Configuration

$$Z = \begin{bmatrix} 0.4960 + j0.2773 & 0.1883 + j0.0204 & 0.1770 - j0.0089 \\ 0.1883 + j0.0204 & 0.4903 + j0.2511 & 0.1983 + j0.0204 \\ 0.1770 - j0.0089 & 0.1983 + j0.0204 & 0.4898 + j0.2773 \end{bmatrix}$$

$$C = \begin{bmatrix} 159.6994 & 0 & 0 \\ 0 & 159.6994 & 0 \\ 0 & 0 & 159.6994 \end{bmatrix}$$

- 607 Configuration

$$Z = [0.8242 + j0.3184]$$

$$C = [146.6753]$$

Transformer, Capacitors and Regulator configuration

IEEE 13 nodes consists of one three phase capacitor bank, single phase capacitor bank, a three-phase regulator, three phase and single phase concentrated loads. In the following tables is shown each one of these characteristics.

Table B-3: Network Transformers IEEE 13 Nodes [32]

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 - Gr.W	0.48 - Gr.W	1.1	2

Table B-4: Network Capacitor IEEE 13 Nodes

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Table B-5: IEEE 13 Nodes Regulator

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	50		
Phases:	A - B -C		
Connection:	3-Ph, LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Voltage Level:	122	122	122

Once the characteristics of the IEEE 13 nodes network have been defined, the model is implemented in the software.

Following voltages profile at bus number 680 are presented:

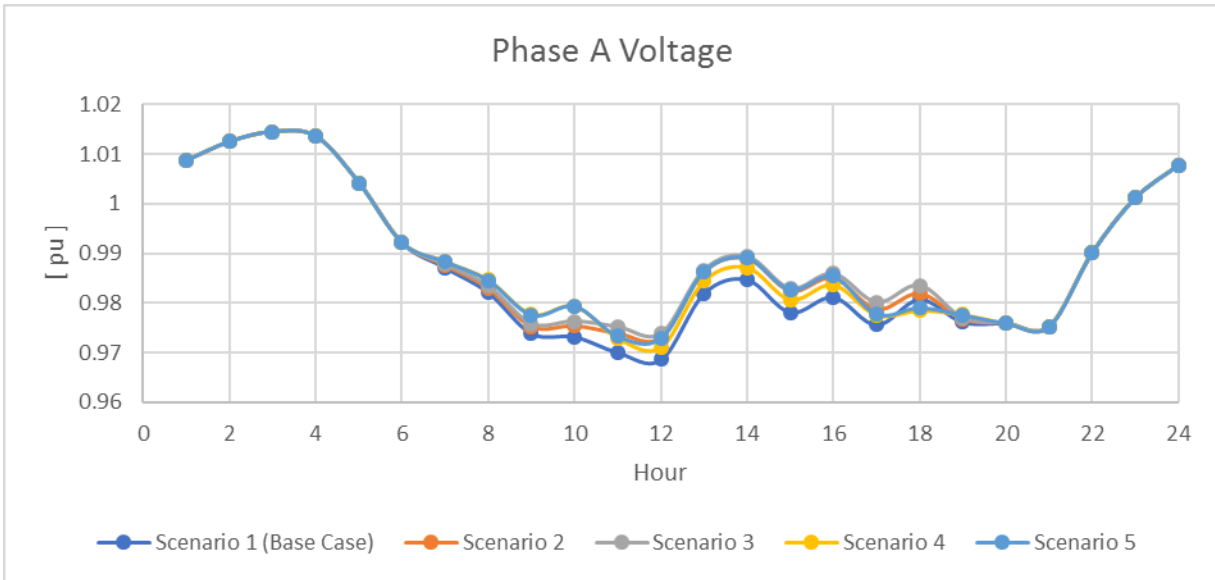


Figure B-1: Phase A Voltage profile for different DG penetration scenarios.

