

# Optimal placement and sizing of battery energy storage using the genetic algorithm

**Mirko Gavrić**



# Optimal placement and sizing of battery energy storage using the genetic algorithm

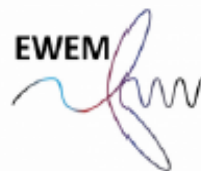
By

Mirko Gavrić

in partial fulfilment of the requirements for the degrees of

**Master of Science,**  
Electrical Engineering,  
Delft University of Technology.

**Master of Science,**  
Technology-Wind Energy,  
Norwegian University of Science  
and Technology.



European Wind Energy Master  
Erasmus Mundus MSc programme

to be defended publicly on Monday October 31, 2016 at 9:00 AM.

Thesis committee:	Prof. Dr. Ir. P. Bauer	TU Delft
	Prof. Dr. O. A. Lara,	NTNU
	Dr. Ir. J. Dong,	TU Delft
	Ir. S. Izadkhast	TU Delft

An electronic version of this thesis is available at <http://repository.tudelft.nl/>



## Abstract

Voltage drop and rise at network peak and off-peak periods are one of the major power quality problems in low voltage distribution networks. Additionally, the ever increasing demand for electricity along with the other requirements are driving modern day power systems towards more distributed generation (DG). Integration of large scale DG can be limited by these voltage variations. Therefore, it is of high interest to investigate the voltage support strategies that are able to successfully mitigate these problems. One of the solutions is to use energy storage systems (ESS). On the one hand limited amount of energy storage might not have the desired impact. On the other hand it is not possible to install large amount of energy storage as this would increase the costs substantially. Therefore it is required to optimally place and size energy storage.

The purpose of this thesis is to investigate the optimal placement and sizing of battery energy storage with the integration of renewable energy sources (RES) in a low voltage distribution network. An optimization model has been developed in order to identify the potential battery size and location combinations that increase the RES hosting capacity of the distribution network. The optimization technique used for this problem is the Genetic Algorithm (GA). Among the most important features of this algorithm stands its robustness and ability to provide good results in optimization processes.

The functionality and the performance of the developed model is assessed using an IEEE benchmark network that has shown to be adequate for both the dynamic and steady-state analyses.

The results of this work show that the voltage problems caused by the integration of RES can be mitigated by optimal placement and sizing of battery energy storage. They also show that besides the the voltage profile improvement reduction of losses can be achieved.

**Keywords:** distribution network, low voltage, distributed generation, reverse power flow, voltage rise, voltage support, battery energy storage systems (BESS), genetic algorithm (GA)



## **Acknowledgements**

First and foremost, I would like to express my profound gratitude to my supervisors, Prof. Pavol Bauer, TU Delft and Prof. Olimpo Anaya Lara, NTNU Trondheim. Their continuous guidance made my work possible.

Furthermore, I am grateful to Seyedmahdi Izadkhast, co-supervisor, for his guidance and valuable insight on the topic.

Special thanks to all of my friends and all the people that I met during my program that made the last two years memorable.

Above all, I would like to thank my parents for their relentless support during my endeavors. Without them I would not be the man I am today.

Mirko Gavrić





# Contents

<b>ABSTRACT .....</b>	<b>III</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>V</b>
<b>CONTENTS .....</b>	<b>VII</b>
<b>LIST OF TABLES .....</b>	<b>IX</b>
<b>LIST OF FIGURES.....</b>	<b>XI</b>
<b>CHAPTER 1 .....</b>	<b>1</b>
<b>INTRODUCTION .....</b>	<b>1</b>
1.1 PROBLEM STATEMENT .....	5
1.2 RESEARCH QUESTIONS AND OBJECTIVES.....	6
1.3 THESIS ORGANIZATION AND OUTLINE .....	7
<b>CHAPTER 2 .....</b>	<b>9</b>
<b>LITERATURE SURVEY .....</b>	<b>9</b>
2.1 TYPES OF ENERGY STORAGE .....	9
2.1.1 <i>Mechanical</i> .....	10
2.1.2 <i>Electrochemical</i> .....	10
2.1.3 <i>Electromagnetic</i> .....	10
2.1.4 <i>Chemical</i> .....	11
2.2 ANCILLARY SERVICES PROVIDED BY BATTERY ENERGY STORAGE SYSTEMS.....	11
2.3 OPTIMAL PLACEMENT AND SIZING TECHNIQUES .....	12
2.4 OPTIMIZATION OF BATTERY ENERGY STORAGE USING GENETIC ALGORITHM.....	13
2.5 CONCLUSION .....	15
<b>CHAPTER 3 .....</b>	<b>17</b>
<b>GRID REGULATIONS .....</b>	<b>17</b>
3.1 GENERAL .....	17
3.1.1 <i>Supply voltage variations</i> .....	17
3.1.2 <i>Voltage sags/swells</i> .....	18
3.1.3 <i>Voltage unbalance</i> .....	18
3.1.4 <i>Flicker</i> .....	19
3.1.5 <i>Active power curtailment</i> .....	19
3.2 VOLTAGE RISE AND MITIGATION TECHNIQUES .....	19
3.2.1 <i>Voltage rise in a feeder</i> .....	20
3.2.2 <i>Solutions to voltage rise problem:</i> .....	21
3.2.3 <i>Grid reinforcement</i> .....	21
3.2.4 <i>Active power curtailment</i> .....	21
3.2.5 <i>Reactive power control strategies</i> .....	22
3.2.6 <i>Energy storage</i> .....	23
<b>CHAPTER 4 .....</b>	<b>25</b>
<b>GENETIC ALGORITHM .....</b>	<b>25</b>
4.1 INTRODUCTION .....	25
4.2 PARAMETERS OF GA .....	28
4.3 CREATION OF THE EVALUATION (FITNESS) FUNCTION.....	29
4.4 SCALING OF THE FITNESS FUNCTION .....	30
4.5 FITNESS FUNCTION AND FORBIDDEN CONDITIONS .....	30
4.6 CHOOSING THE WAY OF CODING .....	31

4.7 CHOOSING THE WAY OF REPRODUCTION – SELECTION .....	32
4.8 CHOOSING THE CROSSOVER METHOD – RECOMBINATION .....	33
4.9 CHOOSING THE MUTATION METHOD.....	34
4.10 INCREASING POPULATION’S DIVERSITY – SHARING .....	35
4.11 CONCLUSION .....	37
<b>CHAPTER 5 .....</b>	<b>39</b>
<b>PROBLEM FORMULATION .....</b>	<b>39</b>
5.1 NODE POTENTIAL METHOD .....	39
5.2 OBJECTIVE FUNCTION .....	41
5.3 CONSTRAINTS .....	42
5.4 OPTIMIZATION OF THE GENETIC ALGORITHM .....	43
5.5 CONCLUSION .....	45
<b>CHAPTER 6 .....</b>	<b>47</b>
<b>RESULTS .....</b>	<b>47</b>
6.1 GENERAL CHARACTERISTICS OF A LV NETWORK AND DESCRIPTION OF THE LV FEEDER .....	47
DESCRIPTION OF THE LV FEEDER.....	47
6.1.1 <i>Characteristics of the lines used in the model</i> .....	49
6.1.2 <i>MV/LV Transformer</i> .....	49
6.1.3 <i>External grid</i> .....	50
6.1.4 <i>Modelling of the distribution grid</i> .....	50
6.1.5 <i>Battery model</i> .....	51
6.2 <i>Daily load profile used for the simulations</i> .....	52
6.3 <i>General simulation assumptions</i> .....	53
6.4 <i>Scenarios formulation</i> .....	53
6.5 <i>Case study 1: No wind turbine installed</i> .....	53
6.6 CASE STUDY 2: MEDIUM SCALE WIND TURBINE.....	57
6.7 CASE STUDY 3: LARGE SCALE WIND TURBINE .....	62
6.8 CASE STUDY 4: DIFFERENT SMALL SCALE WIND TURBINES.....	66
6.9 CONCLUSION .....	69
<b>CHAPTER 7 .....</b>	<b>73</b>
<b>CONCLUSIONS AND RECOMMENDATIONS.....</b>	<b>73</b>
7.1 MAIN CONCLUSIONS OF THE THESIS ARE .....	73
7.2 MAIN CONTRIBUTIONS OF THE THESIS .....	74
7.3 FUTURE WORK AND RECOMMENDATION .....	75
<b>BIBLIOGRAPHY.....</b>	<b>77</b>

## List of Tables

Table 2.1 Comparison of different optimization techniques in EVCS siting and sizing schemes [57] .....	13
Table 4.1 Example of a chromosome set .....	26
Table 4.2 Effects of choosing the parents of the population.....	26
Table 6.1. Impedance data for benchmark network lines [26] .....	49
Table 6.2. Transformer Characteristics .....	49
Table 6.3 MV equivalent network parameters.....	50
Table 6.3 CIGRE LV network load parameters.....	50
Table 6.4 Voltage values at each node (CS1) no storage added.....	54
Table 6.5 Voltage values at each node (CS1) with added storage.....	56
Table 6.6 Voltage values at each node (CS2) without added storage.....	59
Table 6.7 Voltage values at each node (CS2) with added storage.....	61
Table 6.8 Voltage values at each node (CS3) without storage .....	63
Table 6.9 Voltage values at each node (CS3) with added storage.....	65
Table 6.10 Voltage values at each node (CS4) without added storage.....	67
Table 6.11 Voltage values at each node (CS4) with added storage.....	68



## List of Figures

Figure 1.1 Ranges of RE penetration [33] .....	2
Figure 1.2 Prediction of energy storage usage [1] .....	3
Figure 1.3 Amount of battery energy storage used in conjunction with renewables [2] .....	4
Figure 1.4 Electricity services provided by BESS based on the time-scale .....	4
Figure 1.5 Cost predictions for Li-ion batteries [3] .....	5
Figure 2.1 Classification scheme for energy storage technology [58].....	9
Figure 3.1 Voltage sag [28] .....	18
Figure 3.2 Voltage swell [28] .....	18
Figure 3.3 Schematic of a load and a RES connected to a LV feeder [32] .....	20
Figure 3.4 Voltage rise phasor diagram [32] .....	20
Figure 3.5 Voltage-Power characteristic [43].....	22
Figure 4.1 Graphical representation of the roulette spin wheel technique .....	27
Figure 4.2 Crossover between parental and children chromosomes.....	27
Figure 4.3 Minimization of the fitness function [71].....	29
Figure 4.4 Maximization of the fitness function [71].....	29
Figure 4.5 Scaling of the fitness function [71] .....	30
Figure 4.6 Forbidden search fields [71].....	31
Figure 4.7 Selection of the individuals [71].....	32
Figure 4.8 Single point crossover .....	33
Figure 4.9 Multi point crossover.....	33
Figure 4.10 Presentation of scenarios with and without a mutation [71] .....	34
Figure 4.11 Sharing function [71].....	35
Figure 4.12 Results with (left) and without (right) the use of sharing function [71].....	36
Figure 5.1 Generalized branch of the circuit .....	40
Figure 5.3 Flowchart of the genetic algorithm.....	43
Figure 6.1. The benchmark LV residential feeder [26] .....	48
Figure 6.2 External grid element connected to the MV busbar of the transformer .....	50
Figure 6.3 Topology of the LV network modeled for this study.....	51
Figure 6.4 Simplified battery model .....	52
Figure 6.5 Daily load profile for the LV residential feeder [26] .....	52
Figure 6.6 Voltage profile of the feeder (CS1) without added storage.....	54
Figure 6.7 Convergence characteristic of the algorithm (2 batteries).....	55
Figure 6.8 Convergence characteristic of the algorithm (3 batteries).....	55
Figure 6.9 Convergence characteristic of the algorithm (4 batteries).....	55
Figure 6.10 Voltage profile of the feeder (CS1) with added storage.....	56
Figure 6.11 Voltage profiles with and without the use of BESS (CS1) .....	57
Figure 6.12 Wind turbine [60kW] power production and daily load profile.....	58
Figure 6.13 Voltage profile of the feeder (CS2) no storage added.....	59
Figure 6.14 Convergence characteristic of the algorithm (2 batteries).....	60
Figure 6.15 Convergence characteristic of the algorithm (3 batteries).....	60
Figure 6.16 Convergence characteristic of the algorithm (4 batteries).....	60
Figure 6.17 Voltage profile of the feeder (CS2) with added storage.....	61
Figure 6.18 Voltage profiles with and without the use of BESS (CS2) .....	62
Figure 6.19 Wind turbine [80kW] power production and daily load profile.....	62
Figure 6.20 Voltage profile during high production and low demand .....	63
Figure 6.21 Convergence characteristic (2 batteries) .....	64
Figure 6.22 Convergence characteristic (3 batteries) .....	64

Figure 6.23 Convergence characteristic (4 batteries) .....	64
Figure 6.24 Voltage profile with added storage.....	65
Figure 6.25 Voltage profiles with and without the use of BESS (CS3) .....	66
Figure 6.26 Wind turbine [30kW] power production and daily load profile.....	67
Figure 6.27 Wind turbine [40kW] power production and daily load profile.....	67
Figure 6.28 Voltage profile with a high load demand and high production of a turbine [40kW] .....	67
Figure 6.29 Voltage profile with added storage [40kW turbine].....	68
Figure 6.30 Convergence characteristic (3 batteries) .....	69
Figure 6.31 Voltage profiles with and without the use of BESS (CS4) .....	69

---

## Introduction

The climate change has long-since ceased to be a scientific curiosity and steadily became one of the greatest challenges of the modern day society. People are becoming more environmentally aware and have a better understanding of the factors that contribute to the global pollution. One of the main contributors to the global climate problem are the CO<sub>2</sub> emissions which are based primarily on fossil fuel consumption. The United States and China are the countries with the two most energy related CO<sub>2</sub> emissions and together their carbon dioxide footprint accounts for the 40% of the global share. Apart from the industry transport is one of the main sources of pollutants emission. The electricity sector accounts for the 23.2% of the total emission. [31] It is assumed that if these emissions continue at the present rate, Earth's temperature will exceed its historical in approximately twenty years. European Union is committed to drastically reduce the CO<sub>2</sub> emissions by a large amount till 2050.

One of the ways to solve this global problem is to introduce more renewable energy sources to existing systems. Another viable policy is the use of electric vehicles which instead of fuel, use batteries with very low to zero emissions. However although these technologies are a proven choice in order to address the previous mentioned problems, some experts claim that we are not ready yet to completely switch to renewables. However, both parties agree upon one thing, this world is running out of fossil fuels and in the very near future reliable substitutes are necessary.

Similarly to fossil fuels renewable energy sources also have their shortcomings. These resources are weather dependent in such way that any slight change in the weather affects their energy production. In the period of prolonged cloudiness or high winds the production of solar panels and wind turbines can be totally impeded. On top of that the global climate change could make them inoperable within a certain time period. Critics state that this technology is rather pricy rendering the developing countries unable to afford these technologies. Moreover, it is stated that large areas of land are necessary if a larger amount of power is to be produced. However, there are also some advantages to it. The cost of operation of renewables is relatively low, their green-house gases emission is minimal and they require less maintenance on the long run. It is also expected that the integration of renewables in regions with constant winds or large amount of sunny days can increase their reliability even beyond that of the fossil fuels and can create job opportunities worldwide.

In order to make the integration of renewables possible, current distribution power grids need to be improved from a relatively passive state to grids with more "active" power consumers and distributed generation. The aim is for the grids to become economically, ecologically and technology-wise improved. The road towards achieving this goal is not straight forward as there are many challenges along the way. Mainly the uncertainty of renewables poses a challenge for the grid operators. Due to their variability in generation system balancing actions

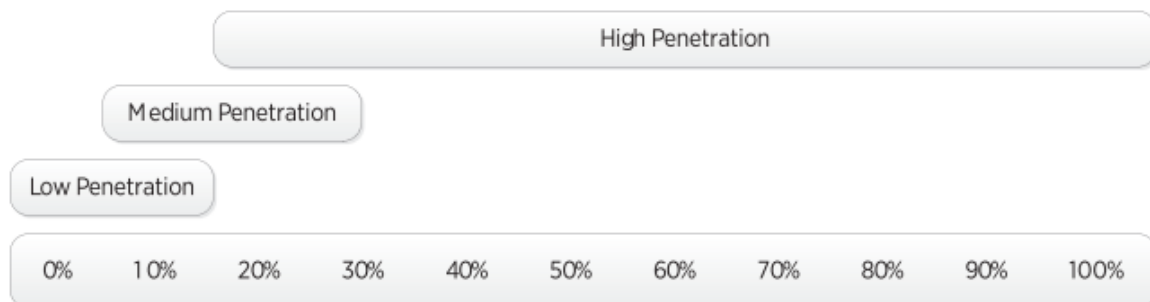
are required. System operators need to make sure that using sufficient resources system balance is maintained. There is a tendency to expand existing grids with digital technology in order to build smart grids which would react to the local changes better and would play a key role in the integration of renewables.

Smart grids are based on two-way digital communication between the consumers and suppliers and this allows better monitoring and control of the supply chain with the aim of reducing the energy consumption and costs.

Modern smart grid should have the following features [32]:

- Enabling Informed Participation by Customers
- Accommodating All Generation and Storage Options
- Enabling New Products, Services, and Markets
  - Providing the Power Quality for the Range of Needs
- Optimizing Asset Utilization and Operating Efficiently
- Operating Resiliently: Disturbances, Attacks, and Natural Disasters

Although this technology can be the key for an efficient integration and use of renewable energy sources, lack of experience and other uncertainties like costs and efficiency make it challenging to settle on this strategy. Additionally the electricity system evolved rather differently across the world. For instance Europe has a stable electricity demand and it is expected that there will not be major oscillations in the demand. However other parts of the world like Asia and Africa, with the increasing economic development will probably have their electricity demand doubled or even tripled in the next 15 years. This requires a lot of decision making on how to introduce smart grids into these systems, especially with the integration of variable renewables. Although each electrical system differs from the other depending on the mix of energy sources, location demand profiles and other, 3 levels of renewable penetration in the system can be considered as shown in the Figure 1 below [33]



*Figure 1.1 Ranges of RE penetration [33]*

Renewable penetration involves a lot of unpredictability in both supply and demand that is extremely difficult to manage. Excess power could be produced so that the system is never undersupplied, but then a lot of energy goes to waste. What can be done instead is to find a



better way to match up supply and demand and this can be achieved with the use of energy storage.

Energy storage fundamentally improves the way we generate, deliver and consume electricity. It can also help during emergencies like outages, equipment failures or accidents. But the game-changer would definitely be the ability to balance power supply and demand within milliseconds making the grid more stable, efficient and in a way cleaner. One famous senior writer Katie Fehrenbacher working in Fortune with a focus on energy and technology once said [33]: “A next generation smart grid without energy storage is like a computer without a hard drive, severely limited.” Figure 2 shows the usage of storage in some past years and predicts what will be its presence in the future (February 20, 2013).

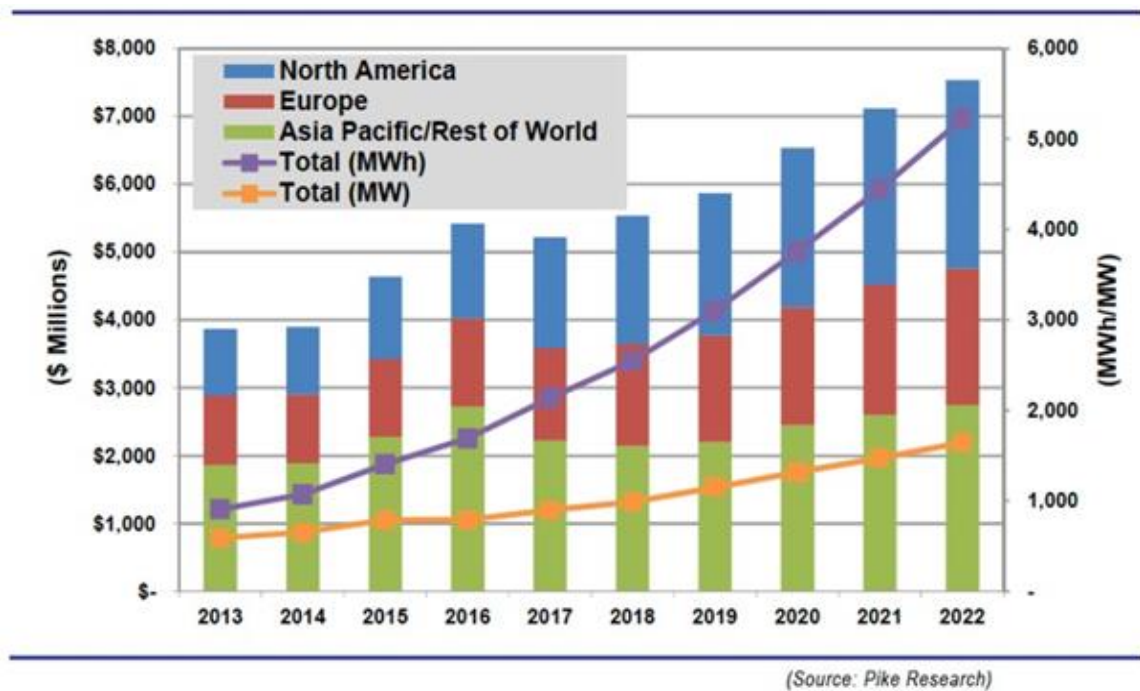


Figure 1.2 Prediction of energy storage usage [1]

There are some challenges associated with the integration of renewables to the existing power grids. First of all the conventional method for planning and operation of the electric grid is disrupted to the intermittency of the energy sources. These fast fluctuations in the power output make it more difficult for the grid operators to predict how much additional energy will be required during the following periods. Renewables along with the power electronics that are used as an interface between them and the grid, generate harmonics as well as voltage and frequency fluctuations that impede the ability of the system operators to meet the power quality requirements of the network. This has gained a lot of attention, and one of the viable solutions as proposed by papers [1] and [2] is to include energy storage in the system.

Important advantage of energy storage is that it is fuel neutral. It does not come into play if electricity is generated from oil, nuclear, wind or solar. The main idea of adding energy storage to a system is to store excess power in the periods when the demand is low and supply it later when the demand is higher, thus yielding larger profit. The Figure 3 below shows the growth of using energy storage in with integration of renewables.

Energy storage technologies include: flywheel storage, pumped hydro, compressed air, battery storage and many more. Although the supremacy of one over the other can be arbitrarily discussed, what is sure about each one of them is that they can also provide ancillary services to the system, some of which are: stabilization of voltage and frequency, power quality improvement, islanded operation, reduction of losses and many others. All of these applications serve to increase the reliability and the stability of the grid [3].

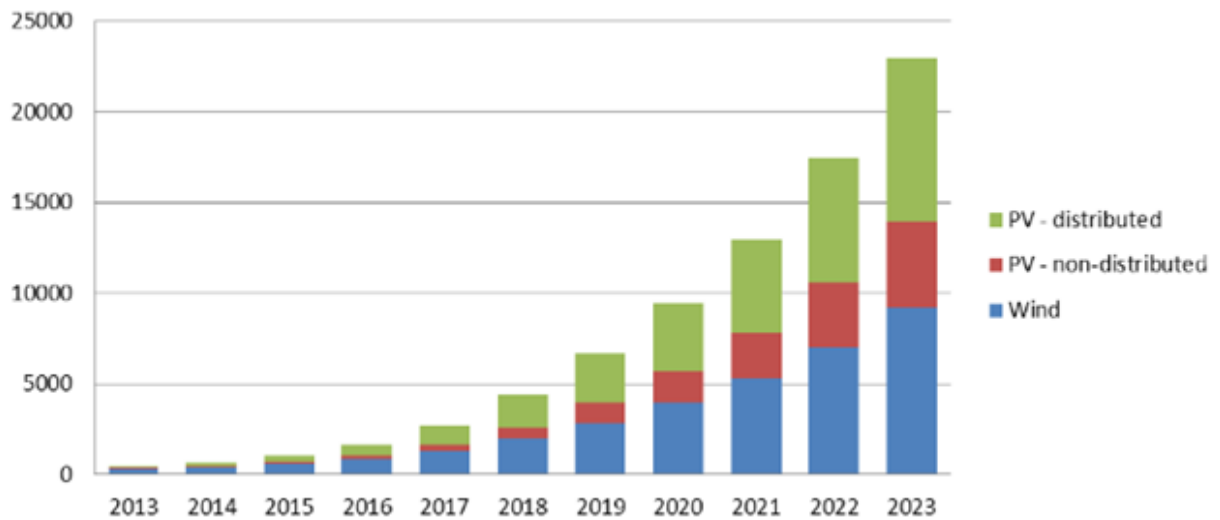


Figure 1.3 Amount of battery energy storage used in conjunction with renewables [2]

From the technical aspect, ancillary services are defined as those services performed by the electrical generating, transmission, system control and distribution system equipment and people that support the basic services of generating capacity, energy supply and power delivery [35]. The following figure presents the ancillary services battery energy storage systems (BESS) can provide [36-39]

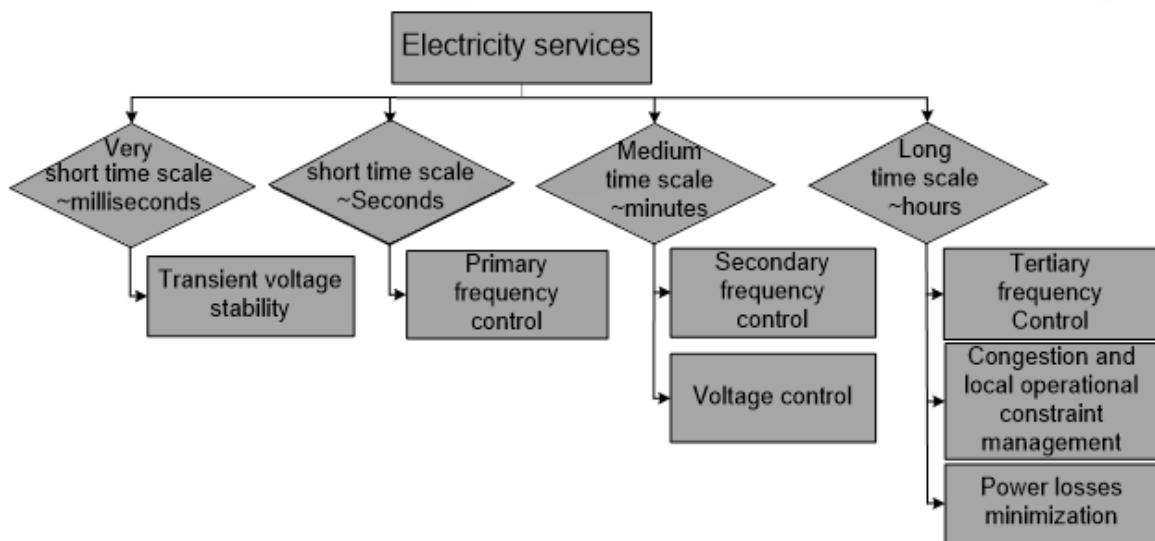


Figure 1.4 Electricity services provided by BESS based on the time-scale

Recent research suggests that the price of energy storage, especially batteries could drop drastically by 2020, which creates better conditions for the widespread integration of renewables, electric vehicles and many others applications. There is however some debate and disagreement over how far will the price drop and whether it is bound to happen in this decade or will it take more time. As new technologies are emerging, the market becomes more competitive, this the price of all the technologies tends to decrease. Many innovations that will speed up the price reduction of energy storage would probably be first realized in electronic industry, where the demand for cheaper and more efficient batteries is intense. Also as the electric car sale continues to rise, battery costs drop even faster [34].

