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Licenciatura em Engenharia Electrotécnica e de Computadores

Design of Future Distribution Grids

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Dedico esta tese:

À minha mãe e à minha família
À minha namorada
Ao futuro

i. Resumo

O presente trabalho introduz o conceito de controlo de tensão em sistemas de distribuição de energia, que incluam geração distribuída e veículos eléctricos. O impacto da geração distribuída e dos veículos eléctricos no abastecimento de tensão será avaliado. Por um lado a geração distribuída providencia mais potência para o sistema, o que pode causar a inversão do fluxo de potência e um aumento no nível de tensão na sua proximidade quando a carga é reduzida. Por outro lado, os veículos eléctricos representam uma carga adicional em sistemas de distribuição, levando ao aumento da procura de mais potência da rede, e da queda de tensão ao longo dos ramos de distribuição do sistema. Ambos poderão causar problemas de tensão no abastecimento de energia, caso não seja implementado um sistema de controlo de tensão. Dispositivos, tais como o transformador equipado com tomadas comutáveis, ou o regulador automático de tensão, que não eram elementos essenciais no passado, são hoje soluções importantes para a regulação de tensão.

Neste projecto diversas soluções para o controlo de tensão são analisadas, tanto de um ponto de vista técnico como económico. No geral, os resultados mostram que diferentes estratégias conduzem a resultados diferentes, e algumas soluções demonstram ser melhores que outras no controlo de tensão. No momento de decidir qual a estratégia a implementar, de forma a obter uma solução adequada para um determinado sistema, é necessário ter sempre em conta a capacidade dos condutores, os limites técnicos de cada dispositivo e os custos associados aos mesmos.

Palavras-chave: Queda de tensão, controlo de tensão, potência reactiva, modelo estático de carga

ii. Abstract

This work presents the concept of voltage control in power distribution systems with distributed generation and electric vehicles penetration. The impact of DG and EV in the voltage supply is investigated. DG provides more power into the system, which can cause the inversion of the load flow and an increase in the voltage supply when the demand is low. EVs on the other hand are additional load in distribution systems, increasing power demand and voltage drop. Both might be a cause of voltage problems in the power supply, when no voltage control is applied. Devices such as the tap-changer transformer or the voltage regulator which were not essential in the past are now important solutions to solve voltage variation issues. In this work, several different solutions for voltage control are analyzed, both technically and economically.

Overall, the results show that different strategies have different outcomes, and some solutions provide better voltage control than others. In order to have a proper solution for a system, when choosing a control strategy, it is necessary to always take into account the cable ampacity, the technical limits of each device and the costs associated with it.

Key words: Voltage Drop, Voltage Rise, Voltage Control, Reactive Power, ZIP Model

iii. Acknowledgements

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DG – Distributed Generation/Distributed Generator

LV – Low Voltage

MV – Medium Voltage

HV – High Voltage

HVAC – Heating, Ventilation and Air-Conditioner

VR – Voltage Regulator

AVR – Automatic Voltage Regulator

OLTC – On Load Tap Changer

ESU – Energy Storage Unit

EV – Electric Vehicle

LVDC – Low Voltage Direct Current

HVDC – High Voltage Direct Current

AC – Alternate Current

DC – Direct Current

SC – Synchronous Condenser

G2V – Grid to Vehicle

V2G – Vehicle to Grid

VRU – Voltage Regulation Unit

ZIP – Constant Impedance (Z), Constant Current (I), Constant Power (P)

Chapter 1

Introduction

This chapter is a general introduction to the work, "Design of Future Distribution Grids". It starts with a brief overview of the power grid concept, how it has been developing from its earlier stages up to the present and how it is expected to change in the near future, to deal with the energy demand, improve itself and become the much spoken smart grid concept. The integration of distributed generation and the expected increase of loads – trough the development of electric cars and heat pumps - in distribution systems are major factors for the power grid need of change and both are then explored further.

1.1 Motivation

Power Distribution System is an essential part of the power system. It makes possible for electric power to reach the end customer, supplying homes, offices and factories with electricity. With the recent development of distributed generation and electric automobile technology and their penetration in distribution systems, the voltage supply is affected, for the worse if no action is taken. More than ever, voltage control is a requirement in such systems. Besides, the technology advancements in several areas of engineering might change the actual power system to a better, more efficient power grid, called the Smart Grid. This could bring endless possibilities for distribution systems but it would probably bring new requirements as well, thus it is important to evaluate new solutions to continue providing a reliable voltage supply.

1.1 Power Distribution: The Past, the Present and the Future

Since it was invented in the nineteen century, the electric power system, also known as the power grid, has been performing a decisive role regarding the social, technological and economic development of every nation. In fact, its creation changed many aspects about life on earth; it supported innumerous technological advances in many scientific areas; it is also related to each nation with its own economy, directly affecting and influencing it, by becoming a piece of the global market in order to sell its primary good, the electric energy. It shaped the world as we know it today and it will also shape the future yet to come.

The power grid is a vast and complex system. It was created to transport electric energy from its connected generation plants to its final consumers, whether they are residential, commercial or industrial customers. In the context of this work, the power grid can be divided in two major parts: <u>the transmission and sub-transmission grid,</u> where electric energy is transmitted in high voltage levels, from the generation plants to the distribution substations; <u>the distribution grid</u>, which is used to deliver electric energy in low voltage levels until the final power customer. The connection between both grids is made through distribution substations, where there are transformers that allow the voltage to be stepped down, so it can be used by the final consumer. The figure on the right shows a typical power grid.

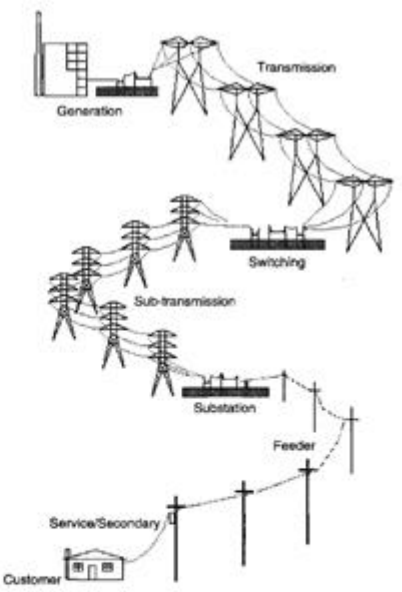

FIGURE 1 – A TYPICAL POWER GRID

Source: Power Distribution Planning Reference Book, Willis.

On its early stage, the generation plants would only connect to the distribution grids through transmission lines, leading to what was called a <u>centralized generation</u>. The power flow in distribution networks was unidirectional since all electric energy would come from a supply point. In this topology, the generation plants were specifically located in the grid – production points - while customers were all at the distribution side.

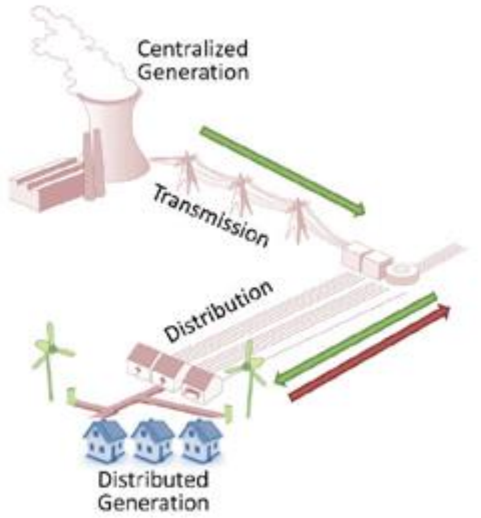

FIGURE 2 – AN ACTUAL POWER GRID WITH DISTRIBUTED GENERATION

Source: http://energy.sia-conseil.com/wp-content/uploads/2010/05/micro1.jpg

However this scenario has been changing due to the development of renewable energy sources in the last decades. These new energy plants are connected directly to the distribution grid, leading to what is called a distributed generation (DG). Since these generation plants are connected on the same local grid as the customers, the power flow will no longer be unidirectional, which may cause an increase on the voltage level. Therefore there will be constraints that need to be considered. Some examples of renewable energy sources which can be connected to distribution grids are solar photovoltaic, wind farms, small geothermal, biomass, small gas turbines and small combined cycle gas turbine (CCGT).

In the coming future, due to the evolution of information technology (IT), more changes are expected to happen on the existing power systems, improving them to an intelligent grid.

In this concept of intelligent grid, also named as “Smart Grid”, computer networks are used to create interconnections inside the grid, improving control and communication between the several grid components. Some possibilities would be a better data management from all the grid participants, starting in the generation plants, the transmission and distribution substations, the customers; better and efficient real time control and full visibility over the grid status, improving reliability; increase of general efficiency through the grid and reduction of energy losses and carbon emissions, e.g., by giving the energy utilities the possibility of adjusting their production to meet the current demand – demand side management – and by being a bi-directional power system, which means that it could recover the unused energy, instead of wasting it – which happens in the traditional power grid with an unidirectional power flow. There is no doubt that this energy recover possibility plays an important role for the development and support of distributed generation and the vehicle-2-grid programs.

Also, the Smart Grid is intended to be an intelligent, resilient and self-healing system, being able to detect the possibility of anomaly before it happens by self-learning and self-diagnosis mechanisms that would allow it to prevent anomalies to repeat, thus gradually eliminating the occurrence of system failures, disturbances or even complete black-outs.

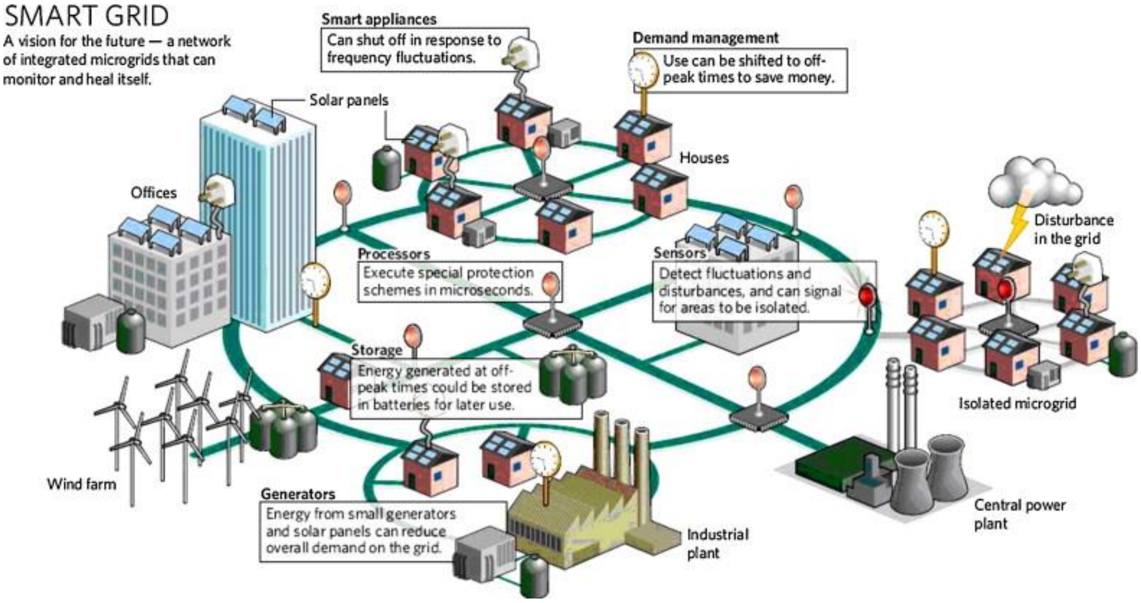

Figure 3 – A vision of the future power grid

Source: http://www.worldwatch.org/smart-grid-and-energy-storage-technologies-spread

1.2 European Smart Grid R&D

Currently there are several European projects and studies related to the implementation of Smart Grids and Smart Metering Systems. Some are included here.

1) InovGrid (Portugal) is a project developed by EDP Distribuição and other industry partners such as EDP Inovação, INESC Porto, EFACEC, LOGICA and JANZ/CONTAR, that aims to create an intelligent electricity grid, where the (already) existing renewable power sources and electric vehicles will take part. The improvement of power quality, control, efficiency and an environmental sustainability are the top priorities. [1] [2]
2) E-Energy (Germany) is the German program for Smart Grids development, including several projects per region of the country. The main goal of these projects is to implement an Information and Communication Technology (ICT) based Energy system, with an intelligent integration of electric vehicles (E-Mobility). Germany is one of the European countries which most invested in smart grid technologies. [3]

1.3 Objectives

The main focus of this work will be the voltage control on a power distribution system, with and without the presence of DG and future loads.

The DG changes the power flow and thus the voltage behavior on the grid, increasing the risk of overvoltage. This requires the addition of voltage mechanisms, including transformers and more recent technologies from power electronics. Besides the DG, also the inclusion of future loads in the distribution grid, such as the electric vehicle, will have a strong impact on the voltage behavior.

To deal with so many different types of loads and analyze how they affect the grid, the general ‘ZIP’ load model will be considered in this work.

Chapter 2

Power Distribution System

This chapter introduces the general concept of Power Distribution System, as a part of the power grid, describing how it works to successfully deliver electrical power to its customers, and at the same time ensure that the requirements for power distribution are met. A power distribution system has proprieties that can differ from one system to another, thus being possible to classify them based on their characteristics. A major characteristic is the type of current used - AC or DC - both having its own advantages and disadvantages when used to distribute power. Finally, at the end of the chapter, there is a brief introduction to one of most important power distribution system components - the load - which represents the consumer side. Based on the customer type and the day time the load level will vary, affecting the system, for the worse if not predicted. In order to ensure the best reliability of the system it is important to model the load behavior. However, load representation is usually very difficult due to the changeable nature and variety of loads.

2.1 Introduction

In a conventional power system, electric energy is produced in a few, large and usually isolated power plants. As seen in chapter one, the generation connects to a transmission system to transport electric energy through long distances, until it reaches a substation, which reduces the voltage level and delivers the electric energy to customers through a distribution system.

The main difference between transmission and distribution systems is the voltage level at each one operate. Unlike the transmission system which uses the highest voltage level to minimize losses during the energy transport, the distribution system delivers power at a low voltage level (below 35 kV). The high transmission voltage is reduced in substations transformers to a primary-distribution voltage which value can be between 4 kV and 35 kV, depending on the equipment used. Typical residential customers will use a secondary-distribution voltage level (in Europe, approximately 230 V phase-neutral or 400 V phase-phase), which is provided by a distribution transformer.

But not only residential customers connect to the distribution grid, but also customers from commercial/public sectors and industrial customers as well. In general, the equipment used by an industrial or commercial customer is different from the equipment used by a residential customer, has a different power demand and affects the power system differently. Thus it becomes necessary to classify customers according to their power needs and adjust the distribution equipment in order to provide each customer the best service possible.

In power systems the term “Load” is used to represent electrical equipment connected to the system that consumes power. In a distribution system, the load is formed by customer’s equipment currently connected to the grid. If more equipment is connected, the load will increase, and more power will be consumed from the source. Usually there are times of day when more customers are using the power system, leading to peaks in power consumption. Thus, load models are required to somehow predict when and how demand can occur to ensure the best reliability of the system and for system planning purposes.

2.2 The Present Distribution System

2.2.1 Structure

In general, the structure of an actual distribution system can be described in two parts: the primary and the secondary system.

The primary system connects a distribution substation to several distribution transformers, through primary feeders. If more than one transformer needs to be connected to the same primary feeder, sub-feeders and laterals are used to connect them. In Europe, typical primary feeders are three-phase, three-wire cables. [4]

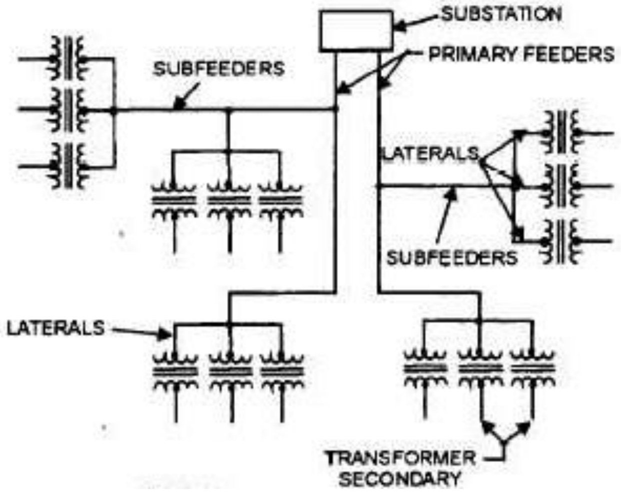

Figure 4 – Primary Distribution System

Source: Power Distribution Planning Reference Book, Willis.

The secondary system connects the distribution transformer to the final consumers. Each transformer connects several customers – or loads – through a secondary circuit, or just "secondaries" [4], which usually is a three-phase four-wire cable, as it also includes a neutral conductor. The transformer has its primary – HV side - delta connected and its secondary - LV side – wye-connected with a grounded neutral, or star-point. . Each load connects to the secondary circuit through a service connection. In the case of residential areas, the service connection is usually a single-phase, two-wire cable, as it also holds a neutral conductor.

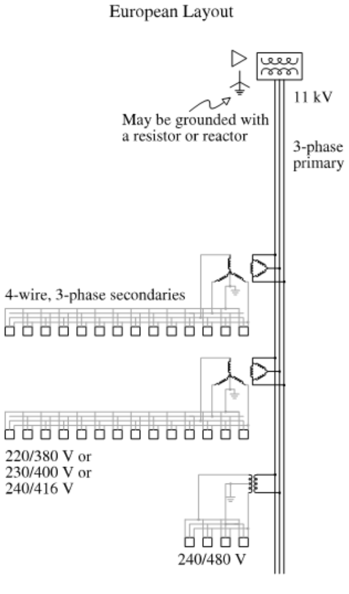

Figure 5 – European Primary System

Source: Electrical Power Distribution Handbook, Short.

2.2.2 Components

An AC distribution system is obviously composed by distribution lines, transformers, switches, protection equipment and voltage regulation equipment.

The distribution lines deliver electric power to customers, connecting them to a distribution substation which, in a distribution grid, can be considered as a power supply point. Distribution lines can either be overhead lines, supported by insulators, mounted on wooden poles/metal towers, or underground cables, which provides a better protection against adverse weather conditions, lightning strikes and terrorism/vandalism. However, underground cables have a shorter lifetime and their installation and maintenance are much more costly than overhead lines.

The distribution transformers are devices capable of changing the voltage level to desirable values. They are available in a wide range of size, type and capacities. Larger transformers are usually three-phase devices, which can transform all three phases. In distribution systems there can be either three-phase and single-phase transformers. Transformers have two types of power losses: the no-load losses or core losses, which are constant and inherent to the operating transformer, and the load-related losses, which may vary depending on the current flowing through the transformer, due to demand. The total transformer's losses is the sum of both no-load and load-related losses. Therefore the transformer's losses varies with the power transmitted through it, but always above a minimum value.

Switches are used in distribution to provide additional control. They can either be normally open (NO) or normally closed (NC) switches. Switches also have a certain rated current and load break capacity, which indicates how much current they can interrupt, with larger switches being able to interrupt higher currents. When a switch is opening and the load is high, it is common to produce an arc of current between its terminals.

In distribution protection equipment is used to isolate faulty/damaged equipment during a system failure, even if it implies the disconnection of some customers from the grid. Protection equipment includes circuit breakers, sectionalizers, fuses and relays. Planning a distribution system protection can inflict certain constraints on distribution equipment size and layout, e.g. in some cases a large conductor has to be replaced by a smaller conductor to be protected safely because there is no protection equipment able to support the larger conductor.

Voltage regulation equipment includes several mechanisms designed to provide voltage regulation on distribution lines, such as voltage regulators, line drop compensators and tap-changer transformers. These mechanisms will be further analyzed in this work.

2.2.3 Requirements

In a distribution system the main goal is to deliver electric power to customers, at their place of consumption and in a ready-to-use form. A distribution utility must ensure that every customer located in its serving area, no matter how scattered it is, is supplied with electricity.

Besides the need of delivering power to all customers, it is required to deliver it in proper conditions. Customer equipment are designed to operate at steady voltage levels, and can be damaged if the voltage level changes too much. This is also called voltage fluctuations, which can happen when the demand increases or decreases too much, causing overvoltage/undervoltage along the feeders. Thus a distribution utility has, among other, the requirement of delivering a steady voltage supply to its customers, and always prevent voltage fluctuations to happen.

2.3 The Load

In a power system, the load represents all kind of electrical equipment that is connected to the grid and consumes electric power to function. It can either be a device used to produce heat, mechanical work, power up electronic circuits, etc. In distribution systems the load is mostly inductive in nature, being defined by their active and reactive power consumption, or by their active power and their power factor.

$$pf = COS(\varphi) = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \qquad \mathbf{1}$$

$$sen(\varphi) = \frac{Q}{S} \qquad \mathbf{2}$$

$$\tan(\varphi) = \frac{Q}{P} \qquad \mathbf{3}$$

Loads can be divided into four main types:

Motors

Lighting

Heating and refrigeration systems

Electronic devices

2.3.1 Load Class

In a distribution system there can be different types of customers, depending on the equipment they use and the total power they require. These can either be:

Residential Customers
Commercial Customers
Industrial Customers
Agricultural Sector
Public Sector
Transports Sector

Residential Customers

The first is the most common type of customer in distribution systems, being however the type of customer which actually consumes less power, since most of the equipment used is single-phase. There are exceptions however, such as buildings with elevators, which require a three-phase power supply to operate. The most relevant and common single-phase equipment used by residential customers, can be assigned into different groups of loads [5]. These are presented next, as well as their typical power consumption.

1) Brown goods – light electronic consumer goods. Can either be equipment for office/communication or for entertainment:

Computer desktop	220 to 300 W
Computer LCD display	90 to 120W
Laptop	50 to 100 W
TV LCD	110 to 170 W
Printer (inkjet)	15 to 30 W
Fax	10 to 20 W
Phone	1 to 10 W
Router	5 to 10 W
CD/DVD player	20 to 50 W
Complete HI-FI system	80 to 200 W
Radio (AM/FM)	10 to 20 W

TABLE 1 – TYPICAL BROWN GOODS

2) White goods – major domestic appliances, including heating and routine housekeeping tasks such as cooking, food preservation or cleaning:

Electric cooker/stove/oven	10 kW
Refrigerator + Freezer (Fridge)	Depends on total capacity. Typical values may be between 0,4 to 1,4 kW
Microwave	0,7 to 1,5 kW
Dishwasher	1,2 to 2 kW
Washing machine	About 2 kW
Clothes dryer	About 4 kW
Water heater (electric)	About 2,5 kW
Electric space heater	0,7 to 2 kW
Heat pump	About 1,5 kW
Air conditioner	About 3 kW

TABLE 2 – TYPICAL WHITE GOODS

3) Small appliances – portable or semi-portable devices, including kitchen appliances and personal care:

Coffee machine	1,2 to 1,5 kW
Kettle	2 kW
Toaster	0,8 to 1,5 kW
Vacuum cleaner	0,2 to 0,7 kW
Hair dryer	1 kW
Clothing iron	1 kW
Blender	0,3 kW
Etc.	

TABLE 3 – TYPICAL SMALL APPLIANCES

4) Lighting

Fluorescent Lighting	10 to 120 W
Incandescent Lighting	60 to 100 W

TABLE 4 – TYPICAL LIGHTING

Depending on the appliances actually used in a household, there can be different types of residential customers. The most common and those which will be considered in this work are as follows.

Customer type	Appliances in use				
	general	Electric stove	Storage water heater	Flow-type heater	Electric space heating
basic	x	-	-	-	-
Partly-electric	x	x	-	-	-
Fully-electric (boiler)	x	x	x	-	-
Fully-electric (flow-type)	x	x	-	x	-
All-electric	x	x	x	-	x

TABLE 5 – TYPES OF RESIDENTIAL CUSTOMERS

Commercial Customers

Commercial customers require a reliable power supply to keep their business running. They can use a wide range of different equipment, from small, single-phase office appliances to large, three-phase machinery, such as ovens or a chiller. Consequently, the total power demand in the commercial sector can vary from one customer to another, depending on the business sector. A small shop, which load is basically composed by lighting and small appliances would have much less power consumption than a restaurant or a hotel. Generally the equipment used in the commercial sector is much identical to the residential sector, with the inclusion of three-phase machinery into the "white goods" and more power demand in the "lighting" group.

1) White goods:
HVAC system
Three-phase oven
Three-phase motor (elevators)
Three-phase HVAC system (chiller)
Three-phase heat pumps

2) Lighting
Fluorescent lighting
Incandescent lighting
Led lighting
Metal halide lighting

Industrial Customers

The third type is the industrial customer. These can either require a MV to HV supply, depending on the industry sector and the equipment used. The industry sector includes small, medium and large industry. The equipment used by industrial customers is different from that used in commercial or residential sectors, being largely composed by three-phase motors, generators (emergency power systems) and other types of high power demand machinery. This type of customer uses much more three-phase power than any of the two previous types, and consequently has higher power demands than those.

Agricultural Sector

The fourth type is the agricultural customer. This type of customer relies on electricity to power up heavy machines and automatized processes used in agriculture. Therefore it is often the use of three-phase motors. Thus the power demand of agricultural customers can be very similar to industry demand.

Public Sector

The fifth type of distribution customer refers to all government and public services, such as hospitals, city halls, schools, universities, libraries, police and firemen stations, etc. Regarding the power demand and consumption, the public sector can be considered similar to the commercial sector, as most of the equipment used is the same, but with the inclusion of three-phase generators, serving as emergency power systems in the case of a power failure or blackout. The power demand in the public can be, therefore, higher than that in commercial sector.

Transports Sector

The last type of distribution customer is the transport sector, including trains and subways, which use electrical energy to move. The main load in this case are DC and induction motors, since their rotating speed can be easily controlled. In the last two decades the transport sector has been changing, with its power demand being gradually increasing. The main reason of this increase is the development of the electric vehicle, which has become more and more popular, not only being used as a personal vehicle, but also as a public transport.

2.3.2 An Introduction to Load Modeling

A load model is a mathematical representation of the relationship between power, voltage and frequency, where the power is either the active and reactive power consumed by the load. In a load model, the voltage and the frequency are the inputs and the power is the output.

There are different types of load models. It can either be a static model, a dynamic model or a combination of both. The difference between a static and a dynamic load model is the influence a time dependency on the dynamic model. Since this work focuses on voltage control, only a small introduction to the load modeling subject will be presented, but it will not be analyzed in further detail.

An important factor which characterizes a load is its dependence on the grid voltage. Therefore, both the active and reactive power consumed by a load can be described as a voltage function. In fact it is also a frequency function, because the load also depends on the grid frequency.

$$P = f(V, freq) \qquad \mathbf{4}$$
$$Q = f(V, freq)$$

Given that in power systems the frequency is usually set within a narrow range of values, it will be, therefore, assumed as a constant in this, so that only the dependence on the voltage is considered. A common model is widely used to express both the active and the reactive power as a voltage function:

$$P = P_0 * V^{\mathrm{K_P}} \qquad \mathbf{5}$$
$$Q = Q_0 * V^{\mathrm{K_Q}}$$

Where P_0 and Q_0 are the active and reactive load power at the nominal voltage of 1 p.u.; K_P and K_Q are the voltage dependency coefficients.

The values of these coefficients K_P and K_Q can model the load as a constant power – either constant active and/or reactive power - , constant current or constant impedance, if their value is equal to 0, 1 and 2, respectively.

Coefficients K_P and K_Q	Constant
0	Power
1	Current
2	Impedance

TABLE 6 – STANDARD LOAD MODELS

Thus, for a constant power load, the previous expressions are:

$$P = P_0 \qquad \mathbf{6}$$
$$Q = Q_0$$

For a constant current load:

$$P = P_0 * V \qquad \mathbf{7}$$
$$Q = Q_0 * V$$

And for a constant impedance load:

$$P = P_0 * V^2 \qquad \mathbf{8}$$
$$Q = Q_0 * V^2$$

Polynomial Model

An actual load in a power system is neither constant power, constant current or constant impedance type, but a mix of these three types. Therefore it can be modelled as a polynomial, as follows:

$$P = P_0 * (a_0 + a_1 * V + a_2 * V^2) \qquad \mathbf{9}$$
$$Q = Q_0 * (b_0 + b_1 * V + b_2 * V^2)$$

In this model, the load power consumption – both the active and reactive power consumption - is described as a quadratic voltage function. The coefficients a_0, a_1, a_2 and b_0, b_1, b_2 represent, respectively, the weight of each one of the three previous types, constant power, constant current and constant impedance. Therefore, this model is a combination of these three, and thus it is commonly known as the ZIP model – Z: impedance, I: current, P: power. This will also be the only load model used in this work.

Exponential Model

The exponential model is also a static load model that represents the relationship between power and voltage through an exponential equation, as follows:

$$P = P_0 * \left(\frac{V}{V_0}\right)^{\alpha} \qquad \mathbf{10}$$
$$Q = Q_0 * \left(\frac{V}{V_0}\right)^{\beta}$$

Where P_0 and Q_0 stand for the real and reactive powers consumed at a reference voltage V_0. The exponents α and β depend on the type of load that is being represented, e.g., for constant power load models $\alpha = \beta = 0$, for constant current load models $\alpha = \beta = 1$ and for constant impedance load models $\alpha = \beta = 2$.

2.3.3 Load Behavior

In a household, each appliance may have a different behavior as a load, meaning they can be either resistive loads, constant power or constant current loads. Appliances used for space and water heating are resistive appliances, thus they can be modelled as constant impedance loads. It is possible to regulate the heat output on such appliances, but it would still be constant impedance operating, just on a higher/lower impedance level. Electronic devices on the other hand, can be modelled as constant power loads, since they consume always the same power, regardless the voltage supply.

It is important to notice that assuming (modelling) a load as a constant impedance does not mean that it always operates based on the same internal impedance, but it represents how the load behaves when the voltage supply changes. For instance, if the voltage level decreases, a constant impedance load will not consume more current from the grid, but its efficiency will decrease. A constant power load on the other hand, will consume more current to maintain the same power, which has several consequences.

Considering as an example a typical household, with a total power installed of 32 kW, equipped with one of each the most common appliances, plus twenty fluorescent lamps and twelve incandescent lamps. The load model for each appliance is also presented.

Load	Load model	Rated Power	Load group
Cooker/Oven/Stove	Constant impedance	10000 W	White goods
Incandescent lighting	Constant impedance	4x100 W; 8x60W	Lighting
Clothing iron	Constant impedance	1000 W	Small Appliances
Kettle	Constant impedance	1200 W	Small Appliances
Toaster	Constant impedance	1500 W	Small Appliances
Clothes Dryer	Constant impedance	2000 W	White goods
Storage water heater (boiler)	Constant impedance	2500 W	White goods
Space heater	Constant impedance	1500 W	White goods
Heat pump	Constant power	1500 W	White goods
Blender	Constant power	300 W	Small Appliances
Refrigerator	Constant power[1]	1000 W	White goods
Washing Machine	Constant power	2000 W	White goods
Dishwasher	Constant power	1500 W	White goods
Microwave	Constant power	1000W	White goods
Desktop Computer+ LCD Display	Constant power	120W+220W=340 W	Brown goods
TV LCD	Constant power	130 W	Brown goods
HI-FI+CD/DVD player	Constant power	150 W	Brown goods
Electronic devices (in general, mobile phone, tablet, mp3 player, netbook, PDA, digital camera)	Constant power	About 20 W	Brown goods
Fluorescent lighting	Constant power	50x15W; 6x60W	Lighting
Vacuum cleaner	Constant power	700W	Small Appliances
Total constant impedance load		22580 W	
Total constant power load		9750 W	
Total power installed		32330 W	

TABLE 7 – EXAMPLE OF A TYPICAL HOUSEHOLD APPLIANCES AND THEIR LOAD MODEL

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[1] Although an operating refrigerator involves several processes, and its power consumption varies with the internal temperature, for the purpose of this work it will be simplified and considered as a constant power load, since it has an internal heat pump which needs constant power to operate. The same simplification applies to the washing machine, clothes dryer and the dishwasher.

As can be seen from the above table, in a typical household scenario, although the number of constant impedance loads is smaller, the power demand of these is much greater, resulting in 70% of the total power demand.

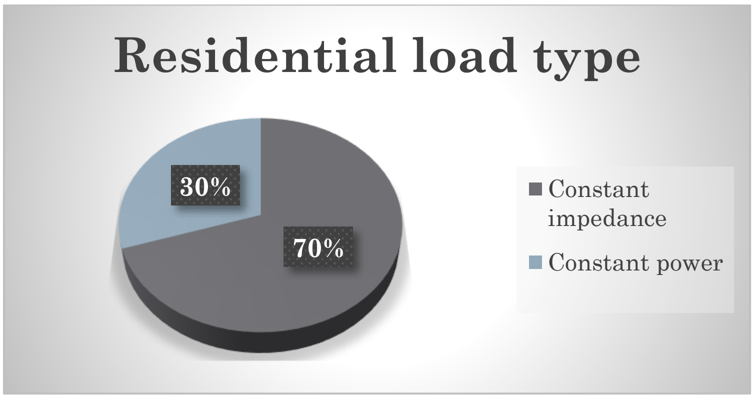

FIGURE 6 – RESIDENTIAL DEMAND BY LOAD TYPE

In this case the constant power loads only represent 30% of the total load, which is the typical scenario for residential loads during the winter season. During summer a common scenario would be the opposite, 70% constant power and 30% constant impedance. [6]

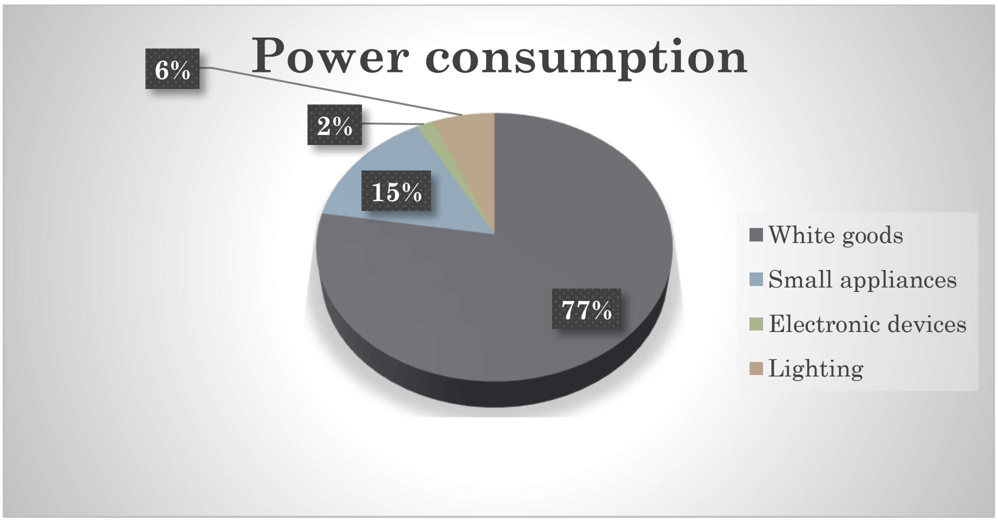

FIGURE 7 – RESIDENTIAL DEMAND BY LOAD GROUP

Load contribution

So far, only the rated power consumption of each load was considered. However, it is wrong to assume that each load in a household has a continuous contribution to the total demand, since not all domestic appliances are used at the same time or with the same frequency. For instance, the cooker is a resistive load with a high power demand, but it is mostly used during short intervals of the day, while a clock has a very low power demand but it is used 24 hours per day. A fridge has a moderate power consumption but it is also used 24h per day to preserve food.

There are several studies about the contribution of each appliance to the total residential load. [7] It is common to assume the following data for some household appliances:

Appliance	Daily use	Utilization per year
Cooker/oven/stove	10h to 12h; 18h to 20h	Very high (almost every day)
Refrigerator	24h per day	Every day
Microwave	11h to 13h; 19h to 21h	Very high
Dishwasher	19h to 22h	Medium
Coffee Machine	7h to 9h	Medium to high
Clothes washing machine	Due to wide disparity of values: 9h to 11h ; 14h to 18h ; 1h to 4h	Medium
Clothes dryer	Same as clothes washing machine	Low
Iron	17h to 19h	Very low
Vacuum cleaner	17h to 19h	Very low
TV, computer, entertainment, electronic devices in general	19h to 1h	High to very high
Lighting	Very dependent on the season: 17h to 24h during winter 19h to 24h during summer	Every day

TABLE 8 – DAILY USE AND UTILIZATION PER YEAR OF COMMON HOUSEHOLD APPLIANCES

The “typical use per day” parameter is strongly dependent on several factors, including the customer everyday life and age group. The presented values consider employed, young adults, between 25 and 55 years old.

Also, some loads such as the clothes dryer, space heating or an air conditioner system are strongly correlated with the season. During winter there can be an increase in power consumption to produce additional heat, while in summer the power consumption can increase with the use of cooling systems, to produce fresh air. Other loads such as electronic devices, computers and TV’s are often used per year, but because these are low power demand loads, they do not have a considerable impact on load contribution, and can be considered part of a constant “base load”. [5]

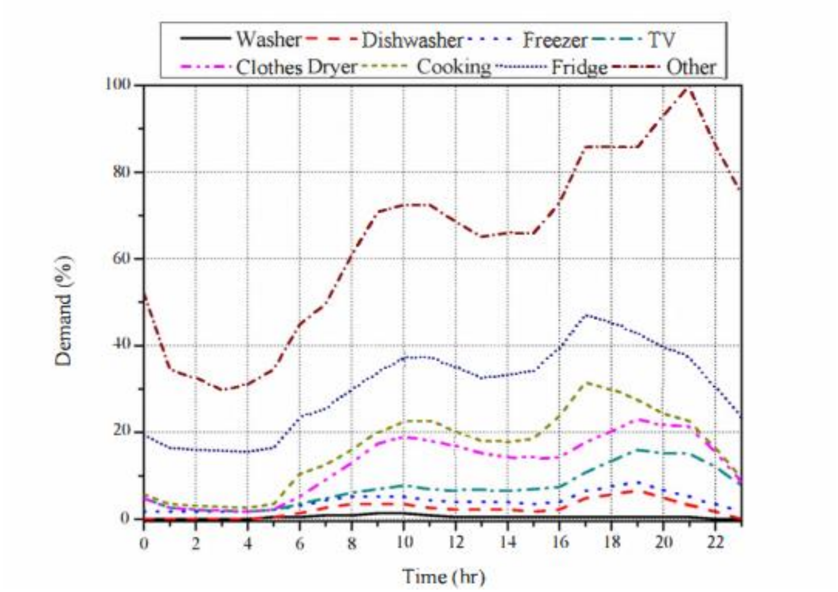

FIGURE 8 – TYPICAL DEMAND OF COMMON APPLIANCES PER DAY

Source: Component-based Aggregate Load Models for Combined Power Flow and Harmonic Analysis, A. J. Collin, J. L. Acosta, B. P. Hayes, S. Z. Djokic

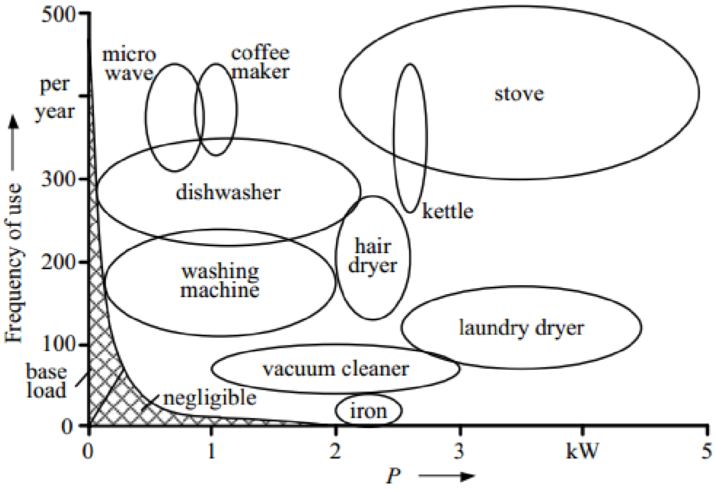

FIGURE 9 – LOAD VS. FREQUENCY OF USE PER YEAR FOR SEVERAL APPLIANCES

Source: Residential Load Models for Network Planning Purposes, J. Dickert, P. Schegner

Thus each appliance contributes differently, for the total demand. Each contribution has its specific weight, regarding how many hours the appliance is used, how often it is used per year and of course, the appliance power consumption. Knowing what type of load each appliance is, as well as the weight of its contribution to the total power demand is important to have a general model of the entire residential load.

The ZIP load model is a simple model that can only represent a static load. Each coefficient of this model will represent the weight associated to a constant power, a constant impedance and a constant current load. There will be a different model for each time of the day. For instance, a residential load can be modelled into a specific ZIP model during daytime, and into a different model during dinner time. The model will be dependent on what type of appliances are being used at the moment.

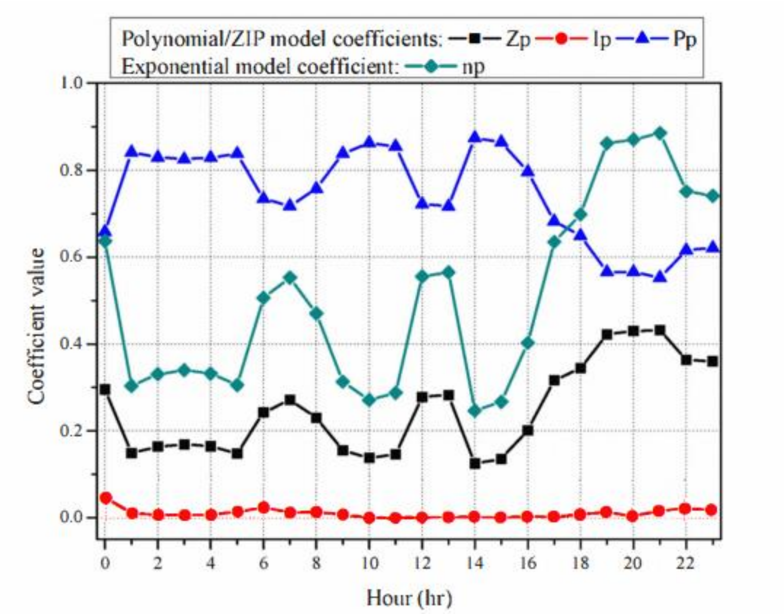

FIGURE 10 – VARIATIONS OF EXPONENTIAL AND ZIP LOAD MODEL COEFFICIENTS DURING A TYPICAL SPRING DAY

Source: Component-based Aggregate Load Models for Combined Power Flow and Harmonic Analysis, A. J. Collin, J. L. Acosta, B. P. Hayes, S. Z. Djokic

As can be seen, between 1h and 17h the constant power coefficient (blue) has a high value - much of the load is constant power - with small time intervals – 6h ~ 8h and 12h ~ 14h - where this coefficient drops a little. The reason for this drop and the consequent raise of the constant impedance coefficient (black) on the same time intervals, is due to the use of resistive kitchen appliances to prepare meals. The same reason also applies to the time interval between 17h and 22h, but in this case the drop of constant power loads and the raise of constant impedance is more severe, because most people are at home during dinner.

