Investigation of the current and future low voltage distribution network

A study what impact more renewable penetration will have on the current electrical system

Master's thesis in Electric Power Engineering

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Abstract

A rapid transition is taking place in the energy sector, where electric generation is shifted from large, centralized power plants to small distributed and renewable power production facilities. This transition is further accelerated by the European Union's ambitious package aiming to deliver a carbon-neutral European continent by 2050. To achieve this, the network operators have major challenges ahead where the low voltage distribution network who is responsible for delivering electricity to the end-users is no exception. The development of new solutions regarding technical, economic and regulations will play a key role in enabling this transition. The distributed system operators responsible for operation of the low voltage distribution networks have adopt to these changes to provide an electrical network for the future.

Important solutions will be smarter technical products that can utilize the current electrical system to allow for future development without massive investments in new infrastructure. This will allow the network to operate in a much more flexible way where flexibility markets will encourage and allow individual users to be part of the electrical market, not only as consumers but also as producers of electric power. Digitalisation of the electrical network aiming to better usage of electricity is also going to be essential to support a more flexible electricity network. The regulations currently in place also need to be updated to enable this future transition.

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Erik Andersson, Gothenburg, June 2021

Contents

Abbreviations

BEV - Battery Electric Vehicle
DSO - Distributed System Operator
EV - Electric Vehicle
HEV - Hybrid Electric Vehicle
PHEV - Plugin Hybrid Electric Vehicle
PV - Photovoltaic
SCADA - Supervisory Control and Data Acquisition
SOC - State of Charge
TSO - Transmission System Operator

1 Introduction

In the beginning of the twentieth century the rapid expansion of electrification in Sweden and Swedish households began. This process has formed much of the electrical system used today. Although many new technical innovations and solutions have been implemented the fundamental design is still the same. In fact, some parts of the electrical system have products that are over 100 years old but still to be found in operation [1], [2]. The electrical system has furthermore become a more important and essential part of our modern society.

With the introduction of more renewable energy generation new challenges have emerged for the electrical networks, as generation is shifted from large centralized production plants to small decentralized power generation sites such as wind or solar. A large portion of this shift is predicted to take place in the low voltage distribution network where individual customers will move from being regular consumers to also become producers of electricity. The low voltage distribution network is also facing new challenges with the predicted higher usage of electricity as an energy carrier where, for example fossil fuel vehicles are phased out in favour for electric vehicles which are going to rely on the low voltage distribution grid to re-charge. This renewable shift will change the low voltage distribution network design from only delivering power to also act as a unidirectional network, where individual users can be a part of the future global energy market, a new task for current DSOs. This transition is further accelerated in the EU where the European Commission has stated that the union should be climate neutral by 2050 [3]. A goal that will depend on the electrical system to future develop and implement new solutions.

This is one of the driving forces why ABB Electrification's business unit Kabeldon is interested in what the future market will expect in terms of product development and innovation. Kabeldon develops and manufactures mainly cable-cabinets and accessories for the distribution network industry, which are essential components for a reliable and safe network.

1.1 Aim

The objective of this master thesis is to investigate what future challenges the low voltage distribution will face, both in a technical, economic and regulatory perspective. The outcome will be an overall view which can help to highlight which areas that are going to be of importance in the future low voltage distribution network.

1.2 Problem under investigation

The purpose of this master thesis is to give a general overview of the current situation of the low voltage distribution network, where factors such as technical design and regulations will be investigated. Furthermore, the thesis will analyse the impact of more renewable penetration to the distribution network. More specific what impact new installations such as EV and PV will have on the current network and what products and solutions need to be considered in the future.

Moreover, the thesis will analyse the low voltage distribution network from a DSOs perspective where Swedish and European trends will be used. The thesis will not limit itself into a set future time span but will instead limit itself to already existing technologies and its known limitations.

The definition of the low voltage distribution network in this thesis corresponds to the equipment in the network with an operating voltage between 0.4 - 40 kV.

2 Theory

The implementation and design of electrical networks differs between nations around the world, although the main layout is based around a transmission network handling the bulk transfer of electric power inside or between countries and a distribution network responsible for connecting individual customers.