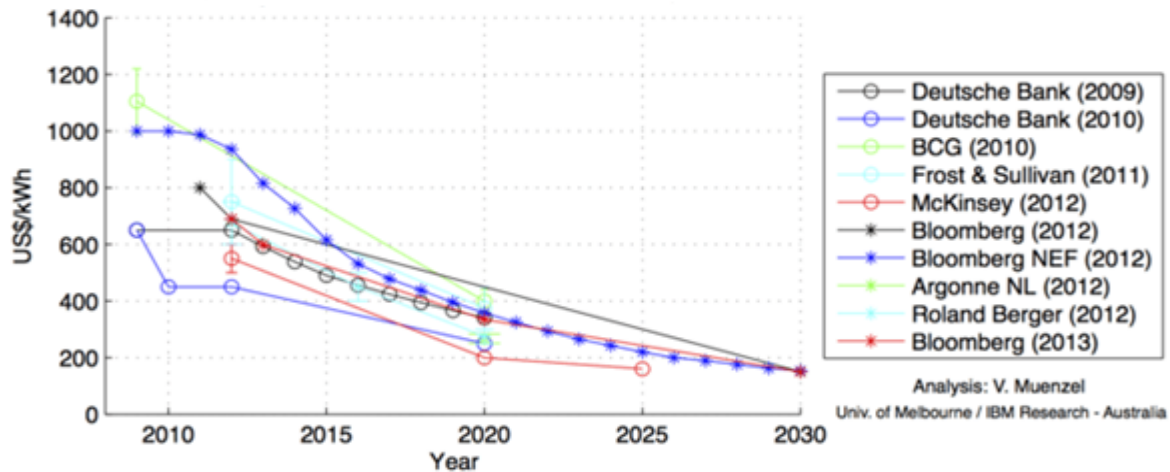


Figure 1.5 Cost predictions for Li-ion batteries [3]

The companies are well aware of this opportunity and this explains why for instance Tesla Motors is making a 5 billion dollar bet in form of an investment into a gigawatt battery factory. [31]. Moreover, the concept of modern day systems is to reduce the size, using for instance small grids with distributed generation and storage. The network itself is designed to act as a smart grid, an intelligent network that can control itself to a certain extent. [4]. Application of storage in this framework is growing rapidly and is becoming of greater importance [5] [6]. In particular battery energy storage systems (BESS) have already proven to be a viable solution, since they are non-polluting, easy to install, efficient and reliable [7]. As also mentioned before they can provide various ancillary services over different time-scales ranging from very-short (e.g. milliseconds) to long (e.g. several hours) [8]. Therefore, the use of battery storage to prevent loss of load in systems with high penetration of renewables is becoming a major area of interest [9]. Research in this area includes how to use BESS in conjunction with Wind Turbines or Solar Panels but also how to properly size the storage and where to place it in the system. In general, the selection of storage sizing and placement are highly interdependent [10]. The focus of this thesis is on optimal placement and sizing of battery energy storage in a distribution grid.

### 1.1 Problem statement

The continuously increasing penetration of distributed generation requires a detailed assessment of the impact this has on the electric power grids. As distributed generation exhibits

high variations in terms of power supply, especially when compared to the demand of the network, solutions that can resolve this problem are required.

It is important and even regulated by law that the power quality of end users is assured, along with stable voltage profiles which are normally affected by the mismatches in supply and demand caused by distributed generation. In a distribution network, when the power produced is much lower than the power consumed a voltage drop can occur, which can exceed the minimum allowed limit. Also, in period of high production and low demand of power, a voltage rise can occur. The maximum allowed limit of the voltage can be violated and a bidirectional power flow in the network can occur. The previously mentioned is manifested especially with the presence of distributed generation (renewables). As a result, these problems can limit the amount of renewables that can be integrated into the existing grids. Another important aspect of distribution grid is how to minimize the total power losses while maintaining efficiency and stability of the grid. As explained in the introduction this can be achieved using energy storage. However in order to introduce energy storage to existing grid while maximizing the benefits this can yield optimal sizing and placement needs to be determined. On the one hand, limited amount of energy storage might not have the desired impact. On the other hand, it is not possible to install a large amount of energy storage in power systems to solve all grid problems, as this increases the overall costs substantially.

Taking into account the facts presented so far, the problem, which constitutes the motivation of this project, is defined as follows: ‘Optimal placement and sizing of battery energy storage in a LV distribution grid’.

## ***1.2 Research questions and objectives***

A lot of research has been done in the area of battery energy storage systems. However by examining the literature it was determined that there are some research gaps, namely using BESS in LV networks to help with the integration of renewables. The aim of this thesis is to optimally place and size BESS in a way that the voltage profile of a LV network can be improved and overall power losses are reduced. The main research objectives are:

- Evaluate the suitability of existing algorithms to solve real scale non-linear optimization problems.
- Examine the impact of RES penetration in a real distribution network
- Develop an optimization model to determine the optimal placement and sizing of BESS
- Implement the optimization model on a real distribution grid and evaluate the results

A series of research questions shall be answered:

- How does the integration of distributed generation affect the voltage profile of the network?
- To what extent could the optimal sizing and placement of BESS help with the integration of renewable energy sources?

- What is the impact of the proposed voltage support strategy on a distribution grid?

### ***1.3 Thesis organization and outline***

The body of this thesis is divided into several chapters and each of the chapters provides an insight about certain aspect of the thesis. To answer the research questions and meet the objectives the thesis is structured as follows:

**Chapter 2** introduces the reader with current state-of-the-art on BESS applications. Specific focus is on optimal sizing and placement of the storage using various optimization tools. It also provides the scope of the current study with the research gaps.

**Chapter 3** provides an introduction to some of the main problems in a distribution grid with respect to the regulations. Additionally, several solutions to voltage problem in the distribution grids are briefly described with the focus on energy storage as it is a part of this thesis.

**Chapter 4** describes the genetic algorithm which is used as the optimization tool in this thesis. The basic mechanics and the functioning of the algorithm is explained.

**Chapter 5** explains the models used in this thesis. The models are described and their implementation is discussed. These models are used to simulate different scenarios in order to obtain the results and to examine the effects of the proposed methodology

**Chapter 6** is a result chapter, where different case studies were analyzed and small discussion of the results is made. Based on the results some conclusions are made that are explained more in detail in the following chapter.

**Chapter 7** is a commentary section where conclusions with respect to the results displayed in the previous chapter are made. Based on the limitations and conclusions, recommendations for future work are presented.



## Literature Survey

This chapter provides a review of the current literature pertaining to this field of research, including the types of energy storage present in today's market, ancillary services provided by energy storage, optimization techniques used for various purposes and specific studies conducted using the Genetic Algorithm. The aim of this review is to examine the most interesting areas of research and investigate for possible gaps in knowledge which open new questions for further analyses.

### 2.1 Types of energy storage

The growing need for energy storage has led to the development of many new technologies. Judging solely from the amount of published work, the interest in the energy storage has exploded in the last years. Although many energy storage technologies (e.g. battery storage) are mature and have proven as a viable asset in the energy power systems, some technologies are still undergoing development as they are still not ready to acquire a stable spot in the energy market [58]. This section will provide a brief overview of various energy technologies. Figure 2.1 below provides an overview of some of the energy storage systems. Most of the technologies convert the electrical energy into another form for storage. The most common types of energy storage are: flywheels, pumped hydro storage, electromechanical batteries, capacitors etc.

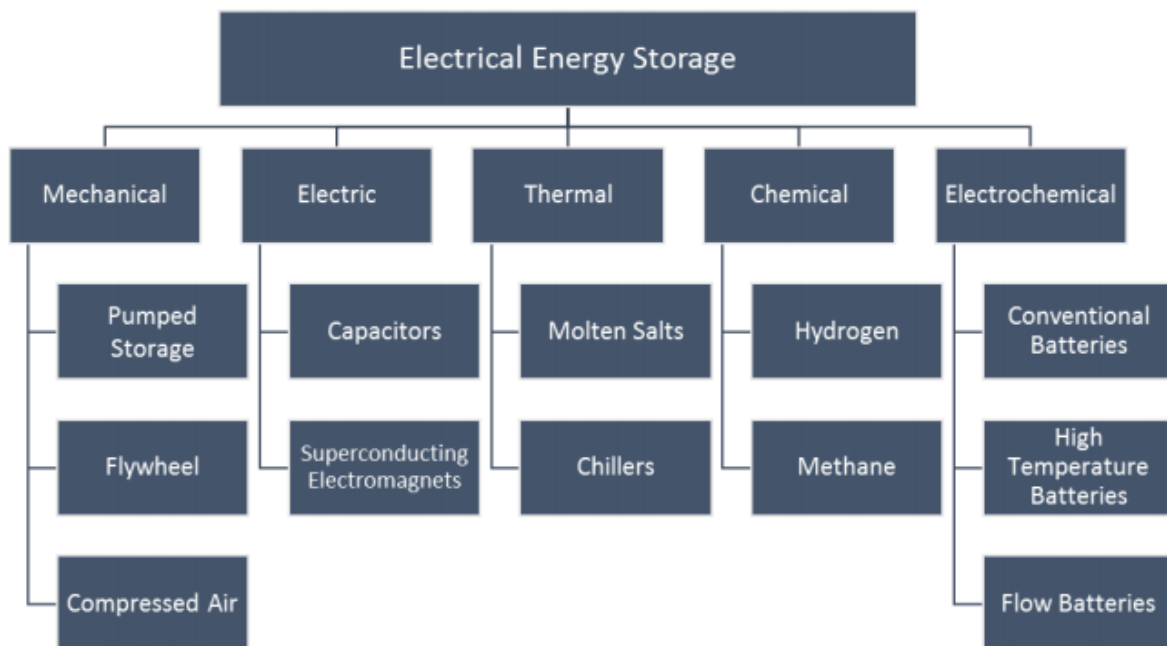


Figure 2.1 Classification scheme for energy storage technology [58]

### 2.1.1 Mechanical

Pumped hydro storage is one of the most mature technologies present. It has a lot of installed capacity worldwide and provides various benefits. This type of storage uses reservoirs and water flow to store or provide energy. When energy is stored, the water is pumped from a lower reservoir to an upper one. It is stored there until there is a need for energy, in which case the water is released from the upper reservoir to flow through the turbines and reach lower reservoir again. The water that flows through the turbine produces electricity. This technology has a long life span, however a spacious areas is necessary since it has specific siting requirements. However it is considered a good solution for the integration of wind farms [57]. Moreover, the installation costs tend to be high. [58]

Flywheel storage is a technology that stores electrical energy by speeding up its integrated rotor. The rotor is the main component of the flywheel and it usually is placed on magnetic bearings in order to reduce the friction and maximize the energy exchange. Characteristics of the rotor determine the energy characteristics of the flywheel. They are normally used for short period discharges making them a good storage technology for power quality improvement [59]. One of the flaws of this technology is low life expectancy that is limited by the number of rotations the flywheel can achieve.

Compressed Air energy storage (CAES) the electric motors are used to store energy in form of compressed air within enclosed volumes. This technology is mainly used for balancing supply and demand and stabilizing conventional generation [60]. Low storage density is one of the flaws of this technology, since it requires a lot of storage space for larger amount of energy.

### 2.1.2 Electrochemical

Electrochemical batteries convert electricity into chemical components for storage and then the reversed process is applied when the energy is to be supplied. The most common types of batteries named by the type of electrolyte employed are: Lead-Acid, Lithium-Ion, Nickel-Cadmium and many other [61].

Flow batteries use the same technology of converting the electricity into energy, however the use external tanks as storage for the electrolyte. However this increases the construction costs of this type of batteries. This technology tends to be expensive and has a limited amount of energy cycles. This type of batteries have shown a strong business case for integration of wind farms [62].

### 2.1.3 Electromagnetic

As most of the technologies tend to store the energy in a different form these two types of storage technology store electrical energy as electricity: superconducting electromagnets and capacitors.

Capacitors consist of two electrical conducting plates which are separated by a non-conducting part (dielectric). Energy is stored in the electric field between the plates. They are suitable for



power quality and suppression of the intermittency of the renewables [63]. However they are prone to fire, explosion and chemical hazards.

Superconducting magnet energy storage uses the current that flows through it to generate a magnetic field that will store energy. Once the field is created the energy can be stored indefinitely. Due to this characteristic they are often referred to as “permanent” magnets. They are very reliable since they are fast-responding and their efficiency with adding few mechanical parts can reach very high levels. The fast responding characteristic makes them viable for grids that experience sudden change of load [64]

#### **2.1.4 Chemical**

The chemical storage technology relies on conversion of electrical energy into hydrogen or methane that can be used as fuel in conventional power plants. The huge advantage of this technology is high energy density when compared to other technologies [65]. The energy using this technology can be stored for long period of time however round trip efficiency is relatively low. This technology is playing an important role in powering transportation that uses gas as a fuel.

### ***2.2 Ancillary services provided by battery energy storage systems***

Ancillary services are electricity services performed by various electric system equipment with the aim of supporting the transmission of power and maintaining a reliable operation of the electrical network. It is estimated that the technical need for ancillary services will grow in the next decade [66] and as a result the demand for energy storage that provides these services will grow as well. [67] Here some of the main ancillary services that battery energy storage systems can provide to the electricity grid will be explained. In Figure 1.4 an overview of the most common electricity services based on the time scale from is presented.

Transient voltage stability refers to the ability of the system to maintain a synchronous operating state after it has been affected by a large disturbance. (Usually a connection or disconnection of large generators). In [48] BESS was used for mitigation of voltage disturbance caused by the connection of the doubly-fed induction generator wind turbine to the grid.

Primary frequency control is a service that helps with the control of the frequency within a few seconds once a disturbance in the frequency occurs. Droop control is a strategy normally applied to generators for primary frequency control. In [49] it was shown that during a disturbance BESS can successfully provide primary frequency control.

Voltage Control is a system service under which the voltage sags, swells and other voltage related problems are monitored and controlled with the use of BESS. Papers [50] [51] propose a strategy for optimal voltage control using battery energy storage. The focus is on the grids that have distributed generation (renewables).

Congestion and local operational constraint management is a system function that makes sure that the operating limits are maintained and not exceeded. Recent studies [52] [53] show that the congestion management can be successfully handled using BESS.

Power loss minimization is achieved using battery energy storage. The minimization is achieved by optimally placing the storage within the network. In [22] genetic algorithm based model was proposed for optimal placement of BESS.

### ***2.3 Optimal placement and sizing techniques***

Optimal placement and sizing of battery energy storage has gained a lot of attention in the last few years. Appropriate sizing and placement of BESS is important in order to reduce or mitigate some of the adverse effects that for instance integration of renewables can have on the grid. The studies conducted can be separated into two areas: economic or grid power-related problems [54]. To that end the aim is to optimally size and place energy storage using an optimization technique. Various heuristic methods are used to tackle the optimization problem, some of which are Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Integer Programming (IP) and many more. Optimal placement of BESS within a grid connected power system or isolated grid is dependent on many factors: voltage levels and variations on each of the buses, type and size of the loads connected to the buses, size of distributed generation connected to the system and type of the distribution network.

Numerous authors considered GA as an optimization tool. In [22] and [25] the authors suggested an optimal sizing model with respect to the power losses and voltage drops in the network. At the same time in [55] a multi-objective planning model in terms of costs was proposed. The model in [22] was tested on IEEE 33-node network and later on compared to the results obtained using Hybrid Genetic Algorithm (HGA) and it was shown that HGA provides better results in terms of efficiency, especially when used for larger systems. In [56] and [29] the models were proposed to obtain the optimal location and capacity of the batteries used for electric vehicles (EVs). The optimization models had many constraints and since the investment costs were taken into account. The technique chosen for both studies was PSO as it showed better response compared to other optimization techniques when handling multiple constraints. Another heuristic optimization technique used to evaluate optimal placement and sizing of BESS is the Ant Colony Optimization (ACO). In [57] the authors found an optimal location of electric vehicles in the distribution grid by minimizing total costs and real power loss while the security and traffic flow were maintained in form of constraints. The weakness of this technique is that it is slow compared with other optimization techniques. Beside the heuristic optimization techniques, other methods were also used to solve the optimization problems. Comparison of different optimization techniques is summarized in Table 2.1

*Table 2.1 Comparison of different optimization techniques in EVCS siting and sizing schemes [57]*

No	Algorithm	Benefits	Disadvantages
1	Genetic algorithm (GA)	Easy to implement; more suitable for placement problems	Takes a long time to solve the placement and sizing problem
2	Particle swarm optimization (PSO)	Simple computation and the ability to find near-optimal solution	Premature convergence; higher possibility to get stuck in local optima
3	Ant colony optimization (ACO)	Positive feedback accounts for rapid discovery of good solutions	Time to convergence is uncertain
4	Greedy algorithm	Fast and guaranteed to produce feasible solution	The obtained solution is normally a sub-optimal solution
5	Integer (linear) programming	Simplicity; solves many diverse combinations of problems	Only works with linear variables; it cannot potentially solve stochastic problems
6	Cplex optimization software package	Efficiently solves linear, convex, or non-convex constrained problems	Difficulty in modifying optimization routines

## ***2.4 Optimization of battery energy storage using Genetic Algorithm***

The use of battery energy storage to prevent loss of load in systems with high penetration of renewable resources is becoming a major idea of interest [9]. To that end there are several aspects regarding battery energy storage that need to be properly addressed. The optimal sizing and placement of the BESS in the distribution system are one of the most important aspects that would maximize the benefits of using BESS in the system [11]. Inappropriate sizing and placement of BESS in the distribution network can cause voltage oscillations. Moreover, there is an impact on the total losses of the system that can be alleviated with properly adjusting the size and the place of the battery storage in the distribution network. It is therefore important to consider an adequate location with respect to the size of the units to obtain an optimal effect. Although, there is no general suggestion for placing BESS in a power distribution system, one of the main ideas is to place them at buses or nodes, where they provide the highest reduction in losses without, keeping the voltage within the desired limits or even improving it. Normally this is not done by pure guessing, trial-and-error or calculations, there is a number of optimization techniques proposed in the literature [12] [13] [14]. The list of the papers that are addressing these issues is quite substantial, the difference is the method used, the type of the system it is being used on and what are the limitations of the system. Tackling the sizing and placement of battery energy storage system within a distribution grid using the Genetic Algorithm (GA) has been investigated in [68] and [69]. Yet there are some papers that use this algorithm as a tool for the minimization of the number of solutions in terms of results. In order to achieve good results a good objective function of the algorithm needs to be clearly defined. The objective function can be defined for various purposes. The work presented in paper [15] aims toward optimizing the placement of distributed generation (DG) and allocate parking lots for electrical vehicles, with the aim of reducing the losses of the network. The objective function contains active and reactive power indices and is minimized using genetic algorithm. The simulations are carried out on a 30-bus system, which is large enough, so that the results obtained are viable and realistic to a certain extent. Genetic Algorithm is used as an optimization tool to allocate a parking lot and a DG in the distribution system. One of the flaws

of this study is that the algorithm is used only for placement of a single DG and one parking lot. Furthermore the time frame used in the system and the amount of vehicles that are used for the simulation are assumed, real-life scenarios can be a lot different, which consequently could lead to very different results. So with the precise parameters the optimal allocation can be more effective. In [16] the optimal placement of distributed energy storage is assessed by comparing the losses reduction when the storage is installed at different bus bars. Additionally, optimization of the total costs is taken into account and is used as an operation constraint of the objective function. Since the mathematical solving of this problem would take too much time, Genetic Algorithm is proposed as a tool to solve this problem. Although costs were considered as one of the minimization functions of the system, the economic benefits of such a system were left out. Moreover, the proper sizing of the batteries was not addressed at all which could lead to some more realistic results. Study [11] proposes a methodology in order to address the optimal placement and size of BESS in a distribution system with the main aim of reducing the distribution losses. Two IEEE benchmark distribution grids (IEEE 13 and IEEE 34) were used, with 13 and 34 buses respectively. However in this work the results were acquired using the Particle Swarm Optimization (PSO) algorithm, as this algorithm is known for its ability to effectively solve larger scale non-linear optimization problems. Results for both systems were obtained with and without an inclusion of a Wind Turbine in the system, in order to assess how the integration of renewables can be improved with proper sizing and placement of the storage. The type of the turbine used in the system is the DFIG, which is modelled as a fixed PQ load in the system for the ease of implementation. Here the minimization functions for the algorithm are the minimization of the losses and a better voltage profile (voltage is within the specified boundaries). The idea proposed here can be used and further studied with the use of a different algorithm (e.g. Genetic Algorithm). A cross-comparison of the results can be done in order to analyze which one is more efficient. When only losses are considered as the objective function of the algorithm, the total losses of the system are reduced. However, when loss minimization along with the control of voltage is taken as the objective function, the distribution of losses is different, but the overall voltage profile of the system is better, since the solutions that have a voltage violation are not considered. The general conclusion of this work is that the algorithm will provide better results, if more objective functions are introduced, so that the study is close to some realistic scenario.

Another paper [17], proposes a methodology on how to optimally place energy storage in the system using GA. The function minimized is the net present value (NPV) whose aim is to limit or decrease the total costs. In addition the algorithm is evaluated for four different load levels with a specific electricity price for each level. Voltage constraints at each node are presented, which guarantee the system stability. Although some interesting results were provided, one of the flaws of this study is that it although the State-of-charge (SoC) of the batteries is considered, the batteries are assumed to be lossless. Additionally placement is analyzed without taking sizing of the storage units into account, which might yield better results in terms of losses. Regarding the economic benefits of the system, although certain results were presented, they remain to be taken as such only regarding the system with that particular choice of storage and

level of loads. The limitation of studies that take costs of a certain system into account is that no general assumptions (e.g. for a different system) can be made, at least with a high level of certainty, since the load patterns, pricing and system limitations are always unique for that very system. Study [18] presents a way in the study on the problem of managing, sizing and siting of energy storage in order to acquire loss reduction, based on PSO. The management strategy used in this paper shows that significant results regarding the placement of storage can be achieved using this algorithm. It is also noted that the results have been compared with the ones when using the genetic algorithm. However it is shown that they are identical. The good research gap of this system would be introducing the voltage constraint which in this study has been purposely neglected.

## ***2.5 Conclusion***

It is clear that optimization of placement and sizing of BESS is a very interesting topic, especially regarding the integration of renewables. Additionally, the optimization of placement and sizing of BESS has a strong business case since oversizing can lead to additional investment costs. Regarding the work that has been done with the optimal placement and sizing of energy storage in distribution networks, various optimization techniques were proposed, however evaluating of the supremacy of one over the other is not straightforward and usually depends on several aspects. Genetic Algorithm has shown to be a good tool for optimization of electrical problems. To author's knowledge not much work has been done using the algorithm in the domain of small scale distribution grids. Most of the research done regarding BESS aimed at reducing the losses and the costs of the system.

In conclusion the review shows that there are interesting topics in the field of BESS and optimization of sizing and placement in particular relating to the minimization of power losses and voltage support in distribution grids.



---

## Grid regulations

This chapter gives a brief introduction to some of the grid regulations regarding the low voltage networks. As voltage rise is one of the main problems in distribution grids, several methods that are used to overcome this problem are presented.

### ***3.1 Distribution grids***

Distribution grids must be handled in such a way that the quality of power supply is high and the voltage level is kept within the specified limits. Depending on the type of the network, consumers are able to work within the certain margins for both voltage and frequency. The European electric power grid is undergoing some important developments regarding the distribution, transmission, generation and utilization as there are some key objectives set by the European Union. [Distributed Generation in Europe: the European Regulatory Framework and the Evolution of the Distribution Grids towards Smart Grids]. What is one of the main contributors to this development is an increase in the installation of distributed generation (DG) normally placed in the proximity of the end user. There is however no globally acknowledged definition of what distributed generation is, but what it is normally referring to is are the units based on renewable energy sources. In the past it was not considered that these sources will be that relevant for the energy system. Another contributor is the intermittency, which sometimes renders these sources to be completely off and as soon as that happens there is a problem in the grid, a voltage or a frequency deviation that needs to be handled promptly. Some countries changed the grid codes and regulations quite a bit in order to handle these problems.