2.3.4 Load Demand

As shown in table 7, residential load levels vary throughout the day, since not all appliances are used at the same time. In fact most of people go to work at morning and only return home at the evening, which results in very low demand during these hours, and an increase in demand during night. But this is what happens in residential loads. Commercial and industrial loads on the other hand, will surely have a much higher demand during the same hours, and less at night.

The differences between each load class can be seen in a load profile. The load profile, or load curve, is a diagram that shows the total load measured at a specific day time.

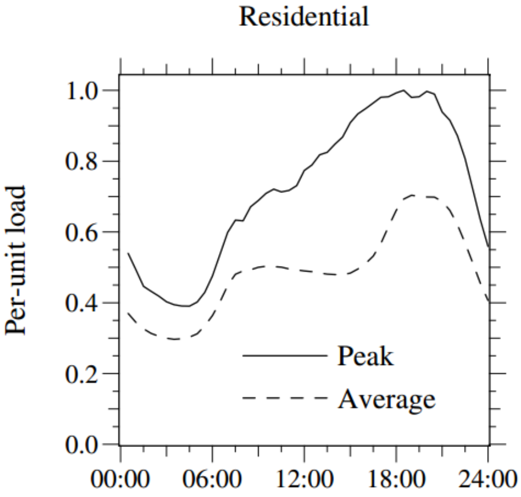

FIGURE 11 – TYPICAL LOAD PROFILE FOR RESIDENTIAL LOADS

Source: Electrical Power Distribution Handbook, Short.

As can be seen, commercial loads show a peak demand at an earlier time (~11h) than residential loads (~17h). Industrial loads have a load profile similar to commercial loads, but with a higher and constant load.

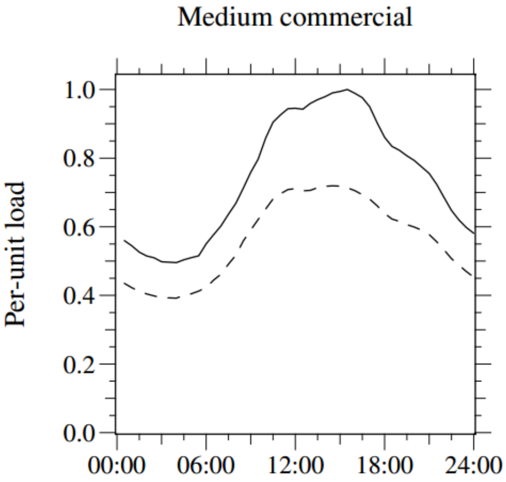

FIGURE 12 – TYPICAL LOAD PROFILE FOR COMMERCIAL LOADS

Source: Electrical Power Distribution Handbook, Short.

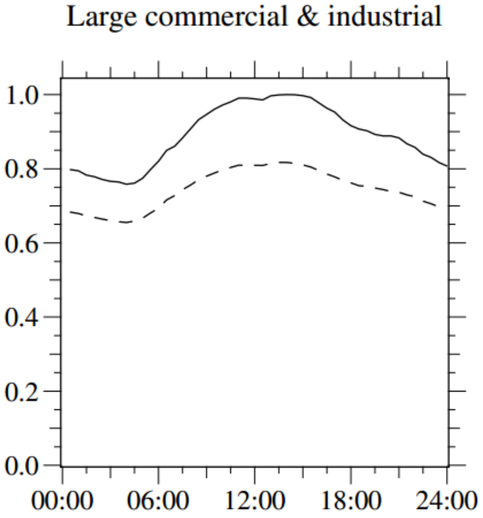

FIGURE 13 – TYPICAL LOAD PROFILE FOR SMALL TO MEDIUM INDUSTRY

Source: Electrical Power Distribution Handbook, Short.

Generally, small to medium industry tend to have a load profile similar to the left, being mostly distributed during daytime. Large industry however, uses large and high power demand machinery which requires several personnel to operate, may have different load profiles. In this case there can be, usually, two to three peak demands during a specific time interval, while in the remaining time the power demand is quite low.

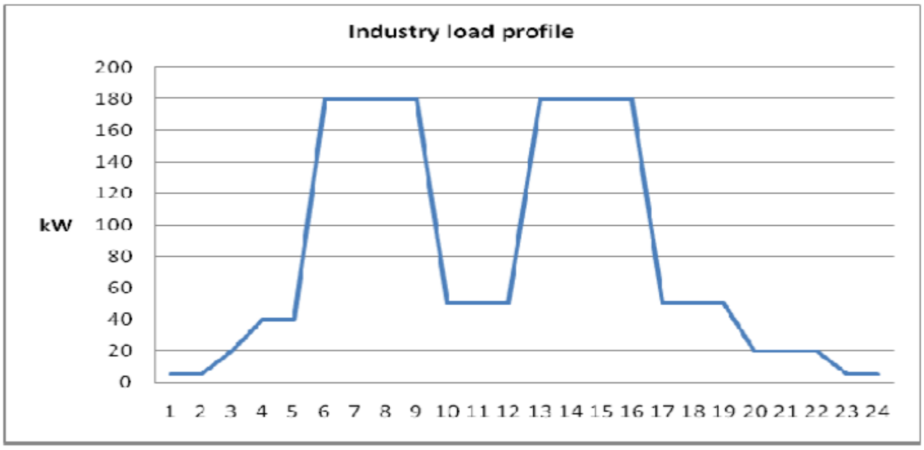

FIGURE 14 – TYPICAL LOAD PROFILE FOR LARGE INDUSTRY

Source: Active Networks Demand Side Management and Voltage Control, Jayanth Krishnappa

Definitions

Some definitions are used to quantify the demand of a distribution system. These include:

Load factor – The ratio of the average load over the peak load. The load factor value is between zero and one. A load factor close to one means an almost constant demand. Residential loads tend to have a lower load factor than commercial or industrial loads. It can be calculated through the total energy used:

$$Load\ factor = \frac{kWh}{Peak_{demand} * h} \qquad 11$$

Where:

kWh is the total energy consumed, commonly measured in kilowatt-hour

Peak demand is the total peak demand in kilowatts

h is the number of hours of the time interval

Coincidence Factor – The ratio of the peak demand of an entire system over the sum of individual peak demands within the same system:

$$cf = \frac{Peak_{system}}{\sum_{i=1}^{n} Load_{peak_i}} \qquad 12$$

Where:

n is the number of customers

Peak system is the peak demand of the distribution system

Load peak is the peak demand of the individual load

Diversity Factor – This is the reciprocal of the coincidence factor. If coincidence factor increases, diversity factor decreases and vice-versa. It is therefore given by:

$$df = \frac{\sum_{i=1}^{n} Load_{peak_i}}{Peak_{system}} \qquad 13$$

Responsibility factor – The ratio between load demand at the time of system peak, over the load peak demand. A responsibility factor equal to one means that the load has a peak demand at the same time of the system peak demand.

There are several studies about the relation between the coincidence factor and the number of customers on a distribution system. An example is the Nickel and Braunstein method (1981) which correlates the coincidence factor c with the number of customers (n) through the following formula:

$$c = \frac{1}{2}\left(1 + \frac{5}{2n+3}\right) \qquad 14$$

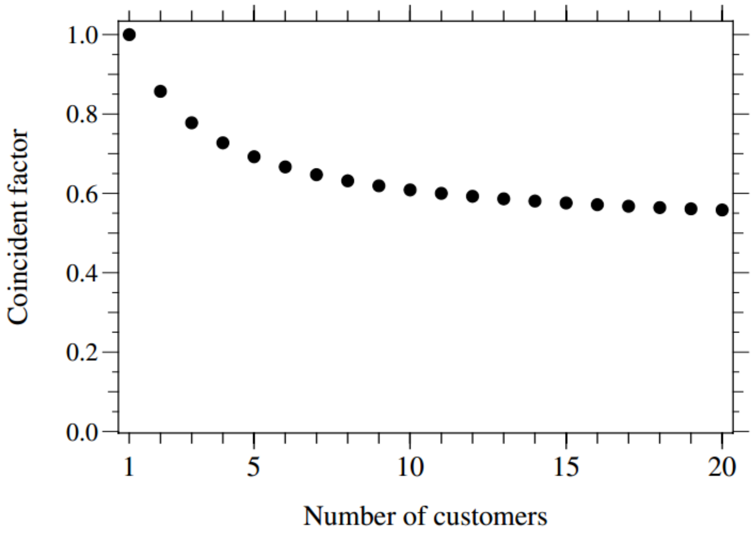

FIGURE 15 – COINCIDENCE FACTOR AS A FUNCTION OF THE NUMBER OF CUSTOMERS

Source: Residential Load Models for Network Planning Purposes, J. Dickert, P. Schegner

For the residential customer types considered in this work, the following coincidence factor values will be used:

Customer type	Maximum Power per customer (kW)	Coincidence factor	Maximum power of 100 customers (kW)
basic	4..6	0,10..0,20	76..168
Partly-electric	5..11	0,10..0,15	95..259
Fully-electric (boiler)	8..12	0,10..0,20	152..336
Fully-electric (flow-type)	30..35	0,05..0,07	435..571
All-electric	25..35	0,70..0,80	1843..2580

TABLE 9 – COINCIDENCE FACTORS AND POWER DEMAND PER CUSTOMER TYPE

2.4 Future Possibilities for Distribution

2.4.1 DC Distribution

In the early stages of electricity distribution, direct current generators were connected to loads at the same voltage. Thus, the generation, transmission and distribution systems had to be of the same voltage, because the voltage could not be changed in DC.

For this reason and also to avoid voltage drop related problems along the line, the required voltage for consumption was not high, because the primary loads were incandescent lamps. This low voltage was a disadvantage concerning power transport, because when the power needed by the loads increase, the current also increase, thus increases the power losses along the line, which are proportional to the square of the current and the resistance of the conductor. Also, large currents require large conductors, which also increases costs. A possible solution would be to increase the voltage level to reduce the current and conductor size, but as mentioned this is not possible in DC. To keep costs within acceptable values, the distances between generators and customers could not be too long. It is also important to note that early DC generators had less efficiency than AC generators, which also contributed to an increase in power losses.

Thus, the electrification system gradually changed to AC, to deliver electricity to customers, which is used to power up many different types of home appliances including electronic devices, electrical machines, heaters, lightning and even to charge batteries. In distribution systems, the use of AC over DC has its advantages, such as:

1) It is much easier to step up or step down the voltage in AC rather than DC, through the use of transformers. To perform the same step up or down in DC first an inverter is needed to convert the DC to AC, after that, a transformer would be used to change the voltage in AC and finally and rectifier to convert from AC back to DC.
2) The ability to reduce energy losses during transport (transmission more significant than distribution) by stepping up the voltage to high levels and therefore minimizing the current flowing through the line.

Today, many different areas of engineering use DC systems. It is used in telecommunication systems, electric traction (trains), electric and/or hybrid automobiles and even on ships with electric propulsion. The reason why DC motors are largely used in electric transports is because it is easy to control its speed, by changing its series resistance. Direct current is also used in electric power transmission, in HVDC systems. This type of transmission system has some advantages over AC transmission, regarding power transmission through long distances (several miles), and the possibility of doing so through underground and underwater cables. Also, another important advantage of HVDC systems is the possibility of connecting two AC power systems of different frequency each. Therefore, DC has obviously a great potential, and it could also be used in distribution systems.

Although at its early stages the distribution systems were DC systems, they were gradually changing and today most of them are AC systems. In AC systems the voltage level can be “stepped up” or “stepped down”, only using transformers, which is an advantage over DC systems. In DC it is not possible to change the voltage level, and to do so it would require converters and rectifiers, to convert from DC to AC, change the voltage level in AC through transformers, and rectify from AC back to DC. By stepping up the voltage to high values, it is possible to transmit power through much longer distances, with minimal resistive losses, which is not possible with conventional DC (not HVDC). Thus, the main reason why AC was chosen for distribution systems instead of DC is the possibility of changing the voltage level.

Even so there are several strong arguments that support the use of DC in distribution systems, including:

High reliability – If there is a disturbance in power transmission, a DC distribution system can be disconnected from the main supply grid and continue to operate as an electric island, by supplying the loads with local energy storage, just like a laptop do when power supply fails. This type of network design follows the concept of “Microgrids”. In this concept, small communities of loads become self-sustainable, through the inclusion of DG on their local grid. A microgrid generates, distributes and regulates the flow of electricity to its customers. They are ideal for the inclusion of DG in distribution systems and to allow the customer participation in the energy market – which is one goal to achieve in the future smart grid. [8]

DC loads – Almost all existing distribution systems use AC to deliver power. Consequently, electrical appliances and equipment are designed to operate with AC. However many of them can operate in DC as well. This is the case of variable-speed drive (VSD) and variable-frequency drive (VFD), used to control AC rotating loads, such as induction motors. These drives use an internal bridge rectifier to convert from an AC supply voltage to a DC voltage. Also, all electronic devices such as computers, LCD TV, battery charger, telecommunication devices and fluorescent lamps with electronic ballast are supplied with AC but they use rectifiers to produce a DC in their internal circuits. There are loads however, that cannot be supplied with DC. These include loads which use a virtual phase created by a reactive component to have a rotating magnetic field. An example of such load is an AC motor. Loads with inductive parts cannot be supplied with DC, because DC creates a constant increasing current through them. Also loads with mechanical breakers designed to operate with AC voltages cannot be supplied with DC, because the breaker would be destroyed when breaking DC due to the absence of current cross-zeros in DC. [9]

Power generation – The number of alternative power sources connected to distribution systems – distributed generation - is actually increasing. Popular ones, such as fuel cell (electric automobile) and photovoltaic technology (solar panels) have a DC output. Therefore a DC to AC converter is needed when this types of power sources are used in distribution systems. If instead of AC, they could connect to a DC system, no converter would be needed anymore. Microturbines are another type of power source that can be connected to distribution systems. This technology can be used as to supply electricity and it can also be used as a heat source, to produce hot water or heat a building space. Similar to motor drives, microturbines also first use a rectifier to convert a high frequency AC to DC, and then an inverter to convert from a high frequency DC to 60Hz (USA) or 50Hz (Europe and Asia) AC. Just like other distributed power sources, microturbines could benefit from the connection to a DC system, since it wouldn't require the final inverter. Wind turbines can also be connected to distribution systems. They produce an AC output, but they also use a rectifier to create a DC internally, before it is converted to the AC again. The reason they use an internal converter is the power output of the turbine, which can be maximized if the speed of the turbine is allowed to change with the wind (though it should not exceed a safe limit). Thus the frequency will vary, but the power output of the turbine has to be synchronized with the grid frequency and this is why they use a rectifier and inverter. Again the inverter could be dismissed if they connect to a DC system instead. Just like wind turbines, hydro and tidal generators also operate with variable speed to produce electricity. [9]

Energy Storage – Uninterruptable power supply systems (UPS) are used to supply loads in AC systems. They store DC internally, but they are supplied with AC from the grid. Therefore they first require a rectifier to convert from AC to DC, to charge the internal battery in DC, and last an inverter converts from DC to AC again, to supply the load. In this case the two converters and the battery are in series with the load.

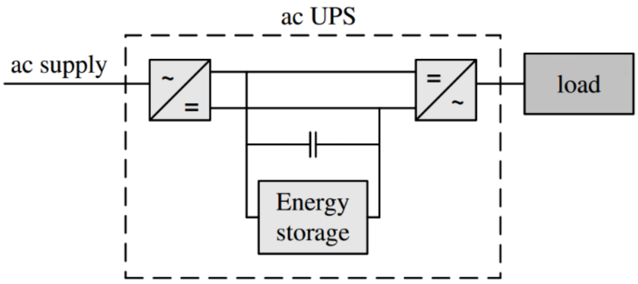

FIGURE 16 – TYPICAL AC UPS SYSTEM

Source: DC Distribution Systems, Daniel Nilsson

If the supply grid would be a DC system, only one parallel DC/DC converter would be required.

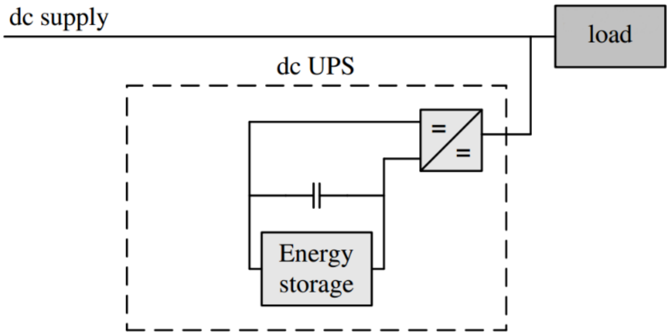

FIGURE 17 – A DC UPS SYSTEM

Source: DC Distribution Systems, Daniel Nilsson

Reducing the number of converters used for supplying the distribution system or the loads has two benefits: first it is more economical, as it reduces the costs associated with equipment and maintenance, and second, it increases efficiency, by reducing conversion losses. [9]

Higher Voltage Level Available – The DC power systems grounding arrangement allows the use of a higher voltage level than AC systems. According to the European Union directive 2006/95/EC, the DC system voltage is defined to be between 75 to 1500 VDC, while AC system voltage is between 50 to 1000V. A higher voltage level can be useful to avoid undervoltage or feeder overload problems, as will be seen further. [10]

Future Distribution Loads – Another important factor that supports the idea of a DC distribution system is the emergence of new DC type loads, such as the electric vehicle, which relies on DC power to charge its batteries. The actual EV technology includes an on-board AC/DC converter to charge the batteries. In a DC distribution system this converter would no longer be required, decreasing power losses, vehicle height and most important, vehicle cost for the consumer. [11]

2.4.2 Single vs. Two vs. Three-phase system

The number of phases used for power distribution is another important parameter that characterizes a power system. This parameter differs between European and American distribution systems.

In Europe, a distribution system is usually a three-phase system. [4] Three-wire cables are used for primary feeders (delta connection), and four-wire cables for secondary feeders (wye connection). In North America four-wire, multigrounded cables are used for primary feeders, carrying three-phases, and two-wire cables for secondary feeders, carrying a single-phase only.

Using three-phase secondary feeders (Europe) has an important advantage against single-phase secondary feeders (North America), regarding the voltage drop and the power losses. In a completely balanced AC system, the current flows from the source towards the load, and then comes back from the load to the source. As the current flows, there are power losses and a voltage drop associated. The advantage of the first case is that these power losses and the voltage drop only occurs while the current flows from the source towards the load, while in the second case, there are power losses and voltage drop on both directions of the current flow. Therefore, a three-phase secondary feeder has less power losses and voltage drop than a single-phase secondary feeder. The main disadvantage of three-phase feeders is the initial high cost when compared to single-phase feeders, which use only two conductors, one neutral and one phase, instead of three (delta-connection) or four (wye-connection) conductors used in three-phase feeders.

There are also single-phase and two-phase distribution systems, although these are not as common as three-phase systems.

In a two-phase (or split-phase) system there are two separated phases. It uses three-wire or two-wire cables, depending if a neutral conductor is present or not, respectively. Two-phase systems are usually used to supply rural areas (farms) without three-phase machinery or small neighborhoods when only two phases are available from a three-phase system.

The number of phases used in a power system has a strong influence over the voltage supply. A single-phase system is more vulnerable to small voltage drops than a two or three-phase system. This is due to the fact that most faults are single-phase. However a three-phase system is no better than a single-phase system when it comes to severe voltage drops, resulting in service interruptions, which are mostly three-phase. Recent studies [12] shown that most of severe voltage drops (below 20% of nominal operating voltage) are more often to occur in three-phase systems, while small-to-medium voltage drops (from 85% to 25% of nominal operating voltage) are more often to occur in single-phase systems.

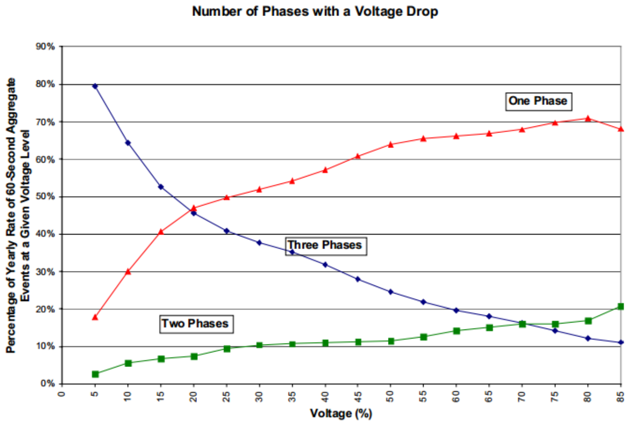

FIGURE 18 – RELATION BETWEEN RATE OF OCCURRENCE AND VOLTAGE LEVEL FOR SINGLE, TWO AND THREE-PHASE SYSTEMS

Source: Distribution System Power Quality Assessment: Phase II, Voltage Sag and Interruption Analysis, EPRI

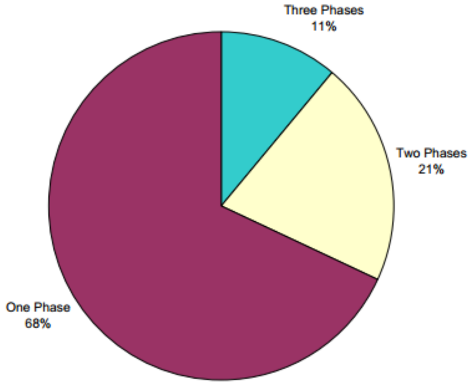

FIGURE 19 – NUMBER OF PHASES ASSOCIATED WITH A VOLTAGE DROP TO 85%

Source: Distribution System Power Quality Assessment: Phase II, Voltage Sag and Interruption Analysis, EPRI

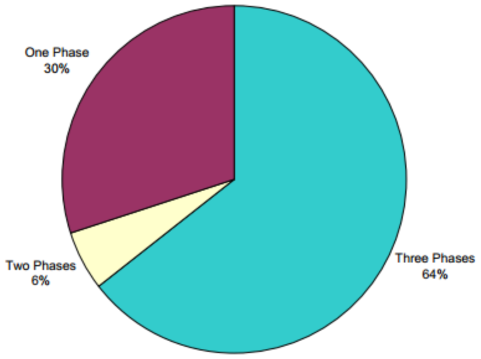

FIGURE 20 – NUMBER OF PHASES ASSOCIATED WITH A VOLTAGE DROP TO 20%

Source: Distribution System Power Quality Assessment: Phase II, Voltage Sag and Interruption Analysis, EPRI

Wye vs. Delta connection

In a three-phase system the phases can be arranged in two possible designs: the wye connection and the delta connection. The difference between the two is the presence of a fourth, neutral conductor in the wye connection. In this neutral conductor usually both the voltage and the current are close to zero. A wye connection can be changed to a delta connection (or vice-versa) through a transformer. Each transformer winding can be either wye connected or delta connected. Therefore there are four different types of transformers regarding the type of connection used: delta-delta, wye-wye, delta-wye and wye-delta.

The substation transformer used to connect a transmission system to a distribution system is commonly a delta-wye transformer, with a delta connection on the transmission side and a wye connection on the distribution side, respectively. There are two major reasons for such arrangement. On the transmission side, almost all electric power transmission is performed using three-phases only, using a delta-connection. On the distribution side, much of the load connected is single-phase, which means that distribution systems need a neutral conductor to connect the loads.

In terms of voltage drop and power losses, both the wye and the delta connection are equivalent, considering that power flow is balanced. Despite that, there are economical differences between them. Theoretically speaking, a delta connection would be less expensive than a wye connection because it uses only three conductors, where a wye connection uses four. However, a distribution system using wye-connected lines would cost less than the same system using delta-connected lines. In a delta-connected systems require expensive transformers and equipment than those used in wye-connected systems. This is another reason why distribution systems are commonly wye-connected instead of delta-connected.

2.4.3 Smart Metering System

A smart meter is a device that is capable of reading, recording and reporting consumption data from a customer to the distribution utility. The smart meter also allows accurate and reliable data to be read remotely, allowing the utility to have access to accurate knowledge about the power consumption per customer.

FIGURE 21 – SMART METER

Source: http://cdn.greenconduct.com/news/files/2013/03/smartgrid.jpg

Besides communication, a smart metering system could also provide some control over the demand, by automatically switching ON and OFF certain loads at specific times for schedule purposes. This measure could improve the system's load balancing and voltage regulation, as well as reduce the utility's costs regarding power reserves.

2.4.4 Voltage Level Used

Another possibility for future distribution is the use of a higher voltage level on secondary circuits, between distribution transformers and the loads. Rising the voltage could bring some benefits. First, it reduces the line overload during peak demands, if power is kept constant. Reducing the feeders overload also reduces losses and costs for the utility. Second, it can be used to solve voltage regulation problems, when only the feeder voltage is increased, but not the supply voltage at the load. In this case, even if the drop below the lower limit, it would still be above the required level for the customer.

An increase in the voltage supply could lead a distribution system into two different directions: the load being supplied by the higher voltage, or the load still being supplied by the standard voltage value (230/400V in Europe), which means an extra transformer per customer, to step down the voltage. Considering the actual systems and existing loads, the second hypothesis is the only one feasible at the moment. In future distribution systems this could probably change, if new loads are designed to operate with higher voltages.

2.4.5 Demand Side Management

The Demand Side Management (DSM) approach is an alternative to technical solutions, that aims to change the consumer habits regarding power consumption, through many different ways, including financial incentives (lower energy taxes during specific low demand periods) and through education.

Despite its positive goals, DSM may cause several problems for utilities and customers as well, including increased costs, loss of revenues and diminished profits for the utilities, and consequently, higher taxes for customers during peak times. [13]

2.4.6 Conductor upgrades

It is also important to mention the traditional approaches to solve overload and voltage drop due to the feeder impedances. Increasing the feeder cross-section reduces the feeder impedance, while the installation of more feeders in parallel reduce the current overload, since the current is divided for each feeder (Kirchhoff's Law). There are situations in a distribution system when upgrading conductors may be justified as the best cost-effective solution, such as some overload in short feeder segments during short intervals of time.

2.4.7 Energy Storage

One of today's greatest concerns in the energy sector is the way energy is produced, consumed and what environmental impacts it has during the process. Thus, in the customer side, it is important to have efficient distribution systems, capable of properly manage the power consumption, in an efficient way, always minimizing power losses. Storing excess power generated for later consumption might be one solution for this concern, reducing the total power generated and thus reducing CO2 emissions.

In In distribution systems the energy is stored using batteries. There are many different types of batteries for use in power distribution systems [14]. A battery is capable of storing energy from an AC source, and deliver it when it is required as a DC source of energy. They may include a DC/AC converter to supply AC energy. This power saving strategy has been under study for a few years, and results show that it provides an effective power flow control in distribution systems. [15]

2.4.8 FACTS in distribution

In transmission systems, where electric currents usually have to travel several kilometers from the power source until they reach the load, voltage control is performed using static equipment, which regulate specific AC transmission parameters, such as the line impedance, and thus providing better controllability and power transfer capability in these systems. These equipment are called flexible AC transmission systems – or FACTS – and may be composed by inductors, capacitors and some power electronics devices, such as diodes, switches and thyristors. When applied in power systems, FACTS may provide series or shunt compensation, depending on the purpose of its application. If the objective is to reduce line impedance, in order to improve the voltage profile, for e.g. in a long line where a large current flows and there is a large voltage drop, then series compensators must be applied. There are different types of series compensation:

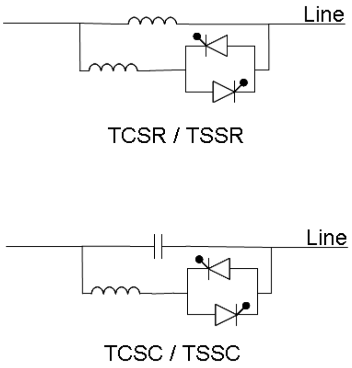

FIGURE 22 – TYPES OF SERIES COMPENSATION USING FACTS

Source: http://en.wikipedia.org/wiki/File:FACTS_series_compensation1.PNG

- Thyristor-controlled series capacitor (TCSC): a series capacitor bank is shunted by a thyristor-controlled reactor
- Thyristor-controlled series reactor (TCSR): a series reactor bank is shunted by a thyristor-controlled reactor
- Thyristor-switched series capacitor (TSSC): a series capacitor bank is shunted by a thyristor-switched reactor
- Thyristor-switched series reactor (TSSR): a series reactor bank is shunted by a thyristor-switched reactor

If, on the other hand, the objective is to perform power factor correction – or reactive power regulation – then shunt compensation should be applied. Examples of shunt compensation may include:

- Static synchronous compensator (STATCOM); previously known as a static condenser (STATCON)
- Static VAR compensator (SVC). Most common SVCs are:

i. Thyristor-controlled reactor (TCR): reactor is connected in series with a bidirectional thyristor valve. The thyristor valve is phase-controlled. Equivalent reactance is varied continuously.

ii. Thyristor-switched reactor (TSR): Same as TCR but thyristor is either in zero- or full- conduction. Equivalent reactance is varied in stepwise manner.

iii. Thyristor-switched capacitor (TSC): capacitor is connected in series with a bidirectional thyristor valve. Thyristor is either in zero- or full-conduction. Equivalent reactance is varied in stepwise manner.

iv. Mechanically-switched capacitor (MSC): capacitor is switched by circuit-breaker. It aims at compensating steady state reactive power. It is switched only a few times a day.

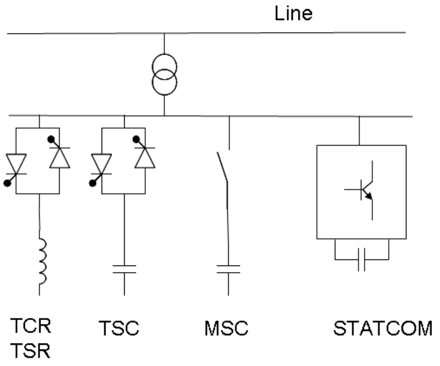

FIGURE 23 – TYPES OF SHUNT COMPENSATION USING FACTS

Source: http://en.wikipedia.org/wiki/File:FACTS_series_compensation1.PNG

Static VAR compensators (SVC) are electrical devices composed by one or more banks of either fixed or switched shunt capacitors and reactors, where at least one bank is controlled by thyristors. Like other compensators, the SVC are also used to generate or consume reactive power from the grid. However, unlike synchronous compensators, SVC don’t have mechanical moving parts and hence the name of static compensators. The following figure shows five basic SVC topologies, composed by the elements described above:

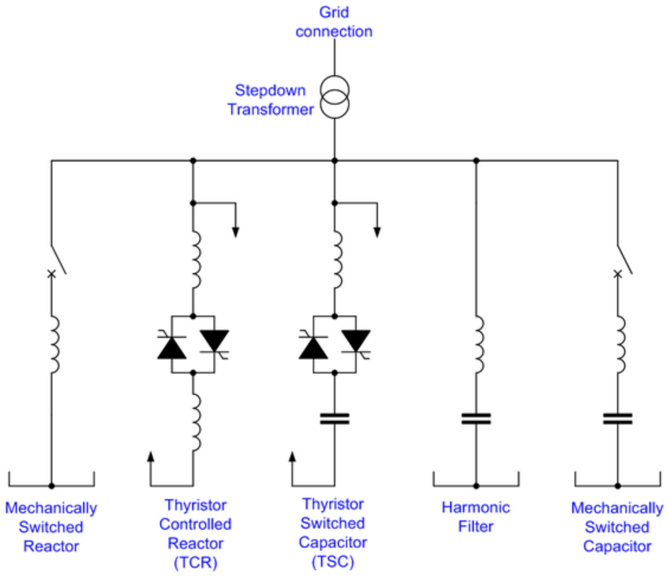

FIGURE 24 – DIFFERENT TOPOLOGIES FOR STATIC VAR COMPENSATORS

When compared to SC, SVC has two important advantages:

- A faster response. After a disturbance, SVC takes less time than SC to reestablish the voltage level.
- Unlike the SC, the SVC doesn’t increase short-circuit current.

2.5 Case study

In this case study the effects of load modeling are analyzed. Different load models are used, including the common static load models, to demonstrate their influence on voltage regulation in distribution systems. The initial scenario for this case study will consist on a radial system, with only one feeder. This system is built using the software DigSilent PowerFactory, version 14. This software calculates the load flow using the Newton-Raphson method. Different system designs will only be used later, in chapter 3's case study.

The distribution system used in this case study is shown next. It's a three-phase radial system, unbalanced, with 19 nodes and 18 segments of cable, each with 30 meters of length. The feeder connects 18 single-phase loads, all-electric type, connected in parallel, each consuming 35 kW with a power factor of 0,93. This can be considered a high demand scenario. The feeding point (distribution transformer) is assumed to be on node 1, which is a slack node. The reference voltage is considered to be 400V=1p.u. The admissible voltage limits are set to ±10% of the reference voltage.

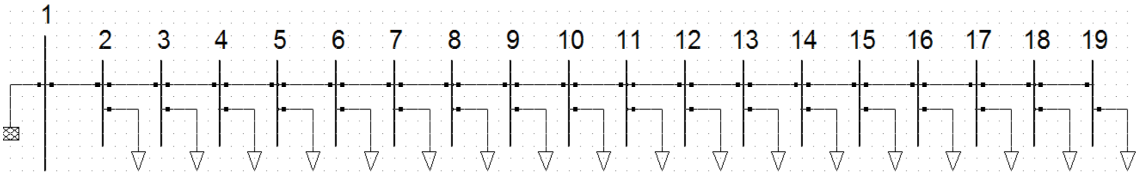

FIGURE 25 – SINGLE RADIAL DISTRIBUTION SYSTEM

The following data was used for simulation:

Distribution feeder – cable used	NAYY-J 4X150SE; R=0,206Ω/Km; X=0,08Ω/Km; $V_{\text{rated}} = 1kV$; $I_{\text{rated}} = 270A$; $f = 50Hz$; Underground cable; Three-phase with neutral (4 wires conductors); Total length= 540 m
Loads (each)	All-Electric type; Three-phase; 35 kW, pf=0,93; Coincidence factor=0,85;

TABLE 10 – SIMULATION DATA

Results

Using the software capabilities, the system was balanced before the load flow calculation. The voltage values are average values, considering the values for each phase. Each load model was compared regarding how each affect the voltage drop.

	Constant Power		Constant Current			
Terminal	Line-Neutral Voltage (V)	Voltage (p.u.)	Line-Neutral Voltage (V)	Voltage (p.u.)	Difference (V)	Difference (p.u.)
1	230,94	1,00	230,94	1,00	0	0
2	223,45	0,97	225,43	0,98	1,98	0,01
3	216,28	0,94	220,22	0,95	3,94	0,01
4	209,45	0,91	215,32	0,93	5,87	0,02
5	202,95	0,88	210,72	0,91	7,77	0,03
6	196,79	0,85	206,44	0,89	9,65	0,04
7	191,01	0,83	202,45	0,88	11,44	0,05
8	185,59	0,80	198,78	0,86	13,19	0,06
9	175,50	0,76	192,04	0,83	16,54	0,07
10	170,91	0,74	188,98	0,82	18,07	0,08
11	166,70	0,72	186,22	0,81	19,52	0,09
12	162,91	0,71	183,77	0,80	20,86	0,09
13	159,62	0,69	181,63	0,79	22,01	0,1
14	156,73	0,68	179,79	0,78	23,06	0,1
15	154,27	0,67	178,27	0,77	24	0,1
16	150,47	0,65	175,82	0,76	25,35	0,11
17	149,00	0,65	174,90	0,76	25,9	0,11
18	147,95	0,64	174,29	0,75	26,34	0,11
19	147,34	0,64	173,98	0,75	26,64	0,11

TABLE 11 – COMPARISON BETWEEN CONSTANT POWER AND CONSTANT CURRENT MODEL

	Constant Power		Constant Impedance			
Terminal	Line-Neutral Voltage (V)	Voltage (p.u.)	Line-Neutral Voltage (V)	Voltage (p.u.)	Difference (V)	Difference (p.u.)
1	230,94	1,00	230,94	1,00	0	0
2	223,45	0,97	226,20	0,98	2,75	0,01
3	216,28	0,94	221,76	0,96	5,48	0,02
4	209,45	0,91	217,61	0,94	8,16	0,03
5	202,95	0,88	213,75	0,93	10,8	0,05
6	196,79	0,85	210,18	0,91	13,39	0,06
7	191,01	0,83	206,88	0,90	15,87	0,07
8	185,59	0,80	203,86	0,88	18,27	0,08
9	175,50	0,76	198,36	0,86	22,86	0,1
10	170,91	0,74	195,87	0,85	24,96	0,11
11	166,70	0,72	193,63	0,84	26,93	0,12
12	162,91	0,71	191,66	0,83	28,75	0,12
13	159,62	0,69	189,94	0,82	30,32	0,13
14	156,73	0,68	188,47	0,82	31,74	0,14
15	154,27	0,67	187,25	0,81	32,98	0,14
16	150,47	0,65	185,31	0,80	34,84	0,15
17	149,00	0,65	184,58	0,80	35,58	0,15
18	147,95	0,64	184,09	0,80	36,14	0,16
19	147,34	0,64	183,85	0,80	36,51	0,16

TABLE 12 – COMPARISON BETWEEN CONSTANT POWER AND CONSTANT IMPEDANCE MODEL

	Constant Current		Constant Impedance			
Terminal	Line-Neutral Voltage (V)	Voltage (p.u.)	Line-Neutral Voltage (V)	Voltage (p.u.)	Difference (V)	Difference (p.u.)
1	230,94	1,00	230,94	1,00	0	0
2	225,43	0,98	226,20	0,98	0,77	0
3	220,22	0,95	221,76	0,96	1,54	0,01
4	215,32	0,93	217,61	0,94	2,29	0,01
5	210,72	0,91	213,75	0,93	3,03	0,02
6	206,44	0,89	210,18	0,91	3,74	0,02
7	202,45	0,88	206,88	0,90	4,43	0,02
8	198,78	0,86	203,86	0,88	5,08	0,02
9	192,04	0,83	198,36	0,86	6,32	0,03
10	188,98	0,82	195,87	0,85	6,89	0,03
11	186,22	0,81	193,63	0,84	7,41	0,03
12	183,77	0,80	191,66	0,83	7,89	0,03
13	181,63	0,79	189,94	0,82	8,31	0,03
14	179,79	0,78	188,47	0,82	8,68	0,04
15	178,27	0,77	187,25	0,81	8,98	0,04
16	175,82	0,76	185,31	0,80	9,49	0,04
17	174,90	0,76	184,58	0,80	9,68	0,04
18	174,29	0,75	184,09	0,80	9,8	0,05
19	173,98	0,75	183,85	0,80	9,87	0,05

TABLE 13 – COMPARISON BETWEEN CONSTANT CURRENT AND CONSTANT IMPEDANCE MODEL

Tables 10, 11 and 12 compare the load flow solutions obtained for different static load models. The voltage profiles along the main feeder for each case, as well as the voltage difference are shown next. A red line shows the lower acceptable limit for the voltage level.

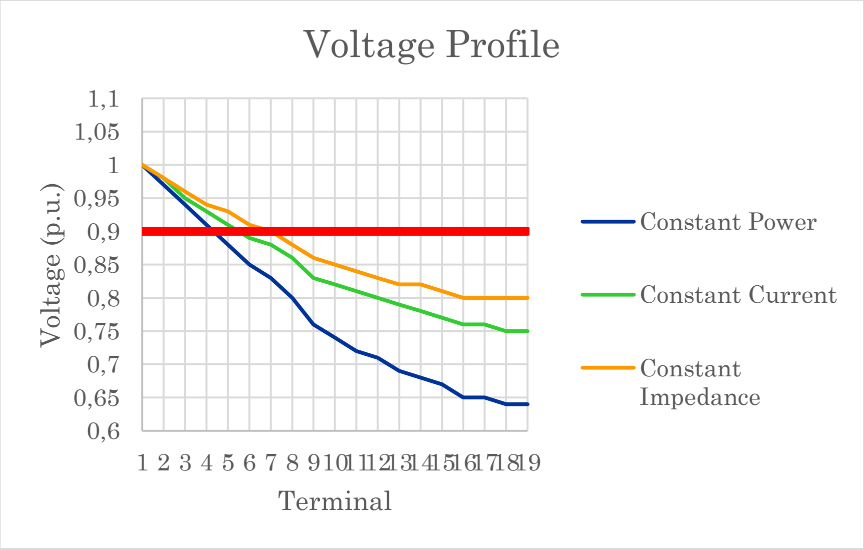

FIGURE 26 – VOLTAGE PROFILE FOR EACH STANDARD LOAD MODEL

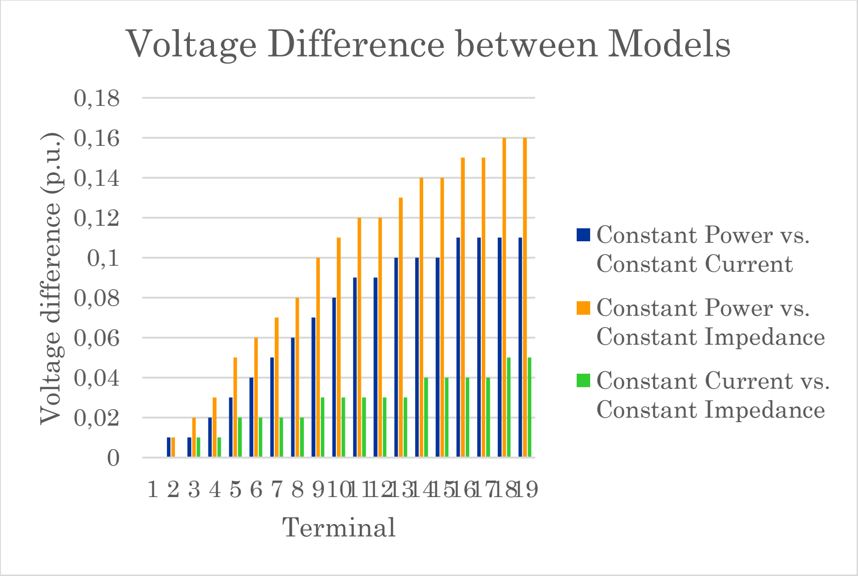

FIGURE 27 – VOLTAGE DIFFERENCE BETWEEN EACH STANDARD LOAD MODEL

As can be seen in Tables 10, 11 and 12, different load models result in different load flow solutions, as expected. The difference between the solutions increases with the distance from the substation. These differences in voltage may lead to significantly different design approaches in a distribution system. Hence, proper load models should be considered in order to obtain more accurate results.

