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Analysis of Large Scale Integration of Electric Vehicles in Nord-Trøndelag

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Problem description

With increasing environmental awareness recent years, the number of electric vehicles in Norway has increased significantly, and is expected to increase further in the future. Based Estimations performed by Grønnbil in Norway predict that there will be a four percent electric vehicle share by 2020. The sales numbers of hybrid electric vehicles are assumed to increase as well, and the predicted total share of chargeable vehicles is seven percent in 2020. The transition to electric vehicles has many benefits, but it also poses challenges to the power grid. The aim of this thesis is to illuminate some of the potential problems arising when integrating many electric vehicles into a residential area. The simulated power system is created from data provided by NTE, from an existing residential area in Steinkjer. The load constituted by the charging of electric vehicles, may result in system voltage variations. The effect of introducing smart charging in the system is evaluated. The system also includes a hypothetical wind turbine, to investigate whether or not it may help mitigating the stress on the system caused by charging of electric vehicles. The simulations are focused mostly on a 24-hour ”worst case” scenario, but more long term simulation is performed as well.

Preface

This thesis is submitted in fulfilment of the requirements for the degree of master of science (MSc) at the Norwegian University of Science and Technology (NTNU) in Trondheim. The work done in this thesis is supported by Nord-Trøndelag Elektrisitetverk (NTE), and could not have been performed without the data provided by them. Jan Foosnæs and Rune Paulsen at NTE have been very helpful in providing me with information and answering questions when needed, and I would like to thank them for their help. I would like to thank professor Marta Molinas who has been my supervisor this last year. Your help and guidance has been invaluable. Trond Toftevaag has been a strong resource for me regarding the use of Simpow, and I am grateful for all your help.

I would also like to thank my family and friends for their support throughout the course of my studies.

Abstract

In recent years, the shift in attitude towards climate and CO_2 emissions has accelerated the sale of electric and hybrid electric vehicles in Norway. Predictions indicate that Norway may surpass 200,000 chargeable vehicles by 2020, which corresponds to seven percent of the total vehicle fleet. This number includes both electric vehicles and hybrid electric vehicles. To explore the impact a large scale electric vehicle adoption will have on the power grid, simulations of an existing low voltage power system have been conducted. The load flow simulation tool Simpow was used for this purpose, and Nord-Trøndelag Elektrisitetsverk provided information on the grid structure and consumer consumption data. From the supplied data, February 2 was chosen for the 24-hour simulation period. This day has the highest energy consumption, and therefore represents the ”worst case” scenario. A hypothetically built wind turbine close to the residential areas was integrated in the system, using wind measurement data from a wind farm in Nord-Trøndelag. Different scenarios were explored, investigating how sensitive the grid is to additional load under different assumptions, and how the wind generation can contribute to a more self-supporting power system. Symmetrical and asymmetrical distribution of electric vehicle charging loads in relation to physical locations have been compared, and the results suggest that one cannot give an exact number of vehicles that the system can handle. The system capacity when operating with dumb charging strategies is varying depending on where the vehicles are situated physically. With many electric vehicles located close together, the given voltage level constraints of the model were violated with a seven percent electric vehicle penetration share. However, assuming that vehicles are more spread out physically, the system restrictions were not violated for a electric vehicle share of 20 percent. In other words, the placements of the additional loads are equally decisive for the system voltage variations as the number of loads. By applying smart charging strategies, the voltage fluctuations in the system during a day are mitigated. For the 20 percent EV penetration scenarios, given the assumptions presented in this thesis, the added load does not seem to put more stress on the system than it can handle. However, for the 50 percent EV penetration scenarios, the charging load might present the system with too much stress, even with smart charging strategies. Other measures will have to be taken if the power system ever experiences an EV share that high. A long term simulation was performed to

verify the results obtained from the 24-hour simulations. It verified that February 2 can be assumed to be the ”worst case” scenario, that is, the lowest voltage levels throughout the year was observed on that day. It also gave an indication on how well the wind turbine is suited to relieve the system of increased consumption due to electric vehicle charging. If the wind generation is assumed to cover the additional load created by the electric vehicles, the need for imported power in the system will not increase. Wind generation during February 2 is higher than the electric vehicles consumption if 20 percent share is assumed. This relation, however, is not representative for the generation throughout the year. Wind generation is unpredictable, and generally higher during winter. Installing an energy storage system makes the wind energy more controllable. Still, days with little or no wind generation will inflict the need of a huge capacity storage system to cover the charging loads at all times. Assuming a lower electric vehicle adoption share, and not requiring the wind generation to cover charging loads at all times, the needed storage system capacity could be realizable.

Sammendrag

Klimaforandringer og CO_2-utslipp har i de senere år blitt en aktuell problemstilling i internasjonal politikk. Debatten om menneskeskapte klimaendringer har bidratt til en dramatisk økning av solgte elbiler i Norge siste årene, og i april 2013 utgjorde elbiler 3.6 prosent av alle nybilsalg. Projeksjoner indikerer at antallet ladebare biler i Norge kan overstige 200 000 innen 2020, hvilket svarer til en andel på syv prosent av den totale bilparken. For å utforske virkningen en storskala integrering av elbiler vil ha på strømnettet, har analyser på et eksisterende lavspentnett blitt utført. Lastflytanalyseverktøyet Simpow har blitt benyttet til dette formålet, og Nord-Trøndelag Elektrisitetsverk har bidratt med informasjon om strømnettets oppbygning og forbruk fra boligområdet. Simuleringsperioden er på 24 timer, og fra tilgjengelig data ble 2. februar valgt fordi den dagen har det høyeste strømforbruket, og gir dermed størst påkjenning på systemet. I tillegg har en hypotetisk bygd vindturbin blitt inkludert i analysen, og data fra Hundhammerfjellet vindpark er benyttet for å beregne produsert effekt for den aktuelle dagen. Ulike scenarier ble utforsket for å teste hvor sensitivt spenningsnivået var for lastvariasjon i systemet, og i hvilken grad vindturbinen kan bidra til et mer selvforsynt kraftsystem. Symmetrisk og asymmetriske fordeling av last med hensyn til fysisk plassering har blitt foretatt, og resultatet indikerer at det ikke uten videre kan anslås et antall elbiler som system kan håndtere uten å bryte gitte grenser for spenning eller varme. Ved bruk av såkalte ”dumme ladestrategier” kan systemet håndtere et varierende antall elbiler i tillegg til baselasten avhengig av hvor disse plasseres fysisk i nettet. Det er punkter i systemet som er svakere enn andre med hensyn til spenningsnivå, og ekstra last bør plasseres andre steder dersom mulig. Med andre ord er plasseringen av elbilene en like avgjørende faktor for kapasiteten til systemet som antall elbiler som integreres. Ved å benytte ”smarte ladestrategier” vil ikke de gitte grensene for systemet bli brutt, ved mindre ekstremt store laster blir plassert på en svak del av systemet. En 11 måneders analyse av systemet ble også utført for å verifisere resultatene fra 24-timers analysene. Antagelsen om at 2. februar var den dagen som gav kraftnettet størst påkjenning ble bekreftet. Det gav også en indikasjon på hvordan en vindturbin kan bidra til å dekke det økte behovet for energi som følge av elbilintegrering. Det er ønskelig å ikke påføre strømnettet ekstra påkjenninger i form av økt last. Produksjon fra vindturbinen er høyere enn forbruket til boligfeltet i løpet av de

24 timene av analysen dersom det antas 20 prosent integrering av elbiler. Denne observasjonen er imidlertid ikke representativ for vindproduksjonen resten av året. Det forekommer perioder med liten eller ingen vindproduksjon, og dersom elbilene skal kunne lades fra vindenergi under slike perioder, må det installeres en form for energilagringssystem. Ved antagelse om syv prosent elbilandel og redusert krav til dekning av ladetimer fra vindenergi vil størrelsen på energilagringssystemet være realiserbart.

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Abbreviations

AMS	**A**utomatic **M**easuring and control **S**ystem
BEV	**B**attery **E**lectric **V**ehicle
DuCh	**Du**mb **Ch**arging
EV	**E**lectric **V**ehicle
LV	**L**ow **V**oltage
NTE	**N**ord- **T**røndelag **E**lektrisitetsverk
PHEV	**P**lug-in **H**ybrid **E**lectric **V**ehicle
SmCh	**Sm**art **Ch**arging
SOC	**S**tate **O**f **C**harge

Nomenclature

Symbol	Name	Unit
κ_n	Power scaling constant	
T_n	Residence energy consumption	kWh
P	Power	W
V_ω	Vertical height factor	
α	Hellman exponent	
U_{LL}	Line to line voltage	V
ϕ	Angle between current and voltage	radians
I_r	Operating current	A
I_{th}	Maximum allowed operating current	A
P_v	Voltage dependency factor	
$E_{battery}$	EV battery capacity	kWh
T_{charge}	Charging time of EV	hours
P_{EV}	Charging power of EV	kW

Chapter 1

Introduction

1.1 Motivation

Norway has, with the ”agreement on climate policy” (klimaforliket), set a goal of reducing emissions by 15-17 billion CO_2 equivalents by 2020, compared to the baseline scenario presented in the National Budget for 2007 [1]. To reach this goal, a reduction of 3-4.5 million tons of CO_2 from the transportation sector is necessary by 2020 [2]. It is stated that the greatest emission reductions in this sector will be achieved by electrification and efficiency improvement of vehicles. To give incentives for people to contribute to this goal, the Norwegian government has, for several years, reduced sales taxes and given other advantages to electric vehicle (EV) owners, and will continue to do so for the next parliamentary term [3]. Another incentive for people to buy electric vehicles is the ever growing problem with local pollution. Norway’s mountainous scenery and cold winters contribute to poor air quality in the larger cities. Many cities are situated in a valley, with mountains acting as walls for the emitted particles. The NO_x gases and hydrocarbons are in the local aspect worse than CO_2. Large accumulation of NO_x gases are what creates the distinctive ”smog” layer, that may be observed especially during cold winter days [4]. These emissions are considered to be unhealthy, and people with asthma are particularly affected. Both gasoline and diesel powered cars produce NO_x gases, even though diesel cars have proven to emit more of these. Hydrocarbons are the result of evaporation emissions in all combustion engines. Being a zero emission solution, the EV does not contribute to any of these emissions, and can therefore help the environment on a local as well as international scale.

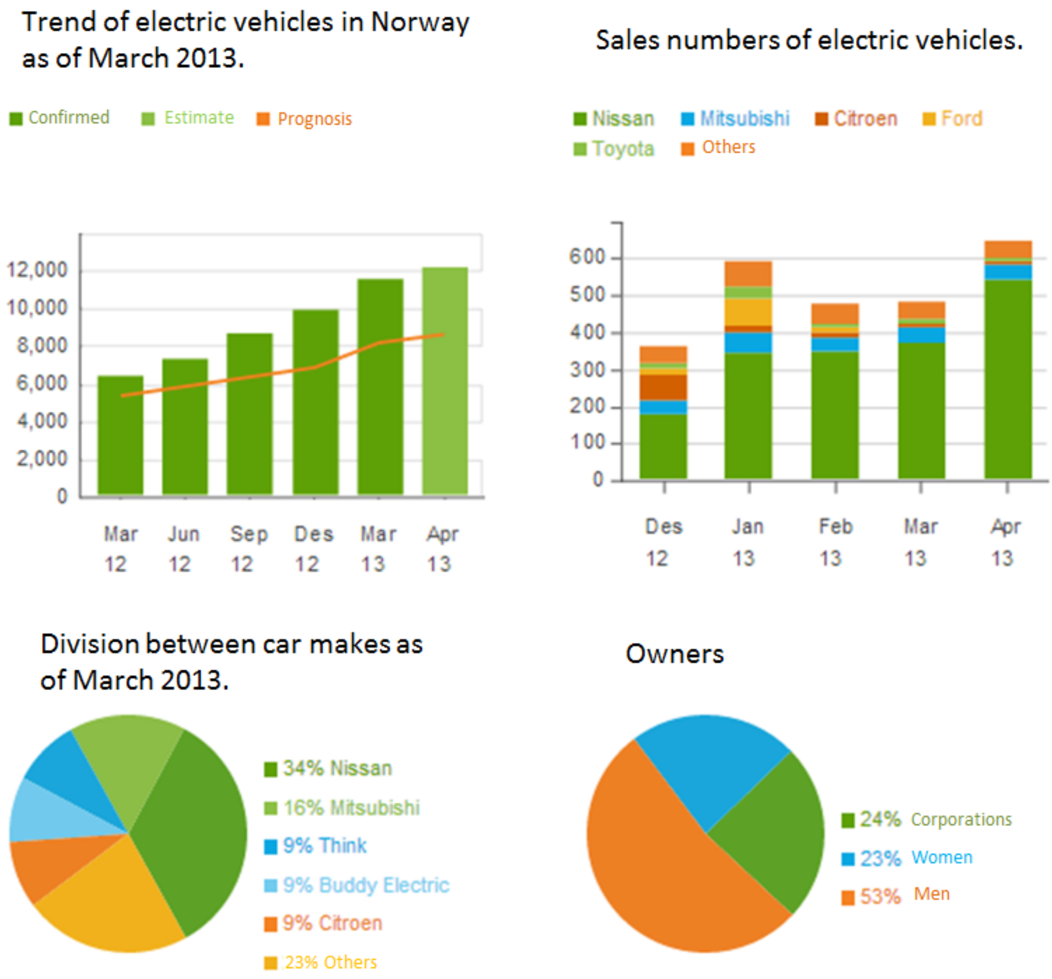

FIGURE 1.1: Trend of electric vehicles in Norway.

1.2 Electric vehicle adoption

As of March 2013 there are 11,425 registered EVs in Norway [5]. The Norwegian electric vehicles association (Norsk Elbilforening) has estimated that Norway will have 115 000 EVs by 2020. The actual sales numbers from the fall of 2012 and spring of 2013 lies well above the estimations from this study [6]. Grønn Bil states in the same article that if this new trend keeps up, Norway will surpass 200 000 chargeable cars by 2020. Chargeable is here defined as both electric vehicles and hybrid electric vehicles. Still, with the current size of the Norwegian vehicle fleet, 200 000 chargeable vehicles will constitute only seven percent of the total number of vehicles in 2020 [7]. This thesis will look at the impact of large scale adoption of EVs in a low voltage power grid. The objective is to chart possible future power consumption challenges, and investigate benefits of load shifting. Different load distribution scenarios will be explored, investigating how many EVs the power system can handle, using ”dumb” and ”smart” charging approaches.

The simulations will be performed in Simpow on an existing power grid located in Nord-Trøndelag. The provided power system consists of a small scale hydro power plant, 32 distribution transformers, about 800 residences, some larger consumers, transmission lines/cables and an external grid.

1.3 Wind power and energy storage

In addition to the given power system, a hypothetical wind turbine will be included, situated some distance away from the system. Wind measurement data from Hundhammerfjellet are provided by Nord-Trøndelag Elektrisitetsverk (NTE), and these will be used to estimate a wind generation profile. The model will contain a slack bus representing a rigid external grid that supplies or extracts power. To mitigate the additional power consumption created by adopting EVs into the system, some form of energy storage will be applied as well. The idea is to investigate whether the combination of wind production and energy storage can cover the EV charging load. The simulations will be performed over 11 months based on consumption and generation data from 2012.

1.4 Purpose and prerequisites

The purpose of this thesis is to assess possible impacts a large scale penetration of electric vehicles might have on a low voltage distribution system. Data from a residential area in Steinkjer has been provided by Nord-Trøndelag Elektrisitetsverk (NTE). This data set contains information of transformers, transmission cables and resident consumption behaviour for approximately 800 residences. The system includes a small hydro power plant called Byafossen, operated by NTE.

1.5 Thesis outline

The thesis is organized as follows: Chapter two explains the difference between the electricity cost calculation method currently used in Norway, and the future possibilities with implementation of automatic measuring and control systems (AMS). Chapter three demonstrates the structure of the network, EV status in Norway today, constraints used for the simulations and assumptions made for the wind turbine integration. Chapter four turns to the building of the Simpow model, and argues for the validity of choices made in terms of obtaining accurate results. This is followed by chapter five which explains the case studies and assumptions made for the simulations. Chapter six presents the results obtained from the simulations, and chapter seven discusses the consequences of these. Finally, chapter eight summarizes the main results obtained from the simulations, while chapter nine outlines further work that could be performed.

Chapter 2

Power system structure

Today, most people use electricity without concern of fluctuations in the voltage level of the system or variations in the electricity spot price. This is partly because electricity is relatively inexpensive in Norway compared to other countries, but mainly because the price people pay does not reflect the spot price at the instant of consumption. Norway is divided into five regions with respect to electricity price, as indicated in Figure 2.1. The price in each region is determined by the relation between supply and demand, and is independent of the other regions. In an ideal power system, the electricity price would be identical across the entire

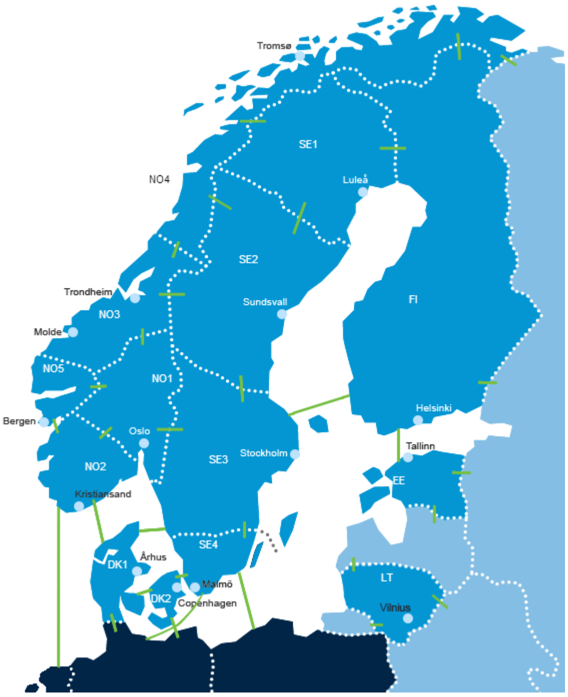

Figure 2.1: Nordic power system overview.

system, but in reality this is not the case. The limiting factor is the transmission lines. If one area has excess generation and another area has deficit generation, the transmission capacity between the two regions must be adequate in order for the total system to remain in balance. If the transmission line saturates, the result will be different electricity prices in the two regions. The regions NO3 and NO4 in Figure 2.1 have a weaker main power grid than the southern part of Norway, and therefore have limited opportunity to import power from the southern regions when needed. This results in a tendency for these regions to have higher electricity prices, especially during winter.

Today, there are no incentives for the customer to move load away from peak hours. However, the Norwegian power system is going to change drastically in the way it is operated in the coming years. The Norwegian government has decided that all residents will have an automatic measuring and control system (AMS) unit installed by January 1 2019 [8], as part of a new smart grid structure. The electricity bill for a normal resident is today calculated based on a manual reading of the electricity meter by the resident every three months or so. This reading tells the power company how much energy the resident has used since the last reading, and the amount of energy is then multiplied with the average electricity price for that period. The AMS unit is a two-way communication system that continuously gives feedback to the power company how much energy is consumed in various residences. In other words, the customer will pay the current electricity price at the time of consumption. It also gives the energy producer the opportunity to send the customer ”price signaling”, future price estimations based on marginal price and load observations. The new technology will hopefully affect the power consumption in private households, shifting the movable part of the load towards off peak hours. By looking at the electricity prices for February 2 2012 in the Trondheim region, we see that the price varies from 39.76 to 253.92 €/MWh [9]. This is an increase of 539 percent within a few hours. The AMS unit will give the residents more accurate consumption data and will give a large incentive to apply smart consumption behaviour. It is reasonable to assume that the installation of AMS units will give incentive to shift consumption from the base load as well, but for the purpose of this thesis, the EV charging will be regarded as a movable load and the remainder of the resident consumption as fixed.

The green line in Figure 5.1 indicates that most people plug in their EVs between 1 pm and 7 pm. The electricity price is still high at this time, and therefore not the economically optimal time to charge. The electricity price is generally lowest in the evening and during the night. People are often home during this time anyway, so it will not inflict any inconvenience to the consumer to delay charging. The specified range of a Nissan Leaf is 100 km assuming winter temperatures, 169 km assuming a nice day, while the daily average distance driven by people using cars is 43.4 km [10][11]. For most owners this range is adequate for daily use, and it is not necessary to recharge the car after work for continued usage

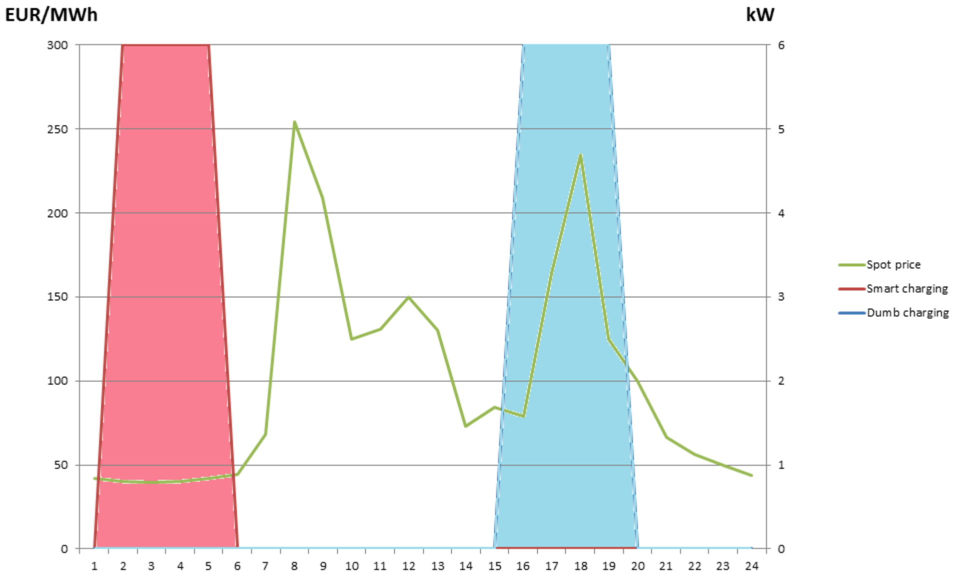

FIGURE 2.2: EV charging habits compared with electricity spot price.

in the evening. If one assumes that the battery capacity of an EV is 24 kWh and it charges at 6 kW it will be fully charged after 4 hours. This scenario is illustrated in Figure 2.2 for two different times during the day. The blue shaded area represents the energy consumption with dumb charging strategies, and the red represents the cost optimal time of charge. In this thesis, the smart charging solution is based on an algorithm to mitigate deviations in system voltage levels. In practice, the charging load will be placed at a time where the base load is low. There is a strong correlation between system load and electricity price, so the smart charging will result in a charging scenario that is close to the cost optimal scenario for the consumer, at least for a low number of EVs. When the number of EVs increases, the charging load at will be more spread out in during the day to ensure the total consumption is as uniform as possible. This is explained more closely in section 5.2. The same amount of energy is consumed in both cases of this example, but comparing the electricity spot prices during charging periods, it is clear that smart charging will result in a lower charging cost. The average charging cost obtained from the dumb charging strategy in Figure 2.2 is NOK 110.58, with the currency exchange rate of February 2 2012. With smart charging strategy, the cost would be NOK 29.79, a reduction of NOK 80.79 or 73 percent. Since the consumption during February 2 is high, the benefit from load shifting is especially prominent. The daily average saving potential from load shifting will be lower than this amount, but can still account for a substantial amount annually.

Chapter 3

System scenarios

3.1 System description

The system which is investigated in this thesis is a residential area in Steinkjer in Nord-Trœndelag in Norway. It is comprised mainly of residential houses, but also schools, kindergartens and other larger consumers. The total number of electrical power consumers is 856, and approximately 800 of these are residential homes. The small scale hydro power plant Byafossen is located in this area, and contributes to the power system. The power plant has a generation capacity of 2.4 MW and an annual generation of approximately 15 GWh.

