Aalborg University
Department of Energy Technology

Stochastic and Optimal Aggregation of Electric Vehicles in Smart Distribution Grids

Master Thesis

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2013/5/30

AALBORG UNIVERSITY
STUDENT REPORT

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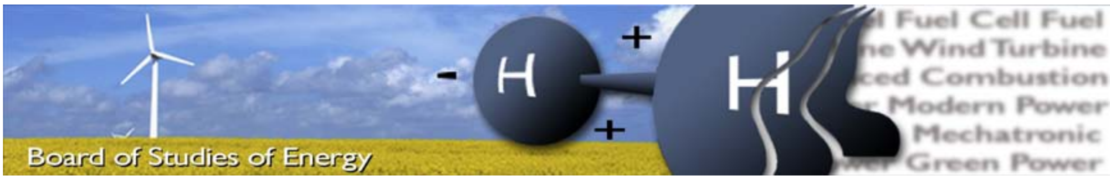

Title:	**Stochastic and Optimal Aggregation of Electric Vehicles in Smart Distribution Grids**
Semester:	**9^{th} – 10^{th}**
Semester theme:	**Master's Thesis**
Project period:	**1^{st} of September 2012 – 30^{th} of May 2013**
ECTS:	**50**
Supervisor:	**Jayakrishnan R Pillai**
Project group:	**WPS4-1050**

[Zheyuan Hu]

SYNOPSIS:

In this report, a study of stochastic and optimal aggregation of electric vehicles (EVs) in smart distribution grid is presented.

The analyses of base cases in the distributions grid connected with EVs show the bottleneck of the system operation. The ability of supporting EVs of the grid is investigated.

The stochastic process of the driving pattern is done to make the outcome of the project more realistic. Based on the stochastic data, the optimization of charging plans is made.

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Appendix:	[16]
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Preface

This is the master thesis made by Zheyuan Hu, a master student at Department of Energy Technology, Aalborg University, Denmark. I am specialized in Wind Power Systems.

This report is based on a long project lasts for nine months in title “Stochastic and Optimal Aggregation of Electric Vehicles in Smart Distribution Grids”. The knowledge learned through the master program has been applied on the project. The courses I have taken and the experiences of former semester projects have been very helpful.

I would like to give special thanks to my supervisor, Jayakrishnan R Pillai, who has been very encouraging to me and given me valuable guidance. I would also like to thank postdoctoral Weihao Hu whose suggestions are very helpful to the project.

Thank my parents who have been very supportive through all my master program study.

Also thank the staffs and classmates in the Department of Energy Technology for the help and supports.

Summary

The background concerned about wind power and EVs is presented along with the motivation of this project. The EVs can achieve zero CO_2 emission to be environment friendly. They have potentials to reduce the cost of the transportation systems [1]. The development of the EVs is on an accelerated pace [2].

As new loads in the distribution grid, charging EVs could influence the operation of the distribution grid. The base cases are set to investigate the capacity of the grid to support EVs. Four representative days have been chosen: summer weekday, summer weekend, winter weekday and winter weekend. Issues of high wind power penetration in Danish power system are demonstrated. With a whole picture of electricity market in Denmark, the architecture of this project is presented.

To make the outcome more realistic, the stochastic data is used in this project. The stochastic data is generated by certain driving patterns using Monte Carlo Method. The stochastic data include driving distance, arriving time and leaving time of 75 EVs. A plan of dumb charging is made based on these data. EVs start to charge as soon as they arrive home and stop charge until the batteries are fully charged.

Because of the fluctuation of electricity price and the wind power production, it is wise to charge EVs during off-peak time of the consumption of electricity. The optimal charging plans are made to reduce the charging cost. The smart charging plans could benefit the gird aggregators and the EV owners.

Contents

Nomenclature

EV	Electric Vehicle
EVs	Electric Vehicles
CO_2	Carbon dioxide
PM	Particulate Matter
PM2.5	Small particles less than 2.5 micrometers in diameter
V2G	Vehicle-to-Grid
SOC	State-Of-Charge
NHTS	National Household Travel Survey
BEVs	Battery Electric Vehicles
HEVs	Hybrid Electric Vehicles
PHEVs	Plug-in Hybrid Electric Vehicles
BEV	Battery Electric Vehicle
NiMH	Nickel Metal Hydride
Li-ion	Lithium ion
Ah	Ampere-hour
DOD	Depth-Of-Discharge
TSO	Transmission System Operator
V	Voltage
pu	per-unit
GPS	Global Positioning System
DSO	Distribution System Operator
C_t	Total cost of charging
m	The No. of charging hour
n	The No. of EVs
c	The price of electricity in a particular hour

p	The charging power
$\mathbf{V_n}$	Voltage of cable box n
$\mathbf{E_n}$	Energy demand of EV n
$\mathbf{C_{DCW}}$	The cost of the dumb charging plan in winter weekday
$\mathbf{C_{SCW}}$	The cost of the smart charging plan in winter weekday
$\mathbf{C_{rW}}$	The amount of reduction of charging cost in one winter weekday
$\mathbf{C_{DCS}}$	The cost of the dumb charging plan in summer weekday
$\mathbf{C_{SCS}}$	The cost of the smart charging plan in summer weekday
$\mathbf{C_{DCA}}$	The average cost of dumb charging of two scenarios
$\mathbf{C_{SCA}}$	The average cost of smart charging of two scenarios
$\mathbf{C_r}$	The total reduction of the cost by using smart charging for one year

1. Introduction

1.1 Background and Motivation

The energy crisis has been an important issue for last few decades. The shortage of fossil fuels is becoming a reality. There is an estimate that the oil production left in the ground can only be used for less than 50 years [3].

The environment problems caused by using fossil fuels are also becoming more serious. The global warming created by CO_2 emission leads to the disorder of ecosystem all over the world [4]. For example, the north part of China nowadays suffers a severe air pollution condition. The PM2.5 (small particles less than 2.5 micrometers in diameter) frequently goes over 300, which is considered hazardous to all humans [5]. The consumption of fossil fuels is considered the main reason for this kind of pollution, including motor vehicles using gasoline and power generation by coal [6].

People have never stopped exploring new energy sources. The nuclear power is one that people place high hopes on. However, the high risk of controlling issues forces people to look for other solutions. Since Fukushima Daiichi Nuclear Disaster, more countries hold a cautious attitude towards nuclear power. Germany announced that nuclear energy will be abandoned completely before year 2022 [7]. Therefore, other renewable energy will play more important roles in the future.

Wind power is environment friendly and matured technology with zero CO2 emission. It is a kind of renewable energy resource which is inexhaustible. Denmark has been committed to developing wind power for decades. Now in Denmark more than 20% electricity is generated by wind [8]. The new initiatives of government would make the share of renewable energy go over 60% of overall electricity consumption in 2020 [9]. In which wind power will cover more than 40% of the consumption, as seen in Figure 1-1. The goal is to be independent from fossil fuels by 2050 [9].

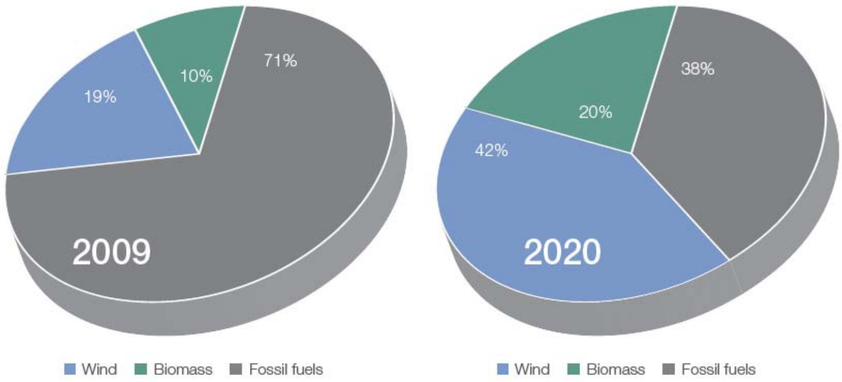

Figure 1-1 Share of renewable energy in electricity production [9]

Besides wind power, Denmark concentrates on many aspects of renewable energy and solutions for dealing with environment issues. The electric vehicles (EVs) have been put on energy agenda to replace the gasoline vehicles in the future. The price of gasoline in Denmark is much higher than in the US. The tax for buying a gasoline car is also very high, while there is low or no tax for EVs [8]. Moreover, the EV batteries as energy storages can support the power system with high wind penetration [10].

With increasing wind power and expected growth of EVs in Danish power system, the impacts caused should be studied. The wind power is hard to forecast and it causes some reliability and stability issues to the grid. The fluctuation of wind production can affect the profits of electricity vitally and can cause troubles in the power systems [11]. EVs can support such a system as new loads and sometimes as generators with technique called Vehicle-to-Grid (V2G) [12]. As sizeable loads, charging EVs can easily affect distribution grid. The voltage will drop considerable and losses in the grid could also increase [13]. The plans for promoting EVs should be made by considering the capacity of existing grid and future smart grids involving information and communication technology.

1.2 Objectives

This project will analyze the aggregation of EVs in power systems in Denmark. Considering the high level of penetration of wind power in Danish power systems, it is worthy to study the possibility of using EVs to balance the systems.

The robustness of the grid will be verified. Some impacts of EVs on distribution power systems have been studied in [14] and [15]. This project aims to do a stochastic process for the analysis. Since the behaviours of EV owners are not deterministic, the stochastic method could make the results more realistic.

And in order to promote the development of the EVs and have stable grid operation, the project aims to make economic charging plans. The optimization of the charging cost and grid losses can benefit both consumers and aggregators.

1.3 Methodology

The first approach to the project is to understand the concepts of EVs. The features of EVs should be studied in order to pick the right case for this project. The driving pattern is useful for predicting the behaviour of the EV owners and the possible consumption of EVs. The features of battery of EV are used to help assume and set the State-Of-Charge (SOC).

This project is based on the power systems in Denmark. So the impacts of high wind power penetration should be well considered. Furthermore, knowing how the electricity market works in Denmark is essential. Danish power system is highly penetrated with wind and the market is volatile. Future market operation may have to be modified. For instance, to use local resources to support wind power, aggregation is required. New system architecture is important to be studied.

The project is focused on residential distribution grid, because most of EVs will be charged at home. There are limited numbers of charging stations. The limitations of the grids should be looked into in advance. Some base cases with EVs charging in the grids will be tested. After this, the data of driving patter and available charging time will be used to generate random behaviours of the EVs. The grids will be studied in these realistic situations. Due to the differences of electricity consumption in different time in Denmark, several scenarios will be set. Some results will be used to analyze the limitations of the grids. The charging plans will be made based on the analyses.

The fluctuating nature of the wind could lead the price of the electricity in Denmark to vary a lot. An optimization process could be done to make the EV charging more economic based on the varying price.

DIgSILENT Power Factor tool is used to analyze the base cases of the distribution grids and verify the results. DIgSILENT is a software used in generation, transmission, distribution and industrial systems [16]. In this project, the base cases of grids connected with EVs are verified in DIgSILENT.

The Matlab is the main tool in this project. It is a high-level language and interactive environment for programming, numerical computation and visualization [17]. In this project, the load flow of the grids will be calculated in the Matlab. The stochastic process and optimization will also be done with Matlab.

To generate random data of the charging EVs, the Monte Carlo Method is used. It is a method to numerically compute integrals and expected values. It is a probabilistic method to simulate random scenarios or outcomes [18]. In this project, the method will be used to generate a matrix which contains the charging EVs with different charging times and powers. The data will be random based on the realistic driving pattern and arriving/leaving times.

1.4 Limitations

In this project, the flicker, harmonics and unbalancing of the grid are not considered. The information and communication technology is not discussed here. The steady state and balanced system are used. There are no dynamic studies involved.

The optimization is based on the Elspot price of the electricity. The scenarios of EVs participating in ancillary services to support grid are not investigated in this project.

The data of arriving and leaving time of EVs is from National Household Travel Survey (NHTS). The data is based on the travel behaviour of the American public. So it may have some variations for case in Denmark.

The future power systems in Denmark could not be fully predicted. The chosen type of EVs may not present the majority of EVs in the future.

1.5 Outline of the Thesis

The Chapter 2 is focused on the State-Of-Art of this topic. The relevant features of EVs are studied first. To understand power systems in Denmark, the issues with high wind power penetrated systems is discussed here. The electricity market in Denmark is explained in order to be associated with future step. The architecture for this project is designed in this chapter.

The Chapter 3 makes the analyses on the distribution grid in this project. An introduction of the grid is presented along with the possible limitation. The DIgSILENT will be utilized here to see the base cases. Due to the actual situations in Denmark, the scenarios are divided into summer weekday, summer weekend, winter weekday and winter weekend. The basic idea is to see how many EVs can be supported in different scenarios and what the grid limitation is.

In Chapter 4, the stochastic method makes the EV behaviours more realistic. The driving pattern and arriving/leaving times are processed to generate random data of charging EVs. The Monte Carlo Method is used here. The consumption of the EVs is estimated. Two kinds of charging plans are discussed in scenarios with and without random process.

Chapter 5 is to optimize the charging plans based on the variation of electricity price caused by fluctuating wind power. The constraints may be voltage drop and battery SOC etc. The method of optimization is illustrated in this chapter. The result provides an economic charging plan which can benefit both customers and aggregators. The stability and quality of the distribution grid would also meet the requirements.

The Chapter 6 gives the conclusions of this project. The work been done in this project is summarized. The contributions and limitations are presented. And based on those, the future work can be done is proposed in Chapter 7. The references and appendixes are followed.

2 Electric Vehicles in Distribution Grid

2.1 Background of Electric Vehicles

2.1.1 History and Types

Electric vehicles are vehicles that are driven by electricity. They normally have one or more electric motors. In a broad sense, the electric vehicles include electric cars, electric boats, electric trains, electric airplanes etc. [19] In this thesis, the Electric Vehicles (EVs) are referred to as electric cars.

The first model of electric vehicles was built in the 1830s. By the end of 19^{th} century, the commercial electric vehicles were on the market [20]. Nowadays, there are many kinds of electric vehicles. They are divided in [20] into 6 types: battery electric vehicles; the IC engine/electric hybrid vehicle; Fuelled electric vehicles; Electric vehicles using supply lines; Solar powered vehicles; Electric vehicles which use flywheels or super capacitors. However, on the consumer market of EVs, the following three types are commonly referred:

Battery electric vehicles (BEVs):

Use electricity to provide the power. They have large batteries to storage the electricity which is used to drive the electric motors. The cars need to be plugged into power supply to charge.

Hybrid electric vehicles (HEVs):

Use the combination of electricity stored in a battery and either a petrol or diesel to drive the motors. This kind of EVs does not need to be plugged in to charge the batteries. They can be charged while the cars are driven.

Plug-in hybrid electric vehicles (PHEVs):

PHEVs normally have much larger batteries than conventional HEVs. And they can be plugged into mains to charge. This kind of EVs can travel relatively longer distance.

Some hybrid electric vehicles have achieved success in the market, like PRIUS made by TOYOTA. In this project, since the electric part is the main section discuss, the EVs will be considered as BEVs to simplify the analyses. The basic concept of BEVs is shown in Figure 2-1.

The BEV has an electric battery, an electric motor and a controller. The battery can be charged by plugging into the mains. In the case for this project, it can be charged by power supply from the house.

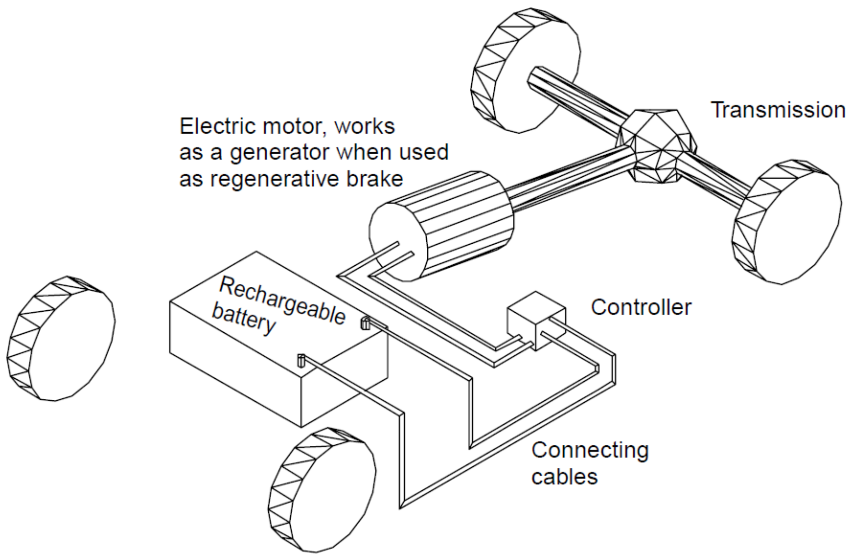

Figure 2-1 Concept of the BEVs [20]

2.1.2 The Advantage of EVs

One of the main motivations to promote EVs is to solve the environmental problems. The CO_2 exhausted by gasoline cars causes global warming. And the emissions of CO and SO_2 of gasoline cars result in serious air pollution. The particulate matter (PM) can causes lung problems and other diseases. The gasoline cars also make much more noise than EVs.

EVs like BEVs, on the other hand, can achieve zero emission in driving. The emissions of hybrid vehicles are also much less than the conventional cars. EVs are relatively quiet when operating. In summary, EVs are environment friendly.

Since electricity is normally cheaper than gasoline, EVs will cost less than conventional cars for driving. Also in a power system with high wind power penetration like Denmark, the customers could benefit more by using smart charging plans. The economic profit could be expected to be more and more in the future. An example of comparison can be seen in Figure 2-2. It is assumed that an owner need use a car for 10 years and drive 17,000 km a year. A petrol car costs 6,900 Euros more than a BEV, and a diesel car costs 5700 Euros more than a BEV [21].

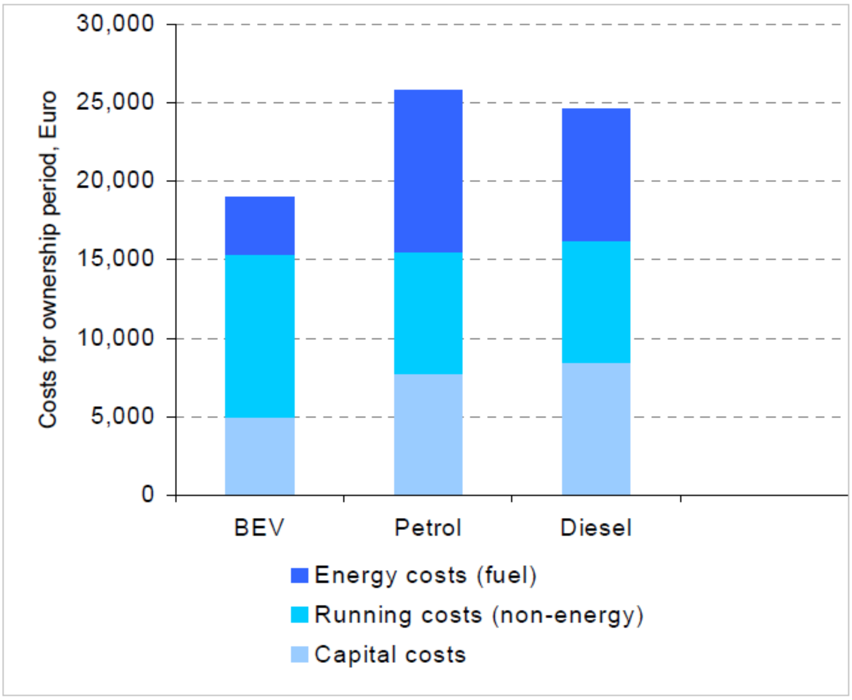

Figure 2-2 Comparison of the costs of ownership of battery electric cars, petrol cars and diesel cars [21]

Because of the features of electric motors, EVs usually have smooth acceleration and deceleration [21].

2.1.3 The Limitations of EVs

The price of the EVs is more expensive than conventional cars. However, the price is expected to be cheaper in the future due to the development of manufacturing technique of batteries [22].

Although the EVs have less or zero emission in driving, the emissions may happen during the processes that the electricity being generated by fossil fuels. If the electricity is generated by renewable energy like wind power, the emission could be much less.

At present, the size of most EVs is small. And due to the limitations of the batteries, BEVs normally have limited driving distance [23]. And the charging infrastructures are not well established.

2.1.4 The Batteries of EVs

One of the key parts of EVs is the batteries. The technology of the batteries affects developing and promoting EVs vitally.

Table 2-1 Batteries used in EVs of selected car manufacturers [24]

Company	Country	Vehicle model	Battery technology
GM	USA	Chevy-Volt	Li-ion
		Saturn Vue Hybrid	NiMH
Ford	USA	Escape, Fusion, MKZ HEV	NiMH
		Escape PHEV	Li-ion
Toyota	Japan	Prius, Lexus	NiMH
Honda	Japan	Civic, Insight	NiMH
Hyundai	South Korea	Sonata	Lithium polymer
Chrysler	USA	Chrysler 200C EV	Li-ion
BMW	Germany	X6	NiMH
		Mini E (2012)	Li-ion
BYD	China	E6	Li-ion
Daimler Benz	Germany	ML450, S400	NiMH
		Smart EV (2010)	Li-ion
Mitsubishi	Japan	iMiEV (2010)	Li-ion
Nissan	Japan	Altima	NiMH
		Leaf EV (2010)	Li-ion
Tesla	USA	Roadster (2009)	Li-ion
Think	Norway	Think EV	Li-ion, Sodium/Metal Chloride

As shown in Table 2-1, the nickel metal hydride (NiMH) and lithium ion (Li-ion) are two main technologies of batteries being used. The NiMH batteries technology is more mature and most of HEVs use this kind of batteries. The Li-ion batteries have potential to obtain higher energy density. Most PHEVs and BEVs use Li-ion batteries and this kind of batteries will be more used [24].

The operating conditions like temperature, charging or discharging current, state of charge (SOC) could influence the performance of the batteries. The SOC is an important characteristic used in this project. It is defined as the remaining capacity of a battery.

$$SOC = \frac{\text{Remaining Capacity}}{\text{Rated Capacity}} \tag{E2-1}$$

The Rated Wh Capacity is defined as

$$\text{Rated Wh Capacity} = \text{Rated Ah Capacity} \times \text{Rated Battery Voltage} \tag{E2-2}$$

The Ampere-hour (Ah) capacity is the total charge that can be delivered from a fully charged battery being discharged [24].

Depth-Of-Discharge (DOD) is the percentage of discharged capacity. It can normally be up to 80%.

$$DOD = 1 - SOC \qquad \text{(E2-3)}$$

The high cost of manufacturing EV batteries leads the high price of the EVs. A cost target of 250 dollars per kWh has been set by the United States Advanced Battery Consortium [25]. It is hard to achieve this target and this price is still relatively high. However the study shows that the costs will be reduced by 2020 as seen in Figure 2-3.

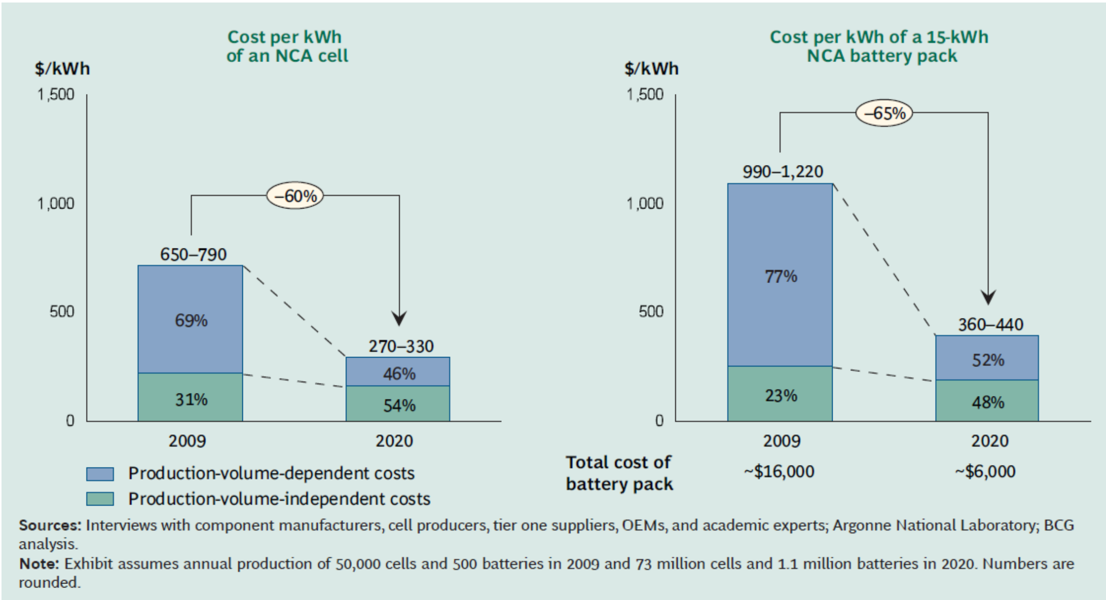

Figure 2-3 Battery cost will be reduced from 2009 to 2020 [25]

2.1.5 EVs in Denmark

A new Energy Agreement was made in Denmark in March 2012. It sets some ambitious goals of green energy development. The EV is an important role to help achieve these goals. The Danish transport sector mostly runs on fossil fuels nowadays. The investment of DKK 70 million will be used to establish more recharging stations for EVs etc. [26]. And DKK 15 million will be used to keep the pilot scheme for electric cars running [26]. The goal is to have 5,000 charging points and 200,000 EVs in Denmark by 2020 [27].

With more wind farms being built, more excess electricity would result and the electricity price would be low when the wind speed is high. EVs can store this surplus energy and benefit economically thus supporting a system with high wind penetration.

2.2 Issues with High Wind Power Penetration

Denmark has a long history of developing wind power since 1980s. Now the wind energy plays a critical role in Danish power systems. Over 20% consumption of electricity is generated by wind power, and the number is planned to be 50% in 2020 [8]. There were 5052 wind turbines in Denmark until May 2010, with a capacity of 3545 MW [28]. The Figure 2-4 shows the increase of the wind power capacity from 1990 to 2011.

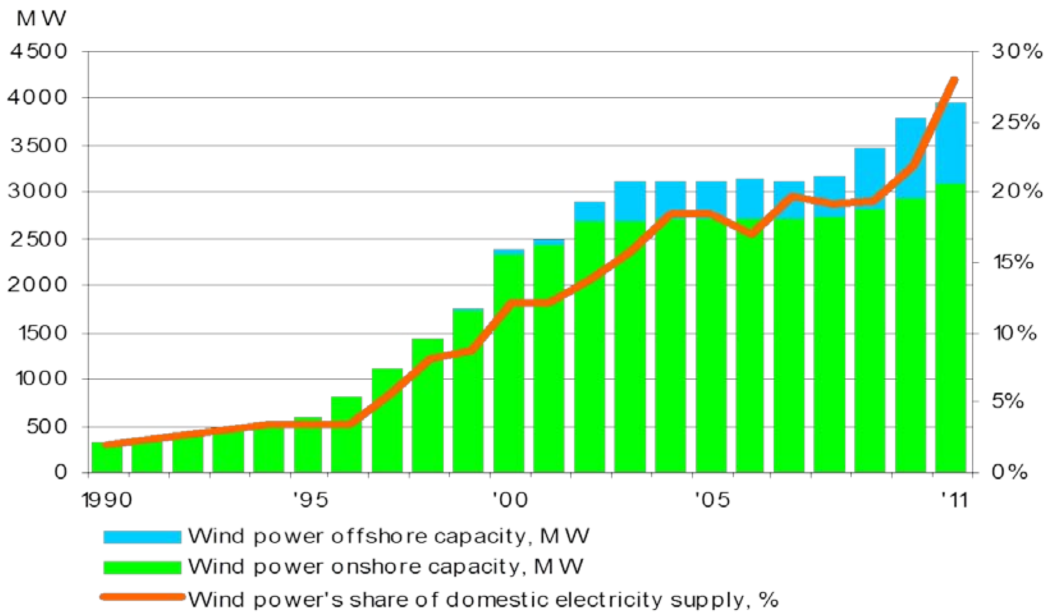

Figure 2-4 Wind power capacity and wind power's share of domestic electricity supply [29]

From the figure it can also be seen that the capacity of offshore wind power increased rapidly these years. To achieve the 50% in 2020, 2000 MW wind power needs to be established. 1500 MW will come from offshore wind farms [28].

In the windy days, the production of wind power could be very high. The exceeded power need to be exported to neighbour countries. Meanwhile the price of the electricity could be extremely low. In days with low speed wind and high demand of consumption, the price of the electricity could be high. Figure 2-5 shows the power systems in Denmark. It is a windy day in March 2013. The power generated by wind turbines is up to 4,002 MW which is more than 80% of the actual electricity consumption. A large amount of power is exported to Sweden and Norway. It can be said that the power system with high wind power penetration is dependent on neighbour countries. The communication and cooperation between these countries are essential to keep the whole grid operating stably and efficiently.

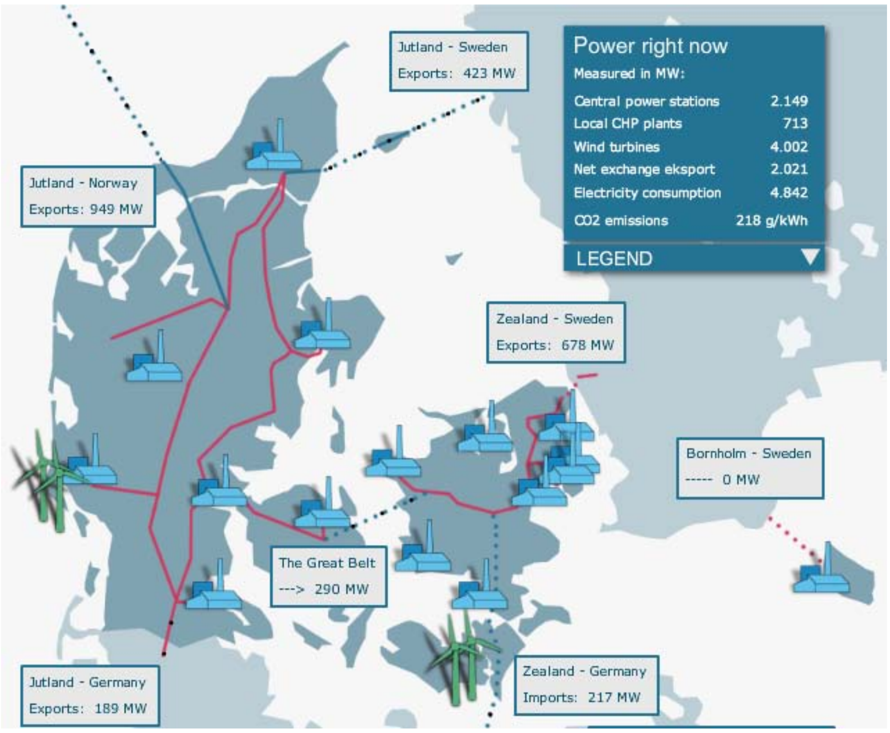

Figure 2-5 Power Systems in Denmark [30]

With the data from energinet.dk, the curves of Elspot electricity price can be plotted. Two days in summer and two days in winter are picked to be compared. From Figure 2-6 and Figure 2-7, several features can be observed: Both in summer and winter, when the windy day comes, the electricity price gets lower; Sometimes when the wind goes strong and the demand of consumption is low, the price could even go below zero; Despite the fact that the consumption is normally higher in winter than summer in Denmark, because of the high production of wind power, the electricity price in winter can be lower than in summer; During one day, the price within off-peak time is much lower, which creates the great opportunity to apply planned charging of EVs.