Voltage Regulation

Once a load flow solution is obtained, the voltage regulation at the end of a feeder can be calculated as follows: [16]

$$V_{regulation} = \left| \frac{V_{nl} - V_{fl}}{V_{fl}} \right| * 100\% \qquad 15$$

Where V_{nl} and V_{fl} are the voltage levels measured in p.u. in the receiving end of the feeder, at no-load and full-load, respectively. Table 13 shows the result of applying the above expression to each standard load model, considering as the sender the transformer and as the receiver the last load along the feeder.

Load model	Voltage regulation required
Constant Power	56,25%
Constant Current	33,33%
Constant Impedance	25,00%

TABLE 14 – VOLTAGE REGULATION REQUIRED FOR EACH STANDARD LOAD MODEL

The voltage drop for constant power load models is the highest of all loads models, as one would expect, since power demand does not change with voltage variations, while in other models the power demand decreases as the voltage goes down.

It is also important to consider, for each load model, the total load demand and total losses on the feeder when the supply voltage level changes within the acceptable range of values. These measurements tells how systems with different loads are affected when there is some type of voltage regulation. The results are shown next.

	Constant Power			Constant Current			Constant Impedance		
Supply voltage	Total power demand (kW)	Total power loss (kW)	$\frac{P_{loss}}{P_{demand}}$	Total power demand (kW)	Total power loss (kW)	$\frac{P_{loss}}{P_{demand}}$	Total power demand (kW)	Total power loss (kW)	$\frac{P_{loss}}{P_{demand}}$
0,9	583,31	18,75	3,21%	411,65	9,34	2,27%	328,41	5,94	1,81%
0,95	563,54	15,70	2,79%	434,75	9,35	2,15%	365,91	6,62	1,81%
1	548,55	13,43	2,45%	457,82	9,36	2,04%	405,44	7,34	1,81%
1,05	536,83	11,67	2,17%	480,88	9,36	1,95%	447	8,09	1,81%
1,1	527,44	10,26	1,95%	503,93	9,37	1,86%	490,58	8,88	1,81%

TABLE 15 – TOTAL LOAD DEMAND, POWER LOSSES AND POWER RATIO FOR EACH STANDARD LOAD MODEL

The above table shows that different load models have different effects on the system power demand and power losses.

1) For power systems with constant power loads, the power demand and the power losses decrease with the increase of the supply voltage. Therefore in this case, in order to minimize both, the system should operate at a higher voltage level, without exceeding the limits.
2) For a power system composed mainly of constant current loads, the power demand and the power losses are almost not affected with the supply voltage change.
3) For a power system composed mainly of constant impedance loads, both the power demand and power losses will increase with the increase of supply voltage, keeping the relation between losses and demand constant. This means that, in this case, in order to minimize losses, the system should operate at a lower voltage level, without exceeding the limits.

Thus, since a distribution system is composed by a mixed type of load, the characteristic of the mixed loads should be thoroughly investigated in order to find the optimum operating voltage of the system.

2.6 Conclusions

This chapter began with the introduction of the concept of a distribution system, as a part of the power grid, which delivers electricity from the transmission system to the final customer. Although the idea is simple, such systems can be complex while operating, as they are used to connect the most unpredictable type of load to the power grid – the residential customer. Thus, planning a distribution system is not a simple task. There are several considerations that must be taken to meet the purposes of distribution. Several parameters have to be analyzed, not only regarding the technology used but also the load type and behavior. In fact, a good planning should start from the load modelling. The chapter ends with many possibilities for future distribution systems, to address some of the common problems of today`s systems.

The next chapter introduces the main subject of the work, the voltage control on distribution system. A base load will be modelled using the polynomial model, and used for the system planning.

Chapter 3

Voltage Control in Distribution Systems

This chapter focuses in the electrical voltage, how it behaves in a conventional distribution system and how it can and must be controlled in such systems. It starts with an introduction to the voltage drop, which is important to consider when planning distribution systems, and therefore relevant for this chapter subject. The effect of voltage drop must be always minimized. To address this issue there are many solutions including mechanisms to control the voltage or the reactive power. The three more common mechanisms will be presented and discussed, as well as brief overview to some other basic methods to improve voltage regulation. This chapter also introduces the distributed generation and electric vehicle subject. Different technologies are briefly overviewed, as an introduction to each subject, as well as the impact of these technologies on distribution systems. At the end of the chapter all the presented solutions are compared and evaluated through a case study in order to simulate and collect results. Different systems with different loads will be considered in this case study, as wells as systems with DG and EV present.

3.1 Introduction

The main purpose of voltage regulation in a distribution system is to keep the steady state voltage level within an acceptable range all time. This control can be obtained by directly adjusting the voltage level on the secondary side, through a voltage regulation unit (VRU), by controlling the reactive power flow – power factor correction - which, as a consequence, will also affect the voltage level, by reducing the load current in the feeders or by reducing the series resistance and reactance of the feeders. Until now, European MV and LV power systems usually did not require VRU's, and therefore the HV/MV transformer was the last VRU in the power supply, before it reaches the load [17]. However this situation is currently changing, with the development and high penetration of renewable energy sources into distribution systems, and the emergence of new loads, such as the electric vehicle, which causes voltage fluctuations and inversion of power flow, resulting in VRU's now being required in MV and LV systems as well. There are many possibilities for the VRU's installation, depending on the voltage problem. If it is a long-range voltage disturb, the VRU should be implemented in the MV feeder. On the other hand, if the voltage problem is located at a specific point on the LV system, then the VRU should be placed near it, or at the MV/LV substation.

There are different types of VRU's. These include On-Load Tap-Changer (OLTC) transformers, automatic – or electronic - voltage regulators (VR) which control the voltage level directly [18]. There are also passive or indirect VRU's, which do not control the voltage directly, but the system reactive power flow instead. These include shunt-capacitors, static VAr compensators, synchronous condensers, or even static synchronous compensators (STATCOM). By controlling the reactive power flow on the system, the voltage level is regulated as well. [19]

3.2 Voltage drop and its impact on distribution

Voltage Drop

In an electrical circuit the voltage drop between two points in a feeder is given by the difference between the emitter voltage Ve and the receiver voltage Vr.

$$\Delta V = V_{\mathrm{e}} - V_{\mathrm{r}} \tag{16}$$

Considering a distribution line where Ve and Vr represent the voltage level at the substation and at the load respectively. The substation delivers a specific voltage value which will be represented by Ve. On the other end of the line, the load receives a different voltage level which will be represented by Vr. The line should always have a longitudinal impedance, which value is related to its length.

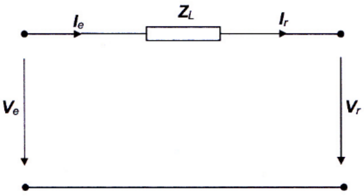

FIGURE 28 – SHORT LINE EQUIVALENT CIRCUIT

Source: Redes de Energia Eléctrica, Uma Análise Sistémica, José Pedro Sucena Paiva

In distribution systems the electrical power is complex, which means the loads have an active as well as a reactive power consumption. Also, the line impedance have a real part which refers to the electrical resistance and an imaginary part which refers to the electrical reactance of the line.

$$\begin{gathered} S_{\mathrm{r}} = P_{\mathrm{r}} + jQ_{\mathrm{r}} \\ Z_{\mathrm{L}} = R_{\mathrm{L}} + jX_{\mathrm{L}} \end{gathered} \tag{17}$$

Where S_{r} , P_{r} and Q_{r} refers to the apparent, active and reactive power consumed by the load, respectively, and $Z_{\mathrm{L}}, R_{\mathrm{L}}, X_{\mathrm{L}}$ refers to the line complex impedance, line impedance real part and line impedance imaginary part respectively. Therefore the current at the load is given by:

$$P_\mathrm{r} + jQ_\mathrm{r} = V_\mathrm{r} I^* \tag{18}$$

The complex current has two parts, the resistive current and the reactive current.

$$I^* = |I| * (\cos\phi + j\sin\phi) \tag{19}$$

Considering the voltage at the load as the reference voltage, the argument of the complex current becomes zero which means the current doesn't have an imaginary part.

$$I = \frac{P_\mathrm{r} + jQ_\mathrm{r}}{V_\mathrm{r}}$$

And therefore, using the Kirchhoff Law, the voltage at the substation Ve is given by:

$$V_\mathrm{e} = V_\mathrm{r} + Z_\mathrm{L} I \Leftrightarrow V_\mathrm{e} = V_\mathrm{r} + (R_\mathrm{L} + jX_\mathrm{L}) I$$

$$V_\mathrm{e} = V_\mathrm{r} + (R_\mathrm{L} + jX_\mathrm{L}) \left(\frac{P_\mathrm{r} + jQ_\mathrm{r}}{V_\mathrm{r}}\right) \Leftrightarrow V_\mathrm{e} = V_\mathrm{r} + \frac{R_\mathrm{L}P_\mathrm{r} + jR_\mathrm{L}Q_\mathrm{r}}{V_\mathrm{r}} + \frac{jX_\mathrm{L}P_\mathrm{r} + X_\mathrm{L}Q_\mathrm{r}}{V_\mathrm{r}}$$

$$V_\mathrm{e} = V_\mathrm{r} + \frac{R_\mathrm{L}P_\mathrm{r} + X_\mathrm{L}Q_\mathrm{r}}{V_\mathrm{r}} + \frac{j(R_\mathrm{L}Q_\mathrm{r} + X_\mathrm{L}P_\mathrm{r})}{V_\mathrm{r}}$$

This can be represented with vectors, where the angle θ represents the power angle between the two voltages Ve and Vr.

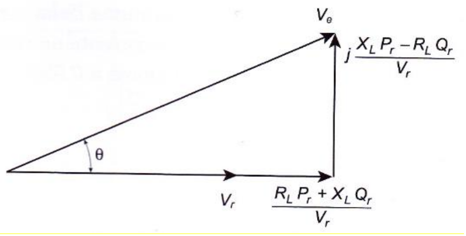

FIGURE 29 - VOLTAGE DIAGRAM USING VECTORS

Source: Redes de Energia Eléctrica, Uma Análise Sistémica, José Pedro Sucena Paiva

At last the voltage drop is given by:

$$\Delta V = V_\mathrm{e} - V_\mathrm{r} = \frac{R_\mathrm{L}P_\mathrm{r} + X_\mathrm{L}Q_\mathrm{r}}{V_\mathrm{r}} + \frac{j(R_\mathrm{L}Q_\mathrm{r} + X_\mathrm{L}P_\mathrm{r})}{V_\mathrm{r}}$$

Looking at the above diagram, if the angle θ is very small the above expression may be simplified to:

$$\Delta V = V_\mathrm{e} - V_\mathrm{r} \approx \frac{R_\mathrm{L}P_\mathrm{r} + X_\mathrm{L}Q_\mathrm{r}}{V_\mathrm{r}} \tag{20}$$

This expression gives the phase-to-phase voltage drop. The phase-neutral voltage drop is given by:

$$\Delta V = V_\mathrm{e} - V_\mathrm{r} \approx \frac{R_\mathrm{L}P_\mathrm{r} + X_\mathrm{L}Q_\mathrm{r}}{\sqrt{3} * V_\mathrm{r}} \tag{21}$$

The voltage drop is, therefore, caused by an electrical resistance (caused by the conductor material), an electrical inductance (a magnetic field created around the conductors) and the power (both active and reactive) consumed by the load. If the current is kept as a complex, the voltage drop is given by:

$$V_\mathrm{e} = V_\mathrm{r} + (R_\mathrm{L} + jX_\mathrm{L}) * (|I|\cos(\phi) + |I|j\sin(\phi)) \Leftrightarrow \\ \Delta V = R_\mathrm{L}|I|\cos(\phi) + jX_\mathrm{L}|I|j\sin(\phi) \qquad 22$$

The impact on distribution

A distribution systems may connect all types of customers to the power grid, so it is common to have different kinds of loads all connected in the same system. When considering the residential customers the common loads are household appliances like a stove or a refrigerator. In commercial customers the loads are probably electronic devices such as computers and printers. Both residential and commercial customers only represent a faction of total consumption.

In addition to residential and commercial customers there can also be industrial customers on the same system, leading to a strong increase in the demand. Normally this type of customers make use of electrical machines which have much higher energy consumption than other loads, making those customers much more energy demand. As a consequence of this increase in demand, the power flow is increased, which also increases voltage drop along the feeders.

If the voltage drops along the feeder, it will reach the customers in a lower level than the standard, causing what is called undervoltage. Today in European LV distribution systems, there is no mandatory rules for the permissible voltage range. Only recommendations are made. The DIN IEC 60038 (VDE 0175): 2002-11 or IEC 60038: 2009-06 recommends that the supply voltage should be within ±10% of its nominal value. The standard DIN EN 50160 (EN 50160): 2008-04 defines all the voltage quality characteristics – including the permissible voltage drop - for a public supply system. [20] [21]. When this effect of undervoltage is significant, it causes problems to the customers' electrical equipment such as:

Malfunction of the devices being powered causing improper, erratic or no operation at all. This applies to electronic devices like computer power supplies, which are non-linear loads, becoming unstable and fail when supplied with a lower voltage than the one they are specified to work with, causing the computer to be shutdown. Another example is lightning. Undervoltage can cause lights to flicker or fail completely when other appliances or equipment are being used. These can be serious concerns in the commercial sector and can increase maintenance and equipment costs for the customers.

Overheating of inductive loads such as motors and electrical ballasts. In this loads, when the voltage decreases, it causes the current to increase, to keep the power constant. The problem of a higher current is that it heats up the equipment, increasing the probability of damaging it or even causing a fire.

Efficiency decrease in resistive loads, such as heaters, since their output power – thermal dissipated energy - depends on the square of voltage, thus they cannot provide the same output if they operate below their rated voltage.

Equipment lifetime reduction due to equipment malfunction or overheating.

Compromises the safety of the equipment and the safety of those who use the equipment.

Moreover, voltage drop may cause other problems to the grid, such as an increase in the current consumption by grid components and the load. For example:

Computers and other electronic devices are powered through a computer power supply that establishes a constant output power. These power supplies are regulated to maintain the output power constant even if the line voltage changes, so if the line voltage drops, they will draw more current from the grid to keep the power at the same value.

Transformers used through the distribution grid which serve as voltage regulators, means that when the voltage drops, in order to maintain the customer's voltage constant, it has to draw more current from the grid.

Synchronous motors can also cause problems to the grid. When voltage drops, the rotation rate does not change nor does the load, which means the current is increased.

Non-synchronous motors have a similar behave when voltage drops, but in this case it is even worse because they actually slow down a bit, changing their power factor to worse and adding a reactive component to the current draw from the grid.

In these four examples, more current is draw from the grid to feed the loads when the voltage drops, which has a negative impact over the grid operation.

3.3 Voltage Control

From 3.2 we concluded that the loads always cause the voltage to drop, as seen with equation 20 and 21. Also from 3.2 there are several reasons to avoid the voltage drop as its effects can be harmful to customers and equipment. Therefore it is clear that voltage drop has strong consequences on a distribution system. This leads to the need of voltage control which can be done through many different mechanisms. Hereafter three basic voltage control mechanism are explained.

3.3.1 On-Load Tap-Changer Transformer

A basic voltage control is performed using a tap-changer transformer. This type of transformer can regulate its output voltage through series of taps. A transformer tap is a connection to a specific node between the two ends of the transformer's winding. Connecting to a specific tap allows a certain number of winding turns to be selected, by adding or subtracting turns, and thus allowing to adjust the output voltage. This tap-changing mechanism is used as a part of HV/MV substations transformers, so the substation output voltage can be regulated. The use of taps in a transformer has some advantages, such as:

- It is possible to have a constant output voltage (secondary voltage) even if the input voltage (primary voltage) changes.
- The ability to manipulate the output voltage level for specific applications, such as lightning or electric motors (starting rotation motors require a low voltage level)
- To provide a natural point for earthing or conducting unbalanced currents in three-wire single-phase circuits or four-wire three-phase circuits.

Based on their operation, there are two groups of tap-changer transformers.

- The No-Load or Off-Circuit Tap-Changer Transformer
- The On-Load or Under-Load Tap-Changer Transformer

The main difference between these two groups is the ability to change taps while the transformer is energized, which is possible in the OLTC but not in the NLTC. The NLTC needs to be disconnected from the grid in order to change the tap connection, which is done manually by means of an external selector. Therefore when it comes to being able to change the output voltage in small intervals of time – like different hours of day - the OLTC have demonstrated to be much more versatile than NLTC, and for this reason they are widely used in distribution systems.

The OLTC mechanism is used as a part of a MV/LV substation transformer, in order to compensate the voltage changes caused by the loads.

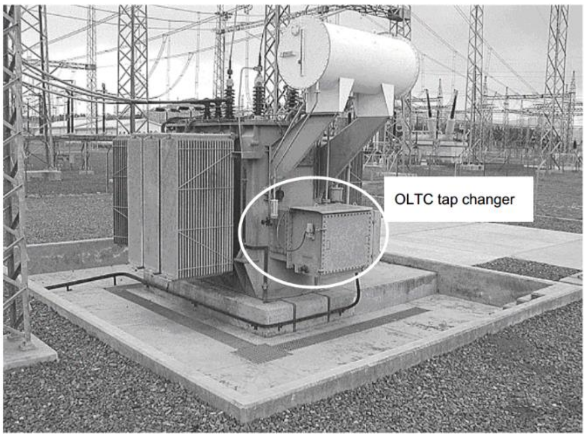

FIGURE 30 – TRANSFORMER EQUIPPED WITH OLTC

Source: Eskom DGL 34-617: Network planning guideline for transformers

There are two conditions that must be verified for a proper operation:

1) During tap changing, taps must never be short-circuited, thus an additional impedance is used to prevent this short-circuit from happening.
2) In order to assure the continuity of service, the loads must not be disconnected from the grid while the tap-change process occurs.

This additional impedance used to prevent the short circuit from happening can be either a tapped resistor or an inductor, so therefore there are two types of OLTC transformers. Those which use a resistor as the additional impedance are called On-Load Resistor Tap-Changer and those which use an inductor are called On-Load Reactor Tap-Changer.

On-Load Reactor

The On-Load Reactor was the first OLTC type, invented in 1926 [18]. Using an inductor instead of a resistor allows the load current to pass continuously, while in a resistor this only happens in a very short time, depending on the resistor ratio.

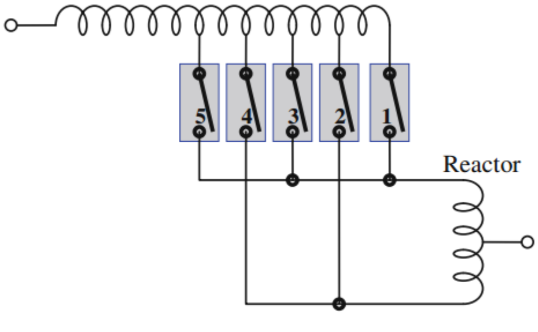

FIGURE 31 – ON-LOAD REACTOR

Source: Electronic Tap-changer for Distribution Transformers, Jawad Faiz, Behzad Siahkolah

The On-Load Reactor uses under-load switches connected to each tap. These switches can be turn on and off under-load. During the tap changing operation there must be always at least one switch off, so the loads are always connected to the system.

Also using an inductor can be a great advantage because of its ability to continuously pass the load current which protects the transformer against damage and failure if the moving mechanical system of tap-changing is damaged and stops.

However the On-Load Reactor also has some disadvantages, such as the size of the reactor which can be considerable, the switches short-life, long arcs occurrence during the tap-changing process and low changing speed. For these reasons they have been replaced by the On-Load Resistors. Despite this disadvantages they are still being improved and used in some countries.

On-Load Resistor

The On-Load Resistor uses one or two resistors instead of a single inductor. Four different arrangements for on-load resistor are shown next:

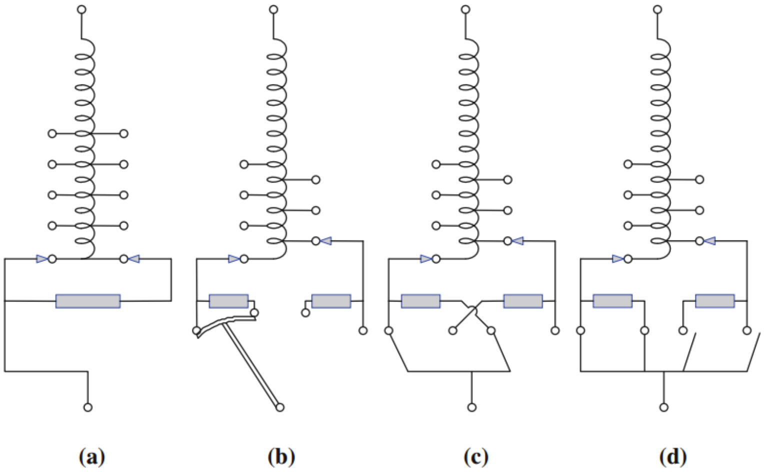

FIGURE 32 – ON-LOAD RESISTOR

Source: Electronic Tap-changer for Distribution Transformers, Jawad Faiz, Behzad Siahkolah

The arrangement shown in (a) only uses one resistor as a selector and diverter switch, while the others arrangements in (b,c,d) use two resistors, one as a selector switch and the other one as a diverter switch.

The basic principles of the tap changing process in the On-Load Reactor also applies to the On-Load Resistor. There must be always at least one switch closed. On arrangement (b) it is the mechanical moving part that does the transition, by moving to the left and right. Considering switch 1,2,3 and 4 from left to right, first both 1 and 2 are closed, then only 2 is closed and 1 opens, then 3 and 2 are closed, then 2 opens and so on.

Despite their popular use in the power systems, tap-changer transformers using on-load resistors still have some drawbacks associated with them:

- The appearance of an electric arc in diverter switches during tap-changing process, which causes impurity in the oil surrounding the diverter switches and increases the wear level of the contacts of the switches.
- High maintenance costs associated with the contacts and the mechanical moving parts due to the previous reason.
- Low speed during tap-changing process due to its mechanical nature.
- Long time needed to store the desirable energy to begin the tap-changing process.

- High losses in On-Load Resistors during tap-changing process due to the use of resistors which dissipate energy.

In order to avoid theses disadvantages associated with mechanical OLTC transformers, another type of tap-changer which uses electronic hardware have been developed and used. These are called Electronic Tap-Changers and can be either electronically-assisted or fully-electronic on-load tap-changer transformers

Electronically-Assisted OLTC

This type of transformer, also called Hybrid Tap-Changer, uses build-in electronic devices together with the mechanical moving parts of the traditional OLTC. These electronic devices are called thyristors and they are used to prevent the electrical arcs from occurring in the diverter switches during the tap-changing process. These thyristors are solid-state semiconductors that can allow or deny the current to pass through them. The following figure illustrates how these electronic thyristors can be used to improve the previous (b) arrangement.

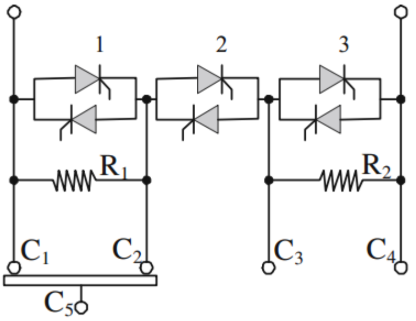

FIGURE 33 – ELECTRONICALLY-ASSISTED VERSION OF ON-LOAD RESISTOR (B) ARRANGEMENT

Source: Electronic Tap-changer for Distribution Transformers, Jawad Faiz, Behzad Siahkolah

During a tap-changing process while the contact C5 is moving, contact C1 becomes isolated. In this case both thyristors in (1) would be turned on to deviate the current so it passes through them instead of reaching C1, therefore minimizing the arc occurrence. After the current reaches zero, both thyristors in (1) are turned off so the load current continues to pass through R1 and C2. While C5 moves, the next two thyristors in (2) are turned on to prevent an arc occurrence in C3. Although this circuit has the advantage of preventing the electrical arc from occurring, it is not very reliable because even if the thyristors are turned on during a short time, they are permanently connected to the diverter switches circuit which makes them vulnerable to damage.

A possible solution to this problem would be the use of thyristors that only connect to the circuit during the tap-changing process and disconnect after it.

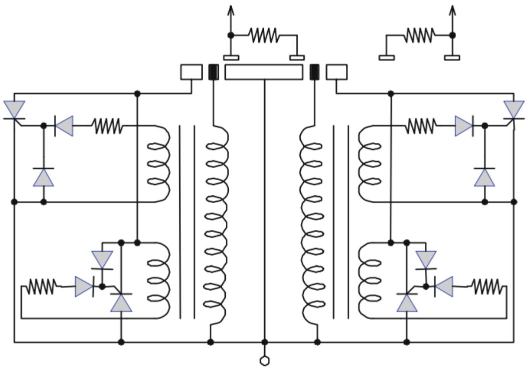

FIGURE 34 – AN IMPROVED VERSION OF THE ELECTRONICALLY-ASSISTED OLTC

Source: Electronic Tap-changer for Distribution Transformers, Jawad Faiz, Behzad Siahkolah

The circuit on the left can perform the tap-changing process with minimum arc. However it still relies on a mechanical switch structure similar to the On-Load Resistor structure and therefore it is still very slow while performing the tap-changing process. It is also possible to see how complex this circuit is compared to previous ones.

In order to solve the low operating performance of Hybrid OLTC it is necessary to replace the mechanical moving parts of the OLTC. Thus, a new type of OLTC is suggested, which only uses electronic devices to perform the entire tap-changing process. These new OLTC are called Full-Electronic Tap-Changers.

Fully Electronic Tap-Changer

The fully electronic Tap-Changer can be considered as an improvement of hybrid electronic Tap-Changers. They do not have any mechanical parts on their structure, therefore they have several advantages comparing to previous versions:

Tap-changing performed at high speed, since these OLTC only use solid-state power switches and no mechanical parts are involved in the process, therefore switching is done at fast speed.

Absence of electric arc occurrence since there are no real physical mechanical switches in this type of Tap-Changer, thus improving reliability.

Low maintenance costs when compared to the electronically-assisted version since no mechanical parts are used.

Tap Jumping is possible because there is no resistor and therefore the circulation current between taps equals zero.

The inexistence of mechanical limitations, the high operation speed and good controllability of solid-state power switches enhances the tap-changer capabilities and performance, such as obtaining more steps with less tap numbers and switches, or the ability to improve the power quality by being able to compensate voltages disturbances.

In spite of the previous advantages, fully electronic tap-changers also have some disadvantages when compared with conventional mechanical tap-changers:

Solid-state switches have a larger switch-on voltage drop than mechanical switches which leads to higher operational losses in the full-electronic tap-changer.

High maintenance costs when compared with conventional tap-changers.

High vulnerability of solid-state switches to short-circuit faults and lightning.

3.3.2 Voltage Regulator

In distribution systems, most voltage regulation problems are caused because there is too much impedance to properly supply the load, because excessive reactive power consumption, or simple because the feeder length, which causes the voltage to drop too low under heavy load conditions. Therefore it is necessary to establish voltage control mechanisms in order to keep the voltage level in acceptable levels. However, when the source voltage is excessively increased, there can be an overvoltage condition when the load drops too low.

Voltage control in distribution networks can be accomplished using Voltage Regulators. These devices are used to compensate the voltage drop effect on the feeders, which can cause several problems to customers, a seen in (3.2). The figure on the left shows three step-voltage regulators. Voltage Regulators are rated on current (IEEE Std. C57.15-1999)

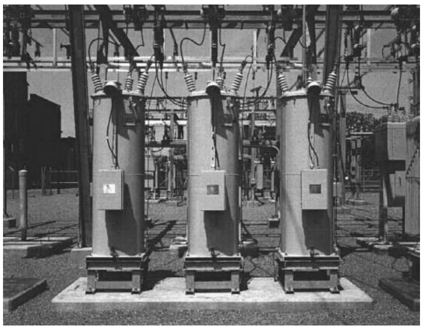

FIGURE 35 – SUBSTATION VOLTAGE REGULATORS

Source: http://www.powerqualityworld.com/2011/04/step-voltage-regulator-utility.html

As can be seen from the above figure, these devices are similar to transformers. In fact a step-voltage regulator is basically a transformer that has its windings – primary and secondary – both physically connected to the primary side. Thus, this type of transformer is also called an autotransformer. The primary winding is shunt-connected and the secondary winding is series-connected. This configuration allows to increase or decrease the output voltage, by changing the secondary winding terminal where the primary side is connected.

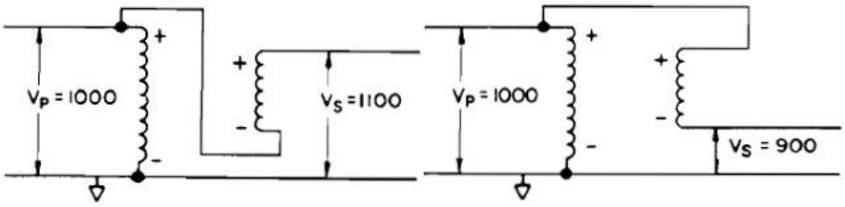

FIGURE 36 – BASIC VOLTAGE REGULATION USING AN AUTOTRANSFORMER

Source: http://www.powerqualityworld.com/2011/04/step-voltage-regulator-utility.html

For e.g. if the transformer has a turns-ratio of 10:1, and 1 kV is applied at the primary side, then the secondary voltage will be 100 V. Changing the connection between taps allows to add or subtract this value from the original input voltage – primary voltage - and thus the output voltage would be 1100 V or 900 V, respectively. In this case the VR has the capability to raise/step-up (boost) or lower/step-down (buck) the output voltage by

FIGURE 37 – MODERN, 32-STEP, SINGLE-PHASE VOLTAGE REGULATOR

Source: http://www.rmreps.com/html/voltage_regulators.html

±10%, which is a common in modern VRs. The figure on the left shows a single-phase VR using this control technology. [22]

FIGURE 38 – SIEMENS THREE-PHASE VOLTAGE REGULATOR

Source: Distribution Voltage Regulators, Siemens

Besides the possibility of switching its terminals, the VR also has series of tap-connections built along either the primary or secondary winding, which allows the number of secondary winding turns to be selected – much like the OLTC transformer – meaning that the voltage value which is added or subtracted can be regulated, thus providing an efficient voltage regulation. Many regulators are also bi-directional units, which means they can regulate the voltage in either direction, depending on the direction of power flow. Voltage regulators can be used either on single-phase or three-phase systems. Single-phase VRs use a delta-delta connection, while three-phase VRs use a star-star connection with a common star-point.

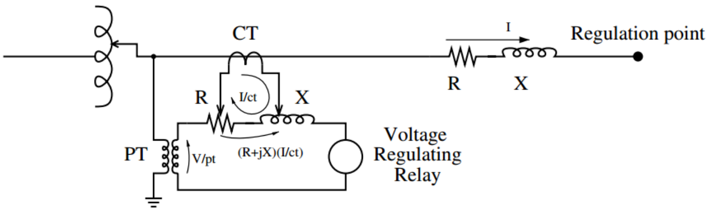

FIGURE 39 – LDC CIRCUIT

Source: Electrical Power Distribution Handbook, Short.

In addition to these basics, regulator controllers also have line-drop compensation (LDC) to increase the voltages supply during heavy load. Controllers also may have high and low voltage limits to prevent regulation outside of a desired range of voltages. [22] The LDC is a part of the VR control system that is capable of adjusting the voltage regulation mechanism, depending on the actual load. It has resistance and inductance parameters (R and X on the above figure) that the user can adjust in order to regulate the LDC. These parameters are set in values of Volt. [23]

The use of LDC also reduces the number of VR required to regulate the voltage along a feeder. For e.g. if the VR is set up to regulate the voltage to V=400 Volt and there is not enough regulation along the feeder, it is necessary to add more VRs. With a higher system voltage level less VRs are required, but during low demand overvoltage problems may occur on some nodes. With VRs using LDC voltage is only boosted during high demand, but not during low demand, thus decreasing the risk of overvoltage. The next figure shows this advantage of using LDC.

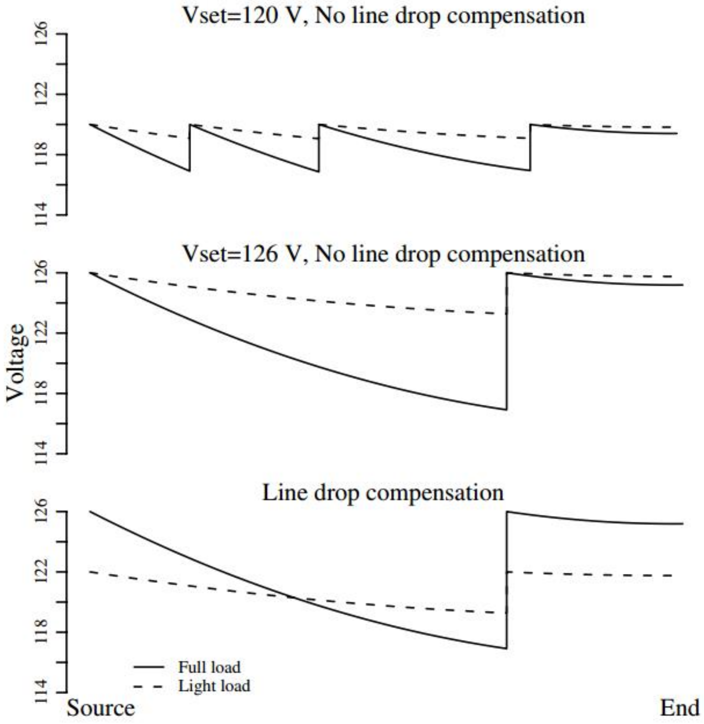

FIGURE 40 – COMPARISON BETWEEN ABSENCE AND PRESENCE OF LDC CONTROL

Source: Electrical Power Distribution Handbook, Short.

3.3.3 Reactive power

One method of controlling the voltage is through the injection of reactive power in the system, in order to compensate the reactive power demand. As seen in equation 20, the voltage drop is proportional to the reactive power consumed in the load (Qr) and therefore, if it decreases, so decreases the voltage drop. The new voltage drop would be approximately equal to:

$$\Delta V = V_\mathrm{e} - V_\mathrm{r} \approx \frac{R_\mathrm{L} P_\mathrm{r} + X_\mathrm{L}(Q_\mathrm{r} - Q_\mathrm{i})}{V_\mathrm{r}} \qquad 23$$

Where Qi is the reactive power injected. Besides, decreasing the reactive power generated by the source also decreases the feeder current and therefore the feeder losses.

$$I = \frac{\sqrt{P_\mathrm{r}^2 + (Q_\mathrm{r} - Q_\mathrm{i})^2}}{V_\mathrm{r}} \qquad 24$$

And the feeder losses are given by:

$$I^2 * Z_\mathrm{L} \qquad 25$$

Which shows that the feeder losses are correlated with the reactive power consumption. Thus reactive power injection reduces system losses by decreasing the reactive power consumed and at the same time improves voltage regulation.

In order to perform an effectively voltage control using reactive power injection, it appears viable to do so in strategic points of the grid. A good idea would be to inject this reactive power near at the consumer's location to avoid the excess power losses due to long distances and to improve voltage regulation at the load terminals. This reactive power control must assure that:

1) The voltage drop is kept within certain limits, since operating beyond these limits have negative effects on performance and may even cause damage to the devices.
2) The reactive power flow through the system is minimized, in order to reduce the power losses and maximize the active power flow.
3) The voltage is stable all over the power system.

There are different methods of reactive power injection. Some of these methods may be used in distribution systems to improve voltage regulation.

Shunt compensation

Shunt compensation is performed using a device that is shunt-connected with the power line. This device can be either a capacitor or a reactor. Shunt-capacitors are used to generate reactive power, in order to compensate the reactive power demand and thus to reduce the source current needed to supply the load. Consequently the voltage drop between the source and the load is reduced, improving the power factor and the active power output available from the source. Shunt-reactors in other hand, are used to consume the excess reactive power produced, to reduce the line overvoltage. The use of either capacitors or reactors to compensate the reactive power flow and thus regulate the voltage level is called volt-VAR control. [19]

For optimal compensation, the placement of shunt capacitors as to follow some constraints. There is a "golden rule" regarding the optimal location and size for this type of compensators, called the two-thirds rule.

- Two-Thirds Rule – For an optimum shunt compensation the size of a single capacitor bank should be equal to $\frac{2}{3}$ of the total reactive power demand (without compensation) and should be placed at $\frac{2}{3}$ of the total feeder length, from the supplying point. If instead of one, two capacitor banks are used, the first should be placed at $\frac{2}{5}$ and the second at $\frac{4}{5}$ of the total feeder length from the supplying point. For three capacitor banks, these optimal locations are at $\frac{2}{7}$, $\frac{4}{7}$ and $\frac{6}{7}$ of the total feeder length. Thus, the optimal capacitor sizing and location are both correlated with the number of banks used, the feeder total length and the total reactive power flow:

$$Cap\ Size = \frac{2}{2N+1} * Q$$

$$Cap\ Location = n * \frac{2}{2N+1} * L \text{ , from the substation, for } n = 1\ to\ N$$

  Where:
  Q is the system total reactive power flow
  L is the feeder total length
  N is the number of banks used

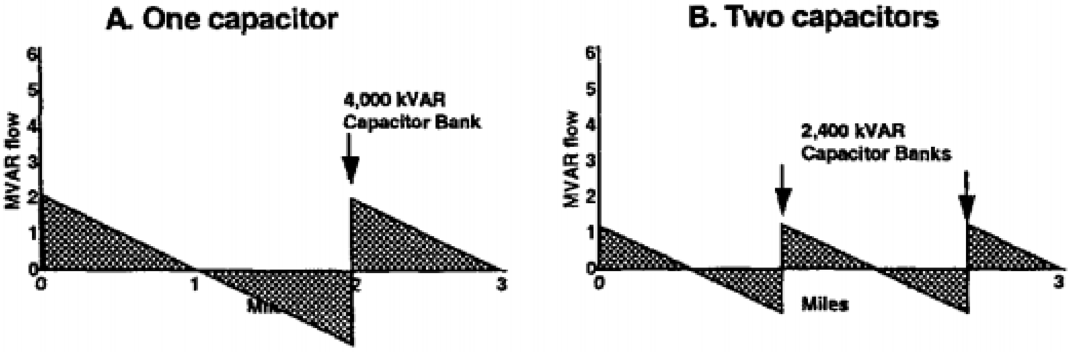

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FIGURE 41 – TOTAL REACTIVE POWER COMPENSATION VS. DISTANCE ALONG THE FEEDER FOR DIFFERENT TYPES OF SHUNT CAPACITORS

Source: Power Distribution Planning Reference Book, Willis.

Synchronous Condenser

In AC power systems, a synchronous condenser is basically a synchronous machine operating in no-load condition, meaning its shaft is not connected to anything. It is used to produce or consume reactive power, depending on the DC field excitation (magnetizing current), which can be adjustable by controlling the field voltage through a voltage regulator.

This magnetizing current is used to produce a magnetic flux in the stator winding, creating a rotating magnetic field which drags the rotor along with it, causing it to rotate. In a synchronous machine the rotor rotates at the same speed as the magnetic field in the stator.

Since the SC needs an external current to function, it consumes power from the grid. However its purpose is not to convert electric power into mechanical power, but to adjust conditions on the electric power transmission grid, by either generating or consuming reactive power to adjust the voltage level.

When the excitation current is decreased to a level below the necessary for the machine to rotate, the grid has to supply it with more power. In this case the machine will operate with a lagging power factor, consuming reactive power from the grid.

In other hand, if the field current is increased to a level above the required, the machine will be more magnetized than it needs to and, as a result, it will have an excess of reactive power and will send it back to the grid. In this case the machine will operate with a leading power factor, generating reactive power.

Therefore the DC field excitation is automatically adjusted, through a voltage regulator to maintain the power factor at the correct setting, so it can compensate either a leading or lagging power factor from the grid. The level of excitation is dependent on the amount of power factor correction desired and the amount of power factor sensed by the condenser controls.

When line voltage drops, the field current is increased and the SC becomes overexcited, generating reactive power to the grid, aiming to increase the voltage level and reduce the voltage drop. In other hand, when the line voltage rises (overvoltage), it aims to decrease the voltage level and reduce the rise, by decreasing the field current enough to become under-excited, thus consuming reactive power from the grid.

The main advantage of SC over other types of reactive power compensation is its ability to deliver different reactive power levels, by varying the machine excitation current. Also, SC has a considerable overload capability. [24] Despite this improvement in voltage control, the SC still has some drawbacks, such as:

- High investment and maintenance costs, since the SC is composed by rotating parts, it has more maintenance requirements than other (static) compensators.
- Relatively slow machine response. Although the excitation procedure is very fast, the SC must operate through its field time constant, and therefore it has a slow response when compared to other compensator types.
- Its higher mechanical complexity leads to higher power losses than other compensation types.
- Being an active element in the grid, their use increases short-circuit currents, and therefore their use leads to additional costs in breakers and switches. However this increase of short-circuit current probability results in the reduction of the equivalent impedance seen from the local where the SC is installed, which improves its voltage regulation.

Despite the above disadvantages, SC are widely used in power systems and are still being improved. For instance, the generators of hydroelectric or thermal (gas turbine) power plants can be used as SC during peak period. These generators are built with a clutch between them and the turbine, which allows the two machines to be unbound and work as a SC.

3.3.4 Load Transfer

A method to assure continuity of service is the load transfer. Basically, load transfer is the transferring of power from one source to another, in order to assure that the customers are not disconnected from the grid. This is a normal procedure during maintenance periods and/or upgrades in the power system. Therefore, loads are switched between two source, the primary source and the alternate/backup or auxiliary source, in the event of a disturbance that would interrupt the power supply from the primary source. This power transfer switching is carried out by electrical devices (switches) called transfer switches. There are different types of transfer switches:

- Open Transition or break before make, is a type of transfer switch that interrupts the contact with the primary source before it connects to a backup source. Therefore the power flow is actually interrupted and loads are disconnected from the grid during a short period of time.
- Closed transition or make before break is a transfer switch that connects to the backup source before interrupting the contact with the primary source. Such switches may be used in hospitals or other critical services that require a constant and stable power source to operate.
- Soft loading switch is a type of transfer switch that allows to change the amount of load accepted by the generator.