Information regarding consumer behaviour is gathered by Nord-Trøndelag Elektrisitetsverk (NTE), and has been shared for the purpose of the work done in this thesis. The provided information consists of grid design, cable characteristics, substation characteristic, hydro generation and the energy consumption of the residences in the area. The system model consists of 32 sub transformers distributing power to various 230 V residential areas. The main power source in the system is a transformer connected to the 66 kV regional grid. Figure 3.1 is a map of the area showing the topography, the high voltage grid and the location of the distribution transformers. Hourly average of active and reactive power transmitted through the feeder is used to estimate consumption behaviour in the system. For each sub transformer, a high load active and reactive power consumption is given. The relation between active and reactive power consumption is assumed to be constant for the simulations performed. The values gives a power factor close to $\cos\phi$=0.98, which is what NTE use in their load flow analysis (ref. mail fra Rune). The reason for this assumption is that the data set containing generation from Byafossen hydro plant includes only active power generation. The reactive power meter had not been in place long enough to provide the needed data.

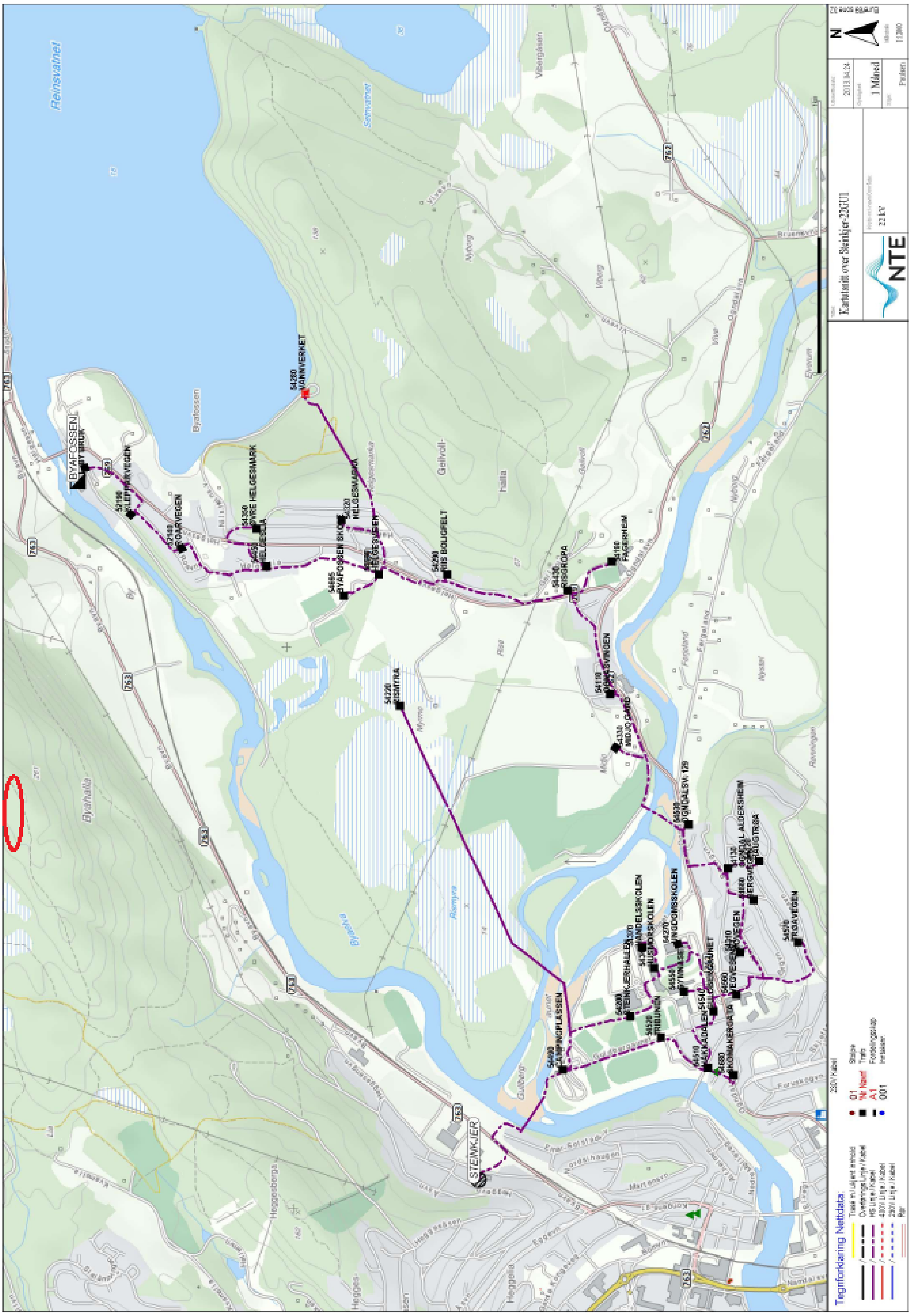

FIGURE 3.1: Overview of the simulated power system.

When combining information from the different components in the system, a complete system model is created. Adding up active power from the feeder and the hydro plant, the active power consumption for each hour is obtained. Assuming constant relation of active and reactive power, β , the reactive power consumed is calculated. The reactive power contribution from hydro is then set to be the difference between the imported reactive power from feeder and the consumed reactive power.

To model the consumption of the sub transformers in the system, the annual energy consumed was used. A factor κ was calculated for every sub transformer based on their energy consumption, and this relation has been assumed constant throughout the simulations. The method of estimating system consumption is presented in Algorithm 1. The longest simulation period performed on this system runs from January 25 until December 31. The reason for not running a full year simulation is that the data from Byafossen hydro contains January 1, 2012 through December 31, 2012, while the feeder data set contains January 25, 2012 through February 5, 2013. The overlapping period is assumed to be adequate to give reliable results.

Algorithm 1 Estimation of sub transformer consumption

```
$\kappa_n = \frac{P_n}{P_{TOT}}$

$\beta_n = \frac{Q_n}{P_n}$

for all Hours h do
    $P_{consumption} = P_{feeder} + P_{hydro}$
    $Q_{consumption} = P_{consumption} * \beta_n$
    $Q_{hydro} = Q_{feeder} - Q_{consumption}$
end for

for all Transformers n do
    for ALL HOURS do
        $P_{transformer_n} = \kappa_n \cdot P_{tot}$
        $Q_{transformer_n} = \beta_n \cdot P_{transformer}$
    end for
end for
```

This thesis will focus mostly on the load demand for February 2, because this is the day with highest overall consumption and therefore represents the worst case scenario.

3.2 System restrictions

According to the governments Regulation on Delivery Quality in the Electric System (FOR-2004-11-30 nr 1557 Forskrift om leveringskvalitet i kraftsystemet), the point of end user is required to be within ± 10 percent of nominal voltage [12]. In addition to this general requirement, SINTEF has proposed guidelines for voltage levels in systems containing distributed generation. These guidelines state that distributed generation units below 1 kV should not contribute to variation in voltage at the point of end user beyond the limits given in Table 3.1 [13].

TABLE 3.1: Voltage constraints for distributed generation units.

	Variation	Per Unit	Volt
Maximum voltage	U_n + 8 %	1.08	248.4 V
Minimum voltage	U_n - 6.5 %	0.935	215.05 V

The possibility of returning power to the grid from EVs or installing PV generation on houses will not be discussed, but the voltage restrictions will be used as if distributed generation occurred in the low voltage network. Thermal limits of the system branch cables can be calculated using the basic power system equation below. An excerpt from "Planleggingsbok for kraftnett" for the most used cables in the system is given in Table 3.2 [16].

$$P_{max} = \sqrt{3} \cdot U_{LL} \cdot I_{th} \cdot cos\phi \tag{3.1}$$

U_{LL} is the line to line voltage. From measurements made on the power system, $cos\phi$=0.98, is considered constant [30]. The maximum amount of power that can be drawn through the cable can then be calculated. For the most used cables in this model, the specific limits are presented in Table 3.3. The majority of the residences are connected to their system node with a TFXP 4x50 AL cable. With the assumptions made in this analysis, this cable can deliver almost 40 kW. Comparing the cable capability with the maximum consumption of the residences, the data suggest that it is unlikely that thermal limits of the branch cables will be a restricting factor for the system. The high voltage distribution cables are mostly TFXP 4x95 or TFXP 4x240.

TABLE 3.2: Excerpt from "Planleggingsbok for kraftnett".

Type and section	R	X	C_j	C_d	I_{th}
PFSP 3x16 CU	1.150	0.085	0.37	0.70	100
TFXP 4x50 AL	1.200	0.082	0.42	0.83	100
TFSP 3x95 AL	0.320	0.076	0.57	1.10	260
TFXP 4x95 AL	0.320	0.076	0.57	1.10	260
TFSP 3x150 AL	0.206	0.072	0.60	1.19	335
TFSP 3x240 AL	0.125	0.072	0.64	1.26	435
TFXP 4x240 AL	0.125	0.072	0.64	1.26	435

Table 3.3: Branch cable thermal limits.

Type and section	$I_{th}[A]$	$P_{max}[kW]$
TFXP 4x50 AL	100	39
TFXP 4x95 AL	260	102
TFSP 3x150 AL	335	131
TFxP 3x240 AL	435	170

3.3 EV status in Norway

Electric vehicles are becoming more popular in Norway, and are for many, a symbol of a environmental support. Nissan Leaf is by far the most sold battery powered vehicle in Norway in 2013, with a market share of 92 percent of sold EVs in April. By the end of April, electric vehicles constituted 3.5 percent of all new vehicle sales, and the Leaf was the 2nd most sold vehicle in the country [22]. The interest in electric vehicles has not declined in recent years. The number of sold electric vehicles has never been higher than April 2013. The sales numbers from the spring of 2013 have surpassed most predictions, and do not show any signs of decreasing interest from buyers. So far, 1,508 electric vehicles have been sold this year. That is an increase of 31 percent compared with last year [23]. The technologies in this market are under constant development, and today it has reached a level that make people see the potential of the electric vehicle. More people choose to have an EV as their second car, because of the financial support and benefits provided by the government in Norway. Another important factor is that the driving range of EVs have become adequate for most peoples daily use. The positive attitude towards electric vehicles is not limited to private individuals. Oslo municipality has decided to invest 50 million NOK in exchanging fossil-fuelled public vehicles with zero emission vehicles over the next few years [24]. Other corporations and companies also show increased interest in buying EVs as company cars, to be perceived as environmentally concious. The infrastructure of fast charging stations in the country is improving. The company Grønn kontakt is owned by 23 power suppliers from all of Norway, and has set a goal of being a national operator of the charging infrastructure in the country. As of today, there are fast charging stations at Kongsberg, Lier, Arendal and Kristiansund. In the future Drammen, Hokksund and Mandal will also be developing fast charging stations [26]. This development also stimulates the general interest in electric vehicles.

A prognosis of future sales of chargeable vehicles made by grønnbil.no is presented in Table 3.4. This prediction includes both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). BEVs run purely on electric batteries, while PHEVs have a combustion engine as well and can switch between the two systems. By the end of 2020, there are assumed to be over 200 000 chargeable vehicles in Norway, and approximately 56 percent of these are expected to be

Table 3.4: Prognosis of future electric and hybrid vehicle sales in Norway.

	2011	2012	2013	2014	2015
Sold passenger cars	138000	140000	140000	140000	140000
Chargeable share	2.0%	3.4%	5.0%	8.0%	12.0%
Of which BEVs	2.0%	3.2%	4.3%	6.7%	8.0%
Of which PHEVs	0.0%	0.2%	0.7%	1.3%	4.0%
Sold passenger cars	2760	4760	7000	11200	16800
Of which BEVs	2747	4505	6020	9380	11200
Of which PHEVs	13	255	980	1820	5600
Outfacing of chargeable	150	200	250	300	350
Of which BEVs	150	200	250	300	350
Of which PHEVs	0	0	0	0	0
Sum of chargeable	6010	10570	17320	28220	44670
Of which BEVs	5997	10303	16073	25153	36003
Of which PHEVs	13	267	1247	3067	8667

	2016	2017	2018	2019	2020
Sold passenger cars	140000	140000	140000	140000	140000
Chargeable share	17.0%	20.0%	23.0%	26.0%	30.0%
Of which BEVs	12.0%	13.0%	10.0%	11.0%	12.0%
Of which PHEVs	5.0%	7.0%	13.0%	15.0%	18.0%
Sold passenger cars	23800	28000	32200	36400	42000
Of which BEVs	16800	18200	14000	15400	16800
Of which PHEVs	7000	9800	18200	21000	25200
Outfacing of chargeable	350	400	450	500	550
Of which BEVs	350	400	450	500	550
Of which PHEVs	0	0	0	0	0
Sum of chargeable	68120	95720	127470	163370	204820
Of which BEVs	52453	70253	83803	98703	114953
Of which PHEVs	15667	25467	43667	64667	89867

BEVs [25]. In recent years, the annual increase in total number of passenger cars has been two to three percent. Assuming a constant future increase of 2.5 percent annually towards 2020, the share of chargeable vehicles in Norway can be predicted to be as illuminated in Figure 3.2.

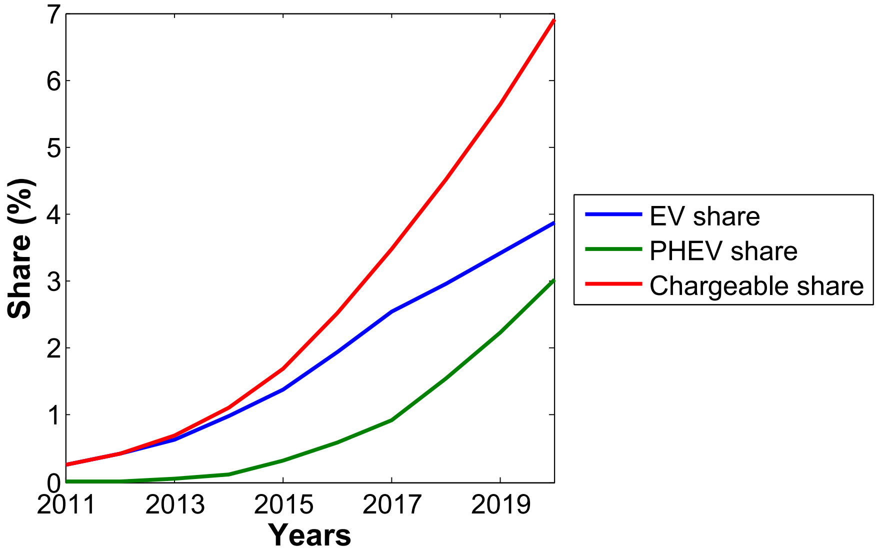

FIGURE 3.2: Prognosis of future chargeable vehicle share in Norway.

3.4 EV adoption

The simulation model contains 856 consumers, and the average number of vehicles owned by a household is assumed to be 1.3. This assumption is based on the average numbers of vehicles per capita and the average number of people per household in Nord-Trøndelag [28][29]. Approximately 800 of the consumers in the system are residential houses, but all consumers are assumed to adapt to EV usage. Schools, companies and other larger consumers have started to adopt EVs as company vehicles, so they will also contribute to a higher EV penetration in the system. This results in an assumed total of 1,113 vehicles in the residential areas combined. For the study performed in this thesis, all electric vehicles are assumed to be Nissan Leafs. The technical specifications are presented in Table 3.5.

TABLE 3.5: Technical specifications for Nissan Leaf.

Seats	5
Maximum speed	145 km/h
Battery type	Laminated lithium-ion
Electric motor	Synchronous AC-motor
Battery capacity	24 kWh
Power	Over 90 kW
Range	175 km (NECD)

Studies on large scale EV adoption performed by Åshild Vatne use the same car model, so similar charging sequence characteristics have been applied in this thesis [14]. The charging time has been set to four hours, an assumption that entails

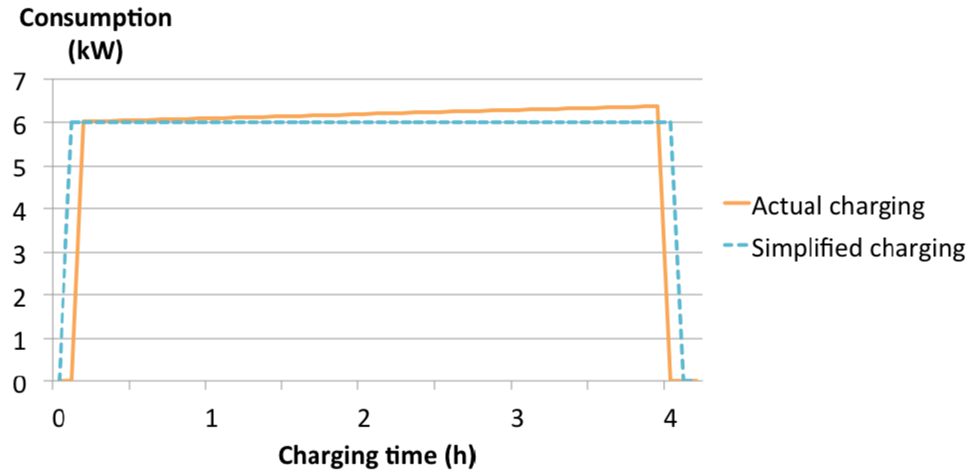

FIGURE 3.3: Simplified charging model compared with realistic charging sequence.

that all EV owners have the same home charge station capacity installed. As in the previous study, the charging power is set to 6 kW and assumed constant for the duration of the charging sequence. Figure 3.3 suggests that the simplified charging profile is a close approximation of what is observed in reality [14]. The most important charging assumptions made in this thesis are presented below.

- All EVs are assumed to be Nissan Leafs
- All EVs are charged at constant power
- Initial SOC is zero percent
- EVs will be charged to full capacity
- Battery capacity $E_{battery}$ = 24 kWh
- Charging time T_{charge} = four hours
- Charging power P_{EV} = six kW

3.5 Wind turbine integration

EVs represent a contribution to reducing local emissions and possibly to reduce emissions on a global scale as well. However, EVs receive their power from the grid, and the pollution caused by additional electricity production affects how environmentally friendly EVs really are [31]. The CO_2 emissions caused by the

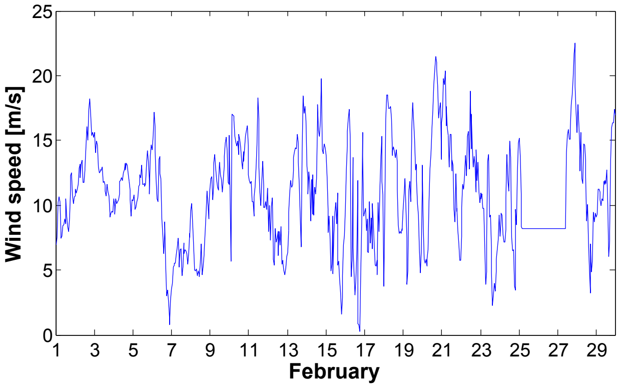

FIGURE 3.4: Hourly measured wind speed at Hundhammerfjellet in February 2012.

power generation mix used to charge vehicles can be expressed as the CO_2 intensity. CO_2 intensity is the average amount of CO_2 emitted per unit of electrical energy generated by all of the power production processes in a mix weighted by the amount of power obtained from each of those processes. Consequently, the degree emission reduction, due to increased usage of EVs, may vary a lot. The possibility of using wind power as compensation for the increased energy consumption due to EVs is explored in this thesis. A wind turbine located near the residences is included in the model. To simulate the integration of a wind turbine in the system, NTE has provided wind measurement data from Hundhammerfjellet wind farm, which is also located in Nord-Trøndelag. The hypothetical wind turbine has a rated generation of 500 kW, and the characteristics have been interpolated from two of Enercons wind turbines with rated generation of 330 kW and 800 kW. Both of Enercons wind turbines are delivered with hub height of 50 meters, so the turbine for this study has also been given hub height of 50 meters. The wind measurements are made at an altitude of 82.6 meters, so in order to simulate the wind turbine with wind speeds at 50 meters height, a vertical height factor V_w is implemented [14].

$$V_w = V_0 \left(\frac{h}{h_{ref}} \right)^{\alpha} = V_0 \left(\frac{50}{82.6} \right)^{\frac{1}{7}} \tag{3.2}$$

where V_0 is measured wind speed, h is turbine height, h_{ref} is measurement height and α is the Hellman exponent. Generation characteristics of the turbine combined with the adjusted wind measurement data from Hundhammerfjellet, give a good indication of expected power generation in the system. The calculated generation values for different wind speeds is presented in Table 3.6. The output voltage of the Enercons E-48 (800 kW) is 690 V, so the turbine in the simulations is set to generate the same [15]. To simplify the integration, reactive power from

TABLE 3.6: Interpolated generation curve for wind turbine.

Wind speed [m/s]	E33 - 330 kW	500 kW	E48 - 800 kW
0	0	0	0
1	0	0	0
2	0	0	0
3	5	5	5
4	13.7	25	25
5	30	45	60
6	55	102.8	110
7	92	160.6	180
8	138	218.4	275
9	196	276.25	400
10	250	334	555
11	292.8	391.9	671
12	320	449.7	750
13	335	507	790
14	335	507	810
15	335	507	810
16	335	507	810
17	335	507	810
18	335	507	810
19	335	507	810
20	335	507	810
21	335	507	810
22	335	507	810
23	335	507	810
24	335	507	810
25	335	507	810

the turbine has been neglected. The turbine is implemented in the system as a ”negative” load, feeding active power into the system.

The town Steinkjer is located at the innermost part of Beitstadfjorden. It is surrounded by an undulating countryside with several hilltops nearby. These hilltops are far enough away from the residential area to accommodate the recommended noise level guidelines given by Klima- og forurensningsdirektoratet (Klif) [27].

The highest hill nearby, marked by a red oval in Figure 3.1, is chosen to be the most suitable for installing one or several wind turbines. The transmission from turbine to the system will be at 22 kV since this is the voltage level of the system. The wind turbine generate power at 690 volts, so a new transformer will have to be installed as well. With a maximum rated power of 500 kW, a 500 MVA transformer will be sufficient for the wind turbine. The characteristics of the transformer is taken from ”Planleggingsbok for kraftnett” for a 500 kVA transformer [16]. The cables used to connect the transformer to the power grid are chosen to be the same as for other high voltage parts of the grid. The costs of installing the wind turbine will not be subject to this work.

3.6 Energy storage

With the integration of wind energy to help support the need of power in the system, it is natural to discuss the potential benefits of an energy storage system. Wind energy is a variable and unpredictable energy source. With weather forecasting, it is possible to estimate production a short time ahead, but long term planning is difficult.

Installing wind generation in a power system also raises questions of some technical issues. The output power from a wind turbine may vary a lot within a few minutes. This causes voltage fluctuations and frequency variations. An energy storage system can help mitigate these variations, creating a more stable power flow. Another issue when introducing wind turbines is that many models consume large amounts of reactive power. This is especially the case with squirrel cage induction generators, and voltage control technology is important to mitigate these effects. The various difficulties regarding the implementation of the wind turbine in the system has been neglected in this model. More detailed information on how energy storage systems may be used to make the wind turbine integration smoother can be found in [32].

In this thesis the energy storage system will be regarded as means to making wind production more controllable. Excess power will be stored during periods with strong wind and supplied when the system experience power deficiencies.

Chapter 4

Simulation model

4.1 Model overview

The basic Simpow power system that has been analysed consists of generation/-consumption loads, transmission lines, transformers, shunt impedance and a slack bus.

4.2 Loads

Loads can be modeled with both active and reactive components. The static and dynamic characteristics of load components are mainly described by two factors, the voltage and frequency sensitivity [21]. Eq.4.1 is considered to be valid for a voltage range of $U_n \pm$ 10 percent, which is sufficient for this model.

$$P = P_0 \left[\frac{V}{V_0}\right]^{P_v} \left[\frac{f}{f_0}\right]^{P_f} \tag{4.1}$$

V_0 is the system voltage and f_0 is the system frequency. The loads in this system are modeled to be purely active loads, so the reactive components are neglected. Frequency variations are not taken into account, so $P_f = 0$ for all loads. The voltage sensitivity varies in different types of loads. In a typical residence, each load will have a different value of P_v, but to simplify simulations, each residence is modeled as a single load. Figure 4.1 indicates that the majority of power consumption in Norwegian households is due to space heating and water heating.