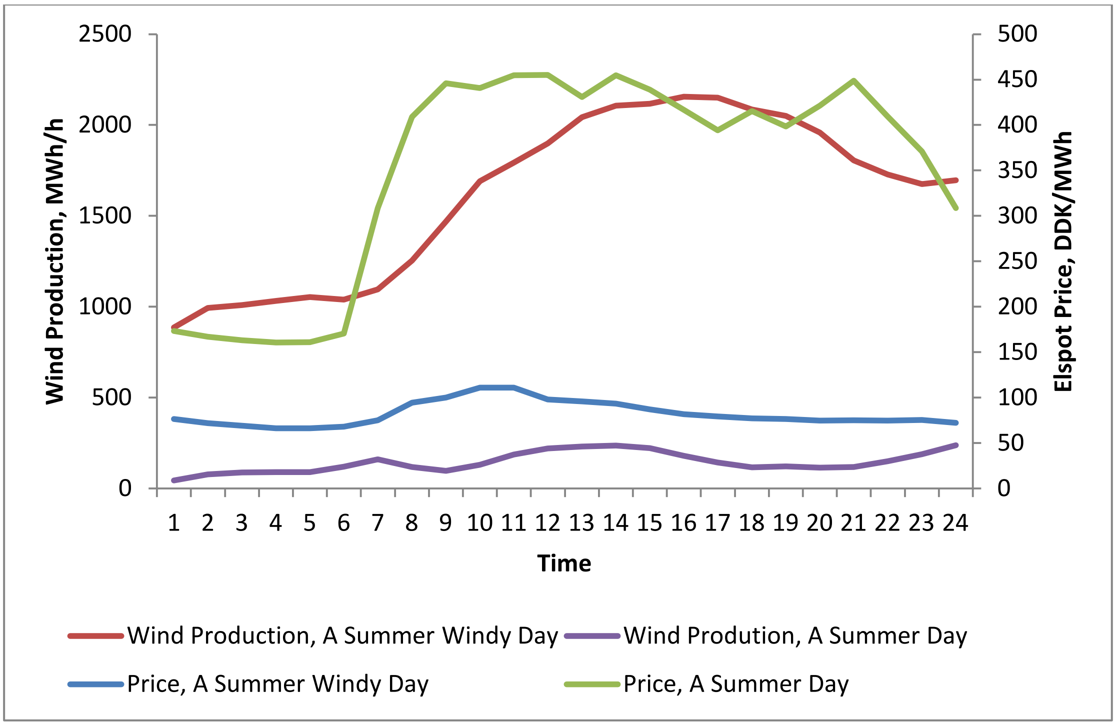

Figure 2-6 The Elspot price in two summer days related to the wind power production

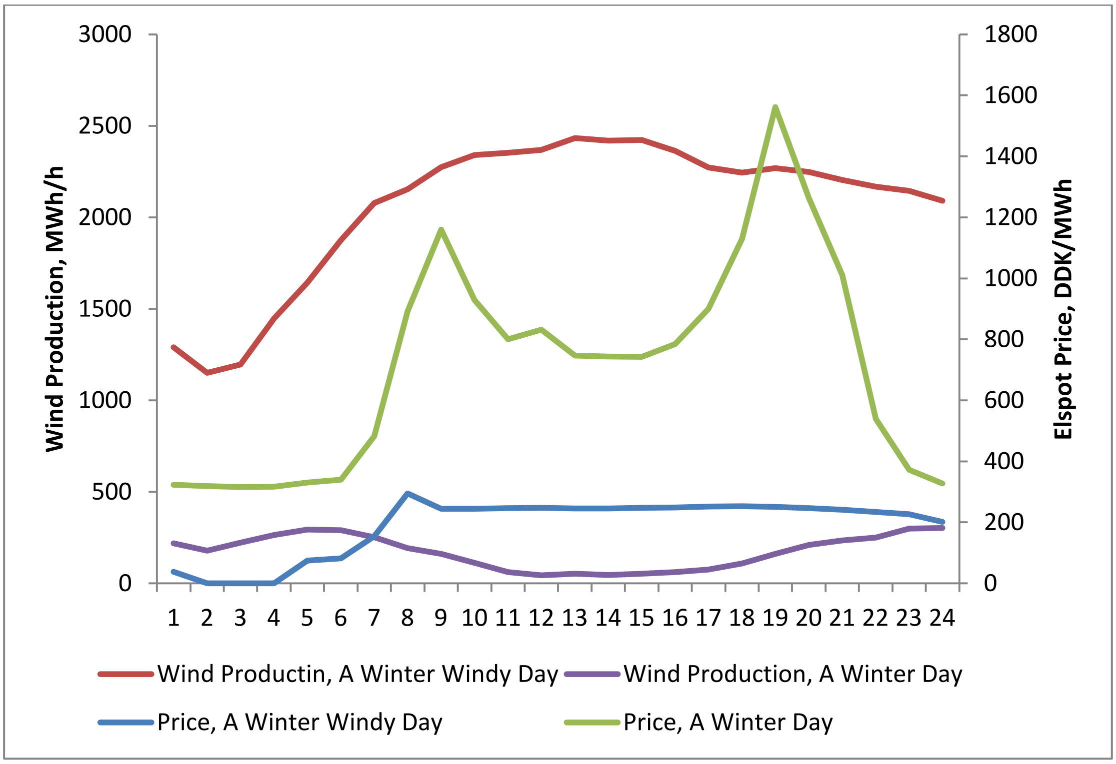

Figure 2-7 The Elspot price in two winter days related to the wind power production

There will be much more wind power production exceeded during the windy days in the future. EVs are considered as a solution to solve the problems caused by high wind power penetration in the grid. Since lots of EVs are new large loads in the grid. They can cause troubles of stability and availability in present distribution grid. Proper charging plan are essential to maintain the stable operation of the grid.

2.3 The Electricity Markets in Denmark

As mentioned before, Danish power system is dependent on neighbouring countries for balancing the grid with high wind power penetration. Denmark, Sweden, Norway and Finland found the Nordic electricity market. The border tariffs have been removed and a common power exchange has been established in this market [31]. The structure of the electricity market is shown in Figure 2-8.

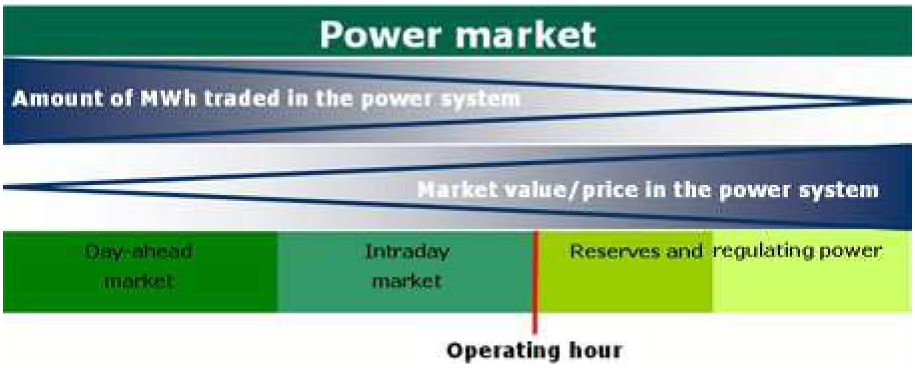

Figure 2-8 Structure of the electricity market [30]

There are several roles of players in the electricity market. Energinet.dk is the transmission system operator (TSO) which ensures the balance of the electricity system. They are doing grid planning and developing power system. They also develop rules and settings for the markets. Other players include balance responsible parties, electricity suppliers (local electricity trading companies), companies with a supply obligation, grid companies, the producer, end users with grid access and Nord Pool [30].

The electricity suppliers have contracts with the end user for the supply of electricity. The grid companies operate the distribution network and ensure the stability and quality of it. There are two market places for electricity trading: Elspot and Elbas. Trade is based on the auction principle on the Elspot. Nord Pool matches bids and offers once a day to calculate the market price [30]. When the Elspot is closed, the players can trade for balance on Elbas.

Regulating power and reserve capacity are needed to maintain the balance in the electricity system. The regulating power is purchased by Energinet.dk. Figure 2-9 and Figure 2-10 are generated by data from Energinet.dk. It can be seen that most of the days, when the wind power production is very high, the downward regulating power has been purchased. And when the speed of wind is low, the upward regulating power is needed.

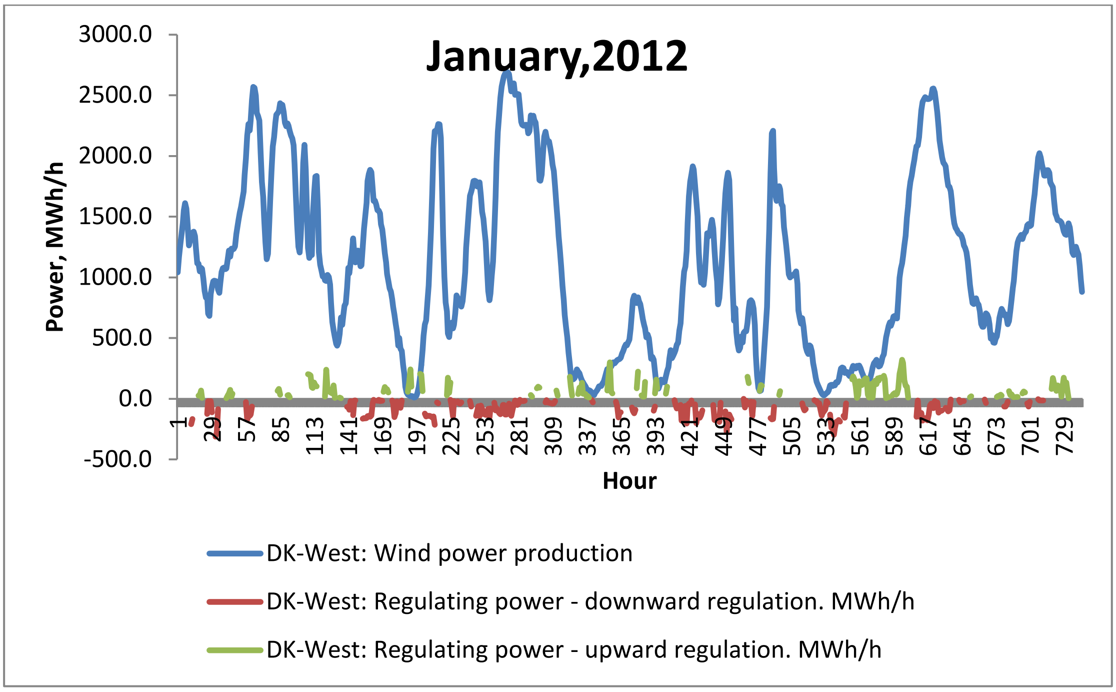

Figure 2-9 Wind power production and Regulating power in January 2012 [30]

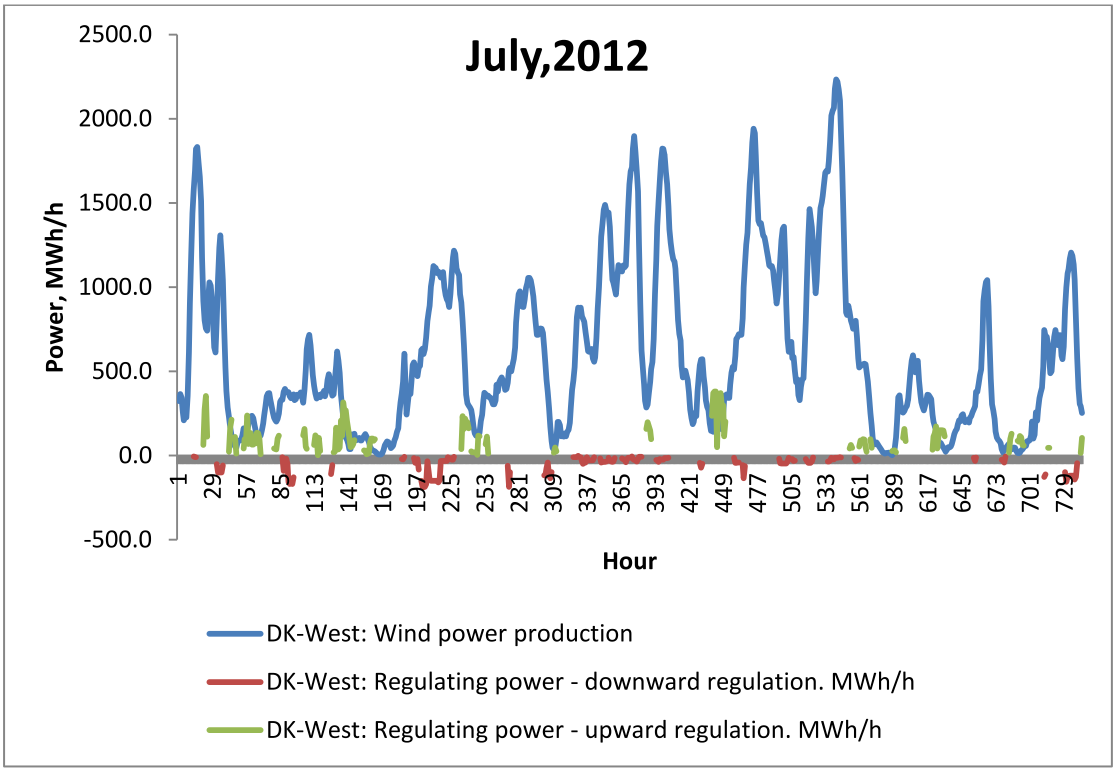

Figure 2-10 Wind power production and Regulating power in July 2012 [30]

With more wind power established in the next few decades, it can be predicted that the regulating power could be affected more by wind production. Denmark is committed to build the Smart Grid system. In this system, users like EV owners have opportunities to participate in the regulating market. This project is not involved in this kind of ancillary services.

The demands of consumption are the main concern of this project. The price of the electricity normally becomes low during the off-peak time of consumption. And the high wind power production could also decrease the price of the electricity.

2.4 Architecture of the Project

To accommodate the increase of electricity consumption, Denmark is promoting the Smart Grid. The basic concept of this grid is to make the system more intelligent with information and communication technology. It can create opportunities to integrate more wind power, along with more EVs in the grid.

The Smart Grid could allow consumers to participate in regulating market and consume electricity more flexibly and economically. For instance, charging the EVs when the price of electricity is cheap. The Smart Grid could also reduce the stress in the distribution grids [32]. Figure 2-11 shows a picture of the Smart Grid proposed by Energinet.dk.

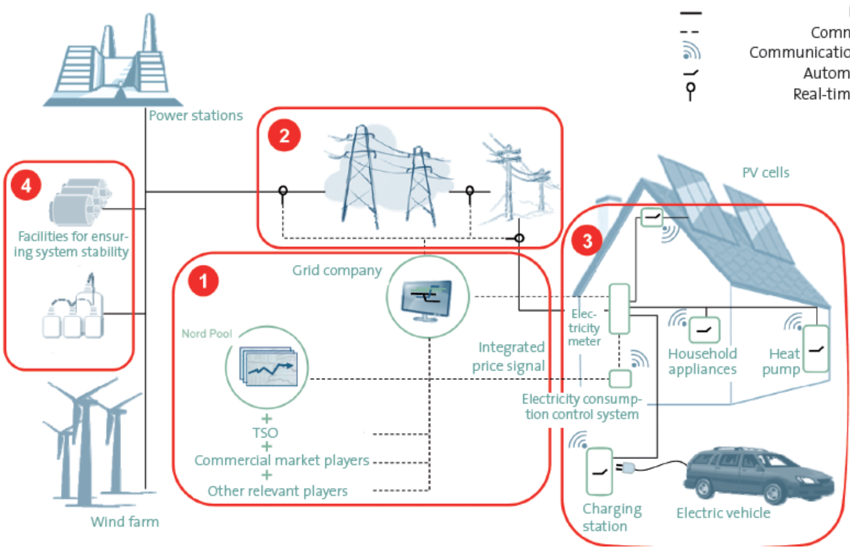

Figure 2-11 Danish Smart Grid [32]

At present, the hourly price of spot market is available one day ahead. However, the electricity companies nowadays cannot use price signals to optimize the charging plan. About 3.2 million consumers do not respond to hourly price signals [33].

In the future, the aggregator of fleet operators could form a key part to develop flexible charging systems of EVs. A large number of EVs can be aggregated by aggregators as a whole in order to bid in the markets. Individual meters allow the consumers to minimize their charging cost by charging at off-peak time of the electricity demand. And aggregators can also develop charging strategies to benefit economically and support the wind power systems properly.

Based on the scheme of the Smart Grid, the architecture has been proposed to be used in this project in Figure 2-12. The customers have contracts with the aggregator. The aggregator sends a plan of electricity demand for next day to TSO. The electricity is traded in the Nord Pool market. The DSO consolidates the data of the electricity consumption of the customers and sends to the TSO. The unbalances between real consumption and planed consumption can be bought or sold from the TSO [34].

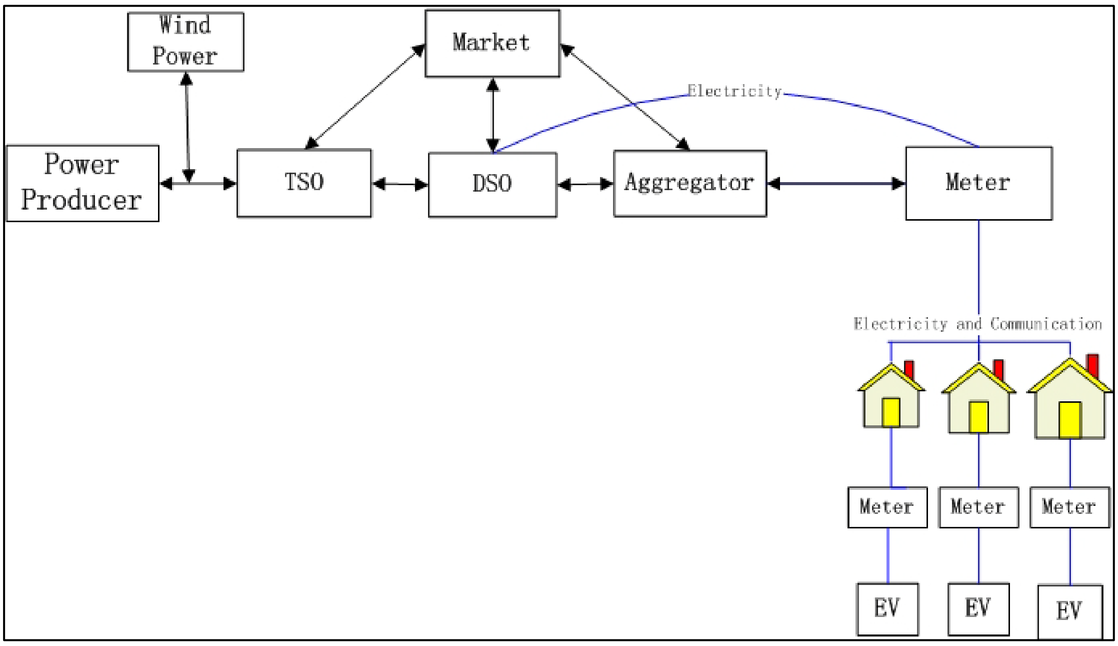

Figure 2-12 A proposed architecture for this project

The charging schedule can be provided by aggregators for distribution grid EV users. The goal is to minimize the cost, stable the grid and support large wind power production. The aggregators can collect the data of individual customers of EVs, while the individuals can also receive the hourly price of charging. Aggregated houses and EVs as one could also have opportunities to trade in new market which could be regulating power market.

The two possible general scenarios of EV charging methods can be established in this architecture.

Scenario 1:

The customers charge their EVs whenever they want. Normally the EVs start to charge as soon as they get home. This may cause a few problems. First, the low price time is normally at midnight. It is inconvenient for EV owners to plug in their cars at that time. Second, a large number of users could probably charge their cars at very same time. This may cause bottlenecks in distribution grid.

Scenario 2:

The aggregators control the charging. Individuals have their EVs plug in when they get home. The aggregators make a plan to decide the charging time and charging power. Customers can sign an agreement with aggregators. Aggregators will make sure the battery is charged to fulfil the demand driving distance before next morning. While minimize the cost to a low level. In this way, the stability of grid is normally ensured.

3 Analyses on the Distribution Grids

3.1 Introduction of the Distribution Network

It can be seen in Chapter 2 that Danish power system penetrated with high amounts of wind power is suitable for promoting EVs. The price of EVs may reduce and the EV battery technology may be developed future. Denmark has established an ambitious goal to promote EVs. The possibility of participating in balancing the grid could benefit owners of EVs. These facts could lead to a massive increase of number of EVs in next decade.

In this project, the maximum of charging power of EVs is 11kW. The owners of EVs normally return home by evening and leave in the morning. And the electricity price at midnight is relatively low. So the charging plans can be made to charging the EVs during the off-peak time (22:00-07:00).

In order to analyze the impact of EVs on distribution grid, the base cases are designed in this chapter. The grid available from [35] is shown in Figure 3-1. The tools to analyzing are DIgSILENT and Matlab.

This is a radial type network with five feeders. Each feeder has different structure so they can be compared. Three phase connections are used in this project. The power factor is considered as 0.95. There are 75 houses in this distribution grid. Each house is assumed to have one EV. That means there are 75 EVs in total in this network.

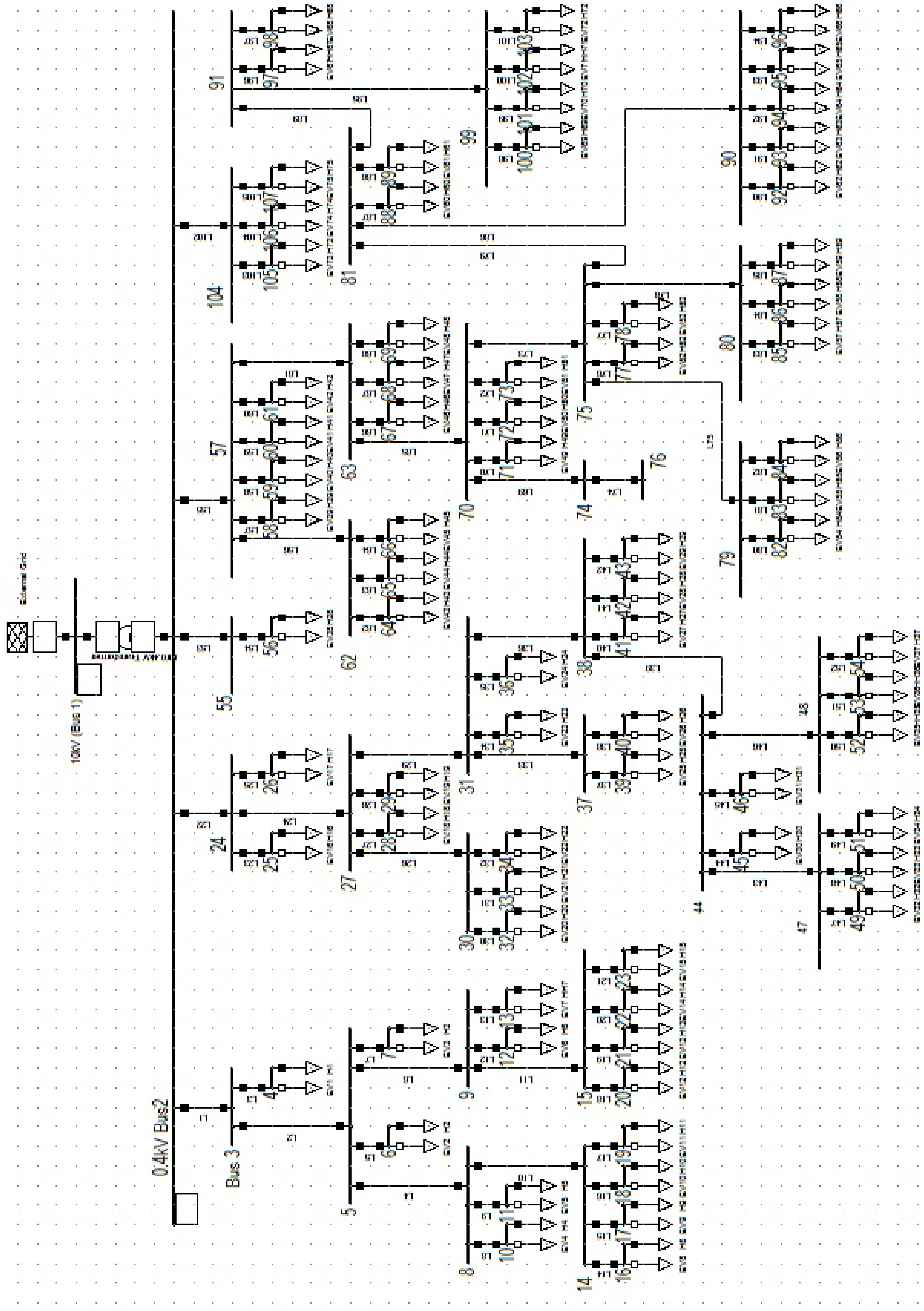

Figure 3-1 Distribution Grid used in this project

Table 3-1 and Table 3-2 show some parameters of this distribution grid.

Table 3-1 Parameters of the Three Phase Transformer

Rated Voltage	10kV / 0.4 kV
Rated Power	0.4 MVA
Nominal Frequency	50Hz
Short-Circuit Voltage uk of Positive Sequence Impedance	4.45%
Copper Losses of Positive Sequence Impedance	4.721kW

Table 3-2 Parameters of some selected lines

Name of Lines	L3, L30, L20, L35, L40, L45, L13, L21, L23, L25, L27, L28, L34, L48, L49, L50, L54, L59, L62, L67, L71, L77, L8, L81, L82, L83, L84, L9, L91, L94, L97, L98, L12, L38, L41, L44, L5, L15, L31, L37, L68, L7, L87, L90, L16, L18, L76, L17, L42, L103, L51, L58, L66, L80, L92, L96, L19, L70, L47, L100, L101, L60, L85, L93, L52, L64, L57, L14, L104, L105, L32, L72, L88, L99, L63
Parameters	Rated Voltage: 1kV, Rated Current: 0.075kA, Resistance R': 1.81Ohm/km, Reactance X': 0.094Ohm/km, Resistance R0': 7.24Ohm/km, Reactance X0': 0.378Ohm/km
Name of Lines	L2, L79, L73, L1
Parameters	Rated Voltage: 1kV, Rated Current: 0.21kA, Resistance R': 0.3208Ohm/km, Reactance X': 0.07539822Ohm/km, Resistance R0': 1.2833Ohm/km, Reactance X0': 0.3015929Ohm/km
Name of Lines	L89, L33, L102, L26, L74, L6, L69, L86, L10, L46, L95, L56, L61, L11, L4, L78, L75
Parameters	Rated Voltage: 1kV, Rated Current: 0.14kA, Resistance R': 0.6417Ohm/km, Reactance X': 0.07853982Ohm/km, Resistance R0': 2.5667Ohm/km, Reactance X0': 0.3141593Ohm/km
Name of Lines	L22, L53, L39, L29, L24, L43, L65, L36, L55
Parameters	Rated Voltage: 1kV, Rated Current: 0.27kA, Resistance R': 0.2075Ohm/km, Reactance X': 0.07225663Ohm/km, Resistance R0': 0.83Ohm/km, Reactance X0': 0.2890265Ohm/km

The load demand of each house is different. Also the consumption of one house differs from every hour, and from summer to winter. In Denmark, the load demand in winter is normally higher than it is in summer, due to the using of lightning etc. See data from [35] in Appendix B.

In Figure 3-2 the load demands are plotted based on data in Appendix B. It is clearly seen that the consumption of electricity in winter is much more than in summer. And in a typical winter weekday, the load demand can go up to the highest. Based on this data, four base cases are discussed to see the behaviours of the distribution grid.

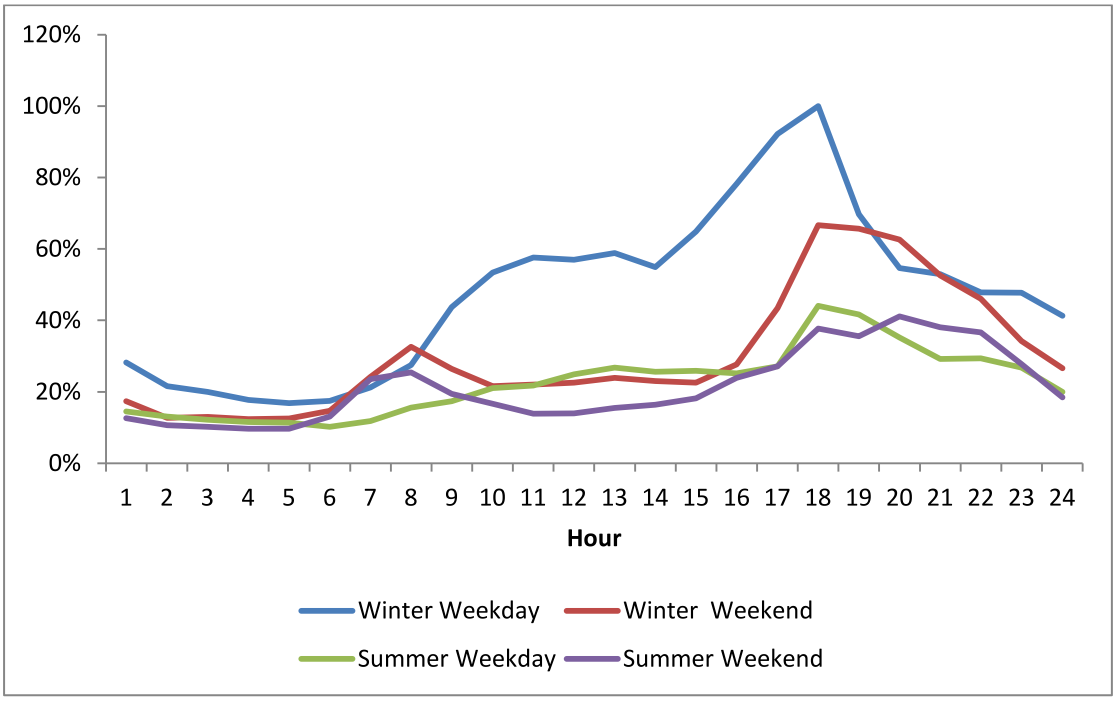

Figure 3-2 Total basic load for 75 houses

3.2 Base Case Analyses

The base case is established to see the influence caused from EVs on the operation of the distribution grid. There are four main scenarios based on the season and weekday/weekend. In each scenario, the number of connected EVs will be assumed to see that how many EVs can be supported by the network. And different time periods will also be considered, since the load demands can distinctly differ. The Matlab coding is made to do the analyses. The constraints in the simulations are: $0.94 \leqslant V \leqslant 1.06$, Loading$\leqslant$100% [36]. The maximum charging power of the EVs is 11kW. All the buses are numbered in the five feeders: Feeder

1(Bus 3 to Bus 23), Feeder 2(Bus 24 to Bus 54), Feeder 3(Bus 55 to Bus 56), Feeder 4(Bus 57 to Bus 103), Feeder 5(Bus 104 to Bus 107).

3.2.1 Case 1: Summer Weekday

Scenario 1: Summer Weekday, without EVs connected

Using the load demand curve in Figure 3-2, the load flow calculation is done in Matlab for 24 hours without EVs. The peak demand 44.0909% happens from 17:00 to 18:00.

In the Figure 3-3, the X axis is bus number, and F1 represents Feeder 1 and so as F2 to F5. The same feeder division (F1: Bus 3 to 23; F2: Bus 24 to 54; F3: Bus 55 to 56; F4: Bus 57 to 103; F5: Bus 104 to107) is used in all figures of following scenarios. The total load is 47.653kW. It can be seen that the voltage drops to the lowest at the end of each feeder. However, without EVs, even in the highest load demand situation, the voltage drop is acceptable for the grid. The lowest voltage happens at the end of Feeder 4 which is around 0.98pu. From this figure it can be said that the Feeder 4 may have less ability to support EVs. Too many branches cause the voltage drop. So in further analyses Feeder 4 is put into account for improving.

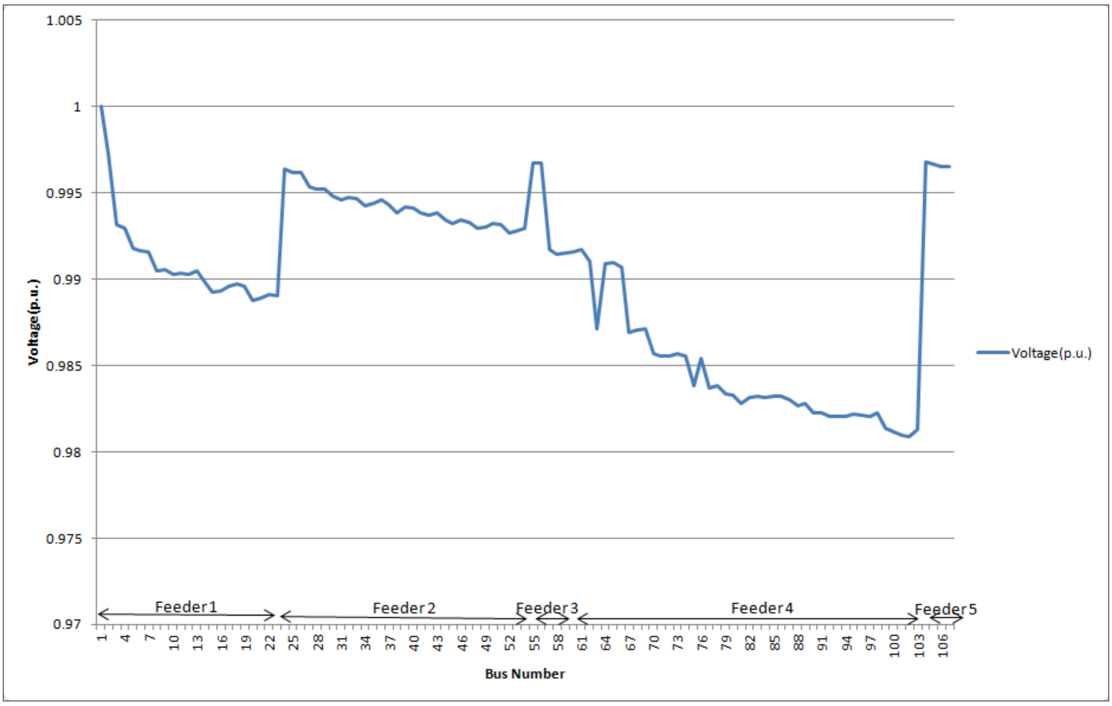

Figure 3-3 Bus voltage during 17:00 to 18:00 on summer weekday (without EVs)

The Bus 103 at the end of Feeder 4 is selected to see the voltage drop during a whole summer weekday. As seen in Figure 3-4, the curve of voltage corresponds to the load demand curve. The voltage drops most heavily around 17:00 to 18:00.