This master thesis will focus on the Swedish system which is divided into two main parts, the transmission network and the distribution network. The distribution network is further divided into two parts, the regional network and local network [4]. In this report the local network is referred to the **low voltage distribution network**.

- The transmission network use 400 or 220 kV and is operated by the Swedish TSO Svenska Kraftnät who have exclusive concession rights at these voltage levels.

- The regional network primary use voltage levels between 130 - 40 kV and is operated by different operators with concession rights to the specific line or area. These are used to connect the low voltage distribution and transmission networks together.

- The low voltage distribution network use voltage levels between 40 - 0.4 kV and is operated by a wide range of different operators with concession rights to the specific area. These networks are used to connect the end customers to the electrical grid. The primary voltage levels used in the Swedish low voltage distribution networks are 20, 10 and 0.4 kV, although exceptions do exist [5].

2.1 Electricity regulation

Around the world there exist many different types of regulations and technical solutions to distribute electricity, where it is common to find different kind of regulatory authorities in different countries. The electrical networks around Europe share many similarities in technology and especially regarding regulations. In general, each country has its own TSO as a result of natural monopoly. These operators are responsible for the bulk power transfer in the high voltage networks, some exceptions exist such as Germany who has four different TSO operators [6]. Historically the TSO's have enabled power transfer within the country itself. However with the deregulation of the power industry in Europe starting around the 1980-1990s, the TSOs play a key role in cross boarder power transfer and open electricity markets [7], [8].

Unlike the TSOs, the implementation regarding DSOs around Europe differs considerably between countries. In some European countries only one DSO will operate in the whole country, while in others multiple DSOs can operate different parts of the electrical network. An example of the later case is Germany who have 883 different DSOs while Ireland has only one. The reason for this is mainly due to historical aspects related to the beginning of electrification in each country [9]. A common characteristic with all DSOs is that they, like the TSOs, operate in a natural monopoly where capital intense investment is needed to an establish functional network [7]. Due to this fact and the regulations set by the European Commission, authorities in each country regulate this kind of operations. The regulations are mainly concerning the DSOs possibility to charge its customers as well as maintaining a high level of efficiency in the network. The main purpose of the regulations is to ensure the DSOs provide a non-discriminatory access to the network, meaning all users should have the same ability to connect and interact with the electricity market [10]. To enable the future of clean renewable solutions across the European continent, the EU is strongly involved in this sort of regulation with the main objective to enable homogeneous regulations across the union. This was recently updated in 2019, where many changes were made regarding regulations to adopt to the EU's new package regarding clean energy for all Europeans [10], [11].

2.1.1 Regulations in Sweden

As previously mentioned, the specific regulations differ between countries. The natural monopoly related to electrical networks in Sweden is regulated by the Swedish electricity law (sv. Ellag) 1997:857 for which the government agency Swedish Energy Markets Inspectorate (sv. Energimarknadsinspektionen) has the purpose of manage and monitor the different operators on the monopoly market [12]. As a result of the Swedish membership in the EU the agency's regulations and the Swedish electricity law is a direct consequence of the regulations set by the European Commission [10]. According to the law, Swedish network operators should operate their network in a secure, reliable and efficient way, furthermore the operators shall operate in an open, non-discriminatory and market-oriented way [12].

The Swedish electricity law regulates the network operators with two main types of concessions. These are concession for a line (sv. Nätkoncession för Linje) and concession for an area (sv. Nätkoncession för Område). The main difference between these two is that a concession for an area licence the operator to exclusively operate an electric network within that area, while concession for a line licence the operator the right to operate a specific line at a specific location. The different types of concession regulate other aspects such as what voltage level the operator is allowed to use [13]. One example of concession for a line is the Swedish TSO Svenska Kraftnät which has the exclusive concession rights to operate 220kV and 400kV networks, another example are the regional networks.

DSOs operate in most cases within their own concession rights for the area they are located within. This enables them to build their network more freely as they are not required to seek new concession rights for changes made to the network. This might include new cables or lines that are built within their operation. The concession right itself is further more followed by rules that defines the maximum voltage level that line or area can operate within. A typical example of this is Göteborg Energi for which their area-concession enable them to exclusively operate a distribution network with a voltage level up to 20 kV in the Gothenburg region, but require them to apply for individual line-concession rights for their own 130 kV network located inside their area-concession. Regional and transmission network operators are required to request new concession permits for any changes to the network. Multiple line-concessions located within one area-concession can exist but not the opposite. These regulations are regulated by the Swedish electricity law [12], which not only regulates the concession rights but also factors such network tariffs, revenue limits and interruption compensation for customers.