The space heating P_v depends, again, on the technology used for heating. Heat pumps have become more popular in Norway in recent years, and in 2009 one-third

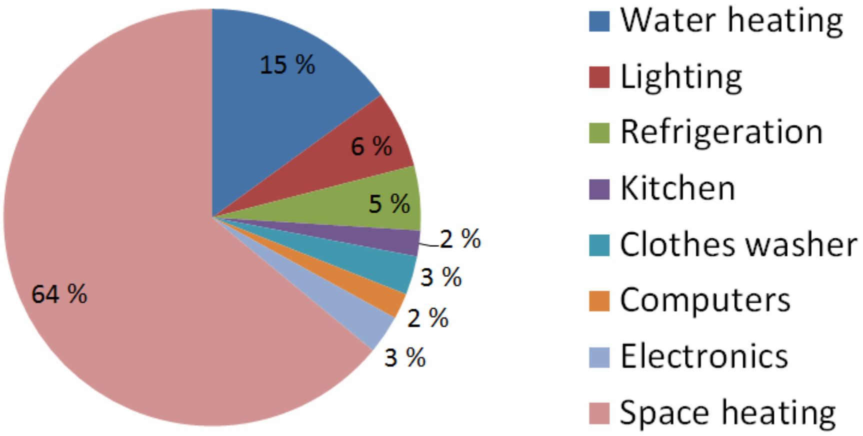

FIGURE 4.1: Average resident consumption apportionment [17].

of all detached houses had one installed [18]. Combining information from Figure 4.1 and Table 4.1 gives an illustration of the total residence power consumption. The weighted average, in relation to load size, gives an aggregated P_v factor for the most significant share of power consumption. This aggregated P_v factor illustrates how the power system sees the sum of loads in a house, and is calculated to be 1.3 The same value has been used for all resident loads. The value P_v of the consumption share that is not covered by Table 4.1 has been assumed to be 0.1.

$$P_v = \left(\frac{1}{3} \cdot 0.2 + \frac{2}{3} \cdot 2.0\right) \cdot 64\% + 2.0 \cdot 15\% + 1.0 \cdot 6\% + 0.8 \cdot 5\% + 0.08 \cdot 3\% + 0.1 \cdot 7\% = 1.3 \tag{4.2}$$

TABLE 4.1: P_v factors for largest energy consumption units.

	P_v
Resistance space heater	2.0
Heat pump space heating	0.2
Water heating	2.0
Lighting	1.0
Clothes washer	0.08
Refrigeration	0.8

4.2.1 Electric vehicles and wind turbine

The EV charging sequence and wind turbine generation are modeled similar to the residence base load. To simplify the simulation system, the the EV loads are combined with the residence loads, modeled as a single load using the calculated P_v. The wind turbine generation is modelled as a ”negative” load, feeding active power into the system. The value $P_v = 0$ for the generator has been chosen to keep the generation consistent with the calculated values in Figure 6.28.

4.3 Transmission lines

Transmission lines are connected between two AC-nodes, represented with a resistance and reactance in series, and a conductance and susceptance in each end of the line[19].

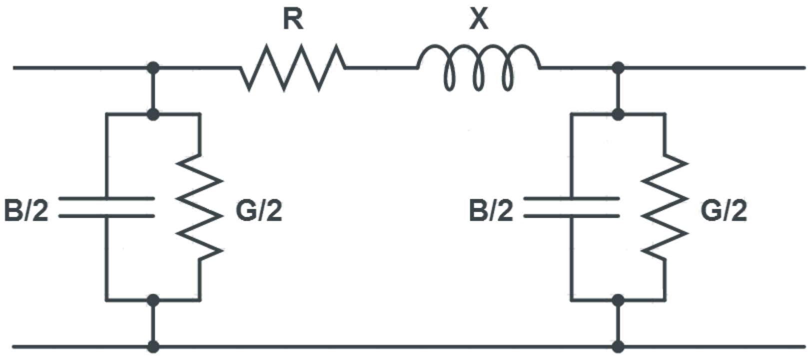

FIGURE 4.2: π - equivalent circuit model.

Based on the necessary accuracy in the model, Simpow allows simplifications of this model. The conductance G represents loss in the conductor due to current leakage throughout the cable insulation. However, these losses are negligible [20] and can be disregarded.

Using the simplified model in Figure 4.3, the line parameters can be extracted from ”Planleggingsboka for kraftnett” [16]. An excerpt is presented in Table 3.2 for the cables used in this model. Values for resistance R and reactance X can be found directly in the table, and the susceptance B can be derived from the total capacitance C_d.

$$B = 2\pi f_0 C_d = 100\pi C_d \tag{4.3}$$

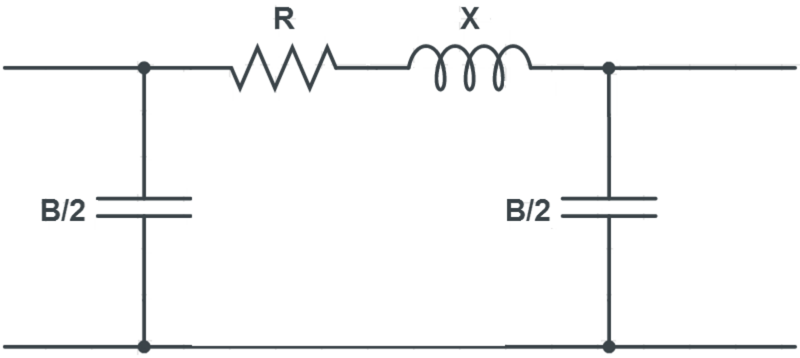

FIGURE 4.3: Simplified π - equivalent circuit model.

4.4 Nodes

Nodes are described by a unique name and base line voltage for the node. In the simulated model, all nodes are either at 230 V, 690 V or 22 kV.

4.5 Transformers

There are 33 transformers in the system, one of which is the main feeder of the system. The other 32 transformers are substations transmitting power from the 22 kV distribution grid down to 230 V in the residential areas. Additionally, one more transformer will be added to the model to simulate the integration of the wind turbine. The transformer must handle rated power from the turbine, so the size is set to 500 kVA. Values in Table 4.2 are taken from ”Planleggingsboka for kraftsystemer” for the chosen transformer size [16].

TABLE 4.2: Transformer loss values.

E_k	4.6 %
P_k	3900 W

To implement the substation in the simulated power system, the following parameters are needed: S_n, U_{n1}, U_{n2}, E_{r12} and E_{x12}. From Table 4.2 we have that

$$E_k = \frac{Z_k \cdot I_n \cdot \sqrt{3}}{U_n} = 4.6\% \tag{4.4}$$

$$E_{r12} = \frac{R_k \cdot I_n \cdot \sqrt{3}}{U_n} = \frac{P_k}{S_n} = \frac{3900}{500 \cdot 10^3} = 0.78\% \tag{4.5}$$

$$E_{x12} = \sqrt{E_k^2 - E_r^2} = 4.53\% \tag{4.6}$$

U$_{n1}$ is the generated turbine output voltage of 690 V, U$_{n2}$ is the system line voltage of 22 kV, and S_n is the transformer rating of 500 kVA. For the other transformers in the system, similar calculations were performed based on data from NTE.

Chapter 5

Case Study

5.1 Base load analysis

Before introducing any changes in the system in the form of wind power or EV integration, it is important to analyze the system in its current state. Different parts of the system may respond differently to load variations depending on whether or not the grid is rigid. A 24-hour simulation will be performed for February 2 which is considered to be the worst case scenario. This base load analysis will be used as reference scenario to compare against the results obtained from EV adoption scenarios. A long term simulation will also be performed to verify the results obtained in the 24-hour simulations. The long term simulation will cover an 11 months period, and indicates how the system is affected by the EV adoption over time. It will also give a better suggestion to how well the wind turbine is suited to cover EV charging loads.

5.2 Charging strategies

The power grid will be introduced to additional loads in the form of EVs to investigate how sensitive the system is to increased consumption. Simulations will be performed using data from February 2, 2012, because load demand for this date is higher than any other during the year. February 2 can be regarded as the worst day from a power system standpoint, so the share of EV adoption that is found acceptable on this day should accommodate any other day as well. To illuminate the benefits of load shifting, the analyses employ two different charging strategies; ”dumb” and ”smart” charging. In addition, importance of physical load allocation will be explored by placing the same amount of EVs in different places in the system, as explained in the section below. Moreover, a longer simulation period will

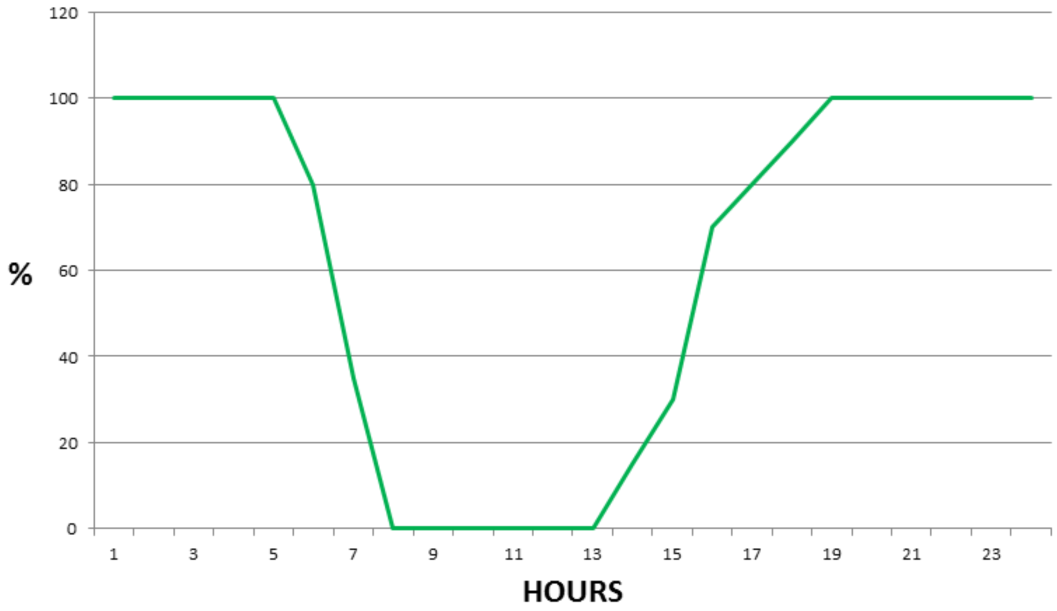

Figure 5.1: Charging habits without incentives to shift load.

be applied, to verify the validity of the results obtained in the 24-hour simulation. This second simulation will also explore the possibility of storing excess energy from the wind turbine.

5.2.1 Dumb charging

For the purpose of this study, the term ”dumb” charging is used to describe the charging pattern that is observed today, with no restrictions or incentives for people to do otherwise. Figure 5.1 demonstrates when most people are plugging in their vehicles. In reality, the share of EVs connected to the grid almost never reaches the extrema zero and 100 percent, but to satisfy the model assumption that all EVs charge every day, it has been slightly adjusted. The most common behavior for an EV owner is to take the car to work in the morning, and plug it into the charger when returning home in the afternoon. This vehicle charging pattern coincides with the peak electricity demand because a lot of other electric components are turned on at the same time. Consequently, increasing the amount of EVs in a power system will contribute to exacerbating the peak power demand significantly. The simulations performed in this thesis aim to estimate how much EV penetration this specific power system can tolerate before the increased load becomes an issue.

5.2.2 Smart charging

The term ”smart” charging of EVs is used in many different contexts, and its meaning is not unambiguous. It sometimes refers to an optimal charging sequence with respect to the battery lifetime. Important factors will then be temperature, initial state of charge, final state of charge, and charging rate. Another approach is to regard the charging sequence as a function electricity spot price. In that case, smart charging utilizes the energy consumption during the day to give the consumer the lowest charging costs. Even though the exact meaning of the term varies, smart charging can be said to be an improved charging pattern that uses two way communication between the EV and the grid. In this thesis, smart charging describes shifting of the moveable load towards off peak hours when demand and electricity price is low. Moving EV charging away from peak load hours will result in less load variations on the grid, which is beneficial from a power system point of view. However, the consumer will also profit from this load shift due to the fact that electricity prices often coincide with low power demand on the grid.

An algorithm has been derived using Matlab to calculate the optimal placing of the EV loads relative to the base load demand. The charging sequence is set to be four hours and all charging sequences will be completed once they have started. That is, there will be no fragmented charging where the EV is connected and disconnected several times during the simulation period. The algorithm aggregates the demand for four-hour intervals to find the optimal time for an EV to start charging. It does not account for the fact that some periods during the day will be impractical for the consumers to charge their vehicles.

As described previously in section 3.1 the simulation model contains 32 substations which supplies residential areas with power at 230 V. One of the residential areas has been modeled at a more detailed level, while the remaining 31 substations are considered to have an aggregated load for the demand on the low voltage side. Since all the connected houses are modeled as a single load, the EV load placed on each transformer is only dependent on the total transformer load. However, for the detailed modeled residential area it becomes a little more complex. The system connected to transformer 54570 is divided into six branches, A-F, as presented in Figure 6.2. The power demand through each of the branch cables is used to calculate the optimal time to charge an EV in a specific branch. Additionally, sub branch F4 is considered to be a separate branch in the algorithm because it is found to be especially load sensitive. The optimal charging time for each EV is calculated using the aggregated branch load from the base load and previously placed EVs. This assists in mitigating the increased peak power consumption in the system. The Matlab code is added in the appendices section. When creating a smart charging schedule for a long term simulation, a few additional assumptions have to be made. The the EVs are assumed to charge one time each day from zero to 100 percent SOC. To avoid that the same vehicle is charged at night and then again the next morning in the model, a minimum of 12 hours between two charging sequences is required.

Algorithm 2 Smart charging

```
Require: $V^{min} < V_i < V^{max}$ for all nodes in the system
         $P_i < P^{max}$

  Choose degree of EV penetration, and calculate the equivalent number of EVs
  that should be placed in each low voltage area
  For the area connected to transformer 54570:

  for Number of EVs in system do
    Choose which house EV number n should be placed at
    for all Hours h do
      Find the four hour sequence with lowest consumption in topical branch
      $LOAD_{SEQ}(h) = \sum_{i=h}^{h+3} P_{branch}(i)$
      Charging time = $\min(LOAD_{SEQ})$
    end for
  end for

  For the remaining transformers in the system:
  Calclate number of EVs connected, and find the four hour sequence with lowest
  load to choose charging time for each EV.

  for all Transformers n do
    Calculate number of EVs in area by number of consumers connected.
    for all Hours h do
      $LOAD_{SEQ}(h) = \sum_{i=h}^{h+3} P_{transformer}(i)$
      Charging time = $\min(LOAD_{SEQ})$
    end for
  end for
```

5.3 Simulation scenarios

5.3.1 Scenario 1 - Balanced load allocation

To explore how many EVs the power system accommodate, assumptions have to be made regarding allocation. In this scenario, the load will be divided as evenly as possible with respect to physical location between the various nodes in the system. The system is simulated with varying degrees of EV penetration, and is

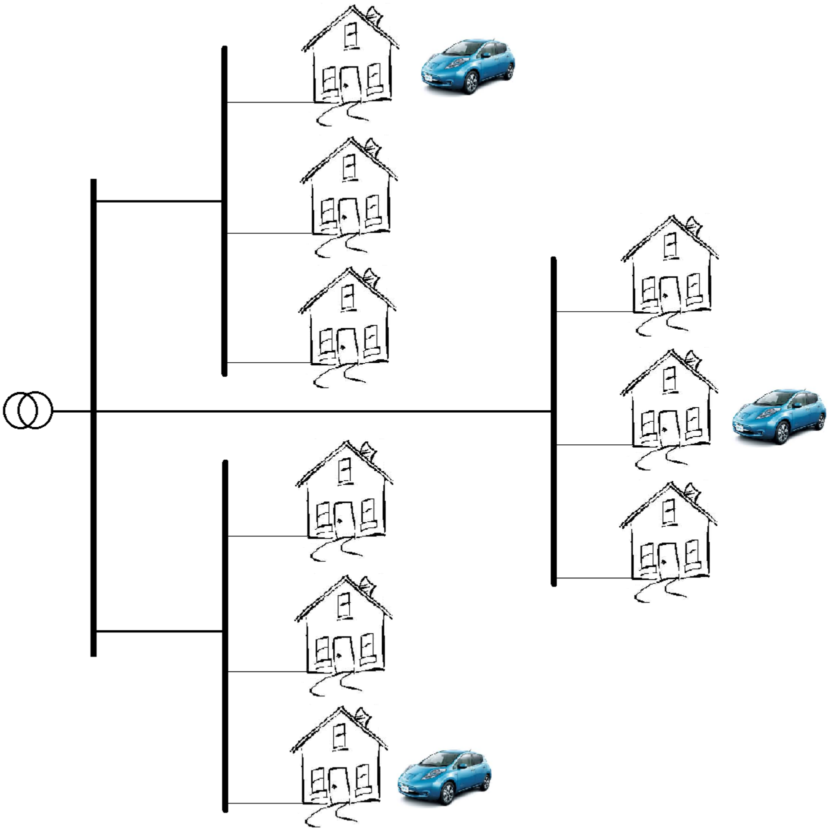

Figure 5.2: Example of balanced allocation of 3 EVs.

considered to be accommodating if the voltage and thermal constraints in Table 3.1 and 3.3 are retained.

5.3.2 Scenario 2 - Imbalanced load allocation

For an arbitrary power system there is no guaranty of balanced division of the loads. To investigate the robustness of the grid with respect to physical location of loads, the system is introduced to EVs located close together, as illustrated in Figure 5.3.

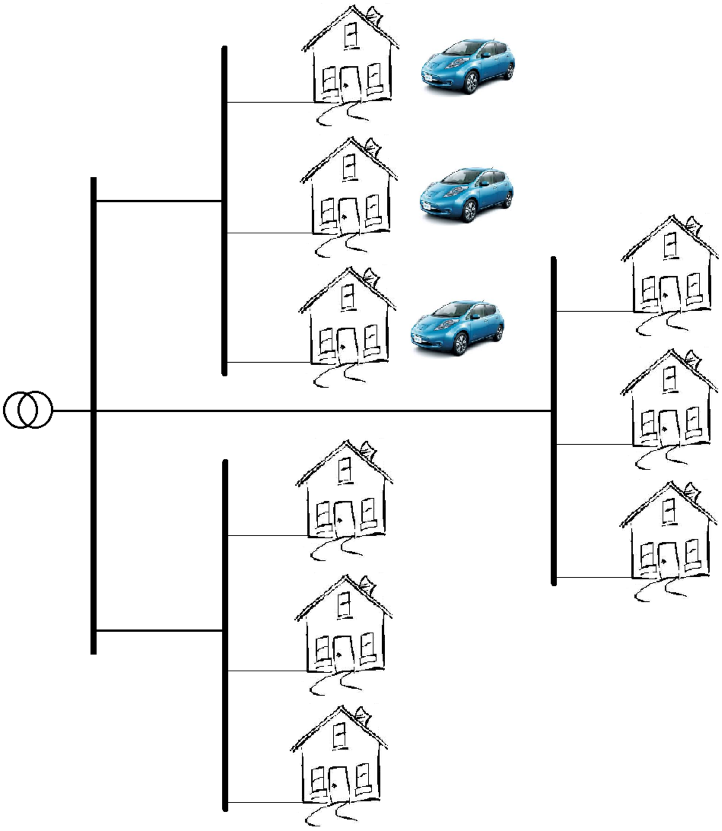

FIGURE 5.3: Example of imbalanced allocation of 3 EVs.

Chapter 6

Results

6.1 Base load analysis

The power system consists of 32 substations providing power to a total of 856 customers. To simplify the simulation model, the system was first created on the 22 kV level. This model includes all the transformers down to 230 V, but all loads behind the transformers are modeled as a single load. Running a high load static simulation of the system, using data from the transformers provided by NTE,

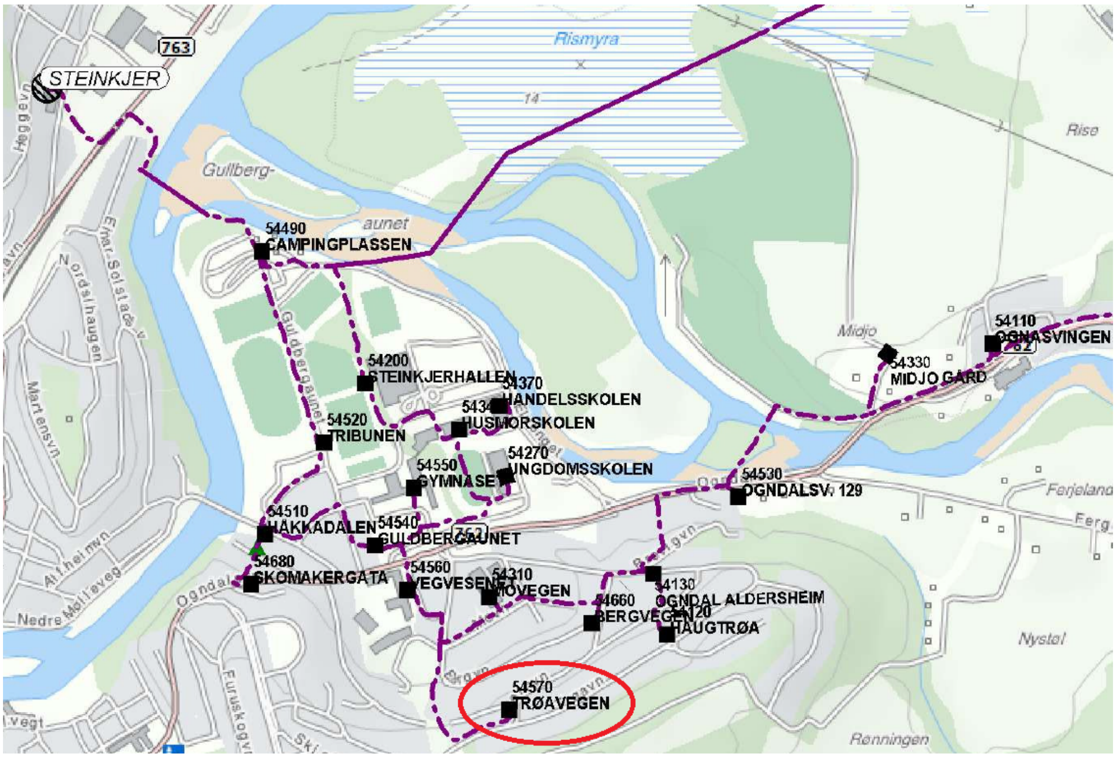

FIGURE 6.1: Location of transformer 54570.

indicates how voltage sensitive each transformer is. High load is defined as the single highest hourly average power consumption observed through a transformer during a year. From the results in Table 6.1, transformers 54680 and 54570 were found to have the largest deviations from their theoretical voltage levels. This indicates that these substations are more influenced by load variation than other parts of the system network. To prevent the model from becoming unnecessarily complex, only one of the low voltage residential areas was modeled at a detailed level. The remainder low voltage sides of the transformers were modeled as a single load at each transformer. For the low voltage part of the simulation model transformer 54570, marked with a red circle in Figure 6.1, was chosen, because it was found to be one of the weaker nodes in the system. It also feeds 62 residences with electricity, making it the second largest transformer in the system in terms of customers connected. It is assumed that the results from this low voltage part of the system is representative for the other parts. This assumption is based on the fact that the amount of EV penetration that is manageable in the weakest part of the system, should also be manageable in the stronger parts. The system analysis will mainly focus on the low voltage part of the system, and how load variations in other parts of the system will influence it.

6.1.1 24 hours - Worst day scenario

The data used in these simulations contains consumption data from January 25, 2012 through December 31, 2012. During this period, the single day with the highest consumption was February 2. It is therefore considered the worst case from a power system point-of-view, and is the main focus of the analyses performed in this thesis. The model was built as explained in previous chapters. There are 62 residences in the low voltage system connected to substation 54570, and the structure of the system is radial as presented in Figure 6.2. A static analysis of the system was conducted to chart which houses are most vulnerable to load variations in the system. The results indicate that the weakest points in the different branches are house numbers 24, 33, 16, 2 and 23; see Figure 6.2. From the 24 hour simulation, the voltage variation in the five points are presented in Figure 6.4, and the power through the substation is indicated by Figure 6.3. There are 62 residences in this low voltage system, and by previous assumptions, there are a total of 81 vehicles in the area. Analyses are conducted featuring different degrees of EV penetration, different charging options and physical placement in the system. The results of the simulations are illuminated in the following sections.

Table 6.1: Result of system static high load analysis.

