Optimal Operation of Battery Energy Storage Systems in Radial Distribution Networks

Aref Behnood
Abstract

**Optimal Operation of Battery Energy Storage Systems in Radial Distribution Networks**

Aref Behnood

In recent years, power systems are facing with various challenges arising from the increased share of renewable energy systems. Among all sections of power systems, distribution grids are affected the most since the majority of renewable energy sources are connected to distribution grids.

As the penetration of Variable Energy Sources increases in electric grids, energy storage systems have become more influential. In this context, this thesis presents a new algorithm for the optimal operation of Battery Energy Storage Systems in distribution grids. The proposed algorithm aims to define the optimal operation of Battery Energy Storage Systems considering the network topology, the output power of Variable Energy Sources and the electricity prices from the one-day ahead electric market as well as real time control of the batteries through smart appliances.

In order to do this, firstly a comprehensive study on the existing Optimal Power Flow methods is carried out. Then, AR-OPF which is a novel Optimal Power Flow method for radial distribution systems is presented and the required mathematical constraints, equations and parameters of Battery Energy Storage Systems for modelling in distribution systems are described. Then, the problem formulation and the proposed algorithm are discussed in detail.

Further to energy storage as the main function of Battery Energy Storage Systems, the impact of the proposed method on other functions of Battery Energy Storage Systems such as voltage control, grid support and loss reduction will be investigated. In order to do so, the proposed algorithm is applied to the IEEE 34 node test system as a case study. This will be carried out through defining several different scenarios. Finally, a sensitivity analysis is performed on the size of the existing batteries and the electricity price. The thesis will be concluded by the findings and possible future works.

Keywords— Optimal Power Flow, Smart Grids, Battery Energy Storage Systems, Electricity Market, Renewable Energy Sources
Acknowledgements

I would like to express my warm appreciation to Dr. Juan de Santiago and Dr. Mostafa Nick for their valuable supports throughout the project.

Also, I would like to thank the Institute of Energy Storage System at Leibniz University of Hannover for warmly hosting me throughout this whole project.

Special thanks to Dr. Astrid Bensmann who provided me with valuable feedbacks and devoted a lot of time for discussing about my thesis.

Finally, I must express my very profound gratitude to my parents and to my beloved wife for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Author

[Aref Behnood]
# Table of Contents

Abstract ................................................................. II
Acknowledgements ................................................ III
List of Tables .......................................................... VI
List of Figures ........................................................ VII
List of Acronyms and Notations .............................. VIII

1 Introduction ................................................................................................................. 1
   1.1 Motivation of the Project .......................................................... 1
   1.2 Objectives ................................................................................. 2
   1.3 Thesis Outline ......................................................................... 3

2 Literature Review ....................................................................................................... 4
   2.1 Effect of VESs on Operation and Planning of Distribution Networks .......... 4
   2.2 Battery Energy Storage Systems for Grid Applications ......................... 6
   2.3 Optimal Power Flow Problem .................................................... 8

3 Methodology .......................................................................................................... 10
   3.1 Classical OPF problem ......................................................... 10
      3.1.1 OPF Variables .............................................................. 11
      3.1.2 OPF Constraints .......................................................... 11
      3.1.3 Objective function ....................................................... 12
   3.2 Contribution of the project ...................................................... 12
   3.3 YALMIP toolbox ................................................................. 12

4 Model implementation ............................................................... 14
   4.1 OPF problem in radial distribution grids with \( \pi \) model ................. 14
      4.1.1 Notation of variables .................................................... 14
      4.1.2 Original OPF equations with \( \pi \) model in radial distribution grids .. 15
      4.1.3 Relaxed OPF formulation (R-OPF) ................................. 16
      4.1.4 Augmented Relaxed OPF (AR-OPF) ............................... 16
4.2 Battery constraints and flowchart of simulations .......................................................... 18
  4.2.1 Battery equations ........................................................................................................ 18
  4.2.2 Proposed algorithm and flowchart of simulation ....................................................... 20

5 Results and discussions ........................................................................................................... 22
  5.1 Case study ...................................................................................................................... 22
  5.2 Applying a 24-hour electricity price from Nordpool .................................................... 26
  5.3 Applying the fixed price to investigate the loss reduction .............................................. 29
  5.4 Unexpected wind power outage for 2 Hours ................................................................. 30
  5.5 Sensitivity analysis ....................................................................................................... 31
    5.5.1 Sensitivity analysis based on the size of batteries .................................................... 31
    5.5.2 Sensitivity analysis based on the electricity price .................................................... 32

6 Conclusions .......................................................................................................................... 34

7 Future works ...................................................................................................................... 35
  7.1 Applying the batteries degradation model ...................................................................... 35
  7.2 Optimal size and location of batteries .......................................................................... 35
  7.3 Improving the proposed model ...................................................................................... 35

Literature ................................................................................................................................. 36
List of Tables

Table 5.1 Network parameters...................................................................................................... 23
Table 5.2 Batteries parameters...................................................................................................... 24
Table 5.3. Updated optimal operation of batteries after Wind Power outage............................... 31
List of Figures

Figure 2.1. Share of different technologies for Electricity Generation (trillion kWh) [12]........ 5
Figure 2.2. Schematic diagram of a smart grid [12] .............................................................. 6
Figure 2.3 Degree of maturity for different energy storage systems [25] ............................... 7
Figure 2.4. Comparison of different ESSs specific energy [26] ............................................. 8
Figure 3.1. Solution categories of an OPF problem [7] ........................................................ 11
Figure 3.2. Four steps of YALMIP optimization ................................................................. 13
Figure 4.1. Classic two port π model of a transmission line [9] ........................................... 14
Figure 4.2. Solution space of AR-OPF as a subset of O-OPF [9] ........................................ 18
Figure 4.3. Schematic diagram of proposed algorithm in the one day .................................. 20
Figure 4.4. Updating the real time operation of batteries based on the ............................... 21
Figure 5.1. IEEE 34 node test feeder as a case study [38] ................................................. 22
Figure 5.2. Schematic illustration of Sodium-sulfur battery [39] ........................................ 23
Figure 5.3. Hourly Nordpool electricity price of March 13, 2019 [40] ............................... 24
Figure 5.4. Hourly PV, Wind and load profile ................................................................. 25
Figure 5.5. Linearized capability curve of BESS ................................................................. 25
Figure 5.6. SoE of batteries according to the proposed algorithm for optimal operation ...... 26
Figure 5.7. Hourly active and reactive power of batteries .................................................... 27
Figure 5.8. Hourly voltages of Nodes 822 & 844 in absence of batteries ........................... 28
Figure 5.9. Hourly voltages of Nodes 844 and 822 after the optimal operation of batteries... 28
Figure 5.10. Injected power to the feeder from the upper grid with and .......................... 29
Figure 5.11. SoE of batteries according to the proposed algorithm for optimal .................... 30
Figure 5.12. Amount of cost reduction as a function of battery’s energy capacity ............ 32
Figure 5.13. Sensitivity analysis of Electricity price on the proposed algorithm ............... 33
List of Acronyms and Notations