A central key concept with the concession regulation is that every area or line is strictly regulated regarding revenue limits which are set in advance over a period of four years. This is done to make sure the network is operated effectively and that fees are reasonable, objective and non-discriminatory to the customers. The revenue limits are directly connected to the cost related to the operation of the network and consists of two parts, the capital cost and operating expenses [13].

Capital costs are mainly the cost related to assets in the network, such as transformers, switchgear, cables etc, which forms the capital base. Other financial parameters such as depreciation and return of assets are also included. The assets in the network are calculated using a list of normal value for specific components provided by the Swedish Energy Markets Inspectorate.

Operating expenses are further divided into unaffected and affectable costs. The affectable costs relate to expenses that the operator has the ability and incentive to affect. Examples of these are maintenance, measurement costs, etc. The unaffectable costs relate to expenses that the operator does not have the ability to affect. Typical examples of this are charges to overlaying regional networks or fees to government agencies.

Until recently, losses in the network where classified as an unaffectable cost. This has recently been changed by the Swedish Energy Markets Inspectorate to adopt to the directive from the European Commission which aims to increase the overall energy efficiency in the EU [14], [15].

2.1.2 Redundancy Criteria

The implication of the redundancy criteria in electrical networks is that there should always exist an extra branch or similar solution to ensure power is not interrupted in case of a fault. This methodology is widely used in electrical networks as a mechanism to provide a stable network and to allow maintenance to be done without the need for interruptions for the users. This is sometimes denoted as the N-1 contingency.

3 Methodology

This section describes the main methods used to complete the work presented in this master thesis. Most of the work is dedicated to present new theories and insights on an overall level for the whole distribution network, rather than specific parts of the system. The result is obtained mainly by doing an analysis of the current situation which is then followed by a second part dedicated to present possible solutions and discussions from what is presented. The thesis will in general focus specific on Swedish distribution networks, but other parts of the European union and the rest of the world will also be covered.

The main result of the thesis will primarily be based on an analysis on technical, economic and regulatory aspects with a deeper focus on the technical subjects. These three areas will supplement each other to present a result that include them all. To establish this, information will be gathered from a technical work done in the industry as well as research. This will further more be supported by interviews with Swedish DSOs where industrial experience will be gathered, primarily of how the DSOs operates the networks and potential challenges that exists.

Relevant economical information will primarily be gathered from guidelines from the Swedish electricity grid association guidelines (sv. ElnätsBranschens Riktlinjer). This is done to present a result that is comparable to the cost estimations used by the industry. The regulatory aspects will deeply focus on Swedish laws and regulations set by the Swedish Energy Markets Inspectorate. Since much of the regulations in place in Sweden are implemented as a direct result of the European commission, regulatory aspects on an European level will also be covered.

3.1 Interview study

To further study the Swedish DSO's operations an interview study was conducted with six different DSOs during the beginning of the thesis. This to get a general opinion of how the operators operate the network and their vision for the future. The primary questions that have been asked are the following:

- How is the grid operated today?
- What challenges do you experience today?
- What challenges do you predict in the future?
- What are the possible solutions to address these potential challenges?

The interviews have mainly been conducted in the beginning of the thesis to establish a general focus area of the report as well as introduce the problems and solutions that might be valid for the project. The interviews have covered the three analysis area of the report (technical, economic and regulatory).

The following list describes the different DSO that have been contacted as part of the interview study for the thesis. The list includes a reference to the specific person who have been interviewed at the corresponding company.

Electrical Company
Alingsås Energi Nät AB [16]
Sollentuna Energi & Miljö AB [17]
Lerum Energi AB [18]
Göteborg Energi Nät Aktiebolag [19]
Mälarenergi Elnät AB [20]
Västerbergslagens Elnät Aktiebolag [21]

4
Results and Discussion

In this section the result and discussion of the master thesis will be presented. This will be done in two main parts. The first section will try to identify the current and possible future problems in the low voltage distribution network. This section will also include some descriptions of how the distribution network is designed today. The second part will present possible solutions and discussions based on the information presented in the first part as well as technical, economic and regulatory aspects.