#### **3.1.1 Supply voltage variations**

According to the European standard EN 50160 voltage characteristics of electricity supplied by public electricity networks under normal operating conditions, which excludes period with faults or any kind of interruption, it is stated that the supply voltage variations should not exceed  $\pm 10\%$  of the nominal voltage. This applies to high voltage and medium voltage networks.

Regarding the low voltage distribution grids standard IEC 60364-5-52 low voltage electrical installations, it is specified that the maximum allowed voltage drop is  $\pm 3\%$  for lightning circuits and  $\pm 5\%$  for all other circuits. This applies for networks that are supplied by public low voltage systems. In case of a supply from a private network these variations are different, however will not be mentioned here.

### 3.1.2 Voltage sags/swells

Voltage sag, also called voltage dip is defined as a decrease of the RMS value of the voltage to 10%-90% of the nominal value for the duration of milliseconds up to a minute. (Standard IEEE 1159). There are three different categories of voltage sags: instantaneous, sag duration is from 1 half-cycle (10ms) to 30 cycles (0.6s), momentary, where the duration is from 30 cycles (0.6s) up to 3s and temporary, lasting from 3s to 1 minute. Example of a voltage sags can be seen on Figure 3.1.

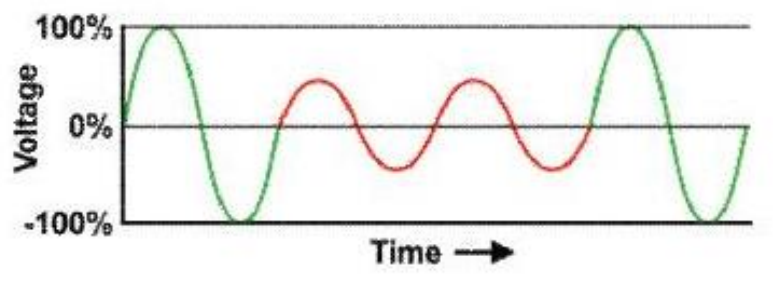


Figure 3.1 Voltage sag [28]

Voltage swell is defined as the increase of the RMS value of the voltage to 110%-180% of the nominal value with a duration of a millisecond to a minute. The same categories in terms of duration as for the voltage sags apply here. They can appear between the conductors. They are less common than the voltage sags and are associated with system fault conditions. Example of a voltage swell can be seen on Figure 3.2.

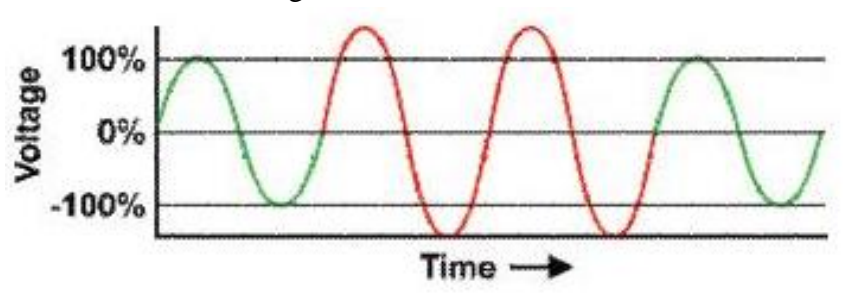


Figure 3.2 Voltage swell [28]

### 3.1.3 Voltage unbalance

Voltage unbalance is a state where the RMS values of the line to line voltages are not all equal. IEEE uses phase-to-phase voltages in the definition, rather than the line-to-line voltages.

According to the standard EN 50160, for LV and MV networks, during every period of the week, 95% of the positive phase components of the RMS value of the voltage shall be within 0%-2% of the positive phase component (The mean 10 min RMS value of the voltage is considered).



### 3.1.4 Flicker

Luminance of light emitting sources can be affected by voltage variations and as a result a visual phenomenon called flicker is created. Flicker may affect sensitive electronic equipment but can also be very annoying to the human eye if the amplitude of the fluctuations changes rapidly. Quantity of the flicker is usually defined as the amount of the fluctuations over a period of time. There are two types of flicker:

- Short-term flicker severity index, up to 10ms interval
- Long-term flicker severity index, up to 2h interval

Due to the variety of the equipment installed in modern day systems, IEC established three different categories of flicker limitation standards [32]:

- Low voltage equipment with rated current less than 16A [IEC 61000-3-3]
- Low voltage equipment with rated current greater than 16A [IEC 61000-3-5]
- Medium and high voltage equipment

For low voltage network it is stated that flicker created by power generating stations with rated currents less than 16A or for rated currents higher than 16A and lower than 75A should comply with these standards respectively.

### 3.1.5 Active power curtailment

An upper limit for the inverter active power is specified. If the grid is for instance PV-system powered, as the power of the PV array is at its maximum point which exceeds the power set point, active power curtailment controls the voltage of the array by increasing it in order to reduce the total amount of power provided by the array. This requirement applies to all PV plants with more than 120kW of power as stated by the European directive.

## 3.2 Voltage rise and mitigation techniques

In a distribution grid, especially with the integration of distributed energy sources, when the consumed power is larger than the produced power, the electricity flows from the DG to other consumers or to higher voltage levels. This reverse power flow due to the utilization of DG leads to certain issues that need to be addressed. It can cause congestion in the system, as transmission lines have maximum allowed power that can be transferred via them thus limiting the maximum current of the lines. The aforementioned can render the lines becoming the bottle necks in the system and as a result a voltage rise can occur with the possibility of exceeding the upper voltage limit. This type of problem is common in times of low consumption and power injection by DG. This can limit the amount of power that can be injected by renewables into the distribution grid. Distribution grids can be split into two categories: urban and rural. Urban grids supply many households in a relatively compact area, line lengths are small and the capacity of the transformer is high, whereas rural grids are more characterized by longer lines and lower number of consumers spread on a wider area. These grids are usually medium

or low voltage. As the grid regulations demand a steady voltage profile and the voltage to be within the specified limits, if there are some violations, they need to be mitigated. Several solutions that help to overcome this problem are introduced in this part.

### 3.2.1 Voltage rise in a feeder

Normally, when distributed generation is not present in a system, the voltage along the distribution lines from the substation to the end of the lines will drop due to the line impedances and loads. However with integration of renewables things become slightly more complicated. The voltage profile can improve on certain segments of the feeder as the amount of power flow throughout the whole feeder is reduced. Yet if the generation is much higher than the demand near the point of connection, there is a surplus of power present and it flows back to the grid. Bidirectional power flow is present. This power flow can create a voltage rise. The more intermittent the production of DGs is, there will be more mismatches with the demand in terms of power.

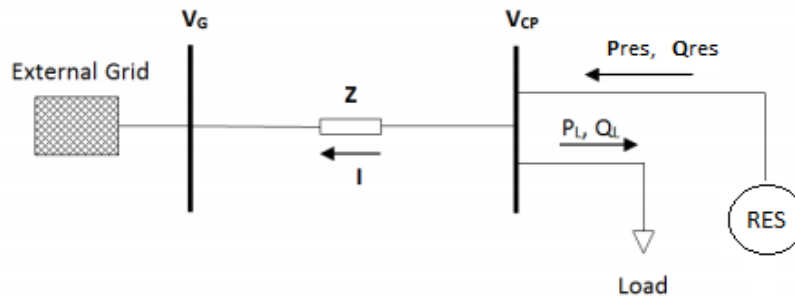


Figure 3.3 Schematic of a load and a RES connected to a LV feeder [32]

With respect to Figure 3.4 the voltage rise along the feeder can be approximated as follows:

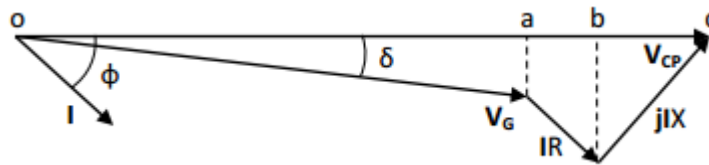


Figure 3.4 Voltage rise phasor diagram [32]

$$\Delta V = V_{CP} - V_G \approx oc - oa = ac = ab + bc$$

$$\Delta V \approx IR \cos \varphi + IX \sin \varphi = \frac{V_{CP} IR \cos \varphi + V_{CP} IX \sin \varphi}{V_{CP}}$$

$$\Delta V \approx \frac{P_{CP} R + Q_{CP} X}{V_{CP}} \approx \frac{P_{CP} R + Q_{CP} X}{V_G}$$

$$Z = R + jX$$

Where:

$$P_{CP} = (P_{RES} - P_L) = V_{CP} I \cos \varphi$$

$$Q_{CP} = (Q_{RES} - Q_L) = V_{CP} I \sin \varphi$$

### 3.2.2 Solutions to voltage rise problem:

There are several solutions proposed in order to mitigate the voltage rise in LV-networks:

- Grid reinforcement
- Active power curtailment
- Reactive power control strategies
- Use of energy storage

### 3.2.3 Grid reinforcement

With respect to the phasor diagram presented in Figure 3.4 it can be observed that with lower  $R$  and  $X$ , thus with an impedance decrease, lower voltage can be achieved. This is manageable with the use of conductors with a larger cross-section. This is one of the main solutions applied for voltage control, yet this can be costly, especially with the use of underground cables as it takes a lot of effort to replace them with new ones and any investor would most probably try to avoid or at least delay this type of investment.

### 3.2.4 Active power curtailment

PV inverters can provide voltage support using the active power curtailment (ACP) technique. This option can aid the increase of PV integrations. In some countries, PV owners are obliged to provide active power reduction capability. Also in some countries reactive power injection is forbidden as it is not allowed to manipulate the voltage of LV feeders. For this reason the active power curtailment has to be used in these cases. Moreover there is a stronger relationship between the active power and the voltage in LV systems than between the reactive power and the voltage. Curtailment is also known as the droop method. The method proposes that the active power injected into the system from a PV array is a function of the bus voltage as can be seen in Figure 3.5.

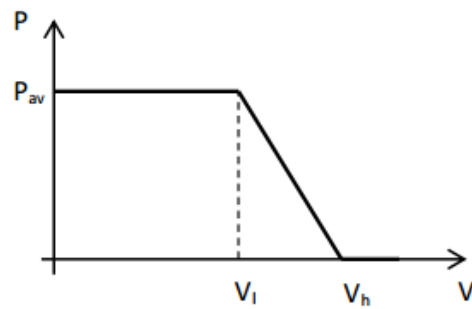


Figure 3.5 Voltage-Power characteristic [43]

Up to the point  $V_l$  there is no power curtailment and as a result the available active power is injected to the system ( $P_{AV}$ ). When the allowed threshold is reached the amount of active power supplied is reduced. The PV system stops producing power once the critical point  $V_h$  is reached.

### 3.2.5 Reactive power control strategies

Another efficient way to support the grid voltage is to use the ability of DG's (e.g. PV inverters) to absorb or supply reactive power while simultaneously feeding the network with active power. There are various methods for this type of strategy, some of which are:

1. Fixed power factor (PF)
2. Voltage-dependent reactive power
3. Active power dependent PF

#### 3.2.5.1 Fixed PF

This method proposes that the absorbed reactive power is proportional to the active power. With low generation both powers are kept low, whereas with maximum active power generation, maximum reactive power is injected.

#### 3.2.5.2 Voltage dependent reactive power Q (V)

This method uses local voltage information that is based on the power production and consumption in the system. The voltage at the terminals of the inverter is used as an input, however this technique will not be further explained here.

#### 3.2.5.3 Active power dependent PF

This method is used when the real power production is low and all the power produced is consumed locally. In this case there is no need for the injection of reactive power as it would

lead to additional system losses. Active power dependent power factor method can improve this drawback but same as previous method, will not be further elaborated.

### **3.2.6 Energy storage**

Another solution to grid voltage support is the energy storage. Energy storage apart from being able to mitigate the voltage rise in the MV/LV distribution grids, can also provide other valuable services that help in maintaining the stability and the efficiency of the system.

As in this thesis battery energy storage system (BESS) is of interest, other energy storage options will not be analyzed. There are two concepts that are used to face the voltage problem: the centralized concept where a system of multiple batteries is placed on a strategically predefined location to provide voltage stability to the whole system, where the other one is the distributed concept, where a number of batteries are placed on different locations in the system to achieve the same goal.

The first concept could face the voltage rise rapidly, as charging and discharging of the batteries can be based on the voltage measurement on the nodes that are the most critical. The second concept can affect the voltage indirectly, as the charging and the discharging of the batteries would be based on the distributed generation and load demand. The difference between these two concepts also lies in the incentives of the distributed system operator (DSO) or the owner of the system. Both concepts should be combined with either active power curtailment or reactive power absorption. The main disadvantages when it comes to battery energy storage is arguably its price, which as mentioned in the introduction part of the thesis is constantly dropping. To support this claim there are more and more PV systems installed and electric cars produced that both require the use of batteries, this the increase in the amount of batteries produced, lowers their price as they are more present in the market. Additional markets with used batteries are also evolving.



---

## Genetic Algorithm

### 4.1 Introduction

Genetic algorithms (GA) are designed so that they imitate natural processes related to evolution, genetics and natural selection. Whether or not, an individual will survive and produce an offspring depends highly on how well it can adapt to the actual environment. The attributes of each individual are defined by chromosomes.

Natural selection enables the successful reproduction of chromosomes. Under successful, different attributes are considered, depending on the context and the environment. During the process of reproduction there are two additional mechanisms, which make the process very complex and unpredictable. One of them is the *mutation*, which can make an offspring much different than its biological parents. The other one is the process of *recombination*, which exploits the genetic material of the parents, combines it differently and result is an offspring that is different than the parents.

Similarly as in nature, genetic algorithms try to find out the best chromosome, manipulating the chromosome's material, not denting too much into the problem that is being solved [2]. What is considered under the term chromosome, when it comes to genetic algorithms, is a binary record of one of the analyzed features. The only thing the genetic algorithms are taking care of is the level of quality of the produced chromosomes. These processes of manipulating the binary record (chromosomes), can solve extremely complex problems without addressing the complexity and the nature of the problem that is being solved.

The basic element GA manipulates is the string and each string represents the binary code of the parameter in the search field [3]. That way each string is a point in the search field. During the application of different operators of the genetic algorithm, the total number of chromosomes remains the same, but their composition changes.

Genetic Algorithm main operators:

- Reproduction
- Crossover
- Mutation

**Reproduction** is a process during which certain chromosomes (binary strings), are copied to the next generation with respect to their criterion functions. Criterion function  $f(i)$  is accompanied to every individual in the population, where high value of this function corresponds to a high level of quality. This function can be any linear, non-linear, differential

or non-differential, continuous or discontinuous, yet positive function (the algorithm only takes its value into account, disregarding all other attributes). The technique of reproduction mimics the roulette wheel concept. By spinning the wheel, the parent which will breed a new member of the population is determined. This technique can be formalized in the following way:

1. All the criterion functions of all the population members are summed up. The sum is called the total performance
2. A random number of intervals  $n$ , is generated, from zero to the total performance
3. First member of the population whose criterion value added to the criterion value of all the previous members is greater or same as  $n$  is chosen

**Example:** A set of six chromosomes (strings) is observed. Their values are presented in the following table:

*Table 4.1 Example of a chromosome set*

Serial number	Chromosome	Fitness function value	Cumulative value
1	01110	8	8
2	11000	15	23
3	00100	2	25
4	10010	5	30
5	01100	12	42
6	00011	8	50

Since the total performance of this set of chromosomes equals 50, in order to select the parents which will reproduce new members, a set of numbers from the interval  $[0,50]$  is randomly chosen. In the following table it is shown how a random set of 7 of these numbers affects choosing the parents of the population.

*Table 4.2 Effects of choosing the parents of the population*

Random number	26	2	49	15	40	36	9
Chosen Chromosome	4	1	6	2	5	5	2

This is totally equivalent to the roulette spin wheel technique. The value of the fitness function directly affects the choice of the chromosomes in the roulette process, as has been stated before.



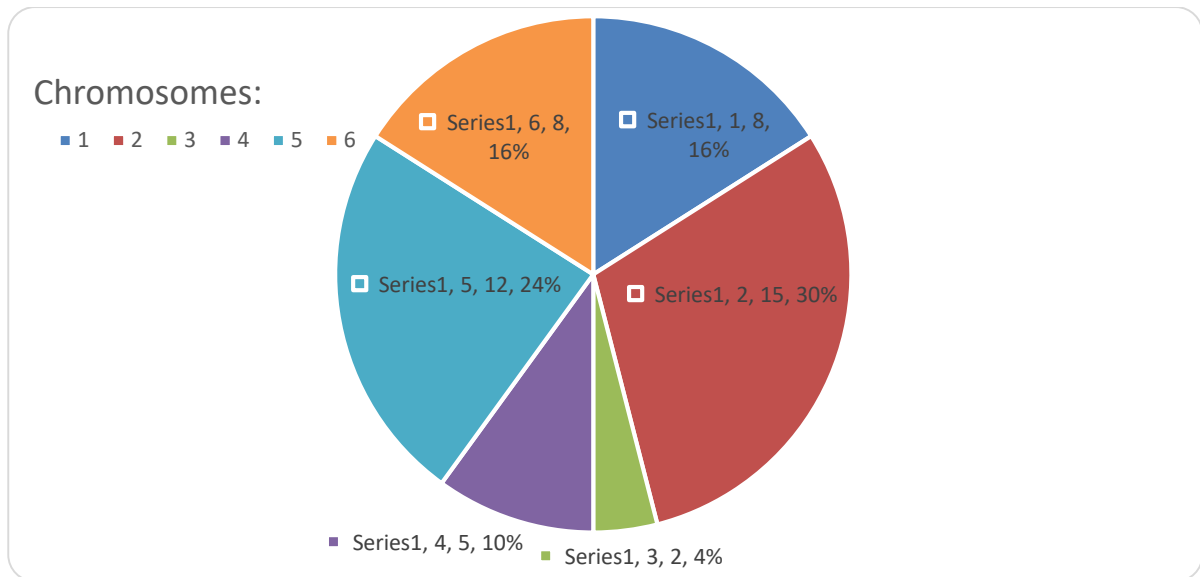


Figure 4.1 Graphical representation of the roulette spin wheel technique

**Crossover:** Unlike reproduction, which takes the best individuals into account, but does not generate new quality in terms of chromosomes, the crossover tries to use the best ones and make even better individuals. In nature, an offspring inherits genes from both parents. The main operator which works with genes of the parents is the crossover and the probability of the crossover is defined as  $p_c$ . First, from the set of individuals that are determined for reproduction, a random two are chosen. Then randomly again, the crossover point is defined, if the individuals with the probability  $p_c$  are chosen for crossover. The parts of the genes are interchanged on the crossover point. This way we get 2 chromosomes that have the starting chromosomes as parenting ones. Reproduction and crossover are the main mechanisms that Genetic Algorithms uses to narrow down the search towards better search fields, using the current knowledge.

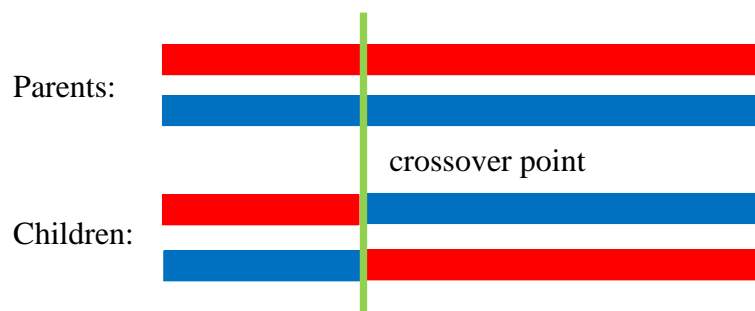


Figure 4.2 Crossover between parental and children chromosomes

**Mutation:** Although reproduction and crossover lead to better results in general, they do not turn up with a new quality or information on a bit level. As a source of different bit values, bit mutation with a low probability  $p_m$  is used, which inverts a randomly chosen bit in a chromosome. As in nature, mutation can lead to degenerative individuals (which the process of reproduction/selection will probably eliminate) or to a totally new quality. The level of mutation should be carefully chosen since it is the operator of a random search

**1100110111** → **1100100111**

## 4.2 Parameters of GA:

The parameters that define the genetic algorithm are defined below:

- $N$  – size of the population
- $p_c$  – crossover rate (probability)
- $p_m$  – mutation rate (probability)
- $G$  – generation gap (determines the amount of population (percentage) which will form the members of a new population)
- Evaluation function (has the same role as the environment of the individual in the natural evolution)

In case of a simple genetic algorithm, it is necessary beside the evaluation (fitness) function and the coding, to specify the size of the population, crossover probability, mutation probability and the generation gap. Reproduction, crossover and mutation operators are applied on a population until a complete next generation population is reached. The newly formed population can be either mutated after the crossover, generated by crossover without further mutations or simply chosen to be involved in the forming of the next generation without additional mutations or crossover. Generation Gap ( $G$ ), represents the part of the population which will be substituted by new members and is given as  $0 \leq G \leq 1$ . In the process of making a new generation  $N \cdot G$  individuals are replaced with new members, while the others remain the same (are simply copied).

There are a lot of technical aspects that need to be addressed when creating a genetic algorithm. Some of those are: how to create the initial population, how to choose the termination criteria, what to choose as a fitness function, how to reproduce the individuals and many others. The success rate of any genetic algorithm is highly dependent on these aspects.

Creation of the algorithm through phases

A general structure of the genetic algorithm which implies solely knowing the evaluation function that adds a numerical value to each chromosome is given as follows:

1. Initialization of a certain chromosome population
2. Evaluation of each chromosome in the population
3. Forming of new chromosomes, parenting chromosomes are chosen among the existing chromosomes, using crossover and mutation
4. Certain chromosomes are removed to make space for the new ones
5. Evaluation of the new chromosomes, followed by joining them to the existing population
6. If the stop criterion is met, the algorithm ends. Otherwise we go back to step 3.

The only connections between this general structure of the genetic algorithm and a concrete problem that is being solved are during the step of coding the chromosomes (forming of the binary string) and the evaluation function. The process of coding can be different and it is shown that the binary coding is optimal. The essence of this proof lies in the fact that it is better

to have many bits with less value possibilities for each bit, than to have a small number of bits with a large variation value for each one of them. The evaluation function, on the other hand, takes the bit record (chromosome) as an input variable and generates the performance criterion which is joint to that chromosome. The evaluation function in genetic algorithms plays the same role as the environment does in the natural evolution. The interaction between an individual with the environment sows the level of quality of the chromosome solution.

### 4.3 Creation of the evaluation (fitness) function:

Fitness function should satisfy at least 2 conditions: it can be implemented in the algorithm and to represent the relation with a real problem one would like to optimize (relation with the objective function). First condition makes the fitness function a non-negative value. The second one is a consequence of a GA using only the fitness function as a connection to the real problem and it will optimize what it is being asked for, so the fitness function should represent well the objective function at least in the search space where we expect to get results.

Adapting the fitness function:

The easiest adaptation of the objective function ( $g$ ) is the interception. In case one wants to minimize the function  $g$ , the choice of the fitness function is graphically presented below:

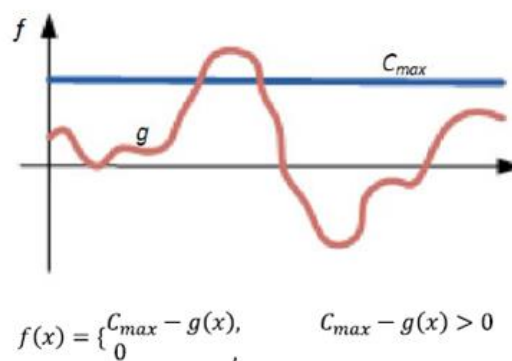


Figure 4.3 Minimization of the fitness function [71]

In case of maximizing the function  $g$ , the fitness function is chosen as follows:

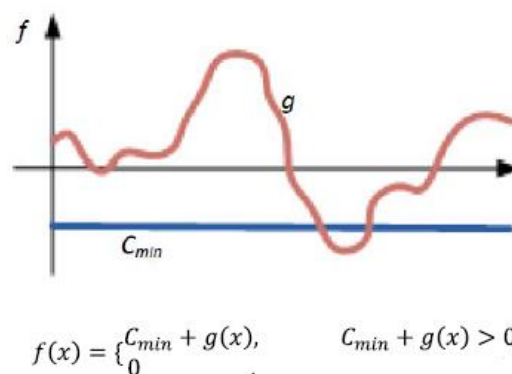


Figure 4.4 Maximization of the fitness function [71]

#### 4.4 Scaling of the fitness function:

During the selection process, the probability of choosing an individual is directly proportional to the value of the fitness function of the given individual. This gives an advantage to better individuals over the less good ones. Sometimes the dynamic of the fitness function is such, that it gives a huge advantage to the better individuals. A different behavior of the GA is achieved if the selection probabilities for 2 individuals are 0.7 and 0.2, then if they are 0.98 and 0.03. The latter shows that the second individual has no chance at all. Such dynamic of the fitness function can lead to the effect of “super” individuals, which is especially bad in the first stages of the genetic algorithm. If there is an individual whose fitness function is drastically higher when compared to other individuals, this individual will dominate and practically destroy the possibility of revealing other potentially good search spots. It is important to allow the less good ones to survive so they can evolve into better individuals and reach better local maximum. One of the basic compromises of the GA is between the speed of convergence and the part of space that is searched over.