- ADN              Active Distribution Networks
- ESS               Energy Storage System
- BESS              Battery Energy Storage System
- VES               Variable Energy Sources
- OPF               Optimal Power Flow
- R-OPF             Relaxed OPF
- AR-OPF            Augmented Relaxed OPF
- RES               Renewable Energy Source
- DSO               Distribution System Operator
- OF                Objective Function
- GA                Genetic Algorithm
- PSO               Particle Swarm Optimization
- $CE(t_k)$         The electricity market price in each time step
- $P_{C,i}$         The nominal power of $i^{th}$ BESS
- $E_{C,i}$         The energy capacity of $i^{th}$ BESS
- $P_{g,i}$         vector of active power of $i^{th}$ BESS
- $Q_{g,i}$         vector of reactive power of $i^{th}$ BESS
- $S_{g,i}$         vector of apparent power of $i^{th}$ BESS
- $SoE_i$           state of energy for each BESS
- $r_{h,i}$         The equivalent resistance of $i^{th}$ BESS
- loss$_i$          Losses of $i^{th}$ BESS
- $t_k$ and $t_{k+1}$ The $k^{th}$ and $(k+1)^{th}$ time step
1 Introduction

Global warming and climate change has turned to one of the most important challenges of human being in this current century. Based on the Paris climate agreement, the increase in the average temperature should be limited to 1.5 °C above pre-industrial levels by 2050 [1]. This also affects the planning of the energy policy makers throughout the world for reducing the share of conventional fossil fuel power plants and instead supplying the demand by green and renewable energies as a feasible alternative [2]. In this chapter, the changes in power grids due to the increased share of renewable energies as well as the motivation and objective for doing this thesis will be studied in detail.

1.1 Motivation of the Project

In recent years, the electric grid has encountered with new challenges due to the increasing share of renewable energy which are mostly considered as Variable Energy Sources (VES). In order to tackle down the intermittent characteristics of these sources, several alternatives have been proposed so far [3]. Energy storage systems (ESS) among others, are the most common and feasible solutions which are widely used in power systems[4]. The idea is to store the excess energy of wind, solar or other variable energy sources and to use them during high load demand intervals as the grid support. Battery energy storage systems (BESS) are the most common type of ESS in distribution grids. Despite the technological advancements in recent years, BESS are still have high capital investment cost which makes the private investors as well as grid owners reluctant to increase their share in the power network [5]. Therefore, defining the optimal operation, location and size of BESS have been one the most hot topics in distribution grids which makes the BESS investments more cost-effective. In this context, the purpose of this thesis is to present an algorithm for optimal operation of batteries in smart distribution grids with variable energy sources. BESS are used in distribution systems for various reasons as follows[6]:

- Energy supply and peak shaving
- Postponing the investments for establishing new feeders
- As hybrid systems for grid integration of variable energy sources
- Improving the system’s reliability and security
- Energy cost management
- Grid support and other ancillary services
Considering the abovementioned functions of BESS, it is also important for the grid operator to operate the BESS optimally in order to minimize the costs. But how could this be achieved? So far, lots of professional power flow tools have been developed for controlling the power flow in the feeders of the grid and other crucial variables of the networks such as the magnitude and phase angle of the nodes’ voltages [7]. In this respect, using the appropriate toolbox for solving the Optimal Power Flow (OPF) problem is considered as the basic requirement for the grid operators which enables them to control the operation of the system as well as solving the Generation Expansion Planning (GEP) and Transmission Expansion Planning (TEP) problems. Selecting an efficient OPF tool also enables the grid owner to control the active and reactive power of Distributed Generation (DG) units as well as charge and discharge patterns of BESS [8]. This cannot only reduces the overall running costs of the electric grid, but also leads to deferral of investment in establishment of new generation units or new feeders.

1.2 Objectives

The main objective of this thesis is to develop a new numerical method for optimal operation of BESS in smart distribution grids. In this regard, it is assumed that the batteries were already installed in some specific nodes of distribution grid and the grid operator plans to find their optimal operation with respect to other system parameters such as the node voltages, available power from other variable energy sources, electric demand and etc. In other words, the grid owner tends to minimize the operating cost of the Active Distribution Network (ADN) by controlling the charge and discharge pattern of batteries. In this context, an algorithm will be presented in chapter 3 for finding the optimal solution for charging/discharging of batteries based on the electricity prices. In a simple expression, the grid operator would like to earn more profit by charging the batteries while the electricity is cheaper and sell it to the grid during high electricity prices periods. Although it looks like a simple idea, but finding the optimal solution requires to meet a lot of grid constraints such as voltage of the nodes, allowable current flows in feeders, supplying the demand in every time step and etc.

Therefore, a powerful OPF tool is required to continuously receive data from all elements of the ADN and update the optimal charge/discharge patterns of batteries with respect to real time values of loads, DG unit productions and other network parameters.