- Static transfer switch which uses specific devices, such as rectifiers, to transfer the load between two sources.

The following figure shows a static transfer switch configuration:

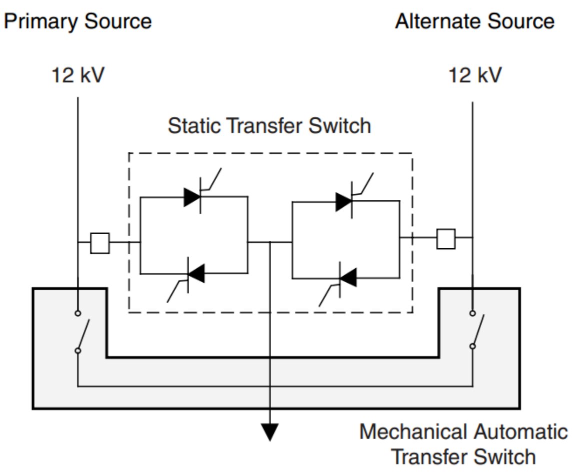

FIGURE 42 – STATIC TRANSFER SWITCH

3.4 Voltage control in the presence of distributed generation

In a conventional distribution system, without any DG present, the power flow is always unidirectional, flowing from the supply point – a distribution substation – to the load. With the inclusion of DG in a distribution system, this may no longer be true, since power is now injected into the system at different points, not only at the substation. This situation has consequences for the distribution system that will be further analyzed. Therefore the presence of DG in distribution systems affects the voltage control, and so it must be coordinated with the available voltage regulation mechanisms – either OLTC, VR or shunt-capacitor banks - in order to maintain proper voltage control in the system.

3.4.1 Overview of distributed generation technology

Decentralized production – or distributed generation – is currently an important area of development on power systems, and probably a solution for tomorrows power demand.

When compared to centralized power plants, the DG technology is composed by small and less complex equipment, which use renewable energy sources (e.g. solar, wind, biomass, small-hydro, geothermal, waves, landfill gas), microturbines or fuel cells to produce electricity. These equipment can either be operated by the energy T&D utility, independent producers or by customers.

Wind Turbines

Wind turbines are asynchronous (induction) generators that use the wind to produce electricity to be delivered into the power system. A particularity about this type of generator is that it consumes reactive power, therefore it also requires the installation of a capacitor bank to compensate the reactive power consumption. [25]

Solar Photovoltaic

Solar photovoltaic panels are used to convert sunlight into electricity. The PV technology is available for residential and commercial use. Actually, the major issues related with this technology is the high investment it requires and the long return period. Also this technology has poor efficiency – around 10% in the practice - which does not make this technology very competitive. PV systems produce DC power, and thus they connect to the grid through a power electronic inverter device. The inverter converts the DC voltage to an AC voltage used by the grid. This device can also control the amount of active and reactive power supplied.

3.4.2 Intermittent Inversion of the Power Flow and its Impact on Distribution

Distributed generators can be located anywhere along a distribution feeder, near or even at the load – e.g. solar photovoltaic panels. Power generated by DG will increase the voltage level, which may cause the voltage at the generator location to be higher than the voltage at the substation. When DG power is high, the power may flow from distribution to the transmission system, causing the voltage level to rise.

Impact on the Voltage Drop

DG may exchange (or not) reactive power with the system to which it is connected. When it does exchange reactive power, it can either consume from the system or produce reactive power into the system. As seen in (3.4), wind turbines are asynchronous generators, therefore they always consume reactive power from the system. In eq. (20) it is shown that the voltage drop also depends on the reactive power flow. Therefore, the contribution of DG in the voltage drop is given by:

$$\Delta V = V_{\mathrm{e}} - V_{\mathrm{r}} \approx \frac{R_{\mathrm{L}}(P_{\mathrm{r}} - P_{\mathrm{DG}}) + X_{\mathrm{L}}(Q_{\mathrm{r}} \pm Q_{\mathrm{DG}})}{V_{\mathrm{r}}} \qquad \mathbf{26}$$

Where P_{DG} and Q_{DG} refers to the DG active and reactive power. The Q_{DG} can either have a positive sign when DG is consuming reactive power and negative when it is producing reactive power into the system. When the DG does not exchange reactive power with the system, or generates reactive power into the system, it will decrease the voltage drop. When a DG consumes reactive power from the system, it can either increase or decrease the voltage drop, depending on the DG active and reactive power relative to the load, and the X/R ratio of the feeder.

If the DG generates more power than the current system load, i.e. if the power generated by the DG is larger than the power demanded by the loads($P_r < P_{DG}$), excessive power will flow from the distribution system back to the transmission system, causing the inversion of the load flow and consequently a voltage level rise.

Therefore, when planning the installation of DG in a distribution system, it is required that the voltage limits are not violated, for any possible scenario, such as:

1) Maximum demand and maximum generation
2) Maximum demand and minimum generation
3) Minimum demand and maximum generation
4) Minimum demand and minimum generation

3.5 Voltage Control in the presence of future loads

Nowadays societies are strongly committed in reducing the carbon footprint and protecting the environment. This new trend plays an important role on society's decisions, regarding electric energy production and consumption, and leads to the emergence of green and highly efficient solutions, providing an alternative path for the future. In the consumer side, these include the well-known electric vehicle and the electric heat pump.

Electric Vehicles

An electric vehicle is a kind of vehicle which uses one, or more, electric motors for propulsion. Regarding their power supply, there are three main types of EVs:

1) Those that are powered directly from an external power source, such as electric trains.
2) Those that are powered through internal energy storage which are charged from the supply grid, such as fully-electric automobiles.
3) Those that are powered by an on-board generator, such as hybrid electric vehicles, which use a combustion engine or hydrogen fuel cells to provide power for the electric motor.

For the purpose of this work, the first and the second type of EVs are the most relevant, since these require power from the grid to operate. There are also some hybrid vehicles (third type) that may be connected to the grid, in order to charge their batteries. These are known as Plug-in Hybrid Electric Vehicle (PHEV) [26].

Electric Heat Pumps

An electric heat pump is an electrically powered device that is able to transfer thermal energy from a heat source to a heat sink, providing heating, or cooling, of an internal space. EHP are very efficient heating/cooling systems when compared with conventional heaters, since these can provide up to three times more heat than the power being consumed [27], while in conventional heaters using an electrical resistance, all heat is produced from the input power supply. Their high efficiency and power saving capabilities makes electric heat pumps a popular application in residential households, and thus these are relevant for the purpose of this work.

3.5.1 Electric Vehicles and Electric Heat Pumps in Distribution Systems

At present, EHPs are widely used in the residential and commercial sector, and the development of EVs as the alternative mobility solution is becoming a reality. As mentioned before, an EHP require a power supply to provide heating or cooling to the building. These are usually connected to the same circuit as other household appliances. Thus, in a grid perspective, an EHP may be considered as an additional distributed load per customer.

In the case of EVs, their technology uses energy storage devices – batteries or supercapacitors – that provide power to operate the EV´s electric motor, and are recharged while the EV is not moving and connected to a power supply. Thus, there is a charge/discharge process associated, which makes EV´s much more versatile as a load. During the charging process, they require power from the grid to charge up the batteries, and are seen by the grid as normal loads, such as other residential/commercial loads.

Since both EHPs and EVs are seen as loads by the grid, they will contribute for the voltage drop during peak times.

3.5.2 Future possibilities for EVs in Distribution Systems

Monitored and Controlled Charging

Following the concept of a smart grid, an important aspect of a power system is the control over its components, including the load. Controlling how and when power is consumed could improve load balancing and the voltage supply. In EVs this type of control should be able to monitor and control on the power supply according to the current battery charge level, decreasing it when the battery is almost fully charged. This measure would cause no impact to customers, as most of them only recharge their EVs at night, during a time interval long enough for slow-charging without causing inconvenience.

Vehicle-to-Grid (V2G)

In an EV, a fully or partially charged battery that is still connected to the power supply, could send its stored energy back to the grid, acting as a power source. This concept is called Vehicle-to-Grid (V2G), and could provide a solution for customers to sell energy they will not use for any possible reasons – thus reducing energy losses – and a solution during high demand periods, providing additional power into the system.

Grid-to-Vehicle (G2V)

A similar idea, called grid-to-vehicle (G2V) aims to provide voltage regulation by regulating the charge rate of EV's, which would be done by the grid operator. Therefore the power flow is still regulated, in a different way. This approach intends to distribute the load caused by EV's during off-peak hours, thus improving the voltage supply.

3.6 Voltage control in DC Distribution Systems

As already mentioned in chapter 2, there are several reasons that support the use of DC in distribution systems. The major drawback of using DC power distribution is perhaps the high cost associated with this technology. In power transmission over long distances the use of DC has some benefits over AC, and therefore its costs may be justified against the AC costs, which would also be very high. However, in distribution

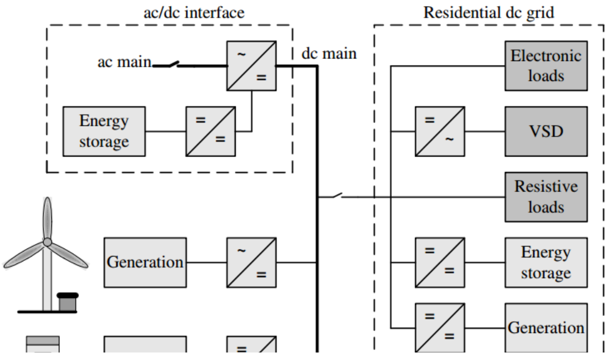

FIGURE 43 – A DC DISTRIBUTION SYSTEM

Source: DC Distribution Systems, Daniel Nilsson

systems, the distance between loads and the substation is much smaller, making it hard for DC to compete with AC, in respect to distribution costs. Still, the idea of using low-voltage DC distribution systems has been analyzed in several studies [28] [11]. The figure on the right shows a possible design for a DC distribution system, including AC/DC converters, energy storage and generation units and residential loads, which are composed by electronic and resistive appliances, variable speed drives (VSD), energy storage and generation units.

In this case the DC system connects to an AC system through an AC/DC interface. This interface plays an important role on the DC system operation. Different topologies for this interface bring different control possibilities for the system power flow. A proper AC/DC interface for future DC distribution systems should be able to provide a controllable DC voltage, support a bi-directional power flow, have low losses and be as low-cost as possible.

Diodes

This is a simple (and cheap) topology that uses diodes for AC to DC rectification, for both single-phase and three-phase systems.

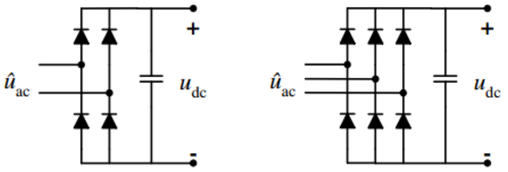

FIGURE 44 – AN AC/DC CONVERTER USING DIODES

Source: DC Distribution Systems, Daniel Nilsson

It has many disadvantages:

1) It is not possible to regulate the DC output voltage in this topology. There is however a modified version that overcomes this limitation – Diode rectifier with Power Factor Correction (PFC) – which includes buck or boost characteristics and allows the DC output voltage to be controlled.

2) The output DC voltage decreases if the load current increases.

3) The power can only flow from the AC side to the DC side, which goes against the idea of a bi-directional power flow.

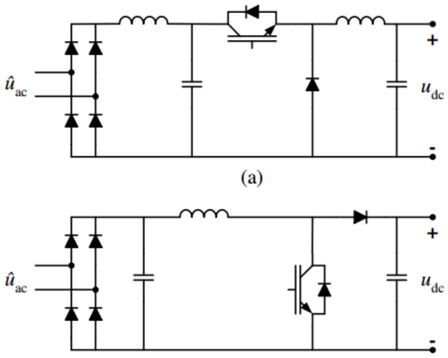

FIGURE 45 – A DIODE AC/DC CONVERTER WITH PFC

Source: DC Distribution Systems, Daniel Nilsson

Transformer and Voltage Source Converter

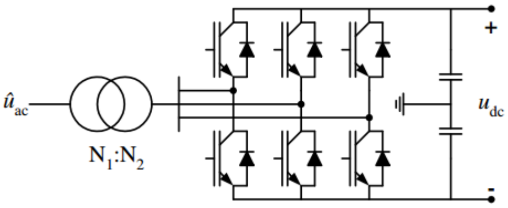

Figure 46 – A VSC equipped with an AC transformer

Source: DC Distribution Systems, Daniel Nilsson

The Voltage Source Converter (VSC) is a different topology which uses six switches (either IGBT's or GTO's) in order to allow a bidirectional power flow [29]. This topology may also include an AC transformer connected between the AC grid and the VSC, which adds regulation functionality to the converter, and thus the DC output voltage can be regulated.

Three-level Voltage Source Converter

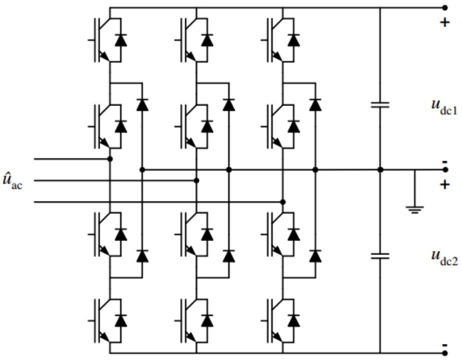

Figure 47 – Three-level VSC

Source: DC Distribution Systems, Daniel Nilsson

This topology is similar to the VSC, but it uses twice more switches. Thus, instead of one output, two DC outputs can be controlled individually. This means that in a DC system, loads can connect to either of the two DC outputs, increasing connection possibilities for supply.

Voltage Source Converter and Buck

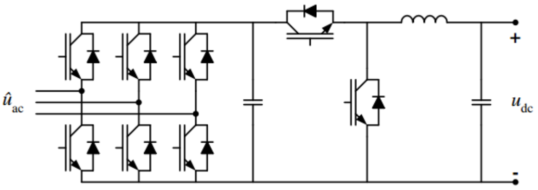

Figure 48 – VSC with buck

Source: DC Distribution Systems, Daniel Nilsson

A different possibility for improved DC voltage control may be using a VSC in series with a buck circuit. This topology increases controllability of the DC output. In this case eight switches are used (six from the VSC plus two from the buck).

It is also important to notice that the conversion losses increase with the number of switches used. A table summarizing each topology attributes and comparing them is shown next.

	Limited output DC voltage (u_{dc})	Number of output DC voltages	Number of switches used	Bidirectional power flow	Cost
Diode	Yes	1	0	No	Low
Diode with PFC (buck)	Yes	1	1	No	Low
Diode with PFC (boost)	No	1	1	No	Low
VSC with transformer	No	1	6	Yes	High
Three-level VSC	No	2	12	Yes	High
VSC with buck	No	1	8	Yes	Medium

TABLE 16 – COMPARISON BETWEEN DIFFERENT AC/DC INTERFACES

3.6.1 Low Voltage Direct Current

A low voltage direct current (LVDC) system is a concept of DC distribution, where existing AC segments are connected through the use of power electronic AC/DC converters. There are different topologies for LVDC systems, regarding the location of converters and the DC technology used.

Wide LVDC Distribution District

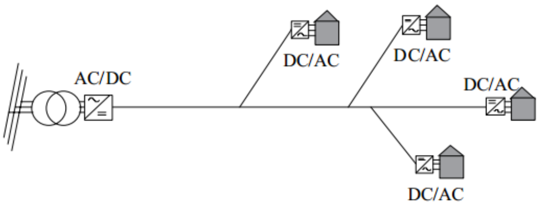

FIGURE 49 – LVDC DISTRIBUTION DISTRICT

Source: An LVDC Distribution System Concept, P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi and J. Partanen

In this topology the DC distribution system is very similar to an AC radial system. Each customer is connected to the system through a DC/AC converter. The distribution transformer connects through an AC/DC converter. The main feeder and the several branches use DC technology, which means that each customer has its own independent AC supply.

LVDC Link Distribution System

This type of DC distribution system uses a main DC link between two distribution transformers, in order to supply the loads. In this case, the customers are connected to the same AC network.

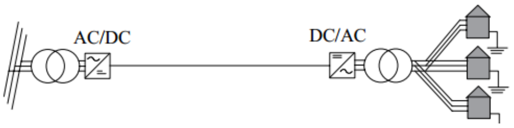

FIGURE 50 – LINK LVDC DISTRIBUTION SYSTEM

Source: An LVDC Distribution System Concept, P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi and J. Partanen

Unipolar and Bipolar DC Systems

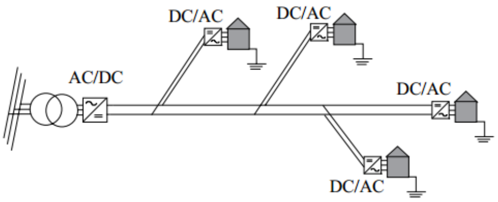

FIGURE 52 – UNIPOLAR LVDC SYSTEM

Source: An LVDC Distribution System Concept, P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi and J. Partanen

Regarding the DC technology used, DC systems may be unipolar (right) or bipolar (below). The difference between them is the presence of an unsymmetrical (negative) voltage in the bipolar DC type, while in the unipolar there is only one (positive) voltage supply level. Thus, in the bipolar type three conductors are used (two voltage levels and a neutral conductor), and in the unipolar only two conductors are used to distribute power. The advantage of a bipolar DC system is that it gives more possibilities while connecting a load. This could be connected using the positive DC voltage and the neutral; the negative DC voltage and the neutral; both DC voltages and both DC voltages plus the neutral. [10]

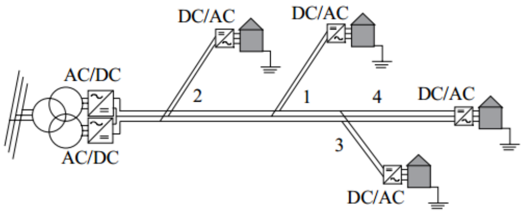

FIGURE 51 – BIPOLAR LVDC SYSTEM

Source: An LVDC Distribution System Concept, P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi and J. Partanen

A LVDC distribution system might have some benefits over a conventional AC distribution system. As already mentioned in chapter 2, with DC it is possible to have higher voltage levels than AC. A higher voltage level means a large covered area, since power reaches more far. Thus, at the same distance from the source, a DC system has more power than an AC system. This means that a LVDC system has higher distribution capacity than an AC distribution system. It is also important to notice that a higher distribution capacity causes smaller currents and less power losses in the cables. Thus, there is also the possibility of reducing the cables cross-section to reduce costs, while maintaining the same current and power losses. Finally, a LVDC system would require less distribution transformers than a conventional AC system. [10]. However a LVDC system is also more complex in operation and electrical safety than an AC distribution system. It requires the use of power electronic converters that cause more system faults. Converters also have a shorter lifetime than AC components, which increases maintenance costs.

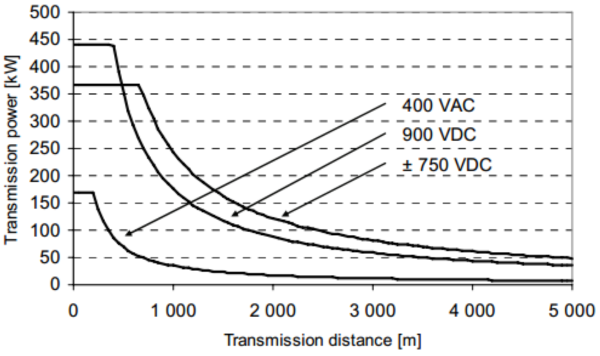

FIGURE 53 – DC DISTRIBUTION POWER VS. DISTANCE

Source: An LVDC Distribution System Concept, P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi and J. Partanen

3.7 Case Study

Each type of voltage control presented in this chapter is tested, through computer software simulation, on three different LV systems, with radial distribution, being the first mainly composed by residential loads, the second being composed by commercial loads including stores, offices and public buildings, the third by industrial loads including factories and warehouses and the fourth by rural loads, such as farms.

System	Load Type	Length of main feeder (meters)	Number of branches	Loads	Distance between loads (meters)
1	Residential (single-phase w/ neutral)	486	3	42 houses + 13 EVs	27
2	Commercial (single-phase w/ neutral)	1134	0	42 Stores + 92 EVs	27
3	Industrial (three-phase)	3500	2	18 factories + 120 EVs	350

Table 17 – Radial systems under study

Each type of loads are modelled using standard ZIP (polynomial) models for each case[1].

Type of Load	Standard ZIP model
Residential	Summer: $P_{LOAD} = P_0\left[0{,}3\left(\frac{V}{V_0}\right)^2 + 0{,}7\right]$ Winter: $P_{LOAD} = P_0\left[0{,}7\left(\frac{V}{V_0}\right)^2 + 0{,}3\right]$
Commercial	$P_{LOAD} = P_0\left[0{,}5\left(\frac{V}{V_0}\right)^2 + 0{,}5\right]$
Industrial	$P_{LOAD} = P_0\left[0{,}2\left(\frac{V}{V_0}\right)^2 + 0{,}8\right]$

Table 18 – Load types under study

Each group of customers also has an associated coincidence factor, which indicates how often a group of loads hit their peak consumption at the same time. Therefore, the value for this factor will be correlated with the total number of loads in the group, decreasing as the number of loads increases. The following table shows, for each type, the coincidence factor per customer for an unlimited number of loads, and the calculated value of this factor for 42 equal loads:

---

[1] According to Willis, 2004, "Consumer Demand and Electric Load", *in Power Distribution Planning Reference Book*, pg. 71

Residential Loads		
Customer Type	Coincidence factor for an unlimited number of loads[1]	Coincidence factor for 42 loads
Basic (5kW)	0,15	0,28
Partly-Electric (8kW)	0,12	0,26
Fully-Electric w/ boiler heater (12kW)	0,16	0,29
Fully-Electric w/ instant flow-type water heater (32kW)	0,06	0,2
All-Electric (28kW)	0,77	0,81

Table 19 – Residential customer types

When the group has a limited number of loads, the coincidence factors for each type are calculated using the following expression:

$$Cf = Uf + (1 - Uf) * n^{-\frac{1}{2}} \qquad 27$$

Where:

Cf is the coincidence factor;

Uf is the utilization factor;

n is the number of customers in the group;

For eq. 27 it is assumed that all customers in a group have the same maximum demand or an average maximum demand per customer can be applied. For this case study, the residential loads will be considered to be on the fully-electric w/ boiler type.

In the commercial and industrial sectors, the load composition also depends on the type of customer. For instance, a restaurant equipped with heating/ventilation systems and large kitchen appliances might have a higher power consumption than a small general store or a small office, where the load is basically composed by lighting and a sometimes optional ventilation system. In this work the following types of commercial and industrial buildings and their respective power consumption and coincidence factor are considered[2]:

---

[1] From “Residential Load Models for Network Planning Purposes”, Table II

[2] The power consumption and coincidence factors for both commercial and industrial loads presented in this work were based on the data provided in Siemens, 2009, “Application Manual – Part 1: Basic Data and Preliminary Planning. Integrated solutions for power distribution in commercial and industrial buildings”.

Commercial Loads	
Building type	Coincidence factor
Small general store (1,5 kW)	0,6
Large clothes store (40 kW)	0,6
Restaurant (90kW)	0,8
Bank (6kW)	0,6
Bakery (30kW)	0,8
Library (2,8 kW)	0,6

Table 20 – Commercial customer types

Industrial Loads	
Building type	Coincidence factor
Cold storage (1 MW)	0,6
Production plant (300 kW)	0,6
Rubber factory (500 kW)	0,6
Storage area (45 kW)	0,3

Table 21 – Industrial customer types

In the commercial system, each restaurant (90kW) is supported with fifteen photovoltaic panels, each one providing 5kW active power and therefore with a total of 75kW per restaurant. Large stores (40kW) are supported by five panels, providing a total of 25kW per store. In total there are 140 photovoltaic panels installed in this system. The system also has power factor correction, through passive compensation, using capacitor banks. These were sized and placed according to the $\frac{2}{3}$ rule.

In general, all stores and restaurants have a higher power factor, since most of the load is composed by highly efficient fluorescent lighting and, in the case of restaurants, electric ovens. The use of air conditioner systems, refrigerators or electric motors may affect the power factor a little, but not significantly. Therefore, the minimal power factor assumed for any load is equal to0,9.

The remaining load is composed by EV's, which are considered to be constant power loads. For these loads it is assumed a 30% penetration in residential systems, starting at the evening of each day until next morning. During daytime most of these loads may be present at commercial and industrial systems, where there is a higher population density. For simplification, the EV load is modeled as a conventional AC load, connected to the same node as the residential customer and to a specific node in commercial and industrial systems. The power consumption of this load will be equal to the charging station capacity. Both the power factor and coincidence factor for these charging stations are equal to 0,9 and modeled according to Int. Std. IEC62196 and IEC61851-1 which defines four modes of charging:

EV loads	
Mode 1 (AC, single-phase)	Slow-charging (3,3kW); $I_{max} = 16A$; $V_{max} = 250V$ charging time 6~8 hours
Mode 1 (AC, three-phase)	Slow-charging (10kW); $I_{max} = 16A$; $V_{max} = 480V$ charging time 2~3 hours
Mode 2 (AC, single-phase)	Slow-charging (7kW); $I_{max} = 32A$; $V_{max} = 250V$ charging time 3~4 hours
Mode 2 (AC, three-phase)	Fast-charging (21kW); $I_{max} = 32A$; $V_{max} = 480V$ charging time 1~2 hours
Mode 3 (AC, three-phase)	Fast-charging (43kW); $I_{max} = 63A$; $V_{max} = 480V$ charging time 20~30 minutes
Mode 4 (DC)	Fast-charging (40kW~62kW); $I_{max} = 100A \sim 125A$; $V_{max} = 400 \sim 500\ VDC$ charging time 20~30 minutes

Table 22 – EV load types

The remaining system elements are modelled as follows:

Distribution feeder	Model: NAYY-J 4X150SE; Parameters: R=0,206Ω/Km; X=0,08Ω/Km; $V_{\text{rated}} = 1kV$; $V_{\text{nom}} = 0{,}4kV$ $I_{\text{rated}} = 270A$; $f_{nom} = 50Hz$; Installation type: Underground cable; Three-phase with neutral (4 wires); According to Int. Std. IEC60502-1 and DIN VDE 0276-603 Branches: Main feeder (green) ; Second feeder (purple); Third feeder (orange); Fourth feeder (light blue)
Distribution Substation	Transformer: 0,63 MVA; 50Hz; 10/0.4 kV; Ratio X/R= 9,95; OLTC with 5 tap-positions and ±10% voltage regulation; Copper losses=7,89 kW Connection type: Delta-Wye w/ Neutral;
Distributed Generation (Wind)	Parameters: $P_{active} = 1{,}2kW$; pf=1
Distributed Generation (Solar)	Parameters: $P_{active} = 5kW$;pf=1 ; 60% penetration in residential systems
Distributed Generation (Fuel Cell)	Parameters: $P_{active} = 25kW$; pf=1

TABLE 23 –SIMULATION DATA

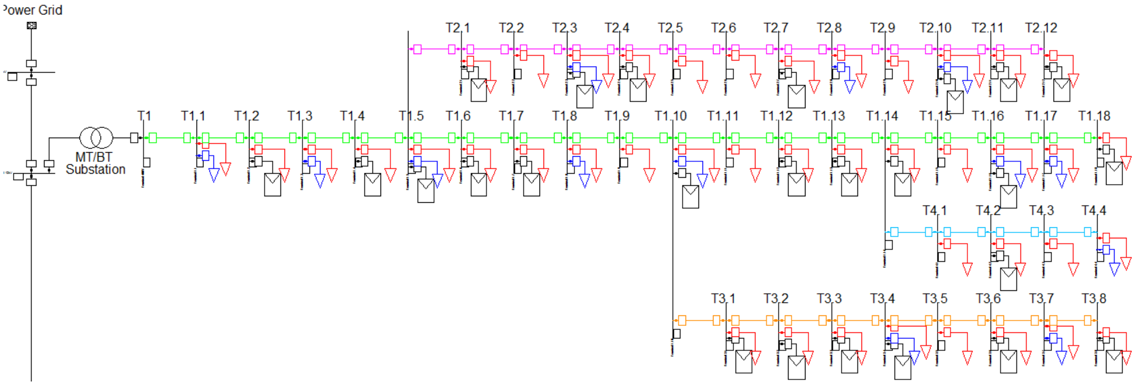

FIGURE 54 – SYSTEM 1 (RESIDENTIAL)

Source: DigSilent PF

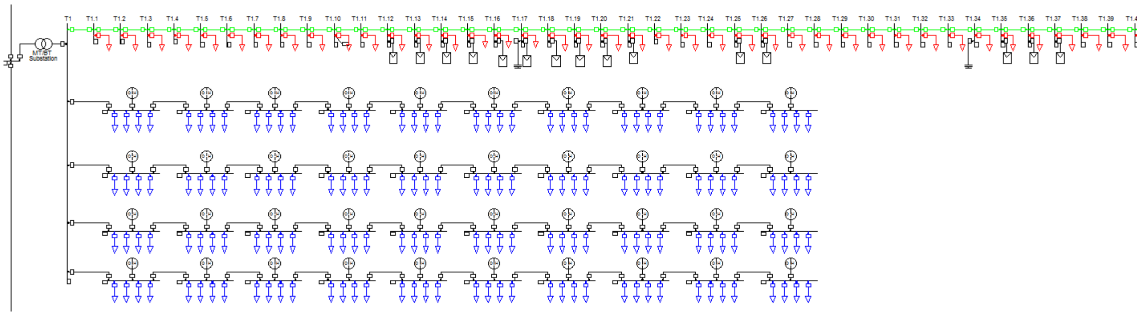

FIGURE 55 – SYSTEM 2 (COMMERCIAL)

Source: DigSilent PF

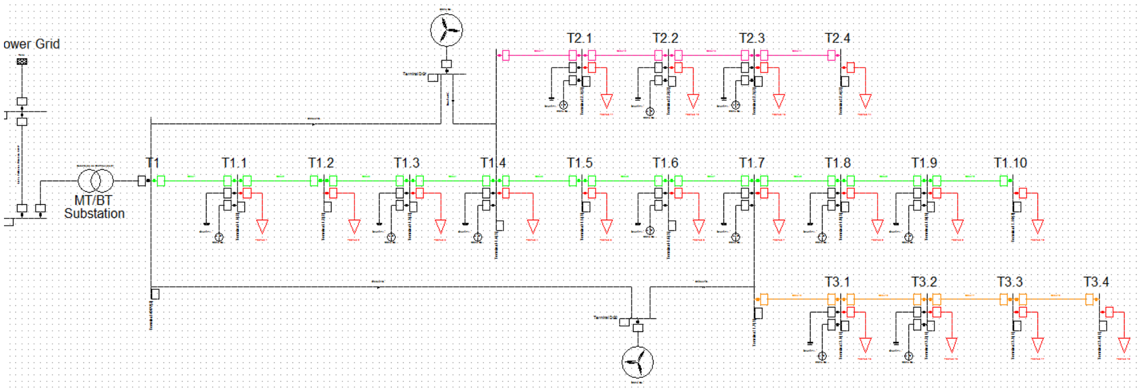

FIGURE 56 – SYSTEM 3 (INDUSTRIAL)

Source: DigSilent PF

As can be seen, static loads such as houses, stores or factories are colored red, while EVs are colored blue. Photovoltaic sources of power, fuel cells as well as wind turbines are represented by custom symbols. The number of EVs in commercial and industrial systems is quite larger than in the residential system, where this loads connect to the same node as the customer. In commercial/industrial system there are specific nodes where this loads connect, such as parks. In both the commercial/industrial system, each four charging stations are connected to a node equipped with a fuel cell, providing enough power for a quick charge.

In this case study the following assumptions are considered:

1) The minimum demand per load is equal to 10% of the load total demand, for e.g., during off-peak times.
2) For simplification, an EV charging station is modelled as an AC load, and will behave as a constant power load.
3) Distributed generators that depend on renewable energy sources (wind turbines and photovoltaic panels) may produce between 0% and 100% of its rated capacity, depending on daytime and weather conditions, i.e. wind strength and clear sun.
4) Distributed generation based on fuel cells always produce 100% of its rated capacity, and can be switched ON and OFF, depending on demand.

3.7.1 Results

Each system was first simulated without any voltage regulation implemented. The results for each system are shown next. There are two cases of interest: high demand with low generation and low demand with high generation. During high demand conditions, there is voltage drop when the DG is low. In the case of low demand, there is voltage rise when the DG is high. Both cases cause improper voltage levels that must be regulated. Besides voltage levels, also the cable load is analyzed for each case. The purpose of this case study will be to compare different solutions to provide the best voltage regulation possible, keeping the minimum cable load as possible.

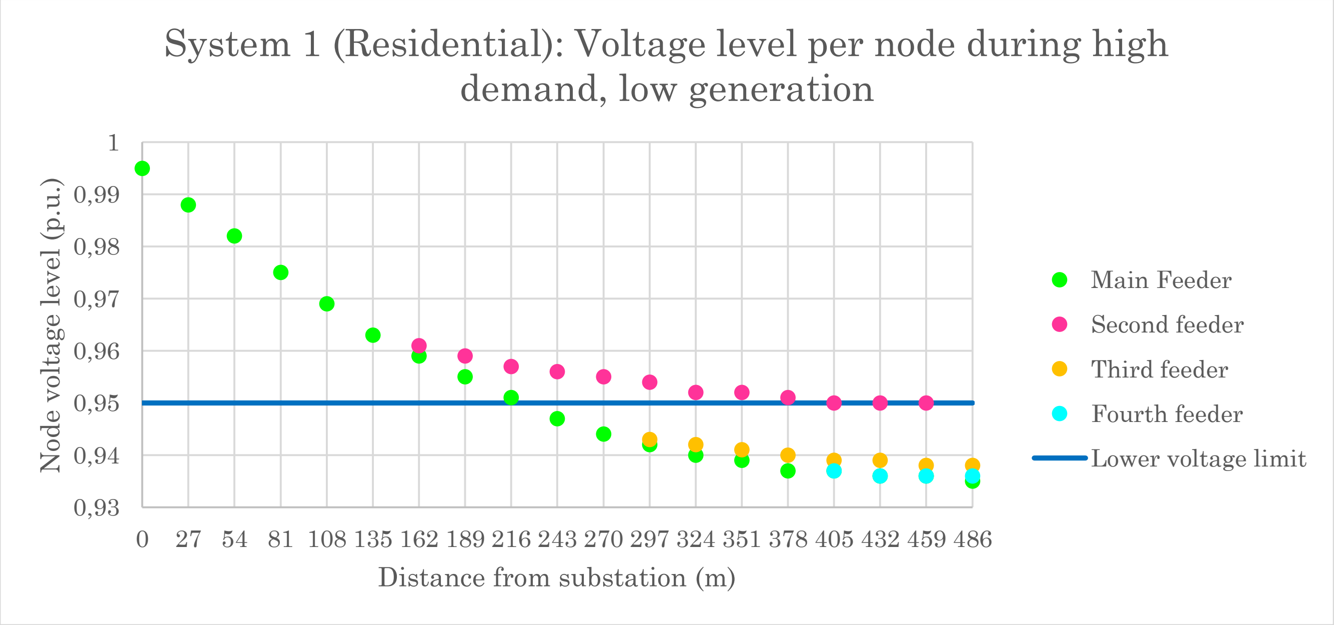

FIGURE 57 – HIGH DEMAND, LOW GENERATION CASE: VOLTAGE LEVEL PER NODE WITHOUT DIRECT VOLTAGE REGULATION

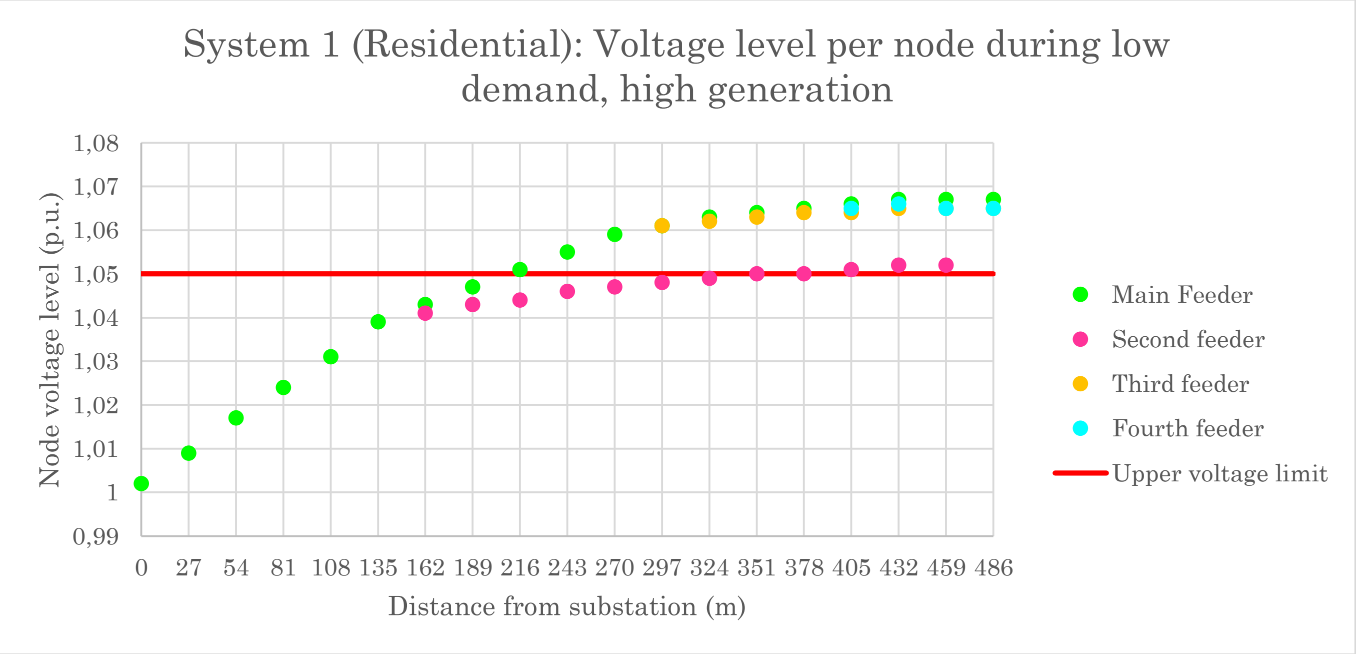

FIGURE 58 – LOW DEMAND, HIGH GENERATION CASE: VOLTAGE LEVEL PER NODE WITHOUT DIRECT VOLTAGE REGULATION

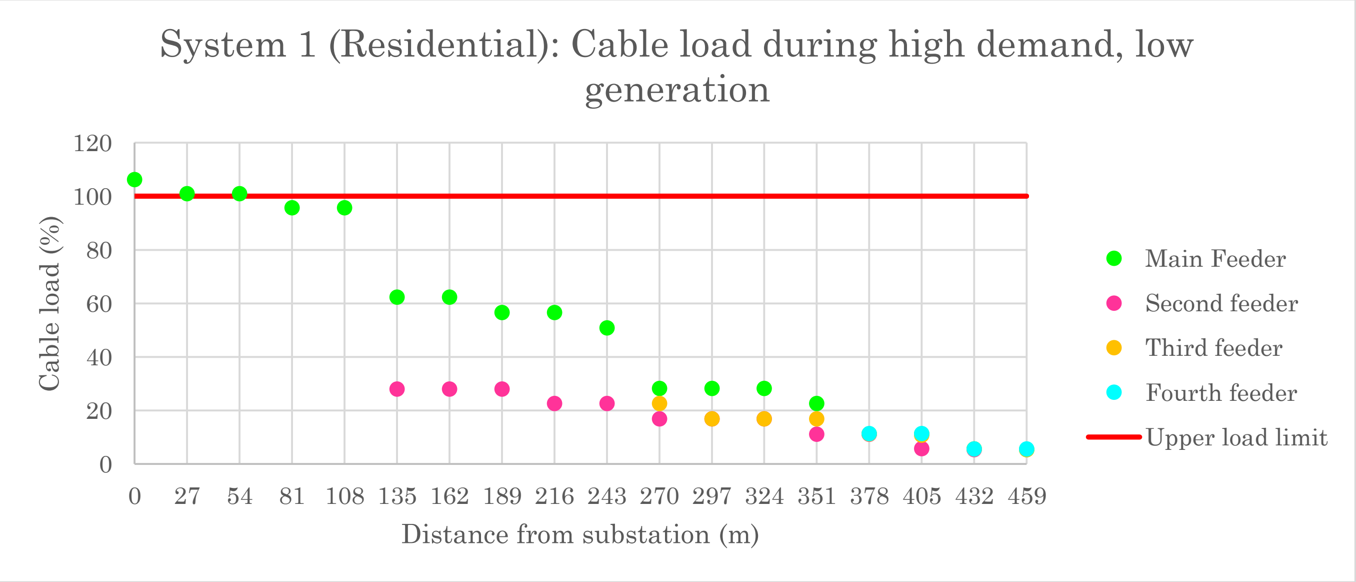

FIGURE 59 – HIGH DEMAND, LOW GENERATION CASE: OVERLOAD LEVEL PER FEEDER WITHOUT VOLTAGE REGULATION

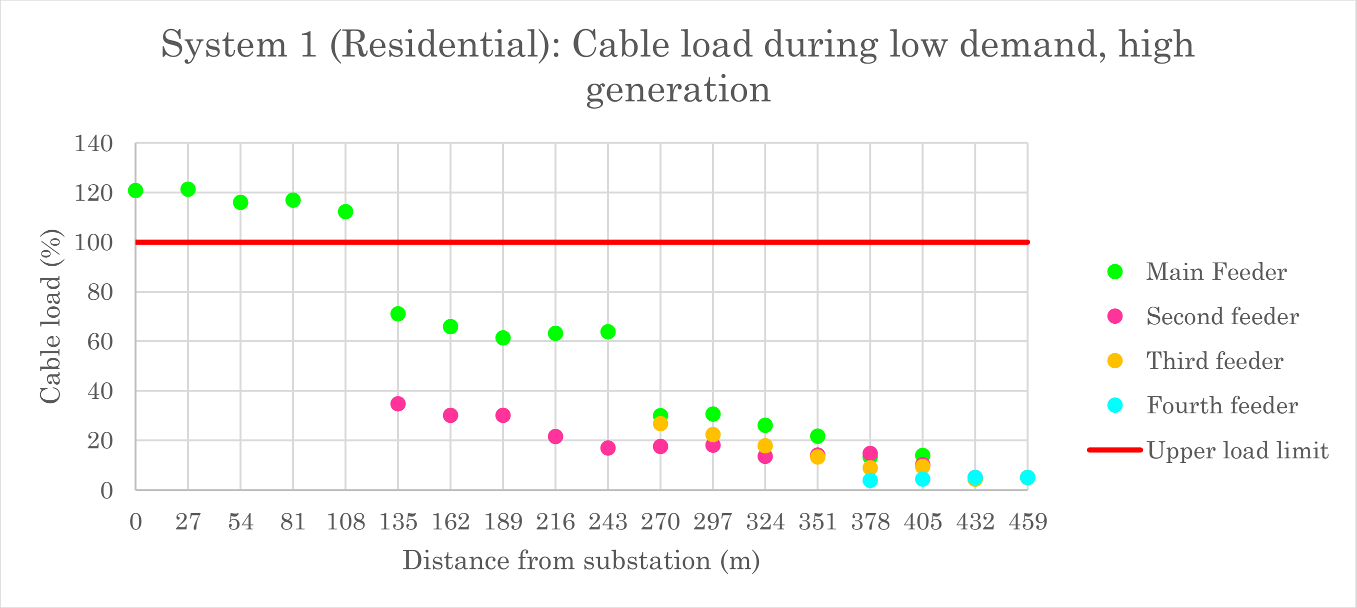

FIGURE 60 – LOW DEMAND W/ HIGH GENERATION: OVERLOAD LEVEL PER FEEDER WITHOUT VOLTAGE REGULATION

Voltage Regulators

Voltage regulators are probably the most common solution to solve voltage regulation issues and are widely used by distribution utilities to provide a reliable voltage supply. [22] In this case study, two different strategies using VR for proper voltage regulation on system 3 are analyzed. The location placement of these devices may give different results on voltage regulation. Thus different cases are considered:

1. VR along the feeder, between loads.
2. VR between the feeder and the load.

In both cases VRs are placed right before the point where the voltage level reaches a minimum value. It is also important to notice that the low demand case in this simulation is divided in "daytime" and "nighttime". The difference between the two is the presence of EVs charging during nighttime (between 24h and 7h) and their absence during daytime (between 8h and 16h). It is assumed that DG are composed by wind turbines, and therefore their maximum generation is achieved at night, since there is more wind during this period. The simulation data and results for each case are shown next.