NODE	Voltage (p.u.)
STEIN-22A	1.00476
STEIN-66T3	1.00000
T52140	0.996273
T52190	0.994916
T52230	1.00065
T54110	0.993889
T54120	0.989851
T54130	0.994807
T54190	0.999844
T54200	0.99841
T54220	1.00096
T54270	1.00043
T54280	0.99781
T54290	0.993691
T54310	0.989509
T54320	0.995332
T54330	1.00183
T54340	0.995606
T54350	0.996544
T54370	0.999213
T54430	0.990562
T54450	0.994474
T54490	1.00135
T54510	0.997972
T54520	0.998434
T54530	0.99861
T54540	0.996289
T54550	0.998805
T54560	0.992059
***T*54570**	0.987786
T54660	0.99808
***T*54680**	0.984667
T54690	0.997352
T54695	1.00182

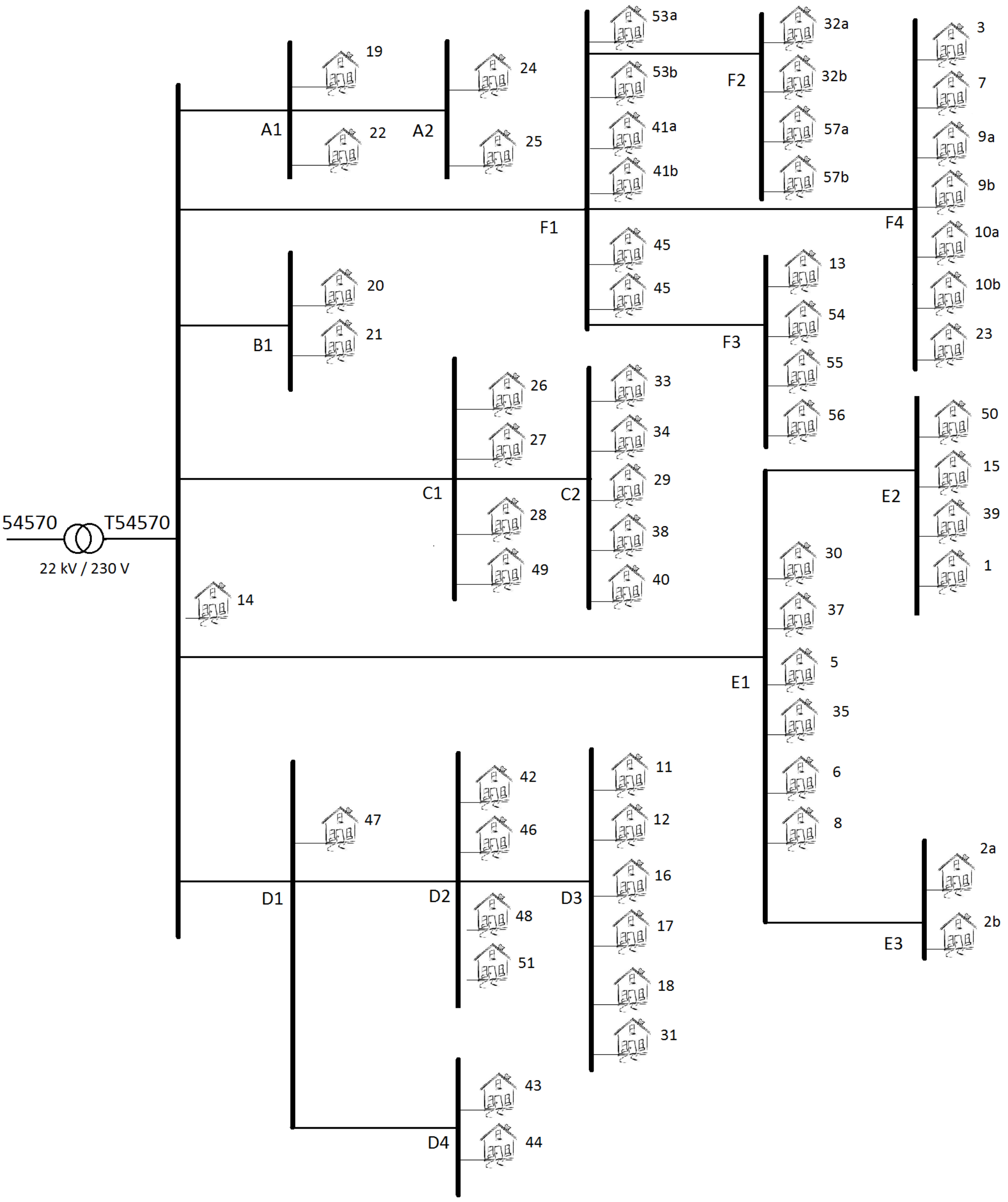

FIGURE 6.2: Grid structure in residential area.

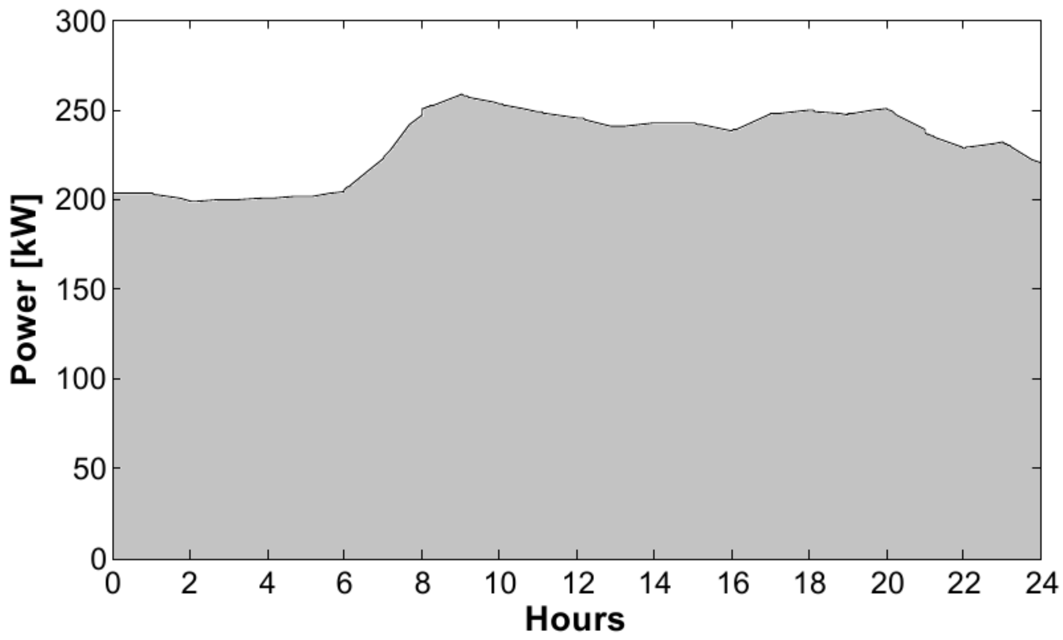

Figure 6.3: Power consumption through substation 54570 for February 2.

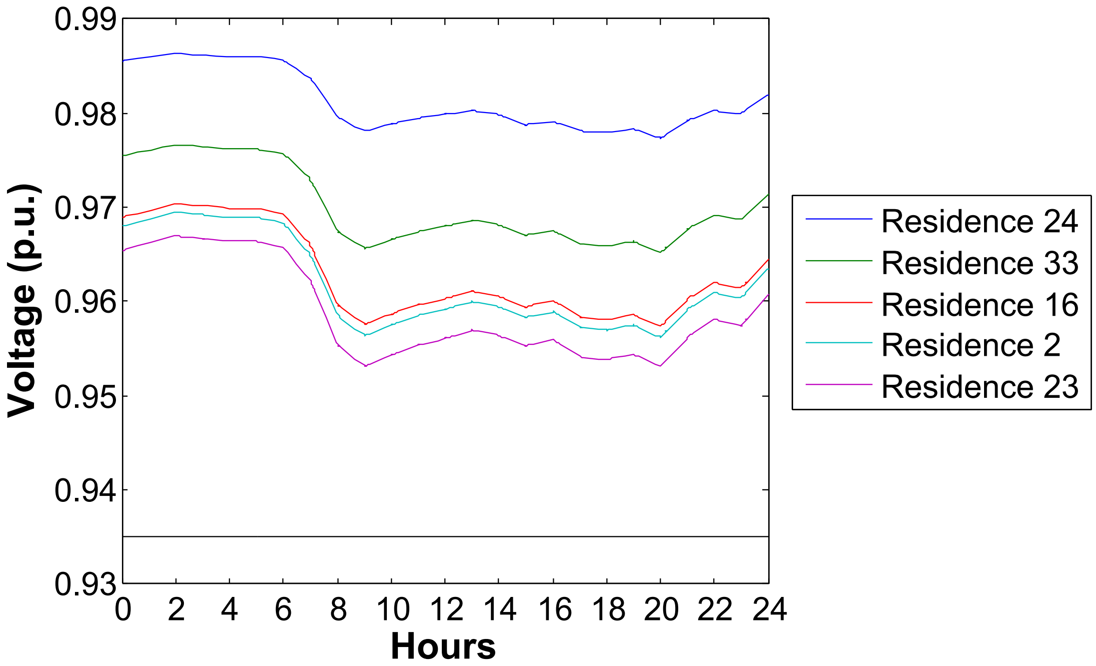

Figure 6.4: Voltage variations observed with base load.

6.2 Seven percent EV adoption

As discussed in section 3.3, there might be as many as 200 000 chargeable vehicles on Norwegian roads by 2020. This prognosis includes both electric vehicles and hybrids, and will constitute approximately seven percent of all vehicles registered in Norway. In this scenario, the EV penetration is assumed to have reached seven percent. For the low voltage network, a seven EV integration corresponds to six EVs added to the system. The total number of EVs integrated in the whole system is 78. For the power system, the charging of EVs will represent an additional stress. Depending on where and when this additional load is placed, it will have varying effect on the system. four different scenarios will be explored for the low voltage part of the system in the sections below.

6.2.1 Dumb charging with balanced allocation of EVs

The EVs are placed randomly at residences that are located at different nodes in the system. The low degree of EV penetration results in only one or two EVs placed at the various nodes. The EVs are assumed to charge according to conventional charging patterns, Figure 5.1. As indicated by Figure 6.5, the voltage levels remain well above the system restriction of 0.935 p.u. Comparing the results with the base load case, some nodes appear to be more affected than others. Residence number 23, which is connected to node F4, experience the largest drop in voltage. This might indicate that node F4 is vulnerable to a more concentrated EV integration. This will be investigated more closely later. It seems reasonable to conclude that with the assumptions given in this scenario, an implementation of 6 EVs in this residential area, and a total of 78 EVs in the system does not stress the system beyond what it can handle, regardless of when the EVs are charging.

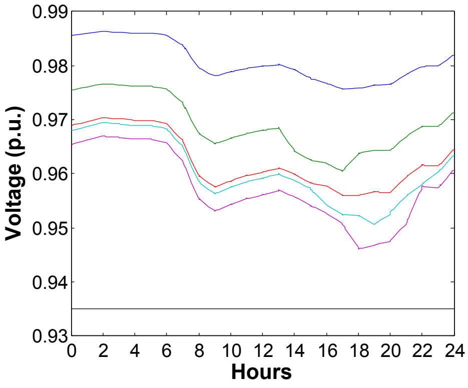

FIGURE 6.5: Voltage levels with seven percent EV adoption, spread allocation and dumb charging.

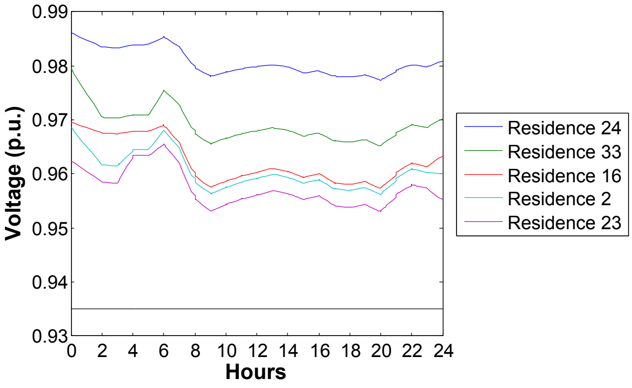

FIGURE 6.6: Voltage levels with seven percent EV adoption, spread allocation and smart charging.

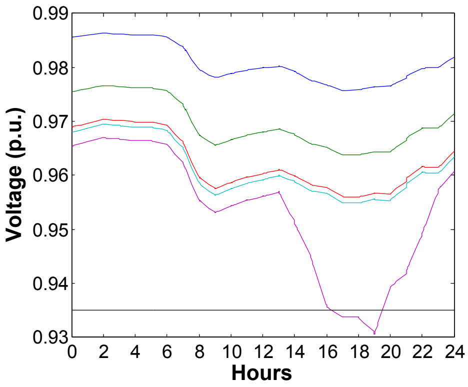

Figure 6.7: Voltage levels with seven percent EV adoption connected to node F4 and dumb charging.

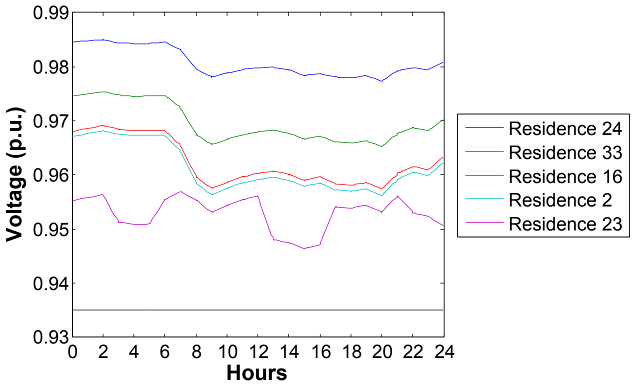

Figure 6.8: Voltage levels with seven percent EV adoption connected to node F4 and smart charging.

6.2.2 Smart charging with balanced allocation

By applying smart charging in the system, the EV charging load is moved away from the afternoon hours. Since the EVs are located at different nodes in the system, they can all charge at the same time without causing excessive stress on the system. As indicated by Figure 6.6, the voltage levels drop noticeably in all branches during the first hours of the day, when compared with the base load scenario. However, this voltage drop is smaller than the one observed later during the base load peak. From the two first scenarios, it can be concluded that with only 6 EVs, evenly distributed in the system, smart charging is not necessary to keep the system within the given limits. On the other hand, by applying smart charging, the EV load is shifted to a more beneficial period for both consumer and system. The consumer will benefit from lower charging costs and the power system will benefit from a more constant load profile.

6.2.3 Dumb charging with imbalanced allocation

In this scenario, the six EVs in the LV part are all placed at residences connected to node F4. The other 72 EVs are assumed to be placed similarly close together in their respective LV parts. However, as explained previously, the other LV systems are modeled as single loads behind the transformers. The assumed allocation pattern is therefore irrelevant for these parts of the model. The increased load on the system may still affect the LV system that is being examined. There are no charging strategies implemented, so the EVs start charging after the pattern given in Figure 5.1. This creates a relatively high power consumption on node F4 in the afternoon. The branch cable between node F1 and F4 is controlled to make sure the thermal limits are not violated for any time during the day. The

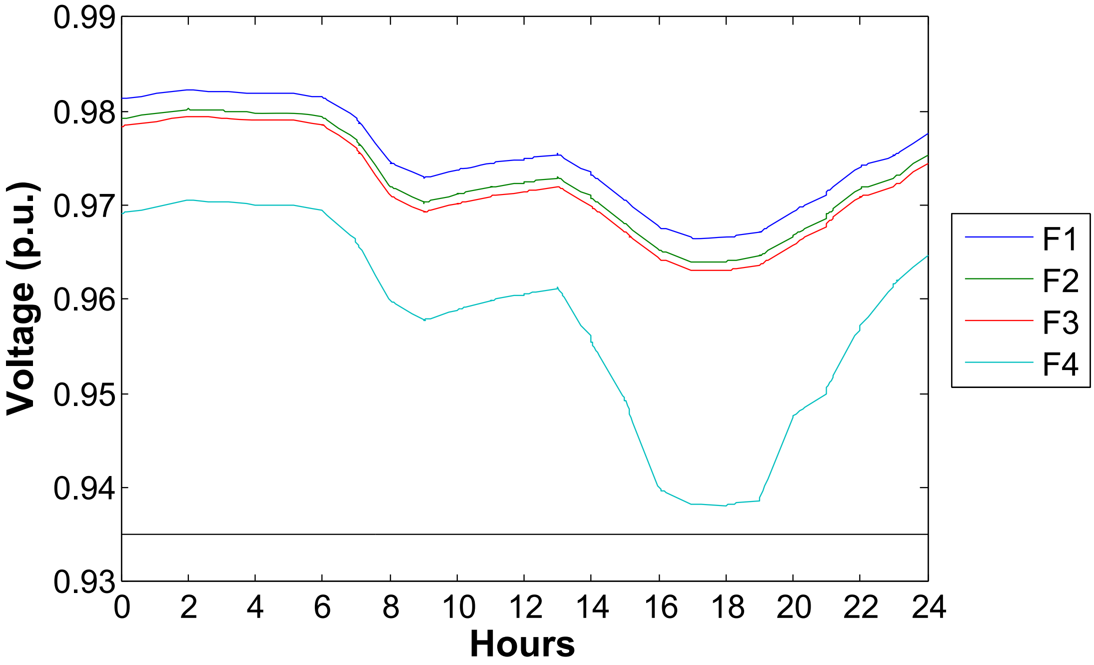

Figure 6.9: Voltage at nodes in the F-branch of the system with seven percent EV adoption and dumb charging.

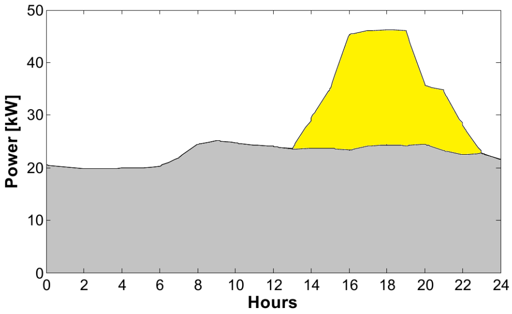

Figure 6.10: Power through cable between node F1 and F4 with seven percent EV adoption and dumb charging.

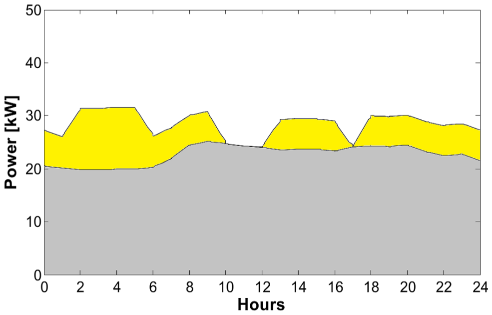

Figure 6.11: Power through cable between node F1 and F4 with seven percent EV adoption and smart charging.

cable dimensions in this branch are constructed to handle a nominal power flow of approximately 100 kW, which is much more than the current power consumption creates. The power through the cable at peak load is approximately 46 kW, as indicated by Figure 6.10, well within its specified limitations.

Assuming a seven percent integration of EVs, the thermal limits of the cables do not appear to be a restricting factor for increased consumption. However, as indicated by Figure 6.7, the voltage level in the F4 branch drops significantly in the afternoon. This voltage drop is due to a large increase in consumption on this specific node. Figure 6.9 presents the voltage level of the different nodes in branch F. The remaining nodes in the F branch appear to be more or less unaffected by the increased consumption at F4. The fact that F4 has a much more load sensitive voltage level than the other nodes in the branch can be explained by the physical extent of the grid. The length of the cable connecting F1 and F4 is twice as long as the one between F1 and F3, and three times as long as the one between F1 and F2. Additionally, residence 23, which has been found to be the weakest spot, is situated relatively far away from F4. All in all, this results in higher impedances and higher losses.

Still, the voltage drop at node F4 is substantial, and, at residence 23 the voltage level drops below the specified system limit. The result suggests that the added load constitutes a significant stress on the system locally. To mitigate voltage drop and reduce transmission losses, smart charging should be applied.

6.2.4 Smart charging with imbalanced allocation

In this scenario, all the EVs are placed at the same residences as in the scenario above. Smart charging strategies have been applied, and the results are presented in Figure 6.8 and 6.11. It is obvious that the power consumption from consumers connected to F4 is much more consistent and the peak power consumption is reduced by 14 kW. The voltage level at residence 23 has smaller fluctuation and remains well within the given limits for the duration of the simulation.

6.3 20 percent EV adoption

The following simulation scenarios are based on the assumption of 20 percent EV penetration. A 20 percent penetration corresponds to 223 EVs in the system model, and 16 of these situated in the LV part connected to substation 54570. The energy consumption of charging 16 EVs under the assumptions presented earlier is 384 kWh, which constitutes about seven percent of the total consumption of the residential area connected to 54570 on February 2. Furthermore, it constitutes 23 percent of the energy consumed at branch F.

6.3.1 Dumb charging with balanced allocation

As in the previous section, the EVs are first assumed to be placed more or less evenly across the system nodes, spreading the additional demand on the power system. The charging loads are based on observed charging patterns as in earlier scenarios and the results are presented in Figure 6.13. Comparing the graph with the results obtained in the previous section (Figure 6.5), it is obvious that

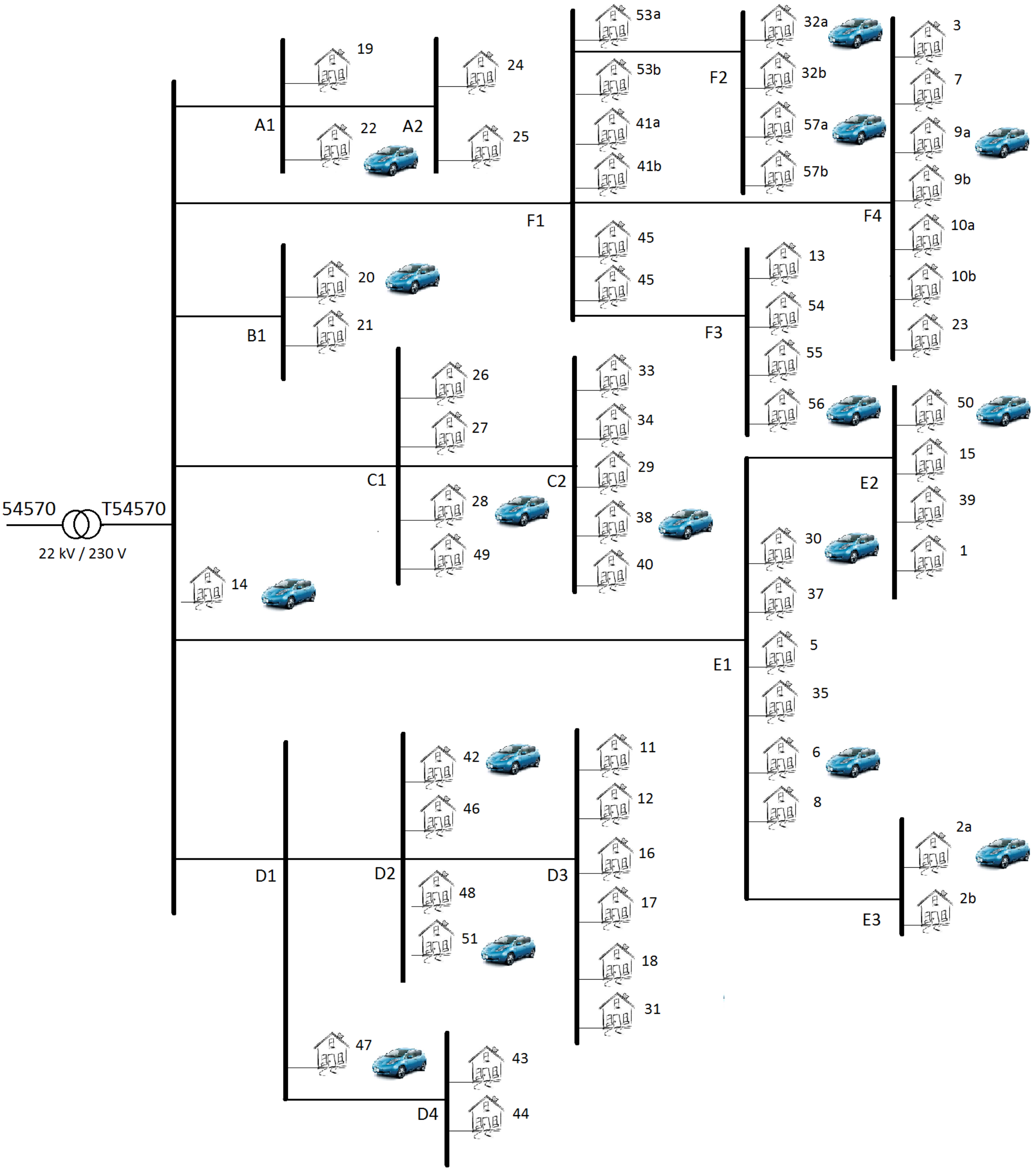

Figure 6.12: Allocation used for the balanced allocation scenarios with 20 percent EV adoption.

the increased degree of EV penetration has affected the voltage level. Still, the difference is not as large as one might have expected. With a total of 16 EVs spread out across the residential area, and charging more or less simultaneously, the voltage levels at the various nodes in the system are still well within the limits. In conclusion, with the assumptions given in this scenario, the system appears to be capable of handling the increased peak power consumption.