Recently, a novel OPF method which is called AR-OPF has been presented by Nick et. al [9], which is suitable for radial distribution systems. Adding new set of constraints in order to guarantee the feasibility of the OPF problem and considering the shunt elements of the line are the two main contributions of this paper. In order to achieve the main purpose of this study, the thesis will investigate the following tasks respectively:

- Studying the AR-OPF for radial grids with π model as well as comparing it with conventional OPF problem
Applying the set of constraints arising from the integration of BESS into the AR-OPF model

Applying the proposed model to IEEE 34 node test system in order to check its validity with respect to a one day ahead electric market

Proposing a new algorithm for real time control of batteries in ADN and update the charging/discharging pattern in case of any unexpected event

Performing the sensitivity analysis with respect to the size of batteries and electricity price

1.3 Thesis Outline

The thesis starts with introduction including the challenges and importance of optimal operation of BESS in distribution grids. In chapter 2, a literature review is carried out together with a short introduction of OPF problem and the advantages of the AR-OPF as a novel method for solving the OPF problem in radial distribution systems. Chapter 3 presents the methodology and a schematic algorithm of simulation as well as the BESS equations which are integrated to the AR-OPF method. Next, IEEE 34 node test system is studied as a case study in chapter 4 and the results of simulation will be presented. In chapter 5, the results of simulation is discussed. Finally, chapter 6 addresses the thesis findings and discusses about the possible future works.
2 Literature Review

In this chapter, a comprehensive literature review regarding the effect of RESs as variable energy sources on operation and planning of Electric Grid is presented. Then BESS as one of the promising solutions for mitigating the intermittent characteristics of RESs in distribution grids is studied. Finally, OPF problem in order to control, operation and planning of smart distribution grids is discussed.

2.1 Effect of VESs on Operation and Planning of Distribution Networks

The distribution system operator (DSO) is responsible for the operation and planning of distribution grids with the first priority of supplying the demands in a safe, reliable and cost-effective way. However, this is not always a straightforward task due to many other factors such as loss minimization or unpredicted faults [10]. In the past decade, this has become more complicated due to the rise of DGs, ESSs, RESs and active loads’ concept in smart distribution grids. In conventional power grids, the power flow was unidirectional with power sources in the range of 100 MW to 1 GW. However, the installation of DG units with power capacities of up to 1 MW close to the final customers in distribution grids have made the power flow bidirectional [11]. In order to meet the Paris agreement, more and more RESs should be installed in the Electric Grid in near future. Figure 2.1 illustrates the estimated share of different technologies for electricity generation until 2040 [12]. Although increasing the installed amount of RESs in distribution grids leads to so many technical and economic impacts as follows [13]:

- Loss reduction
- Voltage’s profile improvement especially at the end of feeders
- Cost reduction in distribution or transmission networks due to investment’s deferral
- Reduction of environmental costs

But still some new challenges in control and operation of distribution grids should be overcome. The main issues in this regard are listed below [14]:

- Voltage control has become more complicated due to the intermittent characteristics of most renewable energy sources such as wind and solar energy
• Reactive power control has become more complicated
• The protection of distribution grid has become more complicated due to the bidirectional flow of power
• The reliability and stability problems are more complicated in grids with high penetration of VES due to the occurrence of unpredicted variations such as blocking the sun by a huge cloud or sudden changes in wind speeds

Considering the abovementioned obstacles in the extension of RESs, numerous researches have been carried out for optimal sizing and location of DGs in distribution grids in recent years. To mention a few as some examples, in [15] the authors have presented a comprehensive review on siting and sizing techniques for DGs in distribution networks. In [16], the authors have used Ant Lion Optimization Algorithm for optimal location and sizing of RESs. In [17], an algorithm has been presented for optimal location and sizing of DG units with the main focus on voltage stability. In [18], the authors have tried to find the optimal sizing and location of DGs with the main focus on loss minimization. In [19], the authors has studied the optimal deployment of DG using a reliability criterion.

Further to the abovementioned problems, emergence of active loads in distribution grids has led to restructuration of distribution grids to the so called smart distribution grids. The schematic diagram of a smart distribution grid is demonstrated in Figure 2.2 [12]. All elements of a smart grid are connected to each other through Information, Communication, and Control Technologies (ICCT). This enables the network operator to optimize the power distribution in the feeders and at the same time to improve the grid stability and reliability.
Considering the hosting capacity of the conventional distribution grids, the installation of DG units are limited due to the overvoltage occurrence [20]. To overcome this problem, the idea of Active Distribution Networks (ADN) has been presented in which communication technologies enables the DSO for productive and secure large scale integration of RESs and DG units in a smart distribution system. In other words, ADN is considered as a distribution networks which is equipped with advanced communicational systems in order to control a combination of generators, active loads, RESs and storage units [21]. In the context of required reformations due to the emergence of ADN, the OPF problem in will be discussed later in section 2.3.

2.2 Battery Energy Storage Systems for Grid Applications

Due to environmental issues, the amount of RESs in electrical grids has increased exponentially in recent years. One of the main solutions to accommodate the intermittent characteristics of these VESs are ESS [22]. ESSs provides the network operator with more flexibility for making a balance between supply and demand. In a simpler expression, the excess energy can be stored instead of wasting and to be used later during peak times. Therefore, ESSs play an important role for improving the grid stability, reliability as well as flexibility for supplying the loads [23]. So many ESSs have been presented so far which can be classified in four main categories as follows [24]:

![Schematic diagram of a smart grid](image-url)
• Mechanical Energy Storage Systems: Including “Compressed air Energy Storage (CAES)”, “Pumped Hydro-Storage (PHS)” and Flywheels
• Thermal Energy Storage: Including “Low Temperature Storage Systems” which are still under development and “High Temperature Storage Systems”. An example of the latter would be the molten salt which is used in order to store the energy in the tower of a Solar Thermal Power Plant
• Electrical Energy Storage Systems: such as Fuel Cells, Capacitors, Supercapacitor
• Chemical Energy Storage Systems: Including conventional, advanced and flow batteries. Some of the main types are: lead acid battery (Pb-acid), Nickel-Cadmium (Ni-Cd), Lithium Ion (Li-ion) and etc.

The degree of maturity for different Energy Storage Systems is illustrated in Figure 2.3[25].

When it comes to choose an appropriate ESS for a specific application, following factors should be considered [24]:
• Storage power rating (both Power Rating (kW) and Energy Rating are important (kWh))
• Round trip efficiency
• Lifetime
• Other important factors such as response time, self-discharge, environmental impact and etc.

Figure 2.4 demonstrates the specific power and specific energy of different ESSs compared to fossil fuels [26]. Considering the abovementioned factors, BESSs usage for grid application is experiencing a growing trend due to their fast response times which enables the DSO to handle the intermittency of RESs. Furthermore, the environmental friendly characteristics of a BESS
compared to conventional fossil fuel power plants makes it attractive to be used for ancillary services such as compensating for the upward and downward ramp rates of VESs. Therefore, BESS is considered as an optimum approach by DSOs to maintain grid stability and flexibility.