Voltage Regulator used	Three-phase Auto-transformer; Wye-Wye; Neutral on both sides; 1,6 MVA; 0,4/0,4 kV; 50Hz; Copper losses=6kW; ±10% regulation with 32 taps; regulation per tap=0,625%, According to Int. Std. IEEE C57.15-1999
VR along the feeder, between loads (case 1)	3 total VR used; locations: (nodes) 1.3; 1.7; 2.4
VR between the feeder and the load (case 2)	42 AVRs used; locations: between feeder and the load

TABLE 24 – SIMULATION DATA FOR VOLTAGE REGULATORS ON SYSTEM 3

VRs may also provide proper voltage regulation on distribution systems with DG present. In this case they may be used in coordination with the loads and distributed generators, receiving relevant data from these and acting accordingly with the demand level.

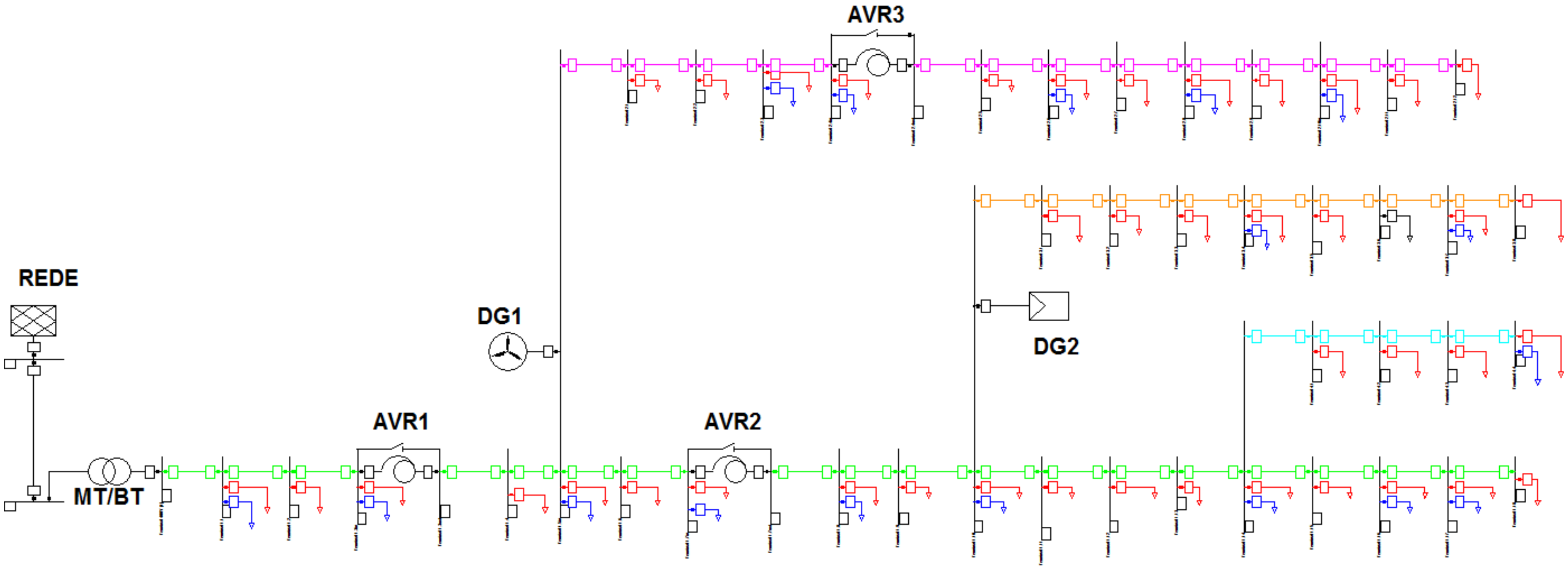

FIGURE 61 – SYSTEM 1 USING VOLTAGE REGULATORS IN SERIES (CASE 1)

Source: DigSilent PF

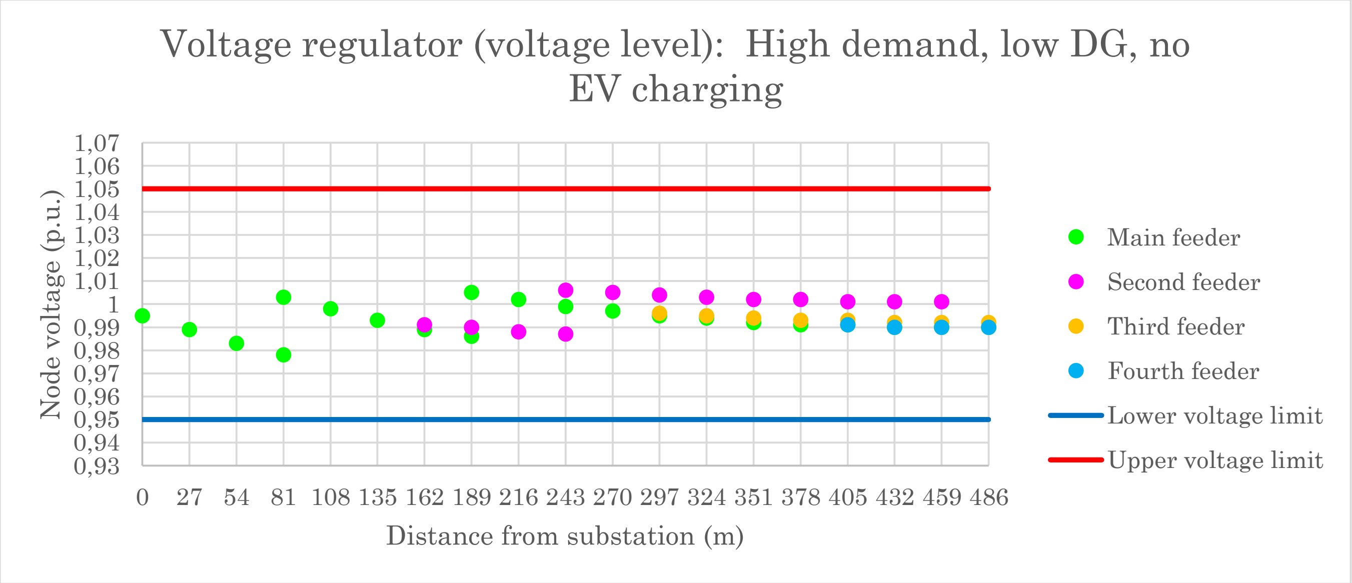

FIGURE 62 – HIGH DEMAND, LOW GENERATION, NO EV CHARGING: NODE VOLTAGE USING VOLTAGE REGULATORS IN SERIES

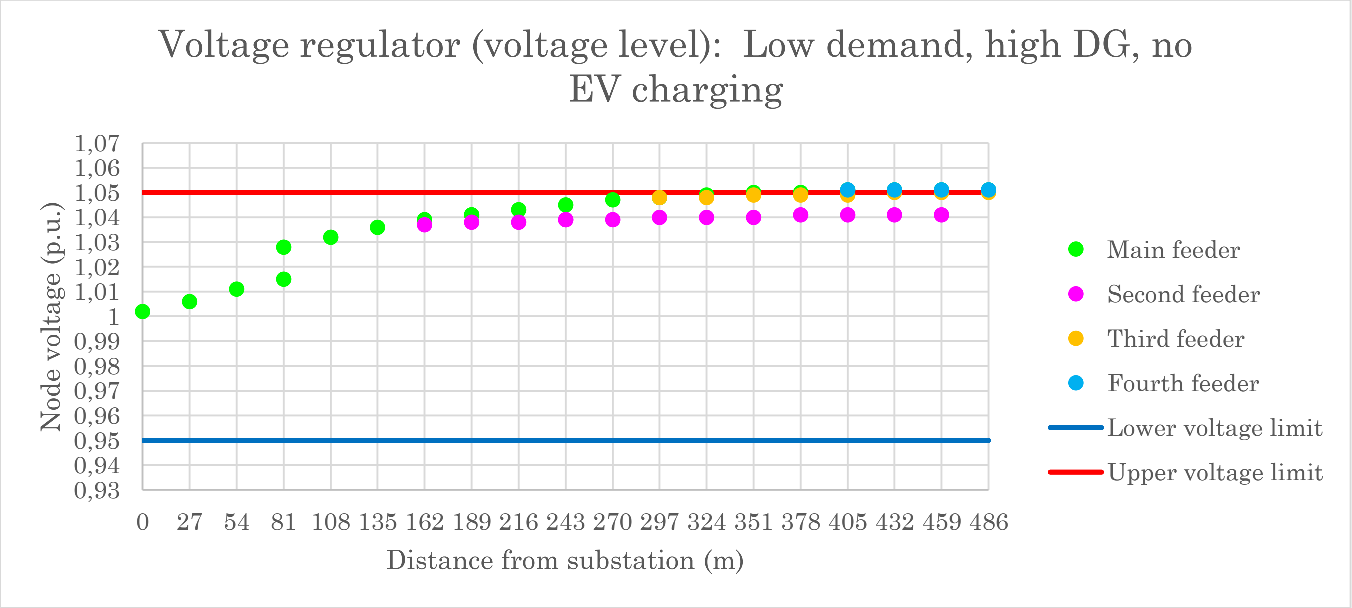

FIGURE 63 – LOW DEMAND, HIGH GENERATION, NO EV CHARGING: NODE VOLTAGE USING VOLTAGE REGULATORS IN SERIES

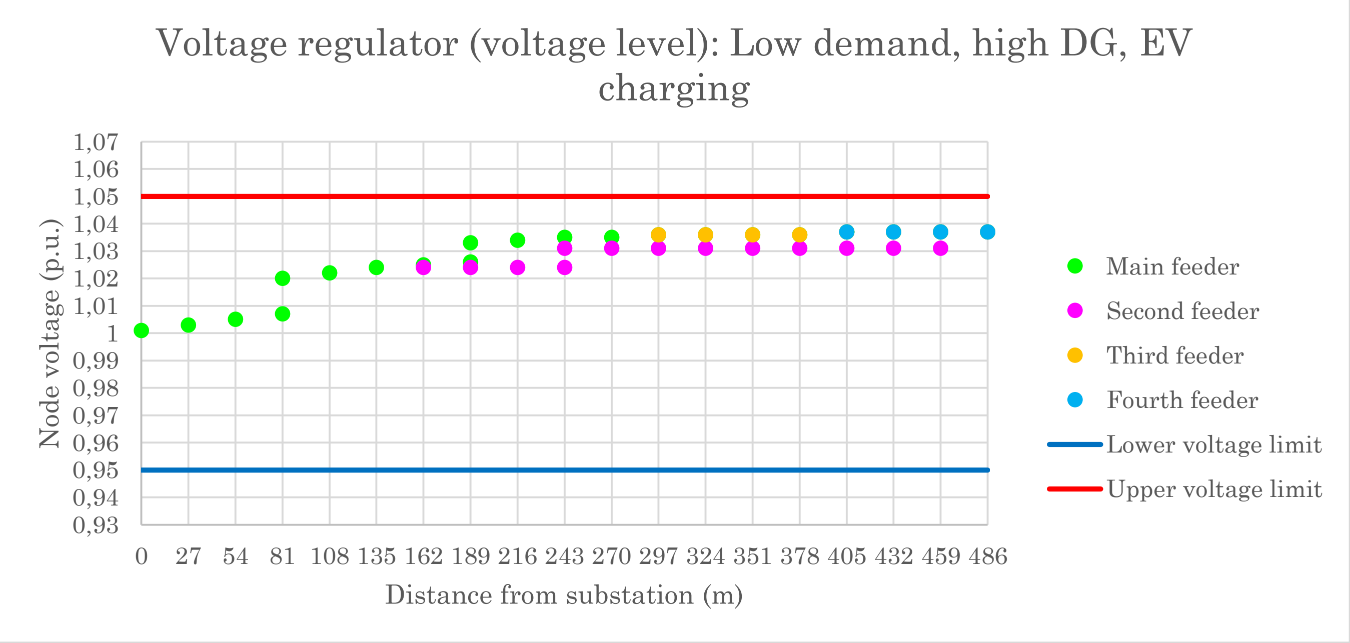

FIGURE 64 – LOW DEMAND, HIGH GENERATION, EV CHARGING: NODE VOLTAGE USING VOLTAGE REGULATORS IN SERIES

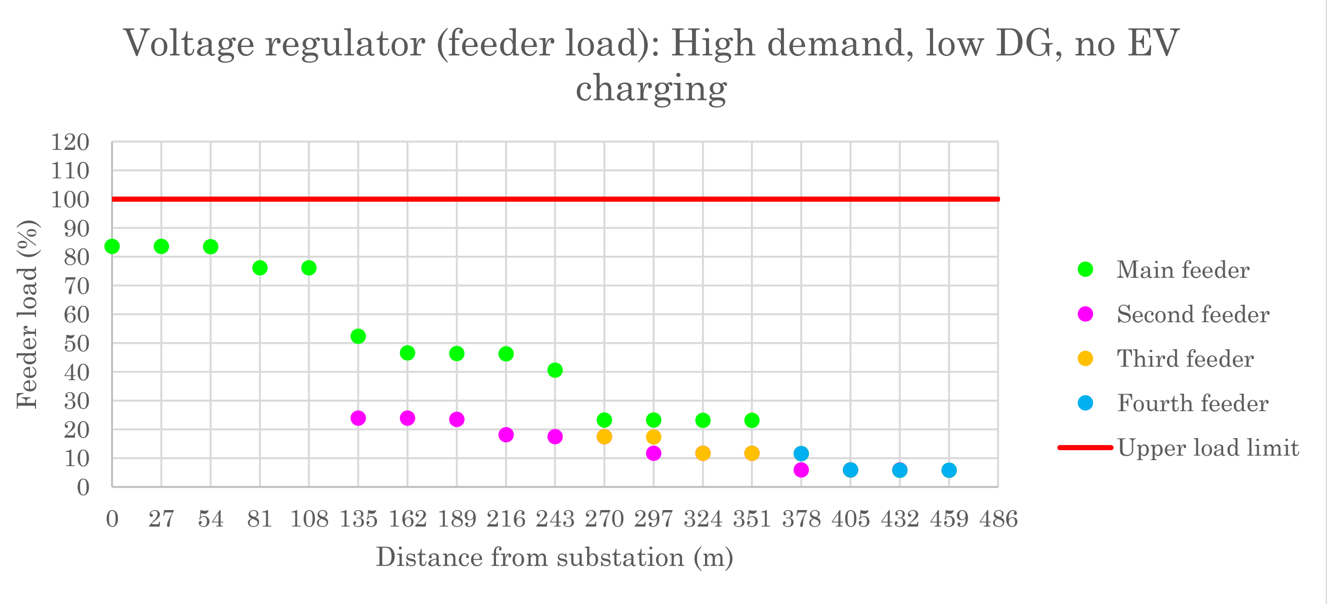

FIGURE 65 – HIGH DEMAND, LOW DG, NO EV CHARGING: FEEDER LOAD USING VOLTAGE REGULATORS IN SERIES

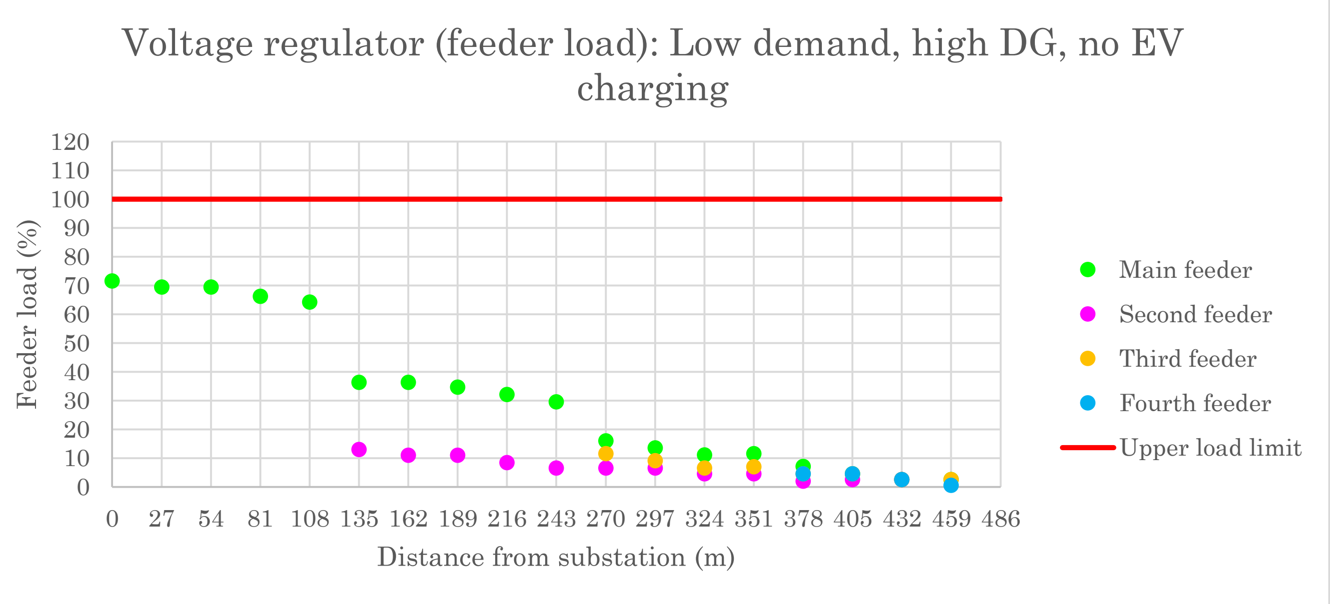

Figure 66 – Low demand, high DG, no EV charging: feeder load using voltage regulators in series

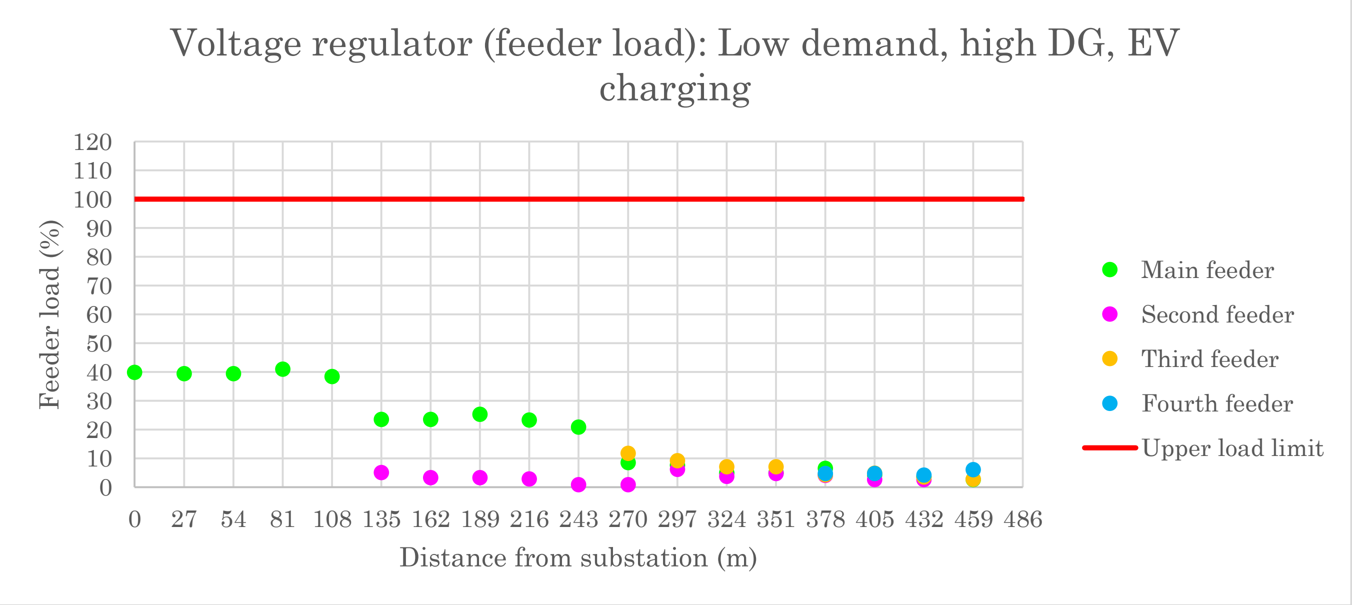

Figure 67 – Low demand, high DG, EV charging: feeder load using voltage regulators in series

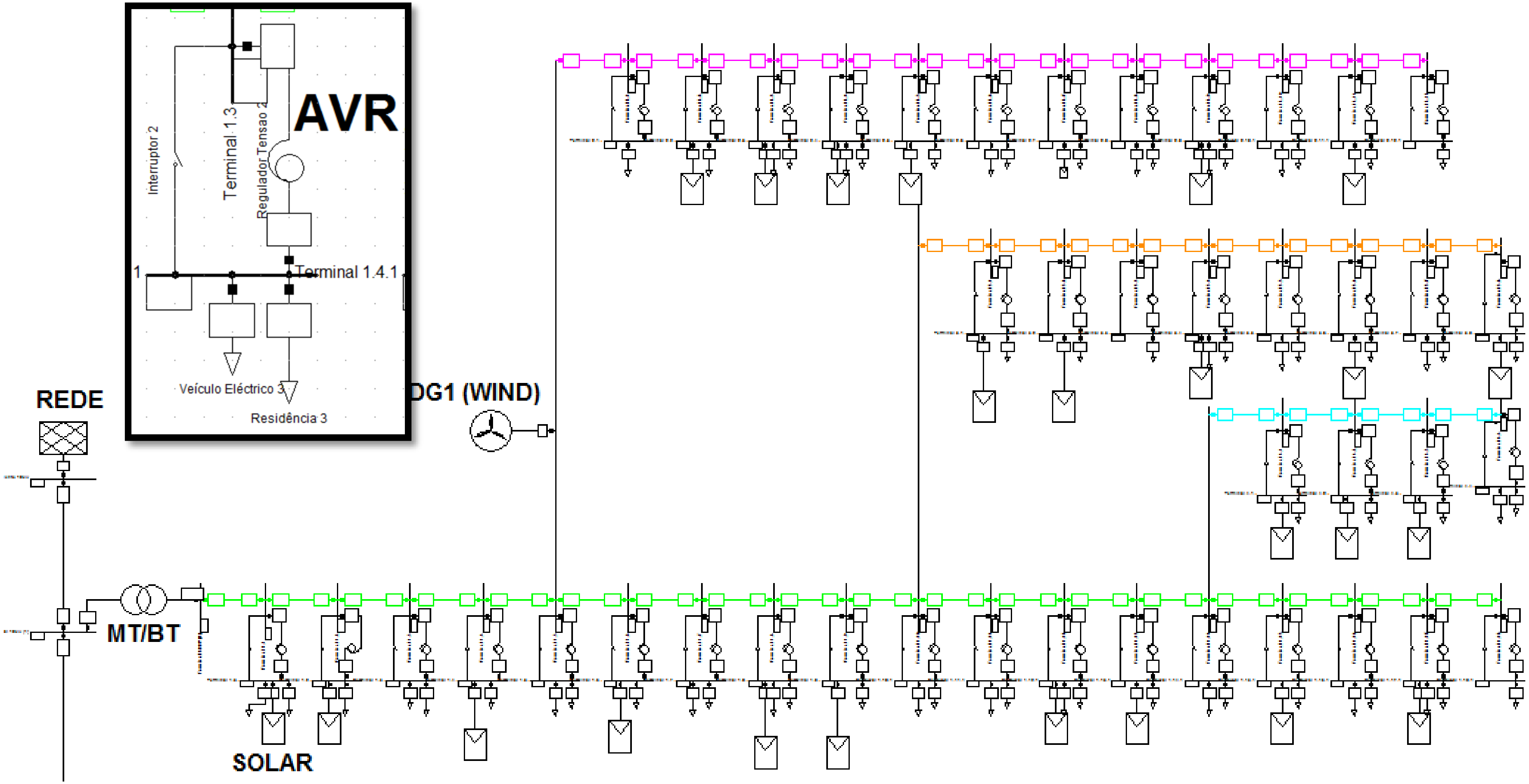

FIGURE 68 – SYSTEM 1 USING VOLTAGE REGULATORS IN PARALLEL (CASE 2)

Source: DigSilent PF

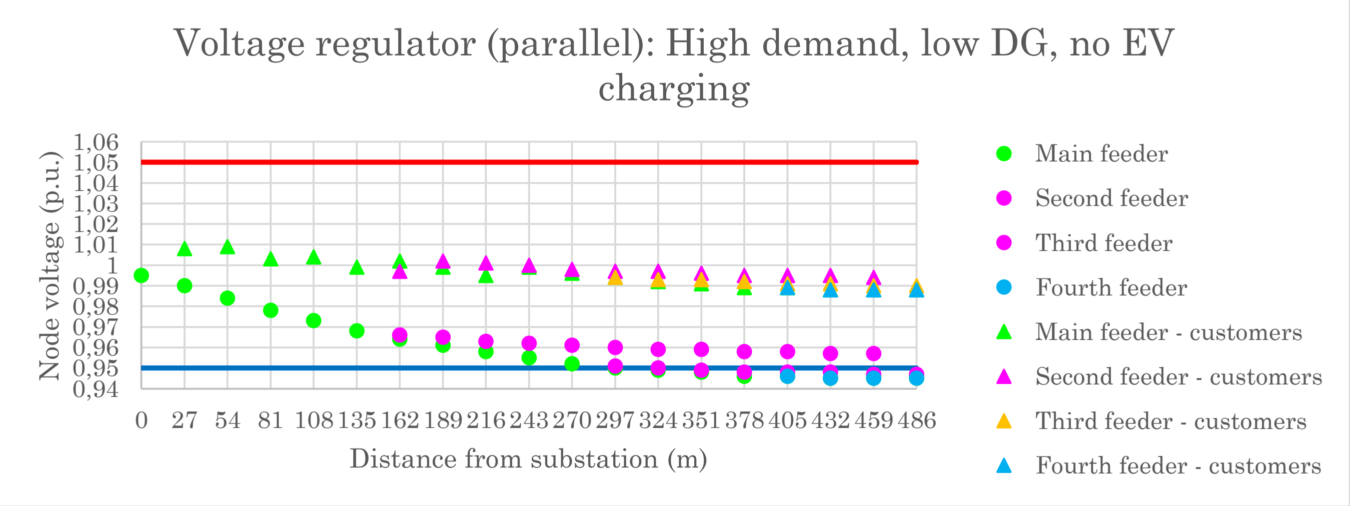

FIGURE 69 – HIGH DEMAND, LOW DG, NO EV CHARGING: VOLTAGE LEVELS USING VOLTAGE REGULATORS IN PARALLEL

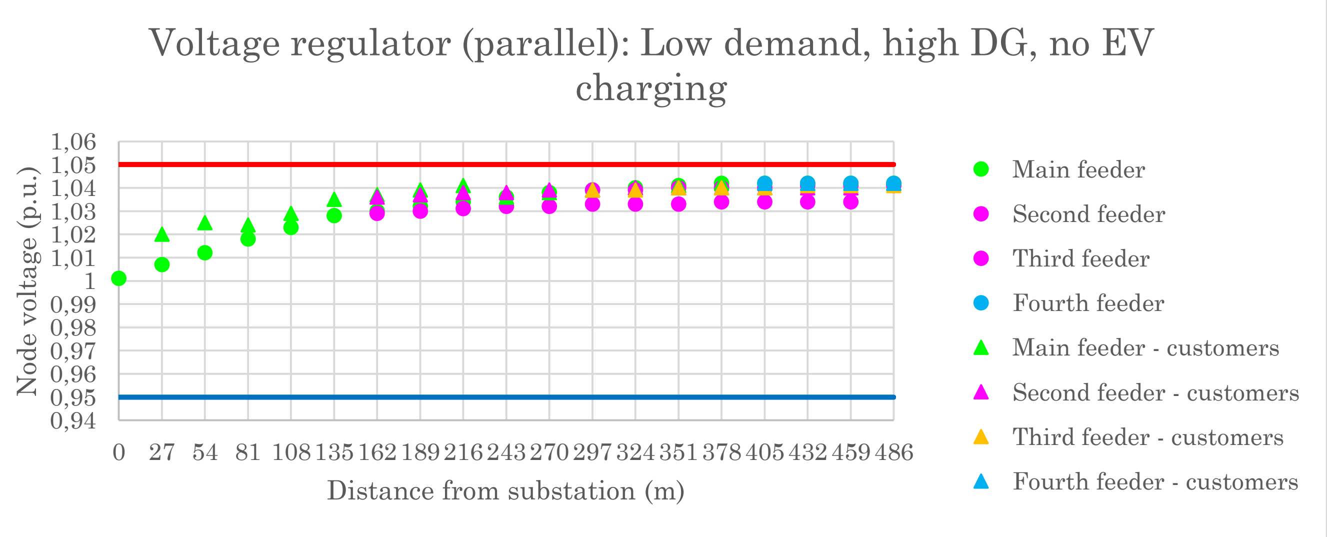

FIGURE 70 – LOW DEMAND, HIGH DG, NO EV CHARGING: VOLTAGE LEVELS USING VOLTAGE REGULATORS IN PARALLEL

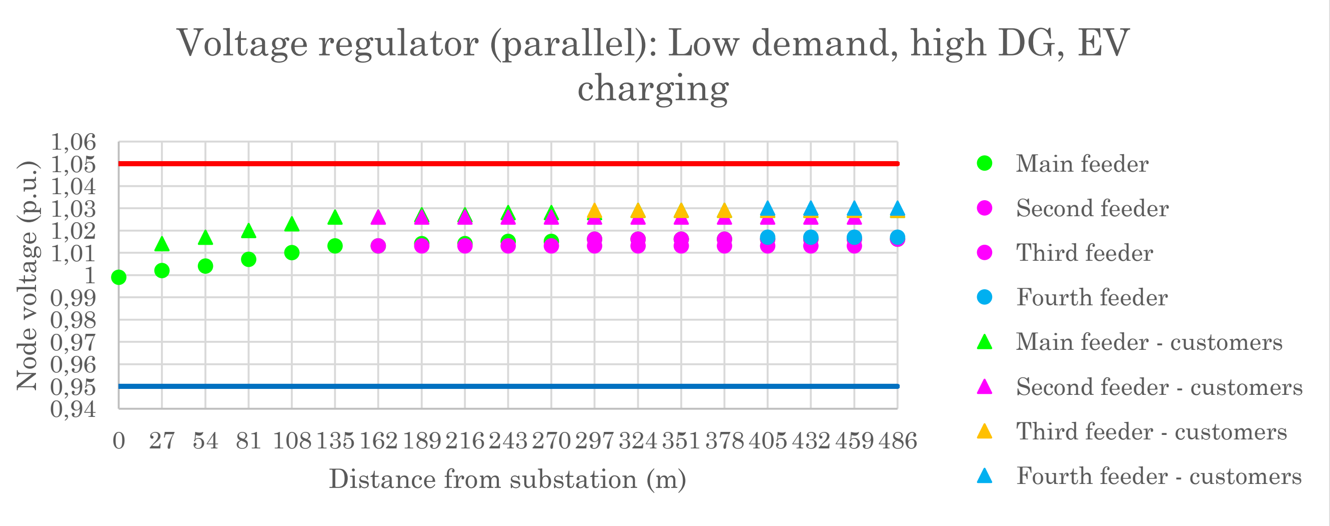

FIGURE 71 – LOW DEMAND, HIGH DG, EV CHARGING: VOLTAGE LEVELS USING VOLTAGE REGULATORS IN PARALLEL

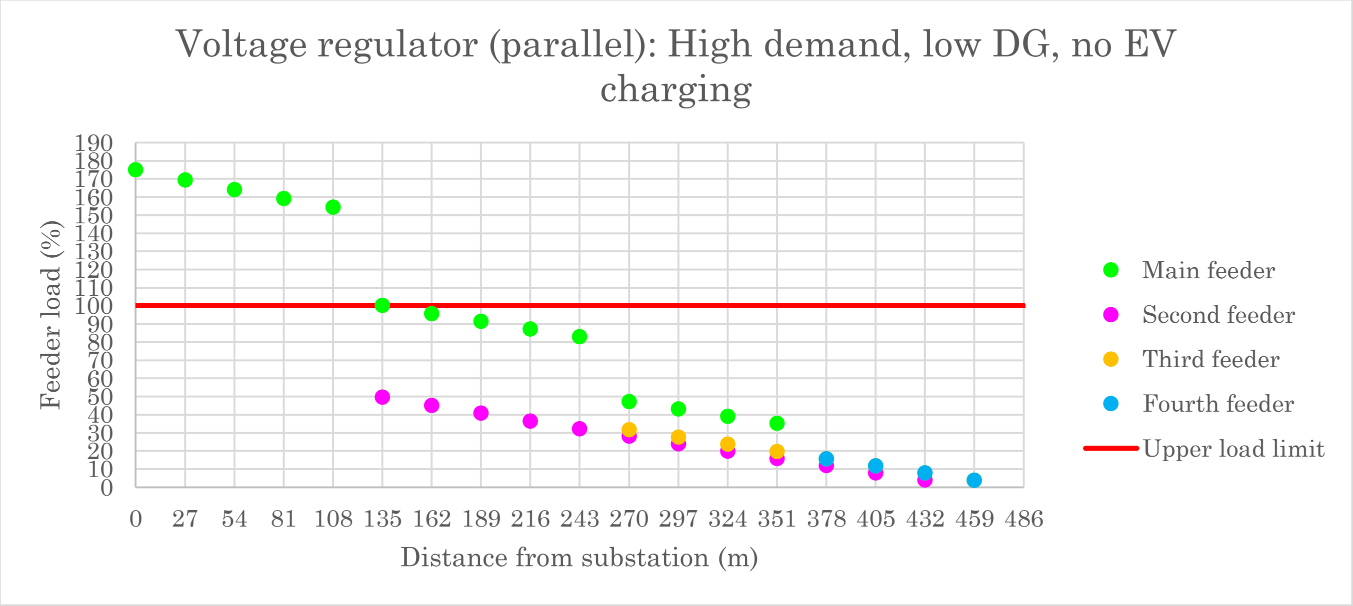

Figure 72 – High demand, low DG, no EV charging: feeder load using voltage regulators in parallel

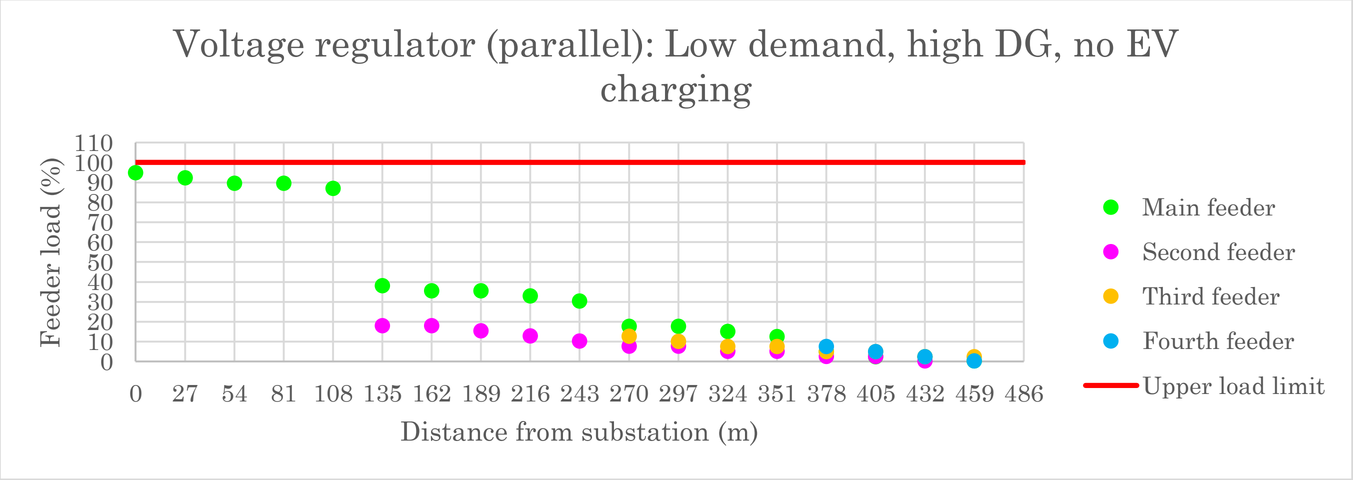

Figure 73 – Low demand, high DG, no EV charging: feeder load using voltage regulators in parallel

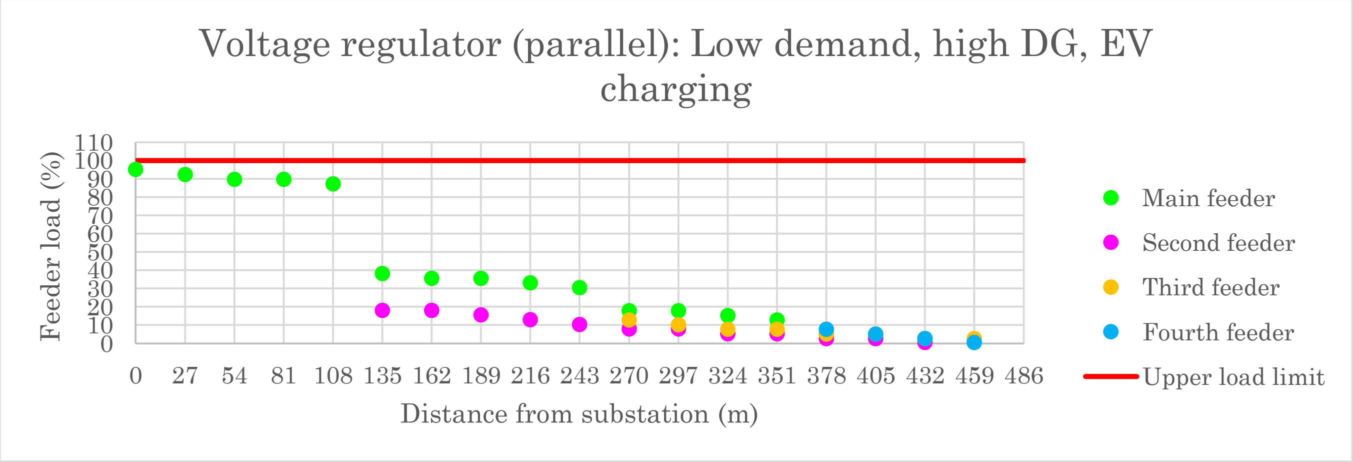

Figure 74 – Low demand, high DG, EV charging: feeder load using voltage regulators in parallel

As can be seen from the above two tables, VRs are able to provide effective voltage regulation when applied between the feeder and the load. However in this case VRs are not able to regulate the voltage level along on the feeder, which results in excessive voltage drop/rise. Therefore, using VRs along the feeder may be a better solution, since it provides the same effectiveness than using a VR per load, and it is a much cheaper strategy, since it only requires 3 VRs instead.

One clear problem by using VRs in parallel that can be seen from the above charts is that using excessive voltage regulators in a system causes too much current to be drawn from the external grid, leading to overload in the feeders close to the substation. This is a major disadvantage of using large numbers of VRs.

Voltage regulators might provide effective voltage regulation during high demand situations, but there is a strong drawback on low demand cases, where the use of these devices – both in series or parallel – might cause overvoltage on the nodes. This happens because the use of VRs causes a small increase of the input voltage, even when it is not needed.

Regulation through the substation – OLTC transformer

Another way to provide voltage regulation on a distribution feeder might be using a special substation transformer that is able to change the voltage level on its output to provide voltage regulation at the feeder supply point, by changing its taps connections, and therefore ensure that the last load is properly supplied in both cases of low and high demand. This would require some type of control system between the OLTC and a voltage level indicator on the last load. During low demand its taps would change to decrease the voltage level, and during high demand they would change to increase it.

However, the results show that using only a tap-changing voltage for regulation is not enough to provide an effective voltage regulation when the system is composed by high demand loads (25kW), with higher coincidence factors (all-electric customers), or when the system has very long feeders (rural/industrial networks), due to the line impedance. This happens because the transformer can only provide voltage regulation at the substation, while the voltage disturb occurs far from it. It did, however, provide good regulation for more standard loads (12kW).