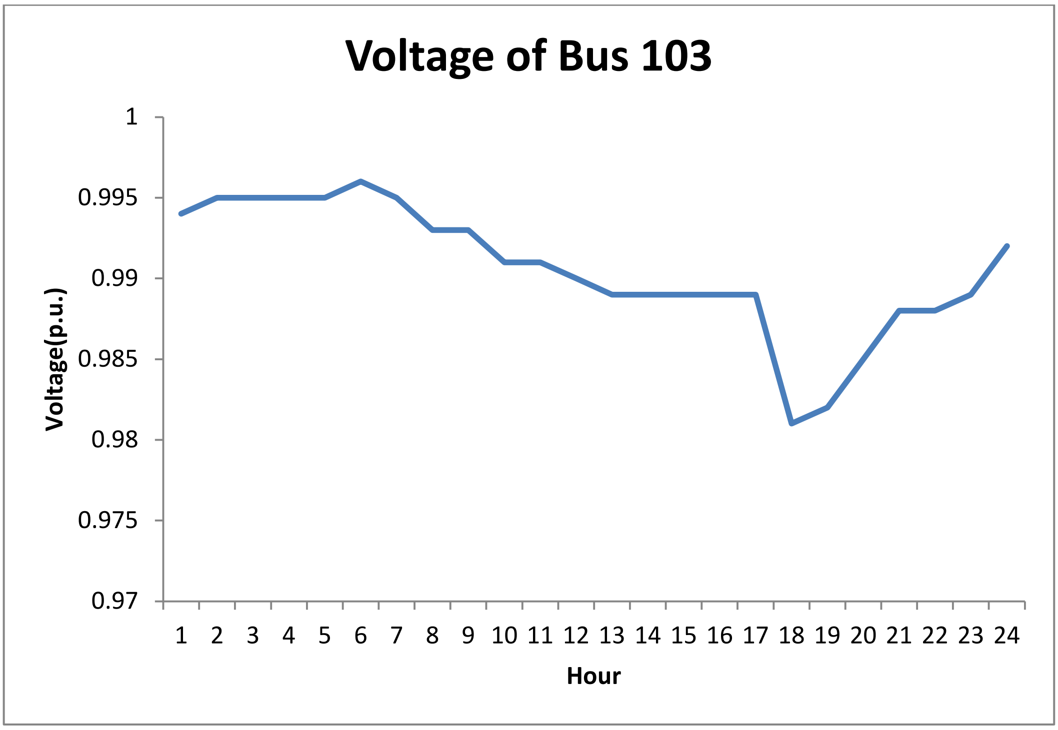

Figure 3-4 Voltage of Bus 103 in Feeder 4 on Summer Weekday (without EVs)

Scenario 2: Summer Weekday, with EVs connected, 11kW

It can be predicted that it is not realistic to connect all the EVs to the grid at 11kW charging power. The total load will exceed the capacity of the transformer. In this scenario, the number of EVs that the grid can support is 22, as shown in Table 3-3. The voltage can be seen in Figure 3-5. In this case there are total 22 EVs (29.33% of total EVs), and 6 EVs (15% of total EVs in Feeder 4) in Feeder 4.

The Feeder 4 can only support about 15% EVs at this period. This indicates it is the weakest feeder of all five feeders.

Table 3-3 22 EVs are connected to the grid, summer weekday

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5
Bus No. connected with EVs	6 10 13 16	25 28 32 33 40 41 45 51 52	56	58 59 65 66 83	105 107
Total number of Houses	15	22	1	34	3
Number of connected EVs	4	9	1	5	3
Percentage of connected EVs	27%	41%	100%	15%	100%

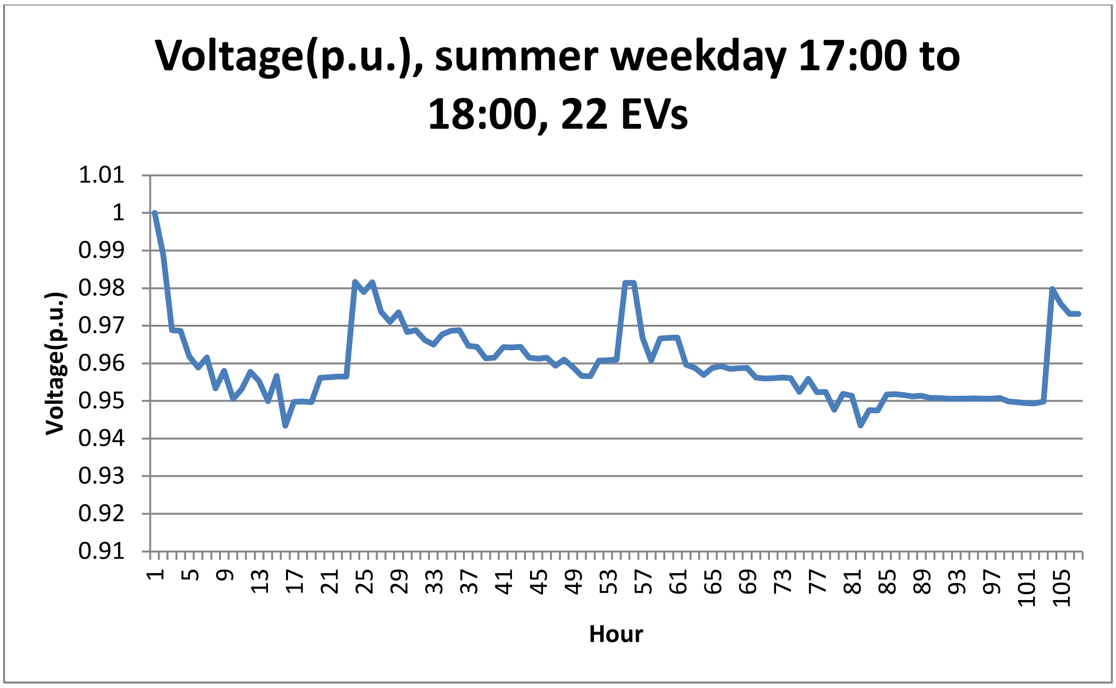

Figure 3-5 Bus voltage (pu), summer weekday 17:00 to 18:00, 22 EVs, 11kW

Scenario 3: Summer Weekday, with EVs connected, 5kW

The average driving distance in Denmark is 42.7 km [37]. Assuming every kilometre requires about 0.15kwh, 6.405kwh is needed for such distance. The available time for charging at night is normally several hours long. So the EVs can charge at a lower power than 11kW to meet the demand. In this scenario, 5kW is taken into account to analyze the network.

In scenario 2, 22 EVs with 11kW charging power can be put into the grid at peak time. Now the charging power is reduced to less than half which is 5kW. Doubling the number could be a reasonable assumption. The structure of connection is shown in Table 3-4. Figure 3-6 shows that the voltage of a few buses at the end of Feeder 4 is closed to 0.94pu. So in this case the Feeder 4 still cannot support more than 50% EVs, while other feeders can nearly support all the EVs. It can be also seen that reducing the charging power is a proper plan to allow more EVs charging at the same time.

Table 3-4 41 EVs are connected to the grid, summer weekday

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5
Total number of Houses	15	22	1	34	3
Number of connected EVs	8	18	1	11	3
Percentage of connected EVs	53%	82%	100%	32%	100%

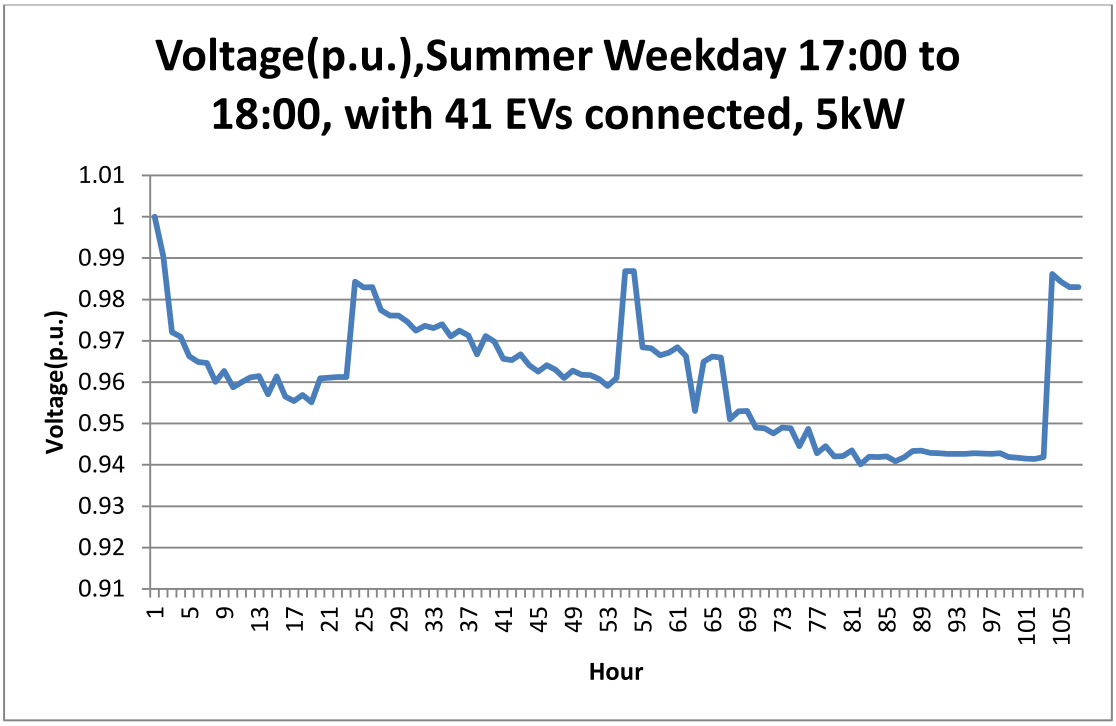

Figure 3-6 Voltage (pu),Summer Weekday 17:00 to 18:00, with 42 EVs connected, 5kW

3.2.2 Case 2: Summer Weekend

Scenario 4: Summer Weekend, 5kW in Feeder 1, 2, 3, and 5, 2kW in Feeder 4

From Figure 3-2 it can be observed that the load curve in summer weekend is similar to summer weekday. Only from 06:00 to 10:00, there is a ridge of wave indicating some more consumption. It could be caused by more activities like doing laundry, cooking and cleaning in the weekend morning. It could be predicted that most of the time of the day, the ability to support EVs is similar to summer weekday.

In Case 1 there is evidence demonstrating that Feeder 4 is weaker than others in supporting EVs. In this scenario, the charging power is reduced to 2kW in Feeder 4 to see the improvement of the grid. The peak time of load demand is 19:00 to 20:00 in this case, which is 41.1136%.

The simulation in Scenario 3 shows that the Feeder 4 can support 11 EVs at 5kW charging. Since the charging power is reduced to 2kW which is less than 50% of 5kW in this Feeder, 24 EVs are connected to the Feeder to observe the voltage. In Figure 3-7, it is shown that Feeder 4 can support 24 EVs (all the bus voltage is above 0.94pu), if the charging power is 2kW.

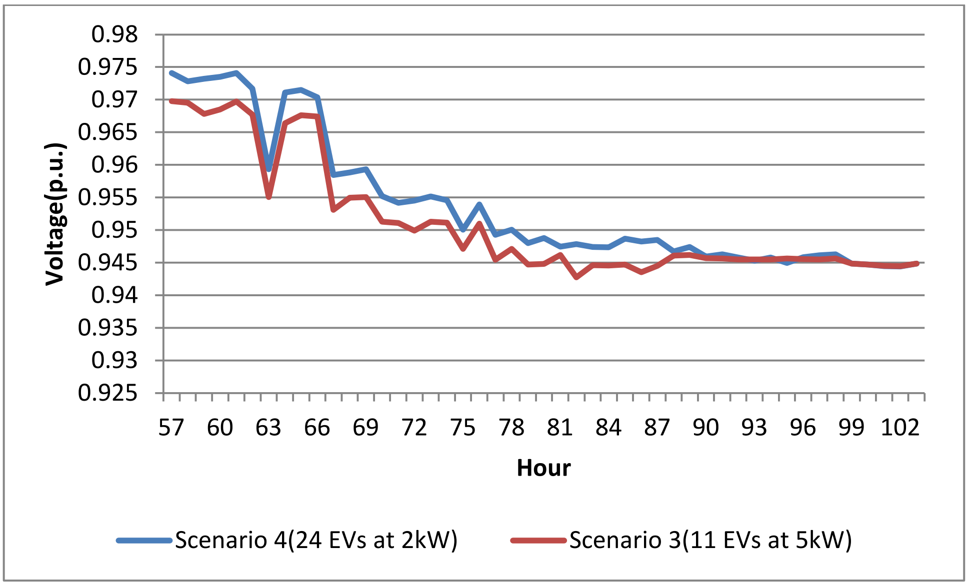

Figure 3-7 Comparison of voltage in different charging power in Feeder 4

From this simulation, it can be seen that without reforming the network, simply controlling the charging power could achieve the goal to charge many EVs at the same time. Even in

Feeder 4 which is weaker than other feeders, there is possibility to charge all the EVs at peak time in summer.

3.2.3 Case 3 Winter Weekday

Scenario 5: Winter Weekday, 11kW

The charging power is up to 11kW. In order to meet the constraints, the number of EVs has to be reduced to 21. Figure 3-9 shows the possible number of EVs supported by each feeder. It can be observed that Feeder 2 is relatively stronger than Feeder 1 and 4. Which means Feeder 2 can support more EVs at the same time with same charging power.

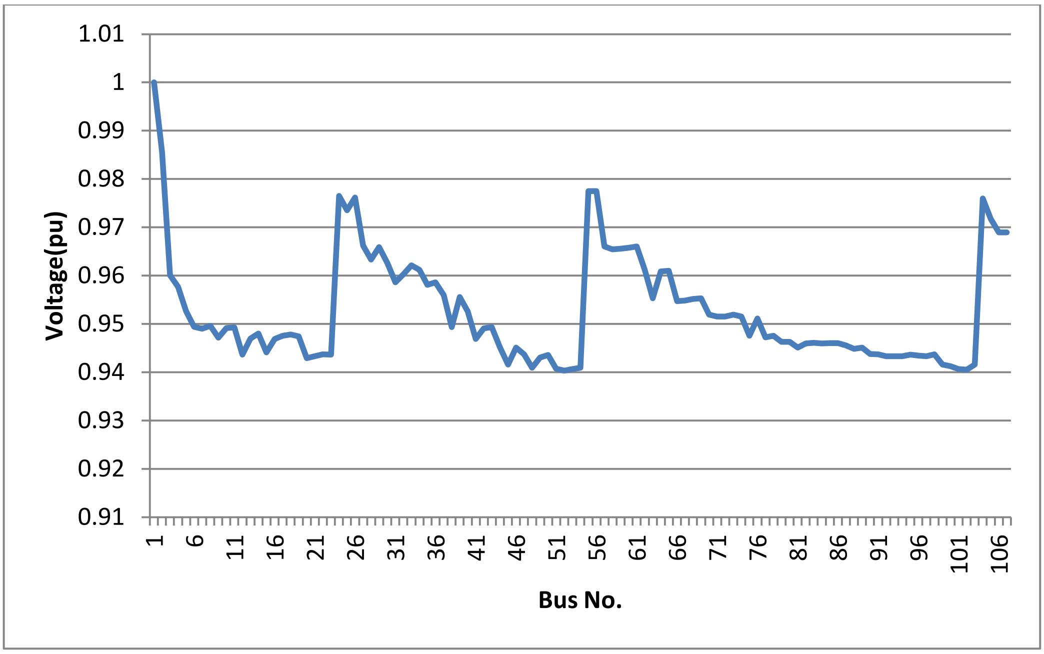

Figure 3-8 Bus voltage at peak time on a winter weekday, 11kW

Table 3-5 21 EVs are connected to the grid, winter weekday

	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5
Total number of Houses	15	22	1	34	3
Number of connected EVs	4	11	1	2	3
Percentage of connected EVs	27%	50%	100%	6%	100%

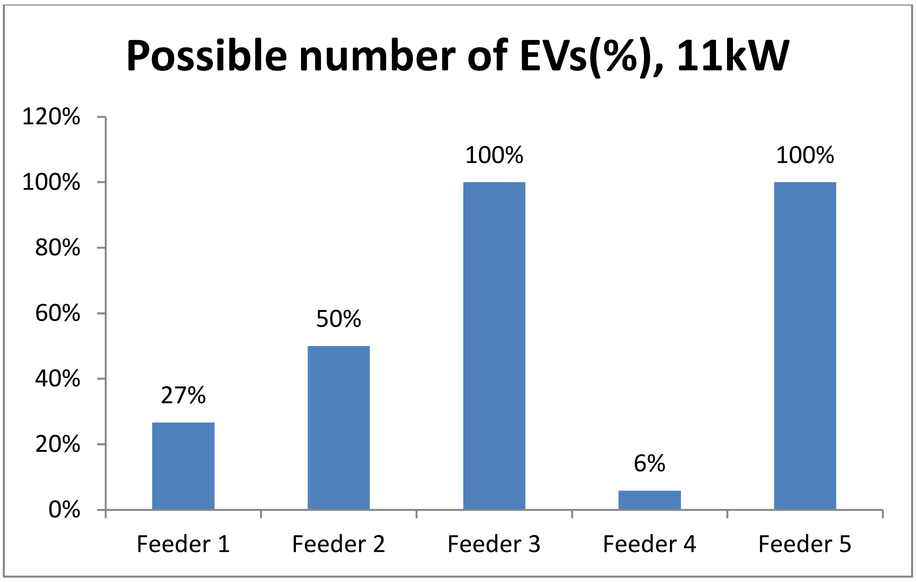

Figure 3-9 Possible number of EVs, 11kW

3.2.4 Case 4 Winter Weekend

Scenario 6: Winter Weekend, 11kW, whole day

At most of the time, the load demand on a winter weekend is lower than a winter weekday. So the number of EVs can be supported is expected to be the same or a little more. In this scenario, Bus 103 is chosen to observe the voltage variation in a whole day. The number of EVs connected to the grid is 21 (2 EVs in Feeder 4) as in Scenario 5. The voltage drops to 0.956 during the time 17:00 to 18:00. From the curve it can be seen that the off peak time has less pressure of voltage drop. Therefore, the charging time is more suitable to be arranged to the time from 22:00 to 07:00.

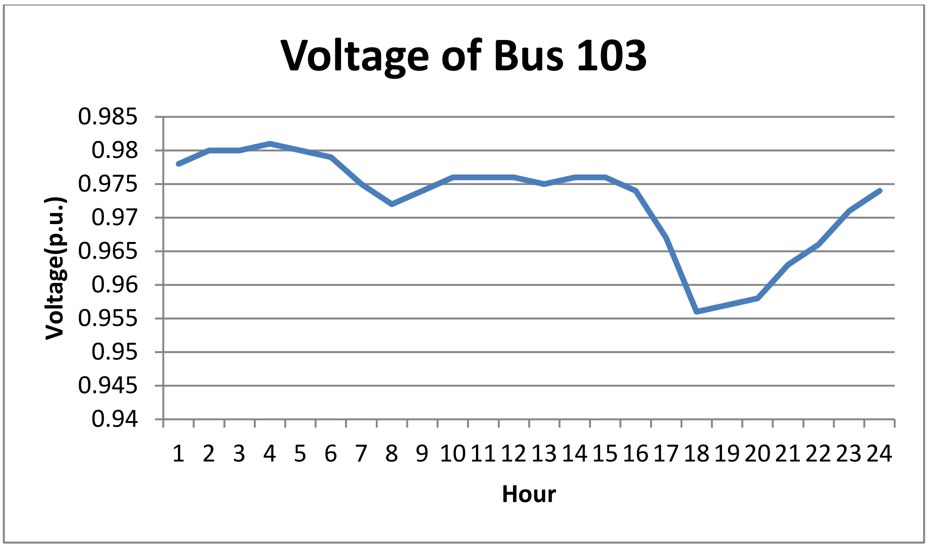

Figure 3-10 Voltage of Bus 103, Winter Weekend

3.2.5 Summary of the scenarios

The base loads of houses are different between summer and winter. And they also differ between weekday and weekend. The 6 scenarios are set to investigate the ability of the grid to support EVs in different time of electricity demands.

Scenario 1 obtains the voltage distribution of the grid without EVs connected. The result indicates that the feeder 4 is weaker than other feeders. In scenario 2, 22 EVs are connected to the grid charging at 11kw. The simulation has proved that Feeder 4 can support less EVs than others. Scenarios 3 and 4 have made the attempts to increase the number of charging EVs. By reducing the charging power, more EVs can be charged at the same time.

Scenario 5 is set in the most critical condition for charging EVs. The consumption of the electricity in winter is much higher than in summer. The base load of houses during the peak time winter weekday is 100%. In this case, the Feeder 4 can only support 2 EVs which is 6% of the total houses in this feeder. And it cannot support any EVs at the bottom of the feeder.

3.3 Load and Line Loss

The limitation of the loading is based on the capacity of the transformer which is 400kW. In scenario 1, 30 EVs of 11kW charging power, the active load is 388.653. Although the voltage of many buses in this scenario is even below 0.9pu, the loading is still not exceeded. So it can be concluded that the loading is not the main limitation of the grid. The overall load and line loss is shown in Table 3-6.

Table 3-6 Load of the transformer and Loss of the Grid

	Load (kW)	Load (kvar)	Line Loss (kW)	Line Loss (kvar)
S1 Summer Weekday	47.653	12.119	0.452	0.324
S2 Summer Weekday 30EVs 11kw	388.653	12.119	28.583	22.385
S2 Summer Weekday 22EVs 11kw	300.653	12.119	11.749	12.093
S3 Summer Weekday 42EVs 5kw	257.653	12.119	9.503	9.064
S5 Winter Weekday 35EVs 5kw	283.08	27.487	11.066	11.232
S6 Winter Weekday 22EVs 11kw	350.08	27.487	15.356	17.16

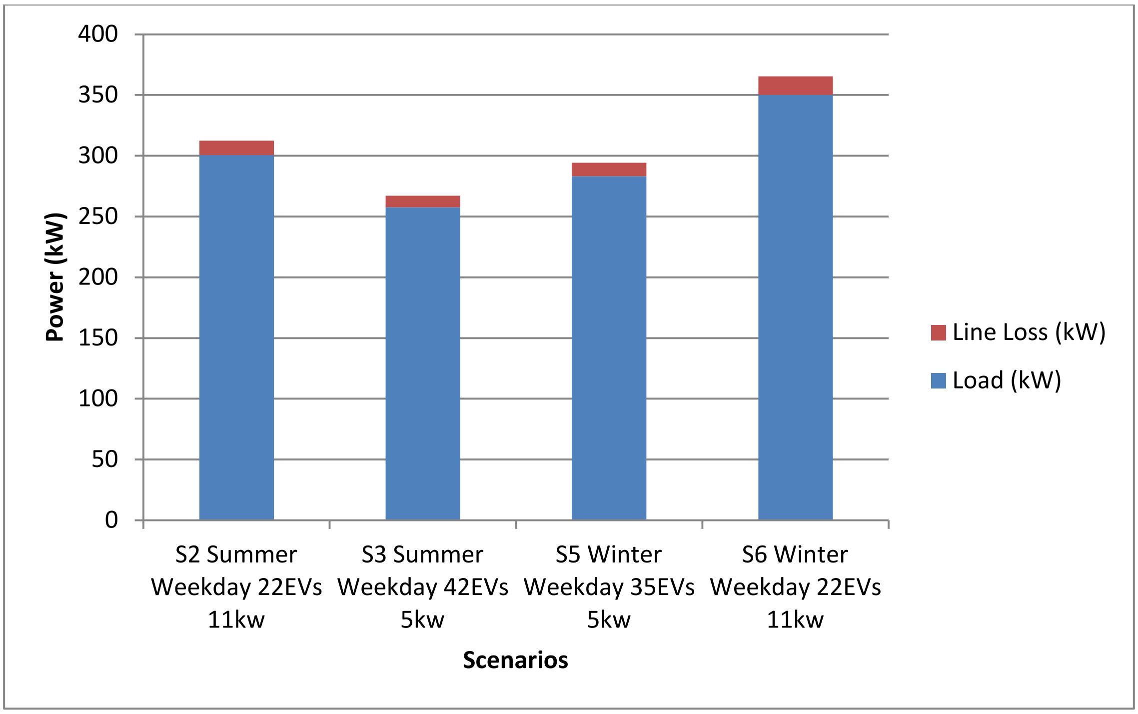

Figure 3-11 Comparison of Load and Loss

Figure 3-11 is the comparison of the load and loss in different scenarios. All these 4 scenarios meet the voltage requirement. It can be observed that the line loss is a small part compared to the total load. And the loss does not differ much between different scenarios with different load.

Based on the analyses above, rather than the load and loss of the grid, the voltage will be the main characteristic to analyze.

Three critical lines are selected to be compared. They are the first line of Feeder 1, Feeder 2 and Feeder4. The loading of these three lines are presented in Figure 3-12. The L22 has the most critical loading stress of the three. This is because that Feeder 2 supports 11 EVs which is 50% of total in this condition.

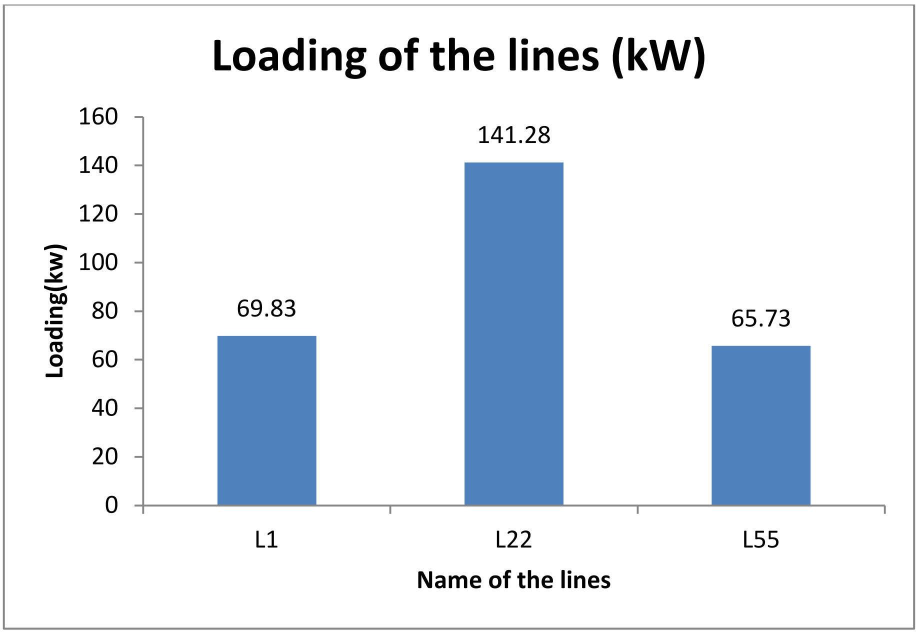

Figure 3-12 Loading of the lines, winter weekday, peak time

3.4 Feeder Reformation to Improve the Behaviour of the Grid

In the section 3.2, 7 scenarios have been analyzed to observe the behaviours of the network with integration of EVs. It can be seen that Feeder 2 is stronger than other feeders for supporting EVs, while Feeder 4 is weaker. The possible reason for Feeder 4 to be weak is that it has too many levels of branch feeders, so the impedance of this feeder is much bigger than other feeders.

The thought is to divide the Feeder 4 into two new independent feeders. It may improve the ability of supporting EVs. As shown in Figure 3-13, the blue line is created to connect Bus 81 directly to the main Bus 2. In that way, two new feeders, called Feeder 4_1 and Feeder 4_2, are established from original Feeder 4. The parameters of the new blue line are shown in Table 3-7. The length of the line is calculated by summing four lines nearby (0.217km, 0.072km, 0.073km, 0.079km).

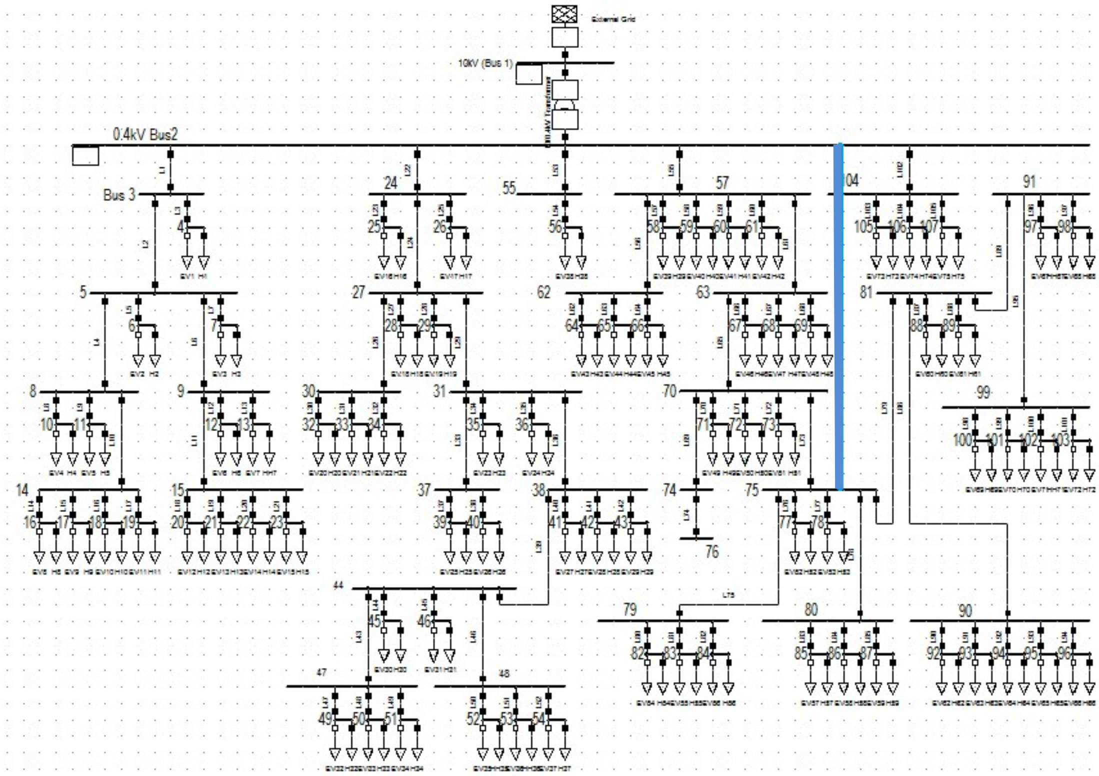

Figure 3-13 Divide Feeder 4 into two new feeders

Table 3-7 Parameters of the new blue line

Length(km)	Resistance R'(Ohm/km)	Reactance X'(Ohm/km)	Resistance R'(pu)	Reactance X'(pu)
0.441	0.2075	0.07225663	0.132079699	0.045993417

In Scenario 5, peak time on winter weekday, the network can only support 2 EVs at front part of Feeder 4. In this new network, 12 EVs is put into the grid at the same position. Figure 3-14 reveals the distinct improvement after the division of Feeder 4. It can be said that new Feeder 4_1 and 4_2 could support more than 12 EVs at the same condition (peak time on winter weekday). The reformation is done by setting a new line.

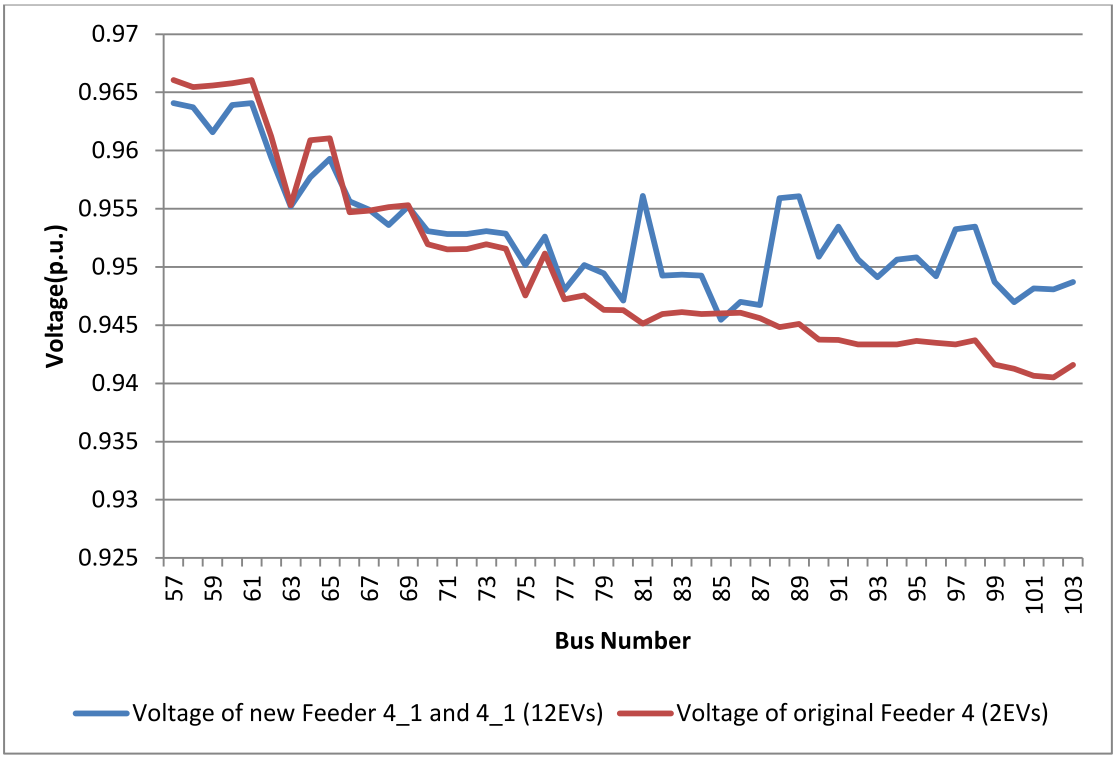

Figure 3-14 Comparison of new grid and original grid

3.5 Conclusion

In this chapter, the operation of the distribution network has been analyzed. 6 scenarios are set due to the different load demands between winter and summer, weekday and weekend. The objective is to observe the ability of the grid to support connected EVs.

It can be concluded that in summer the grid can support more EVs than in winter, for the houses have more consumption in the winter. There are more needs for heating and lighting in the winter. Furthermore, there is more consumption during the weekdays than the weekends.

There are evidences to prove that Feeder 4 is weaker than the other feeders. It is a long feeder and the voltage easily drops at the end of the feeder. A solution to improve the behaviour of Feeder 4 is given. By splitting the Feeder 4 into two new feeders, the ability of supporting EVs is markedly improved.

The loading and loss of the grid are analyzed. They are not the main limitations of supporting EVs. The voltage is proved to be the main bottleneck of the distribution grid.

4 Stochastic Process of EV Integration

4.1 Introduction

In Chapter 3, the distribution grid has been tested with different scenarios. The charging time is chosen to be peak time. During this time, the load demands have extreme value that can be analyzed. The maximum charging power is 11kW, which has been used in some cases to see the ability of the grid to support EVs. Some charging power has been assumed, like 5kW and 2kW, to allow more EVs to charge at the same time. In [14] [15], some work of optimization has been done based on assumption of initial state.