In the early stages of the GA, super individuals lead to premature convergence, but possible passing of the global extreme, which is a consequence of reducing the diversity caused by dominance of the super individual. As a solution to this problem, it is necessary to scale the fitness function in order to get a better fitness function.

$$f' = af + b$$

Coefficients a and b are chosen in such a way that the average value of functions f' and f is the same:

$$f'_{avg} = f_{avg}$$

and that:

$$f'_{max} = C_{max} * f_{avg}$$

Where  $C_{max}$  is chosen as a constant. With the use of it, the expected number of best individuals which is chosen for the next generation can be controlled. For instance, if  $C_{max} = 1.2$  the expected number of best individuals that are chosen for the next generation is 1.2. After scaling, it is possible to get negative values of the fitness function, which need to be set to zero value.

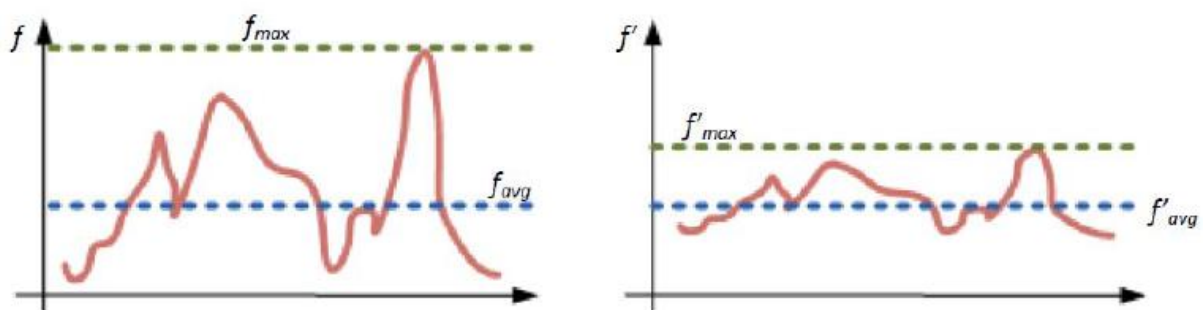


Figure 4.5 Scaling of the fitness function [71]

#### 4.5 Fitness function and forbidden conditions:

Typical situation regarding practical problems that occurs is that there are forbidden parts of a search field. These problems are usually solved with a permit for a variable to be found in the forbidden part with modifying the fitness function so that if the variable is in the forbidden place it is penalized.

The value of the fitness function can be set to zero in these forbidden search fields (green graph on the following figure). It is also possible to penalize the level of violating a certain condition (blue graph on the same figure).

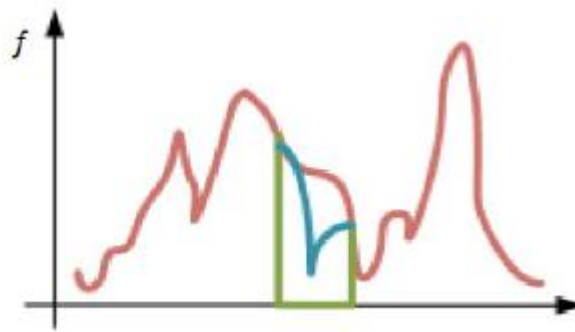


Figure 4.6 Forbidden search fields [71]

#### 4.6 Choosing the way of coding:

As all GA operators work with respect to the coding chromosomes, the way of coding when creating a GA is one of the key choices, which will determine the possibility of other operators to effectively do what they were designed for.

For better understanding of the effect that GA operators have on the performance of the algorithm depending on the way of coding, a term scheme is defined. A scheme is a pattern that depicts a convolution of the coded individuals. For instance, in a convolution where all the individuals are represented with 5-bits, scheme \*110\* represents the convolution of all the individuals whose bits from position 2 to 4 are equal with 110, while for the bits at position 1 and 5, the value is unimportant. So the convolution is {01100, 01101, 11100, 11101}.

Length of the scheme  $\delta(H)$  is defined as a distance between the first and the last fixed bit, for instance:

$$\delta(* 11 ** 1) = 4, \quad \delta(0 ***) = 0$$

The order of the scheme  $o(H)$  is defined as a number of fixed bits in a scheme, for instance:

$$o(* 11 ** 1) = 3, \quad o(0 ***) = 1$$

It can be observed that lengthy schemes have a higher chance of being removed by recombination and large order schemes by mutation. To that end small order and length schemes are defined, which have above average value of the fitness function – building blocks. They have a highest chance to survive.

### 4.7 Choosing the way of reproduction – selection:

The main task of the selection is to ensure that better individuals have a higher chance of survival. Most of the strategies are elitist, which means better individuals are guaranteed a safe spot in the next generation. The importance of elitist strategies can be seen on the figure 4.7. The marked individual is amongst better ones within a population and by all means should lead towards finding the global maximum. In case of a roulette wheel method selection, this individual might not have been chosen to fit in the next generation, rendering the global maximum to stay concealed for a long time (until a certain important mutation), since the individuals close the local maximum would dominate. In case of the elitist strategy, this individual will stay active as long as it is among the good ones in the whole population. Elitist strategies speed up the process of convergence on account of global perspective, but in general improve the performance of GA.

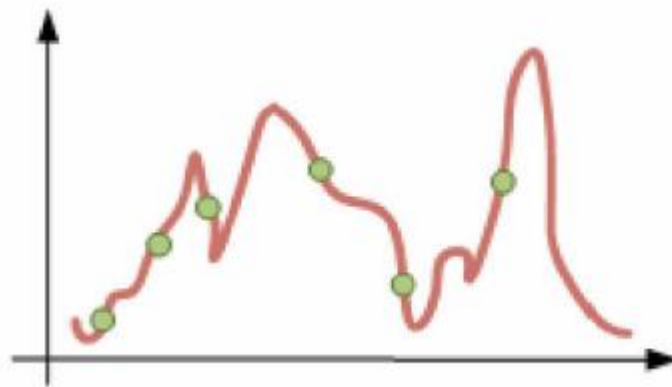


Figure 4.7 Selection of the individuals [71]

Elitism represents a selection method where a certain number of best individuals is instantly copied to the next generation.

Deterministic selection is done in such a way that each individual is guaranteed a number of copies which is the expected number of choices of that individual in the roulette wheel process.

Ranking represents a method in which bad dynamics fitness function is nullified in such a manner that the individuals are chosen with respect to the rank in the whole population. For instance, the best individual receives 3 copies, the following ten 2 copies, next twenty 1 copy and the remaining none.

Tournament is a selection method in which all the individuals are randomly separated into groups (k-number of groups). Out of each group the best individual is selected. This process is repeated until all the individuals are selected. Similarly to ranking, this compensates the bad dynamic of the fitness function to a certain extent, since the probability of choosing an individual is non-dependent on the absolute value of the fitness function, but rather on the rank between the remaining individuals.

Adding random individuals is one of the rare methods which is not elitist and which by adding randomly generated individuals aims on increasing the diversity of the population. Very often, a combination of the described methods of selection is applied. For instance, in the beginning a selection with a mild elitism is conducted with adding random individuals to increase the diversity, followed up by fully elitist methods of selection to speed up the convergence process.

#### 4.8 Choosing the crossover method – recombination:

Until now a crossover at a single point was shown (Figure 4.8):

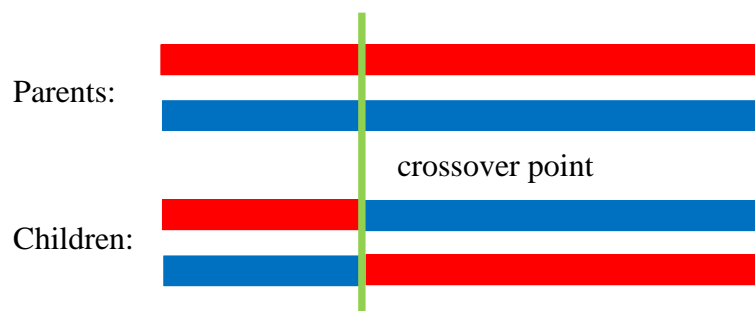


Figure 4.8 Single point crossover

One of the flaws of single point crossover is as follows: when 2 chromosomes crossover, whose building blocks are underlined, there is not a possibility to use the blocks from both chromosomes which would yield an even better individual. This problem can be solved by using multi point crossover, which is illustrated in Figure 4.9:

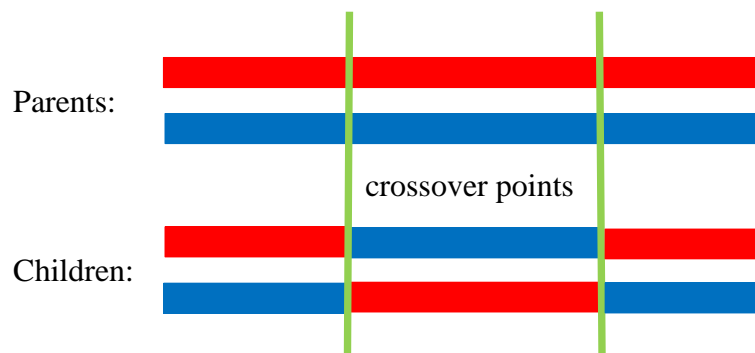


Figure 4.9 Multi point crossover

Multi point crossover increases the chances for decomposition of building blocks.

One of the frequently used methods is also uniform crossover. Using this crossover method only the bits that are chosen by a random selection mask are interchanged.

Parents	Kids
101100100010	100100100110
000111110111	001111110011
001000100100	Mask

### 4.9 Choosing the mutation method:

Mutation is a key factor in getting a new quality. A large mutation can actually degrade the GA performance due to the frequent mutation of the good individuals.

In the following figure, scenarios with and without a mutation are presented. The values of the best individuals in the population are shown. In the second case, the mutation led to the impairment of the situation but on account of revealing the global maximum. In other cases mutation can lead to the worsening of the situation that yields no new quality. Low mutation probability leads to faster convergence towards the local maximum, while higher mutation probability leads to random search algorithms.

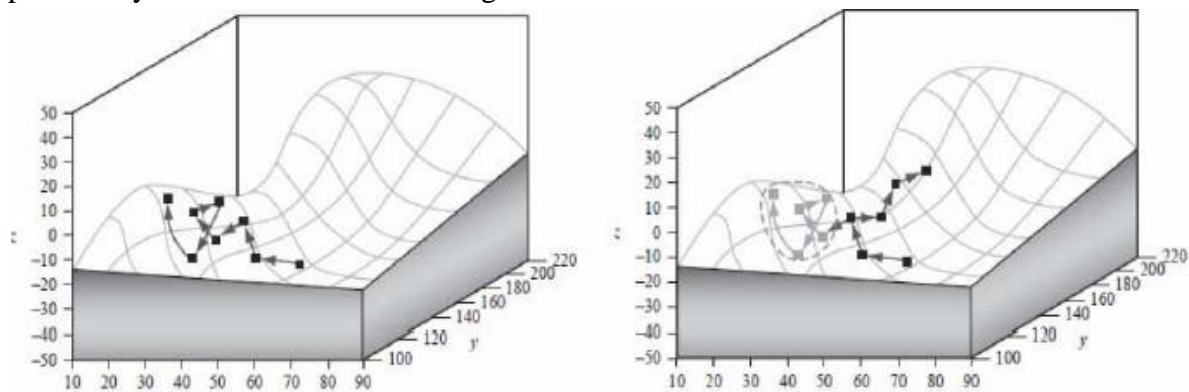


Figure 4.10 Presentation of scenarios with and without a mutation [71]

Bit inverse mutation is a type of mutation that was reviewed so far, where a randomly chosen bit in the chromosome is inverted.

Uniform or non-uniform mutations relate to mutations where the values of the mutated symbol are achieved via random distribution. If it is expected that the optimal solution had low symbol values, the mutated values can be chosen from a similar distribution.

Center and end mutation use a point and change their coordinates to a highest possible, lowest possible or the arithmetic mean value of these two. The goal of this mutation is the increase of the population diversity.

Mutation is most effective in the early stages, when the fruitful parts of the search field need to be established, while in the later stages it can slow down the GA due to the removal of good individuals. Non-uniform decay is a principle by which after a certain point the mutation probability is reduced:

$$p_m = p_{m0} * \min\left\{\frac{l}{g^c}, 1\right\},$$

where:

- $p_m$  – mutation probability
- $l$  – attenuation threshold
- $g^c$  – generation's serial number



#### 4.10 Increasing population's diversity – Sharing

One of the processes in the nature that increases the probability of the survival of a certain species is the *specialization*. Species that are specific and differ from the rest have a feat that increases their survival chance (if all the animals in a certain area feed on grass, those who do not have an advantage in finding food). This leads to the increase of diversity. In the nature some of the specialized species simply become extinct, while some overcome this and survive. One of the ways of modelling these mechanisms in terms of the GA is reflected by introducing the *sharing* function. The aim of the *sharing* function is to allow the individuals which differ from the rest to survive although they are not among the best by modifying the fitness function. This is normally achieved using Hamming's distance of the two binary sequences. That distance represents the bit number on which these sequences are different from one another. Hamming's distance of chromosomes 10110 and 10011 is  $d(10110, 10011)=2$ .

Sharing function  $s(d(x_i, x_j))$  is chosen so that it decreases with the increase of the Hamming's distance  $d(x_i, x_j)$ , since the lower value of the *sharing* function also means less similarities.

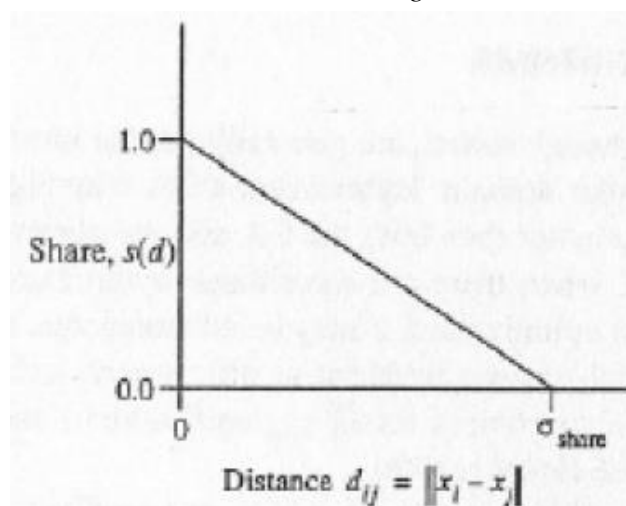


Figure 4.11 Sharing function [71]

The influence of the *sharing* function on the evaluation function, by which we acquire the modified evaluation function is given by the following equation:

$$f_s(x_i) = \frac{f(x_i)}{\sum_{i \neq j} s(d(x_i, x_j))}$$

Consequently, the individuals which are nearby lower the value of the fitness function of each other. As a result an uncontrolled growth of a certain species within the population is achieved.

Results with and without the use of the sharing function are presented below:

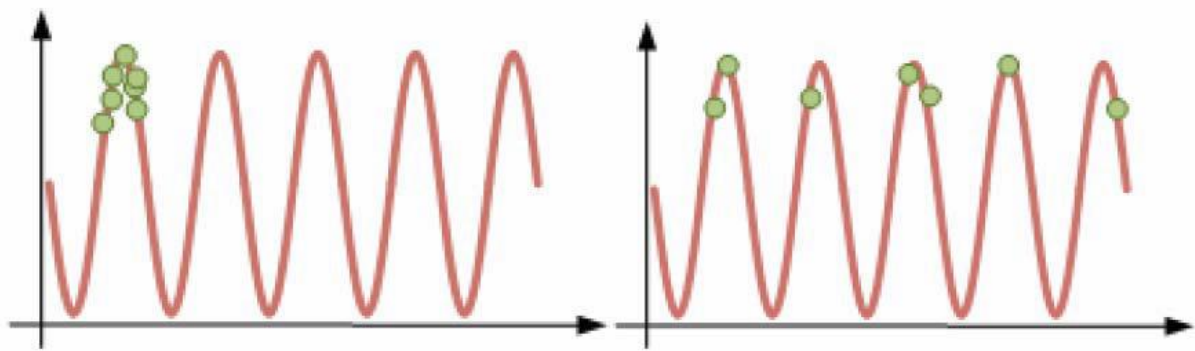


Figure 4.12 Results with (left) and without (right) the use of sharing function [71]

Practical problems in design:

Some of the most frequent practical problems that occur within the GA are mentioned here:

- Generation of possible solutions. Sometimes it is not so trivial to find the initial population. Problem can lie in finding any valid individuals or there is no possibility to choose the initial population which relatively evenly covers the search field
- Measuring of the quality of the individuals. Very often the calculation of the fitness function on a certain individual of the population is a long process which slows the GA by a decent amount. In practical cases, the evaluation of the individuals is done by running the specific simulation with the goal of finding the parameters that are of great importance for the problem that is being solved
- Parameter setting. The choice of a large number of GA parameters drastically affects the performance: the convergence speed and relevancy of the acquired solution

### Hybridization

Hybridization is compound of the GA and the specialized optimization techniques developed for different specific fields. The idea is that the GA takes over the global search role, while after finding the area with the maxima, specialized algorithms that were developed independently from the GA take over the optimization process.

Hybridization of the GA using simulated annealing could mean the modification of the mutation and recombination so that they are executed only if the resulting individuals are of a certain quality. Mutation and recombination would be allowed if the newly formed individual is better than the starting one. Initialization of this algorithm would be allowed and the newly formed individuals which are worse than the starting individual with a higher probability of being accepted, while later on this probability would decrease and worse individuals would not be accepted. Using this the increase in the diversity in the early stages (global GA search) is achieved as well as the effect of the simulated annealing later on.

### ***4.11 Conclusion***

Genetic Algorithms present stochastic optimization methods for solving problems. GA is different from other common optimization methods. First of all, GA manipulates with a large number of strings, seeking higher number of local maxima in a parallel. Applying the GA mechanisms, information about these local maxima is interchanged, not with the aim to terminate the algorithm in one of them, but to recognize which one is also the global maximum. Other important difference is that these algorithms work with coded values of the arguments, not with the actual arguments. Another very important difference is that the Genetic Algorithms require only knowing the evaluation functions, not its derivatives. Finally, the last difference is embedded in the fact the search trajectory is stochastic, it cannot be foreseen. Applying the GA, the search field where the arguments of the functions that are being optimized lie, is effectively examined.



---

## Problem formulation

An optimization model is presented in this chapter that is used in this thesis to optimally place and size battery energy storage in a distribution low voltage network. Genetic algorithm is applicable to solve non-linear problems [45] and as such is implemented in this work to solve the optimization model. The objective function of the algorithm is to minimize the total losses in the system. The genetic algorithm has also shown to be a good optimization tool for this type of problems [46]. The solution has to comply with several engineering constraints such as voltage profile, maximum energy storage size, maximum power supplied by the grid etc. Genetic algorithm has shown superior performance when compared to other meta-heuristic optimization methods in terms of solution error [47]

### 5.1 Node potential method

In this part the node potential method is described as the genetic algorithm uses this method when solving electric power circuits. Using the node potential method we set up a system of equations where the unknowns are the voltages at the nodes of the circuit. Using these voltages, currents in various branches of the system can be determined. This method is also well-suited for computer simulations as the calculation time is shorter and the system is less complex.

Main idea of the node potential method (method of the voltages between nodes) is the following. We observe a circuit that has  $n$  nodes and  $m$  branches. In that circuit there are  $n$  voltages of the branches, they are bound using Kirchoff's voltage law (KVL). In other words, between these voltages there are  $k = l - (n - 1)$  linear relations. Thus in the circuit we have  $(n-1)$  independent voltages. If those voltages are determined, using the Kirchoff's voltage law the remainder of the voltages can be calculated. The number of independent voltages is equal to the number of independent equations with respect to the Kirchoff's current law (KCL).

While deriving the system of equations, first the independent voltage system is formed, using the following pattern. One node (random) is chose as a reference node, which means that we assume its potential to be equal to zero. The reference node is labeled with "0". Remaining  $(n-1)$  nodes ("hot" nodes) are joined with corresponding complex potential  $\underline{V}_1, \underline{V}_2 \dots \underline{V}_{n-1}$ . Alternatively, instead of potentials, voltages between the "hot" nodes and the zero node can be used,  $U_{10}, U_{20} \dots U_{(n-1)0}$ . The voltage of each branch is equal to the difference of potentials of that branch nodes. This way  $l$  voltages of the branches are expressed as linear homogenous combinations of node potentials and the KVL is automatically satisfied for a random contour in the circuit.

In the next step,  $n-1$  linear equation based on the KCL is written for all the "hot" nodes. Those equations are written in a standard form  $\sum I = 0$ . In these equations the currents are substituted

with voltages of the branches and the branch parameters and the voltages are represented using the node potentials. In order to illustrate this substitution, general case of the branch is observed, so called generalized branch, presented on Figure 4.5. For  $\underline{E}=0$  and  $\underline{I}_g=0$ , the branch comes down to a receiver, for  $Z=0$  and  $\underline{I}_g=0$  it comes down to an ideal voltage source, for  $\underline{I}_g=0$ , it comes down to a real voltage generator, for  $\underline{E}=0$  real current generator and for  $Z \rightarrow \infty$  the branch is an ideal current generator. According to the reference directions on Figure 4.5, the following can be written:

$$\begin{aligned}\underline{I} &= \underline{I}_{12} \\ \underline{U} &= \underline{U}_{12} \\ \underline{E} &= \underline{E}_{12} \\ \underline{Z} &= \underline{Z}_{12} \\ \underline{I}_g &= \underline{I}_{g12}\end{aligned}$$

Assuming that  $Z \neq 0$  the current of the generalized branch is:

$$\underline{I}_{12} = \frac{\underline{U}_{12} + \underline{E}_{12}}{\underline{Z}_{12}} + \underline{I}_{g12}$$

Expressed using the node potentials of the branch:

$$\underline{I}_{12} = \frac{\underline{V}_1 - \underline{V}_2 + \underline{E}_{12}}{\underline{Z}_{12}} + \underline{I}_{g12}$$

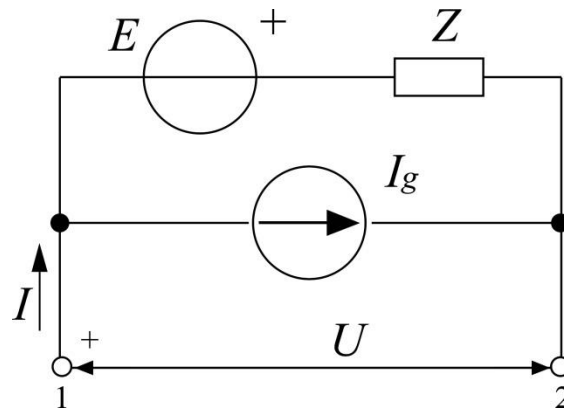


Figure 5.1 Generalized branch of the circuit

After replacement and solving, the following set of equations based on node potential method is obtained:

$$\begin{aligned}\underline{Y}_{11}\underline{V}_1 + \underline{Y}_{12}\underline{V}_2 + \dots + \underline{Y}_{1(n-1)}\underline{V}_{(n-1)} &= \underline{I}_{n1} \\ \underline{Y}_{21}\underline{V}_1 + \underline{Y}_{22}\underline{V}_2 + \dots + \underline{Y}_{2(n-1)}\underline{V}_{(n-1)} &= \underline{I}_{n2} \\ &\vdots \\ \underline{Y}_{(n-1)1}\underline{V}_1 + \underline{Y}_{(n-1)2}\underline{V}_2 + \dots + \underline{Y}_{(n-1)(n-1)}\underline{V}_{(n-1)} &= \underline{I}_{n(n-1)}\end{aligned}$$

Where:

- $\underline{Y}_{nn}, i = 1, \dots (n - 1)$ , is the sum of the admittances of all the branches connected in the node  $i$ , always with a plus sign
- $\underline{Y}_{ij}, i, j = 1, \dots (n - 1), i \neq j$ , is the sum of the admittances of all the branches that are connecting nodes  $i$  and  $j$ , always with a plus sign. Obviously  $\underline{Y}_{ij} = \underline{Y}_{ji}$  (reciprocity)

- $I_{ni}, i = 1, \dots, (n - 1)$ , is the algebraic sum of all the currents and equivalent current sources of the branches that are meeting in the  $i^{th}$  node. The equivalent current generator is obtained by transforming the real voltage generator into the real current generator (complex impedance  $\underline{Z}$  remains the same and the current of the equivalent current generator is  $\underline{I}_g = \underline{E}/\underline{Z}$ , where  $\underline{E}$  is the electromotive force of the voltage generator). If the reference direction of the current of the generator is towards the node the sign is plus, otherwise its minus.

If the circuit has only branches with ideal voltage generators, then all those generators should be connected to the reference node. The equation for the “hot” node which is connected to the ideal voltage generator is not written as previously stated in the set of equations. Instead, the equation is written such that the potential of the node is equal to the electromotive force of the generator with a plus sign if the reference direction of the electromotive force is towards that node and if the reference direction is towards the zero potential node, with the minus sign. There is also a modification equation when the ideal current source is connected between the two “hot” nodes, but this modification will not be presented here. The resulting system of equations is solved using one of the standard methods.

## 5.2 Objective function

The goal of any optimization process is to find the optimal solution of the objective function given certain constraints and with variables that need to be minimized or maximized. The aim could for instance be to minimize the losses without violating a certain constraint that is defined within a range of values. The case studies in this thesis will be explained later, for now the mathematical representation of the objective function used in the case studies is defined followed up by constraints of the system. Genetic Algorithm is a type of discrete optimization, so the optimization process is independent on the type of the objective function that is being optimized (it can be a square, cubic or any other function type). The only important parameter is the value of the function. That is why this optimization technique is unaffected by the type of the function.