An idea to solve this issue might be increasing the number of possible tap-positions, in order to increase the maximum tap regulation. However this idea fails because excessive tap-changing regulation would cause undervoltage/overvoltage at the loads near the substation, before it could properly adjust the system voltage level, which is a drawback of this type of regulation.

Thus, other types of voltage regulation that are not restricted to the substation may be better for regulation high demand systems.

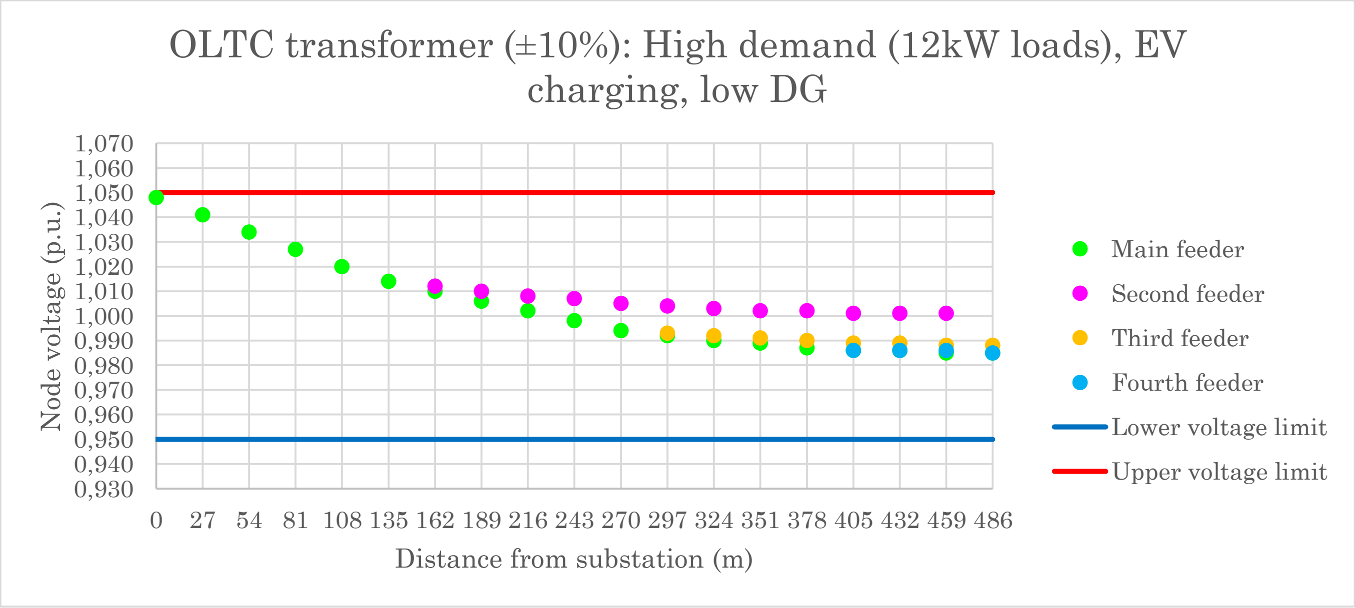

FIGURE 75 – HIGH DEMAND, EV CHARGING, LOW DG: VOLTAGE LEVEL USING OLTC IN SUBSTATION

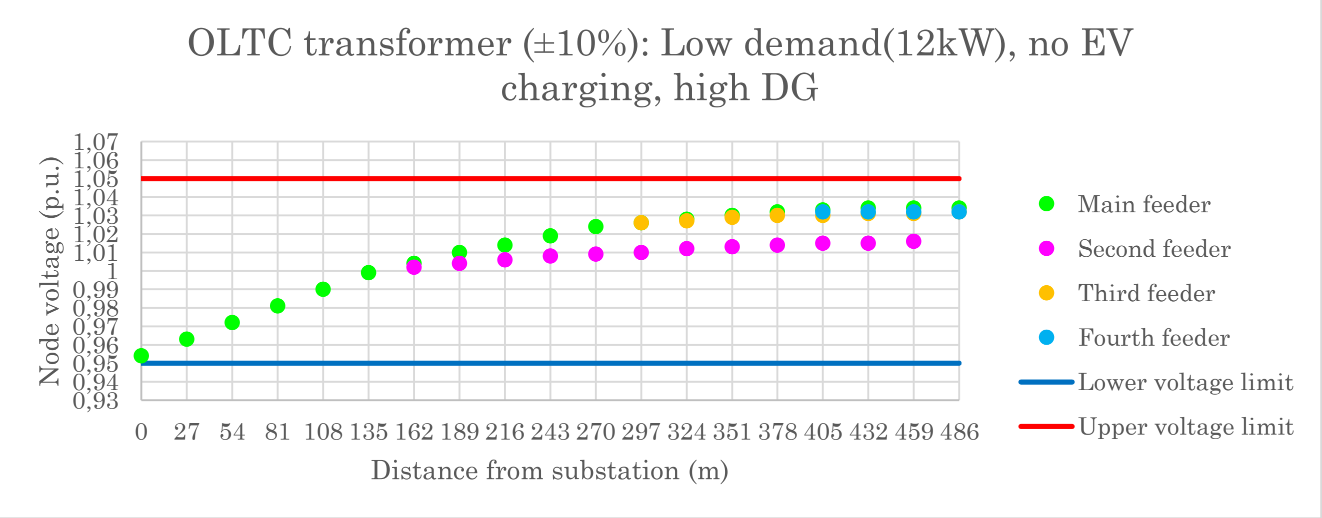

FIGURE 76 – LOW DEMAND, NO EV CHARGING, HIGH DG: VOLTAGE LEVEL USING OLTC IN SUBSTATION

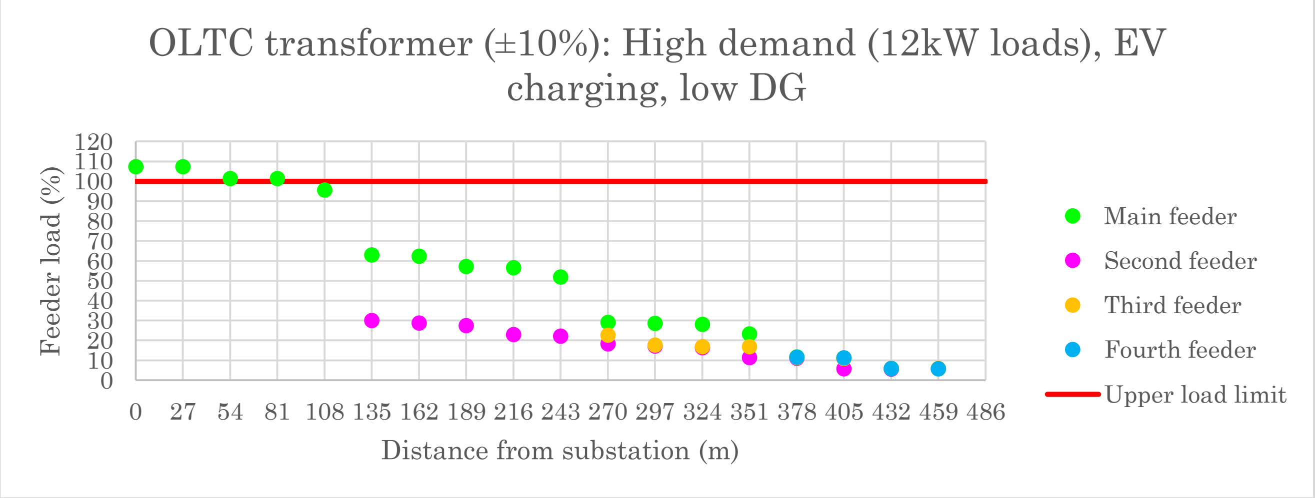

FIGURE 77 – HIGH DEMAND, EV CHARGING, LOW DG: FEEDER LOAD USING OLTC IN SUBSTATION

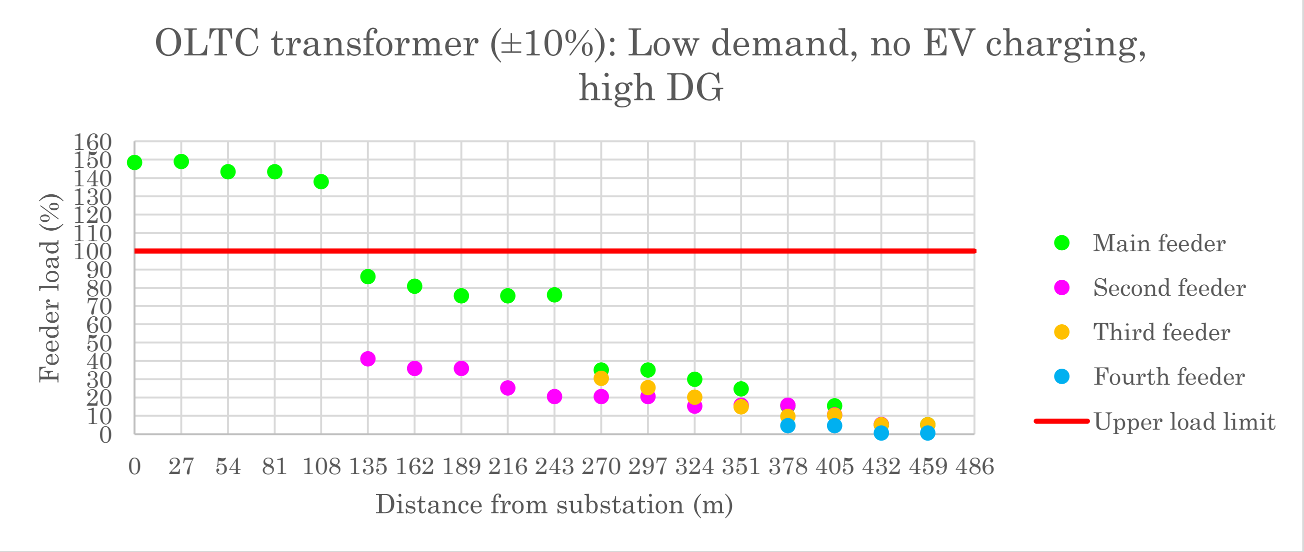

FIGURE 78 – LOW DEMAND, NO EV CHARGING, HIGH DG: FEEDER LOAD USING OLTC IN SUBSTATION

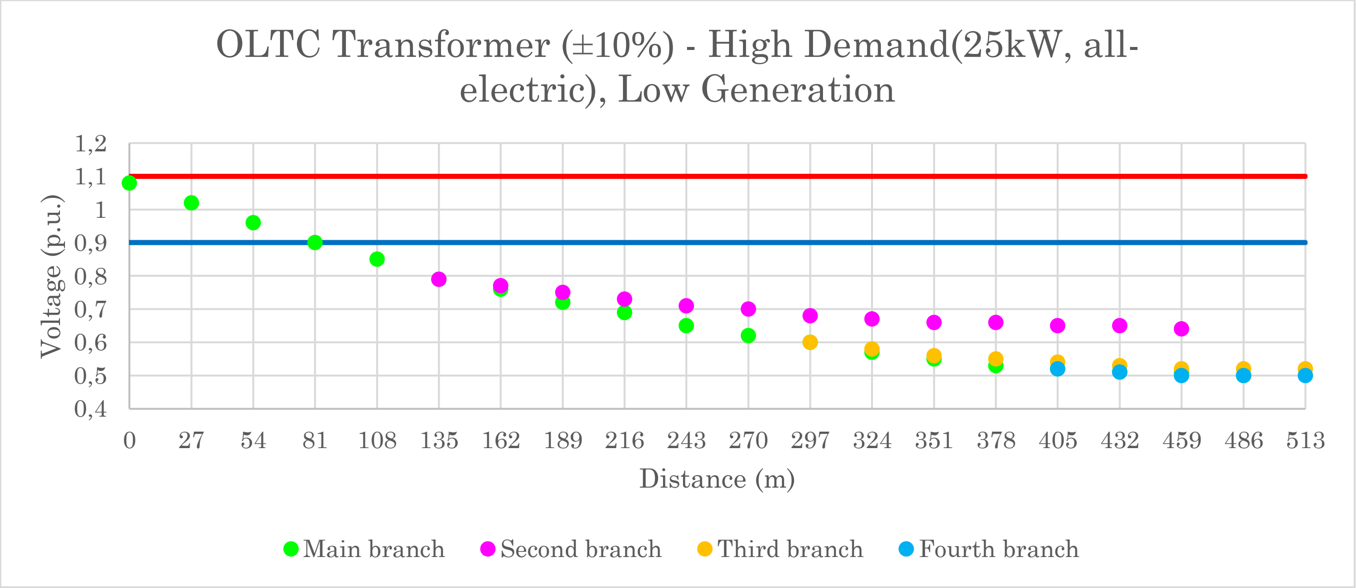

Figure 79 – High demand, low DG: voltage level using ±10% regulation

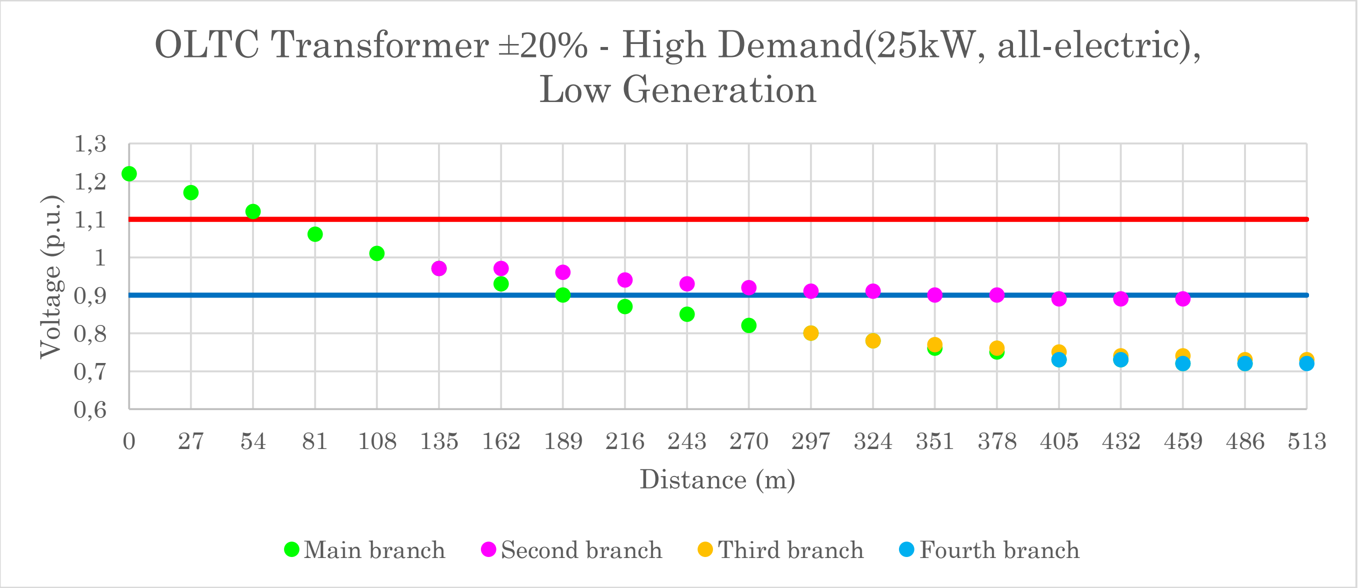

Figure 80 – High demand, low DG: voltage level using ±20% regulation

ESU - Energy Storage Units

In the low demand case, the reason why the voltage rise to much is due to the inversion of the load flow, and because most of the power generated is not being consumed and its returning to the transmission system. Therefore, instead of delivering it back to transmission, unused power could be kept for later used when the demand rises again. This could be accomplished with storage devices – batteries – that would be connected on the same system as the customers, charge when the demand drops and discharging when the demand rises. It would also require a control system to regulate the charge/discharge of the batteries accordingly to the required voltage regulation on the feeders. The location of the storage battery bank, as well as the technical details of the batteries and the simulation results are shown next.

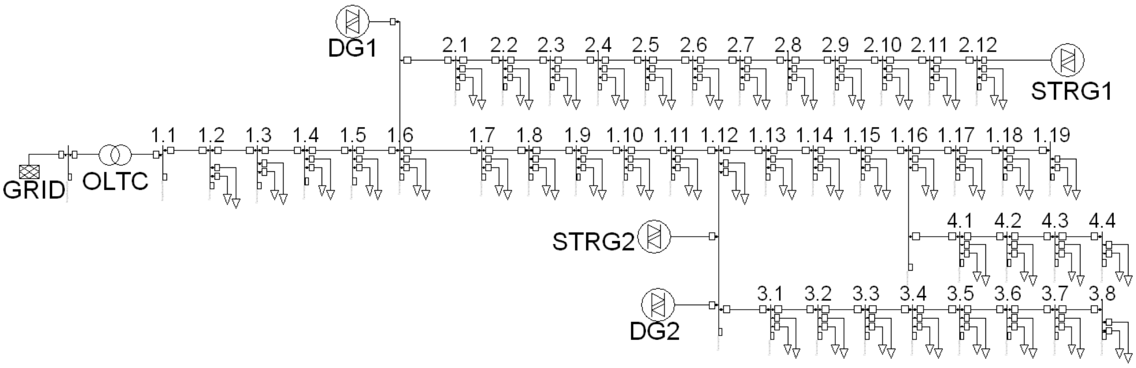

Figure 81 – System 1 with a storage bank and DG (wind)

Source: DigSilent PF

Battery Bank (STRG1 and STRG2)	Rated power=1 MVA, up to 2MVA[1]; Rated voltage=230 V AC, up to 52 kV AC with LV/MV transformer; Rated capacity= up to 500 kWh;

Table 25 – Technical data for the battery bank

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[1] According to Siemens SIESTORAGE technology

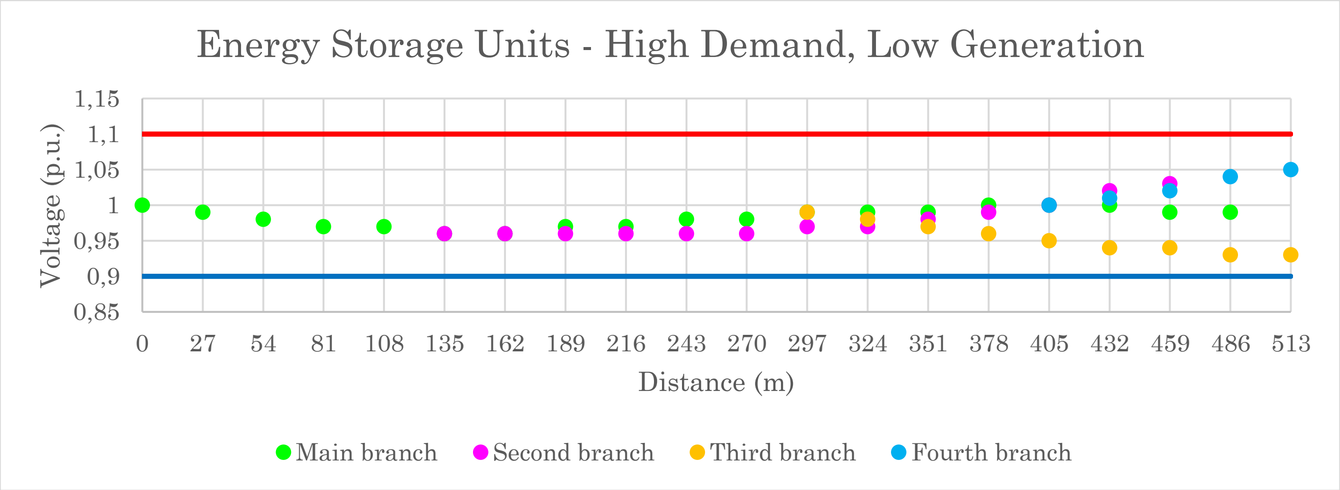

FIGURE 82 – HIGH DEMAND, LOW DG: VOLTAGE LEVEL USING ESUS

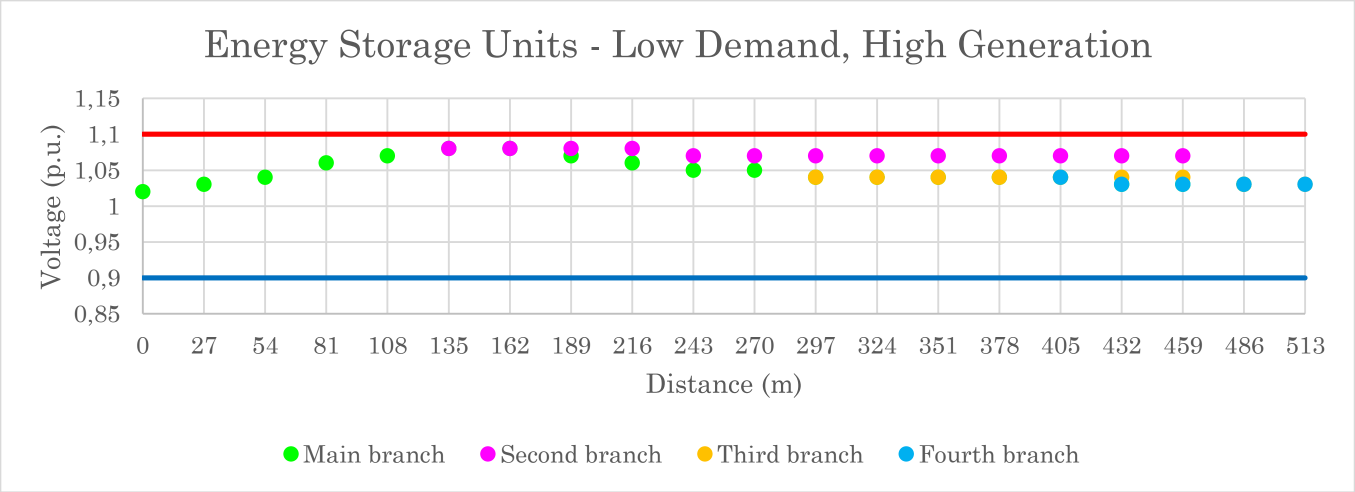

FIGURE 83 – LOW DEMAND, HIGH DG: VOLTAGE LEVEL USING ESUS

	High demand, low generation (p.u.)	Low demand, high generation (p.u.)
No ESUs	88,46%	23,70%
Using ESUs	1%	0,97%

TABLE 26 – ESU: VOLTAGE REGULATION REQUIRED FOR SYSTEM 1 (RESIDENTIAL)

System 2 (commercial) and 3 (industrial) also shown similar results for the ESU solution:

	High demand, low generation (p.u.)	Low demand, high generation (p.u.)
No ESUs	60,65%	35,29%
Using ESUs	3,16%	1,93%

TABLE 27 – ESUS: VOLTAGE REGULATION REQUIRED FOR SYSTEM 2 (COMMERCIAL)

	High demand, low generation (p.u.)	Low demand, high generation (p.u.)
No ESUs	20,73%	12,28%
Using ESUs	8,69%	2,02%

TABLE 28 – ESUS: VOLTAGE REGULATION REQUIRED FOR SYSTEM 3 (INDUSTRIAL)

Increased AC voltage supply

Besides the storage solution, a different approach is proposed to solve the current issue.

From equation (20), the voltage drop increases because the line impedance and the power consumed by the load. Since the load is assumed to grow in the next five years, the power consumption will surely increase, and so will the voltage drop. The inclusion of more DG will address the increasing power demand, but more voltage regulation will be required to avoid voltage rise problems.

Also from equation (20), it can be seen that if the voltage level at the receiving point increases, the voltage variation will decrease. Thus, if the system voltage is increased, the effect of voltage drop under high demand and the voltage rise under low demand are both minimized.

A change in the actual voltage level used in power distribution also has some constraints for the utility company. First, it requires the installation of a new transformer per customer – increasing costs of material, installation and maintenance for the utility - since most appliances are not designed to operate with a higher voltage. However, in the future this condition could probably change, as manufacturers change the current appliance designs to work with higher power supplies. Second, since the voltage is higher and the current may be higher as well – due to load grow – the power drawn from the transmission system will increase substantially, especially during low generation. This will require the OLTC and some feeder segments to be upgraded, also increasing costs. The new system and the new simulation results are shown next.

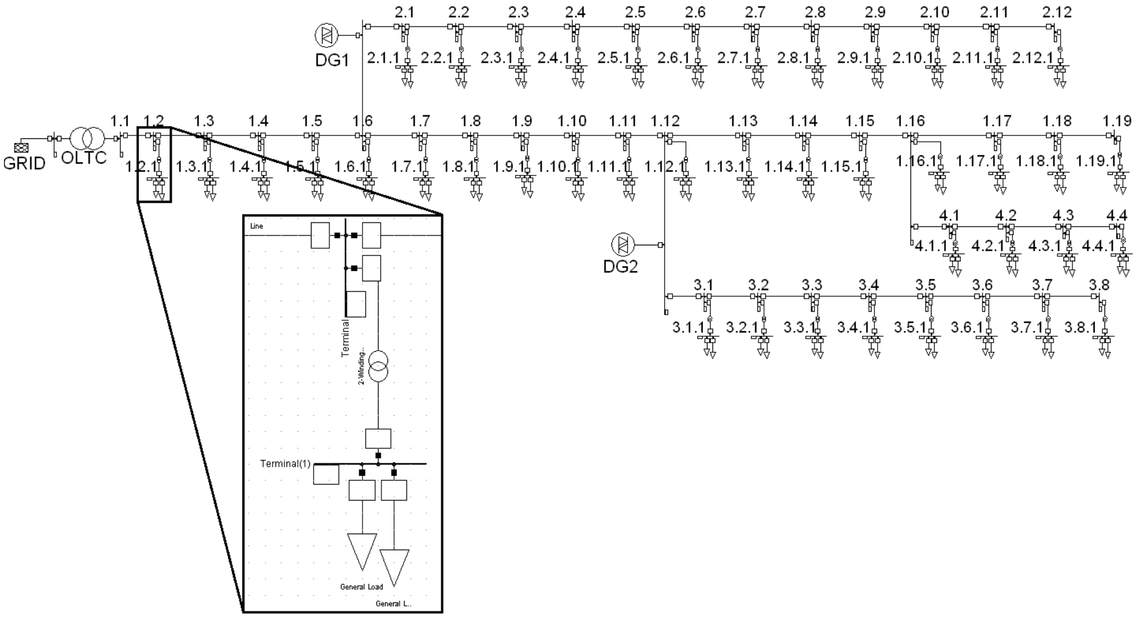

FIGURE 84 – SYSTEM 1 WITH A HIGHER AC VOLTAGE SUPPLY

Source: DigSilent PF

During this simulation the voltage level was doubled and the OLTC was upgraded. Also a new transformer per customer was added, as shown in the above figure. The technical data as well as the simulation results are shown next.

Distribution transformer (OLTC)	3 MVA; 50Hz; 10/0.8 kV; Delta-Wye ; Ratio X/R= 8,5; Copper losses=21kW; OLTC
Distribution voltage level	V=800 V AC
Transformer (per load)	0,1 MVA; 50Hz; 0.8/0.4 kV; Delta-Wye with Neutral; Ratio X/R= 2,29; Copper losses=1,6kW

TABLE 29 – TECHNICAL DATA FOR INCREASED AC VOLTAGE SIMULATION

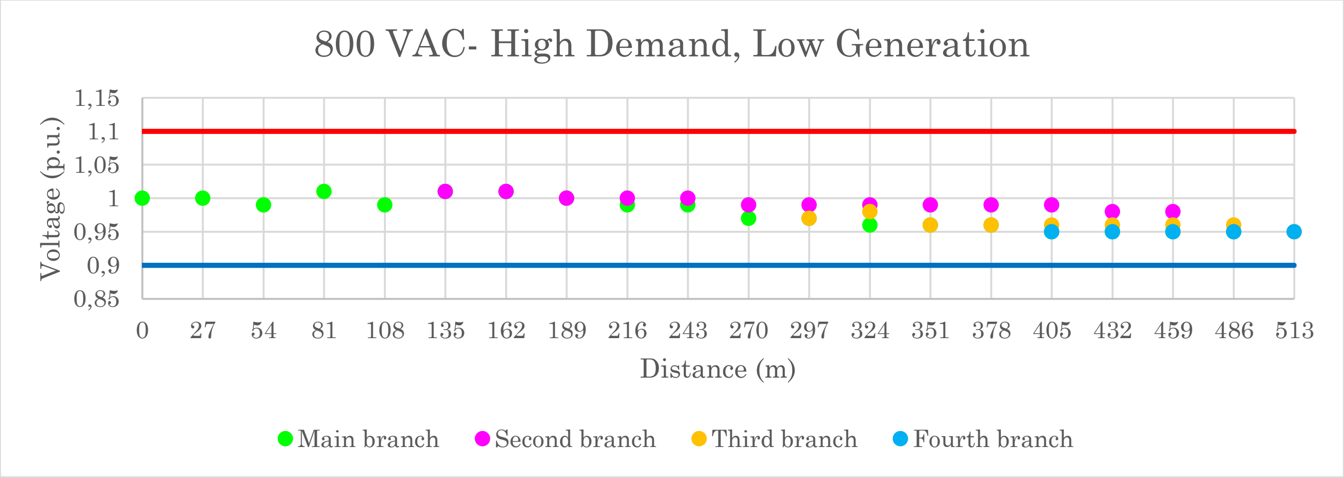

Figure 85 – High Demand, low Generation: voltage level using higher supply voltage

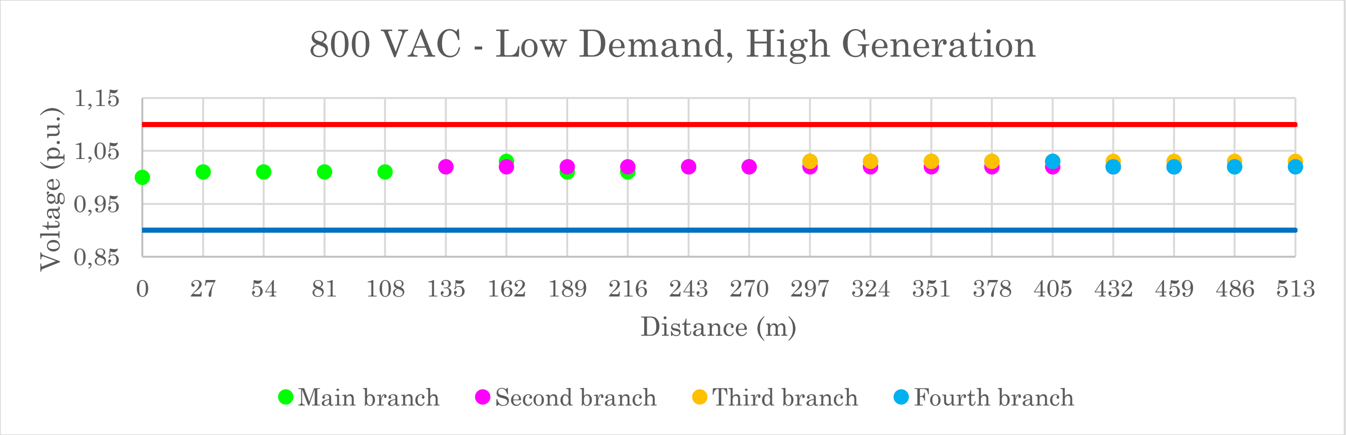

Figure 86 – Low Demand, high Generation: voltage level using higher supply voltage

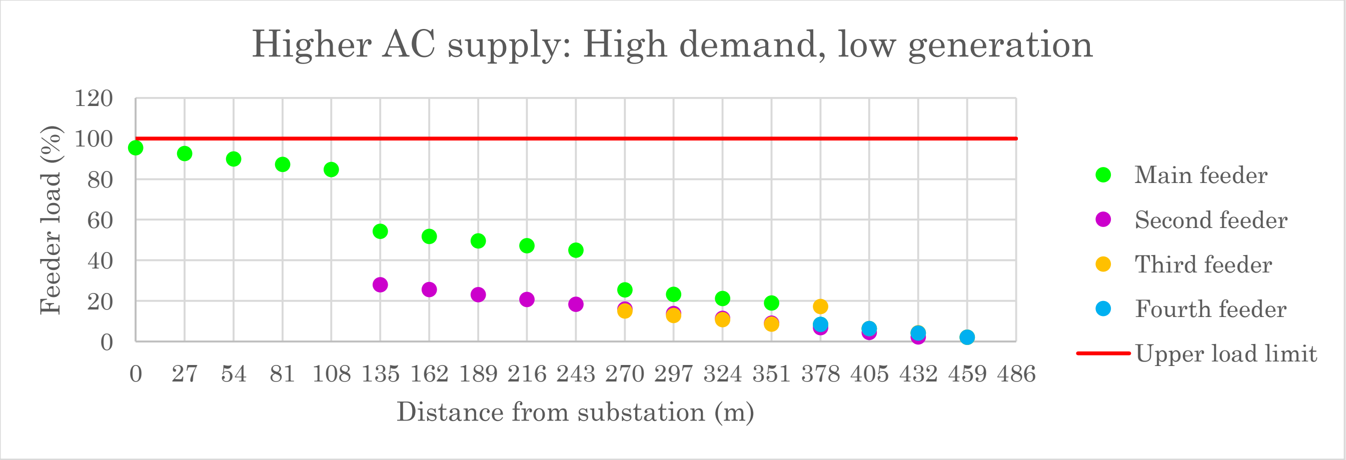

Figure 87 – High demand, low generation: feeder load using higher supply voltage

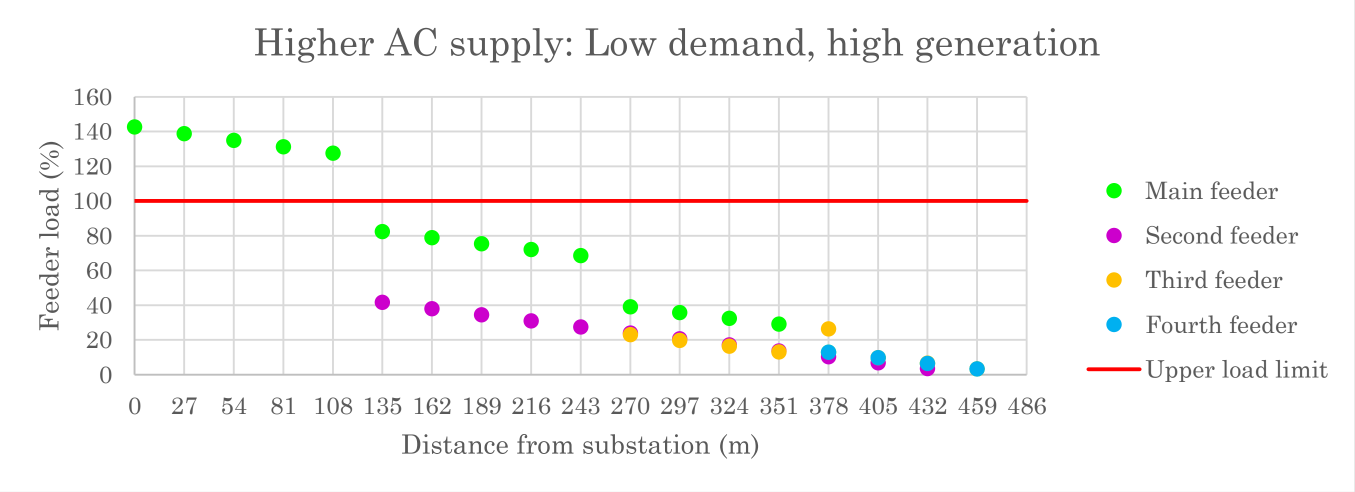

FIGURE 88 – LOW DEMAND, HIGH GENERATION: FEEDER LOAD USING HIGHER SUPPLY VOLTAGE

As can be seen from the results, using a higher AC voltage level provides proper voltage regulation and low feeder load under high demand situations, but may cause some feeder overload under low demand and high DG production.

	High demand, low generation (p.u.)	Low demand, high generation (p.u.)
400 VAC	88,46%	23,70%
800 VAC	6,66%	3,06%

TABLE 30 – COMPARISON: VOLTAGE REGULATION REQUIRED BEFORE/AFTER APPLYING A HIGHER AC VOLTAGE SUPPLY

DC Distribution

It is also relevant for this work to analyze DC distribution. Thus, a unipolar, LVDC Distribution District system is analyzed in this case study. The MV/LV substation transformer is replaced by a DC voltage source, to simulate the behavior of a bidirectional DC power flow, while an AC/DC Pulse Width Modulation converter is used to connect distributed generators to the system. The DC voltage follows the same criteria as the AC voltage, with a ±10% acceptable variation. The simulation data, system and results are shown next.

AC/DC substation rectifier	Six-thyristor rectifier (VSC) with built-in, fixed-tap transformer; rated AC input=10k VAC; rated DC output=750 VDC; rated DC current=0,3k A; internal $\frac{N1}{N2} = 0{,}055$; $f.a._{nom} = 0^\circ$; $f.a._{max} = 180^\circ$
Distribution DC voltage level	750 VDC
Distribution DC feeder used	AXMK insulated cable; rated DC voltage 0,9k/1,5k VDC; rated DC current=0,3k A; R=0,206 Ohm/km; According to Int. Std. IEC60228, IEC 60332-1, IEC 60502-1, HD 603-5D S1 and SFS 4879.
DC/AC inverter (one per load)	PWM converter; sinusoidal modulation; rated DC input=750 VDC; rated AC output=400 VAC; rated power=50 kVA; PWM factor=0,873;
DG AC/DC rectifier	PWM converter; sinusoidal modulation; rated AC input=1k VAC; rated DC output=750 VDC; rated power=50 kVA; PWM factor=0,873

TABLE 31 – TECHNICAL DATA FOR THE DC SIMULATION

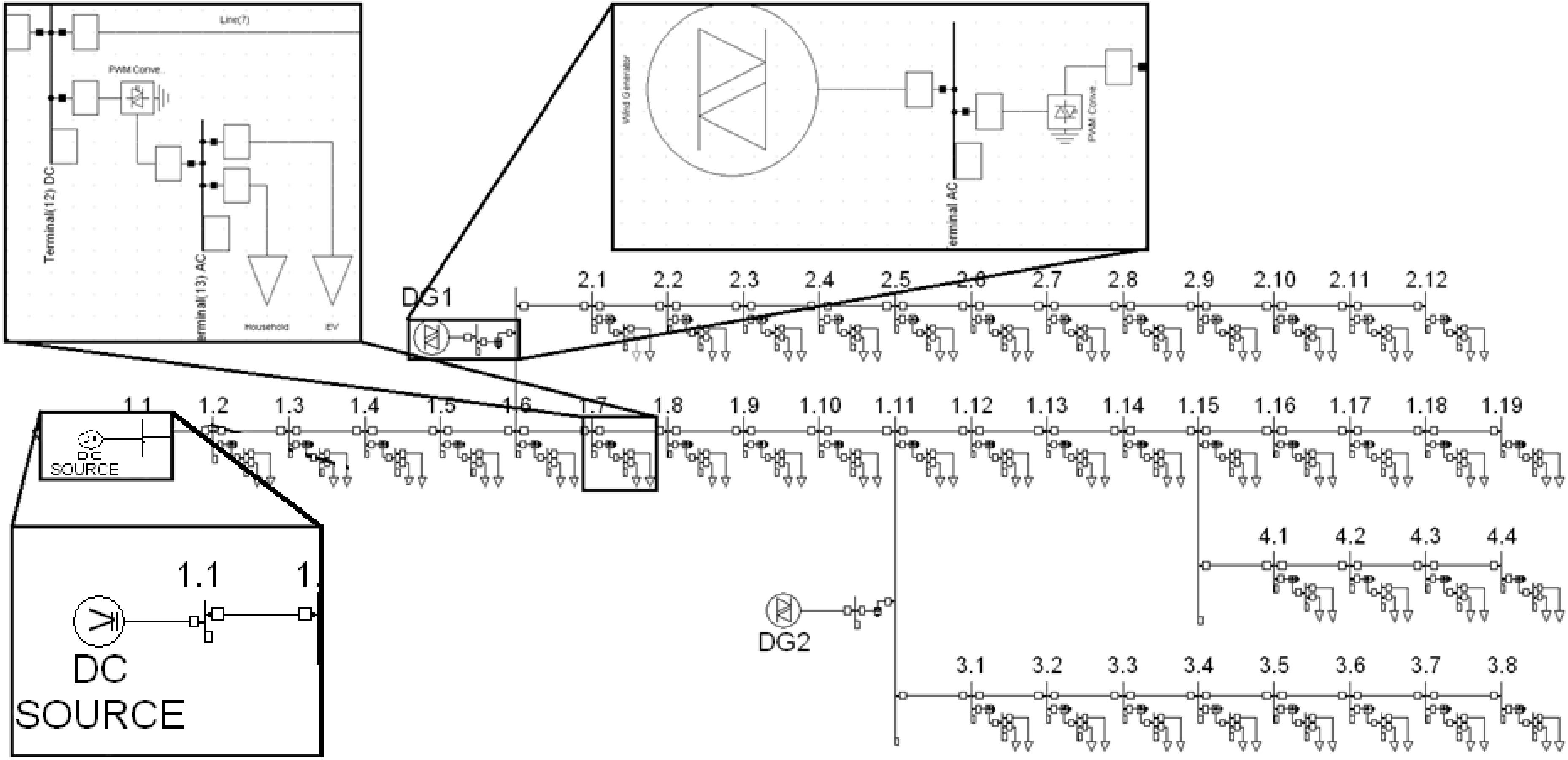

FIGURE 89 – SYSTEM 1 WITH DC DISTRIBUTION

Source: DigSilent PF

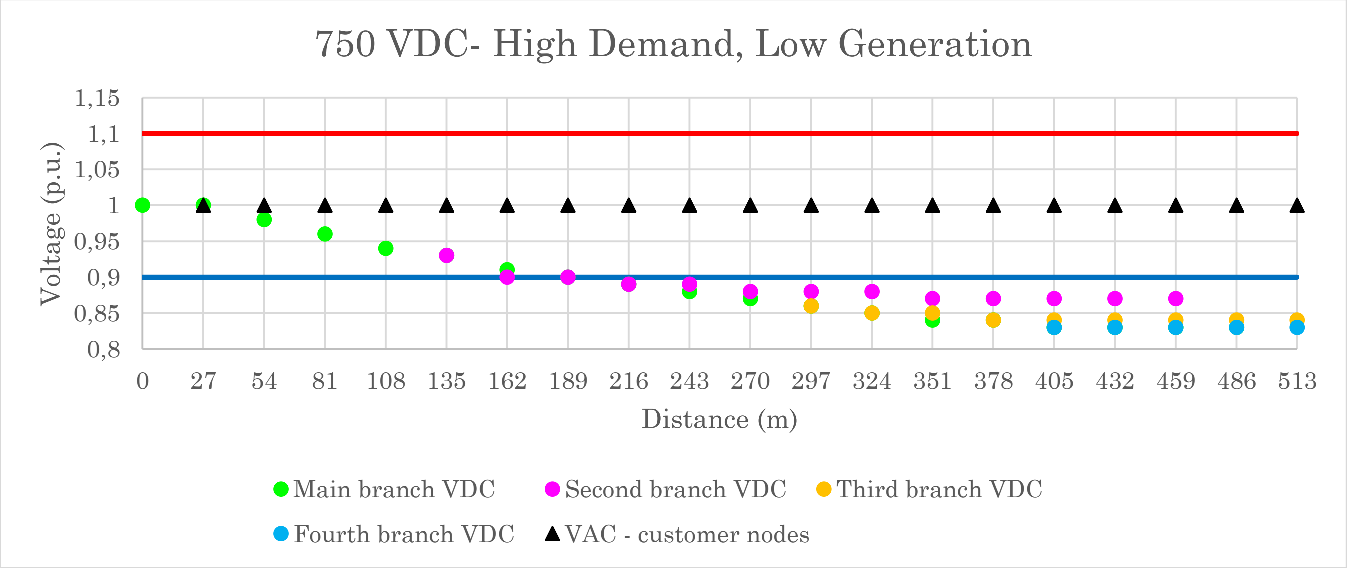

Figure 90 – High Demand, Low Generation: voltage level using a LVDC

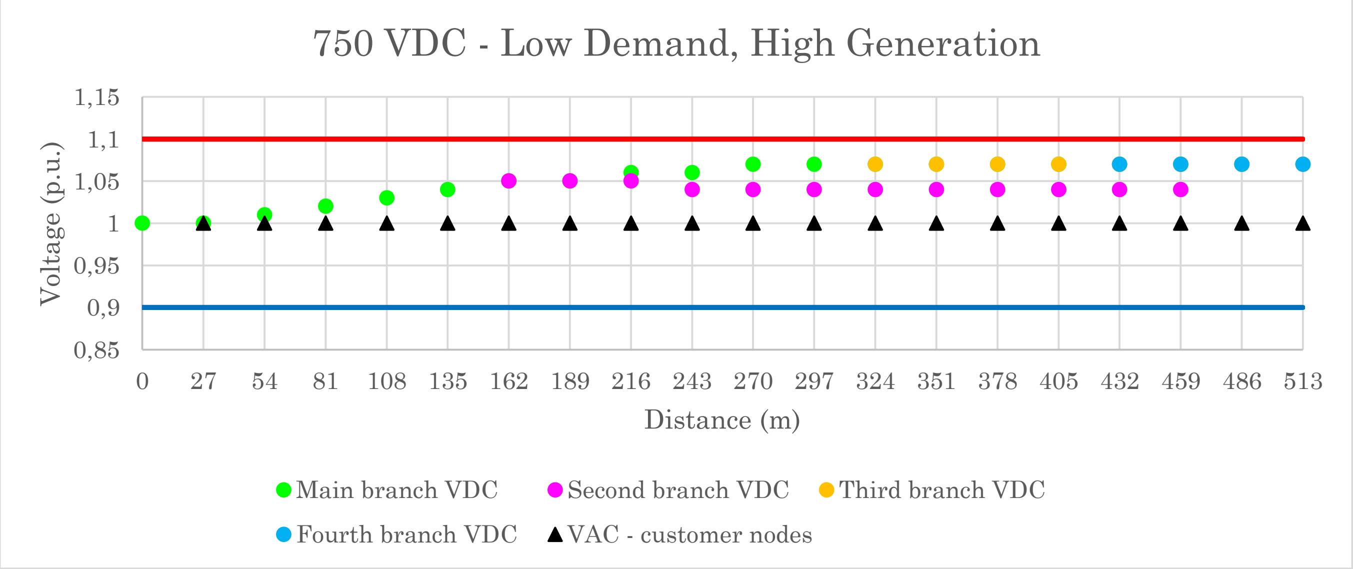

Figure 91 – Low Demand, High Generation: voltage level using a LVDC

Thanks to the capacity of the VSC to maintain a bidirectional power flow, the system voltage level is kept within acceptable limits at all nodes. Then the PWM converter at each load is able to provide a proper voltage supply fixed at 1 p.u. (AC three-phase voltage=400 Volt).