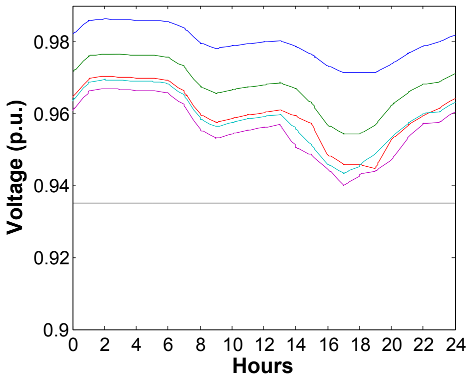

Figure 6.13: Voltage levels with 20 percent EV adoption, spread allocation of EVs and dumb charging.

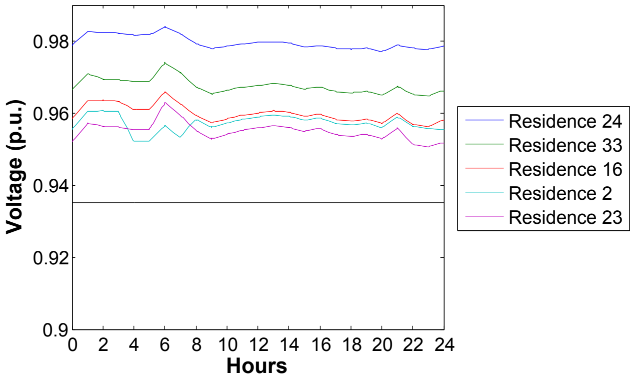

Figure 6.14: Voltage levels with 20 percent EV adoption, spread allocation of EVs and smart charging.

6.3.2 Smart charging with balanced allocation

As in section 6.2, smart charging is not necessary to satisfy the voltage level requirements under the assumptions given in this scenario. However, the smart charging algorithm makes the voltage curve smoother and consumption more constant.

6.3.3 Dumb charging with imbalanced allocation

The 16 EVs are now located at residences connected to the F branch of the grid. This high concentration of EVs in one part of the system will increase the local energy consumption significantly. The EVs are distributed so that the 15 residences on node F2, F3 and F4 have an EV connected, and one of the residences on F1 has been given one as well. That gives a total of 16 EVs located in close proximity, with the same charging pattern as earlier. As previous results have indicated, F4 is much more vulnerable to load increase than the other nodes. As indicated by Figure 6.16, the voltage level in F4 drops below the limit. This discovery is not surprising since the node voltage dropped to an unsatisfactory level in the previous scenario with seven percent EV integration as well. An interesting observation however, is that the voltage levels in nodes F2 and F3 stay above the limit for the entire simulation period. Even though all residences connected to the nodes have EVs charging, the nodes retain acceptable voltage levels. This suggests that the grid is strong on this location, and able to handle a large load increase without violating the given system limits.

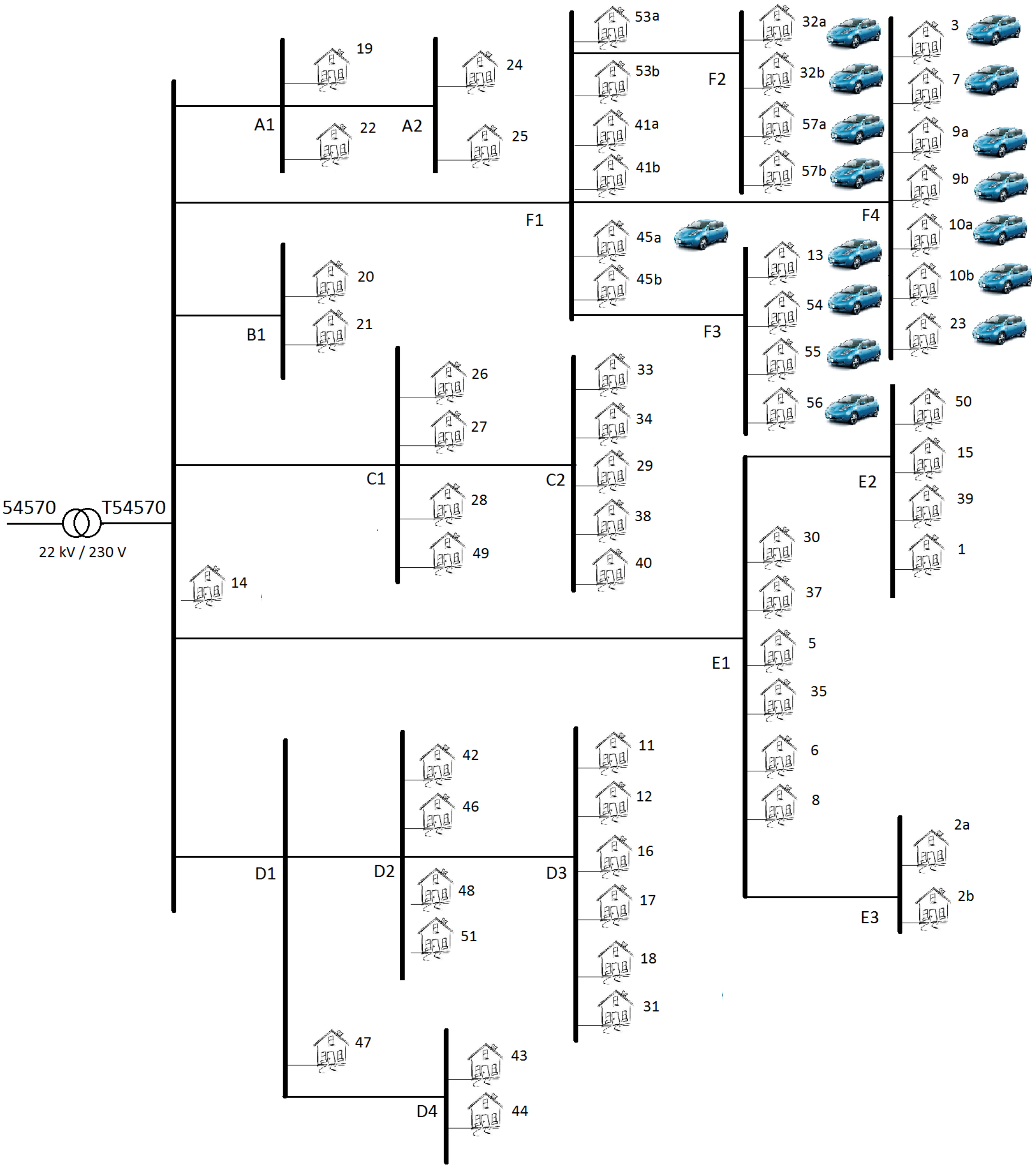

Figure 6.15: Allocation used for the imbalanced allocation scenarios with 20 percent EV adoption.

6.3.4 Smart charging with imbalanced allocation

By applying smart charging in the system, all nodes retain a voltage level within the boundaries of the system. The result indicates that a 20 percent EV penetration of the system is possible, even if the EVs are located in close to one another. Comparing Figure 6.16 and Figure 6.17, it is obvious that smart charging strategies can have a great effect on the voltage levels in a power grid when the degree of penetration increases. Residences 41, 32 and 56 retain a stable voltage level through the simulation period, which indicates that these nodes would be able to handle a even larger EV adoption share.

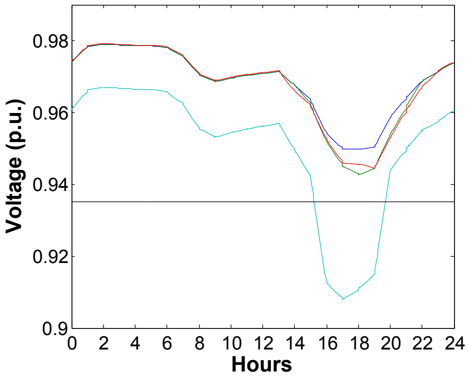

FIGURE 6.16: Voltage levels with 20 percent EV adoption connected to node F4 and dumb charging.

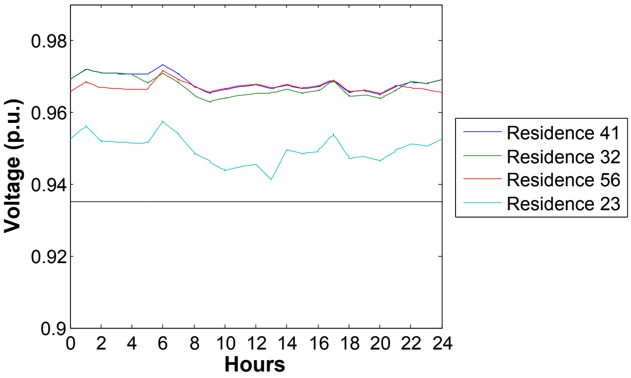

FIGURE 6.17: Voltage levels with 20 percent EV adoption connected to node F4 and smart charging.

6.4 50 percent EV adoption

50 percent EV adoption is a very distant scenario compared with the degree of adoption we have in Norway today. However, it is likely that the share of EVs will be higher than average in urban areas, and lower in more remote location. So, an EV share of 50 percent is not unrealistic in some areas in the future. In any case, it is interesting to observe how a really large adoption share will affect the power system. 557 EVs will be added to the model, and 40 of these are placed at the low voltage part. With this level of EV adoption, 65 percent of all residences will have an EV connected assuming spread allocation.

6.4.1 Dumb charging with balanced allocation

Assuming 40 EVs added to the residential area, the added loads constitute a significant share of the total consumption. Figure 6.18 indicates that the voltage levels in branch C, D, E and F will drop below the limit of the system restriction. This observation implies that the system is not capable of handling the charging loads without implementing smart charging.

6.4.2 Smart charging with balanced allocation

Applying smart charging strategies in the system mitigates the voltage fluctuations. Under the conditions presented in this scenario, it appears that the system is able to accommodate the charging loads of a 50 percent EV share. The implementation of smart charging strategies will undoubtedly mitigate the stress put on the power grid, especially for a high EV penetration level.

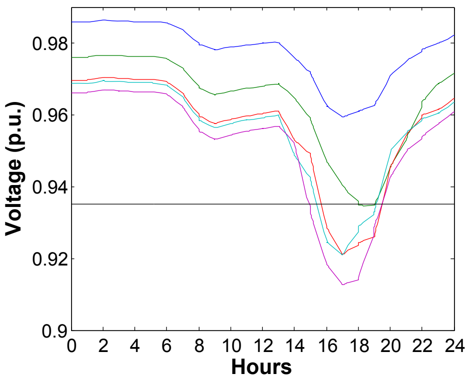

FIGURE 6.18: Voltage levels with 50 percent EV adoption, spread allocation of EVs and dumb charging.

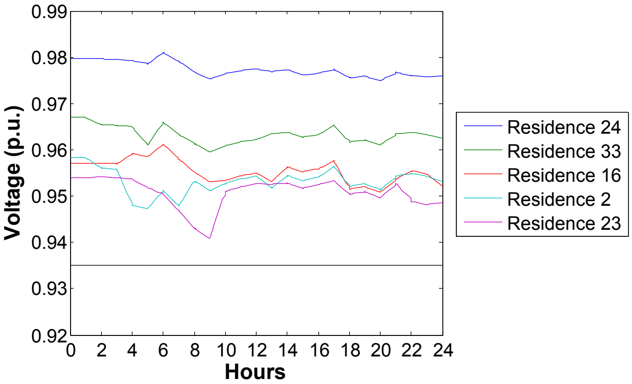

FIGURE 6.19: Voltage levels with 50 percent EV adoption, spread allocation of EVs and smart charging.

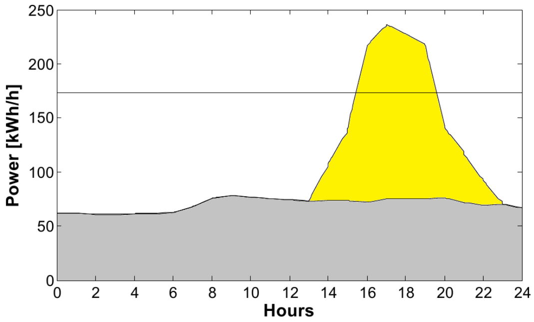

FIGURE 6.20: Power through main cable in F branch assuming 50 percent EV adoption and dumb charging.

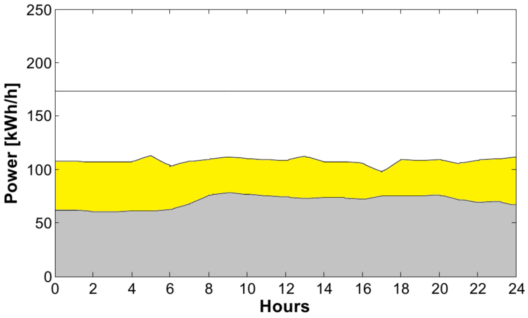

FIGURE 6.21: Power through main cable in F branch assuming 50 percent EV adoption and smart charging.

6.4.3 Dumb charging with imbalanced allocation

Assuming imbalanced allocation, the 40 EVs are divided between the 21 residences in branch F. This means that there are 2 EVs placed on almost every residence in this part of the system. Although most families that decide to purchase an electric car have a fossil-fueled car in addition, it is not unlikely that some families choose to have two electric cars instead. From Figure 6.22 it is obvious that the additional load during peak hours causes more stress than the grid can handle. Additionally, the power consumption of this many electric vehicles charging simultaneously causes the total consumption to exceed the branch cable thermal limit. The characteristics of the main cable between the substation and branch F has a given maximum current of 435 amps. In a three-phase 230 V system with cosϕ=0.98 that allows a maximum power flow of 170 kW. This limit is marked in Figure 6.20 and 6.21 with a black line.

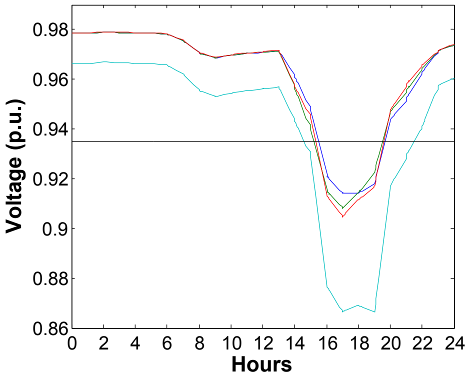

FIGURE 6.22: Voltage levels with 50 percent EV adoption connected to node F4 and dumb charging.

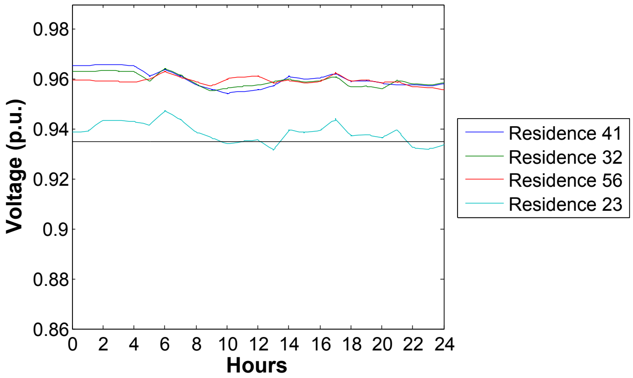

FIGURE 6.23: Voltage levels with 50 percent EV adoption connected to node F4 and smart charging.

6.4.4 Smart charging with imbalanced allocation

By applying smart charging in the system, the thermal power flow through the branch cable is below the maximum limit at all times during the simulation. The voltage drops are also mitigated. The voltage levels at nodes F1, F2 and F3 are within the specified limits for the duration of the 24 hours. However, the voltage level at residence 23 still drops below the minimum allowed voltage level several times. The result suggests that with the given allocation, 50 percent adoption of EVs are more than the grid connecting the residences at F4 can handle. If an EV penetration this high becomes realistic in this part of the system, other actions in addition to smart charging must be taken to retain desired system parameters.

6.5 Wind generation

24 hours simulation

As discussed earlier, the environmental impact EVs impose on their surroundings are closely linked to the source of electric energy. For this reason, the possibility of using wind power to charge the EVs will be explored. A hypothetical wind turbine has been integrated in the model as explained in section 3.5. The wind turbine has a rated power of 500 kW, which gives a potential production of 12,000 kWh daily. The wind measurement data from Hundhammerfjellet has been used to calculate a generation profile for the entire year. For February 2, the generation is indicated by the blue line in Figure 6.24-6.27. The figures compare the energy consumption caused by seven and 20 percent EV adoption, respectively. The yellow-shaded areas represent EV charging that is covered by wind power generation. The green

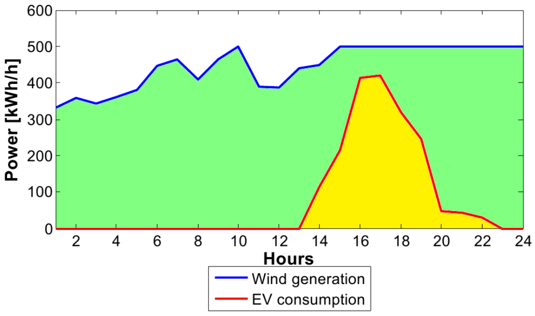

Figure 6.24: Energy consumption due to seven percent EV adoption, using dumb charging.

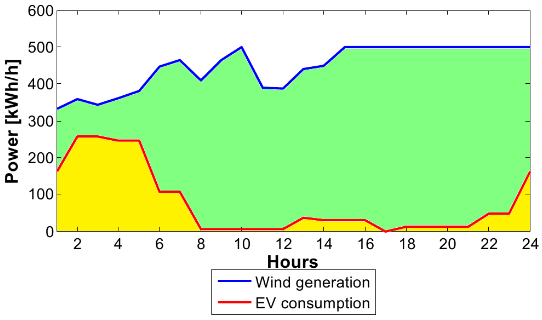

Figure 6.25: Energy consumption due to seven percent EV adoption, using smart charging.

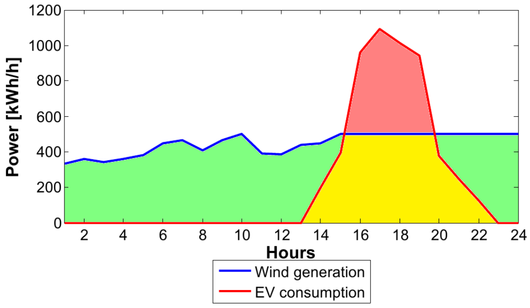

Figure 6.26: Energy consumption due to 20 percent EV adoption, using dumb charging.

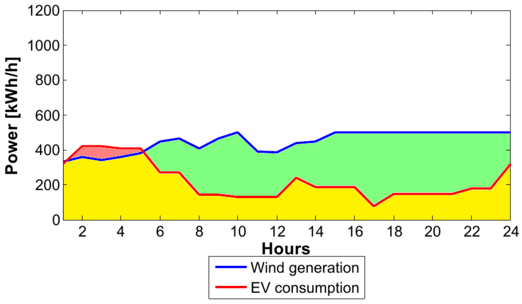

Figure 6.27: Energy consumption due to 20 percent EV adoption, using smart charging.

and red areas represent excess and deficit power. The amount of energy generated on February 2 is much greater than the energy required for charging both with seven and 20 percent EV adoption. Still, with a 20 percent EV share and dumb charging, the power consumption in the afternoon is much higher than the wind production. Further, assuming smart charging, there will also be a few hours of deficit power, but the amount of deficit power will be much smaller than with dumb charging. Judging by the generation profile of February 2, the amount of energy produced during the 24 hours seems to be more than sufficient to cover the EV charging loads. However, wind is varying and unpredictable. The next section compares the expected wind generated throughout the year with required charging power.

Long term simulation

The average daily generation is presented in Figure 6.28, indicated by the black line. The red line indicates the average production over every two weeks. As indicated by the figure, the production is generally higher during winter than summer. To cover the additional load created by 20 percent EV adoption, the

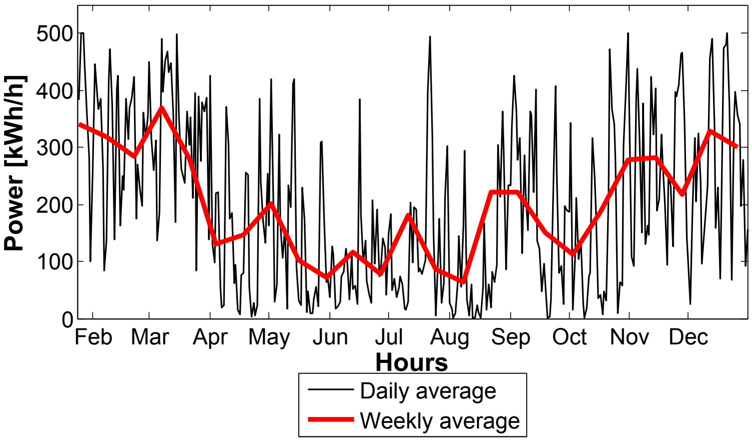

FIGURE 6.28: Wind generation for 2012.

turbine must produce an average of 223 kW throughout the year. The estimated annual production average is found to be 200 kW, which gives an average daily production of 4800 kWh. The energy required to cover the load increase due to EV adoption depends on the number of EVs adopted. Table 6.2 indicates that with the given prerequisites, this wind turbine can produce enough energy to cover the charging load of a 18 percent EV adoption.

TABLE 6.2: Daily EV charging consumption.

EV adoption (%)	Number of EVs	Daily energy demand [kWh]
7	78	1872
10	111	2664
15	167	4008
18	200	4800
20	223	5352
40	445	10680

6.5.1 Energy storage

Even though the total amount of energy generated by wind is sufficient to cover the EV charging load through the year, there may be periods with deficit wind power compared to EV consumption. Wind energy is a non-controllable energy source, and cannot be made to generate according to an EV charging schedule. To completely remove the additional stress a large scale EV adoption would put on the grid, an energy storage would be needed in the system. Then, excess energy from windy periods could be stored and used during periods with low production. There are many different ways to store energy, and some of the most used are given in Table 6.3.

Table 6.3: Different types of energy storage.

Storage
Pumped hydro storage
Compressed air energy storage
Battery Energy storage system
Flow energy storage system
Hydrogen based energy storage system
Flywheel Energy storage system
Superconducting magnetic storage system
Supercapacitor energy storage system

Any energy storage system in this case will need to have a high storage capacity. Storage technologies like flywheel, superconducters and supercapacitors are generally more used for balancing applications than storing large amounts of energy. Compressed air storage may be used to store large amounts of energy, but it requires an underground cavern to store the compressed air. As a result, the available location options for this sort of storage are very limited. Battery storage is found to be the best solution for this application. Lithium-ion batteries have fast charging and discharge capabilities as well as the possibility of high energy storage capacity. More detailed information about the different energy storage systems can be found in "A review of energy storage technologies for wind power applications [32].

Assuming seven percent EV adoption, the total wind production throughout the year is much greater than the EV consumption. However, there are some periods with little or no wind generation. These periods require a large energy storage to cover the entire EV consumption. To be able to cover 100 percent of the EV charging load during the year, a storage capacity of 14,300 kWh is needed. The state of charge of such a storage system is presented in Figure 6.29. The graph indicates that there are a few periods in the course of the year with great deficit production, while most of the year have excess production. By allowing a reduction in number of hours during the year where the storage can cover the EV load, the required storage capacity is reduced. Table 6.4 presents the required storage capacity to cover a given share of the total number of hours. The calculations performed to obtain the required storage capacities assume zero loss when storing energy. In reality, the amount of energy retrieved from a storage system will be lower than the amount injected.