As the installed capacity of RESs increases in distribution grids, large scale stationary BESS are becoming more popular. Based on a recent study, roughly 200 MW grid connected stationary Li-Ion BESS had been installed all over the world until 2016. Since more large scale BESSs are expected to be installed in distribution grids in near future, the electricity market rules have been revised in order to accommodate with this new condition so that the energy storage systems can be used in a more effective way. As a real case example, the California Independent System Operator (CAISO) has assigned some clear constraints on the state of charge or the maximum charge and discharge capacity of batteries which participate in the day ahead electricity market [27]. More discussions will be presented in this regards in chapter 3.

2.3 Optimal Power Flow Problem

The solution to the Optimal Power Flow (OPF) problem is the base of planning and control of power system applications. Since OPF is quite an old optimization problem which was firstly formulated in 1962 by Carpentier, lots of different methods for solving it have been presented so far [28]. Typically, Distributions systems have a mesh configuration. But due to some technical reasons such as easier adjustment of the protection devices or to have lower short circuit currents
are normally operated as a radial network. Therefore, the literature is more focused on radial distribution systems [29].

Since OPF is a non-convex optimization problem, its solution is so challenging. The solution methods can be categorized in 4 group as follows [9]:

1. The physical description of the power flow equations are modified through approximation methods
2. Dist-Flow formulation which is more related to power flow equations in radial networks.
3. Heuristic methods which typically apply Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) methods
4. Convexification of the OPF problem

In this project, AR-OPF which belongs to the last category will be used. Since the last category is more suitable for controlling the Active Distribution Networks (ADN), therefore the Distribution System Operator would be able to control the active loads and VESs and its flexibility in performing the demand response increases.

The contributions of the AR-OPF method compared to the previous OPF methods are as follows [9]:

1. New set of constraints are added to the OPF problem in order to guarantee the conversion and feasibility of the optimal solution
2. The shunt elements of the lines has been considered in the model which improves the exactness of the relaxation
3. A comprehensive mathematical proof has been presented by the authors in order to verify the exactness of the AR-OPF method

The detailed description of AR-OPF method including its constraints and assumptions will be presented in detail in chapter 4.
3 Methodology

In this section, the classical OPF problem is shortly reviewed. Then the contribution of this project as well as the software which was used are described briefly.

3.1 Classical OPF problem

As discussed in chapter 2.3, the OPF problem has a long story and first initiated in 1962 [28]. The OPF specify the optimal operation state of the system by satisfying a set of inequality and equality constraints. The OPF is also used widely by the network operator for performing the control, planning and operation of the power system. Some of the OPF methods which have been presented so far are as follows [7]:

- Static OPF
- Dynamic OPF
- Transient stability-constrained OPF
- Security-constrained OPF
- Deterministic OPF
- Stochastic OPF
- Probabilistic OPF
- AC OPF
- DC OPF
- Mixed AC/DC OPF

Each of these methods only consider some extensions of OPF problem. As a result, a new OPF method can be presented by combining two or more of abovementioned methods. For example, the authors in [30] have presented a new OPF method as probabilistic transient stability-constrained OPF.

All OPF methods afford the feasible solution in one of the following categories which is depicted in Figure 3.1 [7]:

- Global optimum: This is the most desired solution to the OPF problem among all.
• Local optimum: Since most OPF methods are formulated as non-convex and nonlinear equations, several optimum points are achieved where the best solution is the closest one to the Global optimum.
• Sub-optimal: The obtained solution is optimal for a specific trajectory.

![Figure 3.1. Solution categories of an OPF problem [7]](image)

Similar to other optimization problem, the OPF problem consists of three main parts:

3.1.1 **OPF Variables**

In any OPF method, there are two main types of variables as follows [31]:

- Independent variables which are also known as decision or control variables: Such as active power of generation units, SoE of batteries, Tap Changer settings of transformers and etc.
- Dependent variables: such as reactive power of generation units, voltage of load buses and etc.

3.1.2 **OPF Constraints**

There are two types of constraints [31]:

- Equality constraints: Power flow equations are expressed as equality constraints
- Inequality constraints: which normally model the operational limits

The main inequality constraints are listed as follows [7]:

- Active power constraints
- Reactive power constraints
- Voltage constraints
- Current constraints
- Voltage angle constraints
- Tap position constraints
- Capacitor bank switching constraints
Methodology

- Curtailment constraints
- Reserve constraints
- Other inequality constraints

3.1.3 Objective function

The definition of the objective function varies with the desirable solution. For example, DSO might plan to minimize Active losses in the network or maximize the social welfare. Also, minimization of carbon emission in smart grids with high penetration of RESs can be assigned as the objective function of the OPF problem. The detailed description of all possible objective functions has been presented in [7]. The conventional objective function of the OPF problem was to minimize the total generation cost. Therefore, it was formulated as follows [32]:

\[
\text{Minimize:} \\
O. \ F. = \sum_{i \in G} \alpha_i P_{gi}^2 + \beta_i P_{gi} + \gamma_i
\]  

(3.1)

Subject to:

\[
g(X) = 0 
\]  

(3.2)

\[
h(X) \leq 0 
\]  

(3.3)

Where \(P_g\) is the active power of the generation units, the terms \(\alpha_i, \beta_i, \gamma_i\) are the cost coefficients, \(g(X)\) represents the equality constraints and \(h(X)\) represents the inequality constraints. The detailed equations of equality and inequality constraints have been presented in [33].

3.2 Contribution of the project

Among all the available OPF methods, AR-OPF has been used in this project. The reason behind using the AR-OPF as well as its main features have been presented in chapter 4. Then, the BESS model is integrated to the AR-OPF and the objective function is revised accordingly. The biggest challenge in this project was to define a suitable objective function which could be able to represent the optimal operation of BESS in the grid. More description on the BESS constraints as well as the objective function will be provided in chapter 4.

3.3 YALMIP toolbox

In order to run the simulations, YALMIP toolbox is used which is a modelling language for advanced solution of convex and non-convex optimization problems. It is a free toolbox which is
compatible with all Matlab commands and syntax. It solves the optimization problem within four main steps which is illustrated in Figure 3.2.