The complex power of each of the lines is calculated as:

$$\underline{S} = \sum_{i=1}^{N-1} \left| \frac{\underline{V}_{i+1} - \underline{V}_i}{\underline{Z}_{i,i+1}} \right|^2 [\text{Re}(\underline{Z}_{i,i+1}) + j\text{Im}(\underline{Z}_{i,i+1})]$$

The aim of the objective function is to minimize the losses which are calculated as follows:

$$P_d = \sum_{i=1}^{N-1} \left| \frac{\underline{V}_{i+1} - \underline{V}_i}{\underline{Z}_{i,i+1}} \right|^2 \text{Re}(\underline{Z}_{i,i+1})$$

Where:

- $\underline{V}_i$ - is the voltage at a certain node

- $V_{i+1}$  – is the voltage at the neighboring node
- $Z_{i,i+1}$ - complex impedance of a line that connects two nodes
- $i$ -is an index for bus number
- $N$  – is the total number of the nodes

### 5.3 Constraints

#### Voltage drop limit

The voltage of each bus should be within the minimum and the maximum value

$$V_{min} \leq V_i \leq V_{max}$$

Where  $V_{min}$  and  $V_{max}$  are minimum and maximum allowed voltages at a bus,  $V_i$  is a voltage at bus  $i$ .

#### Power flow equality constraint

$$P_L \leq P_G + P_S + P_W$$

Where:

- $P_L$ -active power of the load
- $P_G$ -active power of the main grid
- $P_S$ -active power of the energy storage
- $P_W$ -active power of the wind turbine

#### Battery energy storage size

The total size of battery energy storage used in the feeder is within the specified limits

$$P_S^{min} \leq P_S \leq P_S^{max}$$

Where:

- $P_S^{min}$  – is the minimum size of the storage
- $P_S^{max}$  – is the maximum size of the storage

#### Power supplied from the grid

The grid supplies the system with a certain amount of power which is within the specified range:

$$P_G^{min} \leq P_G \leq P_G^{max}$$

Where:

- $P_G^{min}$  – is the minimum power supplied by the grid
- $P_G^{max}$  – is the maximum power supplied by the grid

#### Power supplied by the wind turbine

$$0 \leq P_W \leq P_W^{max}$$

Where:



- $P_W^{max}$  - is the maximal power supplied by the wind turbine

This constraints are implemented in the algorithm under which the optimal solutions are generated.

#### 5.4 Optimization of the genetic algorithm

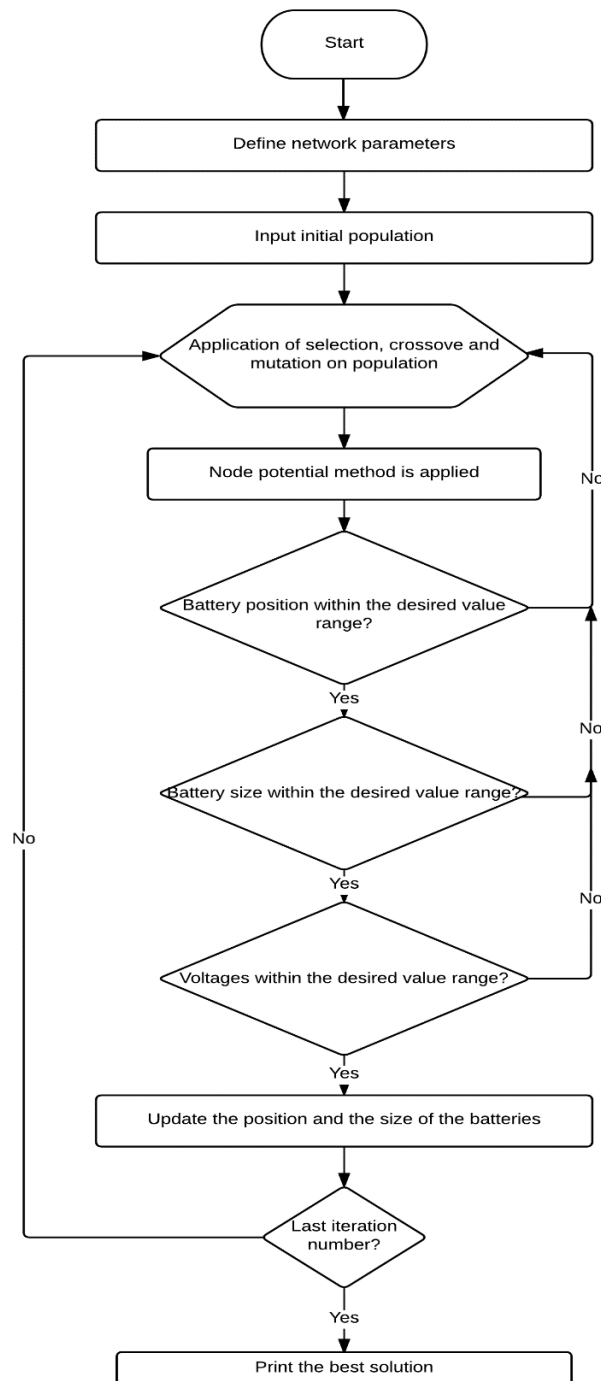


Figure 5.3 Flowchart of the genetic algorithm

With respect to the flowchart presented in Figure 5.3 all the steps of the genetic algorithm optimization process are described in detail in the following part.

Based on the simulation all the voltages in the network as well as the currents of the lines are determined. The losses in the lines are calculated as a sum of losses in each of the lines.

In the first step the voltage constraint is set. The voltage has to be defined within the specified limits  $V_{min} \leq V_i \leq V_{max}$ . The size of the batteries is also specified within the limits  $P_{Bmin} \leq P_B \leq P_{Bmax}$  as well as the position of the batteries. Since there are 10 nodes, each battery is assigned a value from 1 to 10. If this condition is not met, the simulation stops and the new one starts under different parameters. The function that is minimized is actually the function of the input data (values of the impedances, number of batteries, size of a single battery and the position of the batteries in the system), whose output is the power losses that are calculated using equation for the objective function described in 5.2.

In the next step an initial population set is formed which holds the number of batteries as well as their position in the system. This set can be formed by just a few elements and can be up to 20 elements. Each element has the value of the battery size, the number of batteries used and the position of the batteries in the system which are randomly generated numbers from 1 to 10. In this optimization process the initial population consists of 20 elements. Each element has a set of values, which are the position and the size of the batteries. There are three different cases, with 2, 3 and 4 batteries, respectively. Each of these cases is treated separately.

For each of these numbers the simulation is run which determines the power losses of the system. Based on the elements of the initial population parameters such as the position and the size of the batteries are incorporated into the electric circuit. Using the determined values a selection is made such that the members of the population which have the minimal losses are selected and then the crossover between these elements is done which gives a new element. This element contains half of the bits of the first element and the other half of the bits of the second element that were both involved in the creation of the new element. Crossover is done with respect to the steps explained in part 4.1 The value of the crossover function is taken to be 0.5, which means that each element of the population is “cut” in half, after which the crossover of the bits of another population member is performed.

Mutation method is then applied which randomly chooses a random position in a string of bits and changes the value of that bit from 0 to 1 or from 1 to 0. A short example when 2 batteries in the system are used is presented.

Number of batteries: 2

Position of batteries: Nodes 6 and 3

Binary representation of digits 6 and 3: 0110 and 0011

Element A: 110011

Element B: 101001

The new element is reached in the following way:

Element A: 0110 0011

Element B: 0101 0001

Crossover is carried out between the first 4 bits of element A and the last 4 bits of element B.

Two new elements are formed: Element C and Element D

Element C: 0110 0001

Element D: 0101 0011

In the following step the mutation is carried out in the following manner: A random bit of element C, for instance bit number 4 has its value changed from 0 to 1. Element D has a change on bit number 7, from 1 to 0.

Element C: 0111 0001

Element D: 0101 0001

In the previous example, the optimization process is described for a case when the variable that needs to be optimally found is the position of two batteries. In the same manner the algorithm could be expanded for the optimization of a larger number of variables.

Determining the losses for each population member is done as follows. First it is checked whether the positions of the batteries are within the desired set of values, if not the elements which violate this constraint are neglected. Then the voltage of each of the elements of the population is verified. If the value are not within the desired range, the elements with values of the voltage that do not correspond to this range are disregarded. Then the population members that yield the minimal losses are used for the process of crossover and mutation. First the size of the batteries of each of the elements is checked whether it is within the desired limits, same is done for the voltage. Finally, the power losses of the elements are cross-compared. If all of the constraints are met, these elements are substituted with new ones and the population is updated.

This process is repeated until the difference in terms of power losses within a population is less than a predefined convergence threshold.

## ***5.5 Conclusion***

This chapter explained the development of the model used in the optimization process. The model is based on the theoretical analysis of the problem. The objective function with all the constraints that were included in the optimization model is described. Finally the steps of the whole genetic algorithm optimization process are described and the graphical representation of the whole process can be found in form of a flowchart in Figure 5.3.



---

## Results

This chapter of the thesis is dedicated to presenting the results obtained in the simulations. Before the specific case studies are presented and described the whole LV network with the model of all the components is described with specific values provided in the tables. There are 4 case studies in total each addressing certain aspect of voltage problems that arise within this LV network. Worst case scenarios for each of these problems are shown and optimal solution is found.

### ***6.1 General characteristics of a LV network and description of the LV feeder***

Before the benchmark microgrid is presented some technical data about LV distribution grids is presented:

**Structure:** Most of the LV distribution grids have a radial layout. Different number of feeders can be present and each feeder can have one or more branches. Consumers are connected anywhere along the feeder. Presence of single phase lines may exist and they are connected to single phase consumers.

**Line types:** Normally the cables in a LV network are either overhead lines or underground cables with a short node to node distances. Line parameters are usually small.

**Substation:** The substation feeding the LV network usually consists of a single transformer whose rated power can vary but is normally of a few hundred kVA. The windings connection is normally D-Y, delta-connected primary and wye-connected secondary winding.

**Protection:** In LV networks most common mean of overcurrent protection are the fuses. Transformers are protected at their MV side. Since the voltage level and currents are relatively low no other protection equipment is necessary.

#### *Description of the LV feeder*

The LV feeder [26] is illustrated in Figure 6.1. It is an overhead line with 4x120mm<sup>2</sup> Al XLPE twisted cable which supplies a residential area with a limited number of users. The line types are displayed on the network diagram. The corresponding values of the resistances and reactances of the cables are presented in the following sub-part.

Network type is radial with no distributed generation present in this figure. Pole-to-pole distance is fixed and amounts 35m as also stated in the figure. The network is grounded at the substations, every second pole and at each consumer connection point. Earthing resistance value is 40 Ohms. There is a possible neutral bridge that can connect this feeder to another adjacent LV line. Each consumer has maximum allowed current which is same for all consumers and values  $I_s=40A$ . This value corresponds to the rated current of the overcurrent protection element at each connection. The total maximum demand of the feeder is 120 kVA. Special technical details are beyond the scope of this thesis and were not taken into account or

implemented in the modelling of this network. This grid is optimal for integrating distributed generation and this will be analyzed later on. It is also well-suited for both steady state and dynamic analysis.

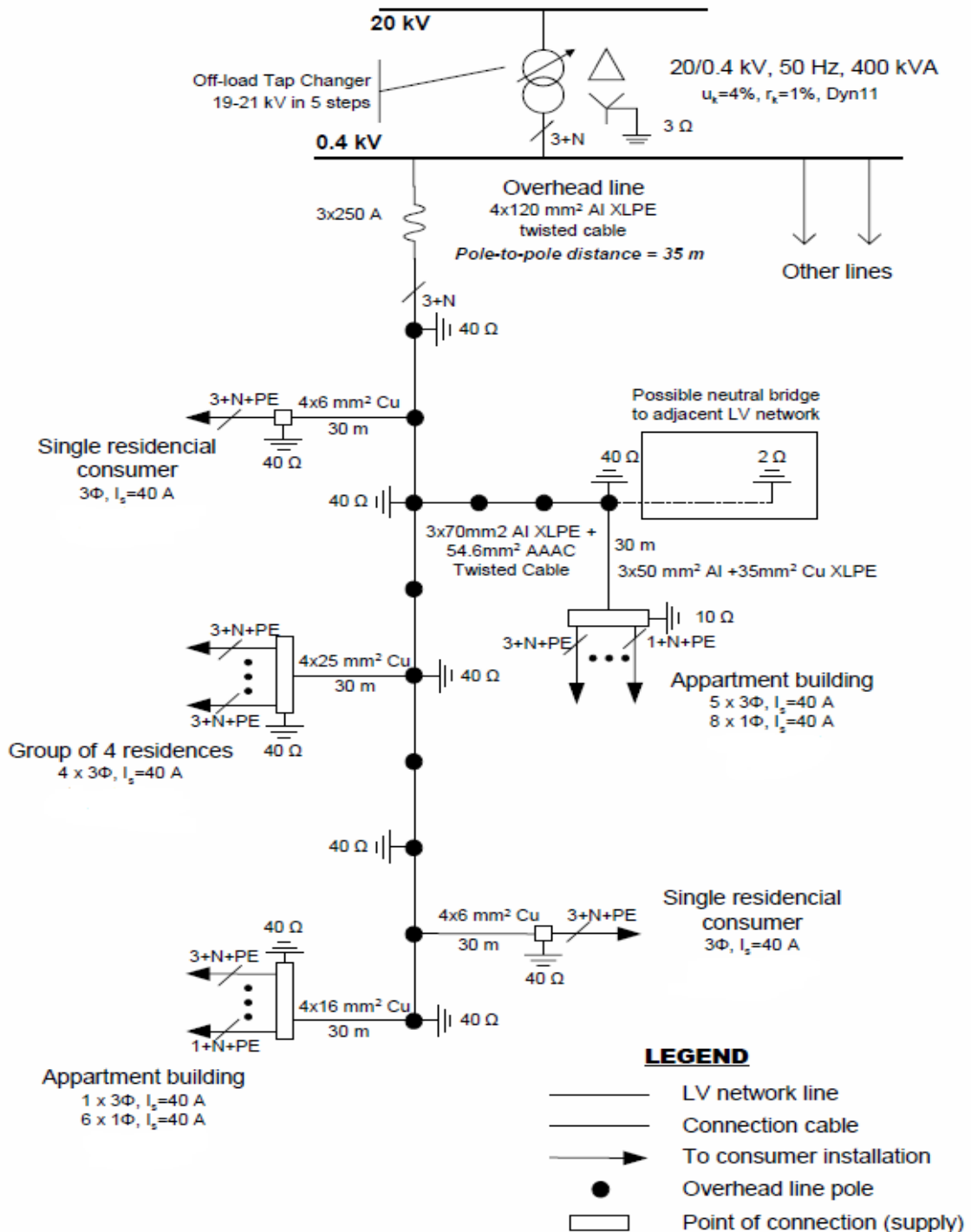


Figure 6.1. The benchmark LV residential feeder [26]

### 6.1.1 Characteristics of the lines used in the model

The impedance data for various types of cables used in the grid is provided in Table 6.1

Table 6.1. Impedance data for benchmark network lines [26]

	Line type	$R_{ph}$ ( $\Omega/km$ )	$X_{ph}$ ( $\Omega/km$ )	$R_{neutral}$ ( $\Omega/km$ )	$R_0$ ( $\Omega/km$ )	$X_0$ ( $\Omega/km$ )
1	OL - Twisted cable 4x120 mm <sup>2</sup> Al	0.284 <sup>(1)</sup>	0.083		1.136	0.417
2	OL - Twisted cable 3x70 mm <sup>2</sup> Al + 54.6 mm <sup>2</sup> AAAC	0.497 <sup>(1)</sup>	0.086	0.630	2.387	0.447
3	OL - Al conductors 4x50 mm <sup>2</sup> equiv. Cu	0.397 <sup>(1)</sup>	0.279			
4	OL - Al conductors 4x35 mm <sup>2</sup> equiv. Cu	0.574 <sup>(1)</sup>	0.294			
5	OL - Al conductors 4x16 mm <sup>2</sup> equiv. Cu	1.218 <sup>(1)</sup>	0.318			
6	UL - 3x150 mm <sup>2</sup> Al + 50 mm <sup>2</sup> Cu	0.264 <sup>(2)</sup>	0.071	0.387 <sup>(2)</sup>		
7	SC - 4x6 mm <sup>2</sup> Cu	3.690 <sup>(3)</sup>	0.094		13.64	0.472
8	SC - 4x16 mm <sup>2</sup> Cu	1.380 <sup>(3)</sup>	0.082		5.52	0.418
9	SC - 4x25 mm <sup>2</sup> Cu	0.871 <sup>(3)</sup>	0.081		3.48	0.409
10	SC - 3x50 mm <sup>2</sup> Al + 35 mm <sup>2</sup> Cu	0.822 <sup>(2)</sup>	0.077	0.524 <sup>(2)</sup>	2.04	0.421
11	SC - 3x95 mm <sup>2</sup> Al + 35 mm <sup>2</sup> Cu	0.410 <sup>(2)</sup>	0.071	0.524 <sup>(2)</sup>		

OL: Overhead line, UL: Underground line, SC: Service connection

<sup>(1)</sup>: Ohmic resistance at 50 °C conductor temperature

<sup>(2)</sup>: Ohmic resistance at temperature 90 °C for phase conductors and 20 °C for the neutral

<sup>(3)</sup>: Ohmic resistance at temperature 70 °C for all conductors

As can be seen from the table the character of the network is mostly resistive, with some inductances present. The values present in the table are used for the simulations. Since no temperature change in the cables was considered in the optimization model, the values of the impedances are assumed constant throughout the whole simulation process.

### 6.1.2 MV/LV Transformer

Normally for LV distribution networks the average transformer power per household is approximately 15kVA. The highest efficiency of the transformer is attained in the range of 50%-70% of full load. Thus, the transformer rated power is scaled to be of 30%-40% higher value than maximum demand of the network. The main characteristics of the transformer are presented in Table 6.2.

Table 6.2. Transformer Characteristics

<b>Rated Power</b>	400 kVA
<b>Rated Voltage (primary/secondary)</b>	20/0.4 kV
<b>Short circuit voltage</b>	4%
<b>Copper losses</b>	2000W
<b>Iron losses</b>	200W
<b>Connection</b>	Dyn11

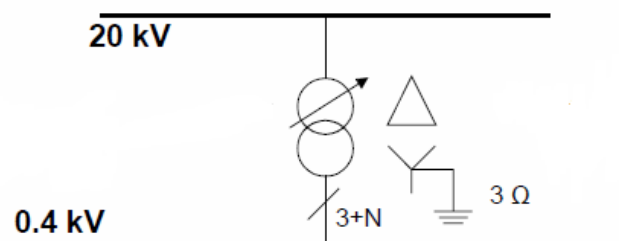
### 6.1.3 External grid

The low voltage (LV) network is connected to the medium voltage (MV) network via the transformer. Based on the CIGRE benchmark the parameters of the MV network are presented in Table 6.3

*Table 6.3 MV equivalent network parameters*

<b>Nominal system voltage (line to line)</b>
20kV
<b>Short circuit power</b>
100MVA
<b>R/X ratio</b>
1

Same values are used for the “external grid” element of this model



*Figure 6.2 External grid element connected to the MV busbar of the transformer*

### 6.1.4 Modelling of the distribution grid

In this section it is shown how the LV distribution grid has been modelled. Apart from the full network that includes the industrial and commercial feeder the residential part was isolated for the study performed in this thesis. The topology of the network is depicted in Figure 6.3. As can be observed the network has 10 nodes, labelled R1 to R10 and 5 loads, labelled L1-L5 respectively. Table 6.3 presents the load parameters of the grid. In this table the active and reactive components of each of the loads presented in the network are specified. It should be noted that these are the maximum values of the loads.

*Table 6.3 CIGRE LV network load parameters*

Load	Active load (kW)	Reactive load (kVAr)
L1	25.7	17.1
L2	62.3	38.6
L3	47.5	21.3
L4	25.7	17.1
L5	34.6	24.4



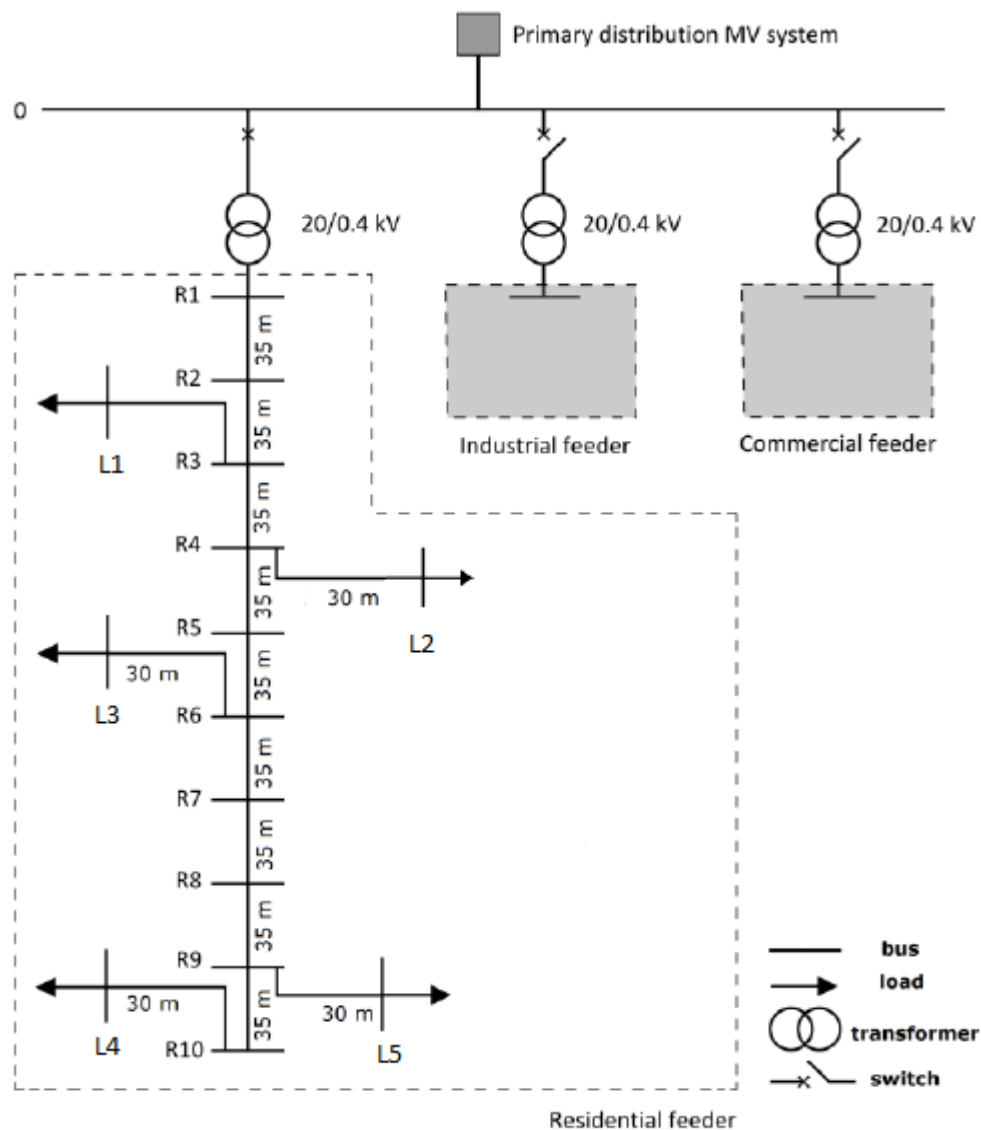


Figure 6.3 Topology of the LV network modeled for this study

### 6.1.5 Battery model

One of the most common models of the battery is used for this system and is shown in Figure 6.4. It consists of a controlled voltage source ( $V_0$ ) and a constant resistance ( $R_{internal}$ ). Simplicity of this model makes it easy to extract parameters. To determine the parameters, open circuit measurement is done to determine  $V_0$  and the other measurement is with a connected load to determine  $R_{internal}$ . The battery is connected to the distribution network via an inverter which controls the flow of power to and from the battery.

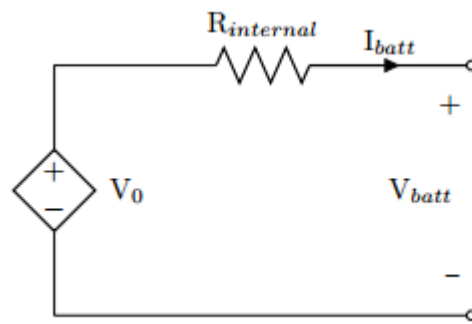


Figure 6.4 Simplified battery model

Since the state of the charge (SoC) of the battery is not considered in this work this model is well suited. Varying state of the charge cannot be taken into account with this battery model so it is not suitable if voltage at different charge levels is of interest. Even with a simple model like this, if necessary the discharge curve can be modelled somewhat accurately.

## 6.2 Daily load profile used for the simulations

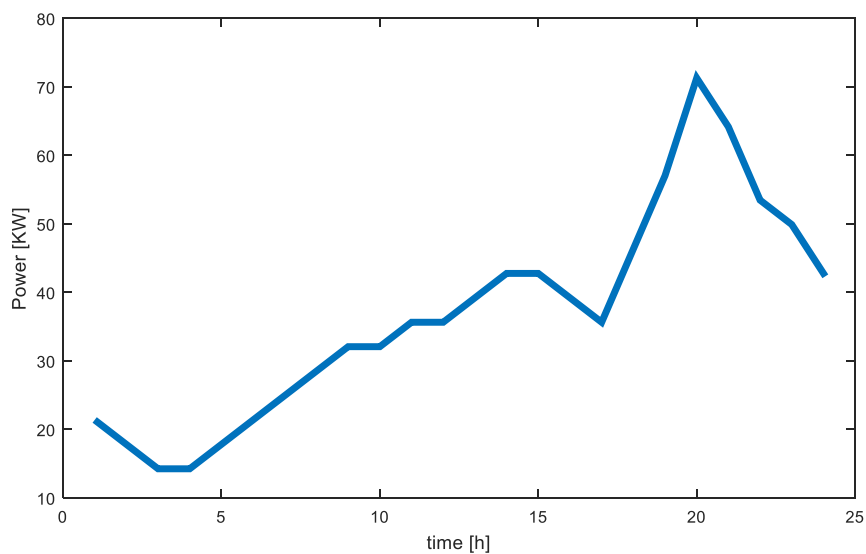


Figure 6.5 Daily load profile for the LV residential feeder [26]

Figure 6.5 is an example of a daily load profile. Measurement of electric power consumption in a household gathered between a period of several years constitutes the source of the load profile provided in the appendix of [26] and is used for the study conducted in this thesis. Some other daily profiles were analyzed however it was determined that in most of the profiles the electricity consumption is much higher in the evening hours. This is normal for residential areas and this behavior corresponds to household families where adults are working and children are in school during the day. Unfortunately only the aggregated load profile model of the network was provided. This can be considered as one of the limitations of this thesis.