In real life, the behaviours of EV owners could be complex. For instance, the driving distance of each EV differs from others; the time of leaving/arriving home is not the same; some families may have needs to drive a lot during weekends etc. Those are random behaviours which also can be predicted based on certain patterns. The patterns can be obtained by large number of survey.

Using those patterns, a stochastic process can be done to generate random data of EVs. This data can reflect the behaviours of EVs in real life. A model can be built on this stochastic process which could make the analyses of the network more realistic. Furthermore, a dumb charging plan based on the stochastic data could be made.

4.2 The Driving Pattern and the Available Charging Times

4.2.1 The Driving Pattern

The main charging places here are the houses of EV owners. The EVs are not considered to be charged at working parking lot or other charging station in this project. So the driving pattern mainly refers to the driving distance. The available charging times are the times during which the EVs are parking at home. Hence the times of EVs leaving/arriving home are essential to the case.

The cases studied in this project are based on Danish power system. Therefore the driving pattern has to be the transportation data of Denmark. There are based on three data bases [38]:

AKTA data (GPS-based data that follow the vehicles);

MDCars (Database of Odometer readings);

TU data (Danish National Transport Survey).

AKTA data are based on the data recorded by GPS with certain participated drivers. Hence, the accuracy of this data is quite high. However, there are only 360 cars in this data base, and the owners all live in Copenhagen [38]. So the samples can hardly represent the behaviours of the majority of car owners in Denmark. The MDCars data are from the collection of odometer data in cars. It has two years data for private cars [38].

TU data provided by Technical University of Denmark is a Danish National Travel Survey data. It was first conducted in 1975, and about 270,000 Danish car owners participated in the survey since 1992 [39]. The data contain 750,000 trip information with details [39]. The group of drivers, region, age, income and day of week are all collected in the survey. Through this data, a proper picture of driving pattern can be revealed. So this data base is used in this project to do the stochastic process.

The Figure 4-1 shows the distribution on transport means in Denmark in 2012. From both distance and times of trips sides, the travels by vehicles occupy the most part. Even though Denmark is well known with promoting bicycles, the vehicles are still the main transport means. Many families go to work by cars and the number of cars is growing. EVs analyzed in this project are seen having the similar behaviours as normal gasoline cars.

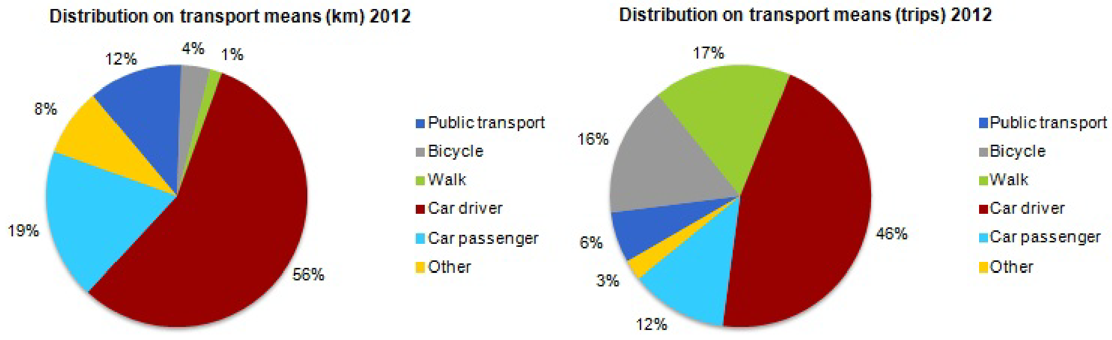

Figure 4-1 Distribution of transport means [40]

Table 4-1 presents the average driving distance in Denmark based on TU data. From this table it can be observed that the average driving distance of all days is less than 30km. This may differ from other countries like America. Since America has larger territory and drivers are expected to drive more distance. Relatively short driving distance is a suitable factor to promote EVs in Denamrk. Because the technique of EV batteries has limited the driving distance of EVs.

The other characteristic shown in Table 4-1 is that EVs tend to drive less on weekends and holidays. The reduction of driving distance at those times could be explained by reduction of work related travels.

Table 4-1 Average driving distance in Denmark [38]

	Average Distance(km)
All Days	29.48
Monday	28.39
Tuesday	31.57
Wednesday	32.19
Thursday	30.98
Friday	33.96
Saturday	26.48
Sunday	24.4
Holiday	18.9

The distributions of driving distance on weekdays, weekends and holiday are shown in Appendix C. Based on these data, the distributions of distance are plotted in Figure 4-2 and Figure 4-3.

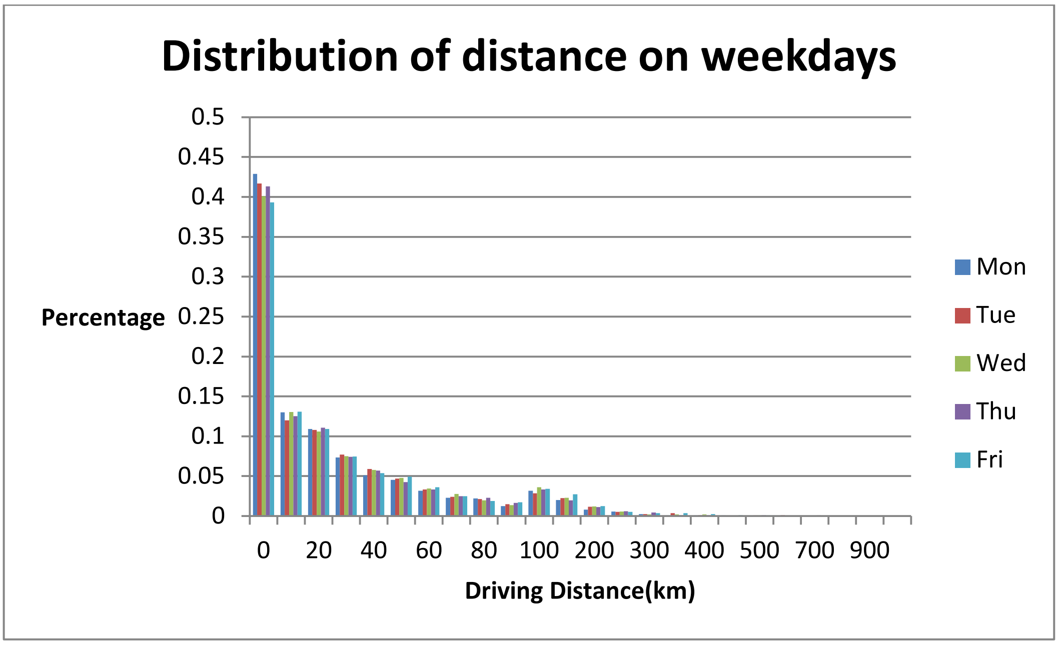

Figure 4-2 Distribution of driving distance on weekdays

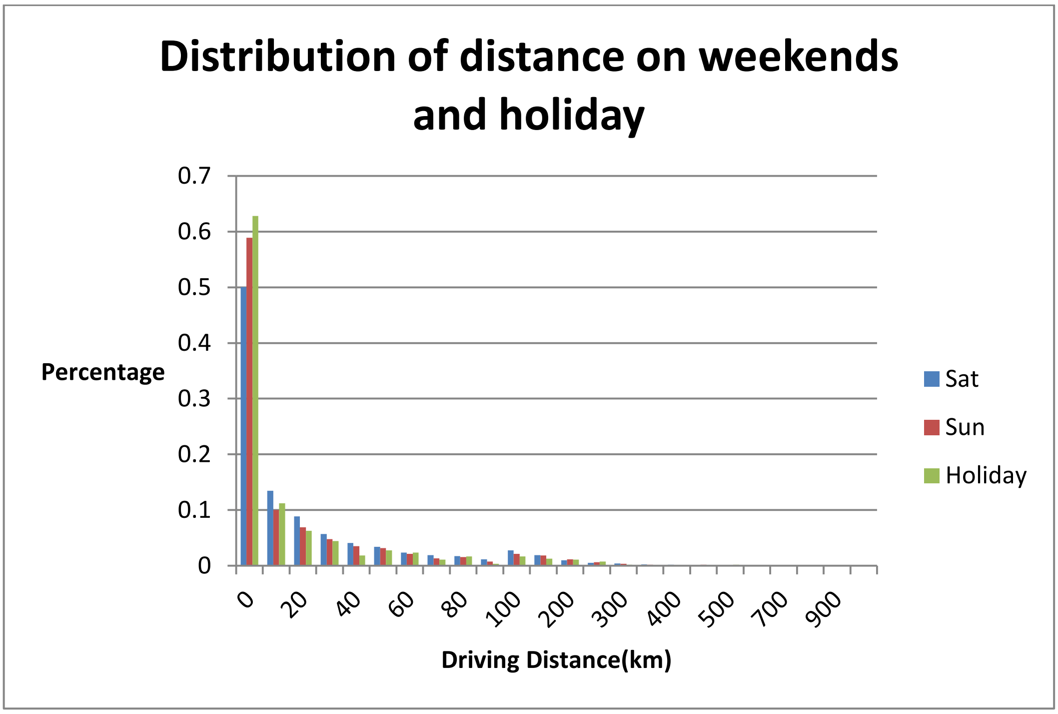

Figure 4-3 Distribution of driving distance on weekends and holiday

From the figures of distribution, the pattern of driving distance can be observed. Figure 4-4 can clearly show that nearly 80% cars drive 40km or less on Wednesday, based on the cumulative distribution curve. And even more cars drive relatively short distance during weekends and holidays.

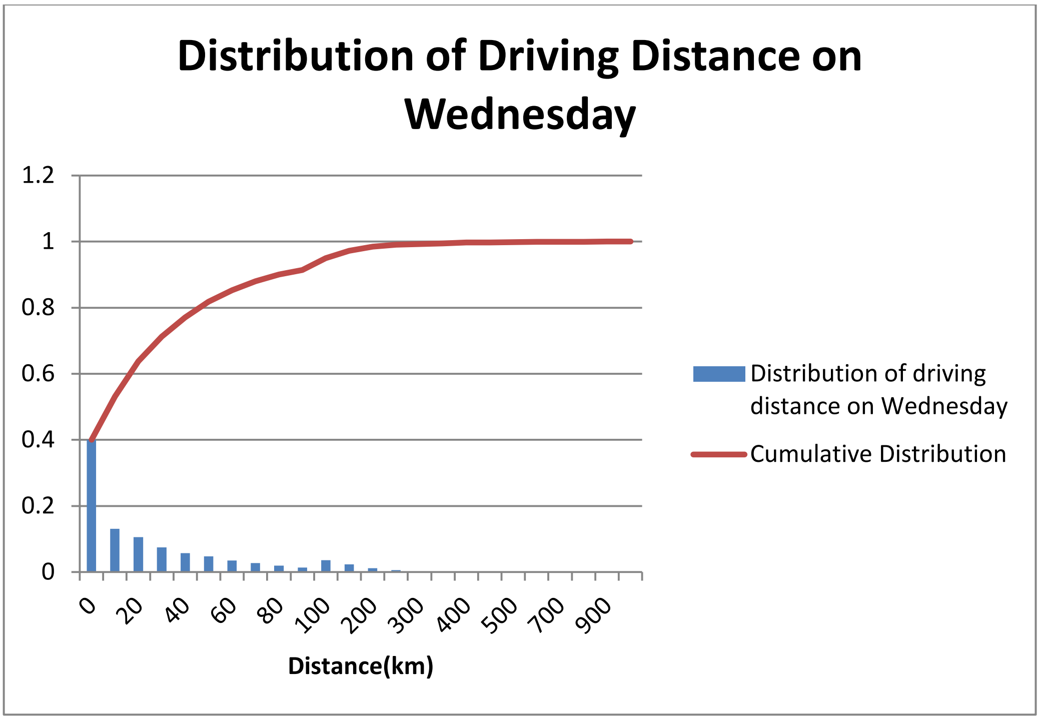

Figure 4-4 Distribution of Driving Distance on Wednesday

4.2.2 Available Charging Times

In this project, the charging times are the times during which the EVs are parked at home, since the distribution grid with houses is the main focus of this project. So the 75 EVs are not charged at office parking lots or charging stations in this project. However, those kinds of charging may be implemented in the future.

So the time between arriving home time of EVs at evening and leaving time next morning is considered as available charging time. As demonstrated in Figure 4-5, the area of green is the available charging time. So the arriving/leaving time is essential to this case.

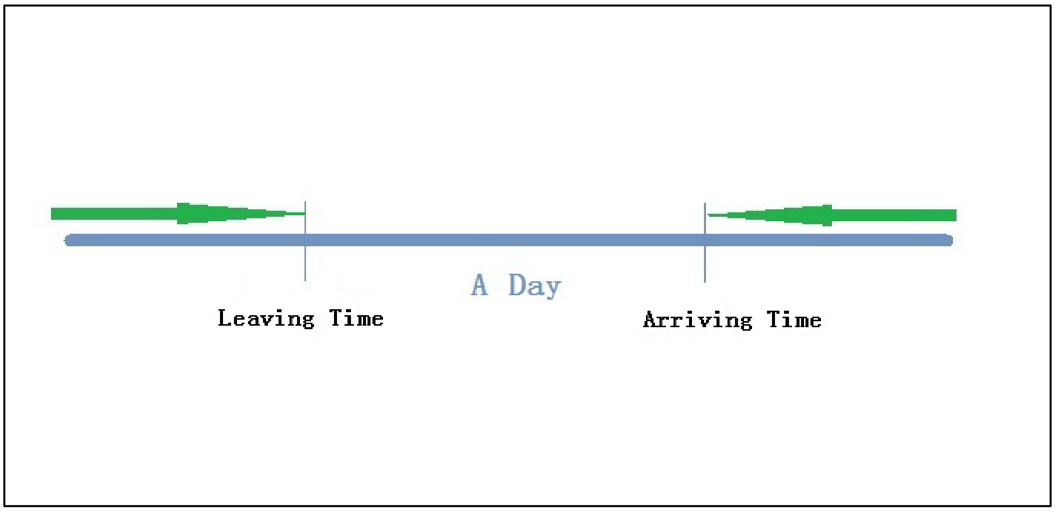

Figure 4-5 Available Charging Time

Normally, the arriving/leaving time of cars is similar in many countries, since most people work at day and get home by evening. The arriving time data in this project is from National Household Travel Survey (NHTS). The data are based on the survey of American vehicle users. Because of the similarity, it could be used in case of Denmark. The arriving data are plotted in Figure 4-6. It can be seen that many cars arrive home around 18:00.

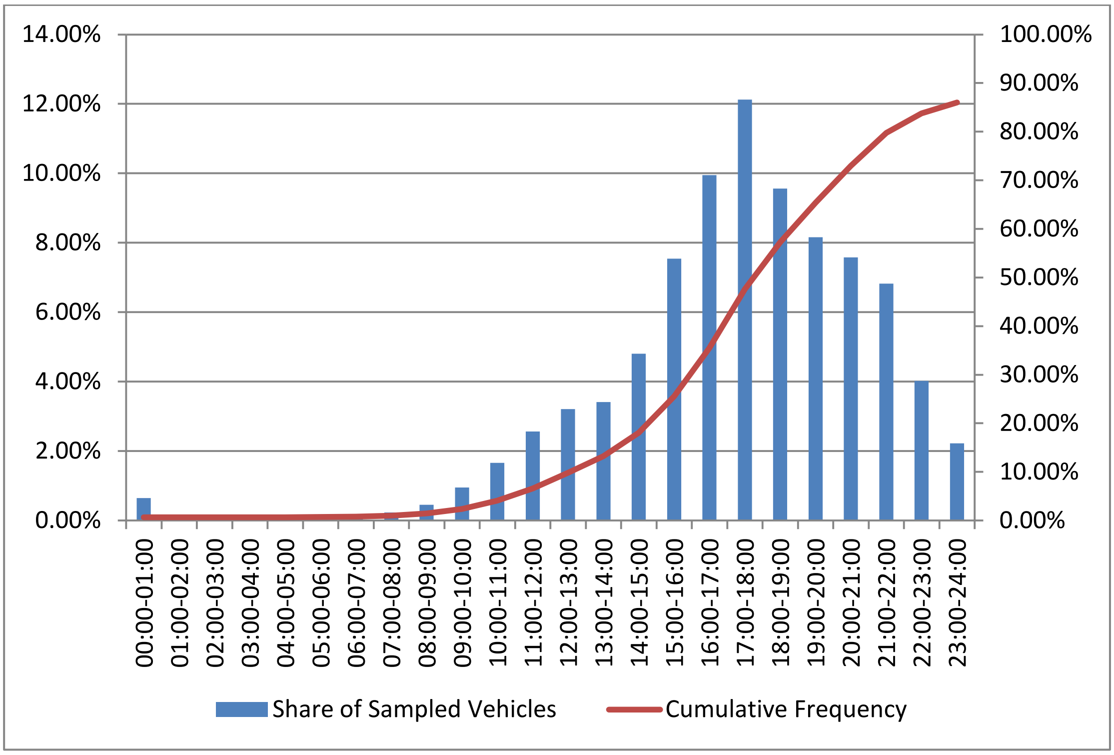

Figure 4-6 Arriving time [41]

In order to get the leaving time of EVs, the similar distribution shape is assumed. Move the ridge of wave of arriving time from 17:00-18:00 to 06:00-07:00 to present the peak of leaving time distribution. The departure time distribution is formed in Figure 4-7.

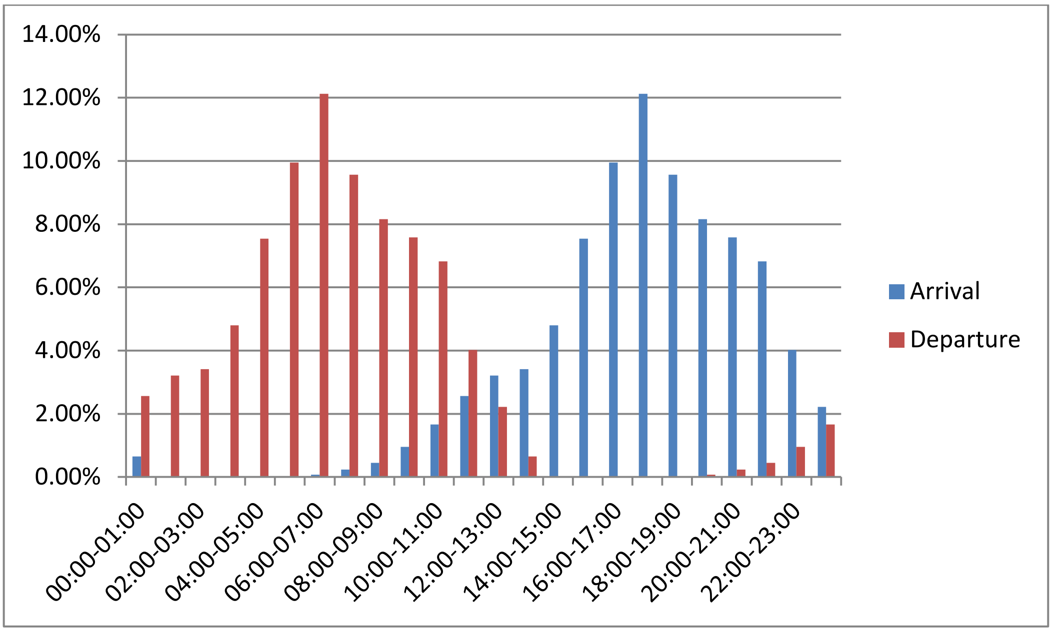

Figure 4-7 Distribution of Departure/Arrival Time

4.3 The Consumption Needed for EVs in the Grid

Electric vehicles normally are more efficient than petrol cars. The average consumption is 0.15-0.25kWh/km including the charging losses, while the petrol cars have to use equivalent at least 0.5 kWh to drive one kilometre [42]. Table 4-2 shows an example of consumption of 4 types of EVs. The FEV refers to Full Electric Vehicles, and the PHEV refers to Plug-in Hybrid Electric Vehicles.

Table 4-2 Example of consumption of EVs [42]

	Electricity consumption kWh/km	Trip on electricity km/year	Annual consumption MWh/year
FEV 0.25	0.25	17400	4.34
FEV 0.17	0.17	17500	2.97
PHEV 0.25	0.25	14100	3.53
PHEV 0.17	0.17	14000	2.38

In this project, the EVs are assumed to use 0.15kWh for one kilometre. Since the high efficiency is the tendency in the future. Thus the energy needed per day could be calculated by following formula:

$$E = 0.15kWh / km \times D \tag{E4-1}$$

where D is the distance(km) has been driven per day.

4.4 The Dumb Charging

Dumb charging is a charging method that allows EV owners to charge their EVs whenever they need. Normally the charging starts at the time they get home. When the EVs are plugged into the mains, the charging begins. And the charging power intends to be the maximum. In this case, the charging power could be 11kW. So the dumb charging is not controlled and planed. It could cause fluctuation in the distribution grid.

The dumb charging has some characteristics [43]:

1. Vehicles begin to charge as soon as plugged in. And normally keep being charged until full charge of the batteries;
2. The load variability in the distribution grid will increase because of the dumb charging;
3. The dumb charging normally does not participate in balancing the power system or V2G.

Many EVs nowadays use dumb charging, because it is convenient and fast. People are used to charge EVs till the batteries are full, like any other electric equipment. Dumb charging is important to network case study. The simulation of dumb charging could affect the ability and stability of the distribution grid to support EVs. A strong network should meet the requirements of dumb charging and minimize the jeopardizing caused by dumb charging.

A dumb charging plan will be made in this chapter based on the stochastic data.

4.5 The Stochastic Simulation

4.5.1 The Stochastic Process for Driving Distance and Available Charging Time

The main goal of this section is to use the driving patterns to obtain the stochastic data of energy demands and available charging times of the EVs. The energy demand is based on the driving distance. And the available charging time is between the arriving time and leaving time.

Normally the cars drive more distance during weekday. The consumption of electricity is also higher during weekdays than weekends. So in order to fulfil the daily driving requirements, a weekday like Wednesday is selected to be analyzed.

Driving Distance on Wednesday

Step 1: Use the distribution of driving distance to generate 500,000 samples of driving distance.

Step 2: Use the Distribution Fitting Tool in Matlab to plot the samples. See Figure 4-8.The Distribution Fitting Tool is a GUI which can be used to fit a distribution to the given data.

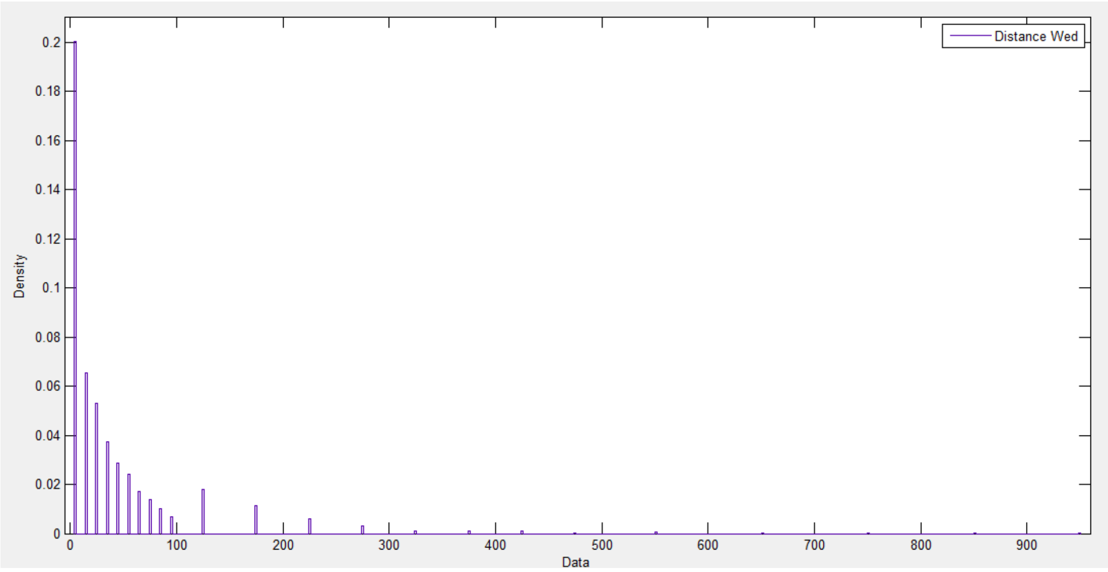

Figure 4-8 Samples of Driving Distance on Wednesday

Step 3: Use the New Fit tool to apply a fitted distribution. In this case, the Weibull distribution is used. See Figure 4-9. The parameters of the distribution are shown in Figure

4-10. For Weibull distribution, a=33.4061 and b=0.798717 are important parameters for next step.

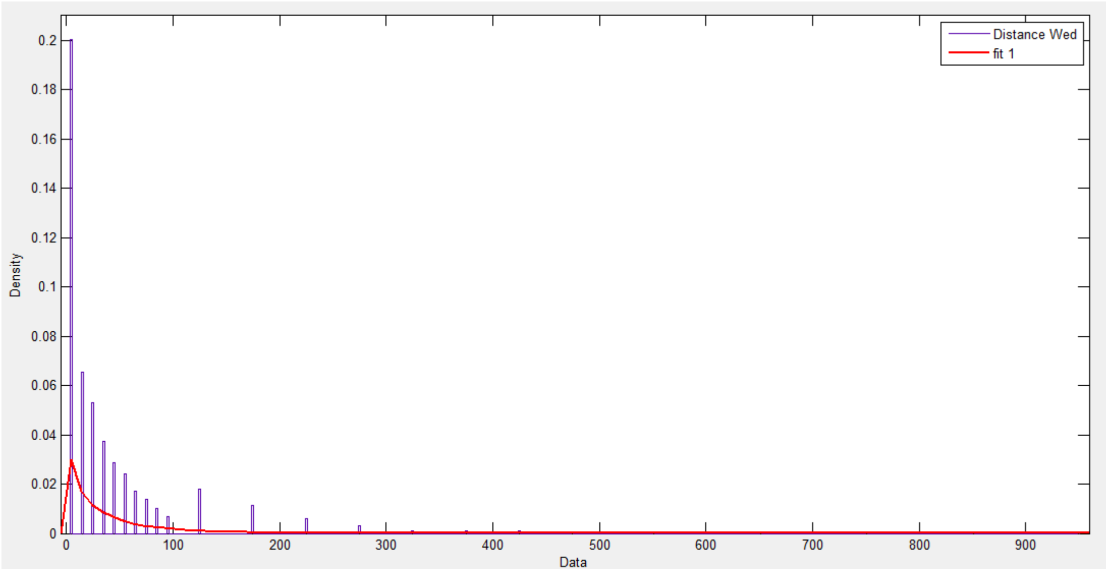

Figure 4-9 A fitted distribution

```
Distribution:     Weibull
Log likelihood:   -2.30367e+006
Domain:           0 < y < Inf
Mean:             37.9541
Variance:         2296.77

Parameter  Estimate   Std. Err.
a            33.4601     0.0629371
b           0.798717   0.000814691

Estimated covariance of parameter estimates:
   a              b
a    0.00396108   1.72906e-005
b  1.72906e-005   6.63722e-007
```

Figure 4-10 Parameters of new fitted distribution

Step 4: Using appropriate source code in Matlab to generated random data of driving distance for 75 EVs, with the parameters of new fitted distribution. Part of the code is shown in Appendix H. Figure 4-11 is the stochastic data of driving distance generated by the program. It can be seen that most EVs drive less than 50 km per day.

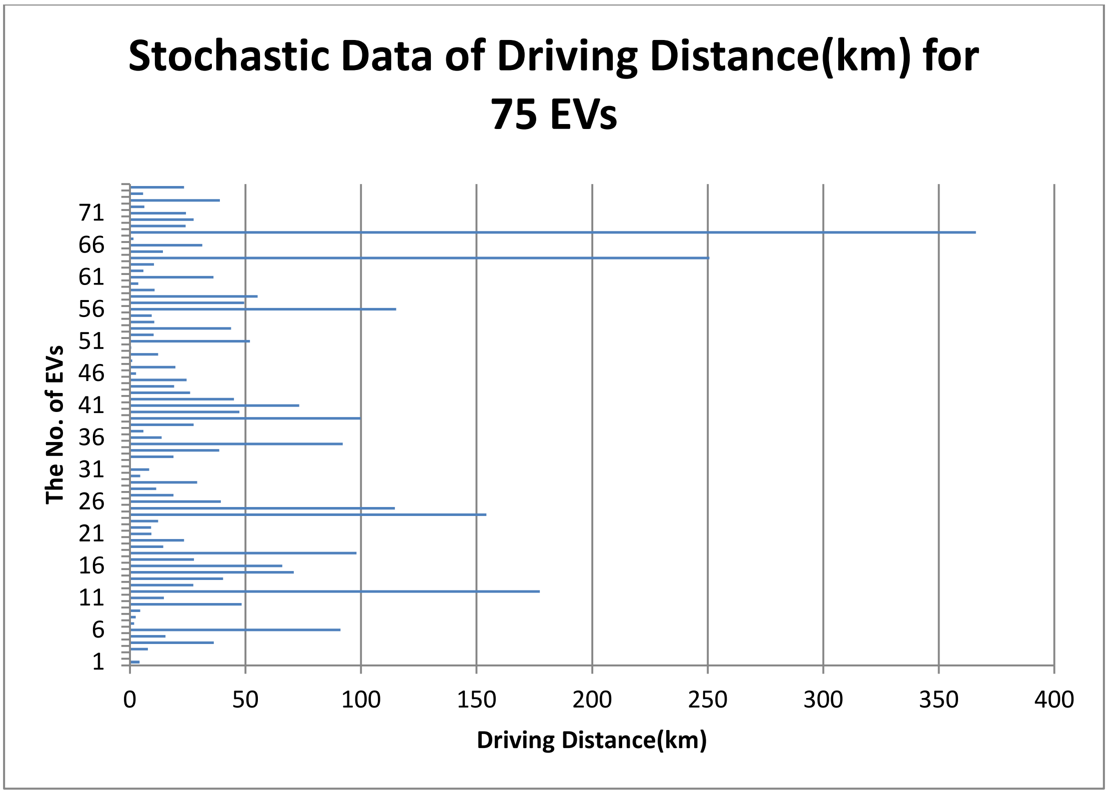

Figure 4-11 Stochastic Data of Driving Distance

Step 5: Using the formula of energy consumption in 4.3. The energy needed for each EV is calculated with driving distance. See Figure 4-12. It can be observed that many EVs need less than 10 kWh per day to fulfil the driving demand.

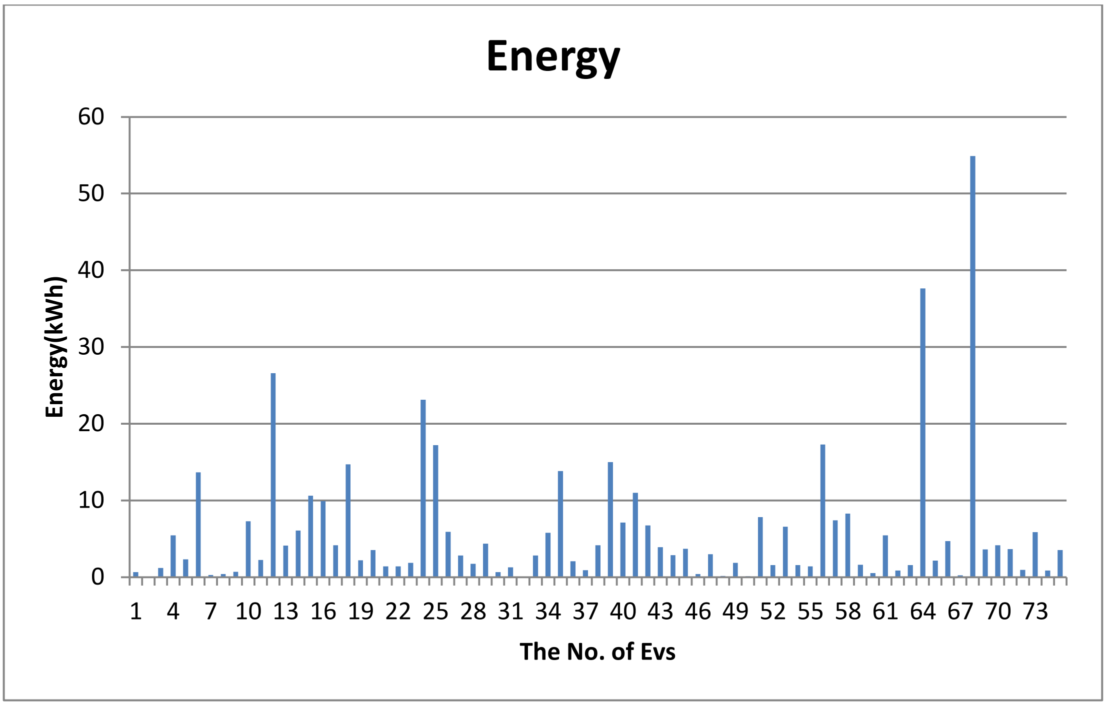

Figure 4-12 The energy needed for each EV

Available Charging Time

Step 1: Use the distribution of arriving time to generate 8,601 samples of arriving time. The number 8,601 is selected because the cumulative frequency of the given data of arriving time is 86.01%.

Step 2: Use the Distribution Fitting Tool in Matlab to plot the samples of arriving time. See Figure 4-13. Many EVs arrive home from the afternoon till the evening.