4.1 Identifying Potential Challenges

This section aims to identify potential or existing challenges in the current low voltage distribution networks. The section will focus on topics that are relevant from an DSOs point of view.

4.1.1 PV Installations

As the price of solar panels has dropped significantly in recent years it has become more and more popular to install PV systems around the world. This also applies to Europe and Sweden where figure 4.1 illustrates the number of PV installation in Sweden between 2016 to 2020 [22]. Although the data do not specify to what kind of electrical network the PV installations are connected to, it can be assumed that a large portion of the installations below 20 kW are connected to the low voltage distribution network due to its relatively low installations capacity. Also included in this statistic are the PV installations with a capacity above 1000 kW but as very few exist they have been excluded in the figure, (a total of 22 installations where installed in 2020).

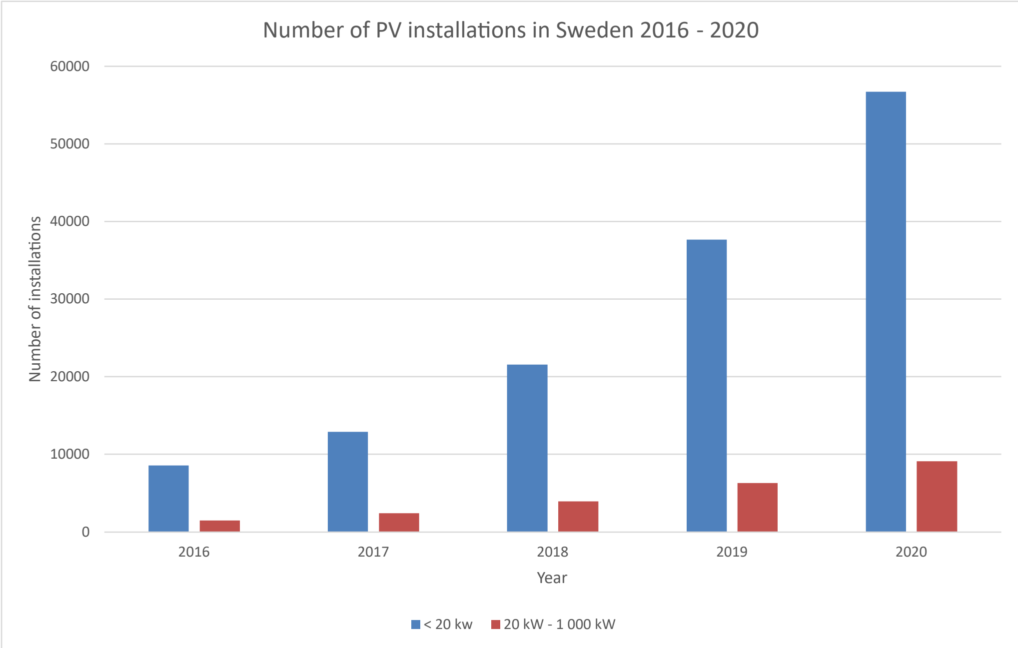

Figure 4.1: PV installation in Sweden between 2016 to 2020 [22].

These installations correspond in terms of total energy produced to a very small amount of the total Swedish electricity production [23]. But with more installations adding up every year and the fact that prices of PV panels are still dropping PV generation has a potential grow in the Swedish energy generation mix. As much of this can be expected to take place in the distribution network the DSOs are facing new potential challenges connected to this, as their roll is shifted from only delivering electric power to the end-user to also enable the end-users to become producers. A futuristic scenario might be that a large portion of the Swedish energy mix is based on distributed renewable power production where individual users become net exporters.

From the interviews performed with the different DSOs, none of the selected answered that they have experienced any major problems related with PV installations in their networks. The problems that have been reported are mainly related to larger installations that have been installed in weak networks far away from the transformer where voltage stability has been an issue.