The only case which cause some undervoltage is high demand and low generation. However, even with some DC voltage drop the PWM converters are able to adjust the AC supply voltage without any issue.

Vehicle-to-Grid

The V2G idea may provide many advantages for voltage control, in both AC and DC systems, and therefore, it is also considered in this case study. It is assumed that each EV can be switched from charging/discharging by the distribution utility only. The customer has no decision in the process. The distribution utility however, has the responsibility to ensure that every customer has its EV charged at the morning. This solution assumes that there is a control system, between the utility and the EV loads, which is able to invert the power flow in any EV load as required to maintain a steady voltage. Slow-charging methods might be a drawback against this solution, since most EV loads are connected during peak time, and with slow-charging it takes too much time for the utility to have useful charge to use in the system, eventually resulting in no EV power available to regulate the voltage supply. Thus, EV fast-charging technology improves the V2G solution. On the other hand, fast-charging may also reduce the battery lifetime, while slow-charging preserves it. Therefore it is also important for the utility to control the charge/discharge rate, accordingly with the demand. V2G may provide an effective solution, not only because it provides additional power when it is required, but also because it reduces the demand, since a discharging EV is no longer consuming power.

In this simulation EV loads are assumed to use fast-charging. This strategy was implemented on system 1 (residential). The relevant simulation data and results are shown next. It is also necessary to consider new situations for application, since during daytime most EV are not available on residential households. Therefore the new criteria for each case is shown.

Residential Loads (each)	42 households; 32kW each, fully-electric flow type, $cf = 0{,}2$; pf=0,95
Electric Vehicle Load (each)	13 EVs (30% penetration); 20kW capacity; pf=1; Modelled as a DC voltage source
EV charge/discharge rate used	50kW for fast-charge (20~30 minutes); 5kWh for four-hour discharge; 15kWh for one-hour and half discharge
Distributed generation	2 photovoltaic panel per house, 5kW each, (10kW total, each house); 50% penetration in the system
High demand	Peak hours during the evening, between 17h and 23h
Low demand	Nighttime, between 24h and 7h

TABLE 32 – TECHNICAL DATA AND ASSUMPTIONS FOR THE V2G SIMULATION

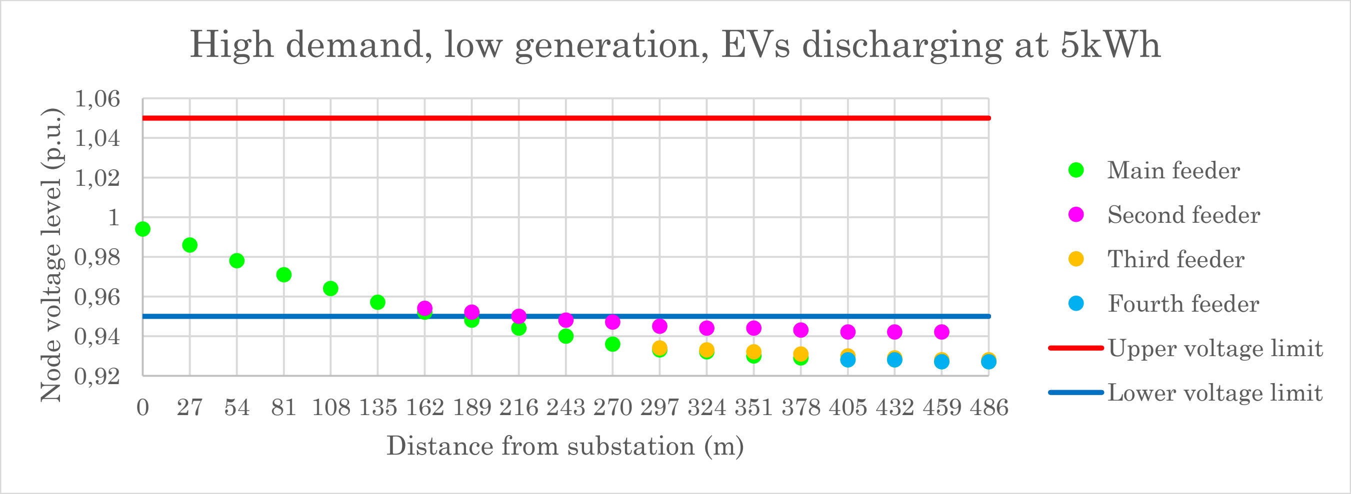

Figure 92 – voltage level control using EVs discharging at 5kWh

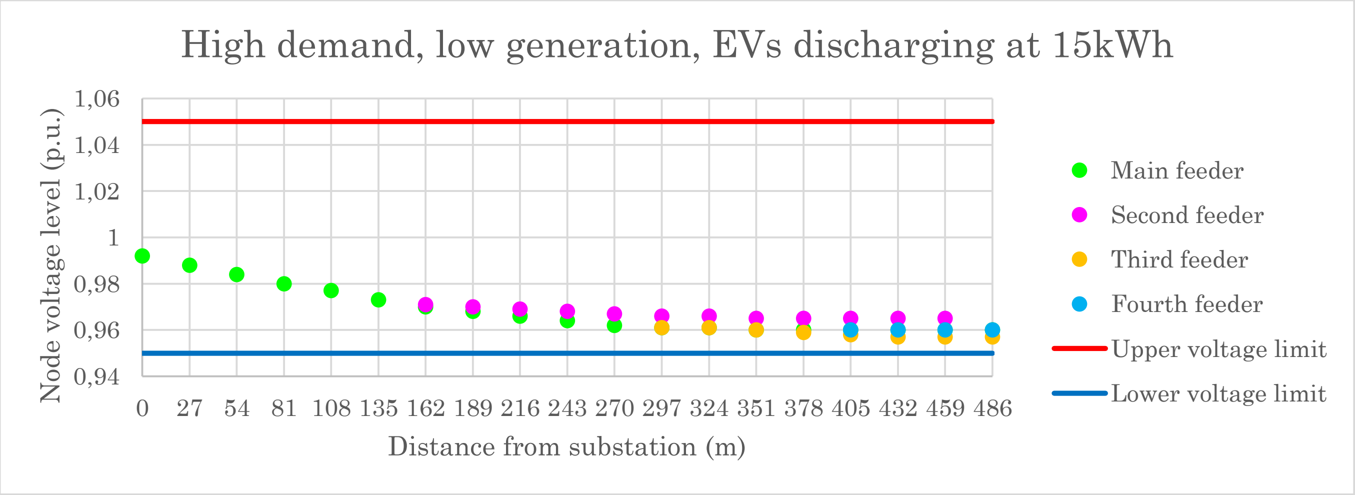

Figure 93 – voltage level control using EVs discharging at 15kWh

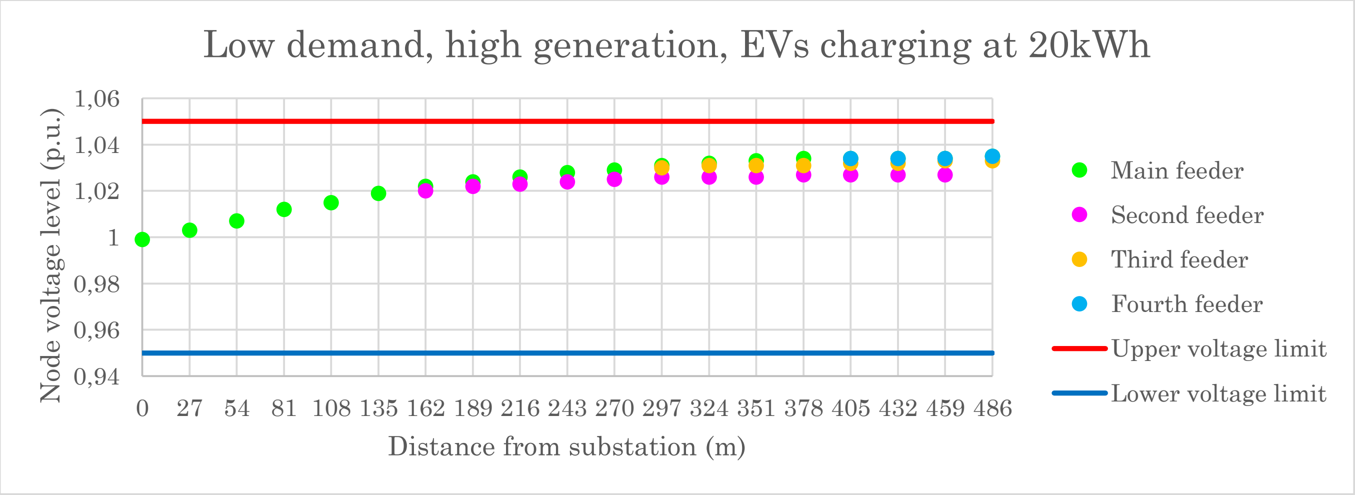

Figure 94 – Low demand, high generation: voltage level control using EVs

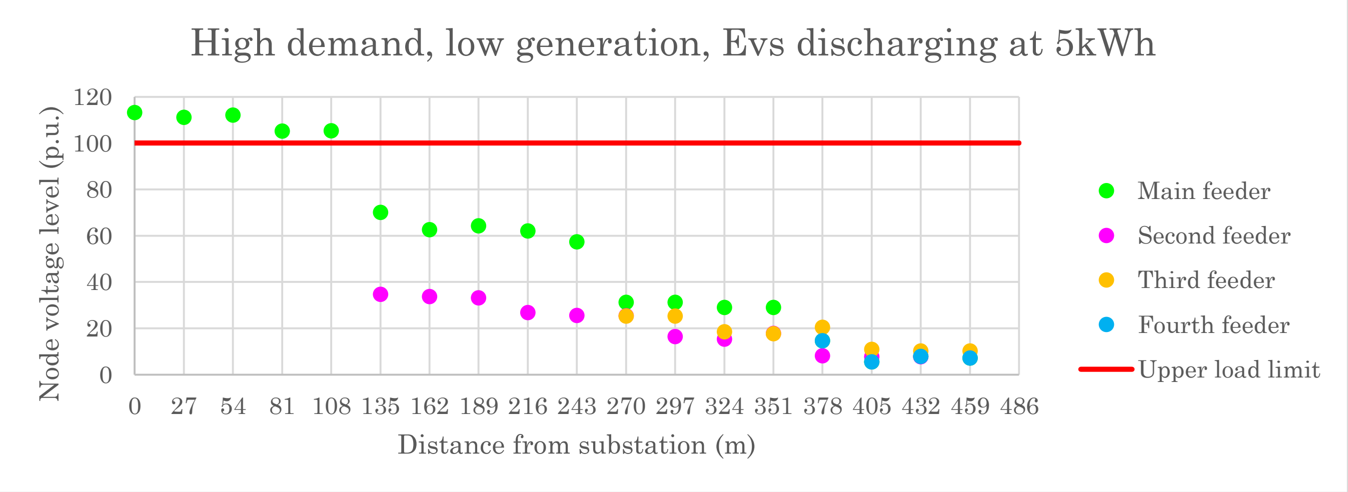

Figure 95 – Feeder load using EVs discharging at 5kWh

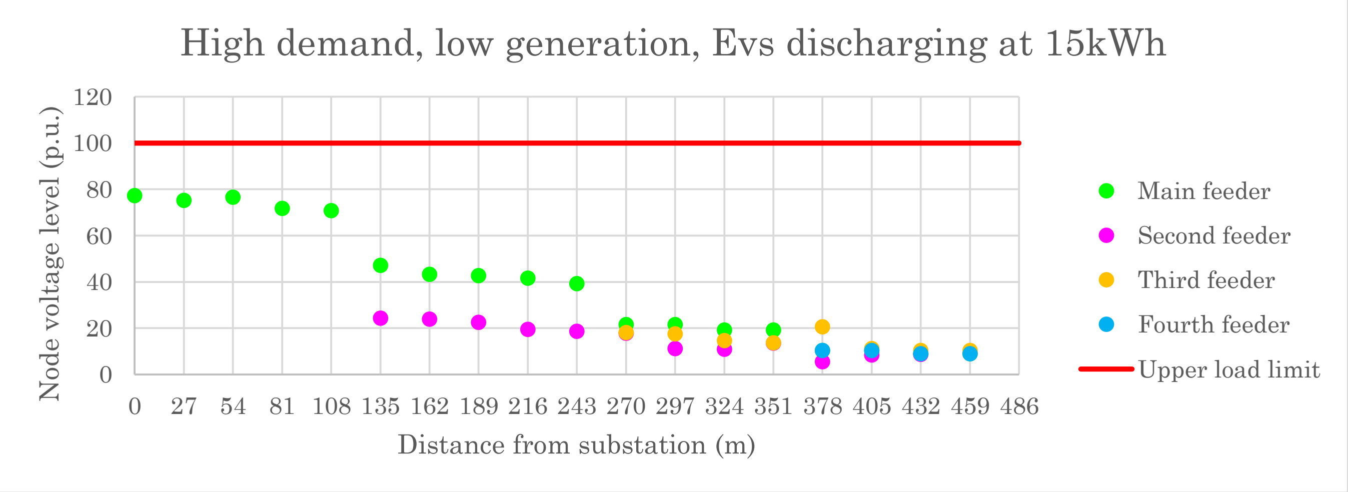

Figure 96 – Feeder load using EVs discharging at 15kWh

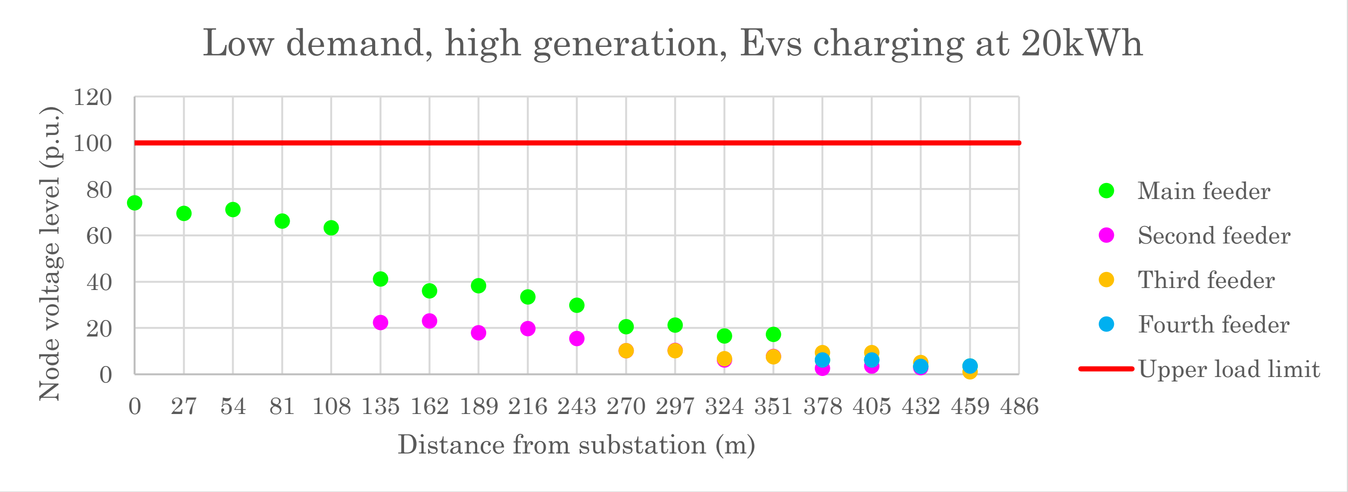

Figure 97 – Feeder load using EVs charging at 20kWh

In a high demand and low generation situations there is excessive voltage drop, and in this case all EVs were switched to provide energy into the grid. On the other hand, if demand is too low and generation is high, overvoltage problems may occur near the generators – for e.g. during a windy night in a system with wind generators - and EVs were switched to consume more power from the grid.

It is also interesting to analyze the low demand and low generation situation. In this case if all EVs are switched to charge their batteries, undervoltage occurs, because there is not enough generation. If they are switched to provide their stored energy, overvoltage may occur, since consumption is low on the system. Therefore it is necessary to reach balance in this case. This could be done by adjusting the charging rate for EVs or by a control system that could manage EV loads, charging some while others would wait in queue. In the following table, the total percentage of EVs charging and discharging for each case is shown. In the low demand and low generation case, the total EVs charging was determined in order to maintain the system voltage within acceptable values.

	EVs charging	EVs discharging
High demand, high generation	83,33%	16,67%
High demand, low generation	0%	100%
Low demand, high generation	100%	0%
Low demand, low generation	33,33%	0%

TABLE 33 – TOTAL PERCENTAGE OF EVS CHARGING OR DISCHARGING IN EACH CASE

As can be seen from the obtained results, the V2G solution provided some voltage regulation under low and high demand situations. However, in order to provide the additional power required under high demand cases, a higher discharge rate was necessary (20kWh), which reduces the discharge time and therefore the system autonomy. Also, such rate may be difficult to achieve with the current storage technology. On the other hand, discharging at a higher rate also results in lower feeder load, since less power is required from the grid. Still it might be a good solution to consider in the future.

Grid-to-Vehicle

On the G2V approach EVs are not used as power sources, but their power consumption is regulated by the utility according to the system load. In a high demand situation, in order to avoid excessive voltage drop, EV's power consumption is reduced, taking longer time for their batteries to charge. On low demand situations, for e.g. nighttime, their consumption is increased. This solution aims to use power more efficiently, avoiding excessive power demand. Although it may not be enough to provide proper voltage regulation during peak hours, it is still a good idea, since it reduces the total voltage regulation required.

Voltage control using switched DG and ESU

In system 2 (commercial), the loads have a higher power factor (close to unity) and therefore they do not consume excessive reactive power from the grid. However, due to the system design and the main feeder length (1134 meters long) there may be excessive voltage drop and feeder overload during high demand. This happens because, at some point, the power source – in this case, substation - is far away from the loads, and all loads are in series, which means that every load will contribute to the voltage drop. Thus, a simple approach to solve this issue may be injecting more power within the system, not only at the substation. This can be accomplish using DGs and ESUs. DGs may inject the additional power required, therefore rising the voltage and avoiding voltage drop during high demand. However DGs may also cause overvoltage when the demand is too low to proper consume the power generated In this case the problem may be solved using switched DGs, such as fuel cells. Using switched DGs, power generation may be switched off when it is no longer needed, and switched on when demand is high.

Besides switched DGs, also ESUs may be widely used in commercial systems. In this case, an ESU is connected to four equally distant points along the feeder and is designed to be in constant charging when no additional power is required, and discharging when the demand rises above generation. It can also provide backup power when DG fail. ESUs are especially useful when continuous DG is used, since they can consume the excessive power generated during low demand to charge up their internal batteries, and thus, with their batteries charged, they can also act as backup power sources, providing additional power when demand is high. By regulating the power flow within the system, also the voltage level is regulated.

The system was first simulated using only the pre-installed DG (photovoltaic panels). Power factor correction was applied to reduce reactive power dependency from the external grid, and voltage levels were regulated. In this system, two compensators were sized and placed according to the $\frac{2}{3}$ rule. The first is placed at 459 meters from the substation, which is the closest node from the required distance, and the second at 918 meters. Both have a capacity of 150 kVAr, which is equal to $\frac{2}{5}$ of the total reactive power consumption from the grid.

$$\frac{2}{5} * 1134\,m = 453{,}6\,m \rightarrow 459\,m$$

$$\frac{4}{5} * 1134\,m = 907{,}2\,m \rightarrow 918\,m$$

$$\frac{2}{5} * 322\ kVAr \cong 130\ kVar\ (per\ capacitor)$$

Then switchable DGs (fuel cells) were introduced, replacing the generators connected to higher demand loads – in this case the restaurants. On another approach, an ESU was introduced instead of the fuel cells. Both were compared in terms of voltage regulation. The results are shown next:

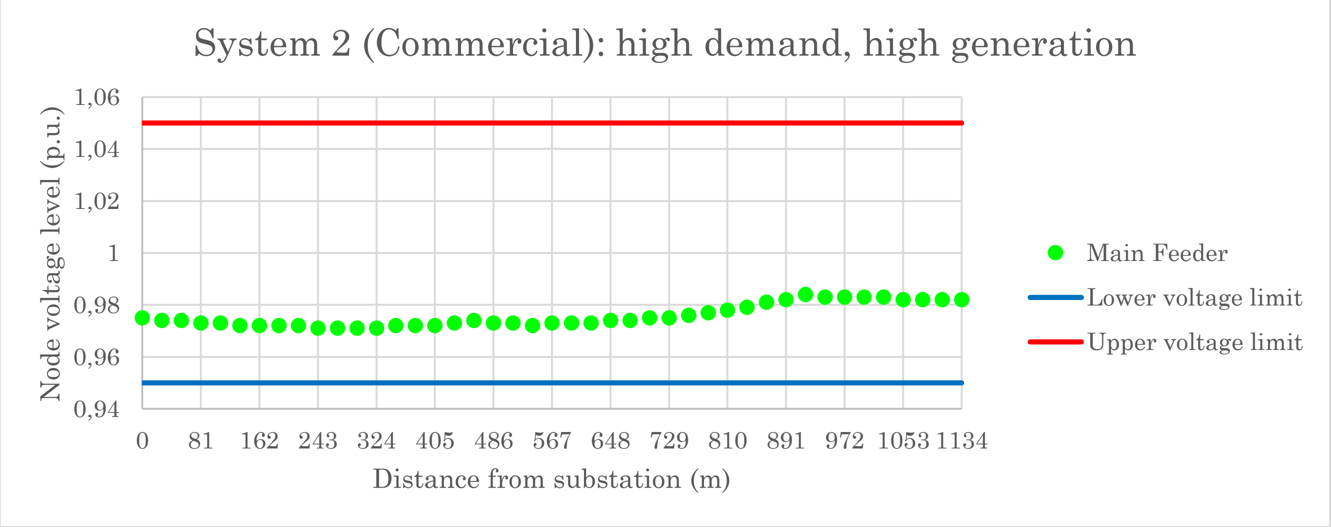

FIGURE 98 – HIGH DEMAND, HIGH GENERATION CASE (SUNNY DAY): VOLTAGE LEVEL PER NODE WITHOUT DIRECT VOLTAGE REGULATION

As can be seen on the above chart, during a sunny day and normal conditions the system is correctly regulated. The situation is different when, for e.g. instead of a sunny there is a cloudy day and therefore no generation is available from photovoltaic sources. The following results are for only 30% of the total possible demand:

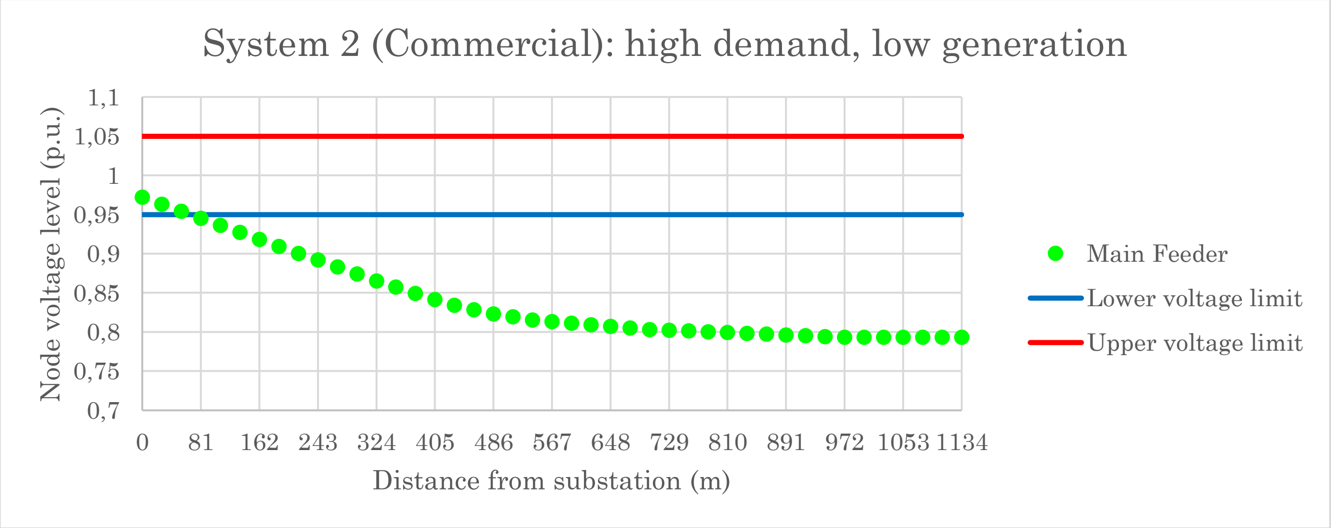

FIGURE 99 – HIGH DEMAND, LOW GENERATION CASE (CLOUDY DAY): VOLTAGE LEVEL PER NODE WITHOUT DIRECT VOLTAGE REGULATION

The other case of a low demand with a high generation may not be so obvious to happen in this system, since the DG is of the photovoltaic type, and the loads are of the commercial type, which means that the load will probably increase only during day and decrease only during night, when no solar energy is available. Still it is an interesting case to consider, regarding the system voltage control:

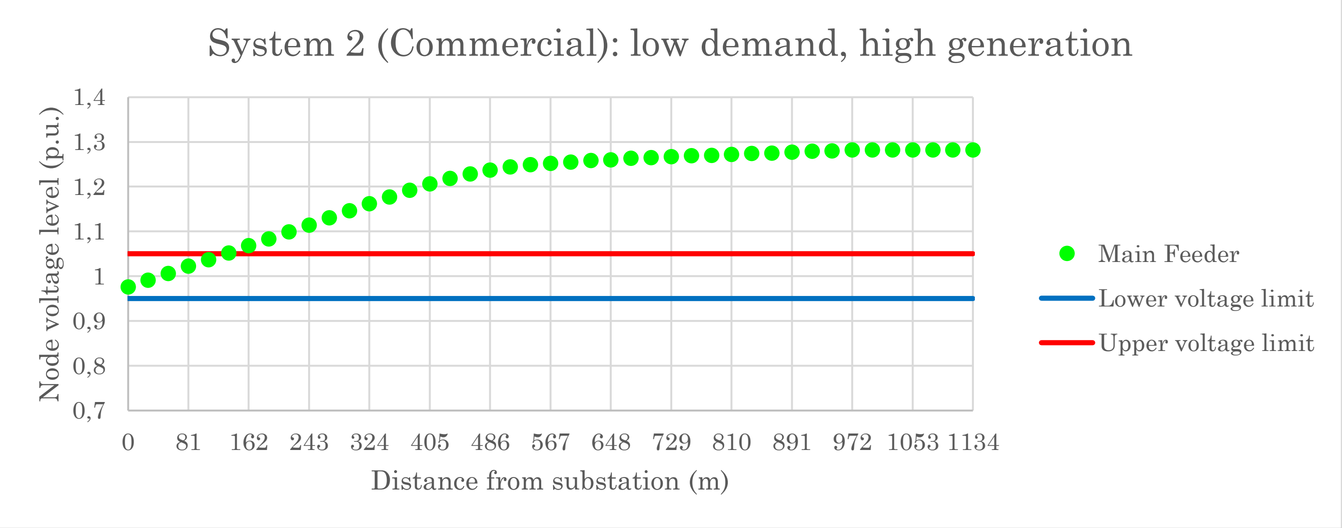

FIGURE 100 – LOW DEMAND, HIGH GENERATION CASE: VOLTAGE LEVEL PER NODE WITHOUT DIRECT VOLTAGE REGULATION

As can be seen the system is not able to control the voltage level properly when the demand or the generation varies. Therefore an uninterruptable DG might be required in this case. Fuel cells may be a good solution, since they are able to continuously inject power into the system, and they do not depend on intermittent power sources such as photovoltaic technology. Thus, the photovoltaic panels for both the restaurants and large stores were replaced. For restaurants, three fuel cells of 25kW each were used (75kW total, per restaurant), while in large stores only one fuel cell of 25kW was used. When demand is low, there is the possibility of switching off the DG to avoid overvoltage in the feeders. The results are as follows:

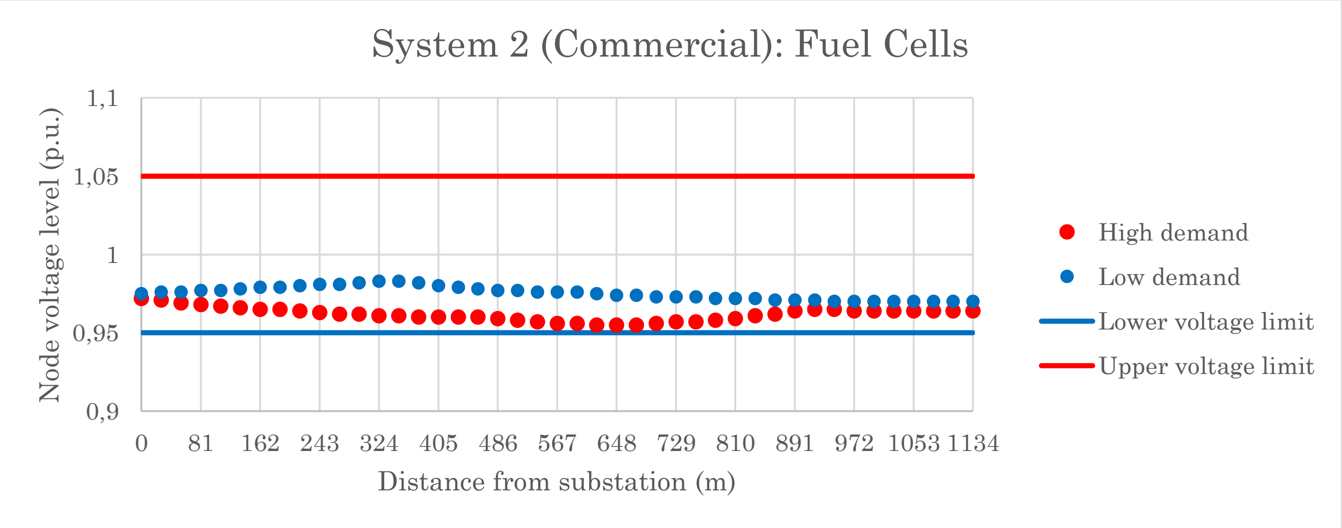

FIGURE 101 – VOLTAGE CONTROL USING FUEL CELLS: HIGH AND LOW DEMAND CASES

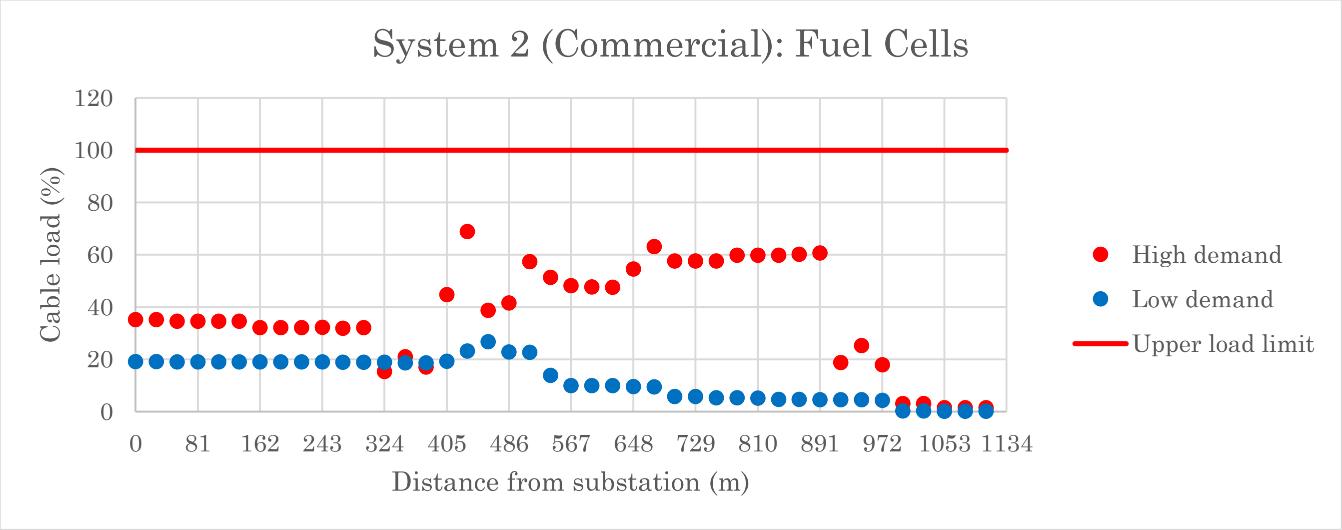

FIGURE 102 – FEEDER LOAD USING FUEL CELLS: HIGH AND LOW DEMAND CASES

In the above chart, one may notice some peaks at approximately 405 meters from the substation. This is the location where the fuel cells are installed.

Fuel cells could also be used to charge EVs in the parks. In this case, each group of four charging station – each station providing 21kW - were powered by three fuel cells, 25kW each.

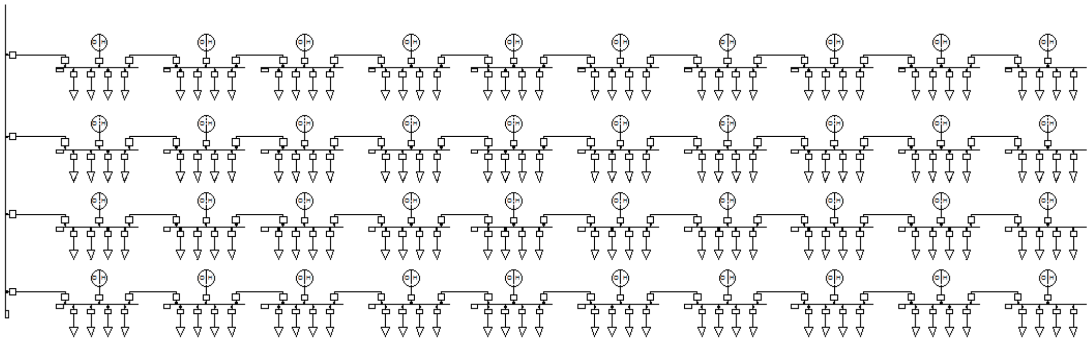

FIGURE 103 –USING FUEL CELLS TO SUPPLY GROUPS OF EVS

Another possibility would be using a combination of generation and storage, in this case, ESUs and the PV generators. The ESUs would be set to charging state when no additional power is required, for e.g. during a sunny day. In this case it would be interesting to connect ESUs directly to the substation, in order to not interfere with the rest of the system. They would be set to discharge state when the demand remains high and generation decreases – for e.g. during a cloudy day or after sunset – thus providing the additional power to regulate the voltage. In this case, it would be interesting to have ESUs connected to the same nodes as higher loads. This means that, to be an effective solution, ESUs connection to the system should be switched between different nodes during different daytimes. In this case study, this strategy was simulated using additional nodes, feeders and circuit-breakers. Two ESUs, with a capacity of providing 400kWh each, were modeled as an AC, constant power load during charging times and as a battery storage generator during discharging times. Both ESUs were connected in parallel to the substation, and the power flow is controlled through circuit-breakers. A computer software could be developed to automate these procedures, by opening and close breakers according to voltage levels in the nodes, power production in DGs and the power flow at the substation. The following results were obtained:

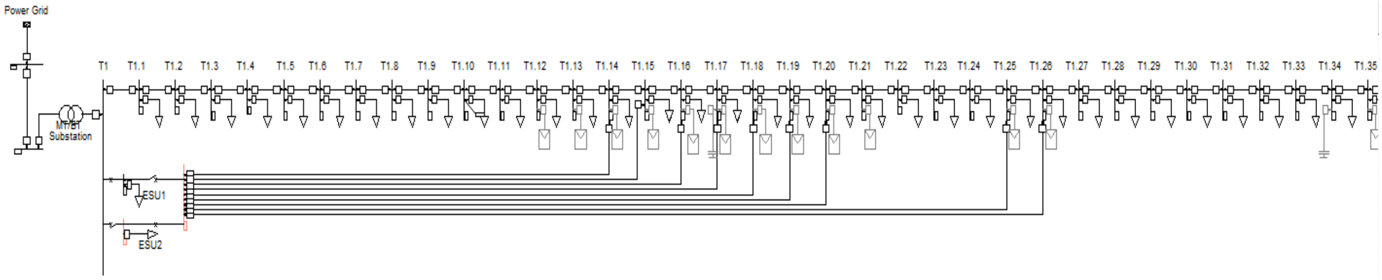

FIGURE 104 – SYSTEM 2 USING ESUS

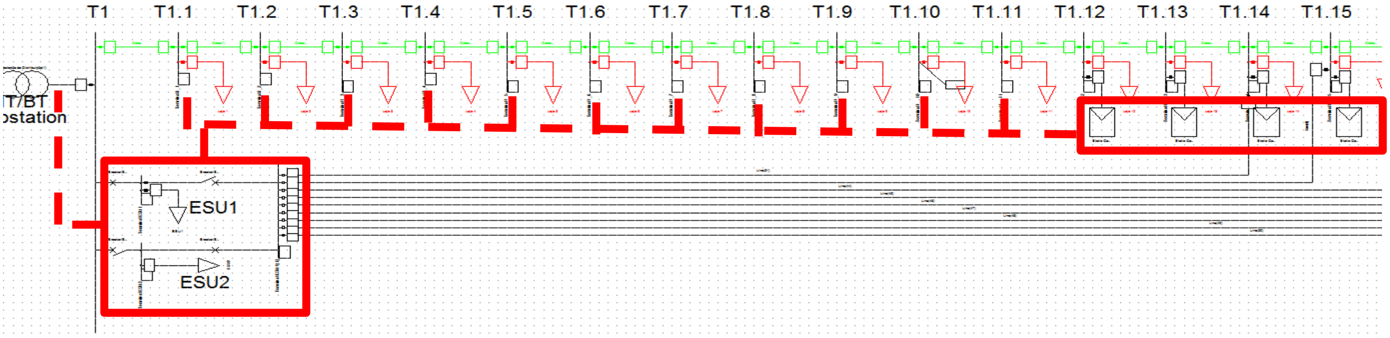

FIGURE 105 – PROPOSED COORDINATED CONTROL USING ESUS, SUBSTATION, NODES AND DG

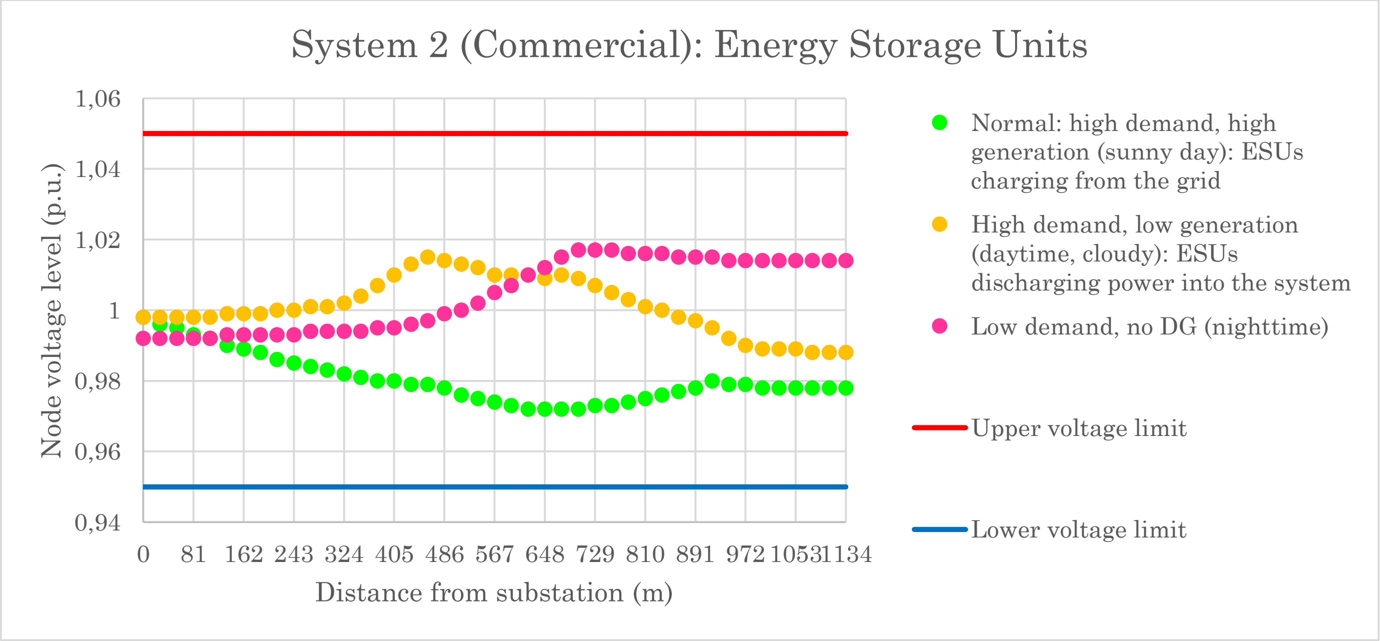

FIGURE 106 – VOLTAGE CONTROL USING ESUS: NORMAL, HIGH AND LOW DEMAND CASES

Shunt Compensation

In the system 3 (industrial), almost all loads have a lower power factor, which means their reactive power consumption from the gird is very high. As a result, the voltage level drops significantly along the feeder length. Therefore a good and cheaper solution for proper voltage control might be through reactive power compensation – or power factor correction - by injecting reactive power within the system, which can be done using passive units, such as shunt capacitors.

