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DER NETWORK EFFECTS AND REQUIREMENTS FOR DISTRIBUTION NETWORK MANAGEMENT

Master of Science Thesis
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ABSTRACT

Joel Hakulinen: DER Network Effects and Requirements for Distribution Network Management
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An increasing amounts of distributed energy resources such as distributed generation and electrical vehicles are connected to the distribution networks. While they have a positive impact on the environment when considering the emissions, they can be detrimental to the stable operation of the networks. The most common renewable energy sources, solar and wind power, are intermittent due to their weather dependency. This unpredictability of production makes it harder to balance the electrical energy production and consumption in the network. When a mismatch happens, such as the production being locally larger than the consumption, network bottlenecks can occur. The bottlenecks, such as component overloading, can lead to the curtailment of generation and lost production as well as component failures. In order to avoid bottleneck situations in Germany, redispatching of power plants is used, which means that generation of power is temporarily shifted from one location to another. Often this requires reserve power plants fueled by traditional power sources, which can be expensive.

In addition to effects resulting from distributed generation, the new loads such as electrical vehicles can also cause network bottlenecks. The electrification of the transport sector is happening rather quickly, which means that a lot of new loads may soon appear in distribution networks. The charging power electrical vehicles can be in the range of 2-10 kW even at standard home charging, which means that the increase in local peak loading can be quite clear. The addition of such loads can cause additional voltage drops and lead to lines and transformers overloading.

The distribution management system MicroSCADA X DMS600 by Hitachi ABB Power Grids can be used for network planning as well as for real-time operation of a distribution network. User interviews were conducted to find out the DER related needs of DSOs. Needs were brought up regarding existing functionalities and also the important future topics were identified. From the existing functionalities, the documenting of LV generators needs improvements in order to make the process simpler and remove the risk of breaking load flow calculations. The most important improvements were related to switching planning as the automatic sequence creation should be able to handle the automatic separation of possible backfeeds caused by distributed generation.

Electrical vehicles were considered a more realistic risk to the network than excess distributed generation by the interviewed Finnish DSOs. It was also noted that the tools for analyzing possible DER effects are quite limited and often have to be created by the DSOs themselves. In order to answer to this need, a prototype for simulating EV loading was created. First an EV load model was created with a C# program that used national travel survey data as basis for modeling charging behaviors. The program outputs a load curve based on the common driving schedules, averages durations and average lengths of the trips. The model was simplified as only each vehicle only did one trip from and back to home, and the vehicles were only charged at home with a power of 3 kW. The resulting load curve was used to insert new load points into the network model. The loads were connected to existing customers and therefore the existing customer data in the network did not have to be modified at all, but the load flow calculations still could show the combined effect of the customer and the vehicle.

The prototype can give a rough idea on possible EV effects. For example, some transformers are easily overloaded, whereas excessive voltage drops may require a very high penetration rate. The implemented violation list can be used to easily detect even remote transformer overloads. The prototype shows that a functionality for EV modeling could definitely be implemented.

Keywords: DER, Distributed Energy Resources, DMS600, Distribution Management System, Electrical Vehicles, EV, Distributed Generation, DG, Load modeling

TIIVISTELMÄ

Joel Hakulinen: Hajautettujen energiaresurssien vaikutukset ja niiden aiheuttamat vaatimukset jakeluverkon hallintaan
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Verkkoon liitettyjen hajautettujen energiaresurssien, kuten hajautetun tuotannon sekä sähköautojen, määrä kasvaa jatkuvasti. Niillä on päästömielessä positiivinen vaikutus ympäristöön, mutta ne voivat aiheuttaa ongelmia verkonhallinnan kannalta. Yleisimmät uusiutuvat energianlähteet, kuten aurinko- ja tuulivoima, ovat hyvin sääriippuvaisia ja niiden tuottama teho voi vaihdella paljon. Tämä sähköntuotannon vaikea ennustettavuus voi aiheuttaa ongelmia kulutuksen ja tuotannon tasapainon säilyttämisessä, ja voi johtaa tilanteeseen, jossa paikallinen tuotanto onkin kulutusta suurempaa. Tämän kaltaisessa tilanteessa verkossa voi ilmetä pullonkauloja, kuten johdinten ylikuormittumista, joiden vuoksi tuotantoa pitää rajoittaa. Saksassa pullonkauloja pyritään estämään siirtämällä tuotantoa väliaikaisesti pullonkaula-alueilta toisiin voimalaitoksiin. Siinä usein tarvitaan perinteisiä tuotantoreservejä, ja operaatiosta koituu kustannuksia.

Hajautetun tuotannon lisäksi myös uudet kuormat voivat olla ongelmallisia sähköverkon näkökulmasta. Liikennesektori sähköistyy melko nopeasti ja sen myötä jakeluverkkoon voi lähiaikoina tulla paljon uusia kuormia. Tyypillinen sähköauton kotilatausteho on välillä 2–10 kW, mikä voi aiheuttaa selviä paikallisia huippukuormituksen muutoksia jakeluverkossa. Verkon kuormituksen lisääntyminen voi puolestaan nostaa jännitehäviöitä ja aiheuttaa komponenttien ylikuormittumista.

Hitachi ABB Power Gridsin MicroSCADA X DMS600 käytöntukijärjestelmää voidaan käyttää verkostosuunnitteluun sekä jakeluverkon tilan reaaliaikaiseen seurantaan. Asiakkaana toimivia jakeluverkkoyhtiöitä haastateltiin, jotta saatiin selville heidän tarpeitaan liittyen hajautettuihin energiaresursseihin. Tarpeita liittyi nykyisiin toimintoihin, mutta myös tulevaisuuden uhkakuvia tuotiin esille. Nykytoiminnallisuuksista kytkentäsuunnittelu sekä pientuotannon dokumentointi nousivat esille. Pientuotannon dokumentointiin pitäisi saada selkeämpää ja se ei saisi missään tapauksessa sekoittaa tehonjaon laskentaa. Kytkentäsuunnittelussa olisi erityisesti tärkeää saada automaattinen kytkentäsekvenssi toimimaan myös pienjänniteverkon puolella ja sen pitäisi osata myös erottaa mahdolliset takasyötöt, kun verkossa on pientuotantoa.

Haastatteluissa sähköautoja lisääntymistä pidettiin pientuotannon lisääntymistä suurempana uhkana Suomessa. Esille nousi myös, että hajautettujen energiaresurssien analysointiin ei ole verkkoyhtiöiden käytössä valmiita työkaluja, vaan sellaisia pitää tehdä itse. Tämän tarpeen vuoksi diplomityössä luotiin myös prototyyppi sähköautojen kuormituksen simulointiin DMS600:ssa. Aluksi sähköautojen lataukselle luotiin kuormituskäyrä C# ohjelmalla. Latauksen mallintamiseen käytettiin apuna henkilöliikennetutkimuksen tuloksia, joissa käsiteltiin autoilijoiden matkojen pituuksia, kestoja sekä ajallista jakaumaa. Mallia yksinkertaistettiin olettamalla, että autot tekevän vain yhden edestakaisen matkan päivässä ja autoja ladataan vain kotona 3 kW vakioteholla. Luotua kuormitusmallia käytettiin, kun sähköautokuormia syötettiin verkkoon. Sähköautokuormat lisättiin olevassa olevien asiakasliittymien yhteyteen, siten ettei olemassa oleviin tietoihin tarvinnut tehdä mitään muutoksia. Tehonjaon laskennassa nähdään kuitenkin asiakaskuorman sekä sähköautokuorman yhteisvaikutus.

Yksinkertaistuksista huolimatta prototyypillä saadaan suunta-antava arvio sähköautojen vaikutuksista jakeluverkossa. Testeissä nousi mm. esille, että jotkin muuntajat saattavat ylikuormittua yhdestäkin kuormasta, kun taas liialliset jännitteenalenemat KJ-verkossa vaatisivat hyvinkin paljon sähköautoja. Simulaattoriin toteutettu listaus kuormitusrikkeistä auttaa käyttäjää huomaamaan myös esimerkiksi syrjäisen muuntajan ylikuormittumisen. Tehty prototyyppi osoittaa, että sähköautoja voisi mallintaa DMS600:ssa.

Avainsanat: Hajautetut energiaresurssit, DMS600, Käytöntukijärjestelmä, sähköautot, hajautettu tuotanto, kuormituksen mallintaminen

PREFACE

This Master of Science Theses was written for ABB Power Grids Finland Oy at the Tampere office in Hervanta. I would like to thank Doctoral Researcher Joni Markkula for instructing the work and giving feedback from the university's side as well as for offering a motivational kick when the schedule seemed tough. Also, I would like to thank product manager Matti Kärenlampi for offering the interesting topic and instruction from the company's side and for being involved in the DSO interviews. Thanks also to all of my colleagues for offering good ideas during the process and even more importantly good laughs during the virtual coffee breaks!

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Lastly, I want to give special thanks to my family and friends for offering support during the whole writing process and the pandemic and all.

Tampere, 21.5.2021

Joel Hakulinen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AMR	Automatic Meter Reading
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DB	Database
DG	Distributed Generation
DMS	Distribution Management System
DSO	Distribution System Operator
EEG	German Renewable Energy Act
EnWG	German Energy Industry Act
EPA	Environmental Protection Agency
EV	Electrical Vehicle
GHG	Greenhouse gas
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LOM	Loss of Mains
LV	Low Voltage
MV	Medium Voltage
NABEG	German Network Expansion Acceleration Act
NE	DMS600 Network Editor
NIS	Network Information System
NTS	National Travel Survey
OPC	Object Linking and Embedding for Process Control
PHEV	Plug-in Hybrid Electrical Vehicle
PV	Photovoltaic
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
SpoC	Single Point of Contact
SQL	Structured Query Language
SVV	Savon Voima Verkko Oy
TSO	Transmission System Operator
TSU-NIS	Tieto Smart Utility Network Information System
V2G	Vehicle-to-grid
WS	DMS600 Workstation

1. INTRODUCTION

The importance of electricity is highlighted every day by all of the technology surrounding us and our society is becoming increasingly dependent on the reliable supply of energy. The average energy consumption is growing world-wide, but also the sources of energy are a topic of constant conversation as climate change is an ever-present issue. While the growth of global greenhouse gas (GHG) emissions has slowed down during the last decade, the total annual emissions still keep growing and the CO_2 emissions by the energy sector remain the largest contributor [1].However, the increasing electrification of many sectors allows for the use of cleaner energy than coal and oil, for example. The increasing utilization of renewable energy sources (RES) is a key component of the European Union's climate targets along with increased energy efficiency requirements across the board [2]. The transportation and heating sectors offer good solutions for energy efficiency through technologies such as electrical vehicles and heat pumps, which can be widely spread to normal households. While the rapid increase of these distributed energy resources (DER) is necessary to combat climate change, they also affect the distribution networks, and these effects must be considered to ensure the reliable distribution of electricity.

The objective of this thesis is to determine what requirements DER sets to the distribution management system (DMS) MicroSCADA X DMS600. The motivation for this topic comes from Germany, as there has been very real and economic effects from the quick integration of distributed generation (DG). For example, local overproduction of energy can require curtailment of generation in order to balance the power flow in the network and reduce network bottlenecks. Such effects related to DG and new electrical loads like electrical vehicles (EVs) have to be seen from the perspective of network operators, so that necessary functionalities can be implemented into DMS600. In order to analyze the DER effects in different countries, DMS600 user interviews are conducted in addition to literature review.

In this work, the general effects and state of distributed energy resources is first discussed, with the focus being on wind and solar power and also electrical vehicles. In chapter 3, the effects are discussed from the perspective of Finland and Germany. Since the interviewees are personnel from Finnish distribution system operators (DSOs), the focus of this work also starts to shift to the Finnish situation. In chapters 4 and 5, the product MicroSCADA X DMS600 by Hitachi ABB Power Grids is introduced and also DER related improvements into the existing functionalities are discussed. For example, the introduction of DG into the network complicates standard network operation and extra caution has to be paid when planning outages.

One of the major topics of this thesis is the effects of electrical vehicles in the distribution system. It is clear that also in Finland, the number of electrical vehicles is quickly increasing and that was also recognized as a possible risk in the interviews. The overall loading of the network will increase, and the loading profile of EV customers will change from the typical load curves that are used today. The possibility of forecasting the EV effects could give the DSOs an idea of what parts of the network will have to be strengthened in the near future and also helps the network planners plan new network. In chapter 6, a method for evaluating the load profile of EV is presented. This simple load profile is then used to create a prototype for simulating EV effects in DMS600.

2. DISTRIBUTED ENERGY RESOURCES

Distributed energy resources are being utilized more and more due to the increasing demand for clean energy. The increasing usage of renewable energy sources such as solar power and wind power means that distributed generation (DG) is becoming very common on all voltage levels. Since renewable energy sources are distributed by nature and the production can vary from small photovoltaic (PV) installations to large fields of wind turbines, the production profile is changing on power system level. In addition to production becoming geographically distributed all over the system, it is also becoming more weather dependent. This makes production forecasts more uncertain than before, which needs to be considered by system operators when maintaining balance between production and consumption. The introduction of DER can also cause protection issues in the power grid that did not exist before. Despite these issues, it is necessary to make the grid withstand the new levels of renewable energy.

In addition to the production profile of the grid becoming more weather dependent, also the consumption of energy is becoming more variable than it was before. For example, electrical vehicles (EVs) and energy storages are becoming more common. With the popularity of EVs increasing, the overall load of the network as well as the possible peak-loads of the network are increasing. There are however many factors that affect the impact that EVs have on the grid. The current state of DG and electrical vehicles are discussed in this chapter.

2.1 Distributed generation

Distributed generation by definition means that the production facilities are de-centralized and often smaller than conventional large power plants. Often this means that the electricity generation is close to the consumers. In this thesis, DG will refer to small-scale production in the distribution network as well as larger variable renewable energy production units. This means that, for example, large wind farms will be considered as DG, whereas hydropower plants will not. This way the effects of DG are somewhat similar to each other and can be grouped together. Since the most common renewable electricity sources are solar power, wind power and hydropower, this means that focusing on solar and wind power gives proper insight onto the effects that DG have on the power system.

The total amount of wind and solar power capacity installed worldwide is forecasted to surpass the capacity of coal based power by 2024, as can be seen in Figure 1[3].

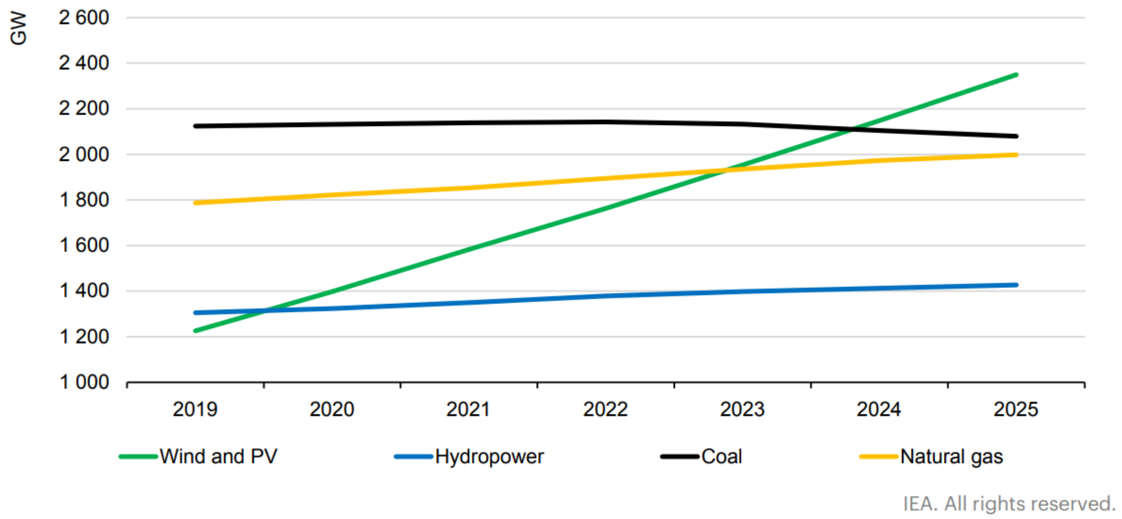


Figure 1 *Total installed power capacity globally by fuel and technology [3]*

At the moment, renewables are the leading form of power capacity additions with PV accounting for the most of that. The total share of wind and solar power is still rather small when compared to traditional electricity generation, but it has increased significantly during the last decade. In Figure 2, the global share of low-carbon sources such as nuclear, wind, PV and other renewable sources (mainly hydropower) are compared with the share of coal in electricity generation.

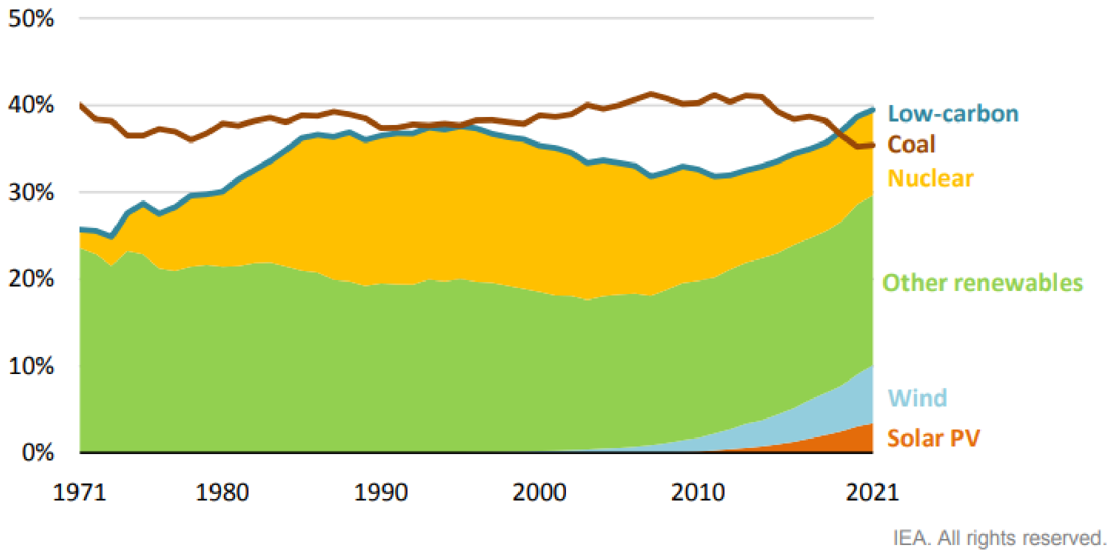


Figure 2 *Share of low-carbon and coal electricity sources in the world [4]*

The total share of wind and solar power is expected to be 6.7% and 3.4% respectively by the end of 2021. The other energy sources not shown in the graph, such as natural gas, account for 25.1% of the global share.

2.1.1 Wind power

Wind power is very well utilized all over the globe. In 2020 the added capacity of wind power was 111 GW [5], which is even higher than previously estimated [3]. The installed capacity and actual generated energy are not the same thing, however. In Figure 3, the capacity and generated energy are shown for the previous decade.

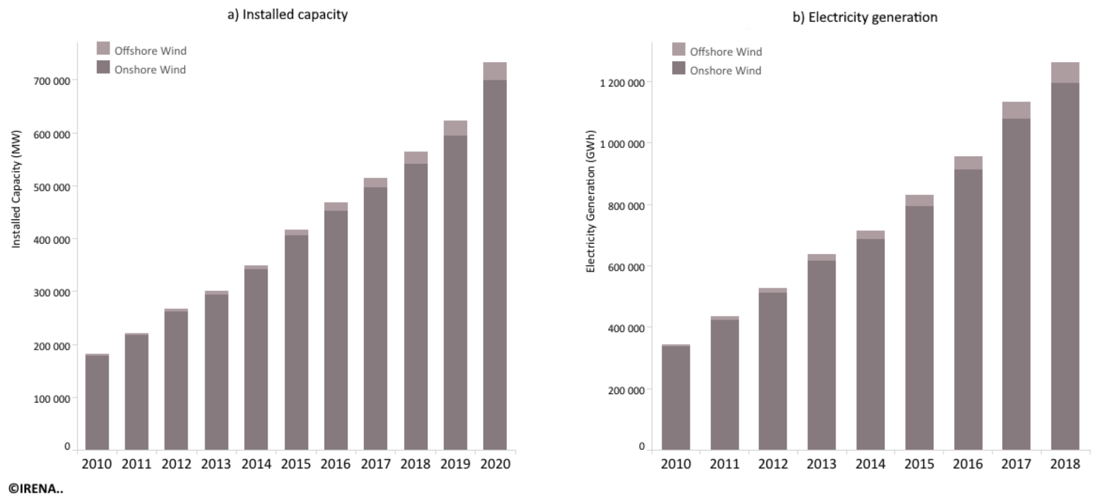


Figure 3 *Trends for a) installed capacity and b) electricity generation of wind power modified from IRENA graphs [6]*

In 2018, the actual electricity generation from wind power was about 1260 TWh and as can be seen from the figure above, it has been steadily increasing. This graph is used for context when comparing the ratio of capacity and electricity generated with solar power in the next chapter.