4.1.2 Electric Vehicles

Likewise with the PV installations, the number of electric vehicles have increased in a rapid pace in Sweden. Figure 4.2 illustrated the number of registered electrical vehicles per year and by type [24]. The interesting technologies are BEV and PHEV as they primarily use the electric network to charge whereas HEV technology has no capabilities of charging via the electric network.

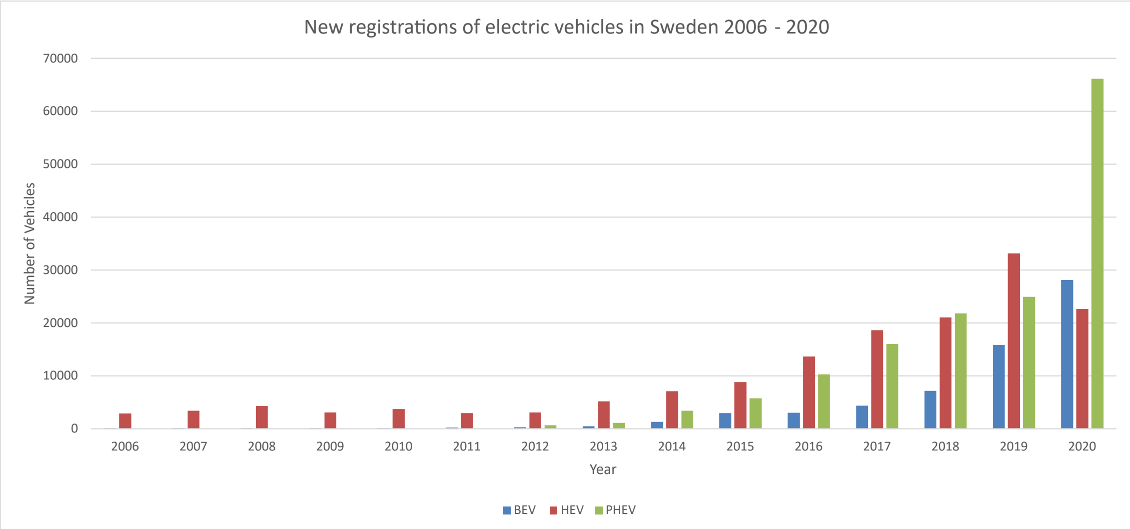

Figure 4.2: New registrations of electric vehicles in Sweden between 2006 - 2020 [24].

The potential rapid grow of electric cars, both PHEV and BEV will face new challenges for the distribution network as charging is going to take place at home, work or at larger EV charger installations. Depending on manufacturer and car model it is not uncommon to find 16 A single or 16 A three-phase on-board chargers. It can be assumed that individual chargers will use the on-board chargers and therefore use regular 230/400 AC outlets. For a normal household the electric car has the potential to become the largest consumer of energy which historically, at least in Sweden has been electric heating. Using the assumption that a full EV car consumes approximately 0,2 kWh/km and that each car in Sweden drives approximately 30 km per day, a normal user will need 6 kWh of energy from the electric network each day.

The potential problem is if every user will connect in their vehicle for re-charging at the same time interval, for example when reaching home during the evening. Then this problem will become real if every user maximises their electric charger at for example 16 A, or in some cases having several EV vehicles for the same household. As most EV are based on lithium-ion technology which will accept full power up until about 60-70 % SOC it is possible that a local congestion in the electrical network of a neighbourhood can occur during specific periods. As many DSOs by today charge for a fixed maximum power tariff, there is no real incentive for the end-user to change its behaviour [25].

The reverse problem is also possible in the case the vehicle-to-grid theory is realized and many customers want to sell their stored energy during the same time.

4.1.3 Network

Due to the regulations regarding guaranteeing a secure delivery of electricity the DSOs electric networks must guarantee a high-level of reliability to the end customers [12]. This regulation has since the past decades become more and more strict in terms of acceptable down time minutes per year, usually denoted as the SAIDI-index. The number of downtime minutes per customer has historically improved over the EU continent, where Sweden today ranks within average [26] [27].

In Sweden specific, the regulations state that the DSOs are required to compensate for any interruptions longer than 12 hours with increasing penalises for every extra 24 hours period [12]. Due to the regulations which are monitored by the Swedish Energy Markets Inspectorate, Swedish DSOs are highly motivated to ensure the stability, not only by high penalties but also because they are able to get a return on the investments made in the network, in terms of adding this to their total capital base.