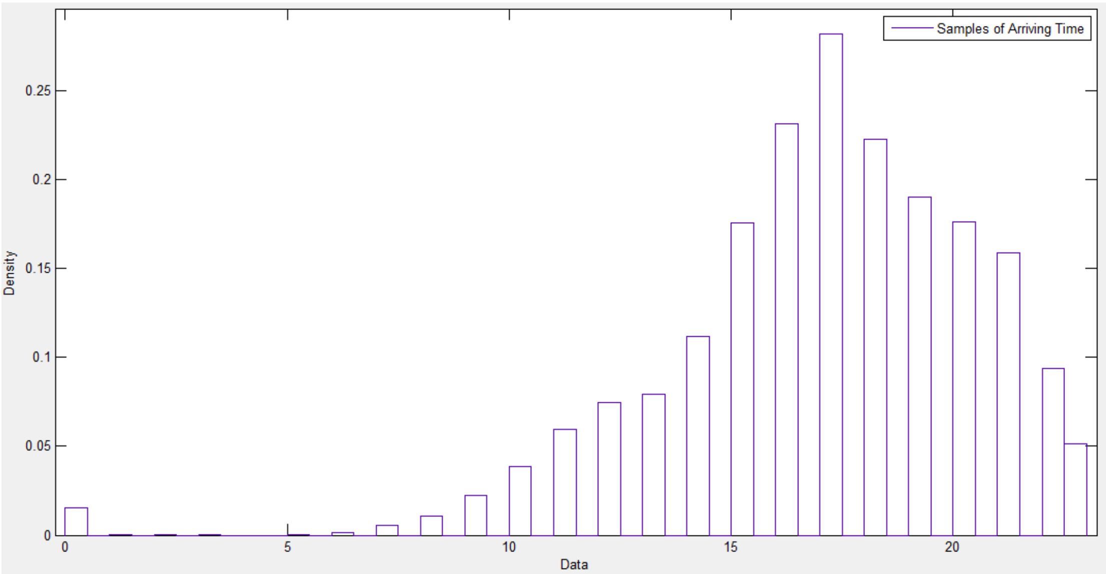

Figure 4-13 Samples of arriving time

Step 3: Find a new fitted distribution. For these samples of arriving time, the Normal distribution is used. See Figure 4-14. The parameters mu=16.8461, sigma=3.60194.

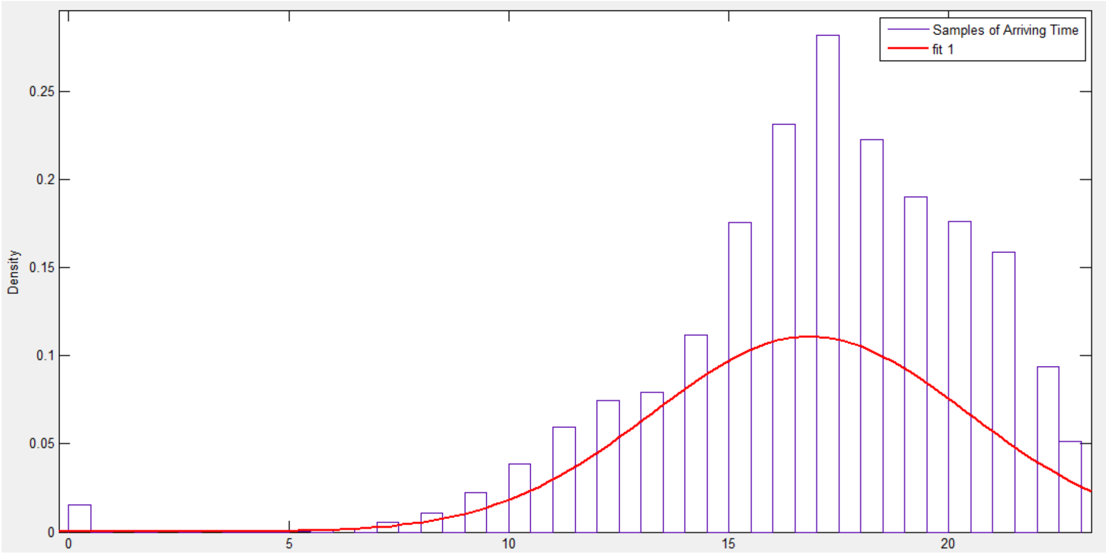

Figure 4-14 Fitted distribution for arriving time

Step 4: The random data of arriving time for 75 EVs are generated, using the parameters of new fitted distribution. The Matlab code is shown in Appendix I. From Figure 4-15, it can be observed that most EVs have arriving times between 14:00 and 22:00.

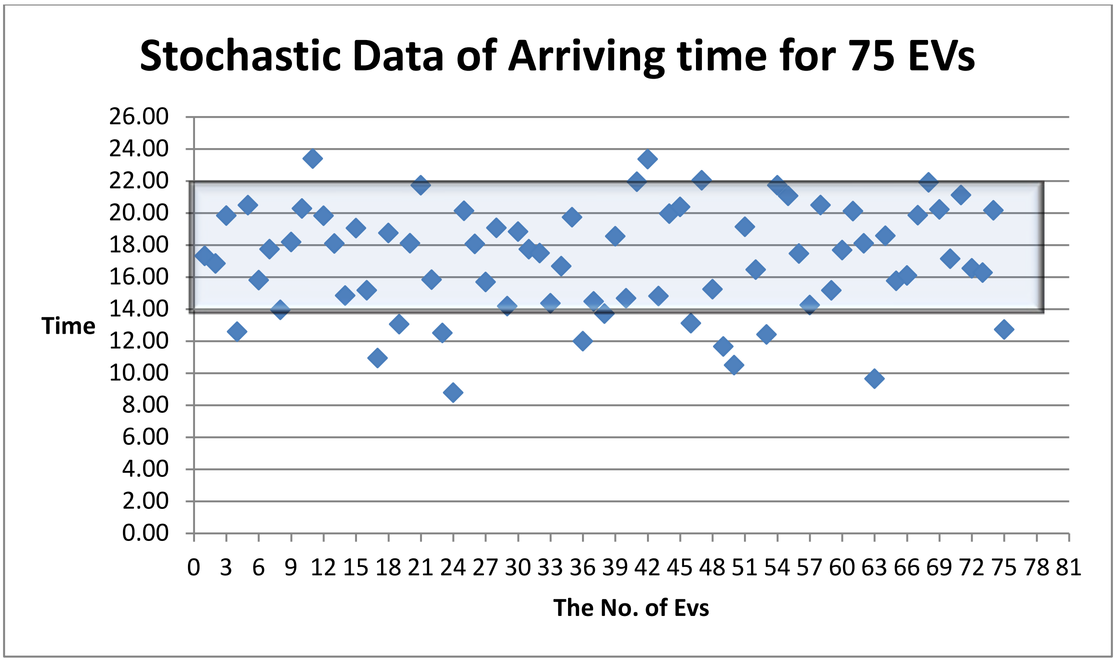

Figure 4-15 Stochastic Data of Arriving time for 75 EVs

Step 5: Use similar method to obtain the stochastic data of departure time for 75 EVs in Figure 4-16. Most of the EVs leave home between 4:00 and 12:00.

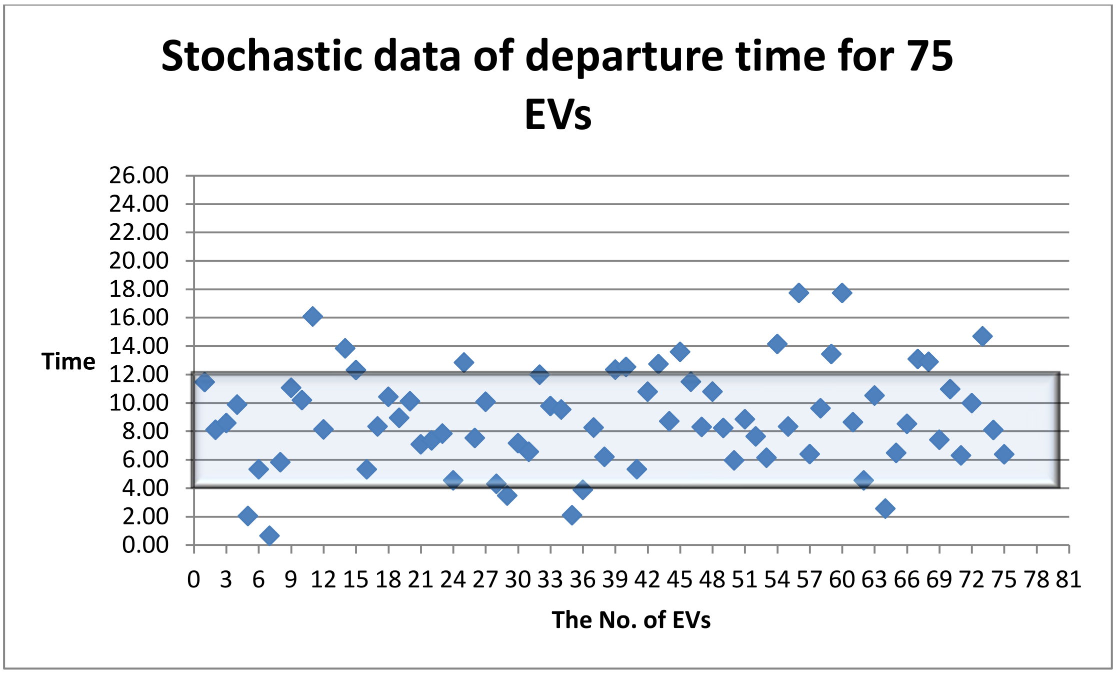

Figure 4-16 Stochastic data of departure time for 75 EVs

4.5.2 Charging plan using stochastic data on Wednesday in summer

In section 4.5.1, the random data of the energy needed for each EV on Wednesday is obtained. Based on these data a charging plan is made. The flow diagram of charging plan for each EV is given in Figure 4-17.

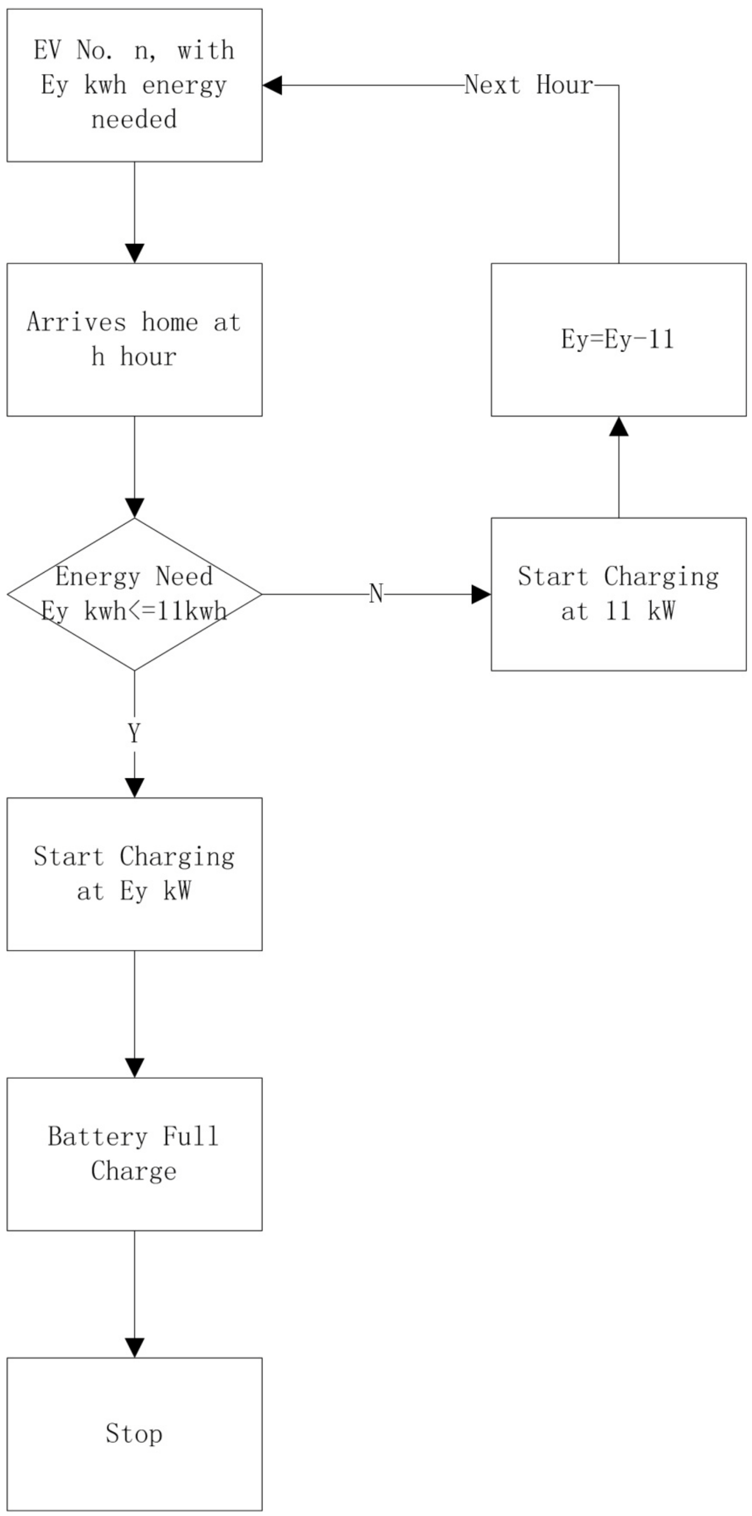

Figure 4-17 Charging Flow Diagram for Each EV

For almost all the EVs, the available charging time during the night is adequate. Hence the arriving time is the major factor of available charging time. The random arriving time is also obtained from the section 4.5.1.

Based on the charging plan for each EV, a Matlab program is made to do the load flow calculation for each hour in the distribution grid. First, the matrices of energy needed and arriving time is set. Then check from hour 1(00:00 to 01:00) to hour 24(23:00 to 24:00). Each EV corresponds to a unique hour of arriving. When the EV arrives, it starts to charge. If the energy needed of this particular car is less or equal to 11kWh, for instance 5kWh, it charges at 5kW. Or if the energy needed is more than 11kWh, for instance 30kWh, it charges at 11kW and charges remain at following hours. When the energy consumption for driving is recharged, it stops charging. So a matrix with the time and charging power of all EVs can be obtained. A part of the matrix is shown in Table 4-3. The full table is in Appendix D. Each column has the total consumption of EVs in one hour.

In the table, most EVs charge from noon 12:00 till night 24:00. They begin to charge as soon as they arrive home. There are more EVs charging at the peak times (16:00-20:00) than other times.

Table 4-3 A part of matrix of charging plan

16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	
0.64	0	0	0	0	0	0	0	EV1
0.03	0	0	0	0	0	0	0	EV2
0	0	0	1.18	0	0	0	0	EV3
0	0	0	0	0	0	0	0	EV4
0	0	0	2.3	0	0	0	0	EV5
2.66	0	0	0	0	0	0	0	EV6
0	0.27	0	0	0	0	0	0	EV7
0	0	0	0	0	0	0	0	EV8
0	0.67	0	0	0	0	0	0	EV9
0	0	0	7.26	0	0	0	0	EV10
0	0	0	0	0	0	2.21	0	EV11
0	0	0	11	11	4.6	0	0	EV12
0	4.12	0	0	0	0	0	0	EV13

Combining each the charging power in each column with corresponding house load, the power consumed in each bus is obtained. Afterwards, then load flow is calculated. As shown in Figure 4-18, the quality of voltage meets the requirement (≥0.94 pu). One of most constrained buses, Bus 103 is chosen in Figure 4-19. It can be seen that there is a steep drop during 19:00-20:00. This phenomenon is caused by six EVs charging at this time in the Feeder 4, which significantly increases the loading.

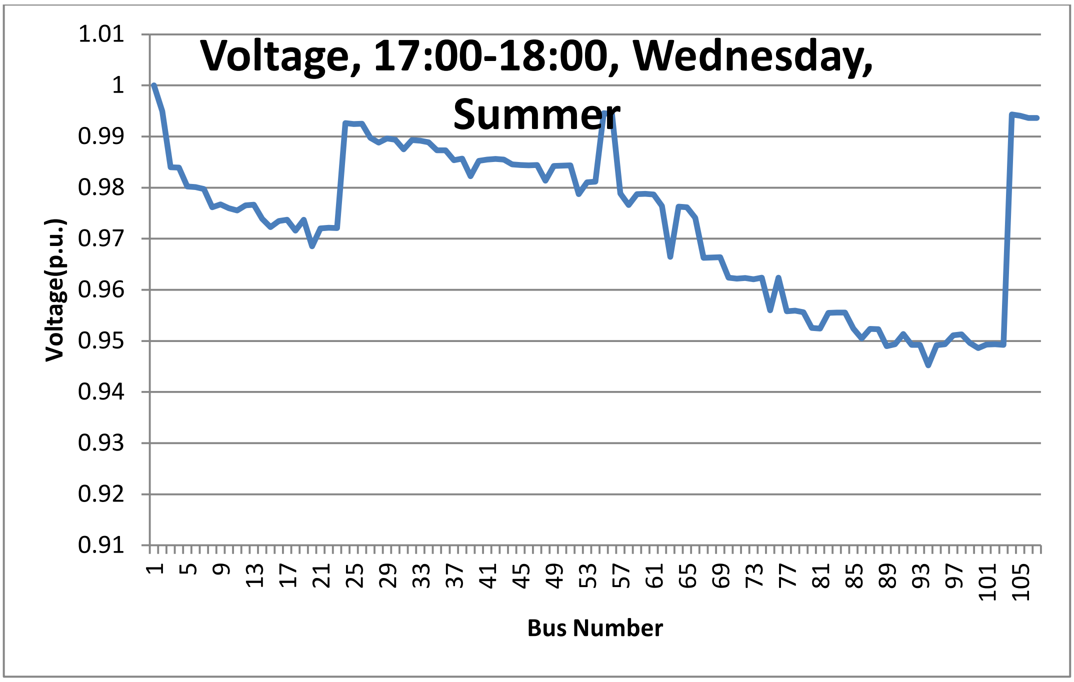

Figure 4-18 Bus voltage at hour 18, Wednesday, summer

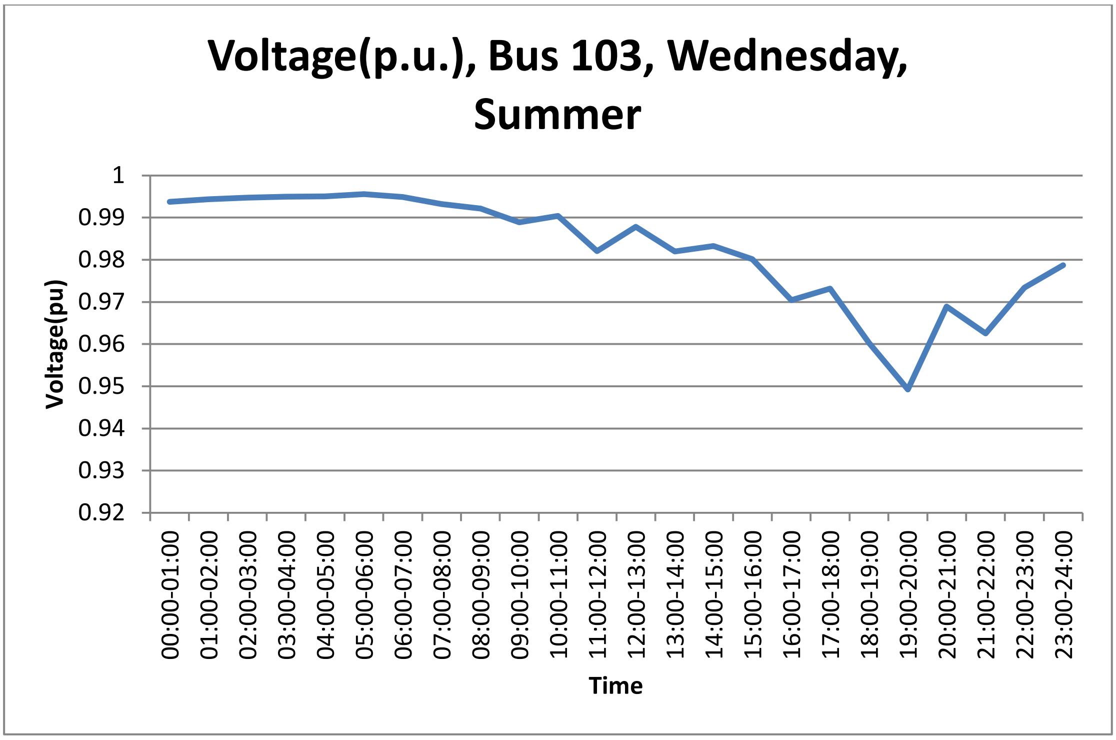

Figure 4-19 Voltage (pu), Bus 103, Wednesday, Summer

4.5.3 Charging plan using stochastic data on Wednesday in winter

From the section 4.5.2, it has been proved that the grid can support the charging of EVs with stochastic pattern in a summer weekday. A Wednesday in winter is picked to be analyzed to compare the results with the section 4.5.2.

The energy needed of EVs is assumed to be the same as in summer. The consumption of house is more, as shown in Appendix B. The voltage comparison is shown in Figure 4-20 and Figure 4-21.

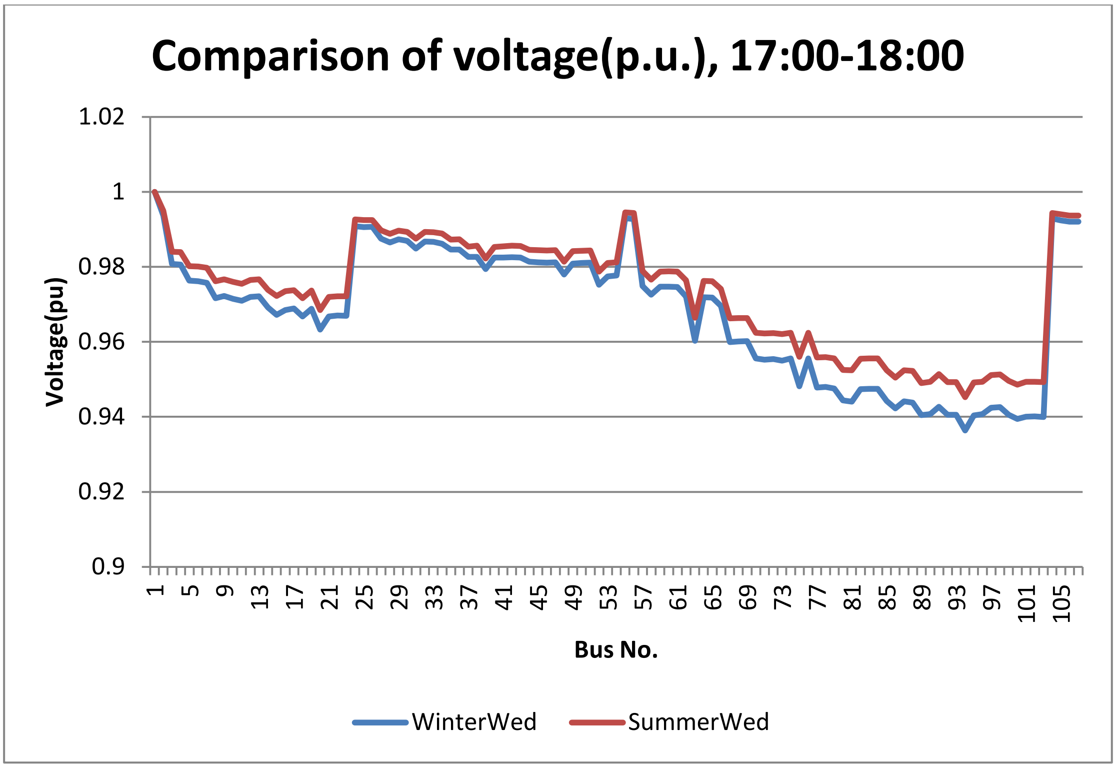

Figure 4-20 Comparison of voltage, 17:00-18:00

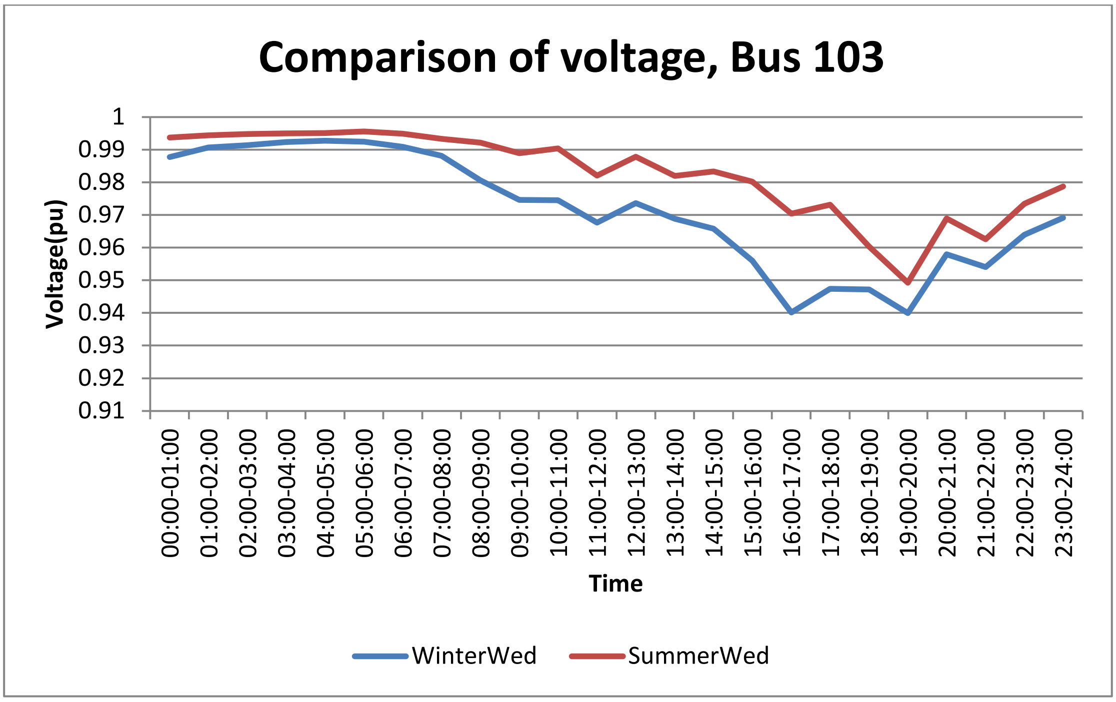

Figure 4-21 Comparison of voltage, Bus 103

Arriving home at different time has reduced the congestions in the distribution grid. Normally the grid allows EVs to charge as soon as they arrive home. However, for the economic reason, charging as soon as arriving is not always recommendable. At midnight, when the house consumption is relatively low and the wind production is high, the price of electricity would drop. Charging at those times could benefit both grid and owners of EVs.

During the peak time in the winter weekday, the Feeder 4 cannot support all the EVs to charge as they arriving home. Using this dumb charging plan may cause steep voltage drop at the bottom of the feeder. A few EVs need to be moved to other times for charging.

4.6 Conclusion

In this chapter, the stochastic data of the behaviours of EVs are generated using the Monte Carlo Method. With arriving time and leaving time, the available charging times for EVs are obtained. The energy demands for each EV are calculated based on the random driving distance.

A charging plan is then made based on the stochastic data. It is a dump charging plan with which EVs start to charge as soon as they arrive. The voltage drops distinctly during the peak time because of the arrivals of many EVs and the peak demands of houses. The grid has much stress during these times. The cost of charging at these times is also high because of the large amount consumption of electricity.

5 Optimization of Charging Plans

5.1 Introduction

In Chapter 3, 6 scenarios have been set to analyze the operation behaviours of the distribution grid. The number and charging power of the EVs have been assumed to meet the operation requirements of the grid. The places to put connected EVs in the grid are also manually selected. These assumptions make it easy to observe the operation features of the grid. However, it is not realistic because the behaviours of EV owners are not deterministic.

Based on the stochastic analysis in the previous chapter, simulations were conducted to reflect a situation closed to the real behaviours of the EVs in the grid. The EVs drive different distance a day and arrive home at different time. The simulation is based on certain pattern supported by surveys. With the stochastic data, charging plans have been made. EVs start to charge when they arrive home. Since most EVs arrive between 14:00 and 22:00 as shown in Figure 4-15, and 16:00 to 20:00 are normally the peak time of electricity consumption, it may cause huge stress on the grid operation.

An optimization methodology is applied in this Chapter, focusing on dispersing the congestions of the grid by moving the charging time of the EVs to off-peak times of the consumption of electricity. The off-peak times of electricity are normally midnight when the price of electricity is relatively low. So by optimizing the charging plans, the economic benefit for aggregators and EV owners may be achieved.

There are some optimized charging plans proposed in [15] [44] and [45]. Most of the plans are based on assumptions rather than stochastic data. In this project, the stochastic process is used to make the optimization outcomes more realistic.

5.2 The Smart Charging

Smart charging is a charging method that requires systematic control system. The efficient management is crucial in this method. Instead of charging immediately and automatically when the EVs being plugged in, the charging happens in different time period at different charging power controlled by the system. This requires the coordination and communication between TSO, DSO, aggregators, EVs owners etc. The data of electricity price should be updated day ahead or even hour ahead. After the smart charging, the SOC of the batteries should meet the demand of driving distance needed. The Smart Grid proposed in Denmark aims to provide a suitable environment for smart charging. Figure 5-1 shows an example of smart charging system.

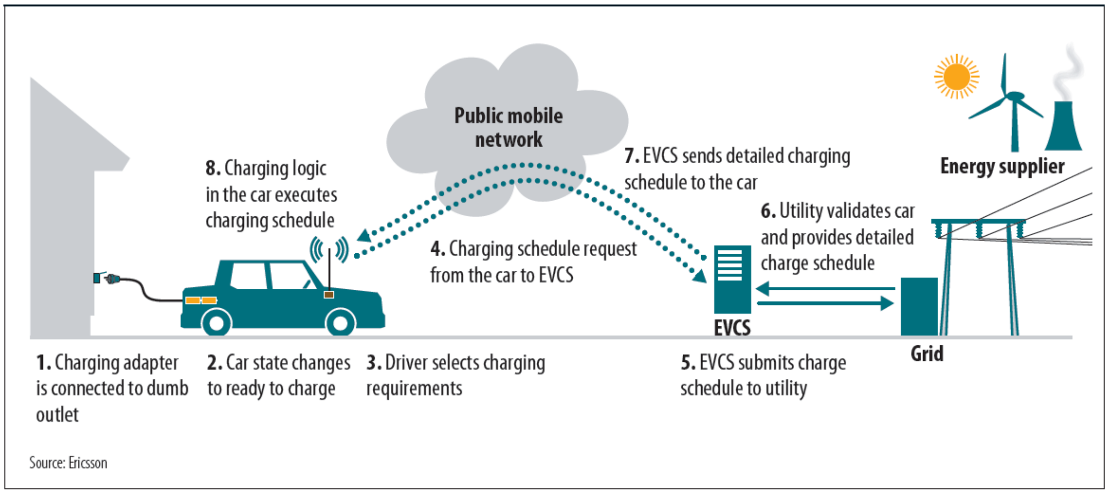

Figure 5-1 An example of smart charging system [44]

The smart charging has following features [43]:

1. Charging plan is normally made one day ahead;
2. The plan can be changed intra-day.
3. The spinning and tertiary reserves can be provided by EVs, along with V2G.

With planed charging at different time period with different charging power, the pressure of operation of the distribution grid can be reduced. This is a hierarchical structure of controlling. The EV owners have to commit to the agreement of controlling. Besides the fact that smart charging can help stabilize the bus voltage and prevent the congestion of the grid, the benefit could be made by smart charging is also attractive to EV owners to make such agreement. Figure 5-2 shows the system and the market benefit of smart charging EVs. The market price of smart EVs is also cheaper than the dumb EVs.

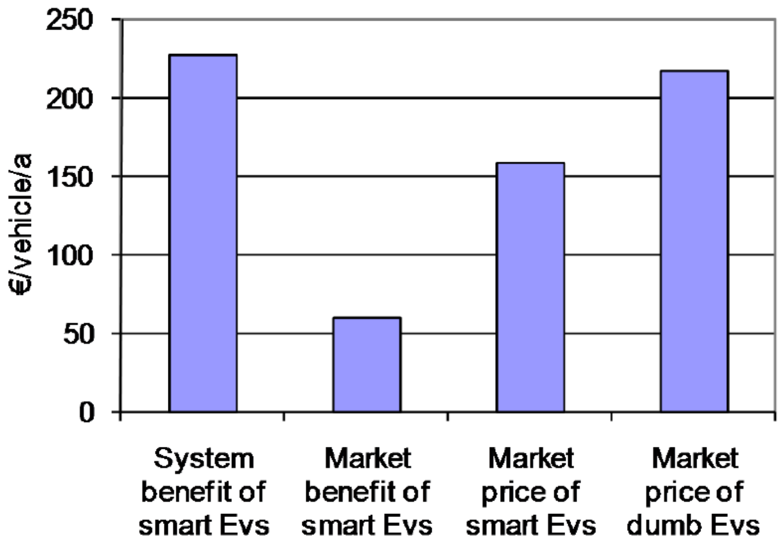

Figure 5-2 Example of benefits from smart charging EVs [43]

In Denmark, the high penetration of wind power could lead the electricity price to very low during windy days. The smart charging makes it possible for EVs owners to benefit from the electricity price fluctuation.

5.3 Wind Power Case in the Optimization Process

The penetration of the wind is very high in Danish power system. The production of wind power could seriously affect the supply and demand relationship of the electricity, thereby affect the price of the electricity. The table of the Elspot price and corresponding wind production for 8 typical days is shown in Appendix E.