While wind power is mostly generated in large wind parks on-shore and off-shore, it is not exactly distributed in the same way as small solar panels. The power provided by these wind farms is still highly intermittent due to its weather dependency, when compared to traditional firm power plants. The power produced by wind turbines has a cubic relation to the wind speed of the area and there are many ways of forecasting the power produced in time-scales of under a week [7]. As the wind speeds also vary from season to season, the performance of generators also has a seasonal and geographical dependency as well [8]. However, even decade long climate variations have an effect on the power produced [9]. Due to the variable nature of wind power, it is important to have accurate forecasts when balancing the grid. This mostly concerns the transmission system operators (TSOs) and is not as important for distribution system operators (DSOs), since TSOs are responsible for managing production reserves.

2.1.2 Solar power

Solar power is the most quickly increasing form of renewable generation, both in total capacity and individual generator units. In 2019 the worldwide capacity addition was 108 GW, and the yearly increase is still steadily, albeit slowly, growing [3]. Yearly data for installed capacity and electricity generated of solar power is shown in Figure 4. When comparing this to Figure 3, one can see that in year 2018, the installed capacity of solar power and wind power were very close to each other. Still the electricity generated by wind power was roughly double the amount of the electricity generated by solar power. While the capacity of solar power is increasing quickly, it is not as efficient in producing energy as wind power is, as solar panels operate on a pretty low capacity factor.

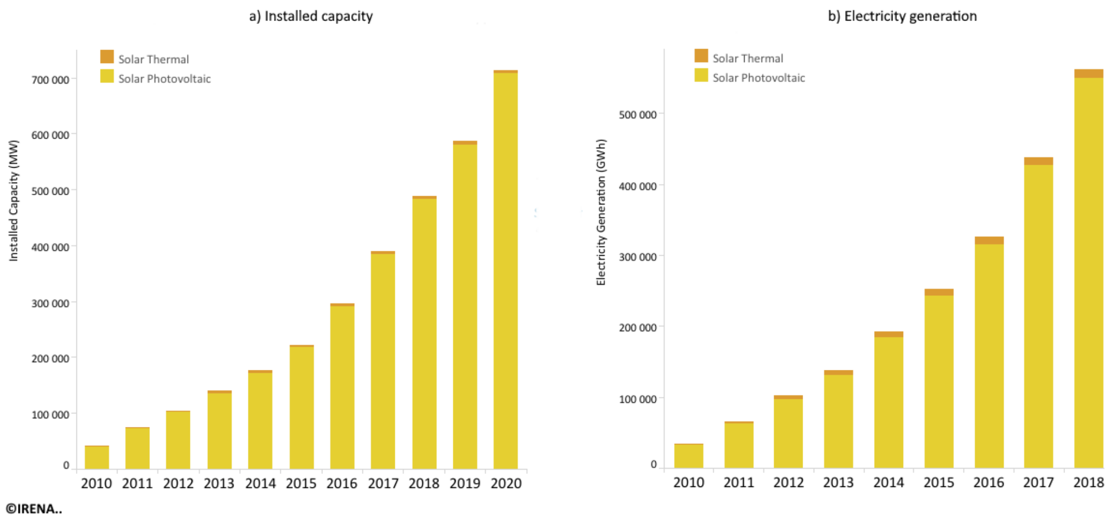


Figure 4 *Trends for a) installed capacity and b) electricity generated of solar power modified from IRENA graphs [6]*

The share of PV capacity additions grouped by the site type is shown in Figure 5. Most of the additions are utility-scale PV plants and for example, only a third of the new capacity in 2020 was from commercial, industrial or residential PV installations, where the electricity is also consumed on-site. This means that even most PV generation is not completely distributed by nature. However, solar panels are more common in distribution networks than wind turbines are, even though their electricity produced is often quite little. Their effect can still be significant as they have a direct impact into the net demand seen at customer nodes.

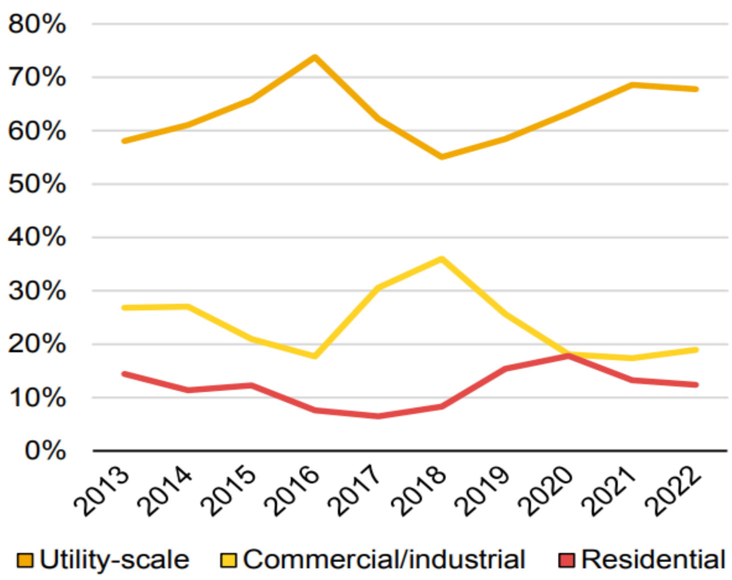


Figure 5 *Solar power additions by site type, modified from [3]*

Like wind power, solar power is very dependent on the weather and season, but it is also directly dependent on the time of day. In Figure 6, an example of the seasonal variability of wind and solar power is shown. The example is from a study based on National Grid transmission system in Great Britain.

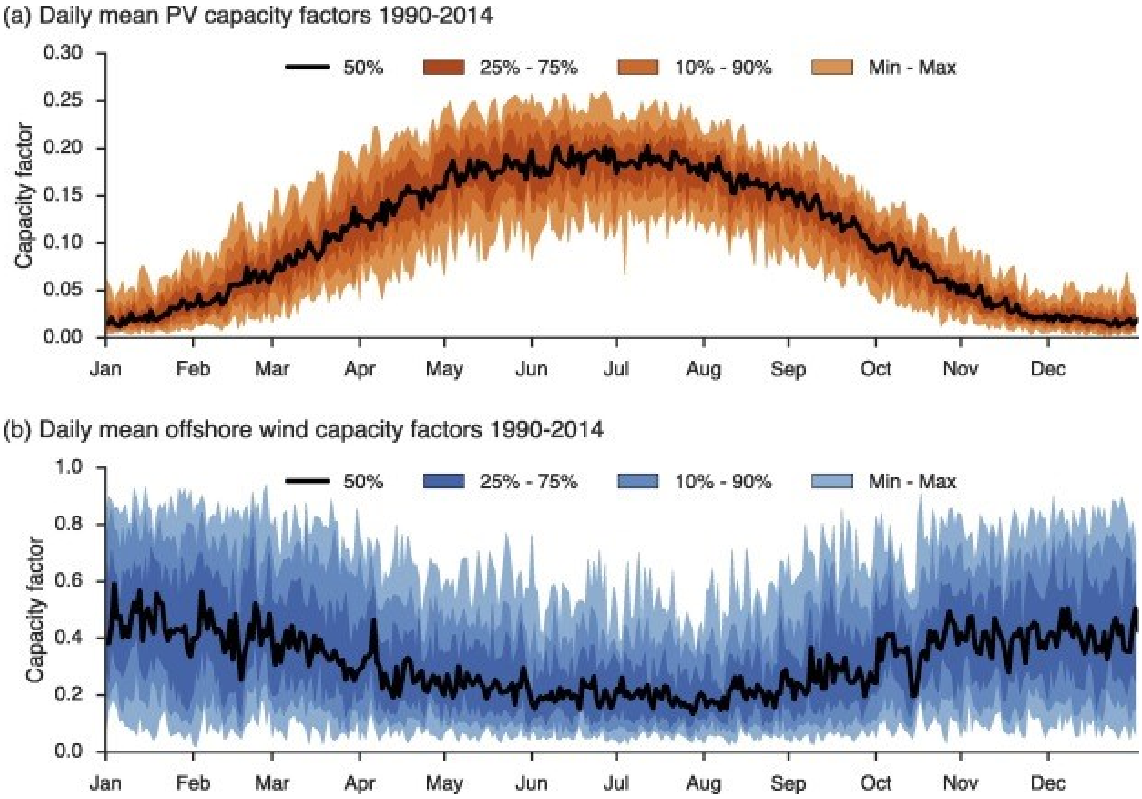


Figure 6 *Daily capacity factors for a) PV and b) Offshore wind based on NASA MERRA reanalysis and Global Solar Energy Estimator model for 25 years. [10]*

As can be seen from the figure above, the seasonal variability of solar and wind power can be opposite from each other. For solar power, the production peaks happen always in the sunny summer months, whereas wind power operates on a high capacity factor in the winter, but that can have regional differences. It is possible that solar and wind power balance each other out in a way when the seasonal difference is as in the example.

2.2 Electric vehicles

Electric vehicles (EV) are quickly becoming popular as the technology gets better, and people are becoming more climate conscious. EVs, however, cause additional stress to the distribution networks as they increase the total load of the network and change the load profile of customers. There are a lot of variables that come into play when considering the effects on the grid. Mostly the charging of EVs is random in the sense that people have different schedules regarding their work, driving patterns and there are many different types of vehicles and ways of charging. There are also many kinds of EVs that have different battery capacities that will also affect the charging behaviors. For example, the difference between plug-in hybrids and full EVs is rather large when considering the mileage available. A plug-in hybrid electrical vehicle (PHEV) will probably have to be charged daily to enable the electricity-based driving whereas a full EV would need to be charged more seldom in day-to-day use. As EVs become more common, the patterns of charging will probably become quite predictable even, as there will be more data available from metering and the technology will start to settle. In this work, EVs are considered to be passenger vehicles.

Overall, the loading of distribution networks will increase when EVs become more common and that may lead to loading peaks which can cause the voltage on the feeders to drop while simultaneously risking overloading of lines and transformers. There are, however, many ways to limit the effects of EVs by controlling the charging so that it occurs during off-peak hours. EVs could also be used as energy storages to balance the loading of the grid by storing energy during off-peak hours and discharging energy to the grid when necessary. This so-called vehicle-to-grid (V2G) operation could also aid in balancing the grid in the future but will not be discussed further in this thesis.

2.2.1 Current state of EVs

The popularity of EVs is increasing rapidly. In 2020, the number of EVs exceeded 10 million, with a 43% increase from 2019 [11]. The most recent developments in the EV stock are shown in Figure 7. Currently Europe is the second largest EV market, with also the highest absolute increase in new car registrations in 2020. Noteworthy is, that full

EVs are globally more common than PHEVs, but in Europe they are split pretty even. In Finland, however, PHEVs are far more common than full EVs.

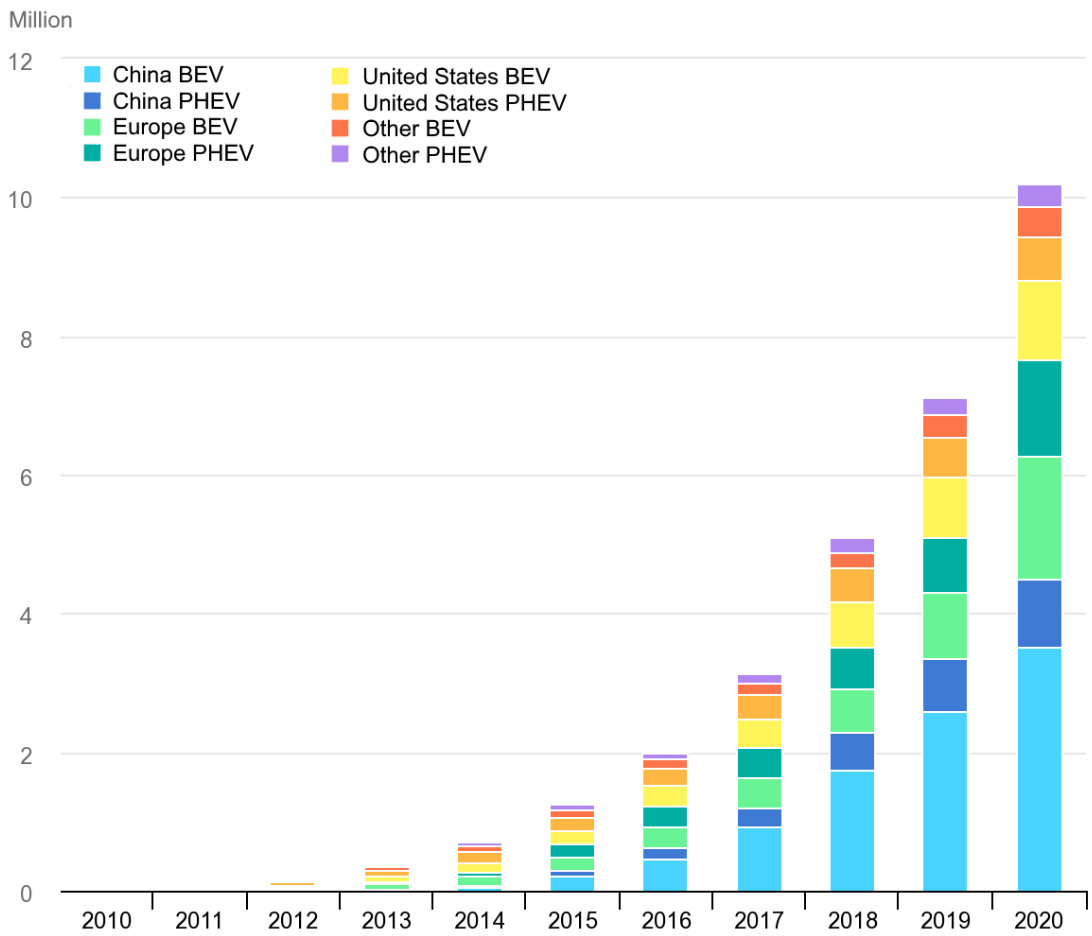


Figure 7 *Development of the global passenger EV stock from 2010 onwards. Modified from [11]*

According to Traficom, the current amount of EVs is 2,1 % (55 322) of total passenger vehicles in the end of year 2020, with PHEVs leading the way with 45 621 vehicles [12].The amount doubled from the year 2019 to 2020 and the strategy for long-term development of total emissions sets the goal for at least 250 000 EVs by year 2030 [13]. With the current rate of growth, the amount of EVs would easily surpass the goal set in the strategy. It is likely that PHEVs will continue to dominate the Finnish market for a while, due to people buying the safe option that can also be driven for longer distances with gasoline. As the driving range of full EVs continues to grow and the availability of fast charging options becomes larger, the trend might change to favor full EVs, like in other countries.

The range of EVs has been increasing quickly and nowadays even most PHEVs can drive common daily trips on purely electric energy. For example, the average range of

PHEVs on the USA market today is 44.5 kilometers [14]. This range is based on the EPA rating which is a combination of the model's highway range and city range. It might not completely match the range of the same models in Finland due to different weather conditions, but it gives an approximation on the range of new PHEV models. Similarly, the average for full EVs available on the US market is 410.7 kilometers. The average battery size for full EVs and PHEVs is 78.9 kWh and 15.2 kWh, respectively.

While the drivable range of EVs is constantly improving, the availability of charging stations has still limited the interest in full EVs especially. At the moment though, the public charging infrastructure is growing at a faster pace than EV sales. From 2018 to 2019 the number of chargers available publicly increased by 60% [15]. Currently there are about 6.5 million private, slow chargers and 0.8 million public chargers worldwide. Europe and China are quite even in the amount of private slow chargers, but China dominates in publicly available chargers with its about 60% share globally. In Europe, it is estimated the currently up to 90% of charging happens at home or at work [16]. But even in Europe the popularity of public charging options might grow as EVs become more viable to also the lower-income households.

2.2.2 EV charging

The existence of EVs itself does not cause stress on the electrical network but the charging of the vehicles does. There are many ways of charging EVs from dumb to smart charging and from slow to super-fast charging. These methods have different impacts on the grid. In the most basic case of dumb charging, the charging happens when the EV customer plugs the charger into the vehicle. Then the car will be charged until it is full and for that time being it will increase the load of the network. This charging method depends only on the needs of the customer, especially when charging at home. Smart charging on the other hand considers the power system needs. Smart charging basically means that the charging can be controlled based on an external variable, like for example the grid frequency, to reduce the charging power and therefore the loading of the grid. Similarly, it would be possible to schedule the charging for off-peak hours to balance to balance the loading of the grid in the other direction. Smart charging could be an effective way to reduce the loading peaks of the power system, but it requires that customers are willing to let the charging duration to increase. Reduction of charging during the day-time peaks would mean that customers would have to be compensated somehow. The incentive to charge during night-time could be based on cheaper electricity prices quite automatically.

The charging power and current are dependent on the types of charging systems used and the properties of the car model. There are four charging modes defined in the standard IEC 61851-1. The modes will not be introduced in detail in this work, but the charging powers available are noteworthy from the power system point-of-view. Typically charging happens with AC current that is converted into DC current inside the car's on-board charger.

Mode 2 is a slow charging AC method with 1- or 3-phase charging with currents up to 32 A. Can be used with existing outdoor Schuko sockets that are common in Finland. With long duration 1-phase charging, the current should be limited to 8 A for safety reasons [17]. Depending on the model however, the manufacturers might enable up to 13 A charging currents. The 3-phase sockets do not restrict the currents in the same way and can be used with the nominal 32 A current, but they are less commonly used. The common charging power is around 2-3 kW with 1-phase charging.

Mode 3 charging is the standard AC charging method. It is the intended way of charging an EV through a dedicated charging socket. They enable a charging current of up to 3x63 A with a maximum power of 43 kW [17]. Mode 3 charging also enables the controlling of the charging current. In practice, the maximum charging power and currents are limited by the on-board chargers of the EV models. For PHEVs typical charging power is around 3.3 kW and for full EVs powers in the range of 3.3-10 kW are quite typical [18].

Mode 4 charging is also known as fast charging and it can reach very high powers in the range of 50-350 kW [17]. These chargers utilize an off-board charger that converts the grid AC-current into DC current outside of the vehicle. Currently, this charging method is mostly available commercially for full EV vehicles.

When considering the charging effects of vehicles at home or at work, the charging modes will most likely be modes 2 and 3. The charging power would then most likely be in the range of 2-10 kW as the car will be parked for longer periods of time.

2.3 Issues with DER

The consumption and generation of the power system must always be balanced. However, this is becoming more difficult for transmission network owners (TSOs) to maintain. With traditional power plants the amount of production has been easy to control, so most of the uncertainty has come from the varying consumption. In developed countries the amount of consumption has been quite easy to predict based on available historical data. This changes when DER is introduced to the mix because now the production is variable and new types of loads are changing the loading profile. Due to differences between predicted and actual generation, the TSO will have to manage reserves more carefully than before.