Figure 3.2. Four steps of YALMIP optimization
4 Model implementation

4.1 OPF problem in radial distribution grids with $\pi$ model

As described in chapter 2, distribution grids are normally operated as a radial network due to some technical reasons. Therefore, studying the original OPF in radial distribution networks in this section would be useful. For a more accurate modelling of the lines in the power system, the classical $\Pi$ model of the lines is applied to the equations which is demonstrated in Figure 4.1 [9].

![Figure 4.1. Classic two port $\pi$ model of a transmission line](image)

4.1.1 Notation of variables

The notations which are presented in this section as well as the variables in Figure 4.1 are described as follows:

- Voltage of the slack bus is fixed and its index is $0$
- $L = \{1, 2, ..., L\}$ represents the buses in the grid
- $up(l)$ specifies the bus which is upstream of bus $l$
- Index $l$ is the label of the line with downstream bus $l$
- $S'_{l} = P'_{l} + jQ'_{l}$ is the complex power entering the line $l$
Model implementation

- $f_l$ is the square of current
- $z_l = r_l + jx_l$ is the impedance of line $l$ and $z_l^*$ is the complex conjugate of $z_l$
- $s_l = p_l + jq_l$ is power absorption at bus $l$ with positive values as power consumptions and negative values as power injections.
- $|P|$ is a column vector with $L$ rows and $|P_l|$ represents its $l$th element
- $G$ is the adjacency matrix of the grid
- $\hat{P}', \hat{Q}', \hat{S}'$ represents lower bands of $P, Q$ and $S$ respectively
- $\overline{S}, \overline{f}$ and $\overline{v}$ represent the upper bound on $S, f$ and $v$ respectively

4.1.2 Original OPF equations with π model in radial distribution grids

Considering the notations in section 4.1.1 and Figure 4.1, the power flow equations for a radial network with a pi model is presented as follows [9]:

$$S_l' = s_l + \sum_{m \in L} G_{l,m} S_m' + z_l f_l - j(v_{wp(l)} + v_l) \frac{b_j}{2}, \ \forall I \in L$$  \hspace{1cm} (4.1)

$$v_l = v_{wp(l)} - 2\Re \left( z_l^* \left( S_l' + j \frac{v_{wp(l)} b_j}{2} \right) \right) + |z_l|^2 f_l, \forall I \in L$$  \hspace{1cm} (4.2)

$$f_l = \frac{\left| S_l' + j \frac{v_{wp(l)} b_j}{2} \right|^2}{v_{wp(l)}} = \frac{\left| S_l^b - j \frac{v b_j}{2} \right|^2}{v_l}, \forall I \in L$$  \hspace{1cm} (4.3)

$$S_l^b = s_l + \sum_{m \in L} G_{l,m} S_m', \forall I \in L$$  \hspace{1cm} (4.4)

Assuming the same objective function as in section 3.1.3 which is minimizing the generation cost, the authors has formulated the following set of equations as the original OPF problem in radial distribution grid [9]:

Minimize:

$$\sum_{l \in L} \left( C \left( \Re (s_l), \Im (s_l) \right) \right) + C^c \left( P_l^c \right)$$  \hspace{1cm} (4.5)

Subject to: (4.1), (4.2), (4.3), (4.4) and the following set of constraints:

$$\psi_l \leq \psi_{\text{max}} \ \forall I \in L$$  \hspace{1cm} (4.6)
4.1.3 Relaxed OPF formulation (R-OPF)

Due to the equation (4.3), O-OPF is a non-convex problem. However, the authors in [34] has shown that the O-OPF would become a convex problem which is called Relaxed OPF (R-OPF) if the equation (4.3) is replaced by (4.12) [9]:

\[
f_j \geq \frac{|S_j^r + j \frac{v_{\text{up}(l)}}{2} b_j|^2}{v_{\text{up}(l)}}, \quad \forall l \in L
\]  

(4.12)

This equation means that the losses in the grid are relaxed which can be explained as a non-negative consumption which is nonexistence in real networks and as a result a physical solution might not be afforded in such cases.

4.1.4 Augmented Relaxed OPF (AR-OPF)

In order to solve the problem of the R-OPF, a novel method which is called Augmented Relaxed OPF (AR-OPF) has been presented by Nick et. al [9]. The authors have added new set of constraints as follows to the R-OPF problem in order to make sure that the resulted OPF solution is also a physical one [9].

\[
v_{\text{min}} \leq v_j, \quad \forall l \in L
\]  

(4.13)

\[
\dot{v}_j \leq v_{\text{max}}, \quad \forall l \in L
\]  

(4.14)

\[
\max \left( |\hat{P}_j|, |\hat{P}_j^r| \right) + j \max \left( |\hat{Q}_j|, |\hat{Q}_j^r| \right) \leq v_j I_{\text{max}}, \quad \forall l \in L
\]  

(4.15)

\[
\max \left( |\hat{P}_j|, |\hat{P}_j^r| \right) + j \left( \max \left( |\hat{Q}_j|, |\hat{Q}_j^r| \right) \right) \leq v_{\text{up}(l)} I_{\text{max}}, \quad \forall l \in L
\]  

(4.16)

\[
\hat{P}_j \leq P_{\text{max}}^l, \quad \forall l \in L
\]  

(4.17)

\[
\hat{Q}_j \leq Q_{\text{max}}^l, \quad \forall l \in L
\]  

(4.18)

\[
P_j \leq P_{\text{max}}^l, \quad \forall l \in L
\]  

(4.19)

\[
Q_j \leq Q_{\text{max}}^l, \quad \forall l \in L
\]  

(4.20)
Then the authors has proposed the following set of equations as AR-OPF:

**Minimize:**

\[
\minimize_{s, \delta, v, \hat{v}, \delta, \hat{\delta}, \delta, \hat{\delta}} \sum_{j \in L} \left(C(R(s_j), 1(s_j)) + C(P_t^j)\right) \quad (4.21)
\]