### 6.3 General simulation assumptions:

- Maximum allowed current of the lines is 250A. Although there are some minor variations for each type of the cable present in this network this was taken as the general value
- The voltage drop/rise limit is 4% as is the standard for the LV networks ( $0.96 < V < 1.04$ ) and is proposed by IEEE standard EN 50160
- The simulations are based on the aggregated load profile of the entire network
- Voltage at the MV side of the transformer is assumed constant. Grid is also assumed to have no voltage variation.
- The power supplied from the grid is in the range  $0 \leq P_G \leq 50kW$
- The limit on the total battery energy size is  $-40kW \leq P_S \leq 40kW$

### 6.4 Scenarios formulation

Different scenarios that are investigated in this thesis are explained in this section. Scenarios are presented in form of case studies with respect to different voltage violation problems. The motivation behind these specific case studies is based on the idea to show the reader what are some of the worst case scenarios that are established in distribution network with or without distributed generation. There are 4 case studies in total. In case study 1 no integration of wind turbine is examined. The aim of this study was to show how the voltage violation can be present in the network even without the distributed generation. It is shown how the voltage drop along with the voltage violation at the end of the feeder can be mitigated using BESS and to what extent. Case studies 2-4 all include integration of different size wind turbines. In these case studies optimal placement and sizing of BESS is also aimed at mitigating voltage violations and reducing the power losses. In these case studies research questions are somewhat answered. The wind turbines used in the case studies were chosen with respect to the load profile of the network.

### 6.5 Case study 1: No wind turbine installed

This section investigates how energy storage affects the voltage profile of the system along with reducing the overall losses in the system. No wind generation is considered for this particular study and this will be included in the following ones. It is shown that installing storage at a specific location in the system has an influence and can improve the voltage profile of the feeder. Additionally subcases are established to show if the different number of batteries used in the system have an impact on the losses and to what extent. Additionally it was estimated how does the number of batteries used affect the optimal positioning. The voltage profile of the feeder when there is no distributed generation installed or batteries connected to the nodes, with the daily load profile at maximum load demand is presented in Figure 6.6 and the specific values in Table 6.4.

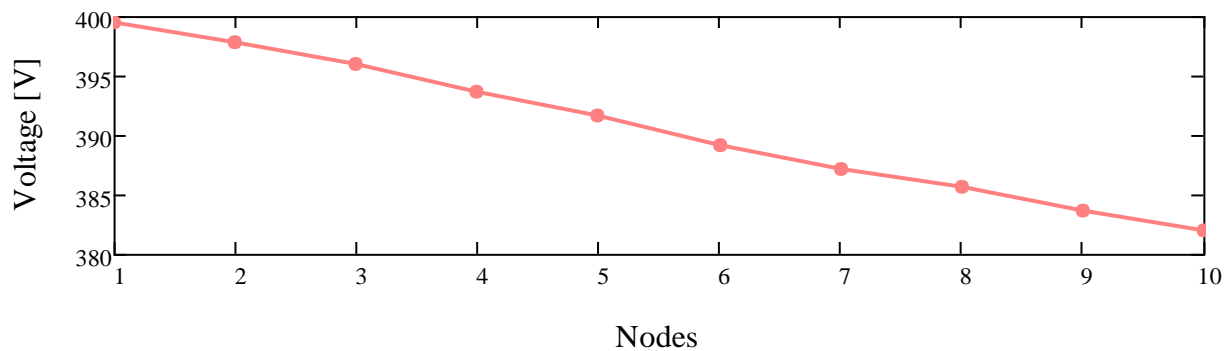


Figure 6.6 Voltage profile of the feeder (CS1) without added storage

Table 6.4 Voltage values at each node (CS1) no storage added

Node	Voltage
1	399.52
2	397.81
3	395.94
4	393.59
5	391.65
6	389.17
7	387.23
8	385.64
9	383.73
10	381.97

As it is expected there is a constant voltage drop throughout the feeder. All the voltages are within the allowed range. This graph can be used as a sort of benchmark for the case studies where energy storage is added but no distributed generation is included. The size of the batteries is determined based on the daily load profile provided in section 6.2. It is also assumed that grid provides a constant power supply that amounts 48kW. The reason for this assumption is that this way the system at certain periods during the day has a lack of energy that can be supplied with the use of storage. If the grid is considered to be able to provide any amount of power to match the demand the need for using storage would not be necessary in this case. The only benefit a system would have is a better voltage profile. To that end, the size in this case is determined to be 21kW and the optimal placement of storage is at the end of the feeder. Larger size of storage was tested but it was shown that the voltage profile and the losses are improved by just a small amount, thus this size was taken as optimal. Now, several different scenarios are analyzed in order to evaluate if the required amount of power divided into several units will impact the location of placement and the overall losses. 3 different scenarios are shown below, when 2, 3 and 4 batteries are used respectively. It is determined that the node of the optimal placement is for each case node 10.

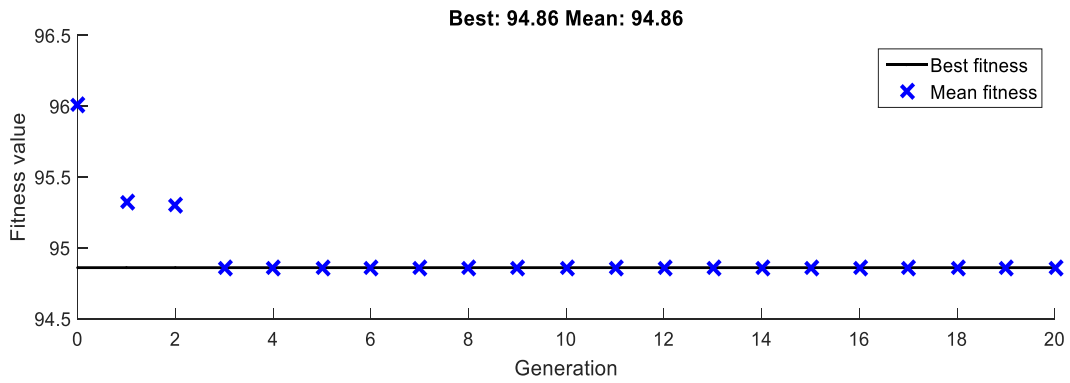


Figure 6.7 Convergence characteristic of the algorithm (2 batteries)

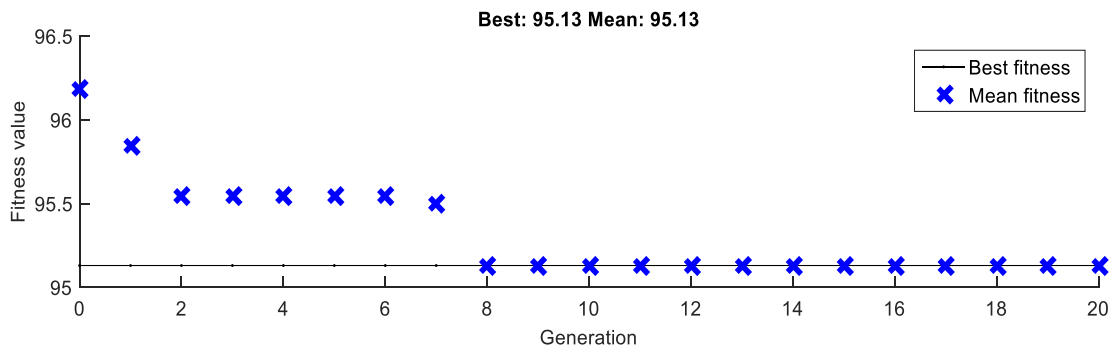


Figure 6.8 Convergence characteristic of the algorithm (3 batteries)

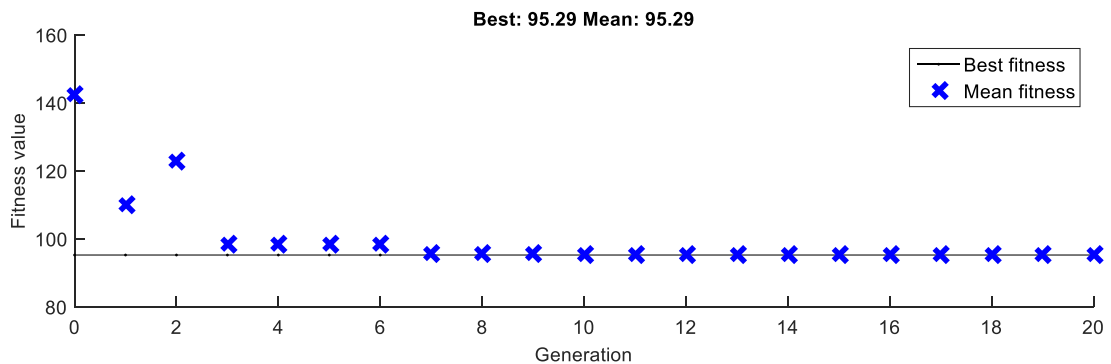


Figure 6.9 Convergence characteristic of the algorithm (4 batteries)

Figures 6.7 to 6.9 present the convergence characteristic of the genetic algorithm for different number of batteries used. Also the value of the fitness function of the algorithm is shown. The value of this function is the representation of the loss reduction, percent wise. For instance Figure 6.4 shows the value of the fitness function to be 95.13. In order to get absolute value of the loss reduction, this number is subtracted from 100 which stands for the amount of the losses that were present in the system prior to installing storage. In the mentioned case the losses are reduced by 4.87%. Beside the losses comparison can be made for the number of generations it takes for the best value of the fitness function to be reached. It can be observed that:

- Near identical results in terms of losses are obtained when different number of batteries are used in the system. The absolute difference is around 0.3%.

- For different number of batteries convergence is reached after a (larger/smaller) number of iterations which makes sense in mathematical terms since there is a larger number of possible position settings for the batteries.
- For different number of batteries the node of the placement remains the same
- The loss reduction for all 3 different cases is 4.87%, 5.13% and 5.42% respectively.

After the batteries were installed at the end of the feeder the voltage profile is improved a bit.

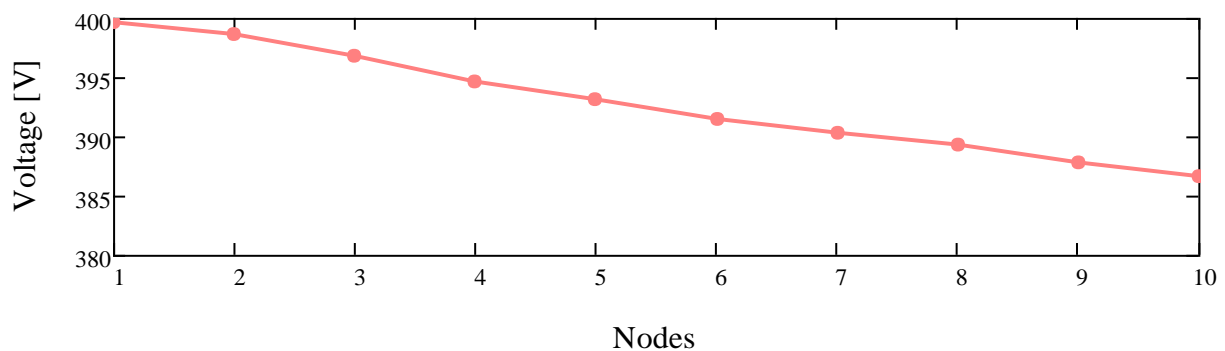


Figure 6.10 Voltage profile of the feeder (CS1) with added storage

Table 6.5 Voltage values at each node (CS1) with added storage

Node	Voltage
1	399.72
2	398.64
3	396.87
4	394.73
5	393.12
6	391.53
7	390.36
8	389.28
9	387.91
10	386.67

For comparison reasons the voltage profile with and without the use of BESS are shown in Figure 6.11

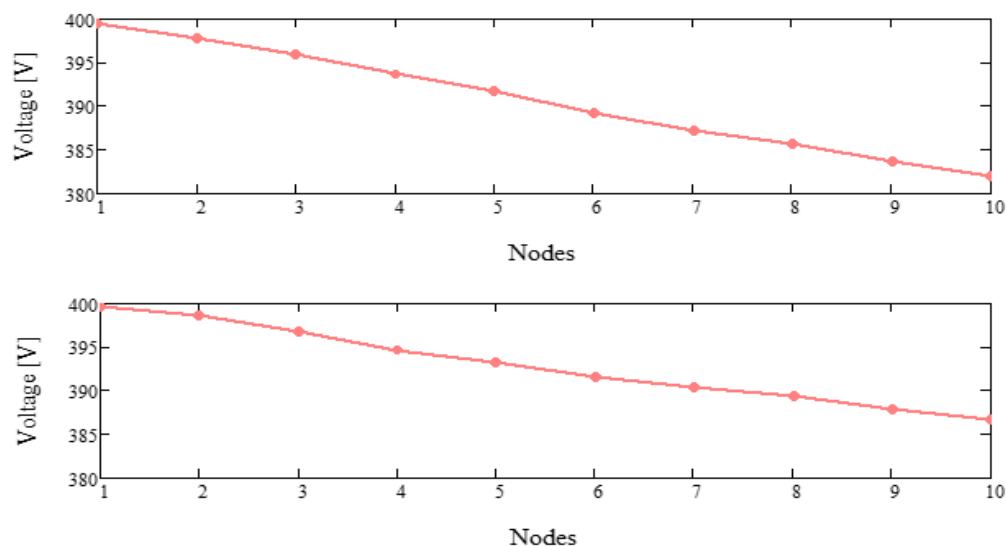


Figure 6.11 Voltage profiles with and without the use of BESS (CS1)

## 6.6 Case study 2: Medium scale wind turbine

In this case study distributed generation is added to the system. Same system as in the previous case study is used and will be used for the rest of the case studies. Several different case studies with wind generation will be analyzed. Different size of wind turbines and their daily profiles have been used. All the profiles were obtained from [70]. There are several assumptions taken into account regarding the choice of the profiles. Since the exact location of the network used for the case studies is not known wind profile for a specific turbine at a random location was chosen, but as it is not of the interest for this thesis to analyze different daily profiles of the same turbine this assumption is justified. Also daily load used in the studies as mentioned previously is acquired from [26] and it presents the aggregated profile of the loads for the entire network. In all the case studies the wind turbine is placed and the end of the feeder as it is determined to be the optimal point. It is worth mentioning that the load profile and the wind turbine profile of a specific turbine would be different for different days as it is normally in a real system. However the aim of this thesis is to find how to optimally place and size the storage in the system with respect to any load or production profile used. The ones used in the case studies are considered adequate since the patterns are rather realistic. In this study a 60kW wind turbine is used in the network and as mentioned is located at the end of the feeder, at node 10. Figure 6.12 shows the power production and the load profile used in this study:

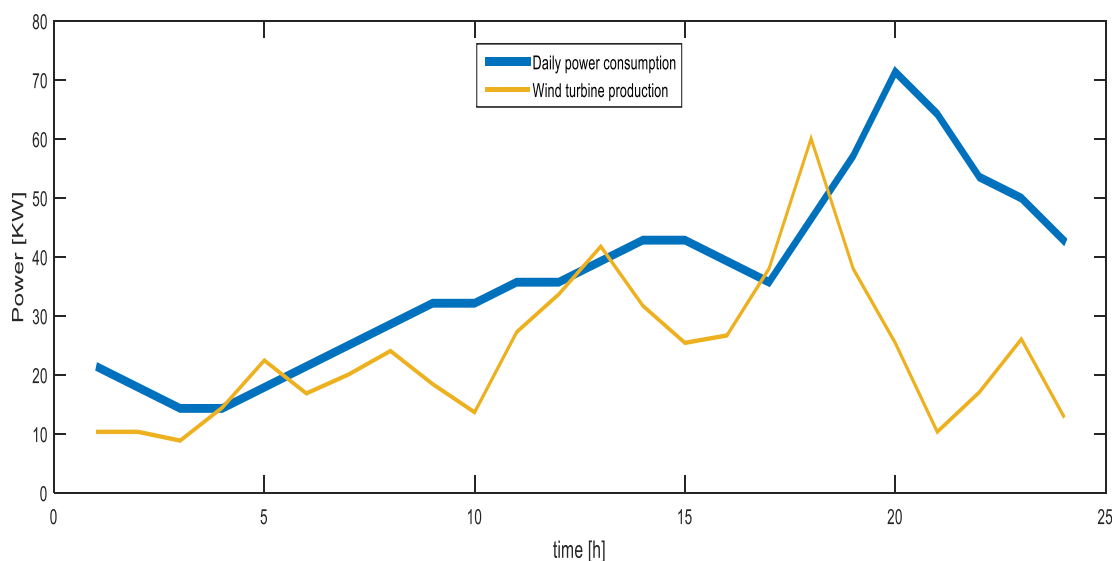


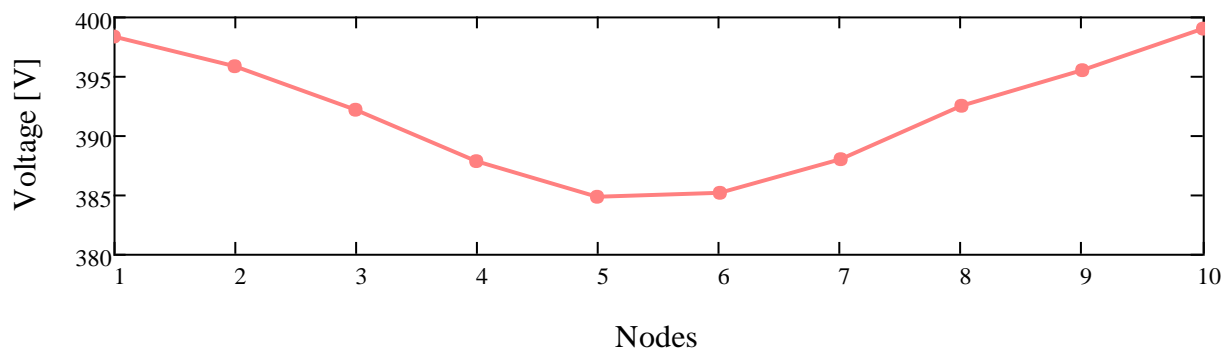
Figure 6.12 Wind turbine [60kW] power production and daily load profile

The blue curve is the daily power consumption of the loads. As mentioned in 6.2 the lowest consumption is during the night and early morning hours, while through the rest of the day the consumption increases to reach its maximum at 20h. Wind turbine production is represented with a yellow curve. In every case study it is assumed that the grid provides certain amount of power. If this assumption was not made, for very small wind turbines the power discrepancy at certain points of the day would be so big that it would require a large storage size in order to compensate for all the mismatches. The equation used for determining the size of the storage and the amount of power necessary to be supplied from the grid is:

$$Total\ demand[KW] = P_b + P_t + P_g$$

Where  $P_b$  is the size of the battery energy storage,  $P_t$  is the power output of the turbine and  $P_g$  is the power supplied by the grid. The amount of power supplied from the grid and the size of the energy storage is based on the critical points between the production and load profile curves for the entire day. Regarding the wind turbine, there are 2 possible nodes where the turbine can be placed, nodes 9 and 10 respectively. These locations were ascertained based on the minimal losses. However node 10 is taken as a preferred solution due to the fact that the total losses are slightly lower with this option. With respect to the daily profiles and the mismatches in supply and demand it was determined that the storage size should be 25kW and the supply from the grid 30kW. In this study the worst case scenario is found to be when the load demand is maximum and the power production of the turbine is relatively low. The voltage profile in this case is presented on Figure 6.13 and the values in Table 6.6





*Figure 6.13 Voltage profile of the feeder (CS2) no storage added*

As can be observed there is a voltage violation on nodes 5 and 6. The voltage at node 5 is exceeding the limit by 1.1V and the voltage at node 6 by 0.8V. The idea with adding storage is to improve the voltage profile, to ensure a better supply of power and to minimize the overall losses in the system. Using the algorithm the location of storage is found to be on these 2 nodes as by placing the storage there, the voltage profile can be improved by far. It was then observed how the placement of battery storage changes with different number of batteries used and how the losses are affected by these different settings.

*Table 6.6 Voltage values at each node (CS2) without added storage*

Node	Voltage
1	398.3
2	395.88
3	392.13
4	387.77
5	384.9
6	385.2
7	387.92
8	392.5
9	395.45
10	399.07

The number of batteries used are 2, 3 and 4 however the total size of the energy storage remains the same. Convergence characteristics of the genetic algorithm for different number of batteries are presented on Figures 6.14-6.16

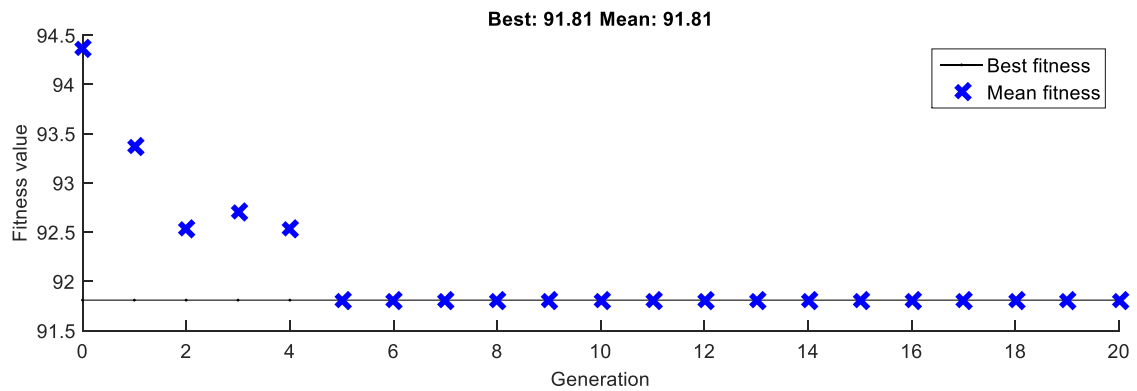


Figure 6.14 Convergence characteristic of the algorithm (2 batteries)

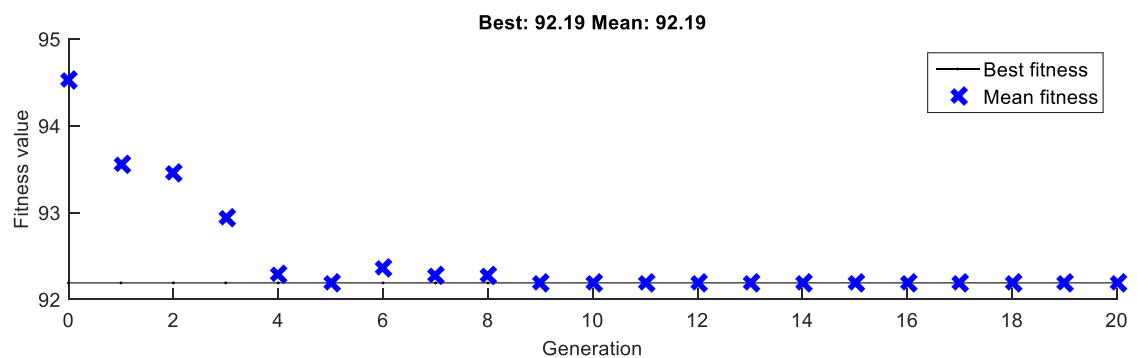


Figure 6.15 Convergence characteristic of the algorithm (3 batteries)

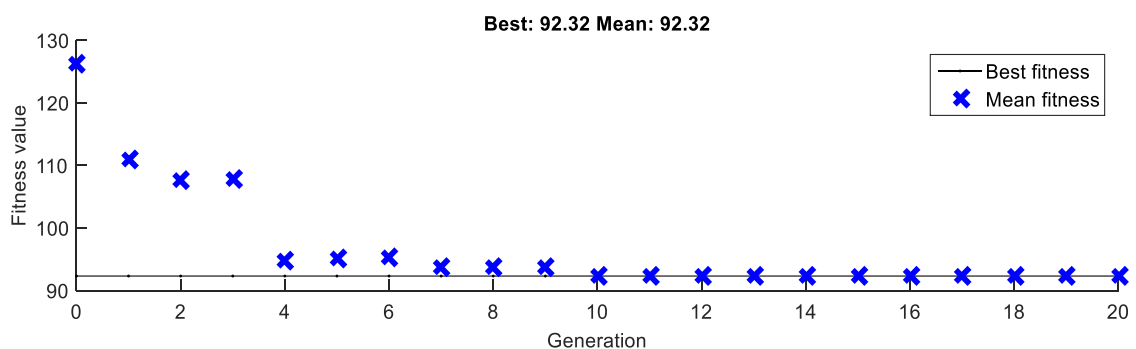


Figure 6.16 Convergence characteristic of the algorithm (4 batteries)

Figures 6.14-6.16 show that for different number of batteries used the amount of loss reduction changes. Regarding the placement of the units it is as follows: when 2 batteries are used the optimal location is at nodes 5 and 6, with 3 batteries, two are placed at node 5 and the third one at node 6 and with 4 batteries, 2 batteries are placed at each of the nodes 5 and 6. Convergence in each of the 3 different cases is achieved after same number of generations unlike the previous case study. The values of the loss reduction for each of the cases are 8.19%, 7.81% and 7.68% respectively.