2.3.1 Frequency issues

When the production and consumption are not balanced, the frequency of the system will start to change. When the consumption exceeds the produced power, frequency in the system will start to drop. Then again when the produced power exceeds the consumption in the grid, the frequency will start to rise. In Finland, the acceptable limits for the grid frequency and other properties related to power quality are given in the standard SFS-EN 50160 [19]. In Finland, the lower limit for the grid frequency in a standard grid is 49,5 Hz and the upper limit is 50,5 Hz during 99,5 % of the time.

In a situation where the grid frequency drops, the underfrequency protection in DG related to anti-islanding protection might trip [20].The tripping of generation causes a loop where the production of energy decreases further. In 2016 a blackout occurred in South Australia after two tornados caused three transmission lines to trip. The following sequence of faults caused the South Australian power system to become islanded after major interconnector tripped as well. The output of generators was less than the consumption in the island, which caused the rest of the generation to drop [21]. In that situation it might have been possible to maintain stability in the island with sufficient load shedding.

Frequency stability and anti-islanding protection are both important for proper operation of the network. In the above example the feeding network tripped, which caused the island. A similar drop in frequency can still happen in a situation where a large power plant failure would cause the production of energy to decrease radically. For this reason, TSOs have production reserves which can be used to ensure sufficient production while simultaneously preventing frequency issues.

2.3.2 Voltage issues

Historically, most power systems are designed to be radially operated with no generation located along distribution feeders, with power flowing from the primary substation to secondary substations that provide power to the customers. DSOs are responsible in keeping the voltage within certain limits, which are in Finland, ±10 % of the nominal voltage in MV and LV networks, in a normal situation [19]. Typically, an overvoltage in the feeder has not been a realistic issue, but rather an undervoltage at the end of a long feeder due to the voltage drop.

When DG is introduced to feeders, the situation changes. Now the even the overvoltage may be a concern in certain situations. For example, if a generator is added somewhere on the feeder, it raises the voltage at that point. It is not an issue in itself, but if the produced energy is greater than the consumption downstream, the power flow will reverse and cause over voltages [22]. There are ways to control the voltage along the feeder with equipment such as on-load tap changers, but if constant operation of such devices is required, it will lead to quicker deterioration of the equipment [23]. At least in Finland, a situation where DG such as small-scale PV generation would lead to reversed power flow is not going to be a common occurrence in some time, but for example in Germany it is possible already.

The effect of new kinds of loads such as EVs will be similar to existing loads. As the loading increases, voltage drops will increase as well. The change in overall loading profile can still be quite big because the annual energy consumption of EVs, for example, is quite large. It is possible that energy storages could, in conjunction with small-scale production, balance out the loading and large voltage drops could be avoided. The allowed voltage variations are also quite lenient, and the voltage drop can be compensated with off-load tap changers if the daily variance of the voltages is not huge.

2.3.3 Fault current issues

DG located along a feeder will change the way power flows in the feeder. In a radial network with no generation, the power could only flow from the substation to the end of the feeder. This made the dimensioning of the feeder, and the setting of protection equipment easy. Most relays and circuit breakers operate using over currents to detect fault situations. Now a generator along the feeder affects the fault currents seen by the relays. This happens in faults located downstream of the generator as well faults located on adjacent feeders. If a fault occurs downstream of the generator, it supplies current towards the fault and therefore reduces the current measured at the protection equipment upstream of the generator. However, most DG is connected to the network through inverters, and therefore for example solar panels’ contribution to fault currents is negligible [24, 25].

3. IMPORTANCE AND EFFECT IN DIFFERENT COUNTRIES

There are clear differences between DER effects in different countries. The reasons can be for example the way the grid is constructed, the difference in regulations between the countries and the differing amount of renewable energy connected to the grid. In this chapter the differences are compared between Germany and Finland.

3.1 DG effects in Germany

In Germany, there is a lot of variance geographically in the energy produced and energy consumed. The German electricity grid also includes a lot of DG, which makes the balancing of the grid problematic. The installed capacity of different energy sources is shown in Figure 8. For these reasons Germany is a good example of DER effects relating to network congestion and bottlenecking. There are situations where the generation and consumption of energy do not match locally, which leads to bottlenecks in the grid. In these situations, the TSOs will interfere with the market to solve the issues.

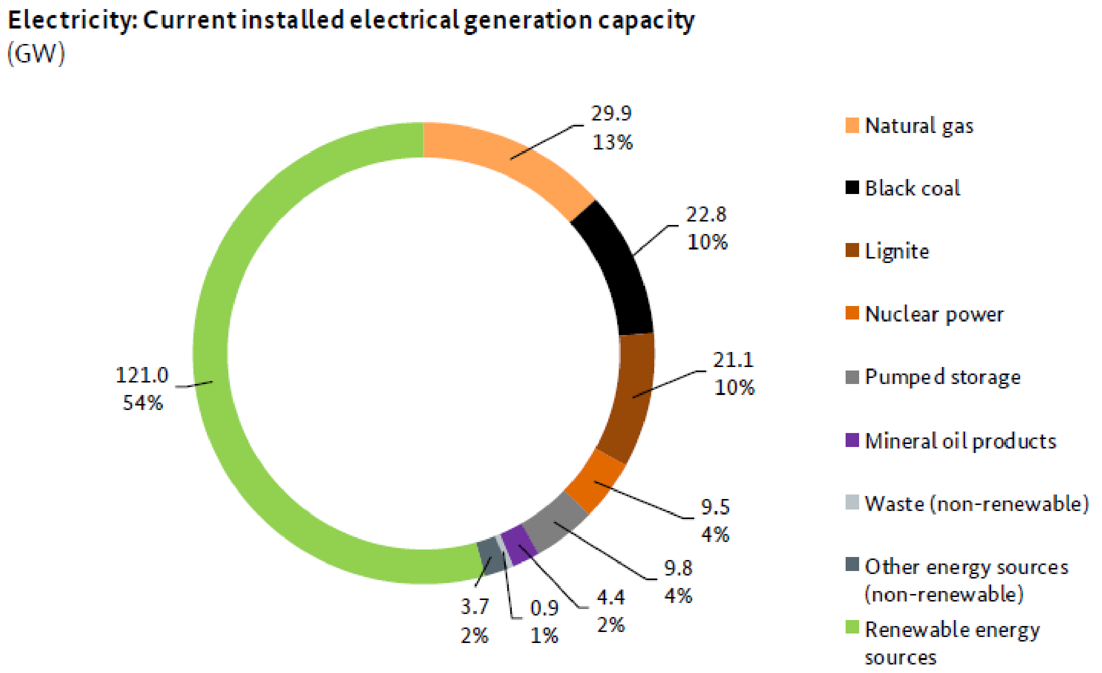


Figure 8. *Installed electrical generation capacity in Germany in 2019 [26]*

It is worth noting that the installed generation capacity is still different from the actual generated energy. In reality not all of the available capacity of renewable energy sources is used. In Figure 9, the total electricity generation in Germany is shown.

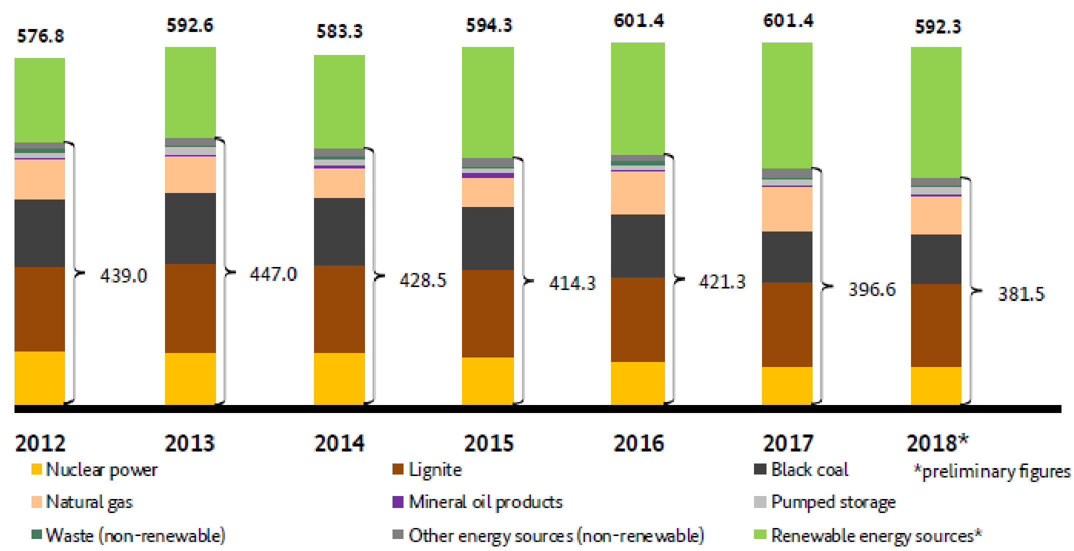


Figure 9 *Net electricity generation in Germany (TWh) [26]*

The aim of security measures is to maintain operational stability while prioritizing the generation of renewable energy. Therefore, the curtailment of renewable generation should be the last step to take while preventing or alleviating line overloading. The main goal is to solve the loading issues by reconfiguring the topology, adjusting loads or re-dispatching, which means geographically adjusting power production between power plants. The redispatching may also include reserve power plants if there is a deficit in redispatching capacity. After these measures, the feed-in from renewable generation can be curtailed. [26]

It can be noted that the current state of the power grid in Germany leads to increasing amounts of feed-in management of renewable energy. In Figure 10 the increase in curtailment during the last decade can be seen. Most of the curtailment involves wind energy, which means that a significant amount of curtailment happens in northern Germany. In total, 2.8% of renewable energy production was curtailed in 2018 [26]. While the amount of curtailed energy is relatively small, it is still significant and should be reduced in the future especially since there will be more and more renewable energy introduced to the grid. Also noteworthy is that most of the curtailment was required by transmission network restrictions but 60% of total curtailed energy happened in distribution networks based on requests made by the TSOs [26]. Reducing the network congestion is very important from an economical viewpoint as well. In 2018 the redispatch and feed-in measures cost approximately 803 M€ and 610 M€ respectively [26].

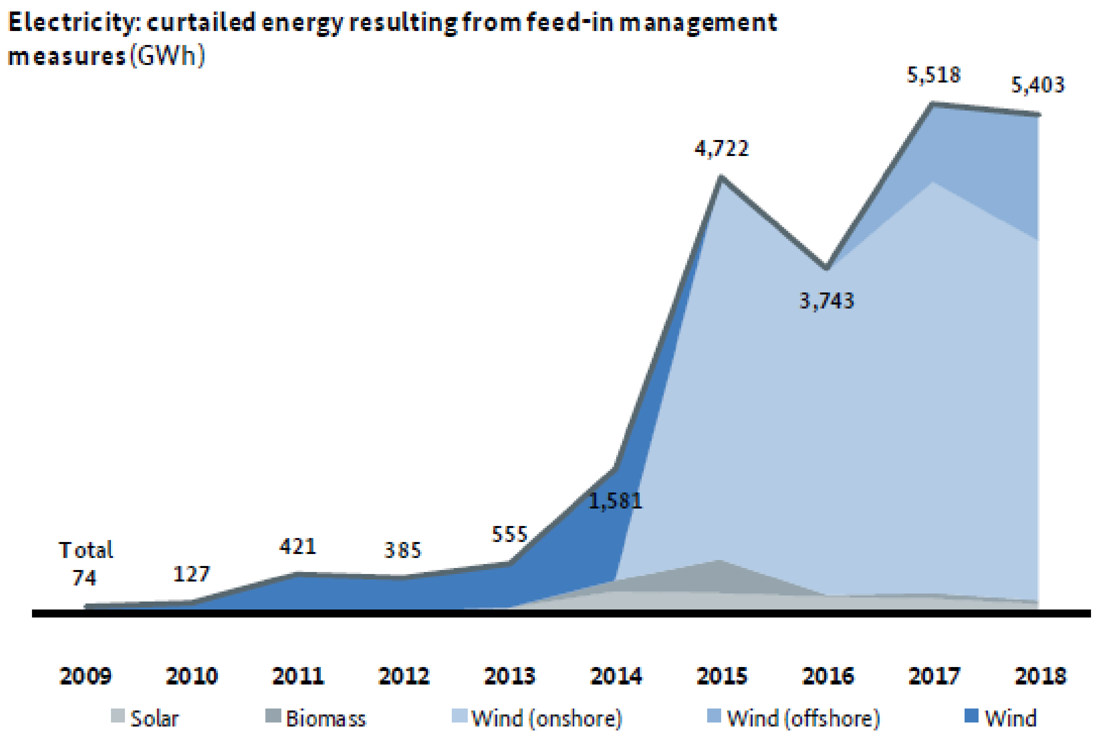


Figure 10. *Curtailed energy resulting from feed-in management measures [26]*

3.1.1 Redispatch

A situation where production and consumption are geographically far away from each other could cause additional stress and thermal overloading on the connecting transmission lines. Congestion occurs when the demand in one area cannot be supplied through existing production transferred from another area. The TSO can redispatch power plants to fix these bottlenecks. That means adjusting the active power fed by power plants in the area by increasing production on one side of the bottleneck and reducing production on the other [27].

3.1.2 German legislature

There has been a large push for more renewable energy in Germany during this millennium. The German Renewable Energy Sources Act (EEG) has been in place to fund new renewable generation to help match the goals set for renewable energy. To cope with the increasing amount of distributed generation, the Network Expansion Acceleration Act (NABEG) was introduced to set new requirements regarding congestion management. NABEG amends the regulations set in the Energy Industry Act (EnWG) concerning redispatching of power plants. As currently set in EnWG §13a, all conventional power plants with a nominal output of 10 MW can be redispatched. Additional regulations for renewable energy and combined heat and power (CHP) feed-in management are given in EEG §14.

The so-called Redispatch 2.0 will expand the possibilities of redispatching. All power plants from 100 kW upwards including renewable energy and CHP must be redispatchable after October 1, 2021. In addition, all systems that are remotely controllable by the network operator will be included. [28] Redispatch was before mostly the responsibility of TSOs but the new requirements will impact DSOs as well. In the future more cooperation is required between network operators and the need for exchanging planning and forecast data is noted [28, 29]. The data exchange needs are met with a Single Point of Contact (SPoC) interface called Connect+ [30]. However, at the moment it is not clear how the interface is implemented, and which protocols and data structures are involved.

3.2 DER effects in Finland

The structure of electricity production in Finland differs from Germany especially on nuclear power generation. The electricity production in Finland by energy sources is presented in Figure 11.

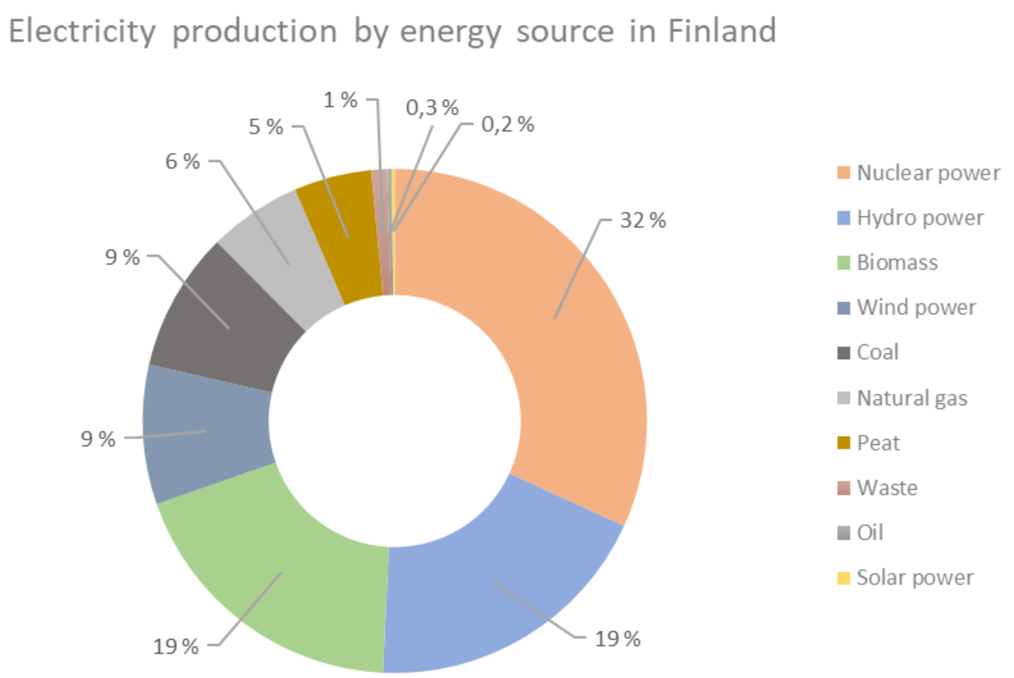


Figure 11. *Electricity production in Finland in 2018 [31]*

In Finland, a third of the production comes from nuclear power whereas in Germany that form of generation has been reduced since the past decade. According to Finnish Energy the overall share of renewable generation is 47 % and almost all of it comes from hydro power and biomass [31]. While the share of renewable generation is close to Germany, the production in Germany is more focused on wind and solar power. Because of this the amount of distributed generation is a lot smaller in Finland so the effects are not the same as in Germany.

Congestion issues are not as common in Finland as they are in Germany. However, bottlenecks can occur on the so-called P1-cut. The P1-cut divides the mostly wind and hydro powered north from the mostly CHP and nuclear-powered Southern Finland. In the future, more wind power will be installed north of the P1-cut and still most of the consumption will be in the south [32]. Therefore, the congestion issues may become more relevant in Finland than they are now. At the moment these issues are mainly not concerning DSOs. The P1-cut and wind power development in Finland is shown in ***Figure*** 12.

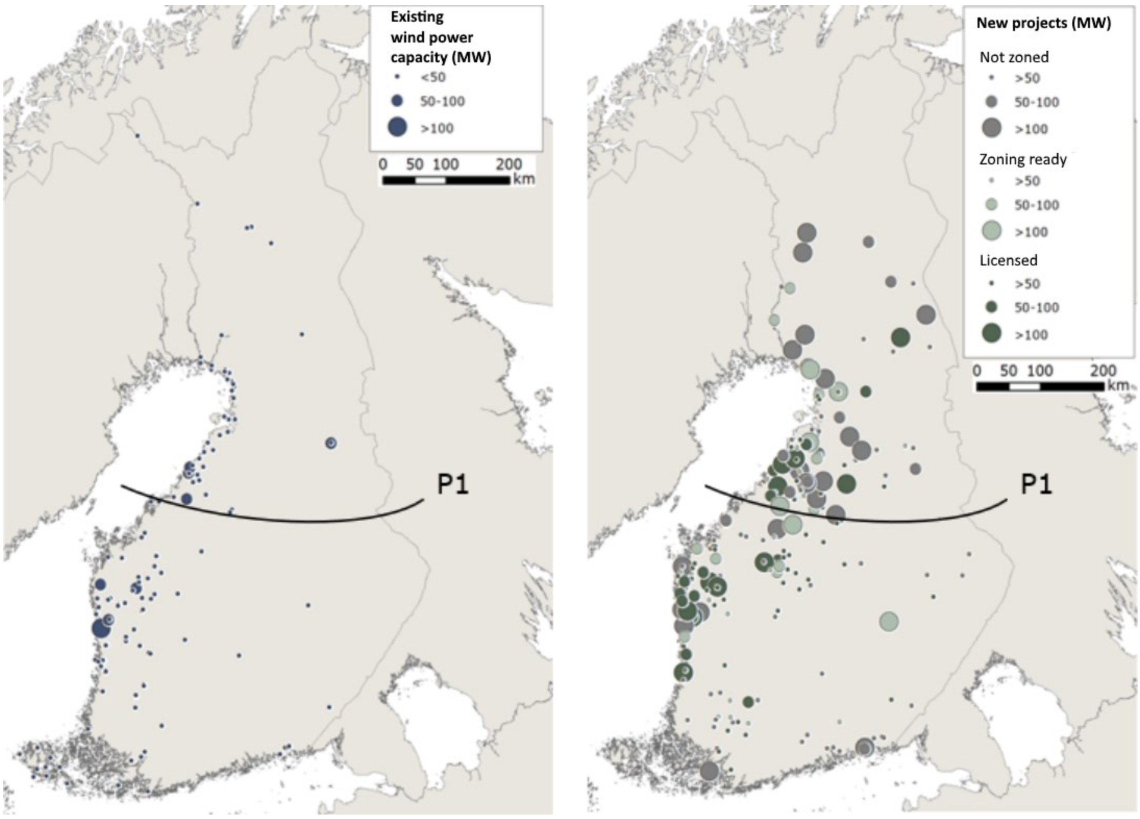


Figure 12 *Wind power development in Finland in the beginning of 2020 [32]*

Since the amount of DG in Finland is quite small when compared to Germany, it is unlikely that excess production of energy would cause major issues here. If the direction of the power flow does not change in the LV networks that contain solar power, for example, the voltage rise in feeders will not be an issue. There may still be other DER related issues in Finland and interviews were conducted with DSOs in order to clarify the situation.