**Subject to:**

(4.1), (4.2), (4.12), (4.4)
(4.10), (4.11)
(4.13), (4.16), (4.15), (4.16), (4.17), (4.18), (4.19), (4.20) and following set of constraints [9]:

\[
\hat{S}_j = s_j + \sum_{m \in L} G_{j,m} \hat{S}_m^j - j(v_{up(j)} + \hat{v}_j) \frac{b_j}{2}, \quad \forall \, I \in L \quad (4.22)
\]

\[
\hat{v}_j = \hat{v}_{up(j)} - 2Re \left(z_j^* \left(\hat{S}_j + j \frac{v_{up(j)} b_j}{2}\right)\right), \quad \forall \, I \in L \quad (4.23)
\]

\[
\hat{S}_j = s_j + \sum_{m \in L} G_{j,m} \hat{S}_m^j + z_j \hat{I}_j - j(v_{up(j)} + v_j) \frac{b_j}{2}, \quad \forall \, I \in L \quad (4.24)
\]

\[
\hat{S}_j^b = s_j + \sum_{m \in L} G_{j,m} \hat{S}_j^m, \quad \forall \, I \in L \quad (4.25)
\]

\[
\hat{S}_j = s_j + \sum_{m \in L} G_{j,m} \hat{S}_m^j, \quad \forall \, I \in L \quad (4.26)
\]

\[
\hat{I}_j \geq \max_{v_j} \left(\left|\hat{P}_j^h\right|, \left|\hat{P}_j^b\right|\right)^2 + \max_{v_j} \left(\left|\hat{Q}_j^h - j \frac{\hat{v}_j b_j}{2}\right|, \left|\hat{Q}_j^b - \frac{v_j b_j}{2}\right|\right)^2, \quad \forall \, I \in L \quad (4.27)
\]

\[
\hat{I}_j \geq \max_{v_{up(j)}} \left(\left|\hat{P}_j^h\right|, \left|\hat{P}_j^b\right|\right)^2 + \max_{v_{up(j)}} \left(\left|\hat{Q}_j^h + j \frac{\hat{v}_{up(j)} b_j}{2}\right|, \left|\hat{Q}_j^b + \frac{v_{up(j)} b_j}{2}\right|\right)^2, \quad \forall \, I \in L \quad (4.28)
\]

The authors has also demonstrated that the solution space of AR-OPF is a subset of the O-OPF. Figure 4.2 provides the comparison between the solution space of O-OPF, R-OPF and AR-OPF.
4.2 Battery constraints and flowchart of simulations

In order to integrate the battery model to the AR-OPF method, the required equations are presented in this section. The important BESS variables for the grid operator are [35]:

- Nominal power of the BESS
- Nominal Capacity of the BESS
- The active and reactive power of BESS
- The BESS state of charge/energy (SoC/SoE)
- The BESS losses due to charge and discharge

4.2.1 Battery equations

Assuming \( P_{g,i}, Q_{g,i} \) and \( S_{g,i} \) as the active, reactive and apparent power of \( i \)th BESS, the following constraint should be met in every time-step for modelling the battery operation in distribution grids [36].

\[
P_{g,i}(t_k)^2 + Q_{g,i}(t_k)^2 \leq S_{g,i}^2
\]

Equation (4.29) depicts the capability curve of a BESS which will be discussed later in chapter 5. It should be noted that negative amounts of \( P_{g,i} \) and \( Q_{g,i} \) represent the charging status of the battery in which the BESS consumes power. The important variable during the operation for the network operator is the State of Energy (SoE) of each BESS. In other words, the ultimate goal of this project is to enable the network operator to specify the hourly SoE of each BESS for the next 24 hours or any other desired time-step based on the predicted electricity price from the one day ahead market.
For a fair comparison of the traded energy by any BESS as well as safety reasons, it is quite common that the SoE of BESS is set to a same value in the first and last time-step. Moreover, based on the recommendations from the battery manufacturers, the SoE of the battery should be normally within the range of 20 to 90 percent in order to minimize the battery degradation [37]. Therefore, the following equations will be applied to the model:

\[
20\% \leq \text{SoE}_i(t_k) \leq 90\% 
\]

\[
\text{SoE}_i(t_k = 1) = \text{SoE}_i(t_k = \text{end})
\]

Where \( t_k \) is the \( k^{th} \) time-step.

Furthermore, the energy balance equation should be applied to the model where the SoE of the next time-step (\( \text{SoE}_i(t_{k+1}) \)) should be equal to the SoE of the current time-step (\( \text{SoE}_i(t_k) \)) plus the charged or discharged amount of energy in previous time-step minus the battery losses as follows:

\[
\text{SoE}_i(t_{k+1}) = \text{SoE}_i(t_k) - P_{g,i}(t_k) \times (t_{k+1} - t_k) - \text{loss}_i(t_k)
\]

Where,

\[
\text{loss}_i(t_k) = r_{n,i} \times \left( \frac{S_{g,i}(t_k)}{V_i(t_k)} \right)^2
\]

According to equation (4.32), if the battery gets charged in the previous time step, the \( P_{g,i}(t_k) \) will be negative and as a result the \( \text{SoE}_i(t_{k+1}) \) for the next time-step would be higher and vice versa. Since the model is applied to large scale BESS which are owned by the DSO, the selling and buying prices of the energy is considered the same.

The Objective function of the DSO company is then to minimize the cost of purchasing electricity from the upper grid by defining the optimal operation of batteries in every time-step as follows:

\[
\text{Minimize } \sum_{t_k=1}^{N} P_{ij}(t_k) \times CE(t_k)
\]

Where \( P_{ij}(t_k) \) is the purchased power from the upper grid in \( k^{th} \) time-step and \( CE(t_k) \) is the electricity price in the time-step \( t_k \).
4.2.2 Proposed algorithm and flowchart of simulation

After modelling the BESS in distribution grids, the next step is to define an algorithm in order to ensure the optimal operation of batteries in distribution grids. The idea is to propose an optimal charge and discharge pattern of batteries based on the one day ahead electricity price. In other words, it is desired by the owner of the batteries to charge them during low loads with cheaper electricity prices and to discharge them during peak loads with high electricity prices. Figure 4.3 illustrates the schematic operation of batteries according to the one day ahead electric market. The input data are the predicted load profile of the next day, the network configuration and estimated production of generating units such as wind and solar plants.