A lower degree of coverage will naturally cause increased consumption in the system. A smaller storage system will also contribute to reducing the import of power when the storage is full and wind production is higher than the EV charging load.

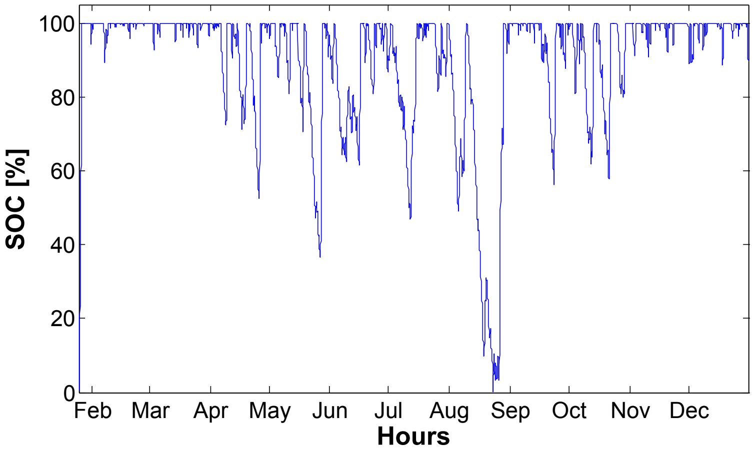

Figure 6.29: State of charge for 14.3 kWh energy storage system with seven percent EV adoption.

Table 6.4: Needed storage to cover seven percent EV adoption charging load.

Hours covered (%)	Storage capacity [kWh]
100	14300
99	8300
95	4200
90	2100
80	450

Assuming that 80 percent annual coverage is acceptable, the needed energy storage is 450 kWh. This storage corresponds to the capacity of 19 Nissan Leaf batteries.

6.6 Long term simulation of power system

To verify the results obtained in the previous sections, an 11-month simulation was performed. Although a full-year simulation is preferable, missing data on power consumption made it difficult. The performed simulation runs from January 25, 2012 through December 31, 2012, and is assumed to give a good indication of how the system will behave over time. In the long term scenarios, the the EVs are assumed to charge one time each day from zero to 100 percent SOC. The smart charging algorithm is made so that there are at least 12 hours between two charging sequences of a vehicle.

The scenario with 20 percent EV penetration located at node F is chosen as the long-term scenario. This scenario is chosen because the number of EVs in the system is great enough to make smart charging necessary to maintain voltage level demands. The long term simulation is run for both smart and dumb charging. The assumption that February 2 is the worst case scenario proves to be accurate. In

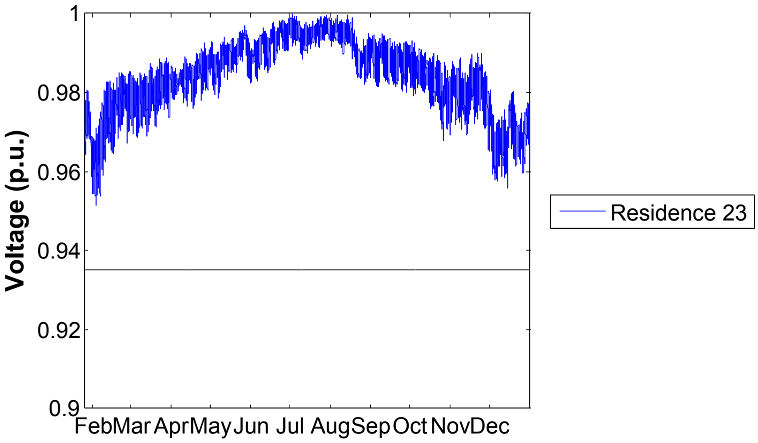

FIGURE 6.30: Voltage at residence 23 over the year with base load.

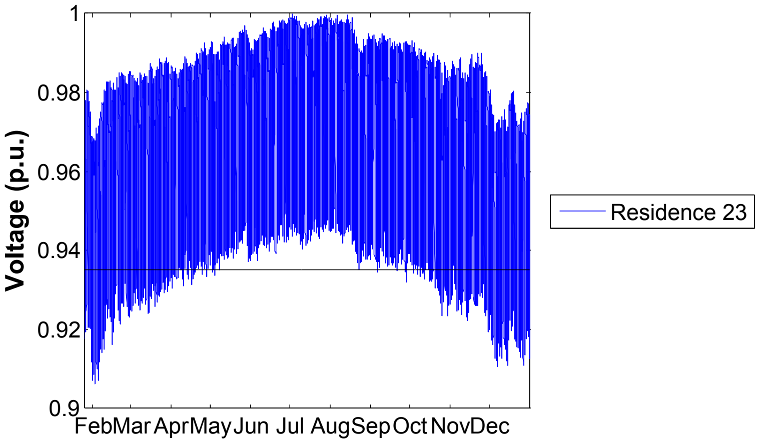

FIGURE 6.31: Voltage at residence 23 over the year with 20 percent EV adoption and dumb charging.

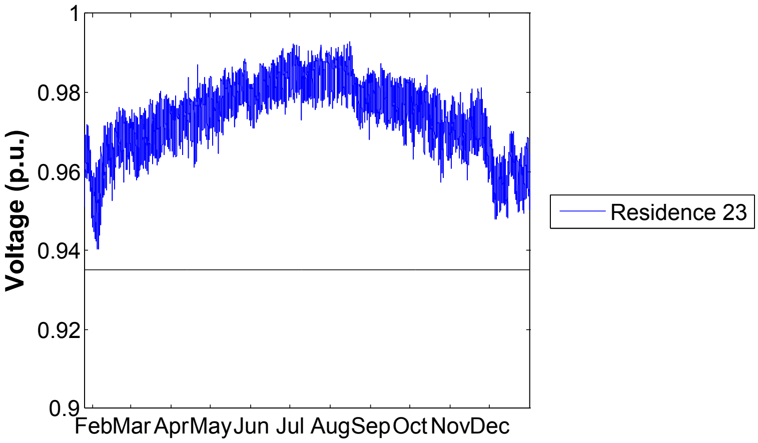

FIGURE 6.32: Voltage at residence 23 over the year with 20 percent EV adoption and smart charging.

both cases, the lowest voltage level occurs at the very beginning of February. Based on this observation, it is reasonable to conclude that the level of EV penetration that is manageable on February 2 will be manageable the rest of the year as well. The variation in voltage level is significantly greater in the case with dumb charging. Figure 6.31 indicates that the voltage constraint in the system will be broken many times during the year, not only on February 2. Implementing smart charging results in a drop in the average voltage value, but the daily deviations are only marginally larger than for the base load scenario. Based on the assumptions and requirements of the simulation, it is clear that smart charging is necessary in the power system with an EV penetration of 20 percent. For the other scenarios simulated in this thesis, the results for February 2 are assumed to apply for the whole year.

Chapter 7

Discussion

The purpose of this thesis was to investigate the impact a large scale electric vehicle adoption would have on a low voltage power grid. The simulated low voltage power system consists of a hydro power plant, 32 distribution transformers, 856 residences, and was provided by NTE from an existing residential area in Steinkjær. Simpow was used as simulation platform, and the model was created from the provided unit characteristics. Additionally, the system was expanded to include a hypothetical wind turbine. This was done to investigate the opportunity of mitigating the additional charging load the EVs put on the system. One of the major challenges in any power system is to transmit power from producer to consumer. Norway has the opportunity to import power from the Netherlands, Sweden, Denmark, Finland and Russia, but most of the high capacity transmission lines are connected to the southern part of Norway. This often results in both deficit power and higher electricity prices in the northern parts during high demand periods. If a residential area, like the one simulated in this thesis, would generate more power, it would contribute to maintaining the system balance by lowering the demand of imported power. The hypothetical turbine was given a rated power of 500 kW, and the generation profile was calculated from wind measurements from Hundhammerfjellet wind farm, situated in Nord-Trøndelag. For the 24-hour simulation period, the wind generation is much higher than the power consumption from the vehicles. During the 24 hours, the total excess energy production is calculated to be 8876 and 5372 kWh with seven and 20 percent EV adoption, respectively. This argues that even with a EV penetration of 20 percent, the imported power to the system during February 2 would be lower due to the wind generation than the observed results from the base load scenario without wind generation. However, the long term simulation of the system indicates that the average produced power over a year will be too low to cover the charging load of a 20 percent EV penetration. Assuming an unlimited energy storage, the produced power throughout the year is sufficient to cover a 18 percent EV adoption. However, the storage system capacity would have to be unrealistically high because of the fluctuating generation profile. Most of the excess power occurs during the winter months. During the spring there is little generation, and the storage system is consistently drained from April through August. For the seven percent EV adoption scenario, assuming 80 percent of the simulation period covered by the storage system, a capacity of 450 kWh would be sufficient. A battery of this size corresponds to the capacity of 19 Nissan Leaf batteries and is not unrealistic to implement.

The main focus of this thesis has been to explore the advantages of load shifting, and also the effects of different load allocation in a power system. Hourly power generation at the hydroelectric power plant as well as the power flow through the main transformer in the system was given. By adding the data, a consumption profile for the power system was created.

The main transformer power flows were given for both active and reactive power. Since the flows are given on an hourly basis, the data set contains only the largest observed value for each hour in both directions. If the production at Byafossen is high and the consumption in the system is low, the system will export energy. If generation and consumption are almost equal, there might be both excess and deficit energy in the system within the same hour. This means that some hours are listed with power flows in both directions. In the model, this is solved simply by subtracting the power outflow from the inflow, using that the difference as hourly value. Similarly, the reactive power flow in the model is given to be the difference between inflow and outflow. For the hydro power plant, the reactive power generation/consumption was not available. Based on e-mail correspondence with an NTE employee it was decided that consumed reactive power in a residential area can be assumed proportional to the active power consumption. This assumption is close to reality, so the results obtained in the simulations should be considered to be realistic.

In addition to residential areas, there are also public buildings such as schoolsa and hotels, that have different load patterns than residences. From the base load scenario, it is clear that the peak load in the system occurs around 9 a.m. This peak might be caused mostly by large consumers such as schools and hotels, and not by the residences. However, with the provided information, it was not possible to differentiate between consumer types in the system. All consumers have, therefore, been assumed to have the same consumption pattern, which is scaled by their annual energy usage. The major simplifying assumptions made for the charging of electric vehicles are:

- Charging frequency
- Identical charging profiles
- Initial SOC = zero percent

- EVs are modelled as part of resident load

With a specified range of 100-169 km, and an average daily driving distance of 43 km, it is probably not accurate to assume that all vehicles will charge every day. It is more likely to assume that the average electric vehicle owner will be charging every second or third day, optionally charging daily with an initial SOC over 50 percent. It has also been assumed in this thesis that all electric vehicles have the same charging pattern. There are many different electric vehicles in the market today, and they are different with respect to battery capacities and charging profiles. Also, the home charging station capacity could vary between the residences. It is assumed that all vehicle owners are capable of recharging their vehicle in four hours, but it is likely that people will choose different solutions unless a standard is introduced by the government. Furthermore, the EV charging sequence is modelled as a part of the residence load as opposed to separate load. The voltage sensitivity of a Nissan Leaf could differ from the calculated resident voltage sensitivity, but no indication either way was found.

One of the most interesting results in this thesis is that a surprisingly low number of EVs can present the power system with problems. It is apparent from the results that the physical location of the load is a significant factor when estimating the system capabilities. The results also suggest that the voltage level in parts of the system where no load has been added is nearly unaffected by the load increase in other parts of the system. Consequently, it is difficult to estimate how much additional load an arbitrary system can handle without doing a specific analysis of the system in question. The challenge is not just to determine how much load the system as a whole can handle, but how much load each node can manage. Regardless, the importance of smart grid implementation and load shifting as the share of EVs increases has been illuminated.

Chapter 8

Conclusion

Previous analyses of a similar power system have illuminated some problems that arise due to large scale EV adoption [14]. It was deducted that the system was not capable to handle an implementation of 10 percent EV share, because one of the residences experienced a voltage level below the given limits. The simulations performed in this thesis are based on a different grid, but the results are to a certain extent comparable. In this thesis, it is proposed that even a smaller amount of EVs can cause system voltage variations beyond the recommended limits. As few as six chargeable vehicles, or seven percent EV share, located at a sensitive node may add more load than the system can handle if charging during peak hours. On the other hand, with a different allocation of the EVs, a larger adoption share is possible. The simulations assume the same charging pattern in the two scenarios, but with the balanced allocation, some of the additional load is placed on more rigid parts of the grid. Assuming balanced allocation of the EVs in the system and the circumstances presented earlier, a 20 percent EV adoption does not seem to cause the power system too much stress, even when dumb charging patterns are used. The voltage sensitivity varies between the residences, based on how far away from the node they are located, and the characteristics of the cables in between. This is the main reason that placing the EV loads at different locations yield different results. Because the power system experiences the stress from a load differently depending on load allocation, there is no way to readily answer how many vehicles an arbitrary system can handle without adopting some form of smart charging. Utilization of smart charging strategies seems to relieve the system of some additional stress, and the voltage issues are mitigated, even for a high number of EVs.

For all simulated scenarios conducted in this research, the voltage limit has been the decisive factor in ascertaining how much load the system can handle. The branch thermal limit was not surpassed in any of the scenarios, except for 50 percent EV adoption with imbalanced allocation and dumb charging. However, the voltage level dropped below the restriction limit of the system already for the 20 percent penetration scenario, which suggests that the thermal limits of the cables are not the restrictive factor in the system. Comparing the peak power from the base load scenario with the peak point from the high level EV penetration scenarios, it is obvious that the grid is constructed to handle much larger power flows than the current consumption constitutes as of today.

The wind turbine generation contributes to a more self-supportive power system. For the 24-hour simulation performed for February 2, 2012, the total generated energy was higher than the energy consumed by the EVs, assuming a 20 percent penetration share. However, for the long-term simulation, the energy produced by wind would correspond to the charging consumption of 18 percent EV penetration. When the energy storage is introduced, it becomes clear that there is much higher wind production during the winter than in the summer months. To refrain from causing additional stress on the grid, the EV charging is assumed to come either from the present wind generation, or the storage system. Due to variations in generation throughout the year, the capacity of the storage system would have to be extremely high to support the charging load of a 18 percent adoption. For the seven percent adoption scenario, the annual wind energy generation is much higher than the added consumption, but a large storage system is still required to cover the charging load at all times. This is because of a few days during the year with little or no generation. During this time, all the charging consumption must be covered by the storage system. By allowing the charging load to be covered by the external grid for some of these low generation hours, the required storage is much smaller. A 450 kWh storage system would be sufficient to cover the seven percent EV adoption load for 80 percent of the hours during a year.

To verify the results obtained in the 24-hour simulation, a long term simulation was performed as well. The 20 percent EV adoption share was chosen as reference scenario, and both dumb and smart charging strategies were investigated. The results illuminate the benefit of applying smart charging strategies when the share of EVs in a system increases. The average voltage level through the year decreases compared to the base load scenario, but the daily fluctuations are only marginally larger. Without the smart charging strategy, the daily voltage fluctuations are a lot larger and the system voltage limits are violated many times during the year.

Chapter 9

Further Work

The optimization algorithm derived in this paper takes in the consumption data for the power system in order to calculate the optimal time of charging from a system voltage level point of view. However, in a realistic situation, one does not have the consumption data for future hours, so the optimal time of charging becomes dubious. An algorithm should be derived to estimate future power consumption based on past consumption patterns, and marginal changes in electricity price and power flows. Other parameters that might help indicate the future demand should also be implemented in the algorithm.

Today, the consumption profiles of residences are becoming more diverse. As distributed generation becomes more common, some residences will periodically generate more power than is consumed. Distributed generation presents the power system with several technical issues; one of which is the power flow direction. With higher generation than consumption in a consumer area, the power flow changes direction and this may have consequences with respect to voltage levels in the grid.

Increasing adoption of electric vehicles leads to increased power and energy consumption in the system. The charging sequence occurs at a relatively high power rate, thus increasing the peak load of some houses. This changes the consumption pattern of these houses compared to previous observations. Even though we increase the number of electrical components in our homes, the total demand of energy does not necessarily increase. This is because manufacturers constantly thrive to make their products more efficient. The largest energy consumption factor in Norwegian households is undoubtedly space heating. With recent years attitude towards energy saving, a large number of houses have installed heat pumps, which are much more efficient than the conventional electric radiator. Additionally, government laws dictate that all new buildings have to meet certain requirements with respect to insulation and energy consumption. It is difficult to model so many different consumer types with a single model, and still obtain accurate results.

Further work would be to conduct a more detailed study of how power consumption actually differs between different types of consumers. With distributed generation becoming more common, and the introduction of smart grid systems, new possibilities in relation to power system control follow. It could be possible to shift EV charging towards periods with high distributed generation, increasing the power consumption in this period, to benefit system stability parameters.

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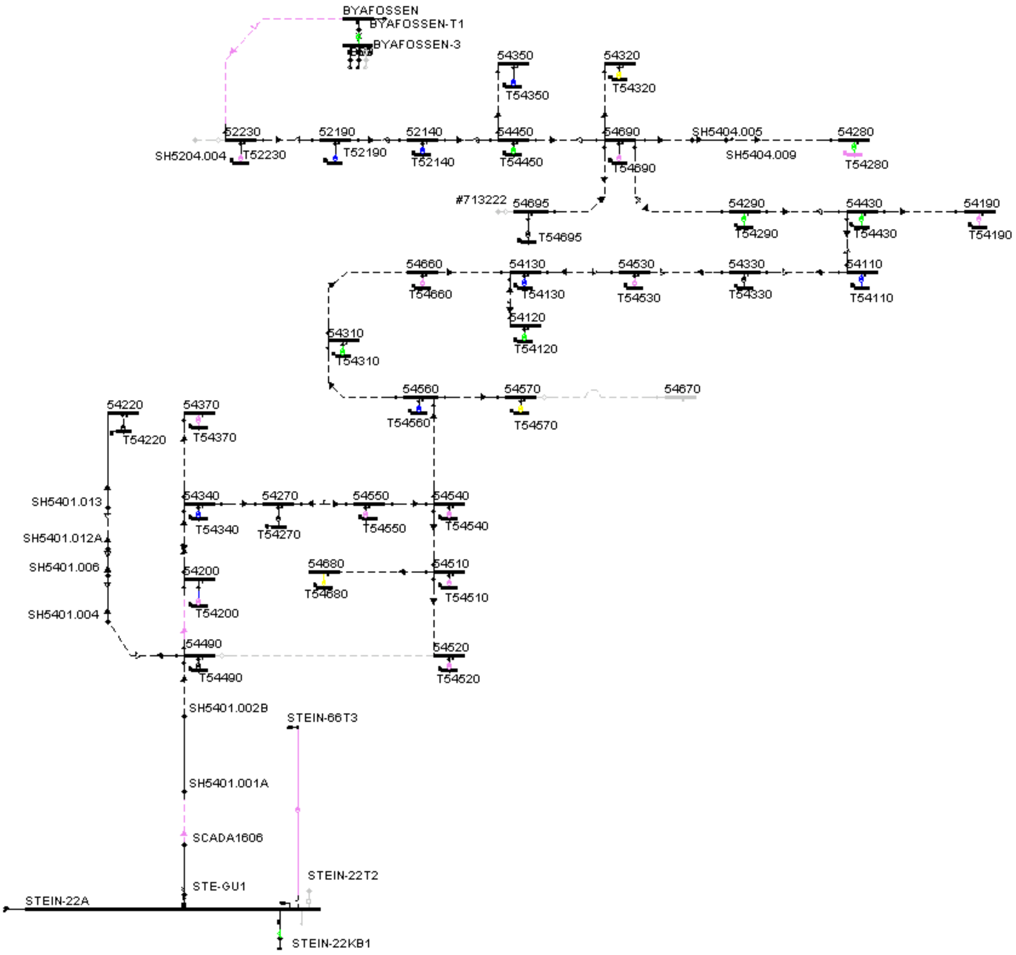
Appendix A

Data provided by NTE

Single line diagram of system



Production at Byafossen

01/01 2010 2076 kWh	01/01 2011 1055 kWh	01/01 2012 1435 kWh
Hour 02 2077	Hour 02 1058	Hour 02 1438
Hour 03 2078	Hour 03 1055	Hour 03 1443
Hour 04 2080	Hour 04 1055	Hour 04 1452
Hour 05 2079	Hour 05 1055	Hour 05 1452
Hour 06 2080	Hour 06 1054	Hour 06 1446
Hour 07 2073	Hour 07 1048	Hour 07 1447
Hour 08 2075	Hour 08 1047	Hour 08 1442
Hour 09 2100	Hour 09 1048	Hour 09 1433
Hour 10 2110	Hour 10 1047	Hour 10 1432
Hour 11 2112	Hour 11 1053	Hour 11 1436
Hour 12 2113	Hour 12 1050	Hour 12 1437
Hour 13 2108	Hour 13 1045	Hour 13 1437
Hour 14 2110	Hour 14 1042	Hour 14 1438
Hour 15 2110	Hour 15 1048	Hour 15 1435
Hour 16 2102	Hour 16 1035	Hour 16 1433
Hour 17 2102	Hour 17 1027	Hour 17 1430
Hour 18 2100	Hour 18 1025	Hour 18 1430
Hour 19 2100	Hour 19 1028	Hour 19 1434
Hour 20 2103	Hour 20 1032	Hour 20 1438
Hour 21 2103	Hour 21 1031	Hour 21 1442
Hour 22 2105	Hour 22 1045	Hour 22 1453
Hour 23 2109	Hour 23 1050	Hour 23 1457
Hour 24 2110	Hour 24 1057	Hour 24 1456
. . .		
. . .		
. . .		
31/12 2010 1027 kWh	31/12 2011 1652 kWh	31/12 2012 1083 kWh
Hour 02 1040	Hour 02 1645	Hour 02 1085
Hour 03 1042	Hour 03 1648	Hour 03 1089
Hour 04 1036	Hour 04 1650	Hour 04 1089
Hour 05 1045	Hour 05 1652	Hour 05 1092
Hour 06 1047	Hour 06 1650	Hour 06 1087
Hour 07 1040	Hour 07 1645	Hour 07 1075
Hour 08 1028	Hour 08 1635	Hour 08 1062
Hour 09 1014	Hour 09 1623	Hour 09 1063
Hour 10 1011	Hour 10 1627	Hour 10 1086
Hour 11 1012	Hour 11 1628	Hour 11 1093
Hour 12 1010	Hour 12 1502	Hour 12 1095
Hour 13 1023	Hour 13 1495	Hour 13 1096
Hour 14 1020	Hour 14 1496	Hour 14 1098
Hour 15 1024	Hour 15 1499	Hour 15 1099
Hour 16 1028	Hour 16 1515	Hour 16 1097
Hour 17 1032	Hour 17 1538	Hour 17 1092
Hour 18 1033	Hour 18 1542	Hour 18 1092
Hour 19 1030	Hour 19 1538	Hour 19 1095
Hour 20 1042	Hour 20 1520	Hour 20 1106
Hour 21 1053	Hour 21 1530	Hour 21 1110
Hour 22 1055	Hour 22 1530	Hour 22 1104
Hour 23 1052	Hour 23 1478	Hour 23 1086
Hour 24 1038	Hour 24 1429	Hour 24 1092