3.3 DMS600 user interviews

To gather information, three Finnish DSOs were interviewed. Two of the DSOs managed larger rural networks and one operated in a mid-sized Finnish city. The questionnaire was given to the interviewees beforehand to let them prepare their answers. The questionnaire was based on DER effects and the topics were:

- The amount of DER in the grid and future trends
- Experiences with issues related to DER
- Remote controllable loads and generators
- LV generation, production curves and forecasts
- Effects of DER on fault management and switching planning
- Challenges and possibilities of DER in the future

While the interviews were conducted remotely with the help of questions presented in a slide show, the sessions mostly focused on open conversation where the questions helped to keep the conversation flowing. The sessions were recorded and transcribed later.

The interviewed DSOs were:

- Rovakaira Oy
- Savon Voima Verkko Oy (SVV)
- KSS Verkko Oy

Each of the DSOs use DMS600 to some capacity. Rovakaira uses the distribution management system as well as the network information system in MicroSCADA X DMS600 while SVV and KSS use the distribution management system DMS600 WS but their network information system (NIS) Tieto Smart Utility (TSU-NIS) is provided by TietoEVRY. Each of these DSOs use MicroSCADA X SYS600 as their SCADA system.

3.3.1 Amount of DER

Every interviewee brought up that the amount of DER, such as PV generation and EVs, is still rather small. At Rovakairas network the increase of PV generation is still exponential but elsewhere the growth has declined to a steady yearly increase. It was also brought up that the power of individual panel systems should usually be dimensioned according to the customer's own consumption, which reduces possible issues of feed-in towards the network. Currently it is improbable that bigger panel systems would become more common because the profitability of selling electricity to the network is low due to low energy prices.

The current amount of EVs did not come up in the interviews but the effects that come up with increasing amounts of EVs was recognized as a more realistic issue in the future than small-scale production, when considering network bottlenecks. As noted in section 2.2.1, the amount of EVs is rapidly increasing in even Finland, so this assumption is not unfounded.

3.3.2 Technical effects of PV generation

Currently the effects of PV generation are quite limited due to the small amount of production currently connected. There have been a couple of cases where a customer's PV system has independently limited its own feed-in or completely shut down due to increased voltage at the connection point. There was also a case where a larger system had to be limited already in the installation phase due the peak power of the system exceeding the transformer's loading capacity. From the DSOs perspective the automatic control of inverters in PV systems does not yet cause technical issues but from the customers' perspective the limiting of electricity production has economic consequences. At the moment it is unclear whether or not the DSO must pay compensations for the lost production. Either way, DSOs are responsible for maintaining a grid that enables the PV systems and treats customers equally and DMS600 should support in this task.

The effects of PV systems on power quality are still a bit unclear. In the interviews one case came up regarding another DSO where some power quality issues were reported. An overly dimensioned PV system had caused power quality issues in the LV network in which the customer was located. Currently DSOs do not have good ways to monitor power quality in individual LV networks and the problems are usually reported by the customer and then the DSOs will monitor the situation. At the moment issues with power quality are rare, but in the future, they might become more common. A possibility came up that when many PV systems are controlling their feed-in at the same time, it might lead to voltage fluctuations and possibly flickering.

Overall, the problems with PV systems currently originate from the system being too large when compared to the customer's own consumption. However, there is currently no need for extensive monitoring of the hosting capacity of LV networks when installing new PV systems because the amount is still small, and the Finnish electricity network is quite strongly dimensioned due to high loading in the winter. While installing new systems is currently not an issue, it was brought up that the increasing amounts of DER have to be considered when planning the network. Since individual network components, such as lines, are built to last for 40 years, they have to endure the changes that happen during their life cycles. A need was recognized for better tools to aid in network planning when considering possible penetration rates in the future. Simulation of DER components by a given penetration rate was seen as a possibility.

3.3.3 DER effects on operations

The increasing amount of DG in the grid means that fault management and the planning of maintenance outages has become more complicated than it was before. The presence of PV generation means that there is always a possibility of backfeeding even though the systems have loss-of-mains (LOM) protection to disable island operation. This puts emphasis on the proper earthing and verification of the absence of voltages for the work crews. So far there have been no cases where the LOM protection has failed but still the possibility of backfeeding must always be considered. When locating the possible backfeeds the visual representation of LV generators in DMS600 is used.

The current needs regarding switching planning are mostly improvements on existing functionalities. At the moment LV switching planning does not automatically create a sequence for earthing steps and needed switching actions around the work location, which would be essential to the usability. The switching planning should automatically add earthing steps against the feeding lines as well as create the switching actions for separating the DG from the work location in both MV and LV planning. It was also brought up that there is currently no correct way of modeling the switches of PV systems, which would be needed in LV planning. In the future there could be separate energy communities that would bring new challenges to switching planning. For example, energy storages may have to be integrated to the planning.

The future outlooks regarding island operation and energy storages were also discussed. The possibility of reducing unsupplied zones and balancing the network during faults and maintenance outages has been considered as a big opportunity in the future. An example of such a case would be a situation where a long feeder has a fault but the customers at the end of the feeder could be supplied through the energy storage. It would certainly have a positive impact on the non-delivered energy, especially since the amount of cabling is constantly increasing and fault clearing times can become longer. However, the economical upside of energy storages is still hard to justify. The storages would have to be utilized in other ways as well like in balancing of loads.

3.3.4 Load profiles and demand response

The change in load profiles caused by PV generation and EVs means that the current way of using load curves is not accurate. Traditionally the load curves are formed using information such as the customer's heating method and historical data, which is then scaled accordingly based on the customer's yearly energy. Issues occur when the customer also generates his own energy which decreases the yearly consumption of energy. This causes the yearly energy to drop which again causes the expected load in the winter to drop. It is not accurate however, due to PV production being smaller in the winter whereas the consumption stays the same while at the same time the expected loads in the summer would be bigger than in reality. One solution to this issue would be to use customer specific hourly measurement data instead of load curves. Also, the possibility of presenting generation data in WS was brought up. The generated power could be averaged for each week and then be used to make load flow calculations more accurate.

Electric vehicles were seen as a realistic cause of bottleneck issues in the future. The EVs are problematic because the charging points and stations can be almost anywhere like for example at work, home or at shops. Also, the loading profiles of these charging points will not be similar to each other, not to mention that the load of one charging point can vary a lot as well. The nature of EV charging means that local bottlenecks could occur in the network, which means that strengthening the network may have to be done. Also, one DSO had already analyzed the effect of EVs on transformers with their own data analytics and noticed clear bottleneck possibilities. Simulating the effects of EV charging is quite complicated however, since normal and smart charging would have to be considered as well as many different user behaviors.

A common theme that came up in the interviews was the importance of demand response in dealing with bottlenecks. Customers already participate in demand response to an extent through different heating methods and tariffs that fit their profile, but in the future more active methods can be possible. For example, energy storages combined with PV generation can help customers shave their peak loading, which is beneficial to the network. Also, the effect of EVs can also be positive with smart charging during hours of low consumption or by even feeding the network. Most of the methods for automated heating and smart EV charging are based on electricity prices. However, in Finland there is only one price zone which might not reflect the actual situation of a distribution network which might lead to local bottlenecks. Also, the automation of equipment based on only the electricity price could lead to a lot of loads such as heating to turn on and off at the same time. The possibility of DSOs buying demand balancing as a service was brought up. If such as market for balancing exists someday, the process of controlling the loads should be automatic and could be implemented in DMS600 in the future.

3.3.5 Summary of the interviews

The increasing amount of DG was not regarded as a big threat from a bottleneck perspective due to the strongly dimensioned network in Finland. EVs, however, were seen as a more realistic threat and bottlenecks could occur as they become more common. For the operation of distribution networks, the possible backfeeds of the DG should be considered in switching planning and the importance of LV switching planning is also increasing. Of the possible solutions to network bottlenecks, the possibilities of energy storages and demand response were highlighted, although there are still limiting factors for those. As energy storages become more economically feasible, they could also be used to feed unsupplied areas during outages. The importance of different topics is summarized in Table 1.

Table 1 *Summary of the importance of main topics discussed in the interviews*

	Time of relevance		
Topic	Today	In the future	Importance
LV switching planning	x		High
Automatic sequence for disconnecting backfeeds	x		High
Proper documentation of LV generators	x		High
EV effects on loading	x		High
DG hosting capacity	x		Medium
Demand response automation		x	Medium
Energy storage usage in operations		x	Medium

4. MICROSCADA X DMS600

MicroSCADA X product family consists of the SCADA system SYS600 and the distribution management system DMS600. SYS600 provides the controlling of equipment and acts as a real-time monitoring system while DMS600 provides the graphical user interface for network operators. DMS600 consists of the distribution management system DMS600 Workstation (WS) and the network information system DMS600 Network Editor (NE). These applications are integrated through background services DMS Socket Service, DMS Service and DMS Server Application which communicate changes happening in the system as well as information to external interfaces, such as outage maps. DMS600 typically uses two SQL databases for storing information: network database and DMS database. The network database contains mostly static information about the network components and imported data from customer information systems. The DMS database then again contains a lot of real-time and historical information from switching states to outage data. An overview of the system is visualized in Figure 13.

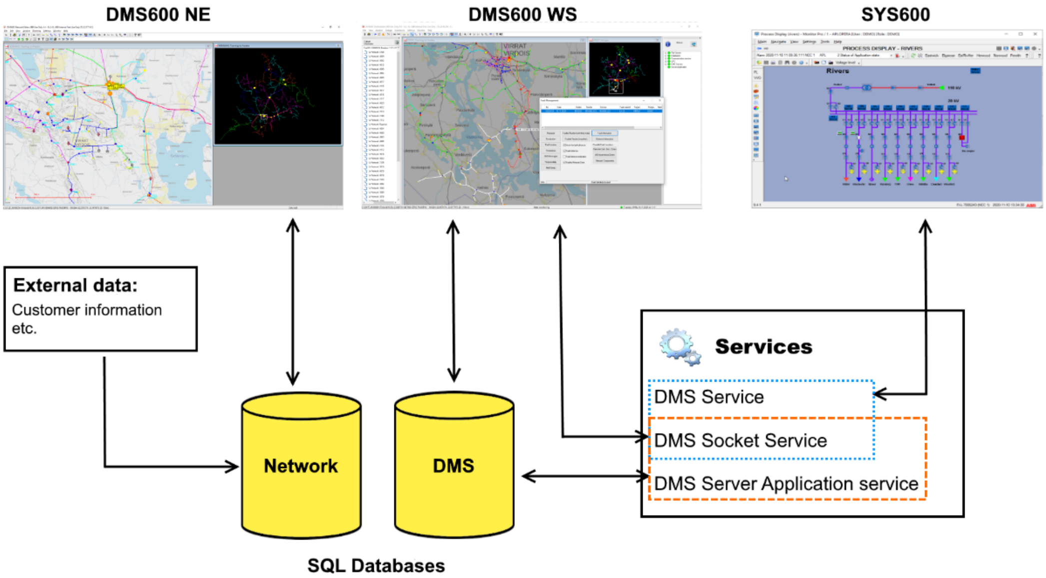


Figure 13 *Overview of a MicroSCADA X system and its communications*

It is also possible to use pieces of DMS600 together with other systems. For example, the network information system TSU-NIS is used together with DMS600 WS by some companies.

4.1 DMS600 Network Editor

DMS600 Network Editor is used to plan and document the network information and save it to the network database as well as the binary network file, often called the binary database, that is used by DMS600 WS when reading the network model. NE is also used to manage the system, as some common settings can be managed there. Network components are modeled on top of the background maps as nodes and line sections, to which technical information can be saved on the components' data sheets. The technical information, such as information about line resistance and other properties, is then used in network calculations. Typical topology includes the entire network from HV/MV primary substations to LV networks and customers.

4.2 DMS600 Workstation

DMS600 Workstation is used to monitor and operate the distribution network. It shows the real-time switching state of the network by using the OPC Data Access (OPC DA) interface to communicate with SCADA. In addition to the states of the switches, other information such as measurements and alarms can be presented on the map-based graphical user interface. The basic functionalities of WS include fault management and switching planning, which will be briefly introduced. A congestion management functionality also exists on a prototype level.

4.2.1 Fault management

Managing faults is an essential part of DMS600. When SCADA receives information of a circuit breaker tripping, DMS600 and the supporting services will determine the fault type. If the fault is cleared by reclosing, DMS600 will automatically generate a reclosing report of the fault. If the fault persists, WS will open a fault management dialog for the network operator. The fault management dialog and user interface of WS is presented in Figure 14. The side-bar on the left-hand side contains information about on-going outages. In this example, there is one fault going on and all of the affected LV networks are listed. The side-bar on the right-hand side displays the status of connections.

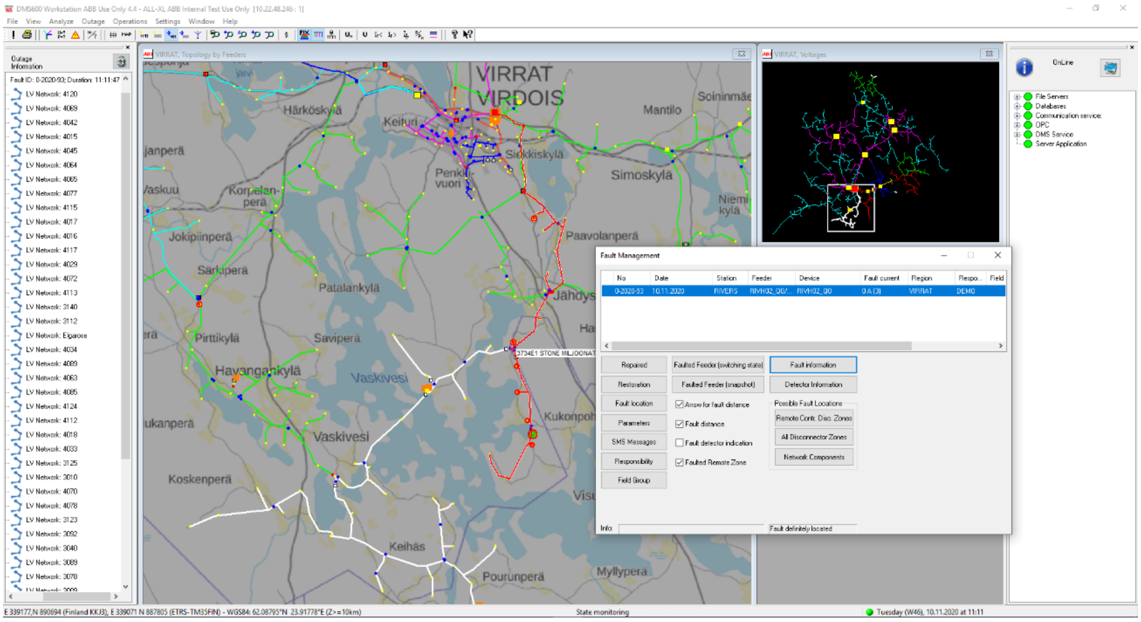


Figure 14 *Graphical user interface of WS during fault management*

When managing a fault DMS600 highlights the faulted zone and shows probable fault locations when fault currents are available. The fault management informs operators of affected customers and also helps to identify disconnector zones. After the fault is cleared, DMS600 creates a fault report which includes the switching sequence, affected customers and also necessary economical information related to the cost of the outage.

4.2.2 Switching planning

Switching planning is a functionality that is used often by network operators to prepare switching sequences for maintenance outages. The switching planning can be started manually or by selecting a work location. When done manually, the user can perform switching actions in a simulation state, and the actions are then saved onto the plan. When selecting a work location, DMS600 will automatically create switching actions that separate the work location from possible feed-ins as well as creating steps for necessary actions such as for grounding. An example of an automatically created switching sequence is presented in Figure 15 along with the switching plan management dialogs. The switching plan management dialog lists the existing switching plans, which can be opened for review even after executing those plans.

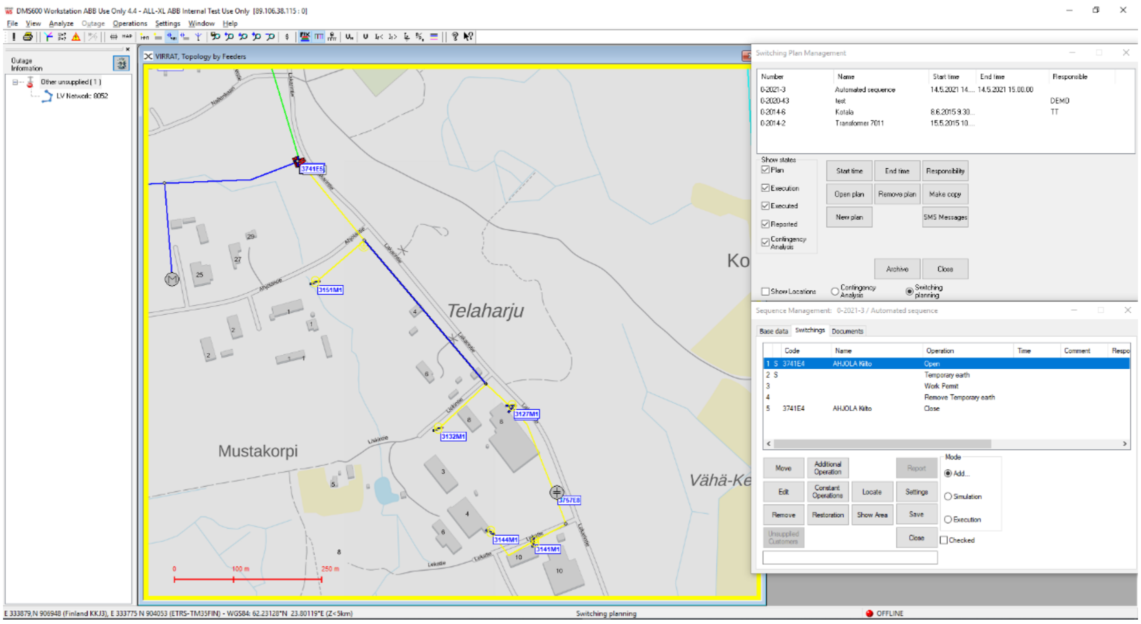


Figure 15 *Switching plan management*

The example sequence is generated by starting switching planning, selecting the line section highlighted by blue as the outage location, and then choosing the automatic sequence creation. As is seen in Figure 15, the outage area is automatically disconnected from the closest disconnector and steps are created for the earthing of the network as well as for walking the work permit. The work permit step is an example of an additional operation that can be added to the automatic sequence by the user.

After the switching sequence is created, the planned sequence can be simulated, and it will generate information about the affected customers. When simulating the steps, WS enters a separate simulation mode. This mode is highlighted with the yellow borders in the network window, as shown in Figure 15. While in the simulation mode, the switching actions are not actually executed onto the real network. When it is actually time to execute the switching plan, it can be done through the sequence management dialog.

The switching plan also prepares a document contain the base data and planned actions, that can be given to people involved in the outage. Switching planning is also often linked to interfaces that inform customers about the planned outages.

4.2.3 Congestion management

A tool for congestion management has been developed as a prototype in 2015 [33]. It is meant to support in situations where a lot of DG exists is the grid like, for example, in Germany.