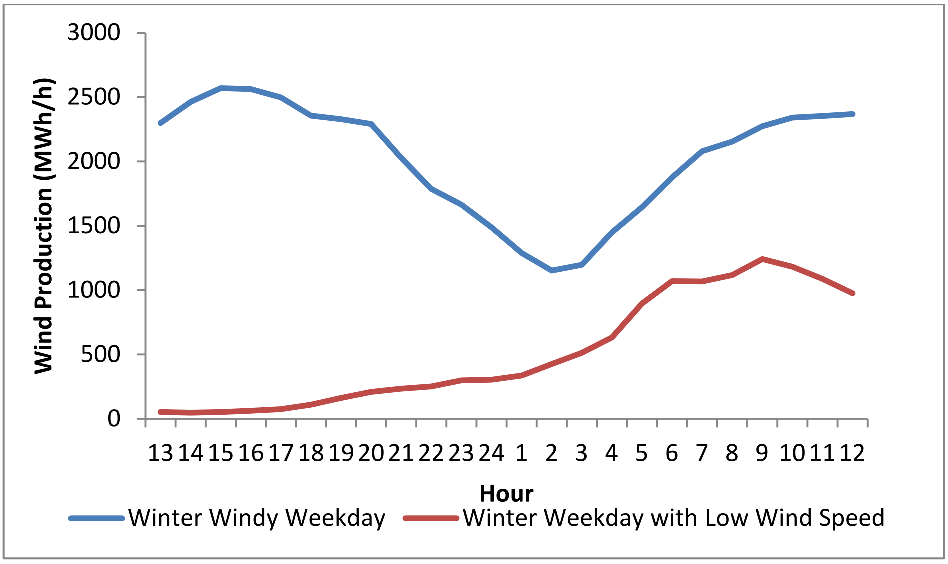

Figure 5-3 Wind Production of two winter weekdays

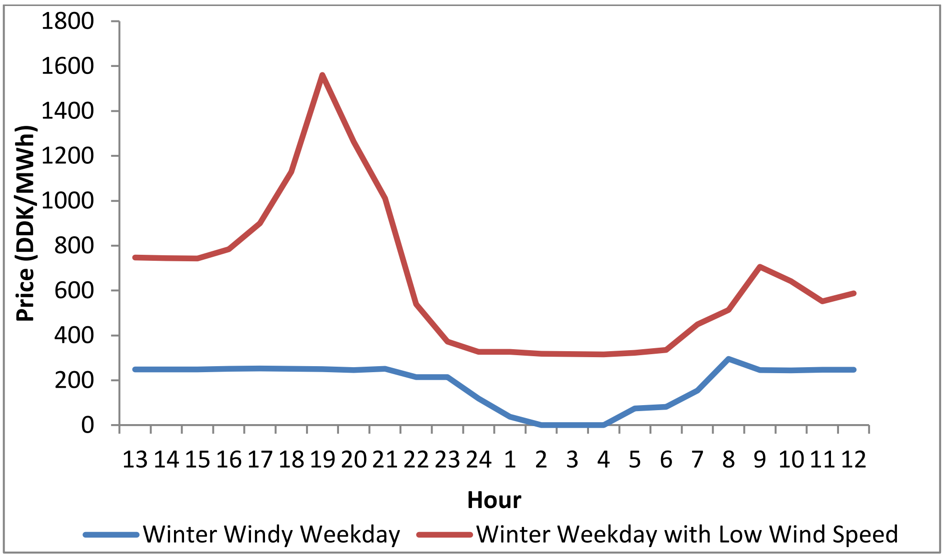

Figure 5-4 Elspot Price of two winter weekdays

Figure 5-3 and Figure 5-4 show the relationship between the wind production and the price of the electricity in two typical winter weekdays. The price in the windy day goes very low, at some hours even closed to zero. This probably caused by that the wind production exceeds the demand of the electricity. In the day with low wind speed, the price goes extremely high, even over 1000 DKK/MWh at some hours. It is because that there is little wind production and most of the electricity has to be generated by conventional power plant.

Beside the wind production, the price could also be affected by the demand of consumption, operations of power system of neighbour countries, market fluctuation etc. In this project, some typical days are chosen mainly based on the wind condition. The price of electricity of typical days is shown in Figure 5-5, Figure 5-6 and Figure 5-7.

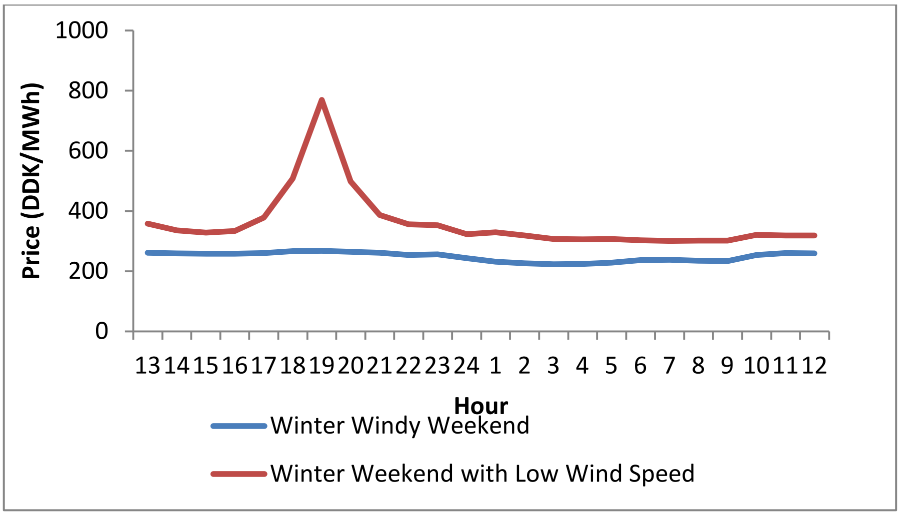

Figure 5-5 Elspot Price of electricity at two winter weekends

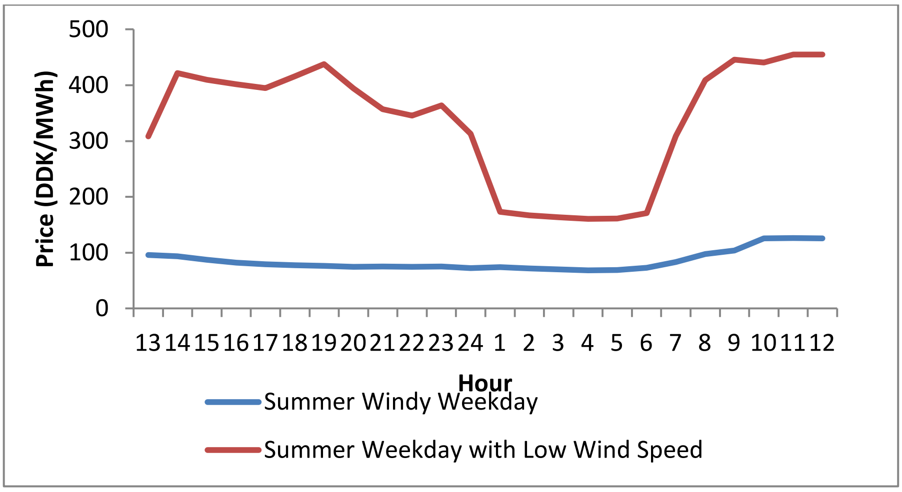

Figure 5-6 Elspot Price of electricity at two summer weekdays

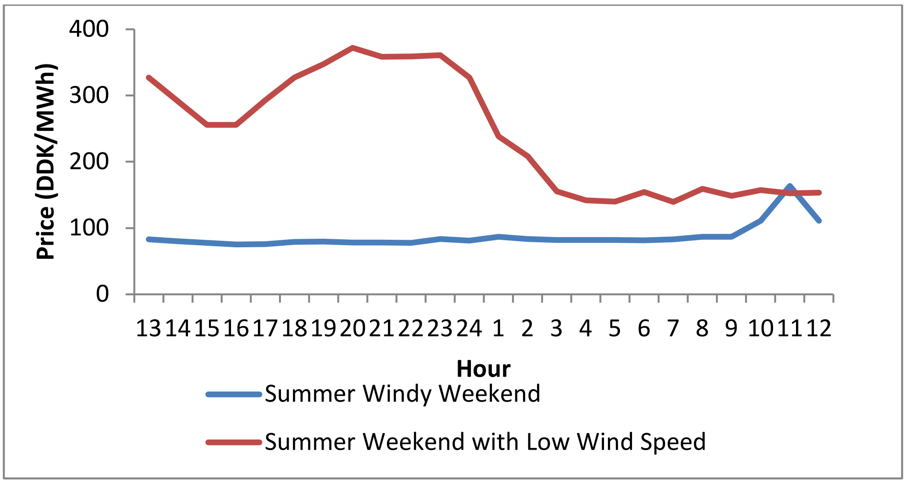

Figure 5-7 Elspot Price of electricity at two summer weekends

5.4 The Objective and Methodology of the Optimization

The main objective of the optimization is to minimize the cost in the EV charging plans, while meeting the requirement of the stable operation of the distribution grid. The price data is from [30] which is the Elspot price in DKK/MWh. To make it more practical, the price is converted to DKK/KWh and added 2 DKK/KWh tax with it [34]. The adding tax will not affect the amount of the reduction of charging cost. Since the available charging times are mostly from afternoon till next day morning, it is wise to choose the 24 hour duration within 12:00 to next day 12:00. Table 5-1 shows an example of converted price in a winter windy day. The complete table of price used in the optimization is in Appendix F.

Table 5-1 Price used in optimization, A winter windy day

Hour	Elspot Price, DKK/MWh	Price, with Tax, DKK/KWh
13	248.32	2.24832
14	248.62	2.24862
15	248.54	2.24854
16	250.7	2.25070
17	252.41	2.25241
18	251.22	2.25122
19	249.73	2.24973
20	245.72	2.24572
21	251	2.25100
22	214.8	2.21480
23	214.5	2.21450
24	118.92	2.11892
1	37.91	2.03791
2	0.52	2.00052
3	0.3	2.00030
4	0.67	2.00067
5	74.34	2.07434
6	81.78	2.08178
7	154.11	2.15411
8	294.99	2.29499
9	244.96	2.24496
10	244.44	2.24444
11	246.67	2.24667
12	247.26	2.24726

The procedure of the optimization for smart charging is explained as following:

1. Generate the stochastic data of energy need and arriving time of EVs.

2. Search the hour with lowest price of electricity.
3. Charge the arrived EVs at the hour of lowest price at 11kW. The remaining needed energy will be moved to the hour of second lowest price. If the energy need is less than 11kWh, for instance 6kWh, then charge at 6kW.
4. Run the load flow calculation, set the constraint of 0.94 pu≤Voltage≤1.06pu
5. If the voltage of any buses is lower than 0.94pu, move certain number of EVs from the hour of lowest price to the hour of second low price. The number of moved EVs is based on the analyses of base cases in Chapter 3. Run the load flow again and repeat this step until the hour of lowest price in which the voltage meets the constraint.
6. Repeat the same step 3, 4, 5 to the hour of second low price. Then move to the hour of third low price etc. Until all the EVs are fully charged.

The optimization process is done by using "fmincon" function in Matlab. The objective function is

$$Ct = \sum_{m=1}^{10} (c_m \times \sum_{n=1}^{75} p_{nm}) \tag{E5-1}$$

Where Ct is the total cost of charging, m is the hour, n is the number of EVs, c is the price of a particular hour, p is the charging power at that hour of an EV which is variable.

The optimization function subjects to:

1. $V_n \geq 0.94 p.u.$, V_n is the voltage of every cable box.
2. $E_n = \sum_{m=1}^{10} p_{nm}$, E_n is the energy need of EV n. This ensures that all the EVs are fully charged.
3. $p_{nm} \leq 11kW$, the maximum charging power of each EV is 11kW.

The flow diagram of the optimization is shown in Figure 5-8.

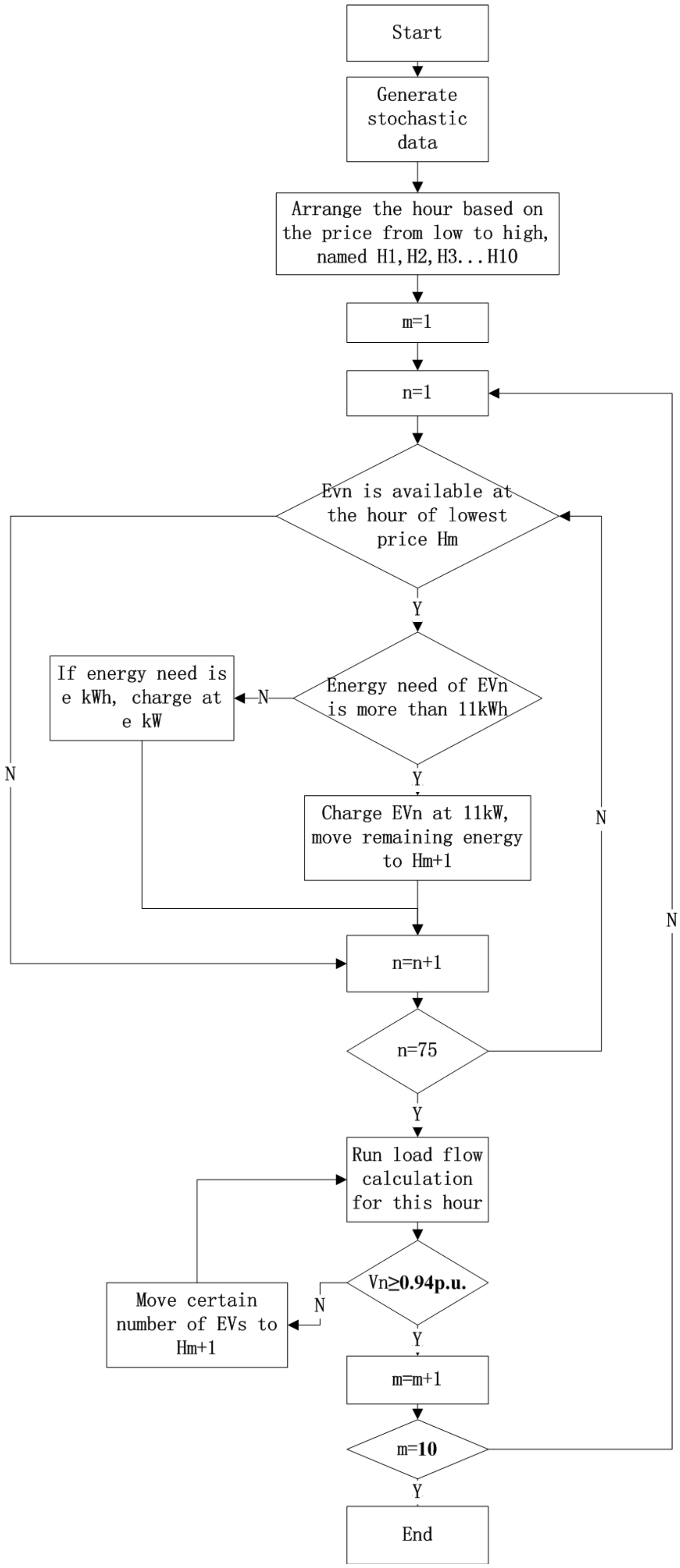

Figure 5-8 Flow diagram of optimization

5.5 The Simulation

5.5.1 Scenario 1: Winter Windy Weekday

Based on the stochastic data of arriving time and leaving time generated in Section 4.5.1, most of the EVs are available between 19:00 and 05:00. These 10 hours are chosen to simplify the optimization and reduce the processing time period. The price of these 10 hours in a winter windy weekday is shown in Table 5-2.

Table 5-2 Price of electricity in a winter windy weekday

Hour	20	21	22	23	24	1	2	3	4	5
Price(DKK/kWh)	2.24572	2.25100	2.21480	2.21450	2.11892	2.03791	2.00052	2.00030	2.00067	2.07434

The energy demand is also generated in Section 4.5.1. The outcome of the optimized charging plans is in Figure 5-9. It can be observed in the plan that many EVs charge during 02:00-03:00 when the price is the lowest. If cannot be fully charged, these EVs charge at 01:00-02:00 and 03:00-04:00.

In the Feeder 4, however, only a few EVs can simultaneously charge during 02:00-03:00, because of the constraint of voltage drop. The EVs are been placed on different time period to charge in the order of price of electricity. The EV68 which needs 54.9 kWh takes 5 hours to be fully charged. And because it is at the bottom part of the Feeder 4, it has not been arranged to 01:00-04:00 to charge.

	Charging Power (kW), Winter windy weekday									
Time	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
Price(DDK/kWh)	2.24572	2.251	2.2148	2.2145	2.11892	2.03791	2.0052	2.0003	2.0067	2.07434
EV1	0	0	0	0	0	0	0	0.64	0	0
EV2	0	0	0	0	0	0	0	0.03	0	0
EV3	0	0	0	0	0	0	0	1.18	0	0
EV4	0	0	0	0	0	0	0	5.44	0	0
EV5	0	0	0	0	0	0	0	2.3	0	0
EV6	0	0	0	0	0	0	2.6109	11	0.0491	0
EV7	0	0	0	0	0	0	0	0.27	0	0
EV8	0	0	0	0	0	0	0	0.38	0	0
EV9	0	0	0	0	0	0	0	0.67	0	0
EV10	0	0	0	0	0	0	0	7.26	0	0
EV11	0	0	0	0	0	0	0	2.21	0	0
EV12	0	0	0	0	0	0	9.497	11	6.103	0
EV13	0	0	0	0	0	0	0	4.12	0	0
EV14	0	0	0	0	0	0	0	6.05	0	0
EV15	0	0	0	0	0	0	10.63	0	0	0
EV16	0	0	0	0	0	0	0	9.89	0	0
EV17	0	0	0	0	0	0	0	4.15	0	0
EV18	0	0	0	0	0	0	3.5014	11	0.1986	0
EV19	0	0	0	0	0	0	0	2.17	0	0
EV20	0	0	0	0	0	0	0	3.51	0	0
EV21	0	0	0	0	0	0	0	1.41	0	0
EV22	0	0	0	0	0	0	0	1.38	0	0
EV23	0	0	0	0	0	0	0	1.84	0	0
EV24	0	0	0	0	0	0	7.7778	11	4.3522	0
EV25	0	0	0	0	0	0	4.74	11	1.45	0
EV26	0	0	0	0	0	0	0	5.91	0	0
EV27	0	0	0	0	0	0	0	2.83	0	0
EV28	0	0	0	0	0	0	0	1.71	0	0
EV29	0	0	0	0	0	0	0	4.38	0	0
EV30	0	0	0	0	0	0	0	0.66	0	0
EV31	0	0	0	0	0	0	0	1.25	0	0
EV32	0	0	0	0	0	0	0	0.07	0	0
EV33	0	0	0	0	0	0	0	2.82	0	0
EV34	0	0	0	0	0	0	0	5.8	0	0
EV35	0	0	0	0	0	0	2.7649	11	0.0451	0
EV36	0	0	0	0	0	0	0	2.07	0	0
EV37	0	0	0	0	0	0	0	0.88	0	0
EV38	0	0	0	0	0	0	0	4.14	0	0
EV39	0	0	0	0	0	0	3.6197	11	0.3703	0
EV40	0	0	0	0	0	0	0	7.11	0	0
EV41	0	0	0	0	0	0	0	10.99	0	0
EV42	0	0	0	0	0	0	0	6.75	0	0
EV43	0	0	0	0	0	0	0	3.91	0	0
EV44	0	0	0	0	0	0	0	2.87	0	0
EV45	0	0	0	0	0	0	3.68	0	0	0
EV46	0	0	0	0	0	0	0.4	0	0	0
EV47	0	0	0	0	0	0	2.97	0	0	0
EV48	0	0	0	0	0	0	0.14	0	0	0
EV49	0	0	0	0	0	0	1.84	0	0	0
EV50	0	0	0	0	0	0	0.1	0	0	0
EV51	0	0	0	0	0	0	7.8	0	0	0
EV52	0	0	0	0	0	0	1.55	0	0	0
EV53	0	0	0	0	0	0	6.57	0	0	0
EV54	0	0	0	0	0	0	1.58	0	0	0
EV55	0	0	0	0	0	0	1.41	0	0	0
EV56	0	0	0	0	0	11	4.8171	0	1.4629	0
EV57	0	0	0	0	0	0	7.41	0	0	0
EV58	0	0	0	0	0	0	0	0	8.3	0
EV59	0	0	0	0	0	0	0	0	1.61	0
EV60	0	0	0	0	0	0	0	0	0.54	0
EV61	0	0	0	0	0	0	0	0	5.43	0
EV62	0	0	0	0	0	0	0	0	0.87	0
EV63	0	0	0	0	0	0	0	0	1.55	0
EV64	0	0	0	0	11	4.62	0	0	11	11
EV65	0	0	0	0	0	0	0	0	2.14	0
EV66	0	0	0	0	0	0	0	0	4.7	0
EV67	0	0	0	0	0	0	0	0	0.24	0
EV68	0	0	11	11	11	11	0	0	0	10.9
EV69	0	0	0	0	0	3.62	0	0	0	0
EV70	0	0	0	0	0	4.13	0	0	0	0
EV71	0	0	0	0	0	3.64	0	0	0	0
EV72	0	0	0	0	0	0.93	0	0	0	0
EV73	0	0	0	0	0	0	0	5.85	0	0
EV74	0	0	0	0	0	0	0	0.85	0	0
EV75	0	0	0	0	0	0	0	3.51	0	0

Figure 5-9 Optimized charging plan of a winter windy day

5.5.2 Scenario 2: Summer Weekday with Low Wind Speed

The same driving pattern as 5.4.1 has been chosen in this scenario. The time period is also the same 10 hours. The price of electricity in a summer weekday with low wind speed is shown in Table 5-3. The outcome of the optimization is presented in Figure 5-10.

Table 5-3 Price of electricity in a summer weekday with low wind speed

Hour	20	21	22	23	24	1	2	3	4	5
Price(DKK/kWh)	2.39420	2.35681	2.34543	2.36402	2.31286	2.17339	2.16707	2.16328	2.16083	2.16090

In this charging plan, the prices during 03:00-04:00 and 04:00-05:00 are very close. This leads to that many EVs approximately evenly charge during these two hours. This disperses the stress of the grid and enables more EVs to charge at low price periods.

	Charging Power (kW), Summer Weekday with low wind speed									
Time	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
Price(DDK/kWh)	2.39420	2.35681	2.34543	2.36402	2.31286	2.17339	2.16707	2.16328	2.16083	2.16090
EV1	0	0	0	0	0	0	0	0	0.4129	0.2271
EV2	0	0	0	0	0	0	0	0	0.0286	0.0014
EV3	0	0	0	0	0	0	0	0.0013	0.6857	0.493
EV4	0	0	0	0	0	0	0	0.0081	2.8155	2.6164
EV5	0	0	0	0	0	0	0	0	1.2444	1.0556
EV6	0	0	0	0	0	0	0	0	6.9199	6.7401
EV7	0	0	0	0	0	0	0	0	0.2285	0.0415
EV8	0	0	0	0	0	0	0	0	0.2824	0.0976
EV9	0	0	0	0	0	0	0	0	0.428	0.242
EV10	0	0	0	0	0	0	0	0	3.7025	3.5575
EV11	0	0	0	0	0	0	0	0	1.209	1.001
EV12	0	0	0	0	0	0	0.4868	4.1132	11	11
EV13	0	0	0	0	0	0	0	0.0015	2.1412	1.9773
EV14	0	0	0	0	0	0	0	0	3.1399	2.9101
EV15	0	0	0	0	0	0	0	0	5.4071	5.2229
EV16	0	0	0	0	0	0	0	0	5.0264	4.8636
EV17	0	0	0	0	0	0	0	0	2.1653	1.9847
EV18	0	0	0	0	0	0	0	0.2952	7.3068	7.0981
EV19	0	0	0	0	0	0	0	0	1.1871	0.9829
EV20	0	0	0	0	0	0	0	0.0501	1.8251	1.6348
EV21	0	0	0	0	0	0	0	0	0.7953	0.6147
EV22	0	0	0	0	0	0	0	0	0.7809	0.5991
EV23	0	0	0	0	0	0	0	0	1.0115	0.8285
EV24	0	0	0	0	0	0	0	3.1587	10.0657	9.9056
EV25	0	0	0	0	0	0	0	1.1404	8.1253	7.9243
EV26	0	0	0	0	0	0	0	0.0607	3.0235	2.8257
EV27	0	0	0	0	0	0	0	0.127	1.4424	1.2606
EV28	0	0	0	0	0	0	0	0	0.9497	0.7603
EV29	0	0	0	0	0	0	0	0	2.307	2.073
EV30	0	0	0	0	0	0	0	0	0.4225	0.2375
EV31	0	0	0	0	0	0	0	0	0.721	0.529
EV32	0	0	0	0	0	0	0	0	0.0695	0.0005
EV33	0	0	0	0	0	0	0	0	1.5203	1.2997
EV34	0	0	0	0	0	0	0	0	2.9869	2.8131
EV35	0	0	0	0	0	0	0	0.0332	6.9636	6.8131
EV36	0	0	0	0	0	0	0	0.0018	1.1273	0.9409
EV37	0	0	0	0	0	0	0	0.0209	0.5188	0.3404
EV38	0	0	0	0	0	0	0	0	2.1618	1.9782
EV39	0	0	0	0	0	0	0	0.4231	7.3504	7.2165
EV40	0	0	0	0	0	0	0	0	3.6548	3.4552
EV41	0	0	0	0	0	0	0	0	5.5858	5.4042
EV42	0	0	0	0	0	0	0	0	3.4512	3.2988
EV43	0	0	0	0	0	0	0	0	2.0463	1.8637
EV44	0	0	0	0	0	0	0	0	1.5311	1.3389
EV45	0	0	0	0	0	0	0	0	1.9401	1.7399
EV46	0	0	0	0	0	0	0	0	0.2929	0.1071
EV47	0	0	0	0	0	0	0	0	1.5757	1.3943
EV48	0	0	0	0	0	0	0	0	0.1395	0.0005
EV49	0	0	0	0	0	0	0	0.0002	1.0073	0.8324
EV50	0	0	0	0	0	0	0	0	0.0985	0.0015
EV51	0	0	0	0	0	0	0	0.1899	3.9014	3.7087
EV52	0	0	0	0	0	0	0	0	0.871	0.679
EV53	0	0	0	0	0	0	0	0	3.3712	3.1988
EV54	0	0	0	0	0	0	0	0	0.8808	0.6992
EV55	0	0	0	0	0	0	0	0	0.7948	0.6152
EV56	0	0	0	0	0	0	0	1.1743	8.0971	8.0086
EV57	0	0	0	0	0	0	0	0	3.7882	3.6218
EV58	0	0	0	0	0	0	0	0	4.2689	4.0311
EV59	0	0	0	0	0	0	0	0	0.8994	0.7106
EV60	0	0	0	0	0	0	0	0	0.3629	0.1771
EV61	0	0	0	0	0	0	0	0	2.8028	2.6272
EV62	0	0	0	0	0	0	0	0	0.5258	0.3442
EV63	0	0	0	0	0	0	0	0	0.8701	0.6799
EV64	0	0	0	0	11	11	4.6735	10.9465	0	0
EV65	0	0	0	0	0	0	0.9779	1.1621	0	0
EV66	0	0	0	0	0	0	2.2566	2.4434	0	0
EV67	0	0	0	0	0	0	0.0257	0.2143	0	0
EV68	0	0	11	0	11	10.9	11	11	0	0
EV69	0	0	0	0	0	1.6915	1.9041	0.0244	0	0
EV70	0	0	0	0	0	1.9598	2.1651	0.0052	0	0
EV71	0	0	0	0	0	0	1.7238	1.9162	0	0
EV72	0	0	0	0	0	0	0.3689	0.5611	0	0
EV73	0	0	0	0	0	0	0	0	3.0058	2.8442
EV74	0	0	0	0	0	0	0	0	0.517	0.333
EV75	0	0	0	0	0	0	0	0	1.866	1.644

Figure 5-10 Optimized charging plan of a summer day with low wind speed

Figure 5-11 shows the voltage of Bus 103 which is one of the most constrained buses in two scenarios. Because of the charging of EVs, the voltage drops during the off-peak time 24:00 to 05:00. The constraint of the optimization function ensures that the voltage is above 0.94pu.

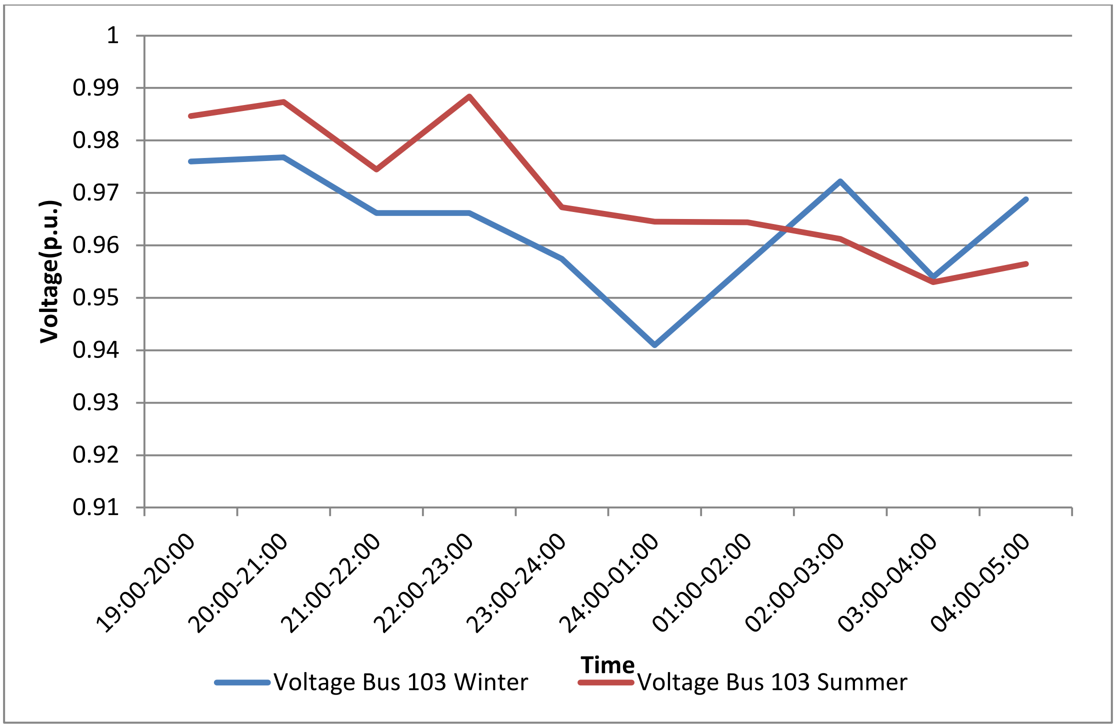

Figure 5-11 The voltage of Bus 103

5.6 Analyses of the Optimised Charging Plans

5.6.1 Voltage, Loading and Loss

In the scenario of winter windy weekday, many EVs charge during 24:00-04:00 since it is the time when the price is low that day. The grid probably goes through with enormous stress on operation during this time. The voltage, loading and loss of the grid at that time are analyzed.

Figure 5-12 and Figure 5-13 show the voltage, load and loss of the grid during the four hours. To make it clear to see the correspondence, there are colour marks on Time axis in Figure 5-13 corresponding to the voltage curve in Figure 5-12.

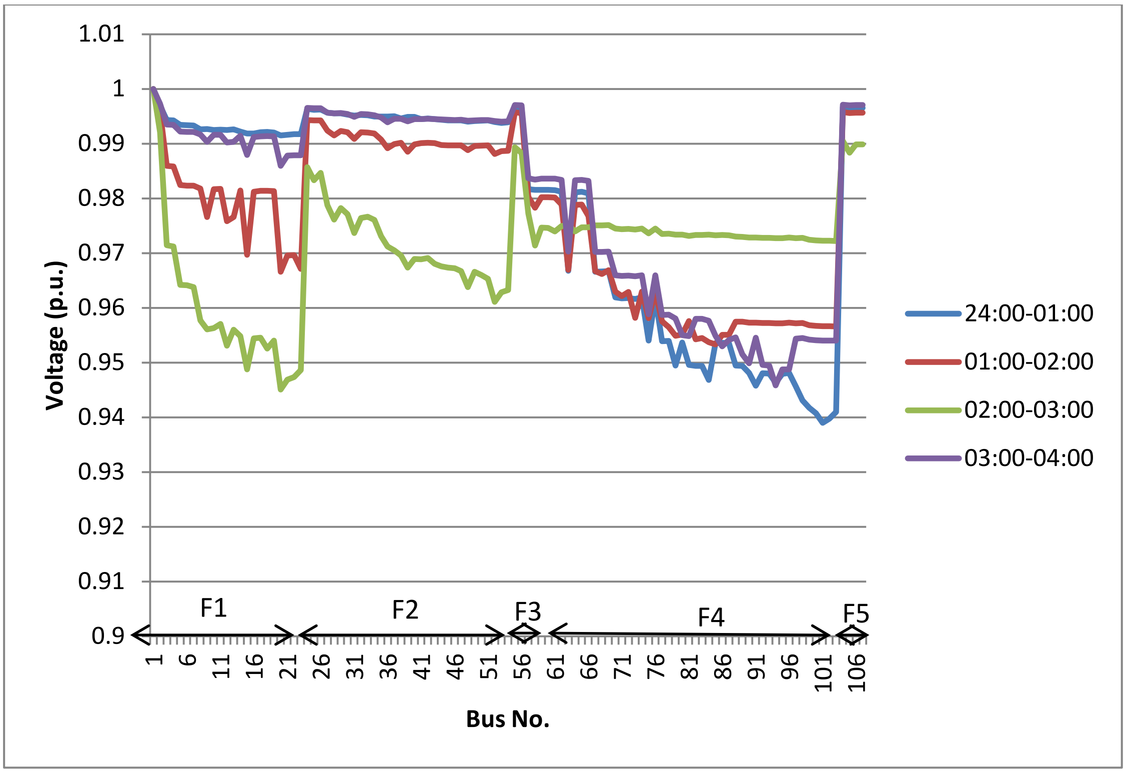

Figure 5-12 Voltage during the four hours, winter windy weekday

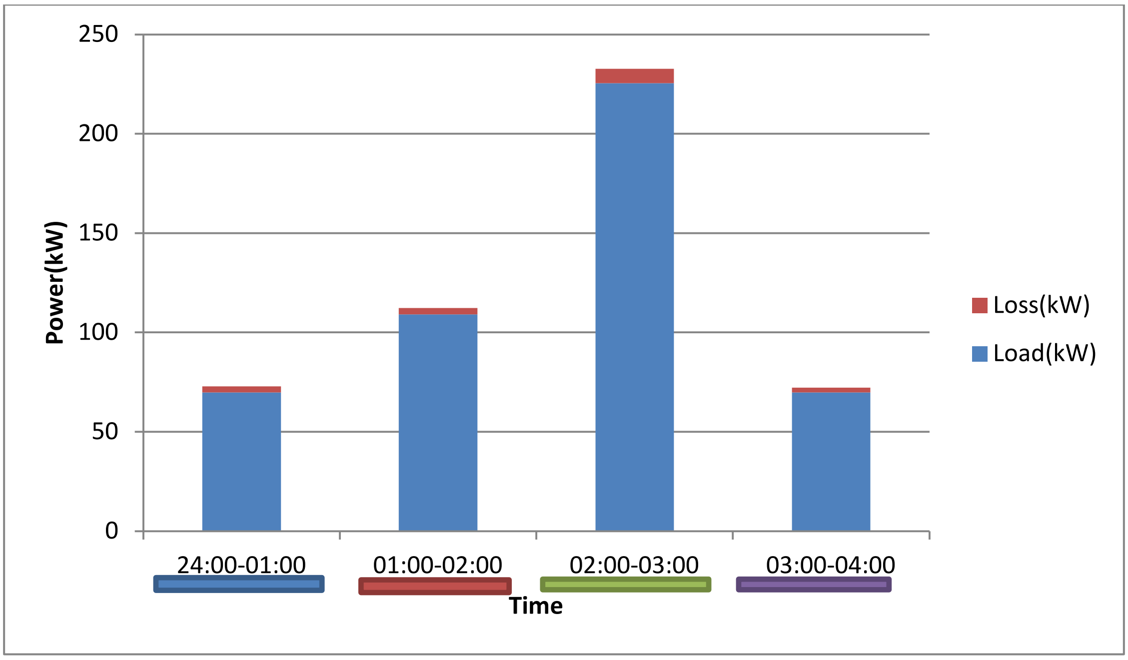

Figure 5-13 Load and loss during the four hours, winter windy day

There are several things can be observed:

1. The highest loading happens during 02:00-03:00. This is because the price of electricity is the lowest during this time, and the objective of this optimized charging

plan is to minimize the charging cost. It can be predict that more EVs charging at this time, more benefit for EV owners will be made.