The voltage violations need to be mitigated by adding storage. For the worst case scenario as defined in Figure 6.13 by optimally placing storage at nodes 5 and 6 the voltage profile can be improved as presented in Figure 6.17 with specific values in Table 6.7.

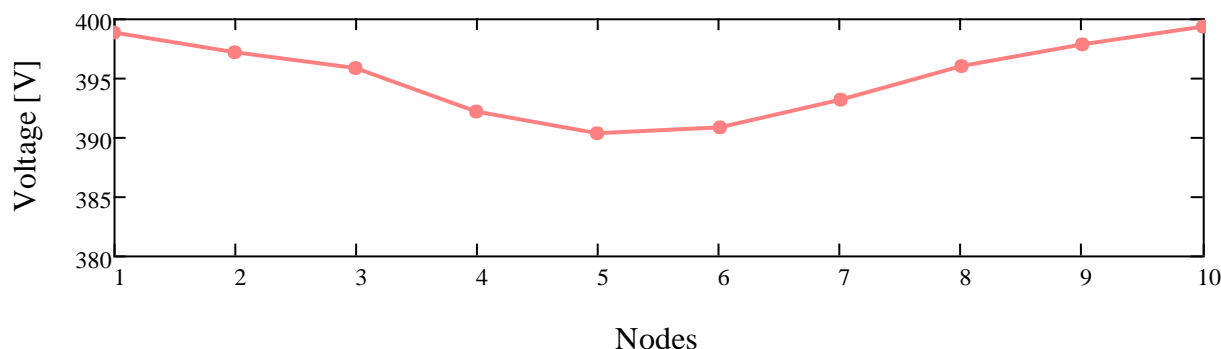


Figure 6.17 Voltage profile of the feeder (CS2) with added storage

Table 6.7 Voltage values at each node (CS2) with added storage

Node	Voltage
1	398.91
2	397.2
3	395.87
4	392.11
5	390.3
6	390.77
7	393.23
8	396.07
9	397.89
10	399.27

The most improvement is made on nodes 5 and 6 (1.38% and 1.425%). As can be seen now there is no more violation of voltage on those 2 nodes. In this case study it was shown that placing storage is found to be optimal on the nodes that have the highest voltage sag. However this is with respect to the daily load profile and the wind turbine production profile used in this study. It is assumed that for larger turbines, in terms of size, with a same production profile as the one used here the violation would be less or it would not be exceeded at all. Yet the energy storage could still help with the improvement of the voltage profile and reduction of losses. For comparison reasons the voltage profile with and without the use of BESS are shown in Figure 6.18

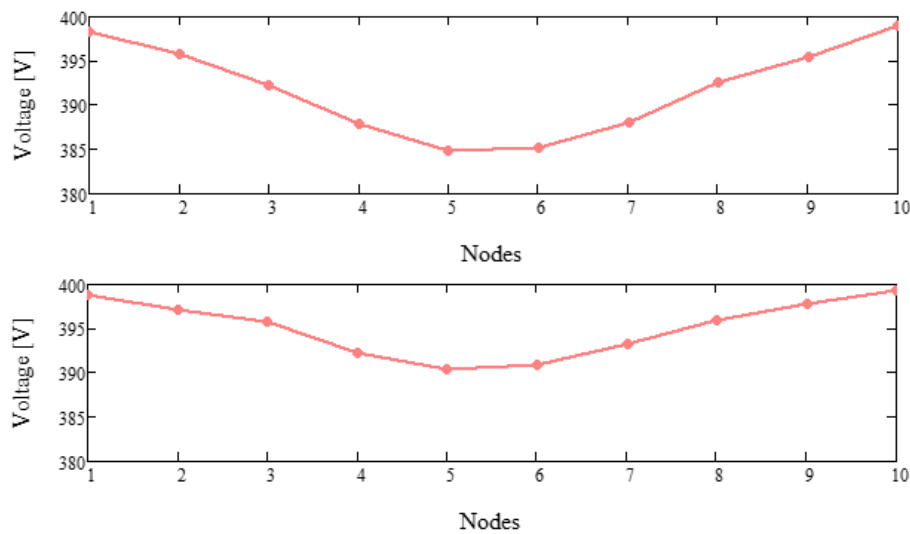


Figure 6.18 Voltage profiles with and without the use of BESS (CS2)

### 6.7 Case study 3: Large scale wind turbine

In this case study a slightly larger wind turbine is tested. In this case the rated power of the turbine is 80kW. However the production profile of the wind turbine is different as can be observed from the Figure 6.19. Production profile of the turbine is also obtained from [70].

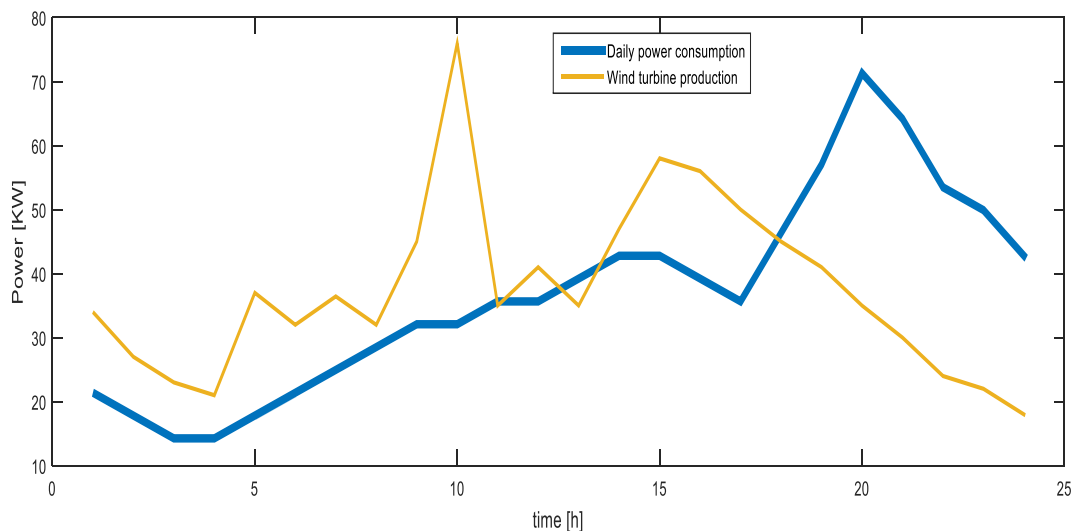


Figure 6.19 Wind turbine [80kW] power production and daily load profile

Since the same daily load profile is used in each case study the daily minima and maxima remain the same. At 20h the load demand is the highest and lowest is in the early hours of the day, during nighttime. It can be observed from the graph that the largest mismatch is at the point of the maximum power production of the wind turbine, where the load demand is relatively low. This case is used as a worst case scenario with respect to these daily profiles analyzed. The turbine is again placed at the end of the feeder, specifically at node 10. When

the power output is the highest a large current is injected in the system and there is a voltage violation. However in this case there is a voltage swell. The voltage violations are on nodes 9 and 10, and voltage at node 8 is close to exceeding the upper limit as can be seen in Figure 6.20 and Table 6.8.

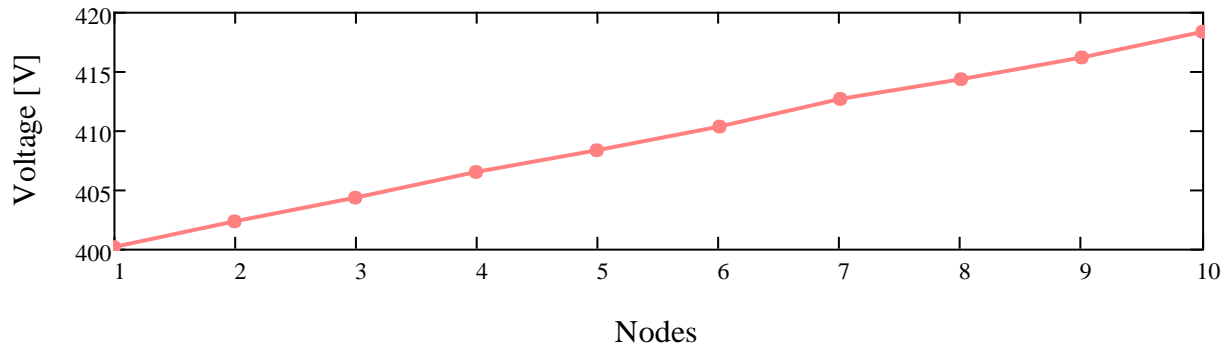


Figure 6.20 Voltage profile during high production and low demand

Table 6.8 Voltage values at each node (CS3) without storage

Node	Voltage
1	400.17
2	402.37
3	404.26
4	406.43
5	408.37
6	410.32
7	412.71
8	414.37
9	416.21
10	418.41

In this case the high injection of power by the turbine cannot be used in the network and there is a bidirectional power flow. It was then tested if adding storage will help alleviate this congestion in the network and to what extent, in terms of voltage profile improvement. It is determined that the size of storage amounts to 35kW and that the optimal placement is at the last node of the feeder, node 10. By placing the storage there, closest to the distributed generation, which is a wind turbine in this case, the high injection of power can be split and partly supplied to the storage, charging it and reducing the stress on the grid. Different number of storage units have also been used to see whether the placement of the storage is affected. Convergence characteristics of the algorithm for different number of batteries are presented in Figures 6.21-6.23.

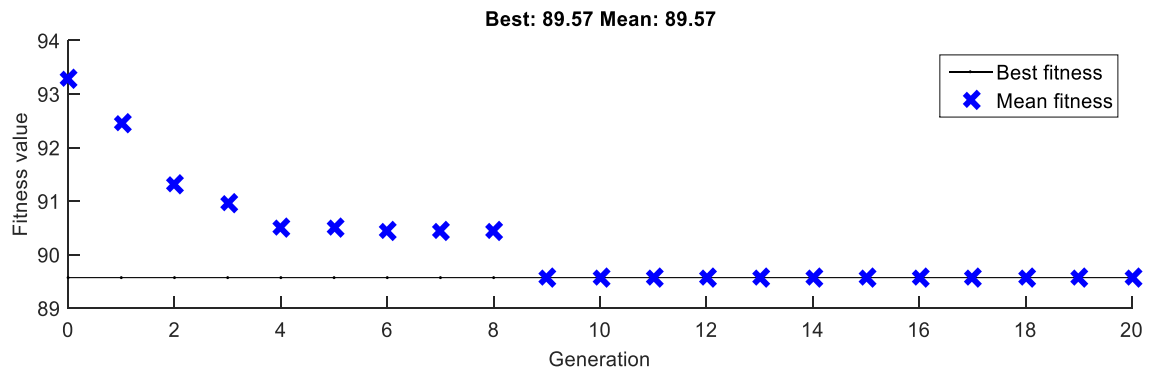


Figure 6.21 Convergence characteristic (2 batteries)

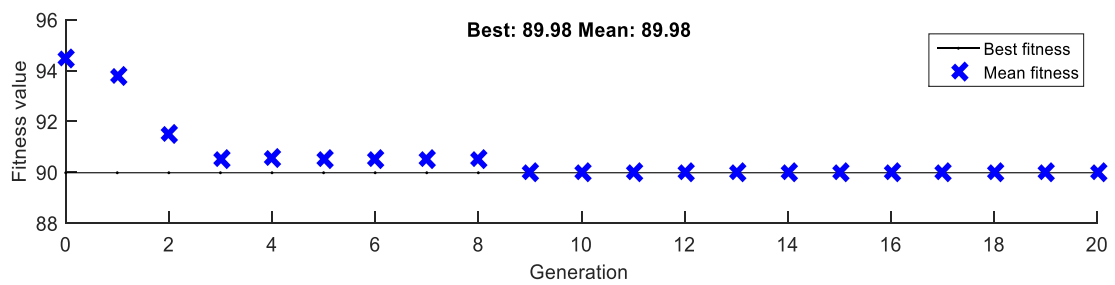


Figure 6.22 Convergence characteristic (3 batteries)

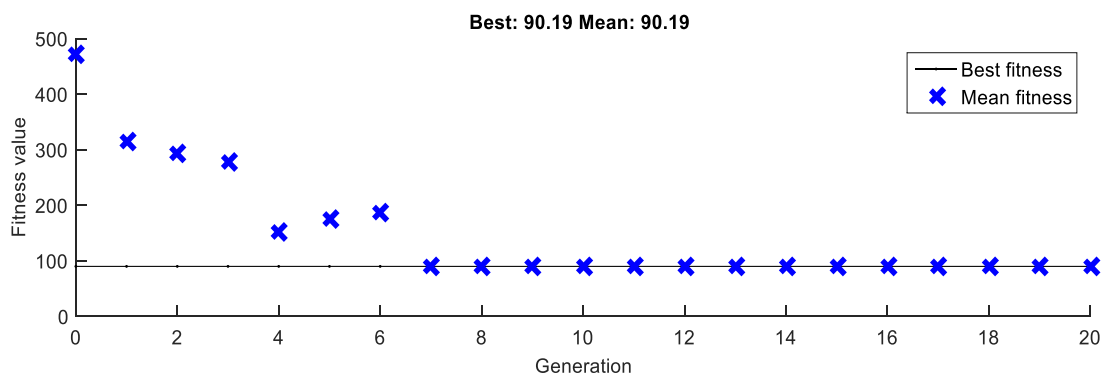


Figure 6.23 Convergence characteristic (4 batteries)

Figures 6.21-6.23 show that for different number of batteries used the amount of loss reduction changes. Regarding the placement of the units it remains the same for each of the different scenarios analyzed (with respect to the number of batteries). Convergence in each of the 3 different cases is achieved after a similar number of generations as in the previous case study. The values of the loss reduction for each of the cases are 10.43%, 10.02% and 9.81% respectively. The voltage profile can be influenced by adding storage. For the worst case scenario as defined in Figure 6.20 by optimally placing storage at node 10 the voltage profile can be improved as presented in Figure 6.24 with specific values in Table 6.9

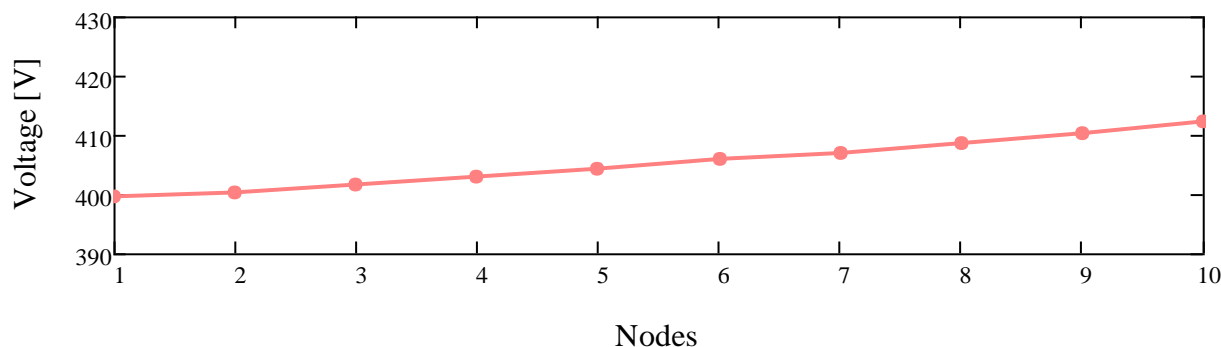


Figure 6.24 Voltage profile with added storage

Table 6.9 Voltage values at each node (CS3) with added storage

Node	Voltage
1	399.67
2	400.47
3	401.53
4	403.06
5	404.42
6	405.91
7	407.13
8	408.79
9	410.17
10	412.27

Main conclusion regarding this case study can be made:

- When there is a voltage violation in the system, namely a voltage swell, adding energy storage and optimally placing it can influence the voltage profile of the network and improve it
- With respect to the previous case it can also be observed that adding storage resolves both under and over voltage problems in the grid, however this study was conducted on a LV network, whether this applies to MV networks remains to be investigated in some future work
- Similar amount of losses is again present when different number of batteries are used in the system, yet as in the case of under voltage problem, the node of placement remains the same
- The number of generations needed to reach the optimal value of the fitness function of the genetic algorithm varies for each number of storage units that are to be allocated in the network
- The congestion in the grid can be reduced by adding storage and from this study it seems it should be placed near the point where the distributed generation is injecting the power to the system
- Again the most voltage improvement is made on the nodes that were the most critical in terms of voltage violation

For comparison reasons the voltage profile with and without the use of BESS are shown in Figure 6.25

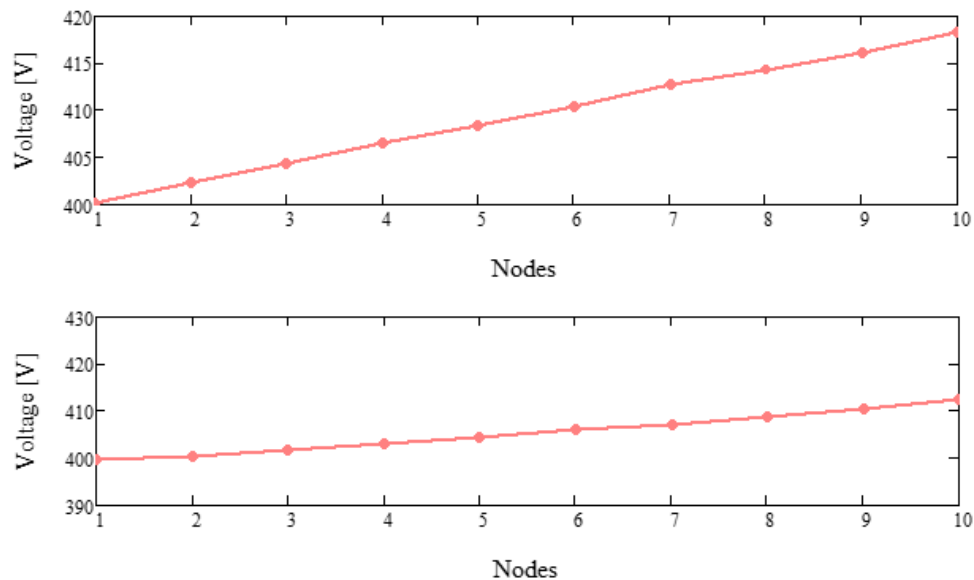


Figure 6.25 Voltage profiles with and without the use of BESS (CS3)

### 6.8 Case study 4: Different small scale wind turbines

In this case study two wind turbines of similar power rating are compared in order to determine the influence the amount of power provided by the distributed generation has on storage sizing. In this case study wind profiles of a 30kW and a 40kW wind turbines are used. Again the data used is obtained from [70] and analyzed with respect to the same daily load profile. The first observation that can be made is that for both profiles, when the load power demand is the highest there will be a large mismatch between the supply and the demand. Although during the period of highest mismatch the power output of the turbines is not maximal, any increase in the production output would still lead to mismatches and as a results would cause voltage problems.



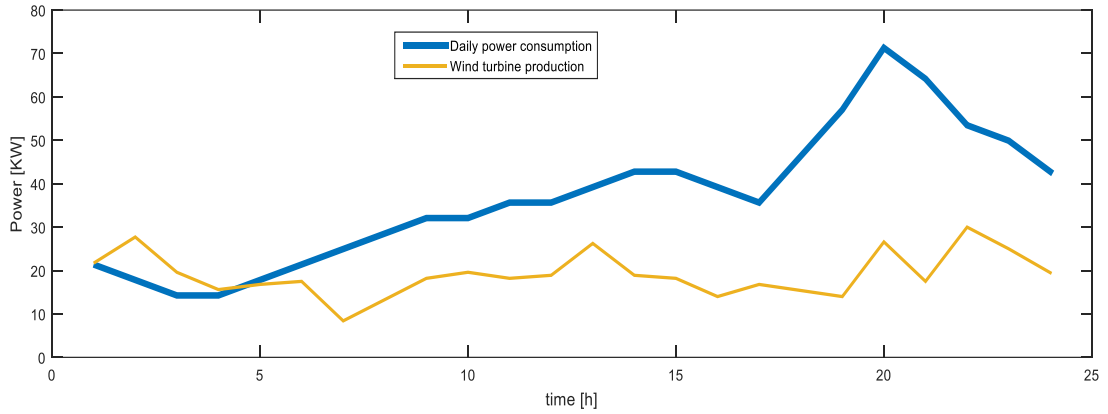


Figure 6.26 Wind turbine [30kW] power production and daily load profile

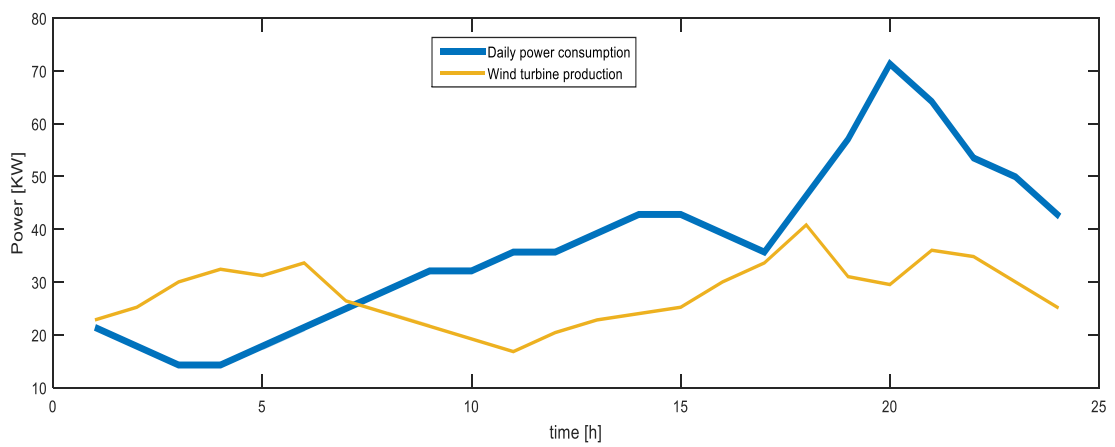


Figure 6.27 Wind turbine [40kW] power production and daily load profile

With respect to the mismatches which are the worst case scenarios it was proven that there is a voltage violation again for both cases. In the first case the violation is more severe as the mismatch is larger. However only one of the two worst case scenarios for the two wind turbine profiles will be presented as the method for improving the voltage violation is the same. For both cases it was determined that the maximum amount of storage size is needed which amounts to 40kW. The voltage profile in the worst case scenario for the maximum demand and almost maximum power output of the turbine is presented on Figure 6.28 with the specific values in Table 6.10

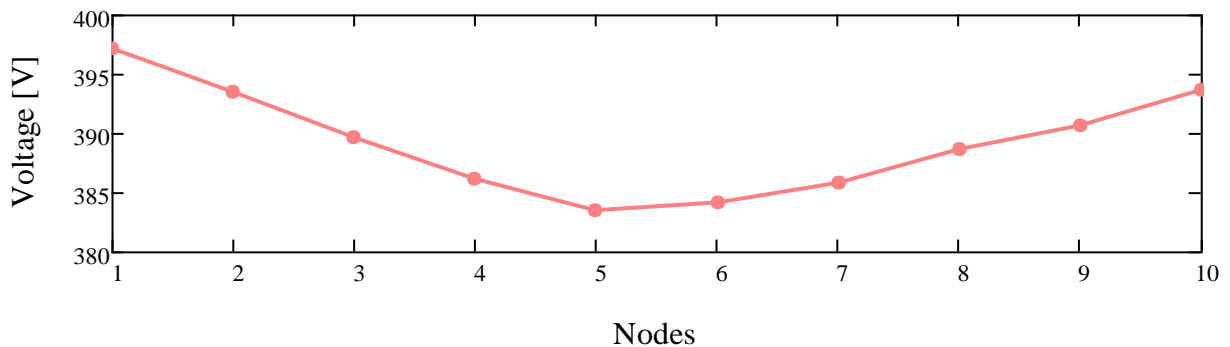


Figure 6.28 Voltage profile with a high load demand and high production of a turbine [40kW]

Table 6.10 Voltage values at each node (CS4) without added storage

Node	Voltage
1	397.2
2	393.52
3	389.67
4	386.13
5	383.43
6	384.14
7	385.87
8	388.64
9	390.71
10	393.64

The violations are present at 3 adjacent nodes in this case study, namely node 5, 6 and 7. Additionally voltages on nodes 4 and 8 have also critical values. This case however is only solved when 3 batteries are used in the network and it is determined that they should be placed at each of the critical nodes. The voltage profile improvement can be seen on Figure 6.29 with corresponding values in Table 6.11

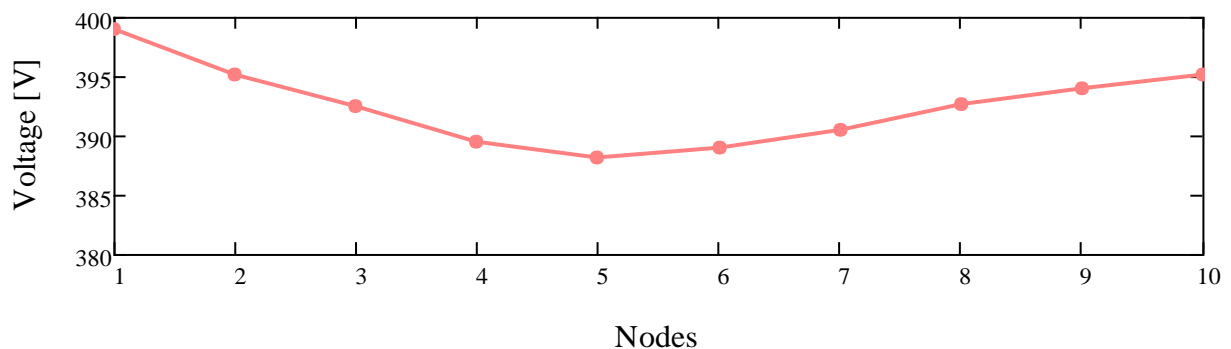


Figure 6.29 Voltage profile with added storage [40kW turbine]

Table 6.11 Voltage values at each node (CS4) with added storage

Node	Voltage
1	399.07
2	395.22
3	392.58
4	389.42
5	388.11
6	389.04
7	390.47
8	392.71
9	393.93
10	395.14

The convergence characteristic of the genetic algorithm is presented in Figure 6.30 for the case where 3 equally sized batteries are placed at each of the nodes 5, 6 and 7.