The functionality checks for network violations that exist in the network currently and for violations that would happen in the future, based on available production and loading forecasts for the next 72 hours. The violation types include overloading of lines and transformers as well as over- and undervoltage of network components in the MV network. For example, one line section with an undervoltage produces one violation. The limits for these are given by the user. The detected violations are then presented as a list of all detected violations and as grouped results based on which feeders the violations were found in, to better identify the bottlenecks. For the summarized results, only the most severe violations on the feeder are presented.

This functionality also calculates the needed curtailments of power to remove the production based bottlenecks from the network. The tool calculates the minimum reduction of power to get the overloading and overvoltage back to the upper limit. It also provides information if previous power curtailments can be released as the grid situation changes and the bottlenecks are over. The needed reductions and possible releases are presented alongside the grouped violations. Congestion management can be used together with an external feed-in management program and SCADA to also execute needed actions based on the analysis results.

4.3 DMS600 calculations

Network calculations are an essential part of any distribution management and network information system. Load flow calculations aid when designing the network as well as when observing the state of the network in real time. For network planners it provides crucial information about the way different network components function in the grid and helps the user in deciding which components should be used. For example, when planning a new line, the calculations help to determine which conductor should be used to ensure proper thermal limits during typical loading and fault situations. For network operators the load flow calculations are used, for example, to provide information during switching planning to maintain the power quality of the network. The calculation results are displayed in node information dialogs in WS and NE, as well as in calculation summaries available in NE. An example of a node dialog for a line section is presented in Figure 16.

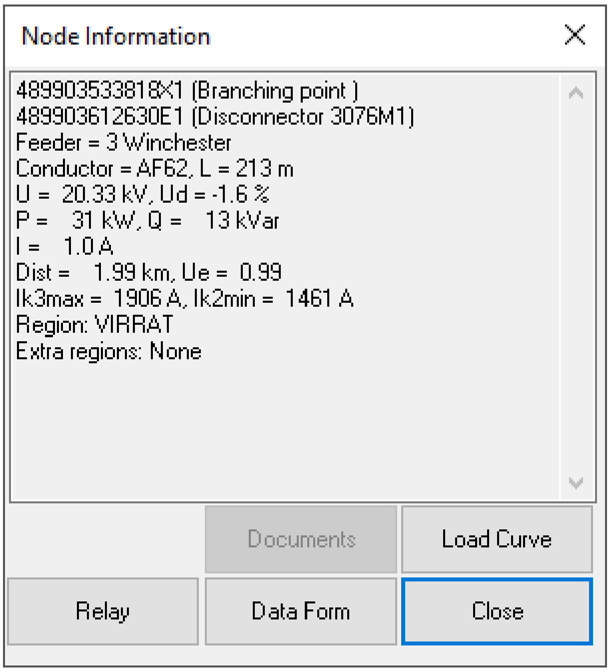


***Figure 16** Node information dialog for a line section in DMS600 Workstation*

The node dialog contains the load flow information of the current hour as well as the fault currents for the section. Also, the fault current calculations are very important when detecting fault locations as well as when analyzing the fault tolerance of network components. Since the fault current contribution from inverter-fed DG is quite negligible, the fault current calculations will not be discussed in detail.

4.3.1 Load flow calculations

DMS600 primarily uses load curves as its basis for load flow calculations. Load curves are a way of representing the mean values as well as the deviation of hourly loading. The load curves contain loading information for every hour of the year. These curves are typically created based on historical data of a large group of customers that fit the same loading profile. In DMS600, the total yearly energy of the 8760 hours is scaled to a total of 10 000 kWh.

The customers are then assigned one load curve that fits into their loading profile and it is then scaled by the customer's yearly energy to get an estimate for the customer's load during each hour of the year. For example, a customer with a yearly energy of 1000 kWh, would have hourly loads that are 10 % of the values in the load curve. In WS the hourly data is used as it is, whereas in NE the yearly peak value of the load is used for each component.

DMS600 can solve the power flow of both radial and meshed networks, but only the radial calculation method is shortly introduced here. When solving the power flow in a radial network, the network is solved by iterating from the furthest node of the feeder towards the substation. It starts by using the hourly loading of the nodes and guessing the voltage of the node based on the voltage level of the feeder. Now the current flowing in the section can be calculated and therefore the voltage drop can also be calculated. The voltages are then calculated for the nodes based on the calculated voltage drops. These steps are repeated while comparing the lowest calculated voltage with the lowest calculated voltage of the previous calculation round until the difference is small enough. In NE the power flow calculations also take into account the statistical element that comes into play with the load curves. For example, two customers might have their peak loading at different times and therefore the peak power value of the line section feeding those customers will not be a sum of their peak powers.

The radial load flow calculations are used in both MV and LV networks as long as the network is not looped. When the network is looped, meshed network calculations are used.

5. IMPROVEMENTS TO CURRENT FUNCTIONALITIES IN DMS600

In this chapter, some improvements to the existing functionalities of DMS600 are discussed. As the amount of DER is increasing in distribution networks, some functionalities' importance is highlighted, and they will need to be improved. Most of the improvements are related to LV networks as they are in the center of changes happening with DG and EVs. Some of these needs for improvement are already brought up by customers beforehand or noted by DMS600 project engineers. Also, the user interviews in 3.3 are considered.

5.1 Generators in LV networks

LV and MV generators are modeled with the same generator component and it is used to document small DG such as solar panels into the network model. In LV networks they are attached to customer nodes with a line section. The component has some data fields purely for documentation, but also some functional data fields. The data form of the component can be seen in Figure 17. The present active and reactive powers can be given, which are then used in load flow calculations. The component can also be linked to real time measurements from SCADA so that the load flow calculations can use actual power values in state monitoring mode. Currently real-time linkage of small units is not possible.

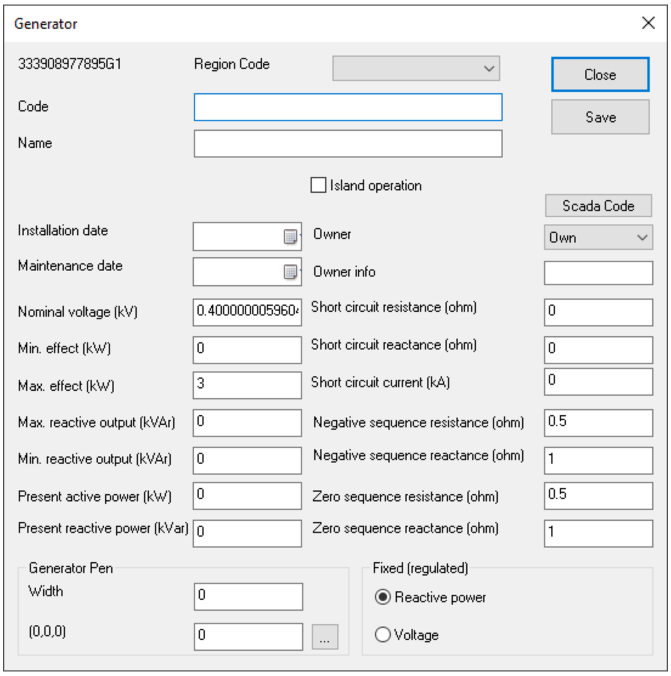


Figure 17 *Generator data form*

It is difficult to utilize the LV generators in load flow calculations because the power generated by the customers' own DG equipment is practically always unknown, except in the context of metering of the customer's loads. The automatic meter reading (AMR) functionalities, however, are only used to monitor LV networks and send alarms in fault situations so it is not possible to use that data to track LV generation. Because the power generated by DG varies a lot, it is impossible to just set one value to the data form that is appropriate for all situations. Therefore, it is impossible to properly take the LV generators into account when calculating the load flow of the network.

Another problem that occurs when a generator is connected to an LV network, is that the network is then considered as a looped network. This leads to meshed network calculations being used, which are often not as accurate as the radial load flow calculations.

5.1.1 Example of LV network calculations

An example of an LV network containing a generator is presented in Figure 18. DMS600 detects a loop caused by the generator and highlights the sections upstream of the generator with the loop coloring, which is pink in this case.

Figure 18 *LV network with an LV generator in NE*

In Table 2, the real powers of the line sections 1-3 are shown, to illustrate the difference between calculation results in looped networks and radial networks, when the network size is small.

Table 2 *Real power values of example line sections*

	Section 1	Section 2	Section 3
With a generator (present active power = 0 kW)	1.7 kW	9.8 kW	9.1 kW
With a generator (present active power = 1 kW)	0.7 kW	8.8 kW	9.1 kW
Without a generator	3.4 kW	13.0 kW	13.8 kW

As can be seen, the difference between radial load flow calculations and the meshed network analysis is very noticeable, even when the generator had zero active power. Even though the loop coloring only shows for the lines that feed the DG customer, the calculations change in other LV feeders as well like in section 3. When the generator had an active power of 1 kW, the generator was calculated as a negative load of 1 kW. Based on field experience, the radial load flow calculations present satisfactory results and they should be considered as the correct values.

Due to the previous example, customers are instructed to add an additional open LV switch between the customer node and the generator, as is demonstrated in Figure 19. This way the network is not considered as looped, and the calculations will work normally. But that is not a good way to document LV generators as it is not intuitive, and the products manual even instructs to connect the generator straight to the customer node [34]. When documenting the generators with this work around way, the users must also remember to mark the owner info of the switch to something else than their own, so that it does not show up in the DSOs asset reports. In addition to the clumsiness of this workaround, the fix has its own calculation issues as well. If the generator is documented like this, the generator's present active power has no effect on the calculations. So far it has not been an issue, but in the future the calculations should work whether or not the switch is documented there, as some DSOs may want to document the customers' DG switches this way.

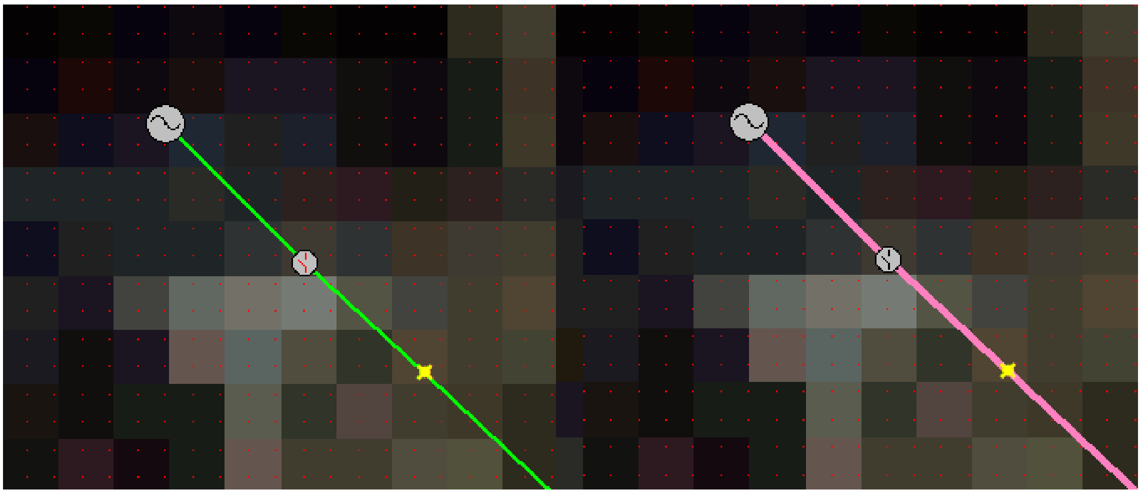


Figure 19 *Generator with an LV switch*

In Finland, DG in LV networks means quite exclusively solar panels and most of the time the generated power is less than the consumption of the customer. In that sense, the panels mostly act as a negative load at the customer node and therefore no loop coloring would be needed in the first place as the panels do not actually feed power towards the network. To solve this basic case of calculations showing wrong results, when generators are connected to the network, DMS600 could simply ignore the generators in when no present power values are given, or they are zero. This would be a quick fix in the current situation, as generation data is not available.

5.1.2 Future improvements on LV generators

So far, the effects of DG have been very limited in Finland, but that is not the case everywhere. Therefore, the effects should be taken into account in load flow calculations. In a situation where generation data is available via forecasts or by real time measurements, that should be used. Since small DG systems will not be found in SCADA, AMR measuring data could be used to set the present power values of the generator in real-time operation in WS. No matter which way the generation data is linked to the generators, meshed network calculation should only be used if the DG feed-in is considerably higher than the consumption. Even if the produced energy is slightly larger than the consumption in a customer node, it is unlikely to cause issues in the network. The limit on what amount of feed-in is considerable, could be a new setting which would be set by the user. When the generator feed-in is considerable, the LV network should also be shown with the loop coloring.

The idea of having measured production data available of customers available in DMS600 has also been brought up by customers. The production data could be shown on the customer node among other customer info, or on the generator. The data could be shown, for example, in a similar format as a load curve, with each with a value for each hour of the year. The actual measured historical data could not be used in calculations though, because the production of DG is very weather dependent, and the hours between last year and this year, have no correlation.

In a situation, where no load forecasts or real time measurements are available, historical measurement data could be averaged to produce an estimate for the production values. The time scale for this would be weeks at best, as the weather can change daily and even during the days. This way the generators could be included in power flow calculations, with seasonally and hourly changing power values. Obviously, it would still be very inaccurate, but if the other option is to include the generators in load flow calculations at all, it might be worth some consideration. If the generators are included in calculations this way, it would grant better results during a sunny weather. Similarly, it would cause error when calculating customer loads when the weather is very cloudy. The worst case would be that data from a very sunny summer week would be used during a very cloudy summer week. This way of including DG generation should not be used by default, but it could be optionally selected. The usefulness of estimating the production in this way is pretty limited since even if the load flow becomes more accurate, it might not be interesting to network operators. It could however provide some insight into possible situations where the production of electricity at customers would be higher than their consumption. This situation could occur during sunny summer days, for example. The realistic production peaks have to be also considered in network planning in order to ensure that LV networks will tolerate the production.

5.2 Improvements to switching planning

As the amount of DG in distribution networks is increasing, the importance of noticing backfeedings and the importance of LV switching planning is increasing. The needed changes to switching planning were discussed in the customer interviews and one important issue is that the switching planning in LV networks is not on the same level as MV switching planning. For example, the automatic sequence creation is not implemented in LV networks, which is a crucial functionality from the user’s perspective.

5.2.1 LV switching planning

The main improvement that is needed to LV switching planning is the automatic sequence creation, that is already available in MV switching planning. The planning should also be able to handle all the necessary steps, such as earthing, when small scale generation exists. In Figure 20, an example of a switching plan with the necessary steps is presented, when the outage area contains an LV generator.

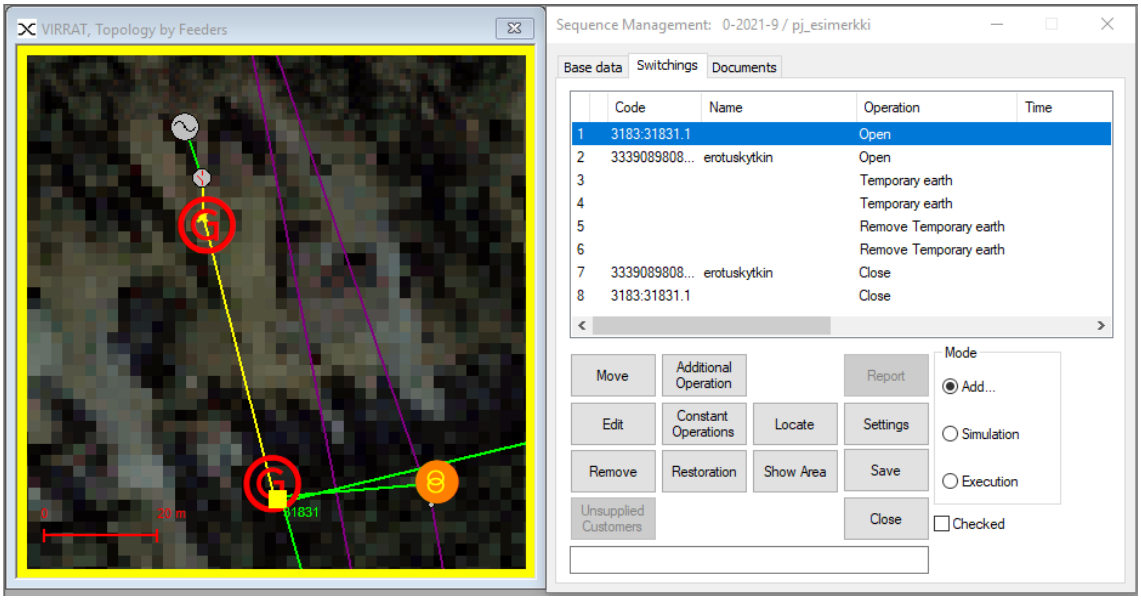


Figure 20 *Switching plan with the required actions in an LV network when the section contains an LV generator*

In this situation, the work location should be disconnected and grounded from both of the possible feeding directions. This means that the groundings should be placed near the LV and at the customer point. In practice, the point where the customer is disconnected, is the switch of the DG system. For this reason, the LV switch mentioned in section 5.1 should be supported as a possible way of documenting customer systems. It is also already possible, to add a temporary line cut to the section, instead of using the LV switches. This could be used when the DSO does not want to document the customers' switches into their network.

5.2.2 MV switching planning

The main DER related improvement to MV switching planning is also related to the automatic sequence creation. As all of the possible backfeeds have to be considered in the plans, DMS600 should automatically disconnect them and add earthings to the possible feed-in directions, as brought up in the user interviews. In Figure 21, an MV switching plan and the automated sequence is presented for an area that contains DG. The outage location is exactly the same as presented in Figure 15, and it is clear that the addition of DG in the network had no effect on the automatic sequence.

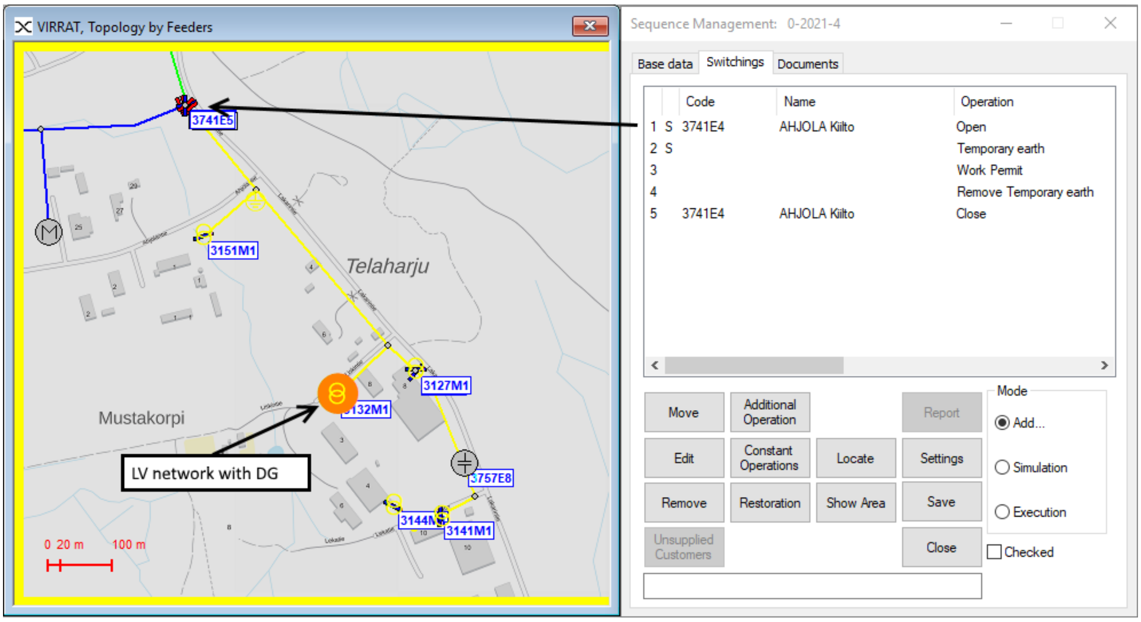


Figure 21 *Current operation of the automatic sequence generation in an MV switching plan*

Even though DMS600 does not include the LV network with DG in the sequence, it is still possible of backfeeding the MV network. The disconnecting of the DG sites should be done as close to the secondary substation as possible. An ideal location would be the MV switch of the substation, if that exists, but also LV side switches would work. The switch or switches that are disconnected should be the most upstream switches in the LV network, to reduce the number of needed actions. The desired switching sequence of the previous example is shown on the in Figure 22.