2. During these four hours, the highest loading is around 225 kW, which does not exceed the capacity of the transformer. And there is relatively little loss during these four hours.
3. The Feeder 2 only has distinct voltage drop during 02:00-03:00, when the price of electricity is the lowest. That means that Feeder 2 has ability to charge most of EVs in Feeder 2 at that time. Another word, Feeder 2 is a strong Feeder.
4. The bus voltage in Feeder 4 drops to the lowest during 24:00-01:00, when the price of electricity is the highest in these four hours. While the load of charging EVs during this hour does not differ from other 3 hours. However, due to the processing sequence of the optimization program, the charging EVs in this hour are at the end of the Feeder. Because Feeder 4 is a long and relatively weak Feeder, the steep voltage drop of cable boxes at the last part of the Feeder could easily happen.
5. Feeder 1, 2, 3 and 5 all restore high voltage quality during 24:00-01:00. This can be seen as a sign that most EVs connected to these Feeders are fully charged during these four hours.

5.6.2 The optimized charging cost

The main objective of the optimization is to come out smart charging plans to reduce the charging cost. In section 4.5.2, all EVs start to charge as soon as they arrive. The cost of this kind of dumb charging is used to compare with the smart charging plans.

The data of dumb charging plan is in Appendix D. The price of electricity of a winter windy weekday is chosen as Table 5-4. The total cost can be calculated by formula:

$$C_{DCW} = \sum_{m=1}^{24} (c_m \times \sum_{n=1}^{75} p_{nm}) \qquad \text{(E5-2)}$$

where C_{DCW} is the total cost of the dumb charging plan. The outcome is C_{DCW} = 996.55 DKK.

Table 5-4 Price of electricity of a winter windy weekday

Time	Price(DKK/kWh)	Time	Price(DKK/kWh)
12:00-13:00	2.24832	24:00-01:00	2.03791
13:00-14:00	2.24862	01:00-02:00	2.00052
14:00-15:00	2.24854	02:00-03:00	2.0003
15:00-16:00	2.2507	03:00-04:00	2.00067

16:00-17:00	2.25241	04:00-05:00	2.07434
17:00-18:00	2.25122	05:00-06:00	2.08178
18:00-19:00	2.24973	06:00-07:00	2.15411
19:00-20:00	2.24572	07:00-08:00	2.29499
20:00-21:00	2.251	08:00-09:00	2.24496
21:00-22:00	2.2148	09:00-10:00	2.24444
22:00-23:00	2.2145	10:00-11:00	2.24667
23:00-24:00	2.11892	11:00-12:00	2.24726

The total cost of smart charging is calculated by:

$$C_{SCW} = \sum_{m=1}^{10} (c_m \times \sum_{n=1}^{75} p_{nm}) \quad \text{(E5-3)}$$

where C_{SCW} represent the smart charging cost. The data in Figure 5-9 is used to calculate. The total cost of the smart charging in a winter windy weekday is C_{SCW}= 905.13 DKK.

By using the smart charging plan, the amount of reduction of charging cost in one day is

$$\mathrm{C}_{\mathrm{rW}} = \mathrm{C}_{\mathrm{DCW}} - \mathrm{C}_{\mathrm{SCW}} = 996.55 - 905.13 = 91.42 DKK \quad \text{(E5-4)}$$

The comparison of charging cost for dumb charging and smart charging for one day is shown in Figure 5-14.

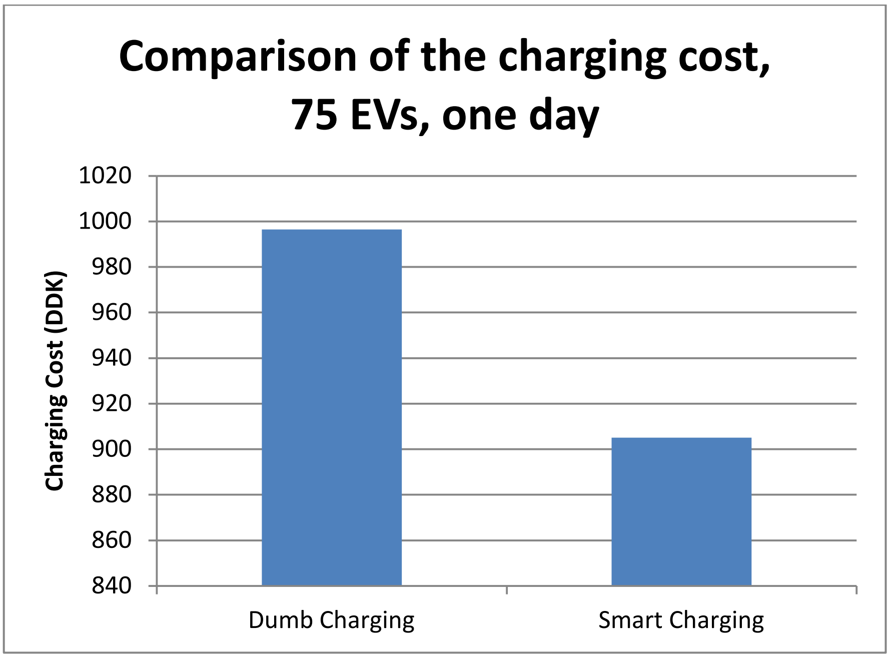

Figure 5-14 Comparison of the charging cost for one day, based on the cost of winter windy weekday

Similarly, the cost of dumb charging in a summer weekday with low wind can be calculated, C_{DCS}=1065.52 DKK. The cost of smart charging in a summer weekday with low wind is C_{SCS}=971.68 DKK.

The average cost of dumb charging of two scenarios is:

$$C_{DCA} = (996.55 + 1065.52) / 2 = 1031.04 DKK \quad \text{(E5-5)}$$

The average cost of smart charging of two scenarios is:

$$C_{SCA} = (905.13 + 971.68) / 2 = 938.41 DKK \quad \text{(E5-6)}$$

A calculation of the total reduction of smart charging for one year can be made based on those average values:

$$C_r = C_{DCA} \times 365 - C_{SCA} \times 365 = 376329.6 - 342519.65 = 33809.95 DKK \quad \text{(E5-7)}$$

So for one year, using smart charging plans can reduce approximately 33809.95 DKK for 75 EV owners. See Figure 5-15.

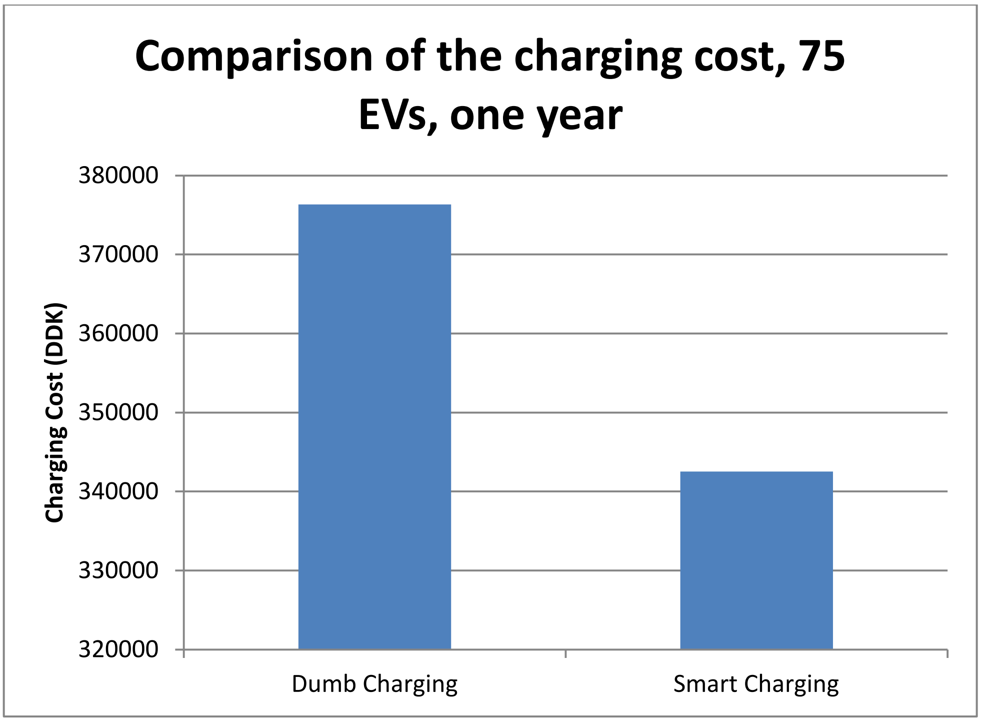

Figure 5-15 Comparison of the charging cost for one year

It can be seen that by using smart charging plans, a considerable amount of charging cost can be reduced. And in winter, summer, windy day or day with low wind speed, the smart charging plan can always bring benefit to EV owners.

5.7 Conclusion

The price of electricity is affected by the demand of consumption and wind power production etc. The optimal charging plans have been made to reduce the charging cost. Available EVs charge at the period of low electricity price. Meanwhile, the stability and reliability of the operation of the distribution grid are ensured. Two main scenarios are chosen to compare the outcome in winter windy weekday and summer weekday with low wind.

The voltage, loading and loss are all used to analyze the network operation. The smart charging plan reduce a lot of charging cost, thus the EV owners can benefit from it.

6 Conclusion

Electric vehicles are environmentally friendly and power efficient. With high wind penetration, Danish power system is suitable for promoting EVs to support the grid. The large number of charging EVs could increase the load demand significantly. This project aims to develop smart charging plans to charge EVs economically and ensure the stability of the distribution grid.

There will be about 50% electricity produced by wind in 2020 in Denmark [28]. Therefore the exceeded power would be more and EVs could support such power system as loads and energy storages. Normally when the wind production is high, the electricity price would decrease. The EV owners could charge their cars during these periods to benefit from the low price. A large number of charging EVs could also balance the production and consumption in the grid.

The investigation of base cases of the operation of the distribution grid is done in Chapter 3. The analyses are important for future conduct the smart charging plans. The main objective of the analyses is to observe the ability of the distribution grid to support charging EVs. The distribution network has 5 feeders and totally 75 houses. Each house has an EV. Scenarios are set due to the fluctuation of consumption in winter and summer, weekdays and weekends. In winter weekday, the stress of the grid reaches the highest level because of the extra consumptions in the winter, like lightning. The Feeder 4 is a long feeder with relatively more EVs connected in each cable box. Therefore the Feeder 4 has less ability to support EVs. Constructing another cable to splitting Feeder 4 into two new feeders is proved to be a solution to improve the behaviours of supporting EVs.

To make the simulations more realistic, the stochastic process is conducted in this project. The Monte Carlo Method is used to generate random data of behaviours of EVs in Chapter 4. The available charging times and the energy need of 75 EVs are obtained. A dumb charging plan is made. EVs get charged when they arrive home. Because many EVs arrive between 16:00-20:00, the voltage in the grid drops significantly. During peak time in winter, the Feeder 4 cannot support the dumb charging plan. And the charging price is also high during this period due to the high consumption.

So the optimal charging plans are made. The smart charging plans control the EVs to charge at low price time when the consumption demand is normally also low. The charging usually happens at midnight and most cars have enough available time to be fully charged. The operation of the grid meets the requirements of stability and reliability.

The calculations prove that the smart charging plans could reduce considerable charging cost for EV owners. Charging at midnight reduce the congestions during the peak time of electricity demand. The charging plans are practical and feasible for promoting development of EVs in the distribution grids.

7 Future Work

With the predicted growth of the number of EVs in the future, the reformation of the distribution grid should be studied to fulfil the demands. The contribution of large number of EVs balancing the power system could be investigated.

The issues of unbalancing, harmonics and flicker of the distribution grid could be analyzed. The information and communication technology, which is important for the smart grid operation, needs to be further studied. The dynamic studies could be done in the future.

The possibility for EVs to participate in ancillary could be analyzed. More research in the characteristic of EV batteries needs to be done in order to make better performance of EVs serving as energy storages. The V2G technique should be discussed for EVs to participate in regulating market.

Furthermore, other distribution grids could be studied. The comparisons can be used to improve the smart charging plans.

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Appendix

A. Resistance and Reactance of Lines in the Distribution Grid

Bus No.	Bus No.	Resistance(Ohm)	Reactance(Ohm)	Resistance(pu)	Reactance(pu)
1	2	0.011803	0.042906	0.011803	0.042906
2	3	0.054215	0.012742	0.078253	0.018392
3	4	0.028960	0.001504	0.041800	0.002171
3	5	0.019248	0.004524	0.027782	0.006530
5	6	0.039820	0.002068	0.057475	0.002985
5	7	0.043440	0.002256	0.062700	0.003256
5	8	0.049411	0.006048	0.071318	0.008729
5	9	0.035294	0.004320	0.050942	0.006235
8	10	0.036200	0.001880	0.052250	0.002714
8	11	0.036200	0.001880	0.052250	0.002714
9	12	0.039820	0.002068	0.057475	0.002985
9	13	0.036200	0.001880	0.052250	0.002714
8	14	0.036577	0.004477	0.052794	0.006462
9	15	0.048125	0.005890	0.069463	0.008502
14	16	0.083260	0.004324	0.120175	0.006241
14	17	0.043440	0.002256	0.062700	0.003256
14	18	0.047060	0.002444	0.067925	0.003528
14	19	0.050680	0.002632	0.073150	0.003799
15	20	0.047060	0.002444	0.067925	0.003528
15	21	0.061540	0.003196	0.088825	0.004613
15	22	0.032580	0.001692	0.047025	0.002442
15	23	0.036200	0.001880	0.052250	0.002714
2	24	0.009545	0.003324	0.013777	0.004798
24	25	0.036200	0.001880	0.052250	0.002714
24	26	0.036200	0.001880	0.052250	0.002714
24	27	0.012035	0.004191	0.017371	0.006049
27	28	0.036200	0.001880	0.052250	0.002714
27	29	0.036200	0.001880	0.052250	0.002714
27	30	0.034652	0.004241	0.050016	0.006122
27	31	0.011620	0.004046	0.016772	0.005840
30	32	0.028960	0.001504	0.041800	0.002171
30	33	0.043440	0.002256	0.062700	0.003256
30	34	0.090500	0.004700	0.130625	0.006784
31	35	0.036200	0.001880	0.052250	0.002714
31	36	0.032580	0.001692	0.047025	0.002442
31	37	0.027593	0.003377	0.039827	0.004875
31	38	0.017015	0.005925	0.024559	0.008552
37	39	0.043440	0.002256	0.062700	0.003256
37	40	0.039820	0.002068	0.057475	0.002985
38	41	0.032580	0.001692	0.047025	0.002442
38	42	0.039820	0.002068	0.057475	0.002985
38	43	0.050680	0.002632	0.073150	0.003799
38	44	0.011413	0.003974	0.016473	0.005736
44	45	0.039820	0.002068	0.057475	0.002985
44	46	0.032580	0.001692	0.047025	0.002442
44	47	0.014110	0.004913	0.020366	0.007092
44	48	0.039144	0.004791	0.056499	0.006915
47	49	0.065160	0.003384	0.094050	0.004884

47	50	0.036200	0.001880	0.052250	0.002714
47	51	0.036200	0.001880	0.052250	0.002714
48	52	0.036200	0.001880	0.052250	0.002714
48	53	0.054300	0.002820	0.078375	0.004070
48	54	0.079640	0.004136	0.114950	0.005970
2	55	0.097525	0.003396	0.140765	0.004902
55	56	0.036200	0.001880	0.052250	0.002714
2	57	0.045028	0.001568	0.064992	0.002263
57	58	0.081450	0.004230	0.117563	0.006105
57	59	0.054300	0.002820	0.078375	0.004070
57	60	0.036200	0.001880	0.052250	0.002714
57	61	0.072400	0.003760	0.104500	0.005427
57	62	0.045561	0.005576	0.065761	0.008049
57	63	0.046202	0.005655	0.066687	0.008162
62	64	0.036200	0.001880	0.052250	0.002714
62	65	0.010860	0.005640	0.015675	0.008141
62	66	0.079640	0.004136	0.114950	0.005970
63	67	0.054300	0.002820	0.078375	0.004070
63	68	0.036200	0.001880	0.052250	0.002714
63	69	0.043440	0.002256	0.062700	0.003256
63	70	0.015148	0.005275	0.021864	0.007613
70	71	0.061540	0.003196	0.088825	0.004613
70	72	0.036200	0.001880	0.052250	0.002714
70	73	0.090500	0.004700	0.130625	0.006784
70	74	0.035294	0.004320	0.050942	0.006235
70	75	0.025343	0.005956	0.036580	0.008597
74	76	0.034652	0.004241	0.050016	0.006122
75	77	0.047060	0.002444	0.067925	0.003528
75	78	0.036200	0.001880	0.052250	0.002714
75	79	0.058395	0.007147	0.084285	0.010316
75	80	0.055186	0.006754	0.079654	0.009749
75	81	0.020210	0.004750	0.029171	0.006856
79	82	0.054300	0.002820	0.078375	0.004070
79	83	0.036200	0.001880	0.052250	0.002714
79	84	0.036200	0.001880	0.052250	0.002714
80	85	0.036200	0.001880	0.052250	0.002714
80	86	0.036200	0.001880	0.052250	0.002714
80	87	0.072400	0.003760	0.104500	0.005427
81	88	0.043440	0.002256	0.062700	0.003256
81	89	0.090500	0.004700	0.130625	0.006784
81	90	0.035294	0.004320	0.050942	0.006235
81	91	0.021818	0.002670	0.031491	0.003854
90	92	0.043440	0.002256	0.062700	0.003256
90	93	0.036200	0.001880	0.052250	0.002714
90	94	0.054300	0.002820	0.078375	0.004070
90	95	0.072400	0.003760	0.104500	0.005427
90	96	0.036200	0.001880	0.052250	0.002714
91	97	0.054300	0.002820	0.078375	0.004070
91	98	0.036200	0.001880	0.052250	0.002714
91	99	0.042352	0.005184	0.061130	0.007482
99	100	0.036200	0.001880	0.052250	0.002714
99	101	0.090500	0.004700	0.130625	0.006784
99	102	0.072400	0.003760	0.104500	0.005427
99	103	0.072400	0.003760	0.104500	0.005427

2	104	0.030160	0.003691	0.043532	0.005328
104	105	0.054300	0.002820	0.078375	0.004070
104	106	0.090500	0.004700	0.130625	0.006784
104	107	0.090500	0.004700	0.130625	0.006784

B. Total basic load for 75 houses [35]

Hour	Winter Weekday	Winter Weekend	Summer Weekday	Summer Weekend
1	28.2500%	17.3636%	14.4773%	12.6591%
2	21.5909%	12.7500%	13.0682%	10.6591%
3	19.9773%	12.9545%	12.1591%	10.2045%
4	17.7273%	12.3409%	11.5682%	9.7045%
5	16.8636%	12.5455%	11.4091%	9.7045%
6	17.4318%	14.6818%	10.2273%	13.0455%
7	21.1818%	24.1364%	11.7727%	23.5227%
8	27.4773%	32.6136%	15.5909%	25.4318%
9	43.7045%	26.4545%	17.4091%	19.4773%
10	53.3636%	21.5682%	21.0682%	16.6364%
11	57.6364%	22.0227%	21.7955%	13.8636%
12	56.9318%	22.5682%	24.8864%	13.9773%
13	58.8409%	23.9091%	26.7727%	15.5000%
14	54.9545%	23.0455%	25.6364%	16.4091%
15	64.8864%	22.5455%	25.8409%	18.1818%
16	78.1818%	27.6818%	25.1818%	23.9545%
17	92.1591%	43.4545%	27.1818%	27.1591%
18	100.0000%	66.6818%	44.0909%	37.7500%
19	69.6818%	65.6591%	41.6591%	35.5682%
20	54.6818%	62.6364%	35.1591%	41.1136%
21	52.9545%	52.6136%	29.1818%	38.0909%
22	47.7955%	46.0000%	29.4091%	36.6364%
23	47.7045%	34.2500%	26.7955%	27.7273%
24	41.2955%	26.5682%	20.0000%	18.4545%

C. Distribution of Driving Distance [38]

Driving Distance(km)	Mon	Tue	Wed	Thu	Fri
0	0.429	0.417	0.4007	0.4132	0.393
10	0.13	0.12	0.1305	0.1252	0.131
20	0.109	0.108	0.1061	0.1109	0.109
30	0.0734	0.0769	0.075	0.0741	0.0748
40	0.0509	0.0589	0.0577	0.057	0.0537
50	0.0454	0.0471	0.0479	0.0425	0.0493
60	0.0319	0.0334	0.0346	0.0332	0.036
70	0.0231	0.0241	0.0276	0.0248	0.0251
80	0.022	0.0215	0.0199	0.023	0.0188
90	0.0126	0.0147	0.0135	0.0166	0.0172
100	0.0317	0.0284	0.0361	0.0332	0.034
150	0.0201	0.0225	0.0229	0.0196	0.0272
200	0.0079	0.0115	0.012	0.0111	0.0126
250	0.0058	0.0051	0.0058	0.0059	0.0052
300	0.0025	0.0024	0.0021	0.0043	0.0035
350	0.0009	0.0035	0.0022	0.0011	0.0037
400	0.0008	0.0011	0.0022	0.0011	0.0024
450	0.0009	0.0005	0.0003	0.0004	0.0011
500	0.0002	0.001	0.001	0.0013	0.0007
600	0.0005	0.0013	0.0006	0.0005	0.0006
700	0.0005	0.0005	0.0006	0.0007	0.0004
800	0	0.0002	0.0002	0.0004	0.0004
900	0.0002	0.0003	0.0003	0	0.0002
1000	0.0002	0.0002	0	0	0.0002

Driving Distance	Sat	Sun	Holiday
0	0.5003	0.589	0.628
10	0.1347	0.1001	0.1123
20	0.0886	0.0691	0.0626
30	0.0569	0.0481	0.0442
40	0.0408	0.0354	0.0184
50	0.0339	0.0317	0.0276
60	0.0238	0.0213	0.0239
70	0.0189	0.0136	0.011
80	0.0172	0.0154	0.0166
90	0.0118	0.0077	0.0037
100	0.028	0.0213	0.0166
150	0.0192	0.0185	0.0129
200	0.0098	0.0114	0.011
250	0.0052	0.0063	0.0074
300	0.0041	0.0033	0.0018
350	0.0027	0.002	0
400	0.0017	0.0013	0
450	0.0007	0.002	0
500	0.0005	0.0009	0.0018
600	0.001	0.0008	0
700	0	0.0002	0
800	0	0.0006	0
900	0.0002	0	0
1000	0	0	0

D. Table of the Dumb Charging plan

	06:00-07:00	07:00-08:00	08:00-09:00	09:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00	05:00-06:00
EV1	0	0	0	0	0	0	0	0	0	0	0.64	0	0	0	0	0	0	0	0	0	0	0	0	0
EV2	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0
EV3	0	0	0	0	0	0	0	0	0	0	0	0	0	1.18	0	0	0	0	0	0	0	0	0	0
EV4	0	0	0	0	0	0	5.44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV5	0	0	0	0	0	0	0	0	0	0	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0
EV6	0	0	0	0	0	0	0	0	0	11	2.66	0	0	0	0	0	0	0	0	0	0	0	0	0
EV7	0	0	0	0	0	0	0	0	0	0	0	0.27	0	0	0	0	0	0	0	0	0	0	0	0
EV8	0	0	0	0	0	0	0	0.38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV9	0	0	0	0	0	0	0	0	0	0	0	0.67	0	0	0	0	0	0	0	0	0	0	0	0
EV10	0	0	0	0	0	0	0	0	0	0	0	0	0	7.26	0	0	0	0	0	0	0	0	0	0
EV11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.21	0	0	0	0	0	0	0
EV12	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	4.6	0	0	0	0	0	0	0	0
EV13	0	0	0	0	0	0	0	0	0	0	0	4.12	0	0	0	0	0	0	0	0	0	0	0	0
EV14	0	0	0	0	0	0	0	0	6.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV15	0	0	0	0	0	0	0	0	0	0	0	0	10.63	0	0	0	0	0	0	0	0	0	0	0
EV16	0	0	0	0	0	0	0	0	9.89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV17	0	0	0	0	4.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV18	0	0	0	0	0	0	0	0	0	0	0	0	11	3.7	0	0	0	0	0	0	0	0	0	0
EV19	0	0	0	0	0	0	2.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV20	0	0	0	0	0	0	0	0	0	0	0	3.51	0	0	0	0	0	0	0	0	0	0	0	0
EV21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.41	0	0	0	0	0	0	0	0
EV22	0	0	0	0	0	0	0	0	0	1.38	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV23	0	0	0	0	0	0	1.84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV24	0	0	11	11	1.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV25	0	0	0	0	0	0	0	0	0	0	0	0	0	11	6.19	0	0	0	0	0	0	0	0	0
EV26	0	0	0	0	0	0	0	0	0	0	0	5.91	0	0	0	0	0	0	0	0	0	0	0	0
EV27	0	0	0	0	0	0	0	0	0	2.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV28	0	0	0	0	0	0	0	0	0	0	0	0	1.71	0	0	0	0	0	0	0	0	0	0	0
EV29	0	0	0	0	0	0	0	4.38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV30	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0	0	0	0	0	0	0	0	0	0	0
EV31	0	0	0	0	0	0	0	0	0	0	0	1.25	0	0	0	0	0	0	0	0	0	0	0	0
EV32	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0
EV33	0	0	0	0	0	0	0	2.82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV34	0	0	0	0	0	0	0	0	0	0	5.8	0	0	0	0	0	0	0	0	0	0	0	0	0
EV35	0	0	0	0	0	0	0	0	0	0	0	0	0	11	2.81	0	0	0	0	0	0	0	0	0
EV36	0	0	0	0	0	2.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV37	0	0	0	0	0	0	0	0.88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV38	0	0	0	0	0	0	0	4.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV39	0	0	0	0	0	0	0	0	0	0	0	0	11	3.99	0	0	0	0	0	0	0	0	0	0
EV40	0	0	0	0	0	0	0	0	7.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.99	0	0	0	0	0	0	0	0
EV42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.75	0	0	0	0	0	0	0
EV43	0	0	0	0	0	0	0	0	3.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV44	0	0	0	0	0	0	0	0	0	0	0	0	0	2.87	0	0	0	0	0	0	0	0	0	0
EV45	0	0	0	0	0	0	0	0	0	0	0	0	0	3.68	0	0	0	0	0	0	0	0	0	0
EV46	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.97	0	0	0	0	0	0	0	0
EV48	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV49	0	0	0	0	0	1.84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV50	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV51	0	0	0	0	0	0	0	0	0	0	0	0	7.8	0	0	0	0	0	0	0	0	0	0	0
EV52	0	0	0	0	0	0	0	0	0	1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV53	0	0	0	0	0	6.57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.58	0	0	0	0	0	0	0	0
EV55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.41	0	0	0	0	0	0	0	0	0
EV56	0	0	0	0	0	0	0	0	0	0	11	6.28	0	0	0	0	0	0	0	0	0	0	0	0
EV57	0	0	0	0	0	0	0	7.41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV58	0	0	0	0	0	0	0	0	0	0	0	0	0	8.3	0	0	0	0	0	0	0	0	0	0
EV59	0	0	0	0	0	0	0	0	1.61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV60	0	0	0	0	0	0	0	0	0	0	0	0.54	0	0	0	0	0	0	0	0	0	0	0	0
EV61	0	0	0	0	0	0	0	0	0	0	0	0	0	5.43	0	0	0	0	0	0	0	0	0	0
EV62	0	0	0	0	0	0	0	0	0	0	0	0.87	0	0	0	0	0	0	0	0	0	0	0	0
EV63	0	0	0	1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV64	0	0	0	0	0	0	0	0	0	0	0	0	11	11	11	4.62	0	0	0	0	0	0	0	0
EV65	0	0	0	0	0	0	0	0	0	2.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV66	0	0	0	0	0	0	0	0	0	4.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV67	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24	0	0	0	0	0	0	0	0	0	0
EV68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	11	11	10.9	0	0	0	0
EV69	0	0	0	0	0	0	0	0	0	0	0	0	0	3.62	0	0	0	0	0	0	0	0	0	0
EV70	0	0	0	0	0	0	0	0	0	0	4.13	0	0	0	0	0	0	0	0	0	0	0	0	0
EV71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.64	0	0	0	0	0	0	0	0	0
EV72	0	0	0	0	0	0	0	0	0	0	0.93	0	0	0	0	0	0	0	0	0	0	0	0	0
EV73	0	0	0	0	0	0	0	0	0	5.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV74	0	0	0	0	0	0	0	0	0	0	0	0	0	0.85	0	0	0	0	0	0	0	0	0	0
EV75	0	0	0	0	0	0	3.51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

E. The relationship between Elspot price and wind production

Winter Weekday					
Hour	Elspot Price,	Wind Production,	Hour	Elspot Price,	Elspot Price,
13	248.32	2297.8	13	747.05	52.1
14	248.62	2462.6	14	743.92	46.7
15	248.54	2568.4	15	742.66	52.7
16	250.7	2561	16	784.21	61.7
17	252.41	2496.7	17	900.17	75.7
18	251.22	2354.7	18	1129.04	109.2
19	249.73	2328.5	19	1560.99	161.3
20	245.72	2291.1	20	1262.92	210
21	251	2028.1	21	1011	234.5
22	214.8	1784.6	22	538.91	251.1
23	214.5	1664	23	371.96	299
24	118.92	1486.9	24	327.14	302.9
1	37.91	1289.4	1	326.44	336.7
2	0.52	1150.5	2	318.56	426.2
3	0.3	1195.2	3	316.62	513.6
4	0.67	1447.6	4	315.36	631
5	74.34	1643.4	5	323.02	895.9
6	81.78	1876.1	6	335.35	1069.9
7	154.11	2078.3	7	448.92	1067.6
8	294.99	2154	8	512.99	1117.3
9	244.96	2273.9	9	705.34	1239.9
10	244.44	2340.1	10	642.17	1182.3
11	246.67	2352	11	552.09	1088.1
12	247.26	2368.1	12	587.24	976

Winter Weekend					
Hour	Elspot Price,	Wind Production,	Hour	Elspot Price,	Elspot Price,
13	261.35	2058.2	13	358.2	107.3
14	259.64	2183.7	14	336.05	91.5
15	258.45	2264.4	15	328.69	65.2
16	258.3	2313.1	16	334.04	61.4
17	260.53	2313.3	17	378.34	75.5
18	266.7	2277	18	507.67	107.9
19	267.74	2137.8	19	769.02	196.9
20	264.84	1978	20	498.83	294.8
21	261.5	1656.2	21	386.29	378.4
22	253.32	1268.9	22	356.34	482.7
23	255.4	1008.4	23	352.47	596.3
24	242.77	1062.1	24	322.89	715.6
1	231.98	1172.5	1	329.08	781.8
2	226.56	1263.6	2	318.75	781.3
3	222.47	1284.6	3	307.15	738.6
4	224.33	1285.7	4	305.74	683.7
5	227.97	1249.6	5	306.56	713.9
6	236.96	1192.8	6	302.47	730.8
7	237.34	1173.8	7	300.69	741.5
8	234.96	1296.3	8	301.65	798.5
9	233.4	1443.8	9	301.5	868.2
10	253.99	1710.8	10	320.98	871.8