Since shunt compensation generates additional reactive power into the system to increase the voltage level, it will only provide effective voltage regulation during high demand conditions, when the voltage level is low. Thus a control system is required to turn on or off the capacitor bank according to the voltage level in the system. Despite this requirement, shunt compensation is still a good and cheap solution, since it is able to regulate the voltage level and reduce the load in the feeder. [30]

In system 3, each factory (300kW) is equipped with seven fuel cells of 25kW each, while rubber factories (500kW) are equipped with twelve 25kW fuel cells and the cold storage warehouse (1000kW) with twenty-six 25kW fuel cells. All fuel cells are switchable and are supposed to be connected only when needed. Besides fuel cells, also two groups of wind farms, each with thirty wind generators of 1,2kW each, are connected to this system, at nodes T1.4 (second branch) and T1.7 (third branch), respectively. These two wind farms are switched between the local system and the external grid, through circuit-breakers. When their production is high and demand increases, they can be connected as an additional source of energy. The system was first simulated without any voltage control, and then shunt compensation was applied, and the results are shown next:

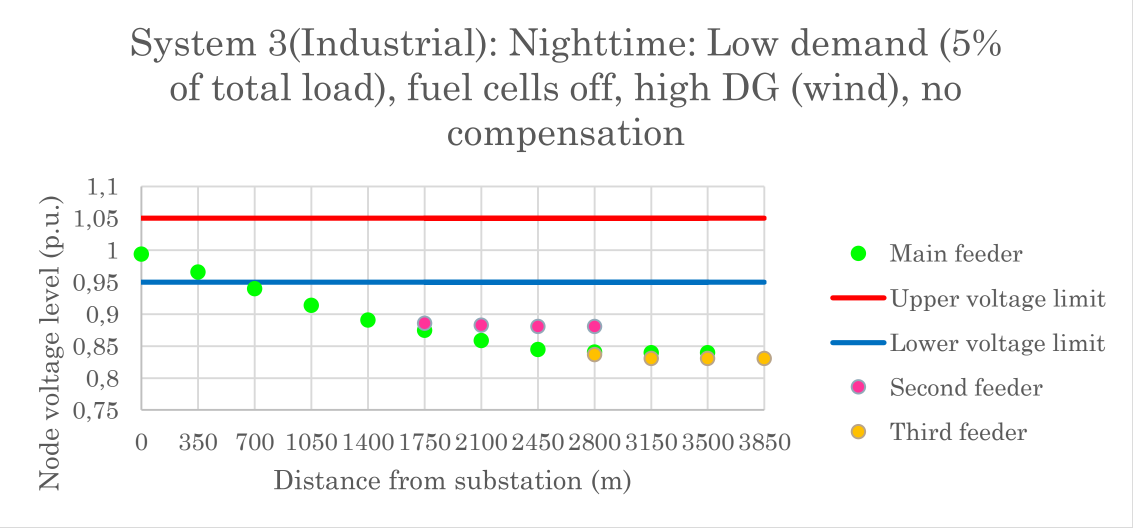

FIGURE 107 – SYSTEM 3 (INDUSTRIAL): LOW DEMAND CASE, WITHOUT ANY VOLTAGE REGULATION

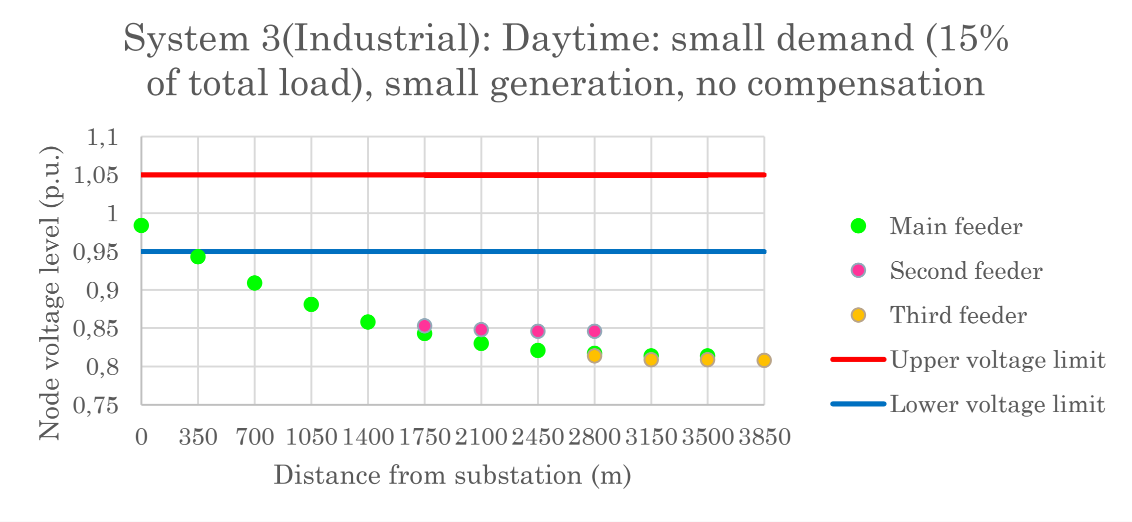

Figure 108 – System 3 (Industrial): increasing demand and generation case, without any voltage regulation

As can be seen from above, the voltage level stays low even when the load and DGs starts to increase. This means that, in this system voltage regulation can only be obtained through power factor correction:

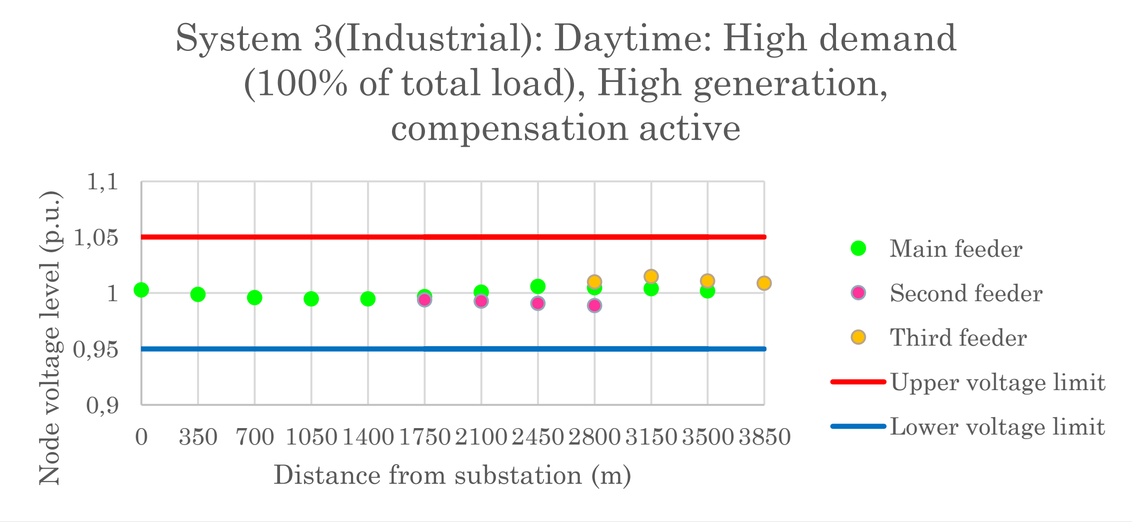

Figure 109 – System 3 (Industrial): voltage level during high demand, high DG generation and power factor correction

Regarding the load in the feeders, there are two situations of interest. The first is when there is no reactive power compensation active and both demand and DG starts to increase. This leads to an increase in feeder load next to the substation, since more reactive power has to be drawn from the external grid. This may also cause more voltage drop to happen in the system nodes. The second situation is when both demand and DG are low and shunt compensators are left active, injecting reactive power into the system. This causes an increase in reactive power going from the system back to the external grid, also increasing the load in the feeders next to the substation. This can also cause overvoltage to happen within the system nodes.

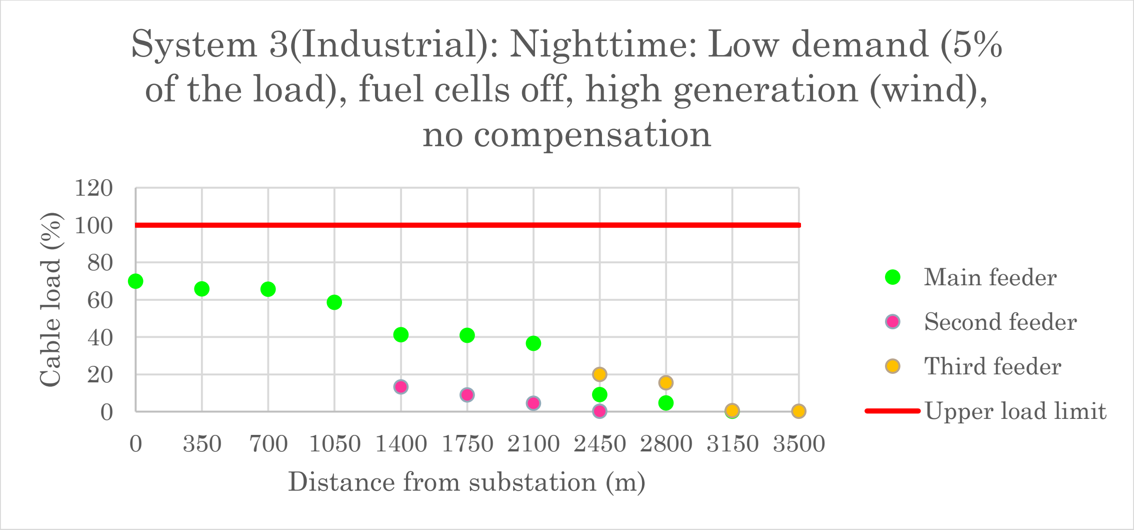

FIGURE 110 – SYSTEM 3 (INDUSTRIAL): FEEDER LOAD DURING LOW DEMAND, HIGH DG GENERATION (WIND) AND NO COMPENSATION

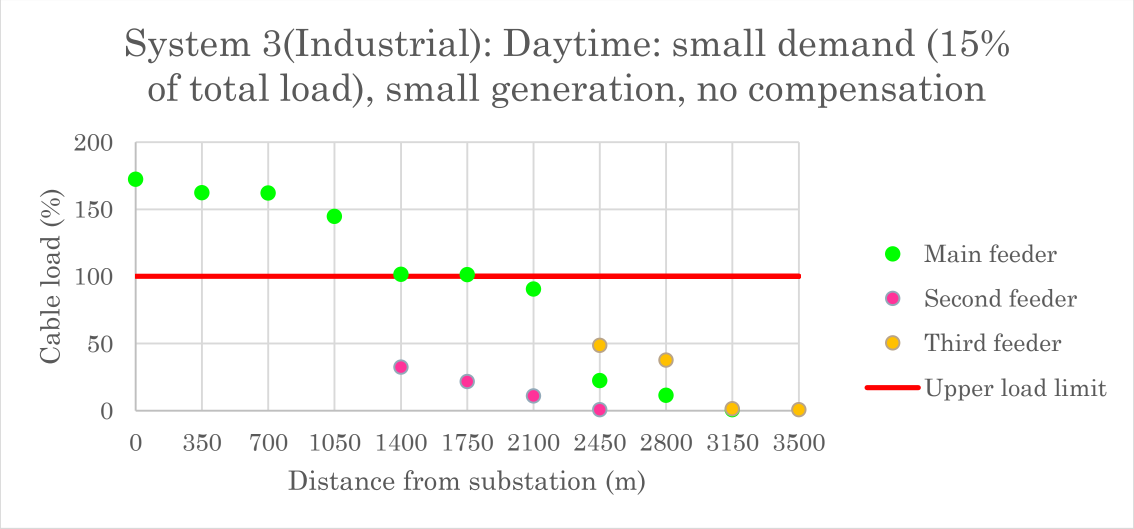

FIGURE 111 – SYSTEM 3 (INDUSTRIAL): FEEDER LOAD DURING AN INCREASING DEMAND AND DG GENERATION (FUEL CELLS) AND NO COMPENSATION (FIRST CASE)

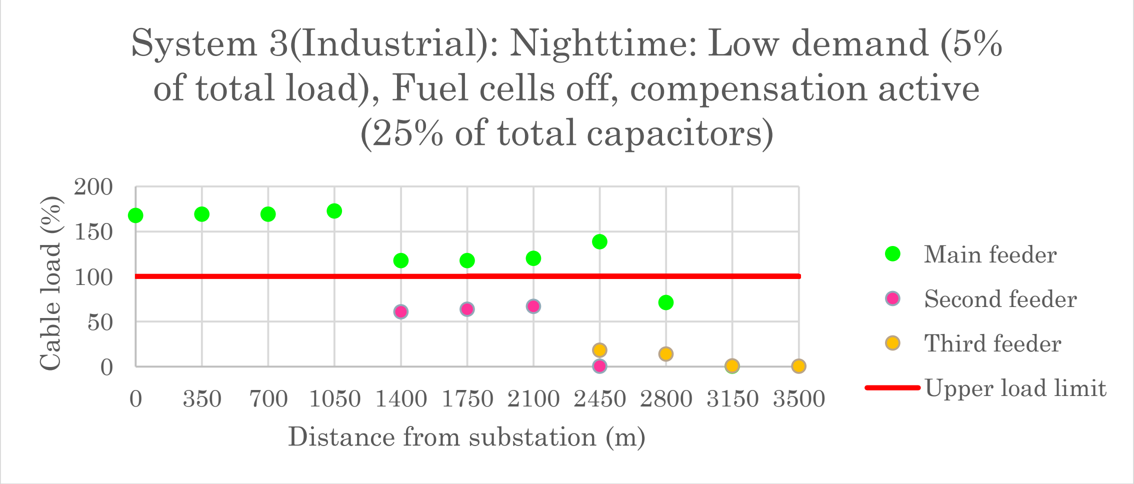

FIGURE 112 – SYSTEM 3 (INDUSTRIAL): FEEDER LOAD DURING LOW DEMAND, LOW DG GENERATION AND COMPENSATION ACTIVE (SECOND CASE)

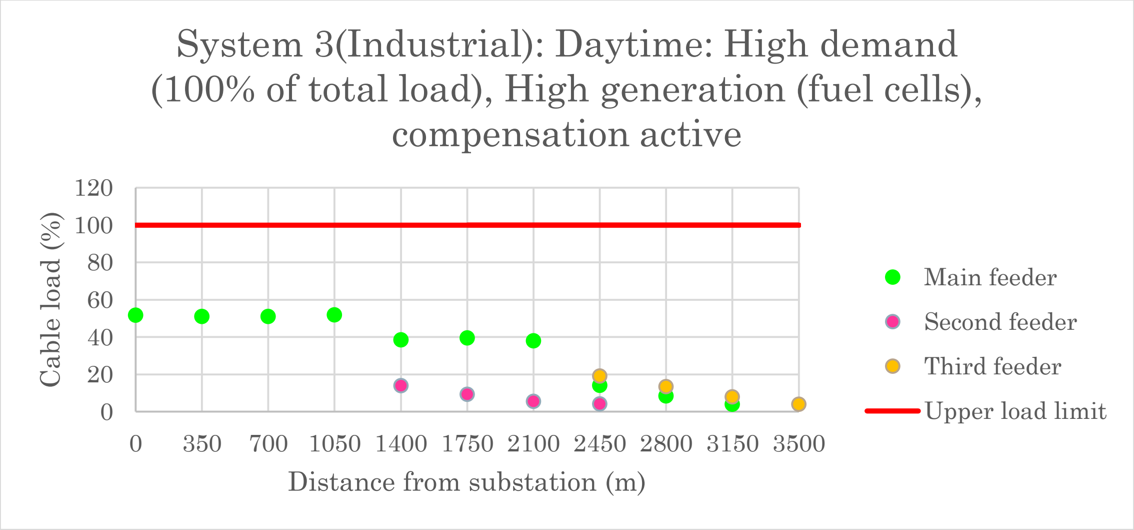

FIGURE 113 – SYSTEM 3 (INDUSTRIAL) NORMAL CONDITIONS: HIGH DEMAND, HIGH DG GENERATION (FUEL CELLS) AND COMPENSATION ACTIVE

3.7.2 Overall Voltage Regulation Required for Each Solution

Different solutions for voltage regulation were analyzed in this case study. It will finish with a final comparison between them, to compare how effective they are against each other, when applied to the same system. This will be a single feeder, with 486 meters long and will supply 18 residential loads, each with a power consumption of 12kW and separated by 27 meters each. The expression that gives the voltage regulation required is written here again, for convenience:

$$V_{regulation} = \left|\frac{V_{nl} - V_{fl}}{V_{fl}}\right| * 100\% \qquad 27$$

Where V_{nl} and V_{fl} are the voltage levels measured in p.u. in the receiving end of the feeder, at no-load and full-load, respectively. No coincidence factor was applied in this case. The lower the voltage regulation required and feeder load for a given solution, the better that solution is.

Solution	No load	Full load	Voltage regulation	Feeder load
None	0,992	0,923	7,48%	117,60%
V2G 5kWh	1,001	0,932	7,40%	103,00%
V2G 15kWh	1,016	0,95	6,95%	77,57%
OLTC 2,5%	0,991	0,94	5,43%	118,01%
OLTC 5%	0,991	0,966	2,59%	119,27%
OLTC 10%	0,991	1,022	3,03%	122,14%
OLTC 15%	0,991	1,085	8,66%	125,56%
OLTC 20%	0,991	1,156	14,27%	129,67%
800 VAC	0,998	0,980	1,84%	161,84%
750 VDC	0,998	0,98	1,84%	105,21%
VR series	0,992	0,956	3,77%	121,97%
VR parallel	1,001	1,004	0,30%	210,14%
Switched DG	0,992	0,99	0,20%	38,88%
ESUs	1,026	0,958	7,10%	55,51%

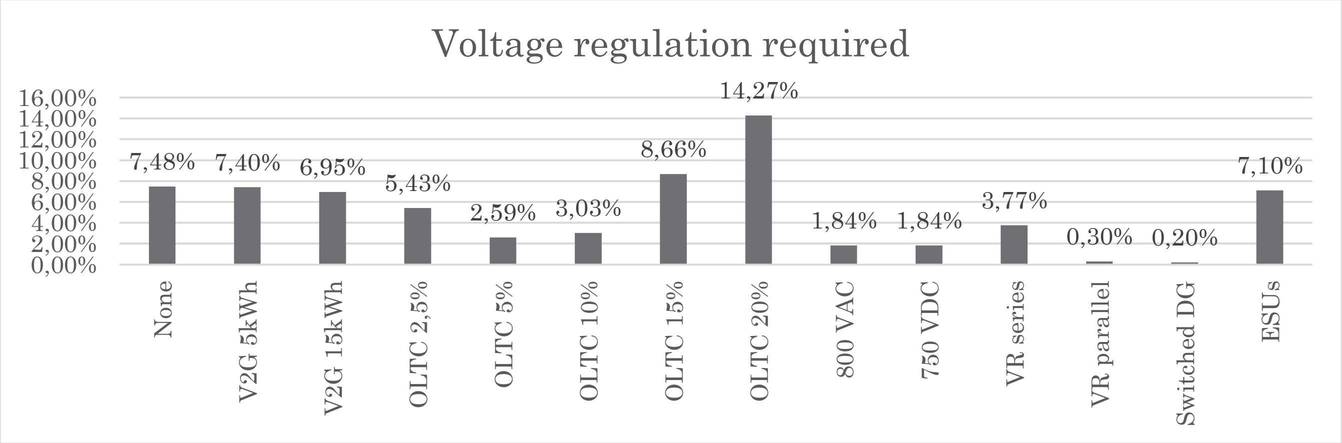

FIGURE 114 – VOLTAGE REGULATION REQUIRED FOR DIFFERENT SOLUTIONS

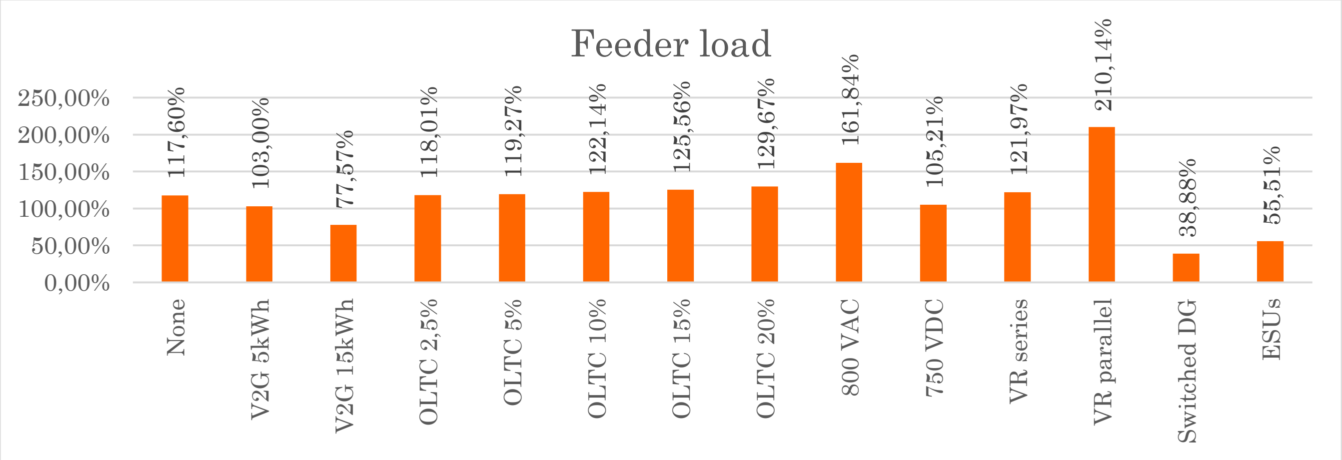

FIGURE 115 – FEEDER LOAD FOR DIFFERENT SOLUTIONS

3.8 Economic Analysis of Different Solutions

Shunt Compensation

Voltage Control using shunt capacitors is perhaps the cheapest and almost maintenance free VRU available [19]. However it is still far from being a complete effective solution, since it only provides proper voltage regulation in systems where the loads have a low power factor. It also helps reducing overload problems in the feeders, by reducing reactive power consumption from the grid, which is good because avoids further expenses with feeder upgrades. Usually one capacitor bank correctly sized and located – following for e.g. the two-thirds rule – will get the job done without heavy expenses for the utility. However, when it comes to excessive overvoltage due to inversion of power flow, these are unable to provide any regulation, and usually need to be turn off. In that case other solutions are required. This limitation automatically excludes them from distribution systems with DG penetration.

On-Load Tap-Changer Transformer

As already mentioned in chapter 3, due to their size and technology, the OLTC transformer is located either at the HV/MV substation – distribution substation - or at the MV/LV substation. Thus, it only provides voltage regulation at this location. Their effectiveness on voltage regulation will be much dependent on the length of the feeders and the number of loads. For small feeders and few loads these might provide a good voltage control.

Like any other transformer, an OLTC has several costs associated with it, which can be divided in two main groups:

1) The costs of owning the transformer – These include the acquisition cost, the installation cost, residual value or cost at the end of the life, as well as costs related with, depreciation, taxes, and other factors.
2) The costs of operating the transformer, which includes the costs of power losses (both no-load losses and load losses) and the maintenance costs.

The acquisition cost of this VRU is much dependent on the type – single or three-phase – and the rated power of the transformer used. Currently the supply of OLTC transformers is small, since only these VRU's have become necessary in distribution systems recently – particularly after the development of DG. The acquisition cost of an OLTC transformer is between 3000€ and 15000€.

Besides the acquisition cost, a transformer also has operation costs, which include both the costs regarding power losses and maintenance costs. More power rated transformers will have higher power losses and require more maintenance, therefore will have higher operation costs than small sized transformers. [31] Regarding the maintenance costs, there are certain types of OLTC that do not require their switching technology to be oil-immersed – dry-type transformers – using vacuum interrupters instead. Dry-type transformers may require the same number of maintenance cycles, but with less maintenance costs, since no oil is used [17].

It is also important to notice the lifetime of a transformer. A transformer with regular maintenances may have a lifetime of about 40 years. [32] When choosing a transformer it is important to consider its total operation cost (TOC), during its lifetime. Usually, choosing a cheaper, less efficient transformer may require less initial investment, but may have a larger TOC, due to high costs of operation (poor efficiency causes higher costs of power losses).

The investment in an OLTC transformer also has some risk associated. Besides the conventional risk resulting from vandalism/theft and natural disasters that could affect the equipment, there is also risk associated with the new trends in power distribution systems that are expected to happen in the near future. The expansion of these systems, with loads increasing both in number and power consumption, feeders becoming more longer, the increasing DG penetration and the emergence of the electric vehicle on such networks will make voltage regulation by OLTC insufficient and ineffective, thus compromising the investment on these VRU's.

Voltage Regulators

The VR has a great advantage over OLTC's: its reduced size when compared with those VRU's. Thus its installation is not limited to be in substations, but it can also be placed along the feeders – pole-mounted - or even near loads. This provides a better an efficient voltage regulation when compared with OLTC's.

Another important fact about VR's is their technology. As already mentioned in chapter 3, a VR is an autotransformer, which means it is single-phase equipment. Usually the acquisition cost of single-phase equipment is lower than three-phase. Therefore, choosing VR's instead of OLTC's would require a lower initial investment. As other transformers, the acquisition cost of a VR will depend on some characteristics such as rated power and protection. Conventional pole-mounted single-phase transformers will have a price range between 800€ and 4000€. [33] Modern, single-phase Voltage Regulators provide a ±10% voltage regulation with 32 steps. [34] Besides, the total costs

– including initial and operation costs – of a VR is lower than the total costs of OLTC technology, over the same period of time. [35] [36]

Since VR's are more versatile then OLTC's regarding voltage regulation, they are also better solutions for future distribution systems. Thus the risk associated with an investment in this technology is certain lower than the risk associated with OLTC technology.

Additional feeders

Adding more (parallel) feeders also has an impact on the voltage level, since more feeders mean less current overload. This may provide an effective solution when voltage regulation problems are mainly caused by feeder overload. When it is caused by other factors, such as, excessive reactive power on the feeders, this is not an appropriate solution. However, despite its effectiveness in reducing the current overload, this solution may lead to high costs for the utility, not only considering the high costs for additional cable but also high installation costs as well. The installation costs include – in the case of urban areas – the general costs for the road work, the personnel, the machinery costs, the necessary fossil fuel, etc. In the case non-urban areas, these costs may be even higher, depending on the terrain. Since this may be a costly solution and there are other, less expensive, alternatives to regulate the voltage level, adding more feeders may only be considered when it is imperative to reduce line overload, e.g. for equipment protection purposes.

Besides, the high initial cost of this solution causes a high risk associated with it. In areas of fast load growth a double feeder system may work properly today, but may face voltage problems in the near future, before the full return of the investment, making the utility to lose money.

Increased AC Voltage Level

This solution approaches the voltage problem in a different way. Instead of regulating the voltage level on the feeders, this solution aims to regulate the voltage level on each load only, through an individual transformer per load. Simulation results show that this approach works, and the transformers are able to proper regulate the voltage level on each load, for both low and high demand situations.

The costs associated with this solution may be only related with the transformers used, including the total cost – acquisition, installation and operation – for each additional transformer per customer and eventually the cost associated with the MV/LV substation transformer replacement or upgrade, in order for this to handle a higher voltage level at its secondary side. The feeders however, may not bring additional costs for the utility, since most of LV feeders have higher rated voltage than the actual voltage level used, which gives some room for voltage expansion without immediate investment required.

An investment on this solution must be careful analyzed. While its effectiveness tend to lower the risk, the required initial investment and the increased operation costs tends to increase it. There is also the possibility, in the near future, that residential appliances develop in a way that they would operate at a higher supply voltage, thus making the additional transformers useless and the utility to lose its investment.

Energy Storage Units

Using Energy Storage Units (ESU's) in distribution systems might be considered a green approach to the voltage regulation problem, not only because it provides an effective solution for voltage control and line overload, but also being an effective solution for power saving as well. By regulating the power flow between the system and the grid, the effect of power flow inversion may be diminished, or even completely eliminated, therefore avoiding problems with voltage fluctuations, including overvoltage and undervoltage problems. ESU's may be composed by battery banks, which consume the excessive power generated by DG, when the demand is low, and provide the necessary additional power to avoid voltage drop problems during peak demand.

The total acquisition cost associated with an ESU includes the energy cost, measured in €/kWh, and the power cost measured in €/kW. The energy cost corresponds to the cost of the devices used to store the energy – batteries - which can be charged and discharged many times. The power cost corresponds to the cost of other ESU's components, such as power electronics, that are required for the ESU to operate. The combination of the two costs gives the initial capital cost for the ESU.

Another important factor is the battery technology used. As already mentioned in chapter 2, there are different types of batteries used in ESU's applications. The initial costs may vary in each type. For e.g. in 2003 lead-acid batteries with a rated power between 0.5 to 2 MW have an estimated energy cost of about 100€/kWh and a power cost of about 140€/kW, while zinc/bromine batteries with a capacity of 250 kW have an energy cost of about 300€/kWh and a power cost of about 200€/kW. [15] Zinc/bromine batteries are better designed for long-term energy storage with low self-discharge rates.

Besides the energy and power costs, batteries also have an expected lifetime of operation and replacement costs. Like other costs, these also vary with the technology used. For e.g. lead-acid batteries have a life cycle of about 6 years before need to be replaced, with a replacement cost of about 150€/kWh, while zinc/bromine batteries have a life cycle of about 8 years, and their replacement cost is about 80€/kWh. [15]

Using ESU's is a very effective, but also an expensive solution. It may not be an affordable investment for utilities with modest revenues, serving small distribution systems. It may be perhaps, a good solution for utilities with large revenues. Due to the initial high investment and high costs during their life cycle, the risk associated with an investment in ESU's is quite high. Several factors, not only technical, such as vandalism and environmental, also increase the risk. The utility may reduce these factors, with higher protection and security, but it will inevitably increase costs as well.

DC Distribution

This approach aims to modify the entire distribution system, by changing its technology to use DC instead of AC. This would involve the replacement of most of the equipment actually used in distribution systems. Although this may seem too radical, there are several technical factors that support this idea. [11] Such modification would bring several costs; not only for the utility but for manufacturers as well. For utilities, it would imply the replacement and acquisition costs of new DC equipment - cables, protection equipment, converters - and later operation costs for these DC devices.

In general, when comparing a LVDC distribution system to an MV/LV AC system, the costs of line investment, line losses, power interruptions and equipment maintenance are reduced in DC, but the investment costs associated with power converters and conversion losses would be higher than the investment costs associated with transformers and transformer's losses.

Regarding voltage control, a DC system may be an effective solution, not only because it may be more suitable and better prepared for the integration new technologies into the power grid, but also because it supports a higher supply voltage level. [10] Besides, the distribution capacity would be large, because there is no sinusoidal frequency and therefore no capacitive current associated, which reduces power losses along the cable. Thus the distribution capacity would be only limited by the cable resistance. However these small resistive losses may become irrelevant, due to the high costs of converters and the increasing size of distribution networks. [37]

The difference from this approach to an increased AC voltage approach, is the absence of an additional transformer per customer; and thus less additional costs for the utility.

An investment in a DC distribution system also has less risk associated than other approaches, because this type of system follows the major new trends in the energy sector and offers enhanced compatibility with new developing technologies. Therefore it is expected that such approach would receive good acceptability from manufacturers and customers as well.

Vehicle-to-Grid

The vehicle-to-grid (V2G) approach might be considered another green solution for the voltage regulation issue, which also contributes to energy saving, through a more efficient use of power from the grid.

The main idea of V2G is to give customers the opportunity to sell the energy stored in their EV back to the system. Therefore an EV may operate not only as a load, but as a power source as well, in order to regulate the system power flow and thus provide a better voltage control.

The effectiveness of such system will depend on how it is implemented. If it is intended to be an optional service, giving the customer the possibility to decide if, after connecting its EV to the power supply, the stored energy is to be sold back to the grid or not, then its effectiveness will depend on the number of customers who decide to sell the energy back, and the risk of implementing such system for a voltage control purpose is high. The risk would be lower however, if it is intended to be a part of the EV supply system, with an automatic control to switch between consuming or sending energy back to the grid, without requiring any decision from the customer. For the purpose of this analysis, it will be assumed that it includes an automatic control. Besides the way it is implemented, also other technical factors – such as the batteries fast wearing due to frequent charge/discharge - contribute to increase the risk of investing in this solution. In order to lower the risk level, it would require also an additional control system, to regulate the charge and discharge rate, which, on the other hand, would also increase costs.

The cost of V2G system would also depend on factors, such as the system technology. Such a system would be oriented to a DC distribution system, in order to avoid the necessity of using at least two converters, required to implement it on an AC system, which would increase costs for the utility. However, since currently most distribution systems use AC, the V2G costs considered in this work are for an AC installation, therefore requiring additional converters.

Grid-to-Vehicle

The G2V idea is similar to the V2G, since it also aims to regulate the power flow, and thus the voltage as well, through adjusting the customer's EV consumption. However it only uses EVs as a load, instead of using them both as a load and as a power source. The risk associated with an (G2V) system would be much smaller than a (V2G) system, since it does not cause additional wear on the EV's batteries, and because it may require less additional equipment to be installed, reducing costs for the utility, while its effectiveness would be surely guarantied.

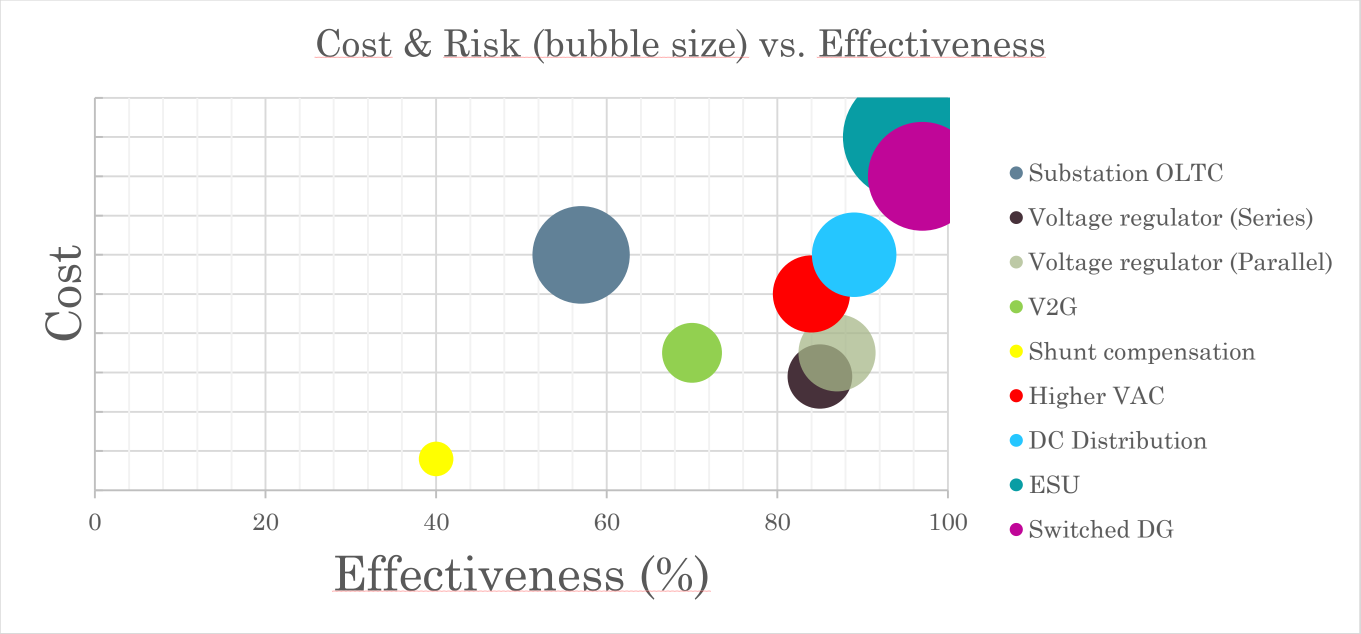

FIGURE 116 – COST AND RISK VS. EFFECTIVENESS OF DIFFERENT SOLUTIONS

3.9 Conclusions

In this chapter the main subject of voltage control was introduced. It began with the concept of voltage drop along the feeders, what causes it and what does it cause on electrical loads. Then several different solutions for voltage control were given, including mechanisms such as OLTC on distribution transformers and devices such as shunt capacitors. However voltage drop is not the only problem in distribution systems. The penetration of DG may cause overvoltage problems as well, which also can cause several problems. In this case, solutions that could work to solve voltage drop issues, fail to provide proper voltage regulation under overvoltage conditions. Then other solutions such as batteries, voltage regulators and new technologies such as an increased AC supply and LVDC systems capable of a bidirectional power flow were introduced.

There are several possibilities for future distribution systems. Thus it is important to consider both technical, regarding their effectiveness on voltage control, and economical differences between them. Therefore this chapter ends with a case study, were each presented solution is simulated and technical evaluated, and an economic analysis for each solution.

Chapter 4

4.1 Conclusions and Future Work

With this work done and all the research it involved, it is now clear the importance to have voltage regulation power distribution. Voltage control is just one of many requirements that utilities have to meet, in order to provide a reliable power supply. There are many different possibilities for future distribution systems. It will depend on implemented strategies to deal with the challenges of the future, regarding DG and EV penetration on distribution networks.

Future work on the distribution sector also depends on the implemented strategies and the devices used. One of the key points of the future Smart Grid is a better communication system within a power system. Voltage control using voltage regulators and OLTC transformers could be improved through the new communication possibilities that the Smart Grid has to offer. These devices could be used in coordination with loads and DG to provide effective voltage regulation, according to the demand. Shunt capacitors can also be coordinated with the demand, to avoid them to cause overvoltage problems during low demand. Future smart grids will introduce new communication technologies and protocols into the power systems, which would improve this coordination between different system components. The Smart Metering is an example of a possibility to enhance data communication between loads and the system components.

Another strategy for distribution is using DC technology. The results in the case study show that this is an effective solution for voltage control. This approach may also bring innumerous possibilities for future work, since a new technology is used and new devices are required to be developed. It may also offer better compatibility with future loads such as EVs, and other voltage control strategies using EVs as power sources, such as G2V and V2G approaches.

Similar to the DC strategy as it also changes the existent distribution systems, there is another approach which was presented in this work that aims to increase the AC voltage supply, in order to reduce the voltage regulation required. The simulation results show that this is an effective solution either. It could also bring new possibilities for future work, since new AC equipment will be probably required, depending on the voltage change.

In a green approach there is also the possibility of using energy storage units together with DG in distribution systems. The results show that using ESUs provides and effective voltage control. It also improves the overall power consumption in distribution systems, requiring less energy from transmission, which means less CO2 emissions. There is always some emissions during battery production, which makes it discussable, regarding their environmental impact. When applied in power distribution, they bring new possibilities for system expansion, since they increase the total system capacity, together with the increase of DG. However their high cost and maintenance surely slows down their acceptability by some utilities.

Other voltage solutions there were not considered in this work might include Synchronous VAr Compensators and Static VAr Compensators (STATCOM) systems.

In order to provide a reliable power distribution, the utility has to guarantee not only a steady voltage supply, but also good voltage quality. This is a vast concept and there are many different types of voltage stability. One type of stability is indeed a steady voltage supply, which was addressed in this work. Future work could be oriented to voltage quality, taking into account transient stability and the effect of harmonics on power distribution.

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