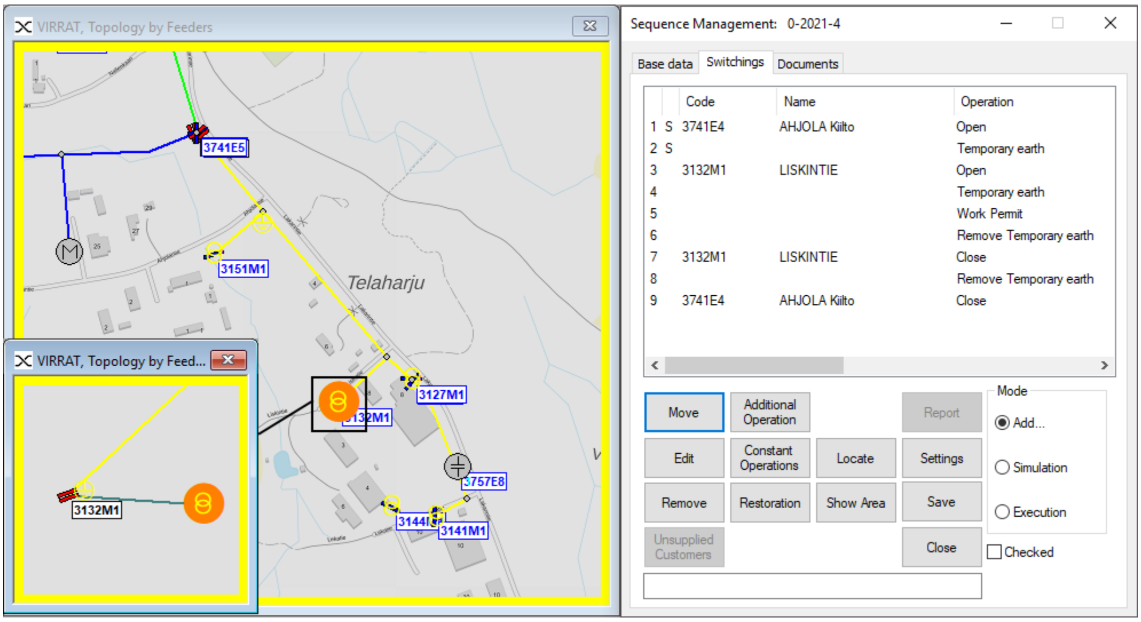


Figure 22 *Proper switching sequence with the possible backfeeds disconnected and earthed*

6. SIMULATION OF EV EFFECTS

The impact that EVs will have on the power system was recognized as a risk in each of the customer interviews, and it was acknowledged that the tools for modeling DER effects are quite limited at the moment. Therefore, a simulation tool for analyzing EV impacts could be useful to find possible bottlenecks in the network. In this chapter, a prototype for simulating the effects of EV loading is introduced. The tool is an integrated part of DMS600 NE, and its purpose is to test the possibilities of EV simulation in the product.

In order to simulate the effects EVs in the network, a loading profile for the EVs must be created and the EV loads have to be inserted to the network model. Afterwards, the existing calculations of DMS600 NE can be used to analyze the effects and identify network violations such as voltage violations and overloading. The methodology of how the EV load model was created and used is presented in this chapter. Also, the simplifications made are discussed along with possible improvements.

6.1 EV load modeling background

In order to model EV charging, the following things have to be considered:

1. The penetration rate of EVs
2. Battery state-of-charge (SOC)
3. Charging power
4. Time of charging.

The penetration rate of EVs changes over time, so it will be given as parameter by the user. This way the user can freely try out different situations. The battery SOC is what sets the limit for the energy that can be charged into the battery when the vehicle is parked to a charging location. This is connected to the vehicle's battery capacity, electricity consumption and driving patterns. The charging power is a property of the charging station and in this work is assumed to be constant, even though it changes according to the battery's SOC. The time of charging is completely related to the driving patterns of the vehicle. The battery capacity and energy consumption can be selected based on the median values presented in chapter 2.2.1. The average value of battery capacity for PHEVs is 15.2 kWh and the average range is 44.5 km, which results in an energy consumption of 0.27 kWh/km, when the all-electric range of the EV is assumed to be until 20% SOC before the ICE kicks in. Similarly for full EVs, the energy consumption is 0.21

kWh/km. Many studies use values 0.15-0.25 kWh/km for full EVs and values 0.15-0.30 kWh/km for PHEVs [35-38].

One way of modeling charging habits is to utilize data from travel surveys such as the Finnish National Travel Survey (NTS) [35-37, 39]. The data includes detailed data about the type of trips that people drive and how often. For example, the average distances of trips from home to work are available as well as the common times for such trips. With this data, the battery SOC can be approximated based on the distance driven and the average energy consumption of the vehicle. The information of the starting locations and the destinations can be used to correctly point the charging to the correct customer load with the time of the trip and the charging power determining the hourly load. The driving patterns should be quite realistic at least for PHEV drivers, as they can be used in the same way as traditional cars.

With the available information of driving habits and car properties, a model for the EV charging can be done. Since DMS600 NE uses load curves in load flow calculations, the EV effects should also be modeled in load curves. In [35], a method to producing such load curves for PHEVs was presented. The method took into account the differences between summer and winter seasons as well as the different days of the week. In *Figure 23,* a load curve from [35] is presented for home charging with 3 kW charging power. The load curve is made by lumping all of the PHEVs in the area together.

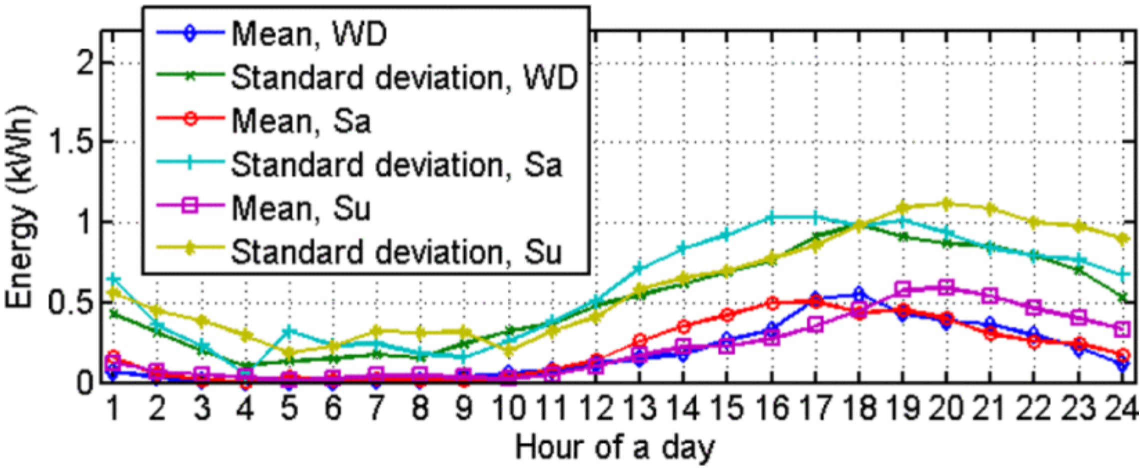


Figure 23 *Mean values and standard deviations of cars which are owned by people living in detached houses or semi-detached houses with a 3 kW charging power for winter workdays, Saturdays and Sundays. [35]*

When considering calculations in DMS600 NE, the above load curve has the problem that even with the mean and deviation values summed together, the value never reaches the actual charging power that is 3 kW. This is due to the curve including a lot of cars that are not charging at the time. This would lead to load flow calculations that represent the total energy consumed by the fleet of PHEVs, but it loses the actual peak power of the charging that is 3 kW. Without the actual loading peaks, some local network violations, such as voltage violations and overloading, close to the customer could be missed. When considering the secondary substations and the MV network, the lumped model probably offers quite realistic results.

6.2 EV load data generator

The EV load curve was generated for the prototype in a C# program that utilized 25 PHEVs as objects and modeled their movement. The basic principle is to track the charge of the vehicles' batteries as they move and calculate the amount of energy charged into the batteries while the car is parked at home. The output of the program is a .csv-file with 8760 hourly values for the charging of each vehicle. Among other simplifications, the vehicles are only charged at home in this prototype.

The program uses static properties that are based on the Finnish NTS data for the whole country as well as the car properties that were discussed in 6.1. These properties are presented in Table 3.

Table 3 *Properties used in EV modeling*

Property	Value	Note
Battery capacity	15.2 kWh	Same capacity for each vehicle
Consumption of energy	0.20-0.30 kWh/km	Varied between the vehicles
Charing power	3 kW	Same for each home
Length of trips	16-26 km	Separate values for different days of the week, same for all vehicles
Duration of trips	21-28 minutes	Separate values for different days of the week, same for all vehicles
Times of trips	hours 05-21	Varied between the vehicles

The driving patterns and the generation of hourly load data are explained in detail in the following chapter. An overview of the creation process of load curves is shown in ***Figure*** 24.

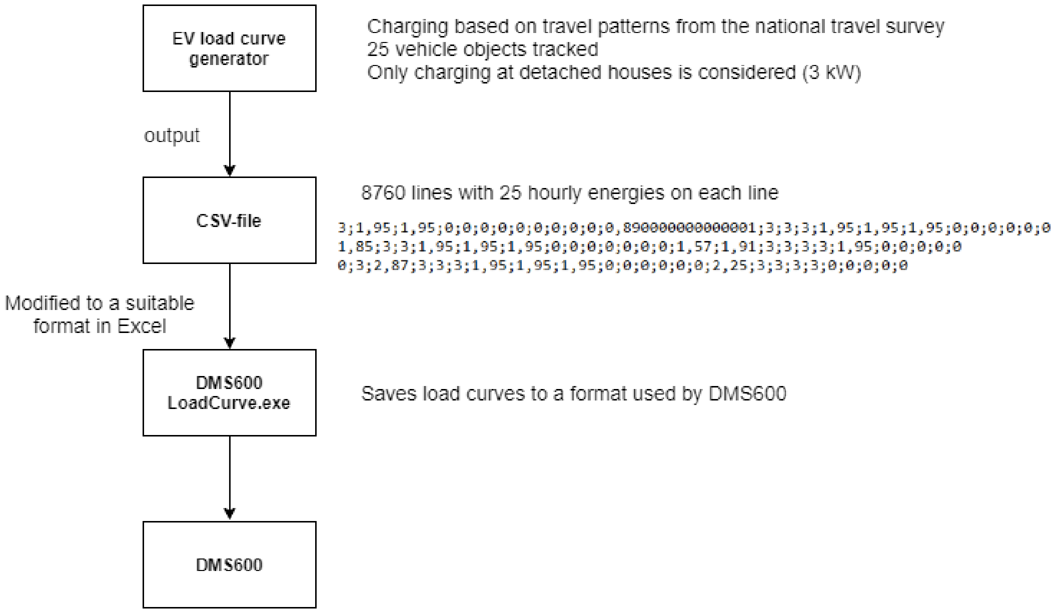


Figure 24 *EV Load curve creation process from the C# program to DMS600*

6.2.1 Driving patterns

Each car was assigned in total four departure times to model trips during workdays and weekends according to NTS data. The temporal distribution of trips during workdays and weekends, with no separate data for Saturdays and Sundays, is shown in Figure 25. The data is not clear on where the trips start from and where they end, but it can be assumed that it contains trips that both depart from home and arrive at home. It can, of course, also include trips that go from work to the grocery store for example, but those are not considered in the prototype.

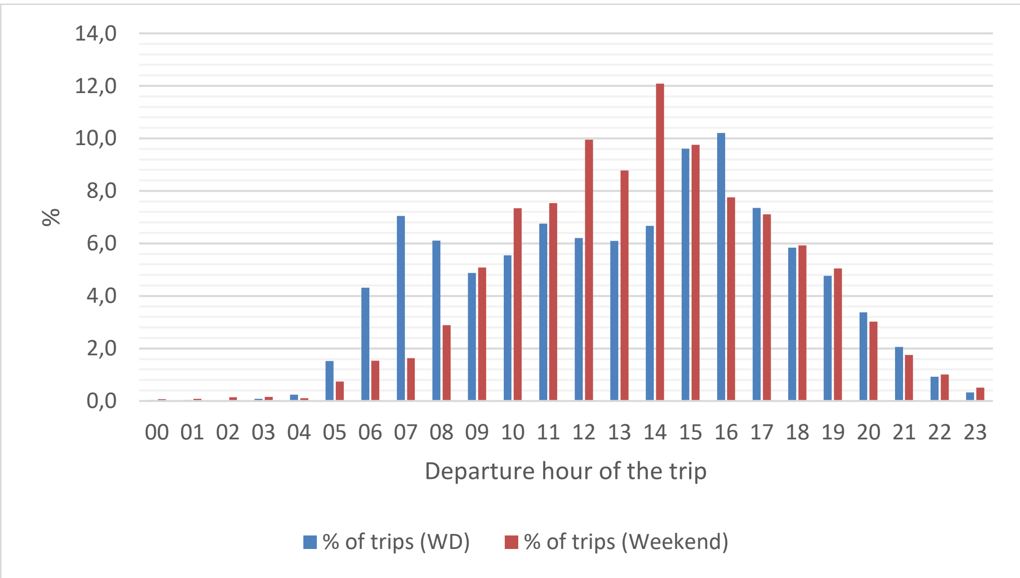


Figure 25 *Temporal distribution of trips during both workdays and weekends based on NTS data on passenger vehicles [40]*

The 25 car objects that are used in the simulation are considered to only drive two trips during a day, one that departs from home and one that arrives at home. This amounts to 50 trips driven each day, and the approximate temporal distribution can be achieved by dividing the percentages presented in the figure above by two. The departure and arrival times of the cars were then set to sum up to the corresponding numbers of the distribution for each hour. The departure times to work and from work were separated by the average length of a workday. A car that departed from home between 07:00 and 08:00, for example, is set to leave work at 16:00. This gives an OK approximation for the schedule of work related trips.

The rest of the trips were then filled in based on own experiences and assumptions, since the survey data had no exact data for the different kinds of trips for each hour, when considering passenger vehicles specifically. There is, however, data available on how the number of different trips is distributed among drivers of passenger vehicles as well as data about the length and duration of such trips. This data could be used in a more used to make the approximations more accurate but was left out from this prototype for simplicity reasons.

6.2.2 Generating hourly load data

With the departure times set for each vehicle, the program iterates through each hour of the year. If the hour is the same as the set departure time from home for the vehicle, its battery will be drained by the average length of a trip. Since only charging at home was considered, no charging happens after the car reaches its destination. Then again when it is time for the vehicle to depart to home, the battery will be charged. If a car leaves at for example 16:00 and the average trip duration is 30 minutes, the battery will be charged for 0.5 times the charging power during that hour. The charged energy is saved into a data storage that contains 8760 values for each car. These are then written into a .csv-file that is further modified to a format that can be imported into DMS600 Load Curve editor. The result of lumping all of the vehicles together into an averaged curve, is shown in Figure 26.

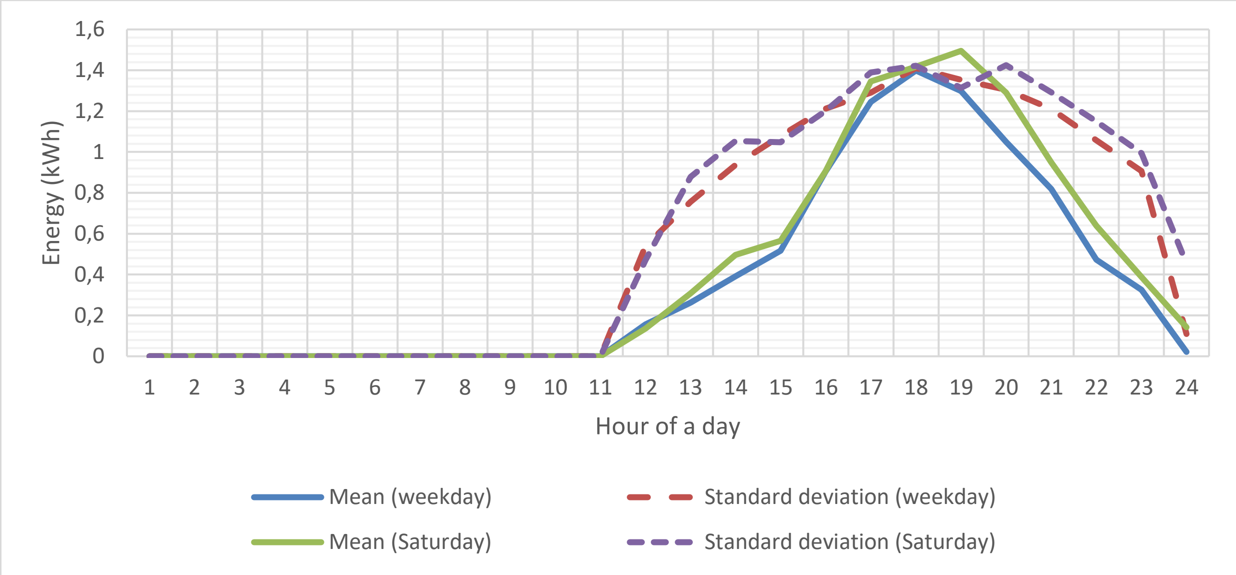


Figure 26 *Lumped PHEV load curve for home charging with 3 kW power*

When comparing the load curve above, to the one presented in Figure 23, we can see that the peaks are higher but there are also more hours with no charging at all. When creating the temporal distribution for the vehicles, the earliest arrival time at home was set to 11. Obviously, no charging can therefore happen before 11:00, which leads to the standard deviation being zero as well. The peak loading happens at 18:00 on weekdays, which seems plausible, since people coming from work between 15:00 and 18:00 could all be charging during that hour.

6.3 Simulating EV effects in DMS600

The prototype is programmed with C++ into a product branch that includes a recent version of the core product as well as the congestion management functionalities made by Janne Kuovi in his master's thesis [33]. The user can give the wanted penetration rate as parameter and insert the EV loads into the network model. The simulator also includes a violation list that is slightly modified from the congestion management functionalities, to help compare the violations found in the network before and after inserting EV loads. The starting dialog of the prototype is shown in Figure 27.

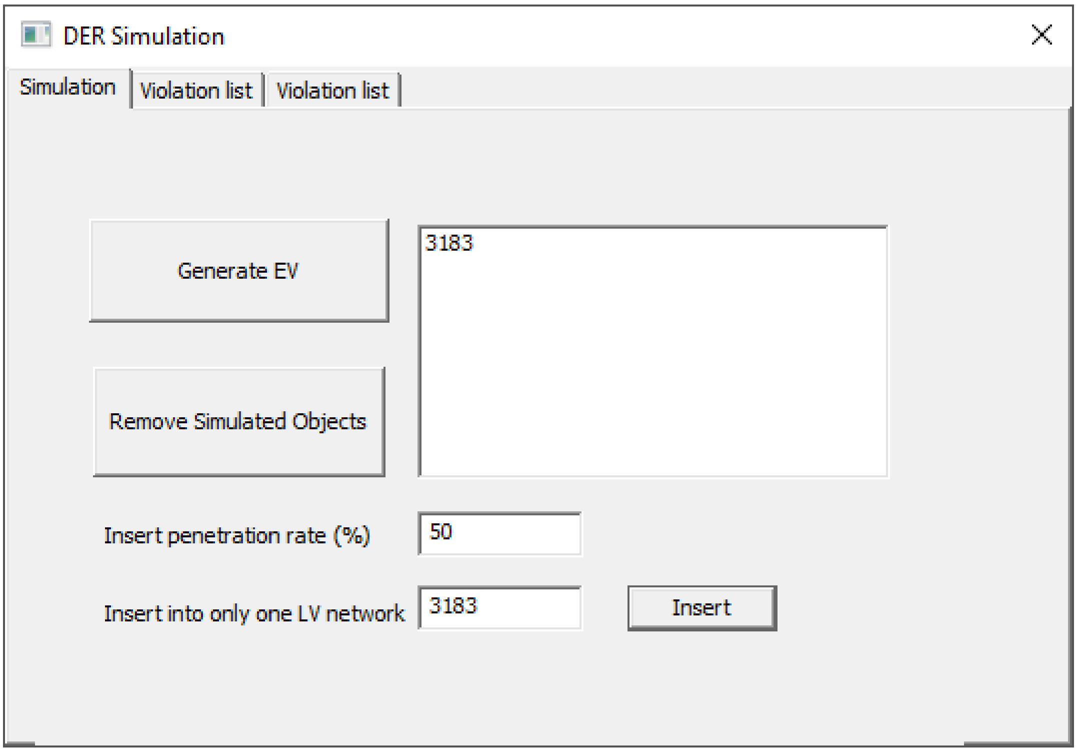


Figure 27 *Simulator starting dialog*

The button “Generate EV” inserts new EV nodes based on the given penetration rate into the whole network, whereas the “Insert” button below can be used to insert EVs only into the given LV network. The dialog also lists affected LV networks. The insertion is done with a pseudo-random selection of the customer nodes, using a static seed number for repeatability. This means that using the same penetration rate will always result in the same customer nodes being affected by the EV loads, unless changes are made in the database.