Power through main feeder in the system

Start time	End time	Act. power IN	Act. power OUT	Rea. power IN	Rea. power OUT
25.01.2012 00	25.01.2012 01	1338	0	0	178
25.01.2012 01	25.01.2012 02	1249	0	0	222
25.01.2012 02	25.01.2012 03	1275	0	0	174
25.01.2012 03	25.01.2012 04	1282	0	0	172
25.01.2012 04	25.01.2012 05	1307	0	0	221
25.01.2012 05	25.01.2012 06	1423	0	0	288
25.01.2012 06	25.01.2012 07	1860	0	0	279
25.01.2012 07	25.01.2012 08	2382	0	0	253
25.01.2012 08	25.01.2012 09	2552	0	0	228
25.01.2012 09	25.01.2012 10	2482	0	0	214
25.01.2012 10	25.01.2012 11	2454	0	0	215
25.01.2012 11	25.01.2012 12	2368	0	0	206
25.01.2012 12	25.01.2012 13	2202	0	0	229
25.01.2012 13	25.01.2012 14	2170	0	0	243
25.01.2012 14	25.01.2012 15	2238	0	0	224
25.01.2012 15	25.01.2012 16	2126	0	0	199
25.01.2012 16	25.01.2012 17	2295	0	4	127
25.01.2012 17	25.01.2012 18	2256	0	0	131
25.01.2012 18	25.01.2012 19	2232	0	0	107
25.01.2012 19	25.01.2012 20	2253	0	0	115
25.01.2012 20	25.01.2012 21	2264	0	0	119
25.01.2012 21	25.01.2012 22	2229	0	0	104
25.01.2012 22	25.01.2012 23	1948	0	0	126
25.01.2012 23	25.01.2012 24	1640	0	0	154
. . .					
. . .					
. . .					
31.12.2012 00	31.12.2012 01	1881	0	796	0
31.12.2012 01	31.12.2012 02	1781	0	773	0
31.12.2012 02	31.12.2012 03	1762	0	814	0
31.12.2012 03	31.12.2012 04	1736	0	795	0
31.12.2012 04	31.12.2012 05	1759	0	816	0
31.12.2012 05	31.12.2012 06	1749	0	789	0
31.12.2012 06	31.12.2012 07	1894	0	721	0
31.12.2012 07	31.12.2012 08	1947	0	605	0
31.12.2012 08	31.12.2012 09	2137	0	634	0
31.12.2012 09	31.12.2012 10	2374	0	833	0
31.12.2012 10	31.12.2012 11	2588	0	860	0
31.12.2012 11	31.12.2012 12	2633	0	864	0
31.12.2012 12	31.12.2012 13	2665	0	840	0
31.12.2012 13	31.12.2012 14	2749	0	887	0
31.12.2012 14	31.12.2012 15	2812	0	897	0
31.12.2012 15	31.12.2012 16	2914	0	889	0
31.12.2012 16	31.12.2012 17	2915	0	887	0
31.12.2012 17	31.12.2012 18	2854	0	859	0
31.12.2012 18	31.12.2012 19	2730	0	883	0
31.12.2012 19	31.12.2012 20	2524	0	932	0
31.12.2012 20	31.12.2012 21	2342	0	956	0
31.12.2012 21	31.12.2012 22	2185	0	877	0
31.12.2012 22	31.12.2012 23	2078	0	734	0
31.12.2012 23	31.12.2012 24	1957	0	745	0

Appendix B

Simpow code

Optpow file

Øystein Sagosen - optpow file for analysis of large scale adoption of EVs with wind generation. This is used to run a static simulation of the system, to calculate initial conditions for the dynamic simulations.

```
optpow_ with_ wind.optpow **

Øystein Sagosen - optpow file for analysis of large scale adoption of EVs

system.optpow **

GENERAL
SN=25
END
NODES
52140 UB=22
52190 UB=22
52230 UB=22
54110 UB=22
54120 UB=22
54130 UB=22
54190 UB=22
54200 UB=22
54220 UB=22
54270 UB=22
54280 UB=22
54290 UB=22
54310 UB=22
54320 UB=22
54330 UB=22
54340 UB=22
54350 UB=22
54370 UB=22
54430 UB=22
54450 UB=22
54490 UB=22
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54520 UB=22
54530 UB=22
54540 UB=22
54550 UB=22
54560 UB=22
54570 UB=22
```

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54570.014.1 UB=0.23
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54570.020.1 UB=0.23
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54570.028.1 UB=0.23
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54570.033.1 UB=0.23
54570.038.1 UB=0.23
54570.029.1 UB=0.23
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T54490 UB=0.23
T54510 UB=0.23
T54520 UB=0.23
T54530 UB=0.23
T54540 UB=0.23
T54550 UB=0.23
T54560 UB=0.23
T54570 UB=0.23
T54660 UB=0.23
T54680 UB=0.23
T54690 UB=0.23
T54695 UB=0.40
STEIN-22A UB=22
STEIN-66T3 UB=66
SCADA1606 UB=22
SH5401.001A UB=22
SH5401.002B UB=22
SH5401.004 UB=22
SH5401.006 UB=22
SH5401.012A UB=22
SH5401.013 UB=22
SH5404.005 UB=22
SH5404.009 UB=22
BYAFOSSEN UB=22
BYAFOSSEN-T1 UB=3.3
WIND UB=22
WIND-T1 UB=0.69
END


LINES
STEIN-22A SCADA1606 TYPE=0 L=0.1
SCADA1606 SH5401.001A TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.438
SH5401.001A SH5401.002B TYPE=2 R=0.190 X=0.290 B=3769.91E-8 L=0.16
SH5401.002B 54490 TYPE=2 R=0.125 X=0.180 B=94.2480E-6 L=0.15
54490 54200 TYPE=2 R=0.207 X=0.121 B=78.9330E-6 L=0.4
54200 54340 TYPE=2 R=0.211 X=0.147 B=75.9270E-6 L=0.285
54340 54370 TYPE=2 R=0.320 X=0.120 B=62.8320E-6 L=0.162
54340 54270 TYPE=2 R=0.208 X=0.121 B=72.8720E-6 L=0.235
54270 54550 TYPE=2 R=0.208 X=0.191 B=103.629E-6 L=0.305
```

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54550 54540 TYPE=2 R=0.208 X=0.192 B=114.320E-6 L=0.185
54540 54510 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.329
54510 54680 TYPE=2 R=1.200 X=0.240 B=59.6900E-6 L=0.167
54510 54520 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.24
54540 54560 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.153
54560 54570 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.49
54560 54310 TYPE=2 R=0.641 X=0.130 B=53.4070E-6 L=0.32
54310 54660 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.28
54660 54130 TYPE=2 R=0.641 X=0.210 B=72.2570E-6 L=0.191
54130 54120 TYPE=2 R=0.209 X=0.159 B=76.2390E-6 L=0.142
54530 54130 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.356
54330 54530 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.517
54110 54330 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.41
54430 54110 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.467
54430 54190 TYPE=2 R=0.320 X=0.210 B=65.9730E-6 L=0.213
54290 54430 TYPE=2 R=0.320 X=0.210 B=65.9730E-6 L=0.517
54690 54290 TYPE=2 R=0.320 X=0.200 B=94.2480E-6 L=0.4
54450 54690 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.46
52140 54450 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.414
52190 52140 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.265
52230 52190 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.33
BYAFOSSEN 52230 TYPE=2 R=0.320 X=0.210 B=65.9730E-6 L=0.182
54450 54350 TYPE=2 R=0.320 X=0.200 B=94.2480E-6 L=0.366
54690 54695 TYPE=2 R=0.211 X=0.190 B=113.117E-6 L=0.162
54690 54320 TYPE=2 R=1.200 X=0.240 B=59.6900E-6 L=0.3
54690 SH5404.005 TYPE=2 R=0.320 X=0.200 B=94.2480E-6 L=0.38
SH5404.005 SH5404.009 TYPE=2 R=0.721 X=0.395 B=2896.54E-8 L=0.481
SH5404.009 54280 TYPE=2 R=0.320 X=0.200 B=94.2480E-6 L=0.06
54490 SH5401.004 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=0.174
SH5401.004 SH5401.006 TYPE=2 R=0.359 X=0.373 B=3075.61E-8 L=0.18
SH5401.006 SH5401.012A TYPE=2 R=0.721 X=0.395 B=2896.54E-6 L=0.745
SH5401.012A SH5401.013 TYPE=2 R=0.320 X=0.120 B=65.9730E-6 L=0.08
SH5401.013 54220 TYPE=2 R=0.721 X=0.395 B=2896.54E-8 L=0.405
T54570 54570.B1 TYPE=2 L=0.081 R=0.206 X=0.072 B=373.84952E-6
54570.B1 54570.020.1 TYPE=2 L=0.029 R=1.830 X=0.088 B=197.92033E-6
54570.B1 54570.021.1 TYPE=2 L=0.03 R=1.830 X=0.088 B=197.92033E-6
T54570 54570.A1 TYPE=2 L=0.035 R=0.125 X=0.072 B=395.84067E-6
54570.A1 54570.022.1 TYPE=2 L=0.036 R=1.150 X=0.085 B=219.91147E-6
54570.A1 54570.019.1 TYPE=2 L=0.062 R=1.150 X=0.085 B=219.91148E-6
54570.A1 54570.A2 TYPE=2 L=0.062 R=0.320 X=0.076 B=345.57518E-6
54570.A2 54570.024.1 TYPE=2 L=0.018 R=0.641 X=0.079 B=339.29199E-6
54570.A2 54570.025.1 TYPE=2 L=0.008 R=1.830 X=0.088 B=197.92034E-6
T54570 54570.C1 TYPE=2 L=0.112 R=0.125 X=0.072 B=395.84068E-6
54570.C1 54570.027.1 TYPE=2 L=0.008 R=1.830 X=0.088 B=197.92034E-6
54570.C1 54570.026.1 TYPE=2 L=0.01 R=1.830 X=0.088 B=197.92033E-6
54570.C1 54570.028.1 TYPE=2 L=0.036 R=0.641 X=0.079 B=339.29199E-6
54570.C1 54570.049.1 TYPE=2 L=0.003 R=7.410 X=0.104 B=150.79644E-6
54570.C1 54570.C2 TYPE=2 L=0.061 R=0.206 X=0.072 B=373.84952E-6
54570.C2 54570.034.1 TYPE=2 L=0.012 R=1.830 X=0.088 B=197.92033E-6
54570.C2 54570.033.1 TYPE=2 L=0.019 R=1.830 X=0.088 B=197.92033E-6
54570.C2 54570.038.1 TYPE=2 L=0.015 R=1.830 X=0.088 B=197.92033E-6
54570.C2 54570.029.1 TYPE=2 L=0.041 R=0.641 X=0.079 B=339.29201E-6
54570.C1 54570.040.1 TYPE=2 L=0.044 R=0.641 X=0.079 B=339.29200E-6
T54570 54570.D1 TYPE=2 L=0.108 R=0.125 X=0.072 B=395.84068E-6
54570.D1 54570.047.1 TYPE=2 L=0.021 R=0.641 X=0.079 B=339.29200E-6
54570.D1 54570.D2 TYPE=2 L=0.078 R=0.125 X=0.072 B=395.84068E-6
54570.D2 54570.048.1 TYPE=2 L=0.014 R=0.641 X=0.079 B=339.29201E-6
54570.D2 54570.051.1 TYPE=2 L=0.038 R=0.641 X=0.079 B=339.29199E-6
54570.D2 54570.046.1 TYPE=2 L=0.048 R=0.641 X=0.079 B=339.29200E-6
54570.D2 54570.D3 TYPE=2 L=0.048 R=0.206 X=0.072 B=373.84952E-6
54570.D3 54570.031.1 TYPE=2 L=0.022 R=0.641 X=0.079 B=339.29200E-6
54570.D3 54570.017.1 TYPE=2 L=0.013 R=0.641 X=0.079 B=339.29201E-6
54570.D3 54570.012.1 TYPE=2 L=0.031 R=0.641 X=0.079 B=339.29200E-6
54570.D3 54570.018.1 TYPE=2 L=0.021 R=0.641 X=0.079 B=339.29200E-6
54570.D3 54570.011.1 TYPE=2 L=0.023 R=0.641 X=0.079 B=339.29200E-6
54570.D3 54570.016.1 TYPE=2 L=0.073 R=0.641 X=0.079 B=339.29200E-6
54570.D2 54570.042.1 TYPE=2 L=0.012 R=1.830 X=0.088 B=197.92033E-6
54570.D1 54570.D4 TYPE=2 L=0.06 R=0.320 X=0.076 B=345.57518E-6
54570.D4 54570.044.1 TYPE=2 L=0.007 R=3.080 X=0.088 B=197.92034E-6
54570.D4 54570.043.1 TYPE=2 L=0.018 R=1.830 X=0.088 B=197.92032E-6
T54570 54570.E1 TYPE=2 L=0.156 R=0.125 X=0.072 B=395.84068E-6
```

```
54570.E1 54570.008.1 TYPE=2 L=0.032 R=0.641 X=0.079 B=339.29202E-6
54570.E1 54570.E3 TYPE=2 L=0.094 R=0.641 X=0.079 B=339.29199E-6
54570.E3 54570.002.1 TYPE=2 L=0.004 R=0.641 X=0.079 B=339.29202E-6
54570.002.1 54570.002.2 TYPE=0
54570.E1 54570.006.1 TYPE=2 L=0.062 R=0.641 X=0.079 B=339.29200E-6
54570.E1 54570.035.1 TYPE=2 L=0.07 R=0.641 X=0.079 B=339.29200E-6
54570.E1 54570.005.1 TYPE=2 L=0.059 R=0.641 X=0.079 B=339.29200E-6
54570.E1 54570.037.1 TYPE=2 L=0.096 R=0.641 X=0.079 B=339.29200E-6
54570.E1 54570.E2 TYPE=2 L=0.042 R=0.320 X=0.075 B=345.57518E-6
54570.E2 54570.001.1 TYPE=2 L=0.008 R=3.080 X=0.094 B=172.78760E-6
54570.E2 54570.039.1 TYPE=2 L=0.017 R=0.641 X=0.079 B=339.29202E-6
54570.E2 54570.015.1 TYPE=2 L=0.022 R=0.641 X=0.079 B=339.29200E-6
54570.E2 54570.050.1 TYPE=2 L=0.059 R=1.200 X=0.082 B=257.61059E-6
54570.E1 54570.030.1 TYPE=2 L=0.038 R=0.641 X=0.079 B=339.29199E-6
T54570 54570.F1 TYPE=2 L=0.068 R=0.125 X=0.072 B=395.84069E-6
54570.F1 54570.F2 TYPE=2 L=0.03 R=0.320 X=0.075 B=345.57518E-6
54570.F2 54570.032.1 TYPE=2 L=0.033 R=0.320 X=0.075 B=345.57519E-6
54570.032.1 54570.032.2 TYPE=0
54570.F2 54570.057.1 TYPE=2 L=0.009 R=0.641 X=0.079 B=339.29199E-6
54570.057.1 54570.057.2 TYPE=0
54570.F1 54570.F3 TYPE=2 L=0.047 R=0.320 X=0.075 B=345.57517E-6
54570.F3 54570.013.1 TYPE=2 L=0.009 R=0.641 X=0.079 B=339.29199E-6
54570.F3 54570.054.1 TYPE=2 L=0.009 R=0.641 X=0.079 B=339.29199E-6
54570.F3 54570.055.1 TYPE=2 L=0.009 R=0.641 X=0.079 B=339.29199E-6
54570.F3 54570.056.1 TYPE=2 L=0.009 R=0.641 X=0.079 B=339.29199E-6
54570.F1 54570.045.1 TYPE=2 L=0.012 R=0.641 X=0.079 B=339.29200E-6
54570.045.1 54570.045.2 TYPE=0
54570.F1 54570.041.1 TYPE=2 L=0.037 R=0.641 X=0.079 B=339.29201E-6
54570.041.1 54570.041.2 TYPE=0
54570.F1 54570.053.1 TYPE=2 L=0.027 R=0.641 X=0.079 B=339.29201E-6
54570.053.1 54570.053.2 TYPE=0
54570.F1 54570.F4 TYPE=2 L=0.091 R=0.320 X=0.075 B=345.57518E-6
54570.F4 54570.003.1 TYPE=2 L=0.004 R=0.641 X=0.079 B=339.29202E-6
54570.F4 54570.007.1 TYPE=2 L=0.015 R=0.641 X=0.079 B=339.29200E-6
54570.F4 54570.009.1 TYPE=2 L=0.031 R=0.641 X=0.079 B=339.29200E-6
54570.009.1 54570.009.2 TYPE=0
54570.F4 54570.010.1 TYPE=2 L=0.048 R=0.641 X=0.079 B=339.29200E-6
54570.010.1 54570.010.2 TYPE=0
54570.F4 54570.023.1 TYPE=2 L=0.051 R=0.641 X=0.079 B=339.29200E-6
T54570 54570.014.1 TYPE=0 !Data missing from sheet for this line
WIND 52230 TYPE=2 R=0.206 X=0.190 B=113.097E-6 L=1.5
END


TRANSFORMERS
52140 T52140 SN=0.315 UN1=22 UN2=0.23 ER12=0.0097 EX12=0.0388
52190 T52190 SN=0.2 UN1=22 UN2=0.23 ER12=0.0117 EX12=0.0415
52230 T52230 SN=0.315 UN1=22 UN2=0.23 ER12=0.0072 EX12=0.0358
54110 T54110 SN=0.315 UN1=22 UN2=0.23 ER12=0.0111 EX12=0.0413
54120 T54120 SN=0.315 UN1=22 UN2=0.23 ER12=0.0101 EX12=0.0399
54130 T54130 SN=0.5 UN1=22 UN2=0.23 ER12=0.0094 EX12=0.0413
54190 T54190 SN=0.315 UN1=22 UN2=0.23 ER12=0.0071 EX12=0.0405
54200 T54200 SN=1.25 UN1=22 UN2=0.40 ER12=0.0086 EX12=0.0569
54220 T54220 SN=0.03 UN1=22 UN2=0.23 ER12=0.0238 EX12=0.0229
54270 T54270 SN=1 UN1=22 UN2=0.40 ER12=0.0085 EX12=0.0490
54280 T54280 SN=0.8 UN1=22 UN2=0.40 ER12=0.0038 EX12=0.0228
54290 T54290 SN=0.315 UN1=22 UN2=0.23 ER12=0.0071 EX12=0.0374
54310 T54310 SN=0.5 UN1=22 UN2=0.23 ER12=0.0088 EX12=0.0485
54320 T54320 SN=0.2 UN1=22 UN2=0.23 ER12=0.0012 EX12=0.0406
54330 T54330 SN=0.1 UN1=22 UN2=0.23 ER12=0.0016 EX12=0.0387
54340 T54340 SN=0.5 UN1=22 UN2=0.23 ER12=0.0081 EX12=0.0468
54350 T54350 SN=0.315 UN1=22 UN2=0.23 ER12=0.0098 EX12=0.0383
54370 T54370 SN=0.315 UN1=22 UN2=0.23 ER12=0.0107 EX12=0.0466
54430 T54430 SN=0.2 UN1=22 UN2=0.23 ER12=0.0102 EX12=0.0363
54450 T54450 SN=0.315 UN1=22 UN2=0.23 ER12=0.0069 EX12=0.0382
54490 T54490 SN=0.8 UN1=22 UN2=0.23 ER12=0.0082 EX12=0.0480
54510 T54510 SN=0.315 UN1=22 UN2=0.23 ER12=0.0100 EX12=0.0391
54520 T54520 SN=0.2 UN1=22 UN2=0.23 ER12=0.0095 EX12=0.0388
54530 T54530 SN=0.2 UN1=22 UN2=0.23 ER12=0.0096 EX12=0.0388
54540 T54540 SN=0.3 UN1=22 UN2=0.23 ER12=0.0100 EX12=0.0459
54550 T54550 SN=0.8 UN1=22 UN2=0.23 ER12=0.0082 EX12=0.0431
```

```
54560 T54560 SN=0.8 UN1=22 UN2=0.23 ER12=0.0106 EX12=0.0542
54570 T54570 SN=0.315 UN1=22 UN2=0.23 ER12=0.0098 EX12=0.0402
54660 T54660 SN=0.2 UN1=22 UN2=0.23 ER12=0.0099 EX12=0.0443
54680 T54680 SN=0.2 UN1=22 UN2=0.23 ER12=0.0125 EX12=0.0450
54690 T54690 SN=0.2 UN1=22 UN2=0.23 ER12=0.0112 EX12=0.0417
54695 T54695 SN=0.315 UN1=22 UN2=0.40 ER12=0.0106 EX12=0.0351
STEIN-66T3 STEIN-22A SN=25 UN1=66 UN2=22 ER12=0.0037 EX12=0.0999
BYAFOSSEN BYAFOSSEN-T1 SN=4 UN1=22 UN2=3.3 ER12=0.0100 EX12=0.0400
WIND WIND-T1 SN=0.5 UN1=22 UN2=0.69 ER12=0.0078 EX12=0.0453
END


LOADS
WIND-T1 P=-0.5
BYAFOSSEN-T1 P=-2.4 Q=-1
54570.001.1 P=0.000593 Q=0.000121
54570.002.1 P=0.005986 Q=0.001221
54570.002.2 P=0.002255 Q=0.000460
54570.003.1 P=0.000358 Q=0.000073
54570.005.1 P=0.003235 Q=0.000660
54570.006.1 P=0.002137 Q=0.000436
54570.007.1 P=0.003964 Q=0.000808
54570.008.1 P=0.004472 Q=0.000912
54570.009.1 P=0.004041 Q=0.000824
54570.009.2 P=0.002891 Q=0.000590
54570.010.1 P=0.005288 Q=0.001078
54570.010.2 P=0.001663 Q=0.000339
54570.011.1 P=0.004825 Q=0.000984
54570.012.1 P=0.003673 Q=0.000749
54570.013.1 P=0.002390 Q=0.000487
54570.014.1 P=0.001174 Q=0.000239
54570.015.1 P=0.003476 Q=0.000709
54570.016.1 P=0.003215 Q=0.000656
54570.017.1 P=0.004247 Q=0.000866
54570.018.1 P=0.003745 Q=0.000764
54570.019.1 P=0.006317 Q=0.001288
54570.020.1 P=0.004764 Q=0.000972
54570.021.1 P=0.010605 Q=0.002163
54570.022.1 P=0.004783 Q=0.000975
54570.023.1 P=0.007046 Q=0.001437
54570.024.1 P=0.007630 Q=0.001556
54570.025.1 P=0.005587 Q=0.001139
54570.026.1 P=0.003244 Q=0.000661
54570.027.1 P=0.003988 Q=0.000813
54570.028.1 P=0.003287 Q=0.000670
54570.029.1 P=0.004780 Q=0.000975
54570.030.1 P=0.005390 Q=0.001099
54570.031.1 P=0.003955 Q=0.000807
54570.032.1 P=0.004092 Q=0.000834
54570.032.2 P=0.003510 Q=0.000716
54570.033.1 P=0.006428 Q=0.001311
54570.034.1 P=0.004147 Q=0.000846
54570.035.1 P=0.006123 Q=0.001249
54570.037.1 P=0.005979 Q=0.001219
54570.038.1 P=0.005766 Q=0.001176
54570.039.1 P=0.004192 Q=0.000855
54570.040.1 P=0.007400 Q=0.001509
54570.041.1 P=0.006197 Q=0.001264
54570.041.2 P=0.002940 Q=0.000599
54570.042.1 P=0.000633 Q=0.000129
54570.043.1 P=0.002874 Q=0.000586
54570.044.1 P=0.004376 Q=0.000892
54570.045.1 P=0.004968 Q=0.001013
54570.045.2 P=0.002023 Q=0.000412
54570.046.1 P=0.002119 Q=0.000432
54570.047.1 P=0.004815 Q=0.000982
54570.048.1 P=0.005419 Q=0.001105
54570.049.1 P=0.000195 Q=0.000040
54570.050.1 P=0.004588 Q=0.000935
54570.051.1 P=0.004400 Q=0.000897
54570.053.1 P=0.009187 Q=0.001873
```

```
54570.053.2 P=0.002071 Q=0.000422
54570.054.1 P=0.002348 Q=0.000479
54570.055.1 P=0.003680 Q=0.000750
54570.056.1 P=0.003556 Q=0.000725
54570.057.1 P=0.003081 Q=0.000628
54570.057.2 P=0.002891 Q=0.000590
T52140 P=0.156 Q=0.032
T52190 P=0.103 Q=0.021
T52230 P=0.116 Q=0.023
T54110 P=0.15 Q=0.03
T54120 P=0.217 Q=0.044
T54130 P=0.221 Q=0.045
T54190 P=0.076 Q=0.015
T54200 P=0.334 Q=0.068
T54220 P=0.004 Q=0.001
T54270 P=0.163 Q=0.033
T54280 P=0.541 Q=0.11
T54290 P=0.211 Q=0.043
T54310 P=0.341 Q=0.069
T54320 P=0.172 Q=0.035
T54330 P=0.012 Q=0.003
T54340 P=0.222 Q=0.045
T54350 P=0.143 Q=0.029
T54370 P=0.068 Q=0.014
T54430 P=0.143 Q=0.029
T54450 P=0.213 Q=0.043
T54490 P=0.133 Q=0.027
T54510 P=0.089 Q=0.018
T54520 P=0.052 Q=0.011
T54530 P=0.05 Q=0.01
T54540 P=0.105 Q=0.021
T54550 P=0.207 Q=0.042
T54560 P=0.392 Q=0.08
T54660 P=0.051 Q=0.01
T54680 P=0.161 Q=0.033
T54690 P=0.069 Q=0.014
T54695 P=0.042 Q=0.009
END
POWER CONTROL
STEIN-66T3 TYPE=NODE RTYPE=SW U=66 FI=0.138 NAME=MYGRID
END
END
```