As a result of this the de facto standard in Swedish city and urban installations is to install underground cabling in the high voltage distribution network stretching from 10 kV up to 40 kV. The 400 V network is also covered by this de facto standard [5].

Cases where overhead lines dominate are mainly in the countryside where especially high voltage distribution networks tend to use overhead lines due to a large difference in cost compared to cables [5], [28].

4.1.4 Power Demand and Flow

By today the majority of the power flow in the distribution network is unidirectional due to the nature of the current system, where power is generated in one end and consumed in the other end. The transmission network has by some aspect adopted this with the introduction of renewable distributed generation, for example large scale wind farms. For the low voltage distribution network this has not yet been introduced in a large scale, only smaller installations like PV installations are in use.

With the introduction of more distributed renewable installations at individual customers, new problems might occur that was not expected when the network was designed, where areas old as from the 1940-1950s can be found in operation [2].

4.1.5 Voltage Stability

One of the concerns related to voltage stability and to reverse power flow is the problem when large PV installations are placed in the far end of weak radial networks, typically agricultural farms which some of the interviewed DSOs can witness about. The problem itself is caused by the high impedance in often very long 400 V cables or overhead lines connecting the end customers to the feeding transformer.

The reverse problem to under-voltage, over-voltage is traditionally a problem in unloaded branches of the electrical network. By installing PV installations there is a possibility for over-voltage to occur in conditions when PV production is high and the local demand is low.

Another challenge with renewable power production, especially with wind and solar is that it is due to nature, more unpredictable compared to other regular production types. This will introduce challenges to the whole electrical grid but looking specifically at the local distribution network the challenges are as previously described related to the new reversed power flow and voltage stability. An example where weather can cause issues are fast moving clouds over a specific geographical location covering many PV installations.

4.1.6 Diversity Factor

The optimization problem related to system design of the distribution network has always been a challenge for the DSOs as cost and capacity must be balanced when the network is designed. Historically and still today are Velanders Method or similar constant-based methods used to estimate the maximum power outage per user. Typical aspects that are taken into consideration when forming these constants are what kind of heating is used (district heating, central heating, etc.) and the kind of end-user (household, apartment, school, office, etc.).

Heavy industries and factories are often excluded from these normal calculations as they are due to their large power demand often directly connected to the substation with high voltage [5]. A crucial parameter in the development of this calculation is, at least in Sweden a typical winter day when the temperature is low and electricity demand is high. This results in a system where utilization is high during some periods while being low in others.

4.1.7 Electrical Safety

With EV and PV installations added to the network rare and new potentially dangerous faults can be introduced, mainly due to the fact that both these type of devices has a high energy concentration in form of high voltage DC capacity. Under normal operation are EV cars of course not designed to export or leak anything, but taking into consideration that a 400 VDC or higher voltage battery pack used in many EV cars has a large short circuit capacity. The potential danger in case of a fault should not be ignored as a fault can be very dangerous. If adding the vehicle-to-grid concept, where EV car batteries are supposed to be attached to the electrical network the rare but potential problem should not be ignored.

The same applies for PV installations where rare malfunction can cause serious issues, especially as a PV panel is to be considered as being live all the time. A potential but rare situation is if the network is taken offline due to maintenance and one customer's PV installation back-feed the whole network when maintenance personal is working. There are already today routines in place for personal working on electrical networks, for example always grounding prior to work. But the risk exist that this routine is forgotten or simply ignored as this sort of faults are very unlikely to happen.

The two described cases are certainly not likely to happen but as products are placed inside the control of end-users it is hard for the DSOs to control the quality and operation of these products. As both products can be seen as products designed for the customer market it is up to the end-user to ensure the operation, safety and maintenance. The same applies to ensure that the product follows the electrical standards set by the manufacturer, such as electrical harmonic distortion or leakage of DC currents.

4.1.8 Distribution Substations with Remote Control

From the survey made with the different DSOs, installations of remote operation of the electrical network are in most instances always made in the primary receiving stations where the incoming regional network is transformed down to 10 or 20 kV. A contributing factor why this is the case is because relay protection with measurement instruments are already installed in this end and connected to a central SCADA system. On the outgoing 10 or 20 kV branches, measurements and control in the distribution stations are not always the case.