6.3.1 Inserting EV loads into the network

With the modeling of EVs done in the load curves, the effects can be analyzed in DMS600 NE by creating new LV customer nodes with the new load curves and yearly energies that match the driving patterns. The insertion of new loading points can be done by inserting the new sections and nodes into the SQL database.

The EVs are modeled as separate nodes so that no changes have to be made to existing customers, their yearly energies or their load curves. Since the average length of a trip made by a passenger vehicle’s driver is 18.9 km and the driver makes two trips per day, the yearly energy amounts roughly to:

$$365 \cdot 2 \cdot 18.9\ \mathrm{km} \cdot 0.27 \frac{\mathrm{kWh}}{\mathrm{km}} \approx 3725\ \mathrm{kWh}$$

The simulated nodes are inserted right above the original nodes with a line section connecting them, as is demonstrated in Figure 28. This way of modeling the EVs lets us analyze the load flow of the original node and the simulated node both together and separately. For the sake of implementation, it also makes removing the new components easy.

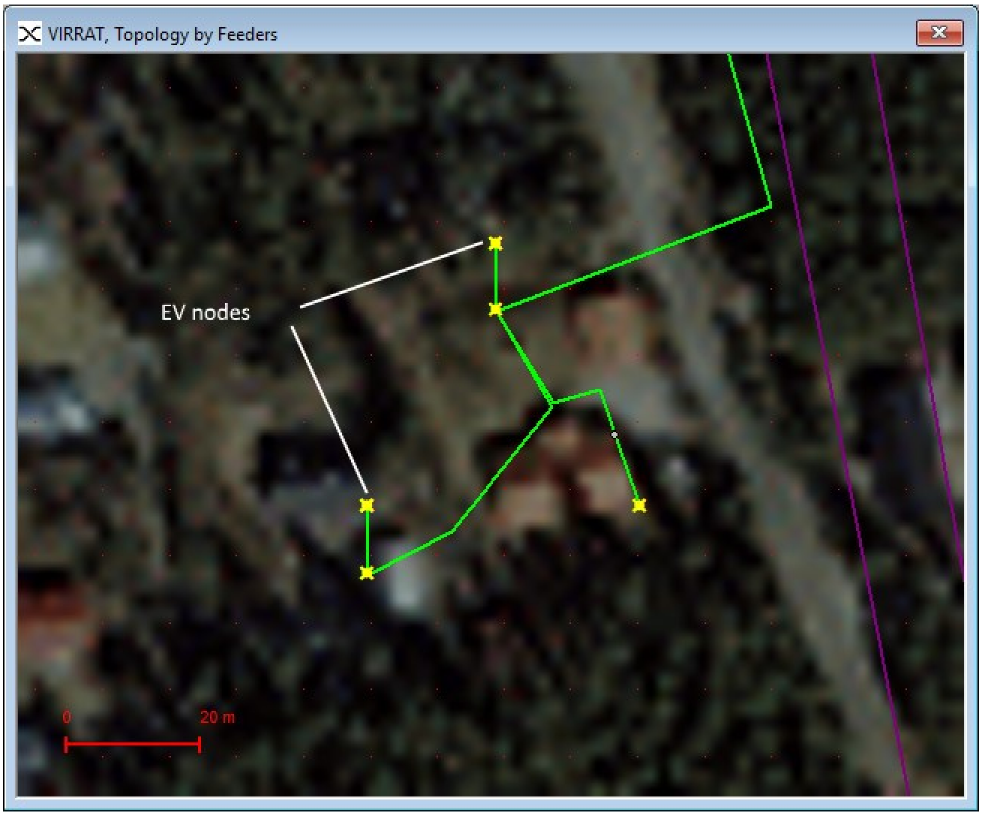


Figure 28 *Example of simulated EV nodes connected to existing customer nodes*

The amount of EVs inserted into the network depends on the penetration rate given by the user. In this prototype, only typical detached houses are considered, and the penetration rate is also a percentage of the detached households and not related to the total amount of cars found in the network area. The possible customers for the simulation are selected based on their fuse size. If the customer node's fuse size is 25 A or 35 A, it is considered to be a detached house, as those are the most common fuse sizes in Finland for such households. When creating the simulation objects, the EVs are assigned randomly, though repeatably, to the detached houses, until the amount of EVs matches the wanted penetration rate. After inserting the loads, the binary database has to be updated to update the loading of the secondary substations. Then the load flow calculations will show updated results in the MV network.

6.3.2 Violation list

In order to easily see differences between the scenarios, a violation list is included. Some of the data fields used in the original violation list are not needed in NE, because the network calculations are always based on the peak hours of the component and therefore the calculation hours are not needed. The same principle is still applicable in this prototype in finding network violations present in the MV network. The list is shown in Figure 29.

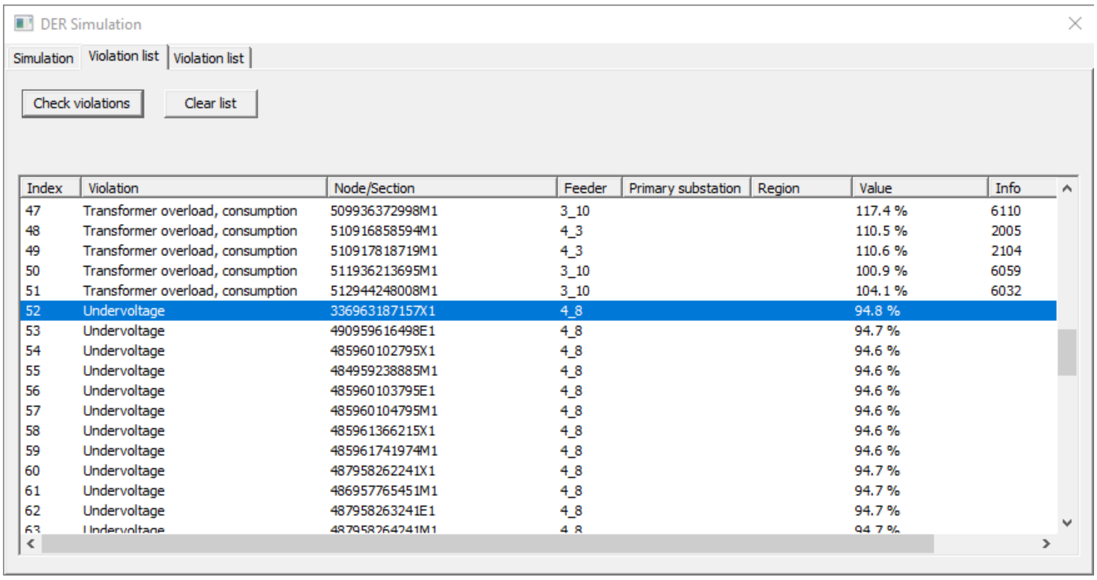


***Figure 29** Violation list*

With two of these tabs side-by-side, it is easy to compare the calculation results between two calculation scenarios. One window can, for example show the violation results of the normal situation, as the other window shows the results for the simulated scenario. The number of violations can then be compared to quickly notice new violations. In addition to more detailed information available in NE, this gives the user a quick summary of the network violations found. Also, by double-clicking the selected violation, DMS600 zooms into that component.

6.4 Analysis of the simulator

In this chapter, the simulator is tested with penetration rates in 10 % steps and the results are analyzed. Thorough analysis is only done for a penetration rate of 30 %. These results are compared to the basic case with no EV loading. The network model used for testing is the usual DMS600 demo environment shown in Figure 30.

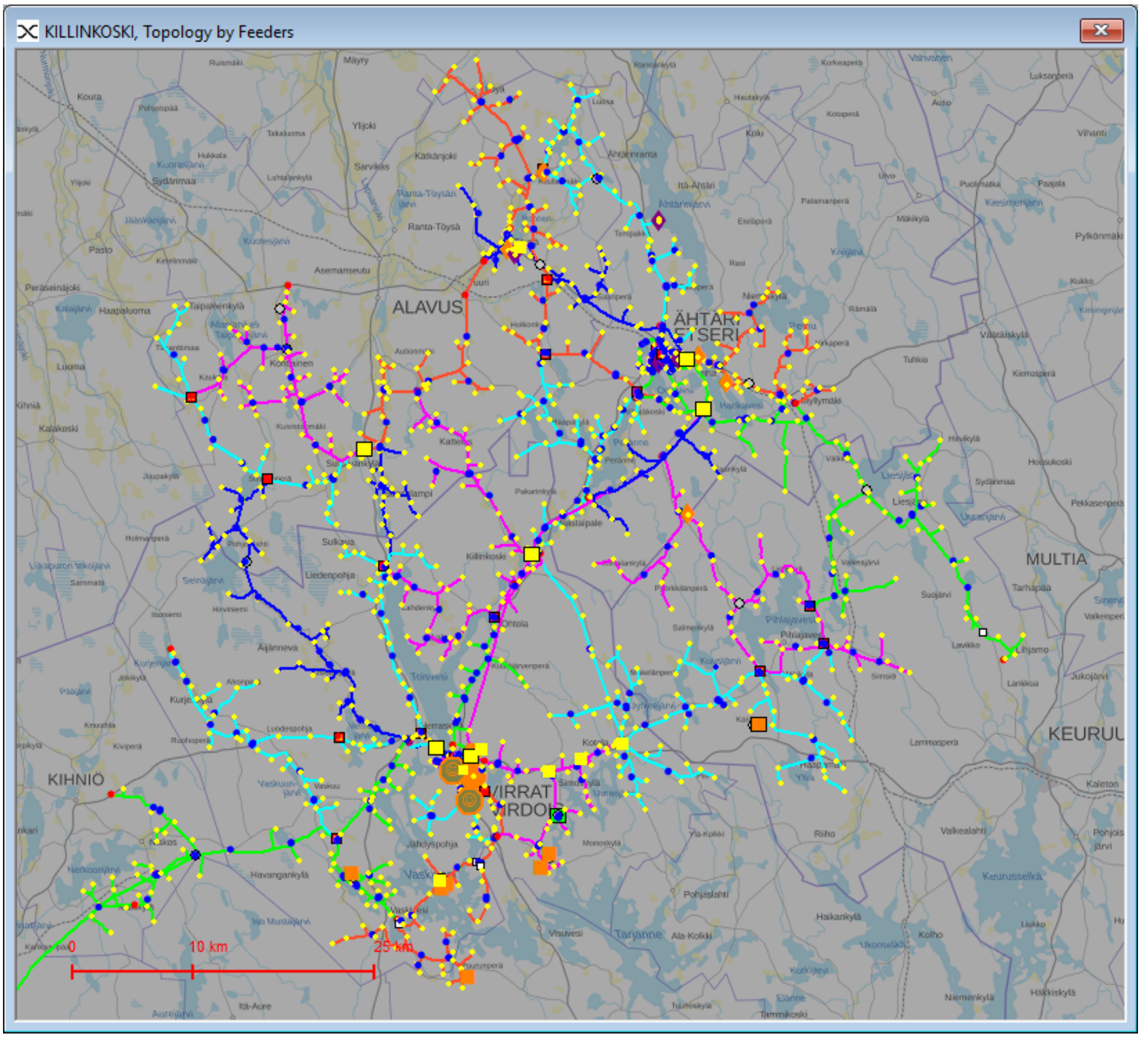


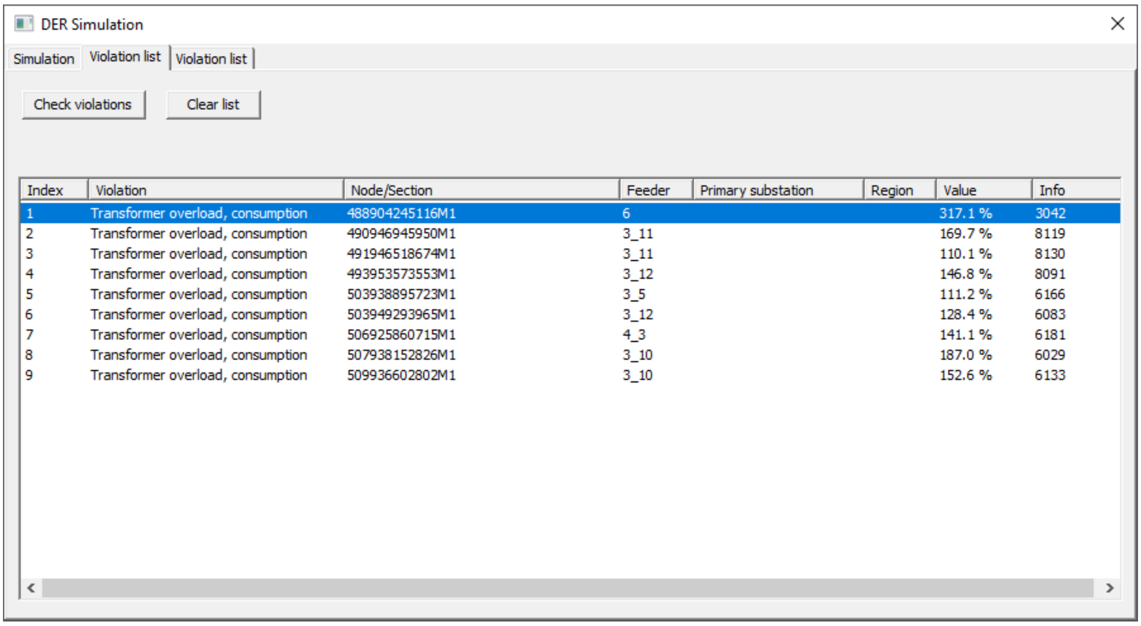
Figure 30 *Overview of the demo network*

The violation limits that are used in the test are shown in Table 4. The voltage limits are arbitrarily chosen to be ± 5% for demonstration purposes.

Table 4 *Violation limits used in the test*

Violation type	Value
Over- / undervoltage	± 5% of busbar voltage
Transformer loading	100% of the nominal power
Line loading	100% of the maximum loading current

The violation list of the basic case can be seen in Figure 31. The only violations present are some transformer overloads, and the total number of violations is 9. This can be used as a benchmark for the other test cases when comparing the results.

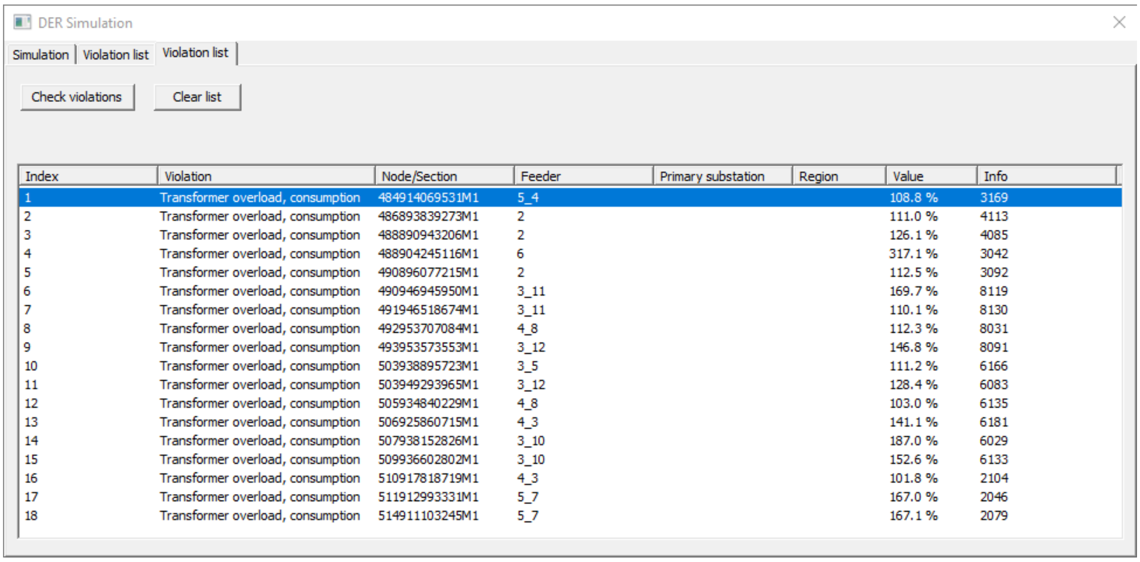


Index	Violation	Node/Section	Feeder	Primary substation	Region	Value	Info
1	Transformer overload, consumption	488904245116M1	6			317.1 %	3042
2	Transformer overload, consumption	490946945950M1	3_11			169.7 %	8119
3	Transformer overload, consumption	491946518674M1	3_11			110.1 %	8130
4	Transformer overload, consumption	493953573553M1	3_12			146.8 %	8091
5	Transformer overload, consumption	503938895723M1	3_5			111.2 %	6166
6	Transformer overload, consumption	503949293965M1	3_12			128.4 %	6083
7	Transformer overload, consumption	506925860715M1	4_3			141.1 %	6181
8	Transformer overload, consumption	507938152826M1	3_10			187.0 %	6029
9	Transformer overload, consumption	509936602802M1	3_10			152.6 %	6133

***Figure 31** Violations present in the network before adding EV loads*

6.4.1 MV network analysis

In the first test case, a penetration rate of 30% was used and EV loads were inserted into the whole network. This value leads to the insertion of 2590 cars among a total of 15 892 customers. The total number of LV networks affected by the addition is 838 out of 1029, which means that load points where indeed scattered around the network, so there should not be large clusters of vehicles in many of the LV networks. Compared to the case with no added EV loads, the number of violations doubled up to 18, as shown in Figure 32. Again, all of the violations were transformer overloads.



Index	Violation	Node/Section	Feeder	Primary substation	Region	Value	Info
1	Transformer overload, consumption	484914069531M1	5_4			108.8 %	3169
2	Transformer overload, consumption	486893839273M1	2			111.0 %	4113
3	Transformer overload, consumption	488890943206M1	2			126.1 %	4085
4	Transformer overload, consumption	488904245116M1	6			317.1 %	3042
5	Transformer overload, consumption	490896077215M1	2			112.5 %	3092
6	Transformer overload, consumption	490946945950M1	3_11			169.7 %	8119
7	Transformer overload, consumption	491946518674M1	3_11			110.1 %	8130
8	Transformer overload, consumption	492953707084M1	4_8			112.3 %	8031
9	Transformer overload, consumption	493953573553M1	3_12			146.8 %	8091
10	Transformer overload, consumption	503938895723M1	3_5			111.2 %	6166
11	Transformer overload, consumption	503949293965M1	3_12			128.4 %	6083
12	Transformer overload, consumption	505934840229M1	4_8			103.0 %	6135
13	Transformer overload, consumption	506925860715M1	4_3			141.1 %	6181
14	Transformer overload, consumption	507938152826M1	3_10			187.0 %	6029
15	Transformer overload, consumption	509936602802M1	3_10			152.6 %	6133
16	Transformer overload, consumption	510917818719M1	4_3			101.8 %	2104
17	Transformer overload, consumption	511912993331M1	5_7			167.0 %	2046
18	Transformer overload, consumption	514911103245M1	5_7			167.1 %	2079

***Figure 32** Violations present in the network with a 30% penetration rate*

Among the new violations, there are various kinds of LV networks involved. It is worth noting, that some of the secondary substations were at remote locations with summer cottages as loads, and therefore a low total loading. An example of a remote LV network and the effect of PHEV loads in it is demonstrated in Figure 33. The peak charging power of the EV loads is 3 kW, when the statistical factor is used, and the deviation is included. Even though the yearly energy of the inserted models does not match the realistic situation at summer cottages, the effects of EV charging can be observed, because the peak power of EV charging used by NE matches a realistic charging power. Since the charging power of roughly 3 kW can be achieved from a standard Schuko socket, a situation with 4 vehicles charging around the same time even at a remote location could be possible. Such a situation could occur during the Midsummer Day for example, when many people gather at cottages. In weak LV networks like this, the effect of even a few EVs can be drastic, as seen from the differences in the peak load of the network.