![Network Configuration](Image)

![Load Prediction for the Next Day](Image)

![Climate Prediction for the Next Day (PV & Wind Generation)](Image)

(AR-OPF)

Optimal Operation of Batteries

Figure 4.3. Schematic diagram of proposed algorithm in the one day ahead electricity market

Furthermore, the distribution network operator should be able to supervise the real time operation of BESSs and modify the planned schedule according to unexpected variations in load profiles, PV or wind power outage, network failure such as a line outage and etc. Meanwhile, if any modification is required in the planned operation of the batteries, smart appliances should be used in order to update the real time operation of BESSs for the remaining time-steps of the day. Therefore, the real time operation of batteries is illustrated in Figure 4.4.
Figure 4.4. Updating the real time operation of batteries based on the proposed algorithm
5 Results and discussions

5.1 Case study

In order to validate the performance of the proposed algorithm, IEEE 34 node test system has been used as a case study which is an actual feeder located in Arizona with 24.9 kV as the nominal voltage [38]. The circuit diagram of this test system has been demonstrated in Figure 5.1. BESS are assumed to be connected to the buses 822 and 844 which have the highest active and reactive loads. It should be noted that the location of BESS or the location of RESs does not affect the performance of the proposed algorithm for defining the optimal operation of the BESS. Finding the optimal location of batteries or RESs requires another objective function for loss minimization or voltage profile improvement.

This test system is a radial network with 33 lines, 34 nodes with a base power of 2.5 MW and base voltage of 24.9 kV. Further to the BESSs, a wind turbine with the nominal power capacity of 200 kW has been connected to the node 844 and a set of PV panels with nominal power of 250 kW are connected to node 890. The summary of network parameters is presented in Table 5.1.
Table 5.1 Network parameters

<table>
<thead>
<tr>
<th>Sr.No</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Nominal Power</td>
<td>250 kW</td>
</tr>
<tr>
<td>Wind Turbine Nominal Power</td>
<td>200 kW</td>
</tr>
<tr>
<td>Base Voltage</td>
<td>24.9 kV</td>
</tr>
<tr>
<td>Number of Lines</td>
<td>33</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>34</td>
</tr>
<tr>
<td>Base Power</td>
<td>2.5 MW</td>
</tr>
</tbody>
</table>

The BESS1 is considered as a Sodium–sulfur battery which is suitable for stationary energy storage applications. Its nominal power has been chosen as 80 kW with nominal capacity of 480 kWh which is approximately 10% of the total peak load [39]. A schematic illustration of a Sodium-sulfur Battery is depicted in Figure 5.2.

The BESS2 is a Lead-Acid battery with 120 kW (15% of total peak load) and 170 kWh as the nominal power and nominal energy capacity respectively. Table 5.2 summarizes the BESSs characteristics which are used in this project.
The one day ahead electricity price is applied to the system based on Nordpool hourly electricity market on March 13, 2019 which is illustrated in Figure 5.3 [40].

Further to the electricity price, other input parameters for running the proposed algorithm are the predicted hourly output power of wind and solar generation units as well as the estimated load profile and the network topology for the next 24 hours. It is assumed in this project that the predicted data are already available to the network operator. The input data in this project are randomly generated proportional to the nominal power capacity of wind and solar generation units. Figure 5.4 demonstrates the hourly output power of the RESs as well as the hourly load profile.
Results and discussions

Figure 5.4. Hourly PV, Wind and load profile

Also, the capability curve of the BESSs which was presented as equation (3.32) has been linearized and applied to the model as depicted in Figure 5.5.

Figure 5.5. Linearized capability curve of BESS
5.2 Applying a 24-hour electricity price from Nordpool

As the first case, the proposed model has been applied to the test system according to the input data in Figure 5.4. The hourly SoE of BESSs are presented in Figure 5.6.

Comparing the electricity price to the SoE1 and SoE2, it can be observed that after 20:00 pm in which the electricity prices are higher, the batteries get discharged. Since the BESS2 has lower energy capacity, it can get charged and discharged in the range of 20% to 90% within one hour. In contrast, BESS2 has higher energy capacity and a full discharge within one hour does not occur. It can be seen that both BESSs start the operation with 30% SoE and set to the same SoE at the end of the day. The interesting thing is the SoE of batteries in the middle of the day where the PV output power is at its maximum value. The batteries don’t get charged by the excess power from the PV panels. Instead, it is more economical to feed the loads directly by the PV panels rather than storing their energy in the batteries. In other words, the algorithm sets the SoE of batteries in order to minimize the cost of purchasing electricity from the upper grid.

If the operation of the batteries is excluded from the proposed algorithm, the cost of purchasing electricity from the upper grid would be 902 Euro/day. However, this amount reduces to 869 Euro/day after the optimal operation of the batteries. The losses in this case is 3.76%.
Figure 5.7 depicts the hourly active and reactive power of BESSs in this scenario.

The overall voltage profile of the feeder has also been improved with optimal operation of batteries as compared to no battery operation. Figure 5.8 illustrates the hourly voltages of the nodes 822 and 844 without the operation of batteries. The highest active load occurs at 20:00 pm. As a result, the voltage of the nodes has its minimum value at that time with values lower than 0.9 p.u. in node 844.

The voltage of nodes 822 and 844 with optimal operation of the batteries has been demonstrated in Figure 5.9. Comparing the results with Figure 5.8, it can be concluded that the overall voltage profile of the system has been improved.

Another interesting parameter is the injected power to the radial feeder from the upper grid which is demonstrated in Figure 5.10. Considering the hourly electricity prices in Figure 5.3, it can be observed that more energy is bought from the upper grid around 6:00 am which has in fact lower electricity prices. In contrast, less energy is bought from the upper grid around 20:00 pm which is during high electricity prices.
Figure 5.8. Hourly voltages of Nodes 822 & 844 in absence of batteries

Figure 5.9. Hourly voltages of Nodes 844 and 822 after the optimal operation of batteries
5.3 Applying the fixed price to investigate the loss reduction

In order to investigate the performance of the proposed algorithm on loss minimization, a fixed price for the entire day is applied to the model. When the price of purchasing the electricity from the upper grid is constant, the proposed model should be able to optimize the performance of batteries in such a way that the losses in the grid becomes minimized. Since, the electricity price is fixed, the objective function automatically minimizes the cost of purchasing electricity by minimizing the losses in the radial grid. Figure 5.11 illustrates the optimal operation of batteries in this scenario. The average of electricity price in Figure 5.3 which is 0.059 Euro/kWh is applied to the model. The cost of purchasing electricity from the upper grid is 893 Euro/day which is less than previous case.