Dynpow file

Dynpow file for analysis of power system with 20 % EV penetration. This file is used to run dynamic simulations of the system for 24 hours. This is the code belonging to the ”smart charging with spread allocation scenario. Similar files have been created for all simulation scenarios presented in the thesis.

```
Smart charging with 20 % EV adoption spread out in the system.

**

CONTROL DATA
TEND=24
END
GENERAL
FN=50
END
NODES
STEIN-66T3 TYPE=1 NAME=EXTERNAL_ GRID
END
```

```
LOADS
BYAFOSSEN-T1 PTAB=3000 QTAB=3500 MP=0
54570.001.1 PTAB=101 QTAB=101 MP=1.3
54570.002.1 PTAB=102 QTAB=102 MP=1.3
54570.002.2 PTAB=103 QTAB=103 MP=1.3
54570.003.1 PTAB=104 QTAB=104 MP=1.3
54570.005.1 PTAB=105 QTAB=105 MP=1.3
54570.006.1 PTAB=106 QTAB=106 MP=1.3
54570.007.1 PTAB=107 QTAB=107 MP=1.3
54570.008.1 PTAB=108 QTAB=108 MP=1.3
54570.009.1 PTAB=109 QTAB=109 MP=1.3
54570.009.2 PTAB=110 QTAB=110 MP=1.3
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152 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
153 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
154 TYPE=0 F
0 2.081 1 2.081 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 2.184 23 2.198 24 2.145
155 TYPE=0 F
0 0.774 1 0.774 2 2.121 3 2.124 4 2.129 5 2.130 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
156 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
157 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
158 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
159 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
160 TYPE=0 F
0 2.461 1 2.461 2 2.445 3 2.448 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
```

```
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 2.524
161 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
162 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 2.841 5 2.842 6 2.856 7 2.925 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1001 TYPE=0 F
0 0.850 1 0.850 2 0.873 3 0.876 4 0.881 5 0.882 6 0.857 7 0.926 8 0.997 9 1.032 10 1.011 11 0.993 12 0.980
13 0.999 14 1.007 15 1.008 16 0.991 17 0.989 18 0.998 19 0.989 20 1.003 21 0.949 22 0.914 23 0.929 24 0.914
1002 TYPE=0 F
0 0.890 1 0.890 2 0.874 3 0.877 4 0.882 5 0.883 6 0.897 7 0.966 8 1.017 9 1.051 10 1.030 11 1.012 12 1.000
13 1.039 14 0.989 15 0.989 16 0.972 17 0.951 18 1.017 19 1.009 20 1.023 21 0.968 22 0.934 23 0.948 24 0.953
1003 TYPE=0 F
0 0.877 1 0.877 2 0.861 3 0.864 4 0.869 5 0.870 6 0.832 7 0.901 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.974 14 0.982 15 0.983 16 0.965 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.928 23 0.942 24 0.940
1004 TYPE=0 F
0 0.854 1 0.854 2 0.878 3 0.880 4 0.885 5 0.886 6 0.860 7 0.929 8 0.999 9 1.033 10 1.012 11 0.994 12 0.982
13 1.002 14 0.970 15 0.971 16 0.954 17 0.951 18 0.999 19 0.990 20 1.005 21 0.950 22 0.916 23 0.930 24 0.917
1005 TYPE=0 F
0 0.856 1 0.856 2 0.840 3 0.843 4 0.848 5 0.849 6 0.863 7 0.932 8 1.014 9 1.048 10 1.000 11 0.982 12 0.970
13 0.977 14 0.986 15 0.986 16 0.969 17 0.978 18 1.014 19 1.006 20 1.020 21 0.965 22 0.931 23 0.945 24 0.920
1006 TYPE=0 F
0 0.855 1 0.855 2 0.839 3 0.842 4 0.847 5 0.848 6 0.835 7 0.903 8 0.986 9 1.020 10 0.999 11 0.981 12 0.969
13 0.976 14 0.985 15 0.985 16 0.968 17 0.978 18 0.986 19 0.977 20 0.992 21 0.937 22 0.930 23 0.944 24 0.918
1007 TYPE=0 F
0 0.852 1 0.852 2 0.915 3 0.918 4 0.844 5 0.845 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.916
1008 TYPE=0 F
0 0.774 1 0.774 2 0.776 3 0.778 4 0.783 5 0.784 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1009 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1010 TYPE=0 F
0 0.774 1 0.774 2 0.794 3 0.797 4 0.802 5 0.803 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1011 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1012 TYPE=0 F
0 0.859 1 0.859 2 0.843 3 0.846 4 0.851 5 0.852 6 0.837 7 0.906 8 0.987 9 1.022 10 1.001 11 0.983 12 0.970
13 0.979 14 0.987 15 0.988 16 0.971 17 0.979 18 0.988 19 0.979 20 0.993 21 0.939 22 0.933 23 0.947 24 0.922
1013 TYPE=0 F
0 0.862 1 0.862 2 0.846 3 0.848 4 0.853 5 0.854 6 0.851 7 0.920 8 1.012 9 1.046 10 1.025 11 1.007 12 0.995
13 0.992 14 1.001 15 1.002 16 0.984 17 1.003 18 1.030 19 1.021 20 1.035 21 0.981 22 0.946 23 0.961 24 0.925
1014 TYPE=0 F
0 0.843 1 0.843 2 0.862 3 0.865 4 0.870 5 0.871 6 0.850 7 0.919 8 0.994 9 1.028 10 1.007 11 0.989 12 0.977
13 0.992 14 0.965 15 0.966 16 0.949 17 0.951 18 0.994 19 0.985 20 1.000 21 0.945 22 0.911 23 0.925 24 0.907
1015 TYPE=0 F
0 0.774 1 0.774 2 1.258 3 1.260 4 1.265 5 1.266 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1016 TYPE=0 F
0 0.774 1 0.774 2 0.785 3 0.787 4 0.793 5 0.793 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1017 TYPE=0 F
0 0.857 1 0.857 2 0.883 3 0.886 4 0.891 5 0.892 6 0.864 7 0.933 8 1.001 9 1.035 10 1.014 11 0.996 12 0.984
13 1.006 14 0.972 15 0.973 16 0.956 17 0.951 18 1.001 19 0.992 20 1.007 21 0.952 22 0.918 23 0.932 24 0.921
1018 TYPE=0 F
0 0.774 1 0.774 2 0.846 3 0.849 4 0.854 5 0.855 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1019 TYPE=0 F
0 0.857 1 0.857 2 0.883 3 0.886 4 0.891 5 0.892 6 0.864 7 0.933 8 1.001 9 1.035 10 1.014 11 0.996 12 0.984
13 1.006 14 0.972 15 0.973 16 0.956 17 0.951 18 1.001 19 0.992 20 1.007 21 0.952 22 0.918 23 0.932 24 0.921
1020 TYPE=0 F
0 0.858 1 0.858 2 0.842 3 0.845 4 0.850 5 0.851 6 0.865 7 0.934 8 1.015 9 1.049 10 1.029 11 1.011 12 0.998
13 1.007 14 0.987 15 0.988 16 0.970 17 0.979 18 1.016 19 1.007 20 1.021 21 0.966 22 0.932 23 0.946 24 0.921
1021 TYPE=0 F
0 0.864 1 0.864 2 0.848 3 0.851 4 0.856 5 0.857 6 0.871 7 0.939 8 1.004 9 1.038 10 1.017 11 0.999 12 0.987
13 1.012 14 0.976 15 0.976 16 0.959 17 0.951 18 1.004 19 0.995 20 1.010 21 0.955 22 0.921 23 0.935 24 0.927
1022 TYPE=0 F
```

```
0 0.908 1 0.908 2 0.892 3 0.895 4 0.900 5 0.901 6 0.915 7 0.984 8 1.026 9 1.061 10 1.040 11 1.022 12 1.009
13 1.057 14 0.998 15 0.999 16 0.981 17 0.951 18 1.027 19 1.018 20 1.032 21 0.978 22 0.943 23 0.958 24 0.972
1023 TYPE=0 F
0 0.889 1 0.889 2 0.988 3 0.991 4 0.881 5 0.882 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.952
1024 TYPE=0 F
0 1.014 1 1.014 2 0.998 3 1.000 4 1.005 5 1.006 6 0.900 7 0.969 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.996 23 1.010 24 1.077
1025 TYPE=0 F
0 0.945 1 0.945 2 0.986 3 0.989 4 0.994 5 0.995 6 0.952 7 1.021 8 1.073 9 1.107 10 1.086 11 1.068 12 1.056
13 1.094 14 1.045 15 1.045 16 1.028 17 1.008 18 1.073 19 1.065 20 1.079 21 1.024 22 0.990 23 1.004 24 1.008
1026 TYPE=0 F
0 0.774 1 0.774 2 0.787 3 0.789 4 0.794 5 0.795 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
1027 TYPE=0 F
0 0.819 1 0.819 2 0.803 3 0.806 4 0.811 5 0.812 6 0.826 7 0.895 8 0.989 9 1.024 10 0.988 11 0.969 12 0.957
13 0.953 14 0.961 15 0.962 16 0.944 17 0.966 18 0.990 19 0.981 20 0.996 21 0.941 22 0.907 23 0.921 24 0.883
1029 TYPE=0 F
0 0.891 1 0.891 2 0.993 3 0.996 4 1.001 5 1.002 6 0.898 7 0.967 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.955
1030 TYPE=0 F
0 0.848 1 0.848 2 0.869 3 0.872 4 0.877 5 0.878 6 0.855 7 0.924 8 0.996 9 1.030 10 1.009 11 0.991 12 0.979
13 0.997 14 1.005 15 1.006 16 0.988 17 0.988 18 0.996 19 0.988 20 1.002 21 0.947 22 0.913 23 0.927 24 0.911
1031 TYPE=0 F
0 0.947 1 0.947 2 0.931 3 0.934 4 0.939 5 0.940 6 0.867 7 0.936 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.963 23 0.977 24 1.011
1032 TYPE=0 F
0 0.774 1 0.774 2 0.758 3 0.760 4 0.765 5 0.766 6 0.780 7 0.849 8 0.959 9 0.993 10 0.972 11 0.954 12 0.942
13 0.922 14 0.930 15 0.931 16 0.914 17 0.951 18 0.959 19 0.950 20 0.965 21 0.910 22 0.876 23 0.890 24 0.837
END
END
```

Appendix C

Matlab code

Smart_ charging.m

This is the function that has been used to create the optimal charge plan. It takes the base demand and number of EVs to be placed in the system as inputs. The optimal time to charge is chosen as the four hour period with the lowest aggregated branch load. The EVs can either be placed randomly, spread out in the system, or at manually chosen houses. When the placement of EVs is decided, the algorithm will find the optimal charging start time for each of the EVs, based on the power consumption over 24 hours in the applicable branch.

```
%Choose the degree of EV penetration in the system
 percentage_of_EVs = input(’How many percent of EVs are in the system?’);
 EVs_pr_transformer; % Calculates number of EVs in the system

 %Number of EVs connected to transformer 52140
 EVs_in_LV_system = EVs_per_transformer(28);

  %Random order of houses to spread out where vehicles are placed
random_house_order= [32 40 22 34 9 6 55 3 16 24 54 30 45 60 62 51 ...
      33 7 38 58 42 28 17 41 47 14 46 56 8 59 5 48 53 29 21 25 52 ...
      37 31 49 27 61 50 26 43 19 44 15 1 36 23 2 4 18 11 39 13 35 ...
      20 57 10 12];

 %Deciding which house EV is placed at
 if percentage_of_EVs ~= 0
 choose = input(’Do you want to choose which houses the EVs should be placed? (y/n) ’,’s’);
 if choose == ’y’
     disp([’There are ’ num2str(EVs_in_LV_system) ’ in the system.’ ])
     i=1;
     while i <= EVs_in_LV_system
        placement(i) = input([’Which house shout EV number ’ num2str(i) ’ be placed? ’ ]);
        i=i+1;
     end
 else
     placement = random_house_order;
 end
 end
```

```
%To make the additional EV load less burdening on the system,
%the charging will be places at hours of low load in that
%part of the system.
%The system is divided in 6 branch nodes; A,B,C,D,E and F

%Find the total consumption at each node for each hour of simulation
node_consumption;


sum_charging_temp = zeros(1,24);
temp_load = zeros(1,24);
start_charging=zeros(days,EVs_in_LV_system);
%Table of charging load at different nodes
node_charge = zeros(days,hours,7);
charging_plan = zeros(days,hours,length(house_numbers));


%Start placing the EVs on the LV system
for j =1:days
cars_placed=0;
i=1;
while EVs_in_LV_system ~= cars_placed
    %Find the hour of the day where EV charging will be
    %most convinient
    %Finds the 4 hour period with lowest load

    for k = 1:24
        sum_charging_temp(k) = sum(charging_plan(1,k,:));
        if k > 21  && j~=days
       temp_load(k) = sum(node_power(j,k:24,house_numbers(placement(i),6))) + ...
       sum(node_charge(j,k:24,house_numbers(placement(i),6))) + ...
       sum(node_power(j+1,1:k-21,house_numbers(placement(i),6))) + ...
       sum(node_charge(j+1,1:k-21,house_numbers(placement(i),6)));
        elseif k > 21
       temp_load(k) = sum(node_power(j,k:24,house_numbers(placement(i),6))) + ...
       sum(node_charge(j,k:24,house_numbers(placement(i),6))) + ...
       sum(node_power(1,1:k-21,house_numbers(placement(i),6))) + ...
       sum(node_charge(1,1:k-21,house_numbers(placement(i),6)));
       else
       temp_load(k) = sum(node_power(j,k:k+3,house_numbers(placement(i),6))) + ...
       sum(node_charge(j,k:k+3,house_numbers(placement(i),6)));
        end
    end

     %To make sure that two EV charging periods does not come
    %closer together than 12 hours

   [load time] = min(temp_load);
   start_charging(j,i)=time;
   if j > 1
   while (24 - start_charging(j-1,i) +time) < 12
       temp_load(time) = 10000;
       [load time] = min(temp_load);
       start_charging(j,i)=time;
   end
   end

   %Place the charging of the EV in the charging plan
   %Add the charging load to the branch load matrix, so it will be
   %accounted for when the next EV is finding the optimal charging time
   if time > 21 && j~=days
     charging_plan(j,time:24,placement(i)) = ...
     charging_plan(j,time:24,placement(i))+6;
     charging_plan(j+1,1:time-21,placement(i)) =...
     charging_plan(j+1,1:time-21,placement(i))+6;
```

```
     node_charge(j,time:24,house_numbers(placement(i),6)) = ...
     node_charge(j,time:24,house_numbers(placement(i),6)) +6;
     node_charge(j+1,1:time-21,house_numbers(placement(i),6)) =...
     node_charge(j+1,1:time-21,house_numbers(placement(i),6)) +6;
   elseif time > 21
     charging_plan(j,time:24,placement(i)) = ...
     charging_plan(j,time:24,placement(i))+6;
     node_charge(j,time:24,house_numbers(placement(i),6)) = ...
     node_charge(j,time:24,house_numbers(placement(i),6)) +6;
   else
     charging_plan(j,time:time+3,placement(i))= ...
     charging_plan(j,time:time+3,placement(i))+6;
     node_charge(j,time:time+3,house_numbers(placement(i),6)) = ...
     node_charge(j,time:time+3,house_numbers(placement(i),6)) +6;
   end

       cars_placed=cars_placed + 1;
       i=i+1;
       if i > length(house_numbers)
           i=1;
       end
end
end

%EV charging load on other transformers:
charge_large_system=zeros(days,hours,length(transformers));

for n=1:days
i=1;
for j = 1:length(transformers)
    cars_placed=0;
    while EVs_per_transformer(j) ~= cars_placed
    %Find the hour of the day where EV charging will be
    %most convinient
    %Finds the 4 hour period with lowest load

    for k = 1:24
        sum_charging_temp(k) = sum(charge_large_system(1,k,:));
        if k > 21
       temp_load(k) = sum(node_power(n,k:24,house_numbers(placement(i),6))) + ...
           sum(charge_large_system(n,k:24,j)) + ...
           sum(node_power(n,1:k-21,house_numbers(placement(i),6))) + ...
           sum(charge_large_system(n,1:k-21,j));
       else
       temp_load(k) = sum(node_power(n,k:k+3,house_numbers(placement(i),6))) + ...
           sum(charge_large_system(n,k:k+3,j));
        end
    end
   [load time] = min(temp_load);

       if time > 21
           charge_large_system(n,time:24,j) = ...
           charge_large_system(n,time:24,j)+6;
           charge_large_system(n,1:time-21,j) = ...
           charge_large_system(n,1:time-21,j)+6;
       else
       charge_large_system(n,time:time+3,j) = ...
       charge_large_system(n,time:time+3,j)+6;
       end

       cars_placed=cars_placed + 1;

    end
end
end
```

Node_ consumption.m

This function is used by smart_ charging to find the optimal start charging time. It calculates the base load consumption for each of the branch cables in the system. When EVs are added to the system, the extra load will be added to the base load of the applicable branch.

```
%Adding up the consumed power in each node in the system
%A=1, B=2, C=3, D=4, E=5, F(1+2+3)=6 F4=7

node_power = zeros(days,hours,7);

for k=1:days
for j = 1:hours
    for i = 1:length(house_numbers)
        switch house_numbers(i,6)
        case 1
          node_power(k,j,1)=node_power(k,j,1) + active_base(k,j,28)*house_numbers(i,2);
        case 2
          node_power(k,j,2)=node_power(k,j,2) + active_base(k,j,28)*house_numbers(i,2);
        case 3
          node_power(k,j,3)=node_power(k,j,3) + active_base(k,j,28)*house_numbers(i,2);
        case 4
          node_power(k,j,4)=node_power(k,j,4) + active_base(k,j,28)*house_numbers(i,2);
        case 5
          node_power(k,j,5)=node_power(k,j,5) + active_base(k,j,28)*house_numbers(i,2);
        case 6
          node_power(k,j,6)=node_power(k,j,6) + active_base(k,j,28)*house_numbers(i,2);
        case 7
          node_power(k,j,7)=node_power(k,j,7) + active_base(k,j,28)*house_numbers(i,2);

        end
    end
end
end
```

dumb_ charging.m

This script is used to create the charging plan for the dumb charging scenarios. The EVs are set to start charging between 2 p.m. and 7 p.m., as is the observed charging pattern today.

```
percentage_of_EVs = input('How many percent of EVs are in the system?');
cd('Y:\Sagosen - Master\Matlab');
EVs_pr_transformer; % Find number of EVs in the system
cd('Y:\Sagosen - Master\Matlab\24_hours');
%Number of EVs connected to transformer 52140
EVs_in_LV_system = EVs_per_transformer(28);

%Use observed charging pattern for EV
charging_pattern = [14 0.15;
                    15 0.15;
                    16 0.4;
                    17 0.1;
                    18 0.1;
                    19 0.1];
%Number of EVs starting to charge at each hour:
EVs_charging = round(EVs_in_LV_system * charging_pattern(:,2));
difference = EVs_charging - (EVs_in_LV_system * charging_pattern(:,2));

%Finds an approximation of how many cars that should start charging
%every hour to match the charging pattern and system EV penetration %
while sum(EVs_charging) ~= EVs_in_LV_system
    if sum(EVs_charging) > EVs_in_LV_system
        [value time]=max(difference);
        EVs_charging(time)=EVs_charging(time) -1;
        difference(time) = difference(time) -1;
    else
        [value time]=min(difference);
        EVs_charging(time)=EVs_charging(time) +1;
        difference(time) = difference(time) +1;
    end
end

%Random order of houses to spread out where vehicles are placed
 random_house_order= [32 40 22 34 9 6 55 44 16 24 1 30 45 60 62 51 33 ...
     7 38 58 42 28 17 41 47 14 46 56 8 59 5 48 53 29 21 25 52 37 31 49 ...
     27 61 50 26 43 19 3 15 54 36 23 2 4 18 11 39 13 35 20 57 10 12];


charging_plan = zeros(days,hours,length(house_numbers));
cars_placed=0;

%Deciding which house EV is placed at
choose = input('Do you want to choose which houses the EVs should be placed? (y/n) ','s');
if choose == 'y'
    disp(['There are ' num2str(EVs_in_LV_system) ' in the system.' ])
    i=1;
    while i <= EVs_in_LV_system
       placement(i) = input(['Which house shout EV number ' num2str(i) ' Be placed? ' ]);
       i=i+1;
    end
else
    placement = random_house_order;
end
```

```
i=1;
while EVs_in_LV_system ~= cars_placed

    %find the hour with most remaining EV charging startups
    [value temp] = max(EVs_charging);
    time = temp + 13;
    EVs_charging(temp) =EVs_charging(temp) -1;


    charging_plan(:,time:time+3,placement(i))=charging_plan(:,time:time+3,placement(i))+6;
    cars_placed=cars_placed + 1;
    i=i+1;
       if i > length(house_numbers)
           i=1;
       end
end

%Additional load on other transformers:

charge_large_system=zeros(days,hours,length(transformers));

for i = 1:length(transformers)
    cars_placed=0;

    %Number of EVs starting to charge at each hour:
    EVs_charging = round(EVs_per_transformer(i) * charging_pattern(:,2));
    difference = EVs_charging - (EVs_per_transformer(i) * charging_pattern(:,2));

    while sum(EVs_charging) ~= EVs_per_transformer(i)
    if sum(EVs_charging) > EVs_per_transformer(i)
        [value time]=max(difference);
        EVs_charging(time)=EVs_charging(time) -1;
        difference(time) = difference(time) -1;
    else
        [value time]=min(difference);
        EVs_charging(time)=EVs_charging(time) +1;
        difference(time) = difference(time) +1;
    end
   end


   j=1;
   while EVs_per_transformer(i) ~= cars_placed

    %find the hour with most remaining EV charging startups
    [value temp] = max(EVs_charging);
    time = temp + 13;
    EVs_charging(temp) =EVs_charging(temp) -1;


    charge_large_system(:,time:time+3,i)=charge_large_system(:,time:time+3,i)+6;
    cars_placed=cars_placed + 1;
    j=j+1;
       if j > length(house_numbers)
           j=1;
       end
   end
end


cd('Y:\Sagosen - Master\Matlab');
```

plot_ results.m

The results are extracted from Simpow as a .txt file containing data. This script show how one of the graphs have been created in Matlab. The other graphs have similar scripts.

```
%Load data set containing voltage levels
% at specified residence homes
load feb_2_7_ev_dumb_spread_voltage.txt
array=feb_2_7_ev_dumb_spread_voltage;

x= array(:,1);
y1= array(:,2);
y2= array(:,3);
y3 = array(:,4);
y4 = array(:,5);
y5 = array(:,6);


%creates system restriciton line
y_min=linspace(0.935,0.935,length(x));


%plot
figure
hold off;
plot(x,y1,x,y2,x,y3,x,y4,x,y5,x,y_min,'k')
xlabel('Hours')
ylabel('Voltage (p.u.)')
axis([0 24 0.93 0.99])

% Adjust XY label font
set(gca,'fontsize',14)
handxlabel1 = get(gca, 'xlabel');
set(handxlabel1, 'fontsize', 16, 'fontweight', 'bold');
handylabel1 = get(gca, 'ylabel');
set(handylabel1, 'fontsize', 16, 'fontweight', 'bold');


h_legend = legend('Residence 24','Residence 33','Residence 16' ...
            ,'Residence 2','Residence 23','Location','EastOutside');
set(h_legend,'FontSize',14);
set(gca,'XTick',0:2:24)
set(gca,'XTickLabel',[0:2:24])


%Sets size of graph window
set(gcf,'Position',[680 558 525 420])

%Function which creates .eps file from graph
screen2eps Feb_2_7_EV_dumb_F4_voltage.eps
```