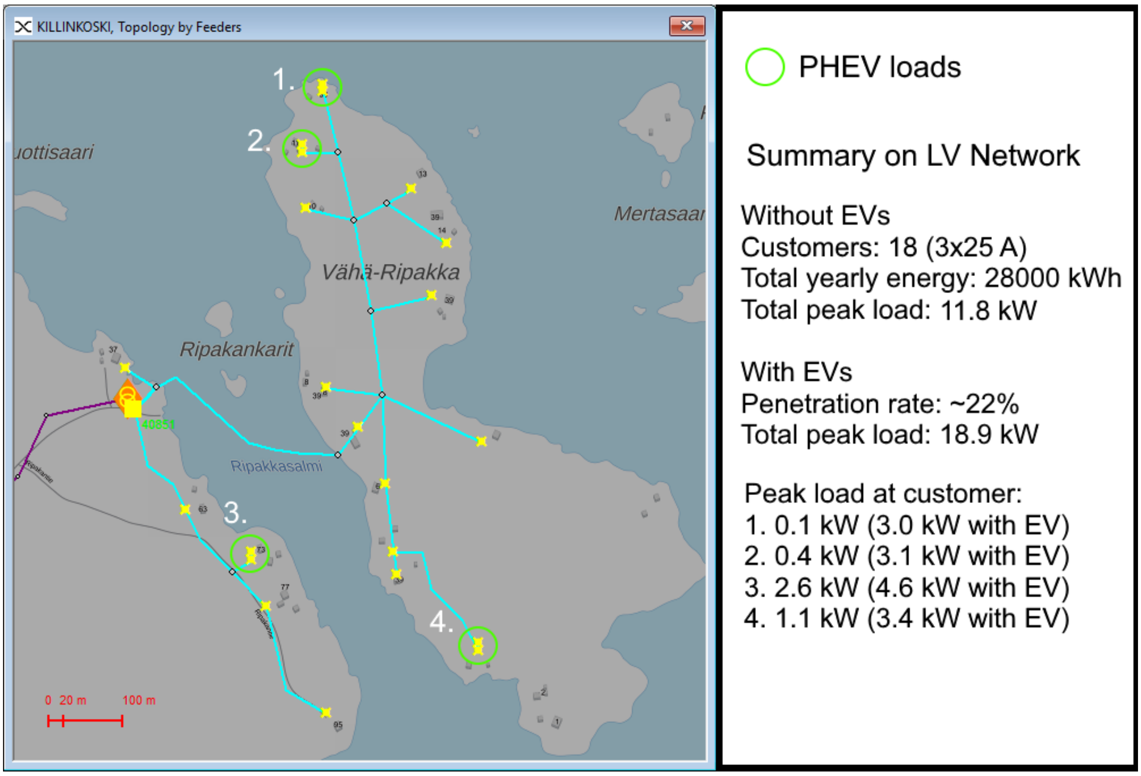


***Figure 33** Summary of a remote LV network with inserted PHEV loads*

It is quite natural that these kinds of LV networks appear on the violation list since they are not designed for such loads. To ignore small customer points, such as summer cottages, the inserting of the new loads could also consider the yearly energy of the original customer node. A typical yearly load for a detached house with no electric heating is around 5000 kWh [41]. A limit could be set to only consider customers with a yearly energy of over 4000 kWh, for example.

In addition to the secondary substations with low loading, the inserted PHEV loads also affected more typical LV networks. For example, LV network 6135 with 14 customers and a peak load of 46.9 kW without EV loads became overloaded after only one new EV load was inserted. Therefore, this simulation could be useful in detecting networks with little capacity for new loads, though due to the randomness of the simulation not all cases will be noticed easily. After detecting a problematic LV network, the effects of EVs can be further analyzed by inserting loads in that network only. An example of the effect of EV loads on the voltage drop of the aforementioned network is presented in Figure 34.

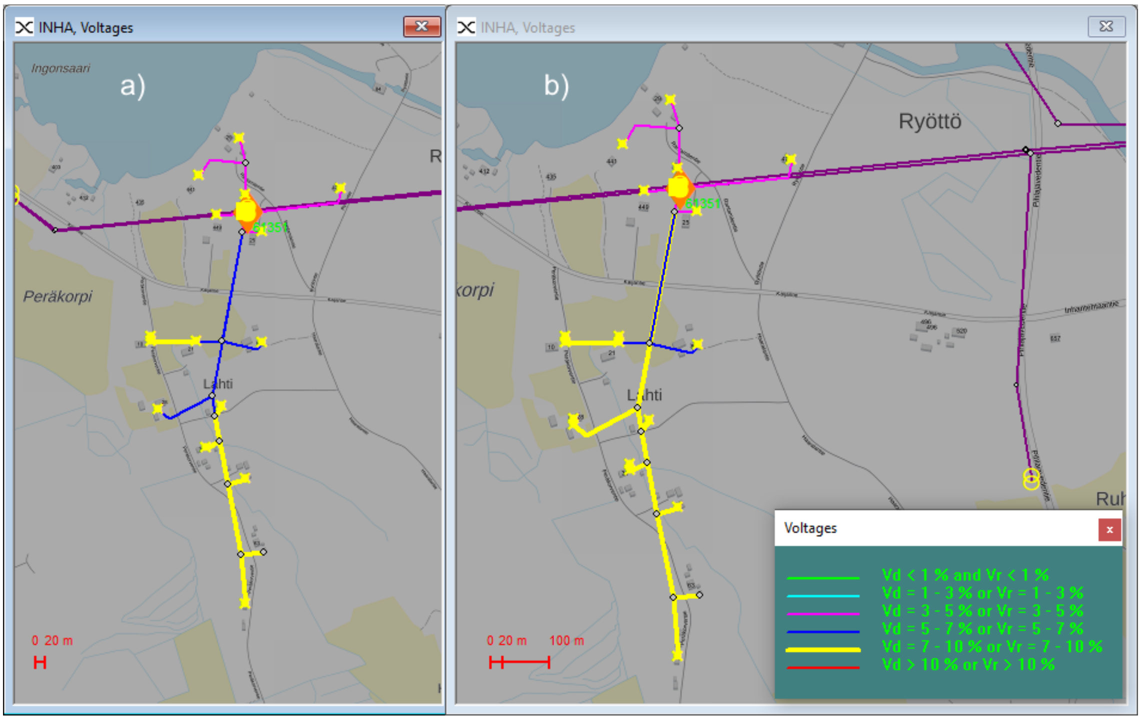


***Figure 34** Effect of EV loads on voltage drop with a) 10 % and b) 30% penetration rate*

Since the network was almost overloaded even without the addition of EV loads, the voltage drops are rather high even with a 10% penetration rate. The addition of three more EV loads still led to more voltage drops of over 7%, which is quite high even though allowed.

6.4.2 Effect of EV loading in an LV network

While the transformer overloads can be detected by using the violation list, there can be problems in the LV networks even without the transformer overloading. Adding EV loads can lead to line overloads and excess voltage drops even if the transformer has ample capacity for extra loads. In Figure 35, the voltage drops, and line loading are presented for an LV network that contains many detached houses.

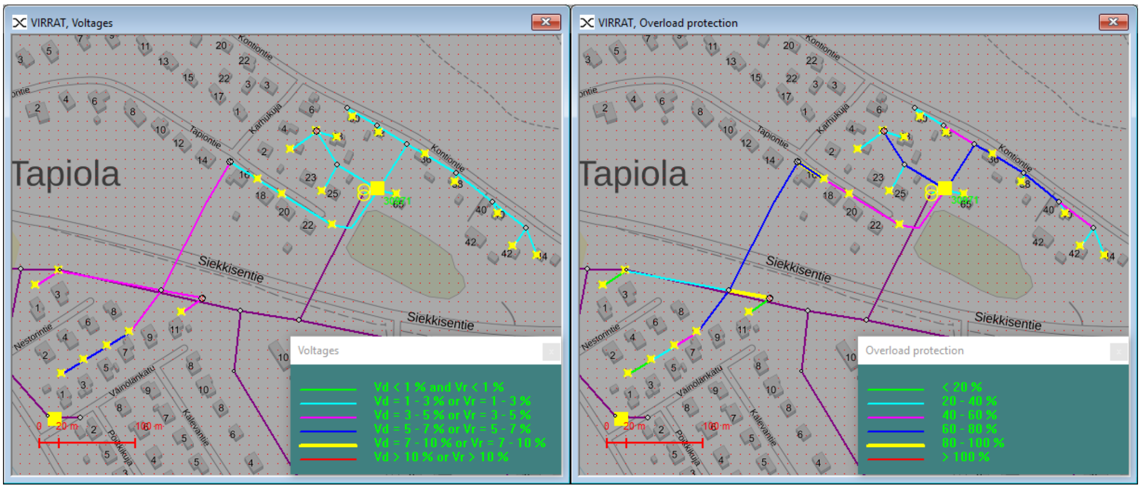


Figure 35 *Voltage drop and loading of an LV network containing many detached houses but no EV loads*

The transformer is rated for a load of 200 kVA and the peak load is 79 kW, so it is not even close to being overloaded. Also, no line section is loaded for over 80% of its rated capacity. The situation after adding EV loads to 30% of the houses, is presented in Figure 36.

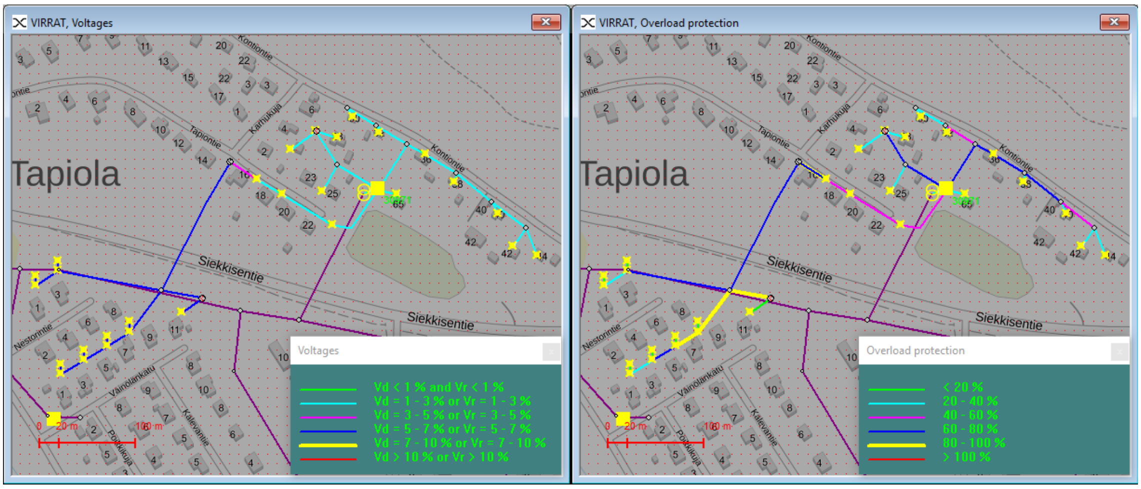


Figure 36 *Voltage drop and loading of the example network after adding EV loads*

The EV loads are centered around the left-hand side of the network and the loading of the lines is near the 100% capacity. The yellow coloring on the right-hand side of the figures means that the line loading is at 80-100% capacity. The peak load of the network is now 89 kW, which is still well below the transformer limit. While no absolute limits were breached in this case, it is clear that line loading can be an issue when EVs are added to the network.

6.4.3 Summary of results

After adding the EV loads into the demo network, it is clear that especially transformer overloads are possible with even low penetration rates. The effects were simulated with different penetration rates in 10% steps and the results are shown in Figure 37. The results also include the nine transformer overloads that were present before adding any new loads. The first new violations occurred at 20% penetration rate resulting at a total of 11 transformer overloads. The first undervoltage of over 5% occurred with a 70% penetration rate but it is worth noting, that the voltage drop increases quite linearly based on the increased load and there is no sudden voltage drop. In the worst case, 256 line sections had a voltage drop of over 5%, compared to the total amount of 4340 line sections. All in all, the amount of voltage violations was relatively small, and they occurred on long feeders at the edges of the network.

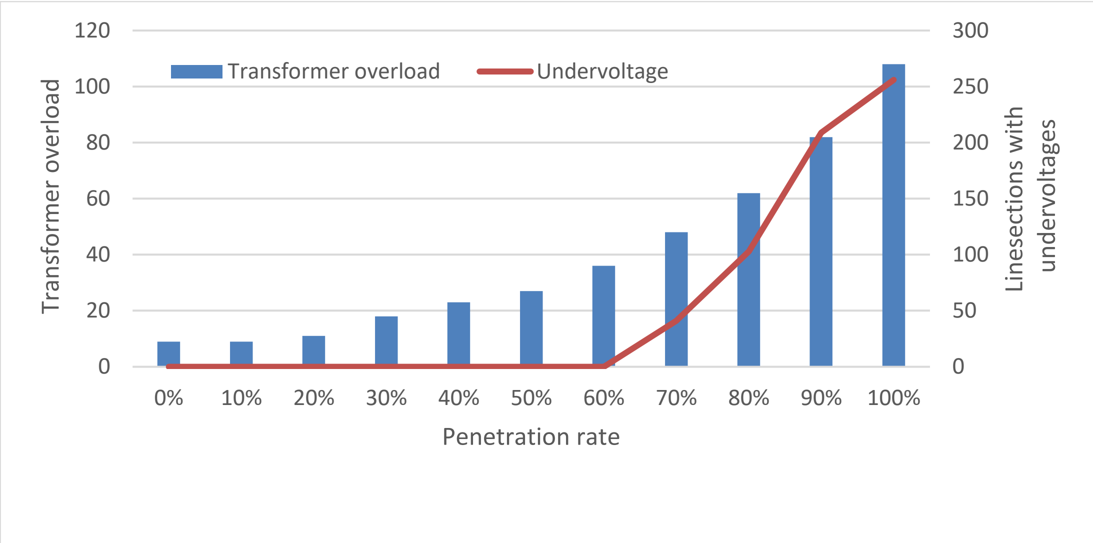


Figure 37 *Network violations by penetration rates with a total of 1029 transformers and 4340 line sections*

In this test, no line overloading was seen. The largest voltage drop was 6.1 % with 100% penetration rate, so it is safe to say that the voltage drop is within allowed limits presented in section 2.3.2. The transformer overloading could be a costly issue however, if many transformers have to replaced. It is also worth noting, that some transformers have a low tolerance for new loads, and the detection of overloads depends on the randomized insertion of loads. For example, the network 6135 which was also brought up in the previous section, first appeared on the violation list at a penetration rate of 30%, even though only one EV load was necessary to overload it.

The above analysis only considered the MV network. For LV network analysis, no functionality is available that generates a summary for all networks, which means that each

LV network has to be analyzed separately. Such a functionality would be necessary since the MV network violations do not completely correlate with possible violations in LV networks and testing different scenarios in every LV network would be very time consuming. On the other hand, running a simulation on each LV network would also be slow and the nodes to which the EVs are added into the networks would have a clear impact on the violations that would appear. After simulating every LV network, the best evaluation of impacts could be made by a user inspecting the situation.

Another problem with the simulation is the used pseudo-randomness of the EV load insertion. There are many different ways in which the EVs can be spread around the network and that obviously affects the results. By adding simulation rounds and using stochastic methods, such as the Monte Carlo simulation, more information about the spatial distribution of the violations could be gathered [39]. After running a lot of simulations with randomized spreading of EVs, detecting the most probable network violations would be easier.

7. CONCLUSIONS

It is inevitable that DER will be an integral part of most distribution networks. With the amount of DG such as wind and solar power increasing globally, and the necessity of, it is unlikely that a distribution network can be completely void of DER. In addition to generation, new kinds of loads will appear in the networks. Loads such as electrical vehicles, with different effects to the total load of the network. Also, the possibility of utilizing energy storages to support balancing the loading of the network as well as feeding unsupplied customers during outages may become practical in the near future.

The distributed generation of energy can reduce line losses as the energy is generated near its consumption, but too large production facilities can cause bottlenecks in the network. For example, over voltages may occur when the power starts flowing towards the primary substation. This can be noticed especially at the end of long feeders. This effect has been present in Germany for a few years already and has led to distributed generation being curtailed. Redispatching production facilities, as in temporarily shifting generation from one location to another, has been used to remove the bottlenecks such as lines being overloaded.

In addition to DG effects, the increased loading caused by EVs can lead to transformer overloading and increased voltage drops in the MV network as well as line overloading in LV networks. The increase of EVs is outpacing the target set in the long-term emission development goals and bottlenecks caused by EVs were recognized as a real threat in the user interviews. The lack of proper tools for analyzing DER effects was also brought up and therefore a prototype for simulating EV effects was created. The tool could also prove valuable outside of Finland as well since the EV market is quickly growing in the whole world.

The prototype for evaluating EV effects is made up from two parts. The first one is a C# program that models the hourly loads of different EV objects. The charging behaviors are estimated from driving patterns based on the national travel survey data. The load model was quite simplified as it was assumed that all charging happens at home, starting immediately after arriving, and all of the vehicles only visit one destination per day. Also, the EV parameters used in the modeling belonged to PHEVs, which would require daily charging. In the case of full EVs, the model might not be accurate as the battery capacity does not require daily charging, and the lack of an ICE might also affect driving patterns.

Overall, the resulting load curve can be used to roughly model the PHEV loads. The effect of fast charging stations was not in the scope of this thesis.

The second part of the simulator is the framework that was implemented into DMS600 with C++. The simulator is used to insert EV loads next to existing customers and then a violation list can be utilized to detect transformer overloads and excess voltage drops in the MV network. The loads are inserted to detached houses based on the fuse size of the connection point, but that is not a fool proof method since even summer cottages may have the same 3x25 A fuses.

The prototype shows that EV loading could be modeled in DMS600, but a lot of improvements would have to be made. Currently the EV load model is sort of a worst case scenario since all of the charging happens in the evenings and at home. In reality, workplace charging and smart charging should be considered, as it could remove a large portion of the required charging needs in the evening. People can also make multiple trips per day, and as a result the charging might not be constant from the time the vehicle first arrives at home, for example. Also, different charging powers should be included. In addition to adding variety to the EV model, the actual simulator should be improved. Currently there is no automatic way of analyzing LV networks and the users would have to identify problematic LV networks themselves. Also, the way EV loads are added to the network requires the binary database to be updated in order to calculate the load flow with new loads in the LV networks. This is unacceptable in a production environment since the simulated loads would be saved into the network model used by operators. Therefore, a simulation mode should be implemented into NE or a way to update secondary substation loading without updating the entire network model.

In addition to the prototype, also existing functionalities were looked at from the perspective of DER related challenges. Currently the way of documenting LV generators has some flaws and improvements were suggested to make it more straight forward, while addressing some issues related to load flow calculations. Switching planning also needs improvements related to the automatic sequence creation when DG is involved. Also, the importance of LV network management is increasing and switching planning should be generally improved on that voltage level.

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