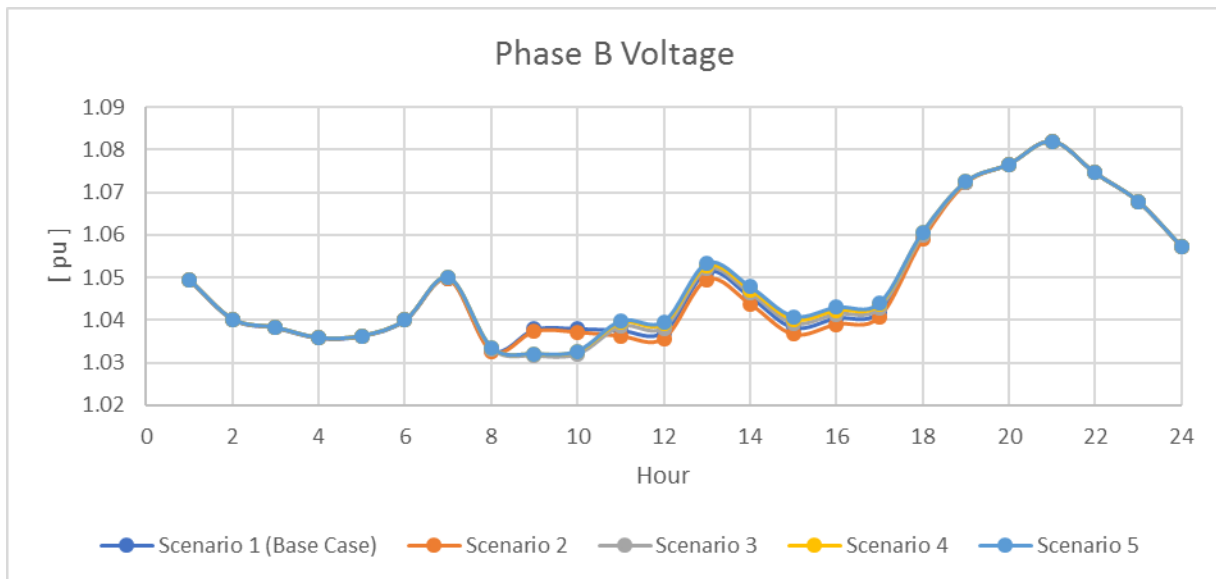


Figure B-2: Phase B Voltage profile for different DG penetration scenarios.

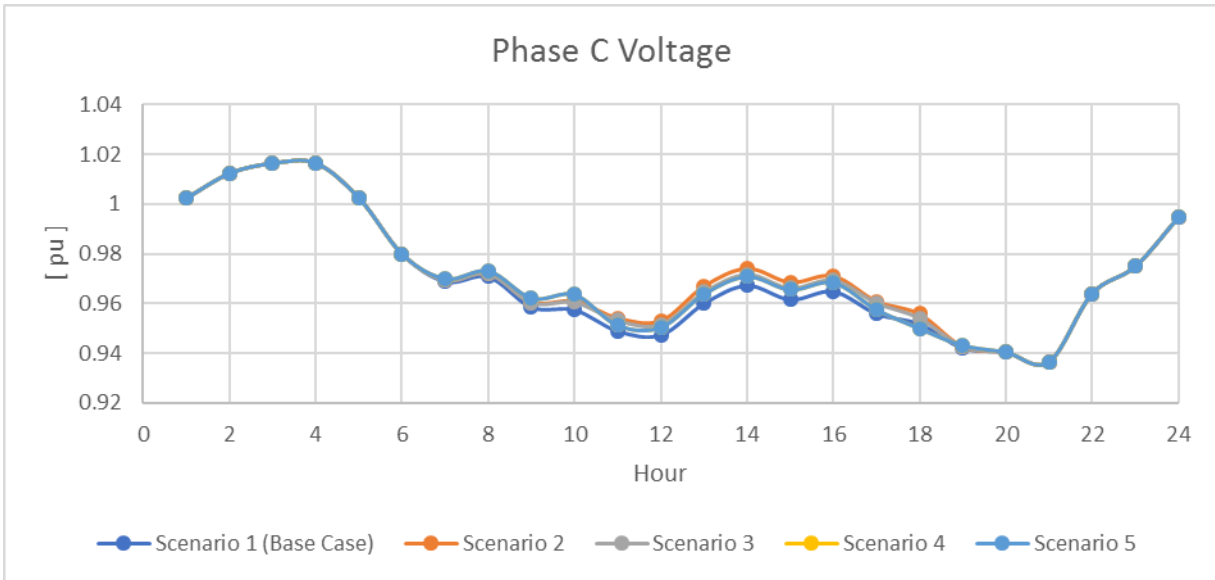


Figure B-3: Phase A Voltage profile for different DG penetration scenarios.