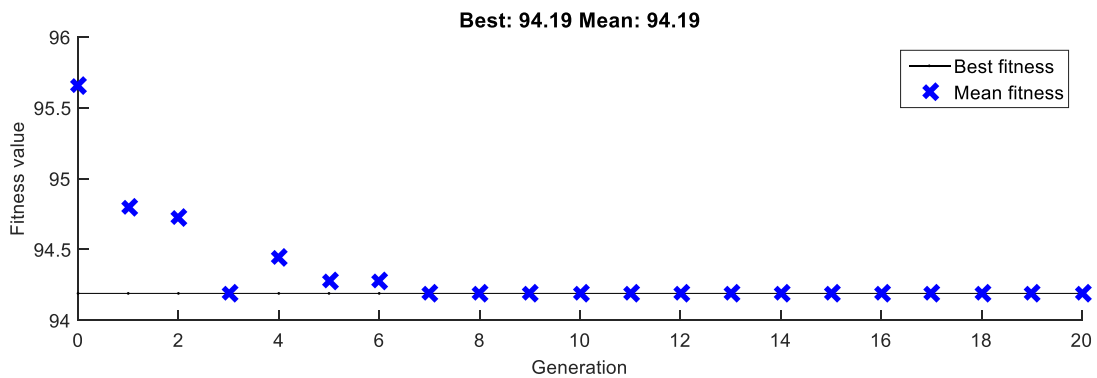


Figure 6.30 Convergence characteristic (3 batteries)

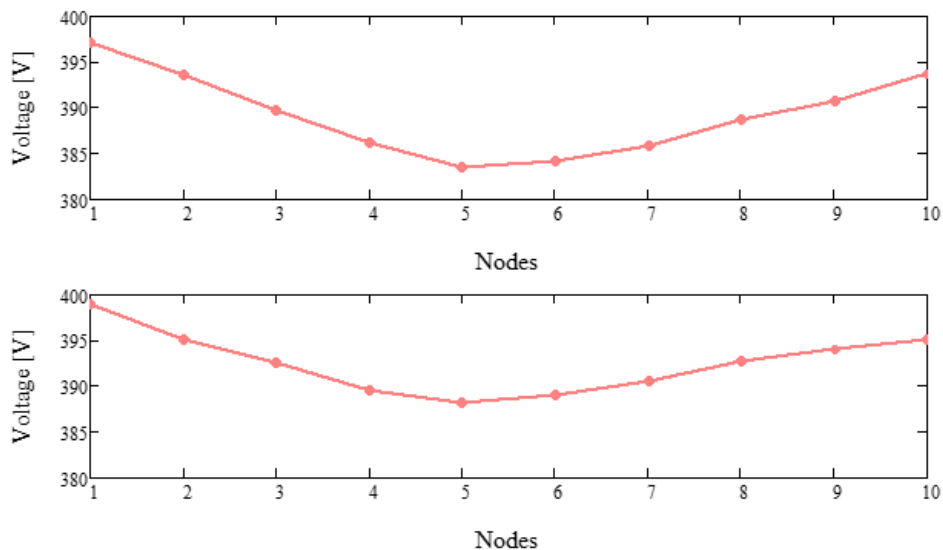


Figure 6.31 Voltage profiles with and without the use of BESS (CS4)

## 6.9 Conclusion

In this chapter the optimization model developed was tested on the LV benchmark distribution network and results from different case studies were obtained. Each of the case studies presented in the results section aimed at displaying voltage problems the network is facing during peak and off-peak periods. First case study addresses voltage problems when no distributed generation is present. In this study as is normally the case, a steady voltage drop is present on the distribution feeder and the voltage decreases more towards the end of the feeder. The optimization model determined that by installing 21kW of battery energy storage at the last node of the feeder (node 10) the losses can be reduced by approximately 5%. The voltage profile improvement in this case study is somewhat expected. Best improvements of the voltage are achieved on nodes 9 and 10 and are 4.18V and 4.75V (1.045% and 1.187%). The

improvement is not substantial, yet all the nodes have a voltage value within the desired range and none of the values are critical.

In case study 2, 60kW wind turbine was integrated to the network. The worst case scenario as defined in the study is during the large mismatch in supply and demand of power. The voltage violation is present at nodes 5 and 6. The optimization process determined the storage size to be 25kW, somewhat larger than in the previous case study, however with the addition of storage to the network the voltage on all nodes is improved. As it is expected the optimal placement for storage is on the nodes that are the most critical in terms of voltage (5 and 6). The improvements made by adding battery energy storage on this two nodes are 5.4V and 5.55V (1.38% and 1.425%). Compared to the previous case study a slightly better improvement in voltage is achieved on all nodes, especially on the most critical ones. The losses for different number of batteries used for the support of the network are on average around 8%.

Case study 3 includes a largest wind turbine integration when compared to all other case studies that consider addition of RES. In this case study a different type of voltage problem is determined. There is a voltage swell at the end of the feeder, which happens during a large mismatch period, however in this case the power produced and supplied is much bigger than the total demand of the network. As a large amount of power is injected to the grid the voltage rise on the entire feeder is present. The voltage is violated on nodes 9 and 10 and it is reaching critical values on several other adjacent nodes. This type of problem, with high power injection causes a bidirectional power flow and the current flows towards the electric grid. Although in this case study this problem was successfully mitigated with the use of energy storage, this surplus of power in the distribution grids of the future could be supplied to some distant consumer. In this case study the requirement for storage is higher compared to the previous two studies and amounts 35kW. Using storage here the voltage violation can be mitigated by charging the battery energy storage during the periods of high power production and thus alleviating the problem. The optimal placement of battery storage is at the end of the feeder closest to the point of power injection. The loss reduction achieved in this study is averaging 10% which is the highest obtained value for all the case studies. This does not lead to the conclusion that with higher distributed generation capacity larger amount of losses can be achieved since this depends on many factors of the network. The voltage improvement in this case study is more evident than in the previous two case studies. Best voltage improvements are seen on nodes 9 and 10 and amount 6.04V and 6.14V (1.51% and 1.53%). The values obtained are the highest so far in terms of improvement.

In case study 4, two similarly sized wind turbines (30kW and 40kW) were tested on the network. The turbines were not connected at the same time, each turbine was tested separately. The purpose of this case study was to evaluate the behavior of the network when smaller scale RES was connected to it. What could be determined from this study is that with small amount of power produced by distributed generation, energy storage is a must since the voltage violation present during the mismatches will be undoubtedly present. However this was determined for the specific settings and model used for the simulation on this network. There

is a probability that different results would be obtained using different methods or models. In this case study the voltage violation is as it is in case study 2 present in the middle of the feeder, specifically on nodes 5 and 6. Another important observation made in this case study is that the sizing of the storage required to mitigate the voltage problems is maximum and amounts 40kW. With this storage size the voltage profile improvement is somewhat similar to previous case studies. On nodes 5, 6 and 7 where the violation was present the improvement is 4.68V, 4.9V and 4.6V (1.17%, 1.225% and 1.15%) respectively. In this study however, the losses are reduced by around 6%, which is not a high value considering the amount of storage used for the support of the network.

Comparing all the case studies, with respect to the optimization model and assumptions used for the simulation, the best results in terms of voltage improvement and loss minimization are obtained in case study 3. However in this case study the amount of storage used for helping with this network problems is not maximal. This leads to a conclusion that the optimization process is very complex and many aspects need to be considered. The solutions somewhat show the reader the necessity for installing energy storage to ease the integration of renewables, however more studies are required in order to fully address the main causes of these problems and best ways to alleviate them.



---

## Conclusions and recommendations

In this chapter the conclusions extracted from this study as well as some recommendations for future work are presented.

In this thesis, an optimization model for the assessment of the optimal placement and sizing of battery energy storage to support the integration of RES in a LV distribution network was developed. To address the computational challenges that this type of problem bears, genetic algorithm was proposed as the optimization tool. The reason for choosing the genetic algorithm among other available optimization techniques was based on previous research, where it has shown to be effective, robust and a convenient tool for solving electrical optimization problems. On top of that, since the objective function used in the optimization process is non-linear, the use of GA is justified since it does not require the calculation of the first derivative of a function, which is normally the case when the local minima or maxima of a function need to be reached. All the results obtained in the optimization process were determined based on the objective function, which is the loss minimization and several other important technical constraints. Different voltage-related problems caused by the integration of wind turbines was analyzed in order to determine the amount of permissible power that could be injected to the grid from distributed generation, the required size and placement of the battery storage and loss minimization within the distribution grid.

### ***7.1 Main conclusions of the thesis are:***

- Grid codes and regulations set the maximum allowed voltage variations in order to secure the power quality and define the prerequisites for the integration of renewable energy sources in LV networks. Possible voltage violations hinder this integration and present an obstacle for the increase of their presence in the power systems of the future
- An IEEE benchmark distribution network was chosen for the demonstration of the optimization model developed. The results of applying this model showed that the voltage rise and voltage drop problems caused by large mismatches in supply and demand can be successfully mitigated using battery energy storage
- The voltage imbalance present in case study 3 is manifested in form of a voltage increase in the distribution feeder. The increase in voltage is more obvious at the end of the feeder, rather than at the beginning and is a result of a high power injection in the system. For higher power rating of DGs, this increase is more obvious. This also causes a bidirectional power flow in the network and the surplus of power that cannot be supplied to the loads is transferred to the grid. By using energy storage and placing it near the point of the large power injection, the surplus of power can be stored and the voltage problems in the network can be mitigated.

- 
- With respect to the optimization model used in this work it was determined that the integration of larger scale wind turbines reduces the necessary optimal energy storage size. Additionally in the case when an 80kW wind turbine is connected to the grid best results in terms of voltage improvement and reduction of losses is obtained using energy storage. The voltage is improved by 6.14V (1.46%) and total power losses are reduced by 10.43%.
  - Different power ratings of distributed generation affect the sizing of energy storage that needs to be installed in the network. For the model used in this thesis and based on the case studies, for smaller wind turbines the size of energy storage is higher. However a linear relation between the two cannot be made as it depends on other factors such as production and consumption profiles.
  - The optimal battery dispatch in the distribution grid was assessed by an optimization algorithm that aimed to maximize the voltage profile improvement while minimizing the power losses. However it was also determined that by installing storage the LV distribution networks' degree of self-sufficiency is increased as the amount of required power from the grid is minimized
  - The computational time of the genetic algorithm increases for the larger number of energy storage units used in the optimization process. This is based on the fact that there are more possible solutions as more units need to be optimally placed within the system

### ***7.2 Main contributions of the thesis***

- Analysis of main implications of using genetic algorithm for optimal placement and sizing of battery energy storage with respect to the loss reduction and voltage profile improvement in a LV network
- This thesis proposes an optimization model for the optimal placement and sizing of battery energy storage in a LV network using the genetic algorithm
- The results obtained in this thesis could be used for some comparative studies in the future regarding the integration of renewables in LV distribution network



### **7.3 Future work and recommendations:**

- Different heuristics such as Particle Swarm Optimization (PSO) could be applied in order to compare and possibly improve the results obtained using the proposed model. With a more complex network representation, possibly more realistic results could be reached, however the computational time and the convergence of the algorithm would increase as well
- The effect of additional battery services such as participation in the electricity market, provision of reactive power and many other could be included in a future study. Additionally the investment costs of the energy storage were not taken into account in this thesis. These additions could be integrated in the objective function of this optimization problem
- In this thesis the aggregated load profile model was used in the simulations. It remains to be investigated how the results would be affected if for every load present in the network its corresponding load profile was used for this analysis
- The optimization model that was developed in this thesis deals with the technical challenges that the integration of RES brings to the distribution grid. However the effects this penetration on the LV level would have on the MV and HV level of the electricity network has not been studied in this thesis.



## Bibliography

- [1] IFL Science <http://www.iflscience.com/technology/battery-costs-drop-even-faster-electric-car-sales-continue-rise/>
- [2] Nature: <http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html>
- [3] Energy Markets of Today: <http://www.energymanagertoday.com/energy-storage-in-commercial-buildings-market-to-reach-7-5bn-in-2022-089368/>
- [4] Green Energy Storage: <http://www.greenenergystorage.eu/en/renewables-integration>
- [5] Klabunde, Christian, et al. "Use of energy storage systems in low voltage networks with high photovoltaic system penetration." *PowerTech, 2015 IEEE Eindhoven*. IEEE, 2015.
- [6] Lombardi, Pio, et al. "Use of energy storage in Isolated Micro Grids." *Power Systems Computation Conference (PSCC), 2014*. IEEE, 2014.
- [7] Dell, Ronald M., and David Anthony James Rand. "Energy storage—a key technology for global energy sustainability." *Journal of Power Sources* 100.1 (2001): 2-17.
- [8] Hernandez, Luis, et al. "A survey on electric power demand forecasting: future trends in smart grids, microgrids and smart buildings." *IEEE Communications Surveys & Tutorials* 16.3 (2014): 1460-1495.
- [9] Ribeiro, Paulo F., et al. "Energy storage systems for advanced power applications." *Proceedings of the IEEE* 89.12 (2001): 1744-1756.
- [10] Grillo, Samuele, et al. "Optimal management strategy of a battery-based storage system to improve renewable energy integration in distribution networks." *IEEE Transactions on Smart Grid* 3.2 (2012): 950-958.
- [11] DeCoster, Dennis. "A state of the art review of energy storage alternatives for mission critical UPS & CPS power systems." *Power Quality Conference*. 2005.
- [12] Enslin, Johan HR. "Integration of photovoltaic solar power—the quest towards dispatchability." *IEEE Instrumentation & Measurement Magazine* 17.2 (2014): 21-26.
- [13] Bose, Subhonmesh, et al. "Optimal placement of energy storage in the grid." *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*. IEEE, 2012.
- [14] Brekken, Ted KA, et al. "Optimal energy storage sizing and control for wind power applications." *IEEE Transactions on Sustainable Energy* 2.1 (2011): 69-77.
- [15] Karanki, Srinivas Bhaskar, et al. "Optimal location of battery energy storage systems in power distribution network for integrating renewable energy sources." *2013 IEEE Energy Conversion Congress and Exposition*. IEEE, 2013.
- [16] Abbey, Chad, and Geza Joos. "Sizing and power management strategies for battery storage integration into wind-diesel systems." *Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE*. IEEE, 2008.

- 
- [17] Dutta, S., and R. Sharma. "Optimal storage sizing for integrating wind and load forecast uncertainties." *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*. IEEE, 2012.
- [18] Baalbergen, Freek, Pavol Bauer, and Jan Abraham Ferreira. "Energy storage and power management for typical 4Q-load." *IEEE Transactions on Industrial Electronics* 56.5 (2009): 1485-1498.
- [19] Moradijoz, Mahnaz, et al. "Optimum placement of distributed generation and parking lots for loss reduction in distribution networks." *Electrical Power Distribution Networks (EPDC), 2012 Proceedings of 17th Conference on*. IEEE, 2012.
- [20] Rao, R. Srinivasa, et al. "Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation." *IEEE transactions on power systems* 28.1 (2013): 317-325.
- [21] Kihara, Hiroyuki, et al. "Optimal placement and control of BESS for a distribution system integrated with PV systems." *Journal of International Council on Electrical Engineering* 1.3 (2011): 298-303.
- [22] Farrokhifar, M., S. Grillo, and E. Tironi. "Optimal placement of energy storage devices for loss reduction in distribution networks." *IEEE PES ISGT Europe 2013*. IEEE, 2013.
- [23] Fogel, David B. "An introduction to genetic algorithms: Melanie Mitchell. MIT Press, Cambridge MA, 1996. \$30.00 (cloth), 270 pp." (1997): 199-204.
- [24] Ewald, Grzegorz, Wojciech Kurek, and Mietek A. Brdys. "Grid implementation of a parallel multiobjective genetic algorithm for optimized allocation of chlorination stations in drinking water distribution systems: Chojnice case study." *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 38.4 (2008): 497-509.
- [25] Kazarlis, Spyros A., A. G. Bakirtzis, and Vassilios Petridis. "A genetic algorithm solution to the unit commitment problem." *IEEE transactions on power systems* 11.1 (1996): 83-92.
- [26] Strunz, Kai, N. Hatziargyriou, and C. Andrieu. "Benchmark systems for network integration of renewable and distributed energy resources." *Cigre Task Force C 6* (2009): 04-02
- [27] Seyedi, Heresh, and Shahab Tanhaeidilmaghani. "New controlled switching approach for limitation of transmission line switching overvoltages." *IET Generation, Transmission & Distribution* 7.3 (2013): 218-225.
- [28] Anxiter: <https://www.anxiter.com/content/dam/Anxiter/Guide/11H0001X00-Anxiter-WC-Technical-Handbook-EN-US.pdf>
- [29] Xiao, Jun, et al. "Determination of the optimal installation site and capacity of battery energy storage system in distribution network integrated with distributed generation." *IET Generation, Transmission & Distribution* 10.3 (2016): 601-607.
- [30] Mohammad Taufiqul Arif, Amanullah M. T. Oo and A. B. M. Shawkat Ali (2013). Estimation of Energy Storage and Its Feasibility Analysis, Energy

- Storage - Technologies and Applications, Dr. Ahmed Zobaa (Ed.), InTech, DOI: 10.5772/52218
- [31] <http://www.eia.gov/forecasts/ieo/footnotes.cfm#331>, US energy information administration
- [32] US energy: <http://energy.gov/oe/services/technology-development/smart-grid>
- [33] Kempener, Ruud, Paul Komor, and Anderson Hoke. "Smart Grids and Renewables. A Guide for Effective Deployment." *Bonn: International Renewable Energy Agency (IRENA)* (2013).
- [34] Roland Berger Presentation, Technology & Market Drivers for Stationary and Automotive Battery systems, p. 28. October 2012
- [35] Hirst, Eric, and Brendan Kirby. *Electric-power ancillary services*. Oak Ridge: Oak Ridge National Laboratory, 1996.
- [36] A. Castillo and D. F. Gayme, "Grid-scale energy storage applications in renewable energy integration: A survey," *Energy Convers. Manag.*, vol. 87, pp. 885–894, 2014.
- [37] J. H. Enslin, "Network impacts of high penetration of photovoltaic solar power systems," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1–5.
- [38] J. H. Enslin, "Dynamic reactive power and energy storage for integrating intermittent renewable energy," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1–4.
- [39] S. Abdelrazek, S. Kamalasadnan, J. Enslin, and T. Fenimore, "Integrated optimal control of battery energy storage management system for energy management and PV Capacity Firming," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 62–69.
- [40] Dugan, R., McGranaghan, M., Santoso, S., and Beaty, H.W. (2004). *Electrical Power Systems Quality* (2<sup>nd</sup> ed.). New York: McGraw-Hill.
- [41] EN-IEC 61000-3-3 Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current  $\leq 16$  A per phase and not subject to conditional connection," ed, 2013.
- [42] N. Rugthaicharoencheep and S. Sirisumrannukul, "Feeder reconfiguration with dispatchable distributed generators in distribution system by tabu search," in *proc. 44th int. university power eng. Conf.* 2009
- [43] T. A. Short, *Electric Power Distribution Handbook*: CRD Press, 2004.
- [44] R. Tonkoski, L. A. C. Lopes, and T. H. M. El-Fouly, "Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention," *Sustainable Energy, IEEE Transactions on*, vol. 2, pp. 139-147, 2011.
- [45] Determination of optimal installation site and capacity of battery energy storage system in DN
- [46] Pregelj, Aleksandar, Miroslav Begovic, and Ajeet Rohatgi. "Recloser allocation for improved reliability of DG-enhanced distribution networks." *IEEE Transactions on Power Systems* 21.3 (2006): 1442-1449.

- [47] Salehi, Javad, and Mahmood-Reza Haghifam. "Determining the optimal reserve capacity margin of Sub-Transmission (ST) substations using Genetic Algorithm." *International Transactions on Electrical Energy Systems* 24.4 (2014): 492-503.
- [48] Ghorbanian, M. J., et al. "Power quality improvement of grid connected doubly fed induction generator using STATCOM and BESS." *Engineering Technology and Technopreneuship (ICE2T), 2014 4th International Conference on*. IEEE, 2014.
- [49] M. R. Aghamohammadi and H. Abdolahinia, "A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 325–333, Enero 2014
- [50] Lee, Yih-Der, et al. "Ancillary voltage control for a distribution feeder by using energy storage system in microgrid." *Power Electronics for Distributed Generation Systems (PEDG), 2016 IEEE 7th International Symposium on*. IEEE, 2016.
- [51] Petinrin, J. O., and Mohamed Shaaban. "A voltage control scheme in a distribution feeder with wind energy sources." *2015 IEEE Conference on Energy Conversion (CENCON)*. IEEE, 2015.
- [52] Hazra, Jagabondhu, et al. "Congestion relief using grid scale batteries." *Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power & Energy Society*. IEEE, 2015.
- [53] Huang, Yang, et al. "Risk-constrained coordinative dispatching for battery energy storage systems of wind farms." *2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. IEEE, 2013.
- [54] ISLAM, Md Mainul, Hussain SHAREEF, and Azah MOHAMED. "A Review of Techniques for Optimal Placement and Sizing of Electric Vehicle Charging Stations." *Przegląd Elektrotechniczny* 91.8 (2015): 122-126.
- [54] Yan X., Duan C., Chen X., Duan Z., Planning of electric vehicle charging station based on hierarchic genetic algorithm, Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), IEEE Conference and Expo, Beijing, (2014),1-5.
- [55] Kerdphol, Thongchart, Yaser Qudaih, and Yasunori Mitani. "Battery energy storage system size optimization in microgrid using particle swarm optimization." *IEEE PES Innovative Smart Grid Technologies, Europe*. IEEE, 2014.
- [56] Ghanbarzadeh, Taraneh, Sassan Goleijani, and Mohsen Parsa Moghaddam. "Reliability constrained unit commitment with electric vehicle to grid using Hybrid Particle Swarm Optimization and Ant Colony Optimization." *2011 IEEE Power and Energy Society General Meeting*. IEEE, 2011.
- [57] Jamii, Jannet, Yahia Saouidi, and Fouizi Mimouni. "Manegement of pumped storage hydro plant coupled with wind farm." *2016 7th International Renewable Energy Congress (IREC)*. IEEE, 2016.

- 
- [58] Kintner-Meyer, Michael, et al. "Energy storage for variable renewable energy resource integration—A regional assessment for the Northwest Power Pool (NWPP)." *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES*. IEEE, 2011.
- [59] Richard, T., et al. "Power quality improvement case study of the connection of four 1.6 MVA flywheel dynamic UPS systems to a medium voltage distribution network." *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*. Vol. 1. IEEE, 2001.
- [60] Kahrobaee, Salman, and Sohrab Asgarpour. "Optimum planning and operation of compressed air energy storage with wind energy integration." *Proceedings of the North American power symposium*. Vol. 1. 2013.
- [61] Saez-de-Ibarra, Andoni, et al. "Analysis and comparison of battery energy storage technologies for grid applications." *PowerTech (POWERTECH), 2013 IEEE Grenoble*. IEEE, 2013..
- [62] Baccino, Francesco, et al. "Power and energy control strategies for a Vanadium Redox Flow Battery and wind farm combined system." *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*. IEEE, 2011.
- [63] Rakos, Balazs, Peter Stumpf, and Istvan Nagy. "Investigation of the effects of nonlinear model of super-capacitors in local DC microgrids supplied by renewables." *15th international power electronics and motion control conference (EPE/PEMC)*. Vol. 4. No. 6. 2012.
- [64] Isobe, Takanori, et al. "Low Loss and Compact Grid Connecting Converter for Superconducting Magnet Using MERS." *IEEE Transactions on Applied Superconductivity* 22.3 (2012): 5400304-5400304.
- [65] Favre-Perrod, P., and A. Bitschi. "A concept for dual gaseous and electric energy transmission." *2006 IEEE Power Engineering Society General Meeting*. IEEE, 2006.
- [66] Zou, Peng, et al. "Evaluating the contribution of energy storages to support large-scale renewable generation in Joint energy and ancillary service markets." *IEEE Transactions on Sustainable Energy* 7.2 (2016): 808-818.
- [67] Olek, Blazej, and Michal Wierzbowski. "Local energy balancing and ancillary services in low-voltage networks with distributed generation, energy storage, and active loads." *IEEE Transactions on Industrial Electronics* 62.4 (2015): 2499-2508.
- [68] Carpinelli, Guido, et al. "Optimal integration of distributed energy storage devices in smart grids." *IEEE Transactions on smart grid* 4.2 (2013): 985-995.
- [69] Biswas, S., and P. Bera. "GA Application to Optimization of AGC in Two-Area Power System Using Battery Energy Storage." *Communications, Devices and Intelligent Systems (CODIS), 2012 International Conference on*. IEEE, 2012.
- [70] NREL: <http://www.nrel.gov/wind/grid-integration.html>
- [71] Signals and systems department <http://automatika.etf.rs/index.php/sr/>