The losses in this case is 3.45% which has decreased by 8.24% according to equation (5.1) as follows:

\[
\frac{0.0376 - 0.0345}{0.0376} \times 100 = 8.24\%
\]

(5.1)
5.4 Unexpected wind power outage for 2 Hours

The optimizer finds the hourly SoE of batteries considering the predicted loads and climate conditions. If an unexpected variation happens in the next day with PV or wind generation due to sudden climate changes or an unwanted failure, the optimizer will modify and optimize the battery operation for the next hours according to the proposed algorithm in Figure 4.4. The new operation plan for the next time steps can be transmitted to the batteries through smart appliances connected to the BMS of the batteries. In other words, the optimal operation of the batteries is decided by the network operator in a one-day ahead electric market. Then the afforded values of the SoE for each BESS are considered as the reference for the following hours. If any unexpected failure such as a PV or wind power outage happens in the grid, it is transmitted to the network operator through smart appliances and the updated SoE of batteries for the next time-steps are decided. In this case, it is assumed that a wind power outage has happened from 17:00 pm to 19:00 pm. Therefore, the
updated SoE of batteries according to the proposed algorithm has been presented in Table 5.3 as follows. The rest of working hour from 00:00 am till 17:00 pm remains the same as Figure 5.6.

<table>
<thead>
<tr>
<th>Number of Hour</th>
<th>Planned ($)</th>
<th>Updated ($)</th>
<th>Planned ($)</th>
<th>Updated ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>18</td>
<td>80.3</td>
<td>74.9</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>19</td>
<td>65.2</td>
<td>59.8</td>
<td>78.1</td>
<td>63.9</td>
</tr>
<tr>
<td>20</td>
<td>50.1</td>
<td>44.8</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td>35.1</td>
<td>29.7</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>23</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>24</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

5.5 Sensitivity analysis

5.5.1 Sensitivity analysis based on the size of batteries

It is expected that the cost of purchasing electricity from the upper grid reduces as the energy capacity of the batteries increases. This happens due to the existence of more energy capacity for storing the energy in BESSs during low energy prices. As a result, less energy can be bought from the upper grid during peak hours with high electricity prices which in turn maximizes the cost saving. However, BESSs have a high capital investment costs. It means that installing the batteries in distribution grids only for this issue which is minimizing the cost of purchasing electricity from the upper grid is not a feasible solution at the moment. However, other BESSs roles in distribution grids such as the grid support, improving voltage profile or loss minimization might justify the high investment cost of large scale batteries in distribution grids.

Figure 5.12 illustrates the amount of cost reduction in Euro/day relative to the batteries energy capacities in section 5.2. It can be observed that increasing the BESSs energy capacities by 10 times leads to the cost savings of 189 Euro/day. Comparing this value to the cost savings of 33 Euro/day in the base case, it can be concluded that the cost saving will be 156 Euro/day more than the base case. However, the capital investment of the batteries has roughly increased by 10 times.
5.5.2 Sensitivity analysis based on the electricity price

It is quite common that the electricity prices become zero or even negative during night hours due to the existence of high wind power amounts in the grid. If the electricity prices become zero from 00:00 am till 6:00 am, the optimal operation of batteries according to the proposed algorithm has been presented in Figure 5.13. The cost saving in this case is roughly 154 Euro/day which is 121 Euro more than our base case in section 5.2. This increase in the amount of cost saving is in line with our expectations since the electricity is free of charge for 6 hours.
Figure 5.13. Sensitivity analysis of Electricity price on the proposed algorithm
6 Conclusions

In this thesis, a new method has been developed which provides as a result an optimal charging pattern for Battery Energy Storage Systems in any radial distribution grids. First, a comprehensive overview on different OPF method was carried out and AR-OPF method as a novel solution to the OPF problem has been discussed in detail.

Then, an algorithm for optimal operation of batteries in active distribution grids has been presented in order to minimize the cost of operation. The proposed algorithm is composed of two different levels. At first, the input data including the predicted load, RESs estimated output power and the network topology are applied to the model considering the electricity prices from the one-day ahead electric market. Then the network operator assigns the hourly SoE of batteries for the next 24 hours in such a way that the cost of purchasing electricity from the upper grid becomes minimized. Next, the real time operation of batteries are controlled and supervised by the network operator through smart appliances. In case of any unexpected failure in the system such as wind or PV power outage, the SoE of the batteries get updated accordingly.

As a case study, the proposed algorithm has been applied to the IEEE 34 node test system. The simulation results revealed the good performance of the proposed algorithm by applying it to several different scenarios. It is concluded that the proposed algorithm is capable of minimizing the cost of purchasing electricity from the upper grid by assigning the SoE of batteries in the system. Further to the operational cost minimization, the effect of the proposed algorithm on the losses has been studied. The simulation results demonstrated that the proposed algorithm also reduces the losses. Moreover, the voltage profile of the system has been studied with and without optimal operation of the batteries and it has been concluded that the overall voltage profile of the grid has improved with the proposed model.

As a sensitivity analysis, the amount of operational cost saving relative to the size of BESSs has been studied. As it was expected, we conclude that the cost of purchasing electricity from the upper grid decreases as the size of batteries increases. This is because of the existence of extra energy capacitites in batteries for storing the energy during cheaper electricity prices and discharge it back to the grid during high electricity prices. However, installing the batteries in distribution grid only for reducing the operational cost is not a feasible solution due to the high capital investments of batteries at the moment.
7 Future works

7.1 Applying the batteries degradation model
In order to improve the proposed model, it is recommended to apply the batteries degradation model to the proposed algorithm. In real applications, since the operational cost of batteries per cycle could be quite high, it might not be always cost effective to charge and discharge the batteries in order to save a little amount of money. Therefore, modifying the objective function so that the degradation cost of batteries is considered together with minimization of operational cost could be an interesting topic as a future work.

7.2 Optimal size and location of batteries
In this project, it was assumed that the size and location of the batteries are already set and the focus was on optimal operation of batteries. However, it would be interesting to define the size and location of the batteries as independent variables. Then, the objective function could be modified and applying the yearly input data to the model will yield the optimal size and location of the batteries in distribution grids.

7.3 Improving the proposed model
Other optimization techniques such as PSO or Genetic Algorithm could be combined to the proposed algorithm in order to improve the planning of distribution grids which is mentioned in section 7.2.
8 Literature