11	260.53	2071.9	11	318.3	849.1
12	259.49	2339.9	12	318.3	934.2
Summer Weekday					
Hour	Elspot Price,	Wind Production,	Hour	Elspot Price,	Elspot Price,
13	95.83	2042.6	13	308.63	1194
14	93.3	2106.6	14	421.71	1042.8
15	87.27	2117.4	15	409.97	763.5
16	81.84	2156.3	16	401.64	525.1
17	79.53	2149.8	17	394.58	385
18	77.38	2085.3	18	415.84	286
19	76.48	2050.5	19	438	230.3
20	74.7	1958.1	20	394.2	166.9
21	75.07	1804.6	21	356.81	120.7
22	74.85	1727.5	22	345.43	99.9
23	75.44	1674.7	23	364.02	80
24	72.47	1696	24	312.86	53.9
1	74.07	1698.9	1	173.39	45.2
2	72.06	1680.3	2	167.07	78.8
3	70.2	1629	3	163.28	88.2
4	68.56	1614.6	4	160.83	89.6
5	68.86	1560.3	5	160.9	91.2
6	72.66	1537.4	6	170.64	120.3
7	83	1517	7	308.72	161.6
8	97.82	1550.3	8	408.95	118
9	103.85	1708.1	9	445.9	97.1
10	125.36	1821.6	10	440.7	131.8
11	125.96	1884.7	11	454.9	188.1
12	125.81	1838.3	12	455.05	221.5
Summer Weekend					
Hour	Elspot Price,	Wind Production,	Hour	Elspot Price,	Elspot Price,
13	82.71	903.8	13	327.36	11.5
14	80.03	957.2	14	291.63	24.5
15	77.58	1071.9	15	255.9	44.2
16	75.35	1157.9	16	255.83	56.4
17	75.5	1279.8	17	292.82	66.2
18	78.99	1345.4	18	326.99	65.2
19	79.44	1359.1	19	347.68	53.7
20	78.1	1160.6	20	372.02	41.1
21	78.32	900.5	21	358.7	30.7
22	77.5	694.7	22	358.92	33.4
23	83.23	616.9	23	361.08	41.6
24	80.93	669.8	24	327.21	50.9
1	86.59	674.8	1	238.34	41.3
2	83.17	577.8	2	208.34	42.7
3	81.98	586	3	155.34	50.2
4	82.13	501.4	4	142.02	60.2
5	81.76	435.2	5	139.64	55.8
6	81.24	451.8	6	154.3	52.5
7	82.87	360	7	139.56	64.7
8	86.82	329.7	8	158.99	65.3
9	86.67	409.4	9	148.57	49.8
10	110.92	453.4	10	157.35	59.6

11	163.67	459.3	11	152.52	70.4
12	111	592	12	153.41	71.1

F. The Price used in Optimization

	Price(DKK/KWh)			
Hour	Winter Windy Weekday	Winter Weekday, Low Wind	Winter Windy Weekend	Winter Weekend, Low Wind
13	2.24832	2.74705	2.26135	2.35820
14	2.24862	2.74392	2.25964	2.33605
15	2.24854	2.74266	2.25845	2.32869
16	2.25070	2.78421	2.25830	2.33404
17	2.25241	2.90017	2.26053	2.37834
18	2.25122	3.12904	2.26670	2.50767
19	2.24973	3.56099	2.26774	2.76902
20	2.24572	3.26292	2.26484	2.49883
21	2.25100	3.01100	2.26150	2.38629
22	2.21480	2.53891	2.25332	2.35634
23	2.21450	2.37196	2.25540	2.35247
24	2.11892	2.32714	2.24277	2.32289
1	2.03791	2.32644	2.23198	2.32908
2	2.00052	2.31856	2.22656	2.31875
3	2.00030	2.31662	2.22247	2.30715
4	2.00067	2.31536	2.22433	2.30574
5	2.07434	2.32302	2.22797	2.30656
6	2.08178	2.33535	2.23696	2.30247
7	2.15411	2.44892	2.23734	2.30069
8	2.29499	2.51299	2.23496	2.30165
9	2.24496	2.70534	2.23340	2.30150
10	2.24444	2.64217	2.25399	2.32098
11	2.24667	2.55209	2.26053	2.31830
12	2.24726	2.58724	2.25949	2.31830
	Price(DKK/KWh)			
Hour	Summer Windy Weekday	Summer Weekday, Low Wind	Summer Windy Weekend	Summer Weekend, Low Wind
13	2.09583	2.30863	2.08271	2.32736
14	2.09330	2.42171	2.08003	2.29163
15	2.08727	2.40997	2.07758	2.25590
16	2.08184	2.40164	2.07535	2.25583
17	2.07953	2.39458	2.07550	2.29282
18	2.07738	2.41584	2.07899	2.32699
19	2.07648	2.43800	2.07944	2.34768
20	2.07470	2.39420	2.07810	2.37202
21	2.07507	2.35681	2.07832	2.35870
22	2.07485	2.34543	2.07750	2.35892
23	2.07544	2.36402	2.08323	2.36108
24	2.07247	2.31286	2.08093	2.32721
1	2.07407	2.17339	2.08659	2.23834
2	2.07206	2.16707	2.08317	2.20834
3	2.07020	2.16328	2.08198	2.15534
4	2.06856	2.16083	2.08213	2.14202

5	2.06886	2.16090	2.08176	2.13964
6	2.07266	2.17064	2.08124	2.15430
7	2.08300	2.30872	2.08287	2.13956
8	2.09782	2.40895	2.08682	2.15899
9	2.10385	2.44590	2.08667	2.14857
10	2.12536	2.44070	2.11092	2.15735
11	2.12596	2.45490	2.16367	2.15252
12	2.12581	2.45505	2.11100	2.15341

G. Part of Matlab source code for Load Flow

```
clc
clear all
basekva=400; accuracy=0.001; maxiter=10;
%SummerWed
%HLoadHour=[0.144772727 0.130681818 0.121590909 0.115681818 0.114090909 0.102272727
0.117727273 0.155909091 0.174090909 0.210681818 0.217954545 0.248863636 0.267727273
0.256363636 0.258409091 0.251818182 0.271818182 0.440909091 0.416590909 0.351590909
0.291818182 0.294090909 0.267954545 0.2];

%WinterWed
HLoadHour=[0.2825   0.215909091 0.199772727 0.177272727 0.168636364 0.174318182
0.211818182 0.274772727 0.437045455 0.533636364 0.576363636 0.569318182 0.588409091
0.549545455 0.648863636 0.781818182 0.921590909 1   0.696818182 0.546818182
0.529545455 0.477954545 0.477045455 0.412954545];

ECharge=zeros(75,24);
V103=zeros(1,24);

EyAll=[0.64 0.03    1.18    5.44    2.30    13.66   0.27    0.38    0.67    7.26
2.21    26.60   4.12    6.05    10.63   9.89    4.15    14.70   2.17    3.51    1.41
1.38    1.84    23.13   17.19   5.91    2.83    1.71    4.38    0.66    1.25    0.07
2.82    5.80    13.81   2.07    0.88    4.14    14.99   7.11    10.99   6.75    3.91
2.87    3.68    0.40    2.97    0.14    1.84    0.10    7.80    1.55    6.57    1.58
1.41    17.28   7.41    8.30    1.61    0.54    5.43    0.87    1.55    37.62   2.14
4.70    0.24    54.90   3.62    4.13    3.64    0.93    5.85    0.85    3.51];
%AT=[17 17  20  13  20  16  18  14  18  20  23  20  18  15  19  15  11  19  13  18  22
16  13  9   20  18  16  19  14  19  18  17  14  17  20  12  14  14  19  15  22  23  15
20  20  13  22  15  12  10  19  16  12  22  21  17  14  20  15  18  20  18  10  19  16
16  20  22  20  17  21  17  16  20  13];
AT=[11  11  14  7   14  10  12  8   12  14  17  14  12  9   13  9   5   13  7   12  16
10  7   3   14  12  10  13  8   13  12  11  8   11  14  6   8   8   13  9   16  17  9
14  14  7   16  9   6   4   13  10  6   16  15  11  8   14  9   12  14  12  4   13  10
10  14  16  14  11  15  11  10  14  7];

EyR=zeros(1,75);
for h=1:24
    Ey=zeros(1,75)+EyR;
    for i=1:75
        if Ey(i)>11
            EyR(i)=Ey(i)-11;
            Ey(i)=11;
        else
            EyR(i)=0;
        end
        if AT(i)==h
            Ey(i)=Ey(i)+EyAll(i);
            if Ey(i)>11
                EyR(i)=Ey(i)-11;
                Ey(i)=11;
            end
        end
    end

    ECharge(:,h)=Ey';

    PHLoad75=[1.74 1.20 1.67 1.70 1.17 2.20 0.68 2.11 1.61 0.79 1.72 3.72 1.86 1.82
1.84 1.97 1.46 1.28 1.28 1.15 1.60 2.31 2.22 2.44 1.26 1.39 2.03 0.56 1.19 1.32 2.13
1.36 1.48 0.57 1.37 2.47 0.88 1.90 0.90 1.13 1.30 1.11 1.69 1.33 2.28 1.48 1.28 0.59
```

```
1.38 1.10 1.75 1.74 1.01 1.01 0.94 0.77 1.44 1.06 0.90 1.43 1.03 1.11 1.41 1.73 1.14
0.22 1.17 1.02 2.01 1.44 1.59 2.24 2.31 1.01 1.01];
    PHLoad=[0 0 0 1.74 0 1.20 1.67 0 0 1.70 1.17 2.20 0.68 0 0 2.11 1.61 0.79 1.72
3.72 1.86 1.82 1.84 0 1.97 1.46 0 1.28 1.28 0 0 1.15 1.60 2.31 2.22 2.44 0 0 1.26 1.39
2.03 0.56 1.19 0 1.32 2.13 0 0 1.36 1.48 0.57 1.37 2.47 0.88 0 1.90 0 0.90 1.13 1.30
1.11 0 0 1.69 1.33 2.28 1.48 1.28 0.59 0 1.38 1.10 1.75 0 0 0 1.74 1.01 0 0 0 1.01
0.94 0.77 1.44 1.06 0.90 1.43 1.03 0 0 1.11 1.41 1.73 1.14 0.22 1.17 1.02 0 2.01 1.44
1.59 2.24 0 2.31 1.01 1.01];
    Pload75 =HLoadHour(h)*PHLoad75+Ey;
    PHLoad=HLoadHour(h)*PHLoad;
    n=1;
    for m=1:107
        if PHLoad(m)==0
            Pload(m)=0;
        else
            Pload(m)=Pload75(n);
            n=n+1;
        end
    end
    Qload = [PHLoad(1)*0.251 PHLoad(2)*0.251 PHLoad(3)*0.251 PHLoad(4)*0.251
PHLoad(5)*0.251 PHLoad(6)*0.251 PHLoad(7)*0.251 PHLoad(8)*0.251 PHLoad(9)*0.251
PHLoad(10)*0.251 PHLoad(11)*0.251 PHLoad(12)*0.251 PHLoad(13)*0.251 PHLoad(14)*0.251
PHLoad(15)*0.251 PHLoad(16)*0.251 PHLoad(17)*0.251 PHLoad(18)*0.251 PHLoad(19)*0.251
PHLoad(20)*0.251 PHLoad(21)*0.251 PHLoad(22)*0.251   PHLoad(23)*0.251 PHLoad(24)*0.251
PHLoad(25)*0.251 PHLoad(26)*0.251 PHLoad(27)*0.251 PHLoad(28)*0.251 PHLoad(29)*0.251
PHLoad(30)*0.251 PHLoad(31)*0.251 PHLoad(32)*0.251 PHLoad(33)*0.251 PHLoad(34)*0.251
PHLoad(35)*0.251 PHLoad(36)*0.251 PHLoad(37)*0.251 PHLoad(38)*0.251 PHLoad(39)*0.251
PHLoad(40)*0.251 PHLoad(41)*0.251 PHLoad(42)*0.251 PHLoad(43)*0.251 PHLoad(44)*0.251
PHLoad(45)*0.251 PHLoad(46)*0.251 PHLoad(47)*0.251 PHLoad(48)*0.251 PHLoad(49)*0.251
PHLoad(50)*0.251 PHLoad(51)*0.251 PHLoad(52)*0.251 PHLoad(53)*0.251 PHLoad(54)*0.251
PHLoad(55)*0.251 PHLoad(56)*0.251 PHLoad(57)*0.251 PHLoad(58)*0.251 PHLoad(59)*0.251
PHLoad(60)*0.251 PHLoad(61)*0.251 PHLoad(62)*0.251 PHLoad(63)*0.251 PHLoad(64)*0.251
PHLoad(65)*0.251 PHLoad(66)*0.251 PHLoad(67)*0.251 PHLoad(68)*0.251 PHLoad(69)*0.251
PHLoad(70)*0.251 PHLoad(71)*0.251 PHLoad(72)*0.251 PHLoad(73)*0.251 PHLoad(74)*0.251
PHLoad(75)*0.251 PHLoad(76)*0.251 PHLoad(77)*0.251 PHLoad(78)*0.251 PHLoad(79)*0.251
PHLoad(80)*0.251 PHLoad(81)*0.251 PHLoad(82)*0.251 PHLoad(83)*0.251 PHLoad(84)*0.251
PHLoad(85)*0.251 PHLoad(86)*0.251 PHLoad(87)*0.251 PHLoad(88)*0.251 PHLoad(89)*0.251
PHLoad(90)*0.251 PHLoad(91)*0.251 PHLoad(92)*0.251 PHLoad(93)*0.251 PHLoad(94)*0.251
PHLoad(95)*0.251 PHLoad(96)*0.251 PHLoad(97)*0.251 PHLoad(98)*0.251 PHLoad(99)*0.251
PHLoad(100)*0.251 PHLoad(101)*0.251    PHLoad(102)*0.251 PHLoad(103)*0.251
PHLoad(104)*0.251 PHLoad(105)*0.251 PHLoad(106)*0.251 PHLoad(107)*0.251];
    counter=1;

%        Bus Bus  Voltage Angle   ---Load---- -------Generator----- Injected
%        No  code Mag.    Degree  kW          kvar        kW   kvar Qmin Qmax     Mvar
busdata=[1   1    1.0     0.0     Pload(1)    Qload(1)    0.0  0.0   0    0        0
         2   0    1.0     0.0     Pload(2)    Qload(2)    0.0  0.0   0    0        0
         3   0    1.0     0.0     Pload(3)    Qload(3)    0.0  0.0   0    0        0
         4   0    1.0     0.0     Pload(4)    Qload(4)    0.0  0.0   0    0        0
         5   0    1.0     0.0     Pload(5)    Qload(5)    0.0  0.0   0    0        0
         6   0    1.0     0.0     Pload(6)    Qload(6)    0.0  0.0   0    0        0
         7   0    1.0     0.0     Pload(7)    Qload(7)    0.0  0.0   0    0        0
         8   0    1.0     0.0     Pload(8)    Qload(8)    0.0  0.0   0    0        0
         9   0    1.0     0.0     Pload(9)    Qload(9)    0.0  0.0   0    0        0
        10   0    1.0     0.0     Pload(10)   Qload(10)   0.0  0.0   0    0        0
        11   0    1.0     0.0     Pload(11)   Qload(11)   0.0  0.0   0    0        0
        12   0    1.0     0.0     Pload(12)   Qload(12)   0.0  0.0   0    0        0
        13   0    1.0     0.0     Pload(13)   Qload(13)    0    0    0    0        0
        14   0    1.0     0.0     Pload(14)   Qload(14)    0    0    0    0        0
        15   0    1.0     0.0     Pload(15)   Qload(15)    0    0    0    0        0
        16   0    1.0     0.0     Pload(16)   Qload(16)    0    0    0    0        0
        17   0    1.0     0.0     Pload(17)   Qload(17)   0.0  0.0   0    0        0
        18   0    1.0     0.0     Pload(18)   Qload(18)   0.0  0.0   0    0        0
        19   0    1.0     0.0     Pload(19)   Qload(19)   0.0  0.0   0    0        0
        20   0    1.0     0.0     Pload(20)   Qload(20)   0.0  0.0   0    0        0
        21   0    1.0     0.0     Pload(21)   Qload(21)   0.0  0.0   0    0        0
        22   0    1.0     0.0     Pload(22)   Qload(22)   0.0  0.0   0    0        0
        23   0    1.0     0.0     Pload(23)   Qload(23)   0.0  0.0   0    0        0
        24   0    1.0     0.0     Pload(24)   Qload(24)   0.0  0.0   0    0        0
        25   0    1.0     0.0     Pload(25)   Qload(25)   0.0  0.0   0    0        0
        26   0    1.0     0.0     Pload(26)   Qload(26)   0.0  0.0   0    0        0
        27   0    1.0     0.0     Pload(27)   Qload(27)   0.0  0.0   0    0        0
        28   0    1.0     0.0     Pload(28)   Qload(28)   0.0  0.0   0    0        0
        29   0    1.0     0.0     Pload(29)   Qload(29)   0.0  0.0   0    0        0
        30   0    1.0     0.0     Pload(30)   Qload(30)   0.0  0.0   0    0        0
        31   0    1.0     0.0     Pload(31)   Qload(31)   0.0  0.0   0    0        0
        32   0    1.0     0.0     Pload(32)   Qload(32)   0.0  0.0   0    0        0
```

```
33   0    1.0     0.0     Pload(33)  Qload(33)    0    0    0   0       0
34   0    1.0     0.0     Pload(34)  Qload(34)    0    0    0   0       0
35   0    1.0     0.0     Pload(35)  Qload(35)    0    0    0   0       0
36   0    1.0     0.0     Pload(36)  Qload(36)    0    0    0   0       0
37   0    1.0     0.0     Pload(37)  Qload(37)  0.0  0.0    0   0       0
38   0    1.0     0.0     Pload(38)  Qload(38)  0.0  0.0    0   0       0
39   0    1.0     0.0     Pload(39)  Qload(39)  0.0  0.0    0   0       0
40   0    1.0     0.0     Pload(40)  Qload(40)  0.0  0.0    0   0       0
41   0    1.0     0.0     Pload(41)  Qload(41)  0.0  0.0    0   0       0
42   0    1.0     0.0     Pload(42)  Qload(42)  0.0  0.0    0   0       0
43   0    1.0     0.0     Pload(43)  Qload(43)  0.0  0.0    0   0       0
44   0    1.0     0.0     Pload(44)  Qload(44)  0.0  0.0    0   0       0
45   0    1.0     0.0     Pload(45)  Qload(45)  0.0  0.0    0   0       0
46   0    1.0     0.0     Pload(46)  Qload(46)  0.0  0.0    0   0       0
47   0    1.0     0.0     Pload(47)  Qload(47)  0.0  0.0    0   0       0
48   0    1.0     0.0     Pload(48)  Qload(48)  0.0  0.0    0   0       0
49   0    1.0     0.0     Pload(49)  Qload(49)  0.0  0.0    0   0       0
50   0    1.0     0.0     Pload(50)  Qload(50)  0.0  0.0    0   0       0
51   0    1.0     0.0     Pload(51)  Qload(51)  0.0  0.0    0   0       0
52   0    1.0     0.0     Pload(52)  Qload(52)  0.0  0.0    0   0       0
53   0    1.0     0.0     Pload(53)  Qload(53)  0.0  0.0    0   0       0
54   0    1.0     0.0     Pload(54)  Qload(54)  0.0  0.0    0   0       0
55   0    1.0     0.0     Pload(55)  Qload(55)  0.0  0.0    0   0       0
56   0    1.0     0.0     Pload(56)  Qload(56)  0.0  0.0    0   0       0
57   0    1.0     0.0     Pload(57)  Qload(57)  0.0  0.0    0   0       0
58   0    1.0     0.0     Pload(58)  Qload(58)  0.0  0.0    0   0       0
59   0    1.0     0.0     Pload(59)  Qload(59)  0.0  0.0    0   0       0
60   0    1.0     0.0     Pload(60)  Qload(60)  0.0  0.0    0   0       0
61   0    1.0     0.0     Pload(61)  Qload(61)  0.0  0.0    0   0       0
62   0    1.0     0.0     Pload(62)  Qload(62)  0.0  0.0    0   0       0
63   0    1.0     0.0     Pload(63)  Qload(63)  0.0  0.0    0   0       0
64   0    1.0     0.0     Pload(64)  Qload(64)  0.0  0.0    0   0       0
65   0    1.0     0.0     Pload(65)  Qload(65)  0.0  0.0    0   0       0
66   0    1.0     0.0     Pload(66)  Qload(66)  0.0  0.0    0   0       0
67   0    1.0     0.0     Pload(67)  Qload(67)  0.0  0.0    0   0       0
68   0    1.0     0.0     Pload(68)  Qload(68)  0.0  0.0    0   0       0
69   0    1.0     0.0     Pload(69)  Qload(69)  0.0  0.0    0   0       0
70   0    1.0     0.0     Pload(70)  Qload(70)  0.0  0.0    0   0       0
71   0    1.0     0.0     Pload(71)  Qload(71)  0.0  0.0    0   0       0
72   0    1.0     0.0     Pload(72)  Qload(72)  0.0  0.0    0   0       0
73   0    1.0     0.0     Pload(73)  Qload(73)  0.0  0.0    0   0       0
74   0    1.0     0.0     Pload(74)  Qload(74)  0.0  0.0    0   0       0
75   0    1.0     0.0     Pload(75)  Qload(75)  0.0  0.0    0   0       0
76   0    1.0     0.0     Pload(76)  Qload(76)  0.0  0.0    0   0       0
77   0    1.0     0.0     Pload(77)  Qload(77)  0.0  0.0    0   0       0
78   0    1.0     0.0     Pload(78)  Qload(78)  0.0  0.0    0   0       0
79   0    1.0     0.0     Pload(79)  Qload(79)  0.0  0.0    0   0       0
80   0    1.0     0.0     Pload(80)  Qload(80)  0.0  0.0    0   0       0
81   0    1.0     0.0     Pload(81)  Qload(81)  0.0  0.0    0   0       0
82   0    1.0     0.0     Pload(82)  Qload(82)  0.0  0.0    0   0       0
83   0    1.0     0.0     Pload(83)  Qload(83)  0.0  0.0    0   0       0
84   0    1.0     0.0     Pload(84)  Qload(84)  0.0  0.0    0   0       0
85   0    1.0     0.0     Pload(85)  Qload(85)  0.0  0.0    0   0       0
86   0    1.0     0.0     Pload(86)  Qload(86)  0.0  0.0    0   0       0
87   0    1.0     0.0     Pload(87)  Qload(87)  0.0  0.0    0   0       0
88   0    1.0     0.0     Pload(88)  Qload(88)  0.0  0.0    0   0       0
89   0    1.0     0.0     Pload(89)  Qload(89)  0.0  0.0    0   0       0
90   0    1.0     0.0     Pload(90)  Qload(90)  0.0  0.0    0   0       0
91   0    1.0     0.0     Pload(91)  Qload(91)  0.0  0.0    0   0       0
92   0    1.0     0.0     Pload(92)  Qload(92)  0.0  0.0    0   0       0
93   0    1.0     0.0     Pload(93)  Qload(93)  0.0  0.0    0   0       0
94   0    1.0     0.0     Pload(94)  Qload(94)  0.0  0.0    0   0       0
95   0    1.0     0.0     Pload(95)  Qload(95)  0.0  0.0    0   0       0
96   0    1.0     0.0     Pload(96)  Qload(96)  0.0  0.0    0   0       0
97   0    1.0     0.0     Pload(97)  Qload(97)  0.0  0.0    0   0       0
98   0    1.0     0.0     Pload(98)  Qload(98)  0.0  0.0    0   0       0
99   0    1.0     0.0     Pload(99)  Qload(99)  0.0  0.0    0   0       0
100  0    1.0     0.0     Pload(100) Qload(100) 0.0  0.0    0   0       0
101  0    1.0     0.0     Pload(101) Qload(101) 0.0  0.0    0   0       0
102  0    1.0     0.0     Pload(102) Qload(102) 0.0  0.0    0   0       0
103  0    1.0     0.0     Pload(103) Qload(103) 0.0  0.0    0   0       0
104  0    1.0     0.0     Pload(104) Qload(104) 0.0  0.0    0   0       0
105  0    1.0     0.0     Pload(105) Qload(105) 0.0  0.0    0   0       0
106  0    1.0     0.0     Pload(106) Qload(106) 0.0  0.0    0   0       0
107  0    1.0     0.0     Pload(106) Qload(106) 0.0  0.0    0   0       0
];
%                                     Line code
```

```
%         Bus bus   R      X     1/2 B   = 1 for lines
%         nl  nr  p.u.   p.u.   p.u.     > 1 or < 1 tr. tap at bus nl
linedata=[1 2   0.0118025   0.0429063   0   1
2   3   0.135538    0.03185575  0   1
3   4   0.0724  0.00376 0   1
3   5   0.04812 0.011309725 0   1
5   6   0.09955 0.00517 0   1
5   7   0.1086  0.00564 0   1
5   8   0.12352725  0.015118925 0   1
5   9   0.08823375  0.010799225 0   1
8   10  0.0905  0.0047  0   1
8   11  0.0905  0.0047  0   1
9   12  0.09955 0.00517 0   1
9   13  0.0905  0.0047  0   1
8   14  0.09144225  0.011191925 0   1
9   15  0.12031275  0.014726225 0   1
14  16  0.20815 0.01081 0   1
14  17  0.1086  0.00564 0   1
14  18  0.11765 0.00611 0   1
14  19  0.1267  0.00658 0   1
15  20  0.11765 0.00611 0   1
15  21  0.15385 0.00799 0   1
15  22  0.08145 0.00423 0   1
15  23  0.0905  0.0047  0   1
2   24  0.0238625   0.008309525 0   1
24  25  0.0905  0.0047  0   1
24  26  0.0905  0.0047  0   1
24  27  0.0300875   0.0104772   0   1
27  28  0.0905  0.0047  0   1
27  29  0.0905  0.0047  0   1
27  30  0.0866295   0.010602875 0   1
27  31  0.02905 0.010115925 0   1
30  32  0.0724  0.00376 0   1
30  33  0.1086  0.00564 0   1
30  34  0.22625 0.01175 0   1
31  35  0.0905  0.0047  0   1
31  36  0.08145 0.00423 0   1
31  37  0.06898275  0.008443025 0   1
31  38  0.0425375   0.0148126   0   1
37  39  0.1086  0.00564 0   1
37  40  0.09955 0.00517 0   1
38  41  0.08145 0.00423 0   1
38  42  0.09955 0.00517 0   1
38  43  0.1267  0.00658 0   1
38  44  0.02853125  0.009935275 0   1
44  45  0.09955 0.00517 0   1
44  46  0.08145 0.00423 0   1
44  47  0.035275    0.012283625 0   1
44  48  0.09785925  0.011977325 0   1
47  49  0.1629  0.00846 0   1
47  50  0.0905  0.0047  0   1
47  51  0.0905  0.0047  0   1
48  52  0.0905  0.0047  0   1
48  53  0.13575 0.00705 0   1
48  54  0.199099975 0.01034 0   1
2   55  0.2438125   0.00849015  0   1
55  56  0.0905  0.0047  0   1
2   57  0.11256875  0.003919923 0   1
57  58  0.203625    0.010575    0   1
57  59  0.13575 0.00705 0   1
57  60  0.0905  0.0047  0   1
57  61  0.181   0.0094  0   1
57  62  0.11390175  0.013940825 0   1
57  63  0.115506    0.014137175 0   1
62  64  0.0905  0.0047  0   1
62  65  0.02715 0.0141  0   1
62  66  0.199099975 0.01034 0   1
63  67  0.13575 0.00705 0   1
63  68  0.0905  0.0047  0   1
63  69  0.1086  0.00564 0   1
63  70  0.03786875  0.013186825 0   1
70  71  0.15385 0.00799 0   1
70  72  0.0905  0.0047  0   1
70  73  0.22625 0.01175 0   1
70  74  0.08823375  0.010799225 0   1
70  75  0.063358    0.01489115  0   1
74  76  0.0866295   0.010602875 0   1
```

```
75  77  0.11765 0.00611 0   1
75  78  0.0905  0.0047  0   1
75  79  0.14598675  0.0178678   0   1
75  80  0.1379655   0.01688605  0   1
75  81  0.050526    0.011875225 0   1
79  82  0.13575 0.00705 0   1
79  83  0.0905  0.0047  0   1
79  84  0.0905  0.0047  0   1
80  85  0.0905  0.0047  0   1
80  86  0.0905  0.0047  0   1
80  87  0.181   0.0094  0   1
81  88  0.1086  0.00564 0   1
81  89  0.22625 0.01175 0   1
81  90  0.08823375  0.010799225 0   1
81  91  0.0545445   0.006675875 0   1
90  92  0.1086  0.00564 0   1
90  93  0.0905  0.0047  0   1
90  94  0.13575 0.00705 0   1
90  95  0.181   0.0094  0   1
90  96  0.0905  0.0047  0   1
91  97  0.13575 0.00705 0   1
91  98  0.0905  0.0047  0   1
91  99  0.1058805   0.012959075 0   1
99  100 0.0905  0.0047  0   1
99  101 0.22625 0.01175 0   1
99  102 0.181   0.0094  0   1
99  103 0.181   0.0094  0   1
2   104 0.07539975  0.009228425 0   1
104 105 0.13575 0.00705 0   1
104 106 0.22625 0.01175 0   1
104 107 0.22625 0.01175 0   1
];
        lfybus;
        lfnewton;
        lineflow;
        busout;

        V103(h)=Vm(103);

%         for i=1:107
%             if Vm(i)<0.94
%                  pause;
%             end
%         end

end
```

H. Part of Matlab source code for generating stochastic data of driving distance

```
clc;
clear all;
d = random('Weibull',33.4061,0.798717,75,1);
hist(d,75)

Sample=[1:75]';
% xlswrite('DDRandom.xlsx',[Sample d],1,'A2')
% xlswrite('ChargingRandom.xlsx',[Sample d],1,'A2')
```

I. Part of Matlab source code for generating stochastic data of arriving times

```
clc;
clear all;
% mu=16.8461;
% sigma=3.60194;
% sample=75;
% for i=1:sample
%     at(i)=mu+sigma*randn(1);
% end
```

```
% min(at)
% max(at)
% at;
% hist(at,75);

at1=random('Normal',16.8461,3.60194,75,1);
min(at1)
max(at1)
hist(at1,75);

Sample=[1:75]';
%xlswrite('ATRandom.xlsx',[Sample at1'],1,'A2')
%xlswrite('ChargingRandom.xlsx',at1',1,'E2')
```

J. Part of Matlab source code for optimizing the charging plans

```
clc;
clear all;
x0=zeros(750,1);
lb=zeros(750,1);
ub=ones(750,1)*11;
a=eye(75,75);
b=ones(1,10);
Aeq=kron(a,b);
beq=[0.64;  0.03;   1.18;   5.44;   2.3;    13.66;  0.27;   0.38;   0.67;   7.26;
2.21;   26.6;   4.12;   6.05;   10.63;  9.89;   4.15;   14.7;   2.17;   3.51;   1.41;
1.38;   1.84;   23.13;  17.19;  5.91;   2.83;   1.71;   4.38;   0.66;   1.25;   0.07;
2.82;   5.8;    13.81;  2.07;   0.88;   4.14;   14.99;  7.11;   10.99;  6.75;   3.91;
2.87;   3.68;   0.4;    2.97;   0.14;   1.84;   0.1;    7.8;    1.55;   6.57;   1.58;
1.41;   17.28;  7.41;   8.3;    1.61;   0.54;   5.43;   0.87;   1.55;   37.62;  2.14;
4.7;    0.24;   54.9;   3.62;   4.13;   3.64;   0.93;   5.85;   0.85;   3.51];
[xopt,fopt]=fmincon(@evfun7510WWeekday,x0,[],[],Aeq,beq,lb,ub,[],optimset('Display','i
ter'));
EV=zeros(75,10);
n=1;
for i=1:75
    for j=1:10
        EV(i,j)=xopt(n);
        n=n+1;
    end
end
EV
```

K. Part of Matlab source code for improving the smart charging plans

```
clear all;
clc;
EV=[0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.6400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0300  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.1800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  5.4400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.3000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.6109  11.0000 0.0491  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.2700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.3800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.6700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  7.2600  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.2100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  9.4970  11.0000 6.1030  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.1200  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  6.0500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  10.6300 0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  9.8900  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.1500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.5014  11.0000 0.1986  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.1700  0.0000  0.0000
```

```
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.5100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.4100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.3800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.8400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  7.7778  11.0000 4.3522  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.7400  11.0000 1.4500  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  5.9100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.8300  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.7100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.3800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.6600  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.2500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.8200  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  5.8000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.7649  11.0000 0.0451  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.0700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.8800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.1400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.6197  11.0000 0.3703  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  7.1100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  10.9900 0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  6.7500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.9100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.8700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.6800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.4000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.9700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.1400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.8400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.1000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  7.8000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.5500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  6.5700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.5800  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.4100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.8171  11.0000 1.4629  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  7.4100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  8.3000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.6100  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.5400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  5.4300  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.8700  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  1.5500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  4.6200  11.0000 11.0000 11.0000 0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  2.1400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.7000  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.2400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  11.0000 11.0000 11.0000 11.0000 10.9000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.6200  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  4.1300  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.6400  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.9300  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  5.8500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.8500  0.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  3.5100  0.0000  0.0000
];

Et=0;
m=[8 7 9 6 10 5 4 3 1 2];
for j=1:9
    Et=0;
    for i=39:72
        Et=Et+EV(i,m(j));
        if Et>45
            if EV(i,m(j+1))==0
                EV(i,m(j+1))=EV(i,m(j));
            else
                if EV(i,m(j+2))==0
                    EV(i,m(j+2))=11;
                else
                    if EV(i,m(j+3))==0
                        EV(i,m(j+3))=11;
                    else
                        if EV(i,m(j+4))==0
                            EV(i,m(j+4))=11;
                        else
```

```
                            if EV(i,m(j+5))==0;
                                EV(i,m(j+5))=11;
                            end
                        end
                    end
                end
            end
            EV(i,m(j))=0;
        end
    end
end
for j=1:9
    Et=0;
    for i=1:15
        Et=Et+EV(i,m(j));
        if Et>55
            EV(i,m(j+1))=EV(i,m(j));
            EV(i,m(j))=0;
        end
    end
end
```