Based on the survey made with the different DSOs some differences can be noted for the 10 and 20 kV distributing stations. The DSOs tend to move into connecting their transformer stations located in urban areas with monitoring equipment like voltage, current and earth leakage detecting. This kind of installations are mainly done on new deployments or when the whole station is upgraded due to age or similar.

The main argument why to connect the distribution stations is that it will enable better monitoring of the system and the possibilities to remotely operate breakers in case of faults or similar. The opposite argument why not to connect them is the fact that it will not add much value in terms for the network operator, as for example fault clearing might still require service personnel to physically visit the station to clear the fault. Another factor is that installing breakers will increase the complexity of the network and therefore adding potential sources of error. Breakers also need regular maintenance to guarantee their operation. In some stations the breakers might never operate if no problems occur, why such investment could be questioned.

In general, remote measurement and remote controlled breakers are of interest in networks located in rural areas compared to stations located in urban areas. This is mainly due to the fact that troubleshooting and transportation in rural areas takes considerably longer time as distances are greater. This further justifies the cost of installation for the DSOs as it reduces the downtime in case of a fault, this also enable the DSOs to add this cost to their capital base.

4.1.9 Single Phase loads

In a three-phase system that is widely used in residential installations in Sweden, it is always favourable to have a balance between phases as it enables maximum utilization of the system [5]. High current applications such as electrical machines are in most cases three phase loads.

With an expected grow in PV installations their is a likelihood that many of the PV inverters is going to be single phase, as many of these products are designed for a global market where many households around the world are connected to single phase with higher current capabilities per phase, compared to the standard of three phase in Sweden. This can further also create problems for EV, where many plug-in-hybrid cars are single phase only.

A possible scenario where this can cause problem is for example a residential area with many individual households, whereby coincidence many of the PV installations are installed on the same phase causing unnecessary congestion in the electrical network. Although there exists several three phase inverters and other products for end-user to balance phase currents, there are today no real benefit for the end-user to invest in such products because of the high investment cost.

4.2 Future Solutions

This section aims to present possible improvements and important factors to take into consideration for the low voltage distribution network. Discussions will be based on the presented challenges in previous section with the focus on technical, economic and regulatory aspects.

4.2.1 Redundancy Criteria

With the current regulations from the European Commission and Swedish Energy Markets Inspectorate the DSOs are strictly controlled by how to operate their network. One of these regulations regulate how the reliability in terms of electrical interruptions in the network shall be handled. As the Swedish electricity law (sv. Ellag) has strict regulations to not allow any discrimination between different customers, all penalty fees related to interruptions are the same for all customers [12]. This is one major reason why DSO has invested much into designing redundant networks with multiple branches and transformers in the high voltage network, which in the end fulfils the goal set by the regulations.

A possible problem related to this method is when deploying large scale fast charging stations for EVs around the country. As an example, if a 150 kW fast charging station with 20 parking spaces is constructed in an area with limited capabilities in the existing distribution network, it is possible that the current network is unable to allocate the new 3 MW power needed. Taking the redundancy criteria into consideration it is likely that two new transformer stations must be built just for this specific installation. Another aspect to take into consideration is the utilization factor for an EV charger which is going to vary heavily over the day with possible periods with no utilization at all.

The Swedish Transport Agency estimated that an investment of about 550’000 SEK is needed per fast charger of a capacity of 100 kW. 50 % of this investment is estimated to costs regarding connecting the charger to the electrical distribution network [29]. To shrink this, a cost trade-off between the redundancy criteria and the user’s need for uninterrupted electricity delivery can be made. A possible scenario might be that EV stations are connected using a simplified connection where costs related to the connection is reduced at the expense of less reliable connection to the electrical network. This sort of implementation needs adjustments in the current Swedish electricity law.

4.2.2 Network extension

A method to extend the current capacity in a network is adding an extra branch or more branches to an already existing network. An example and typical implementation of this is, within a 10 kV ring network to add a third connection to enlarge the power capability. This method can and is used widely at different voltages levels by the DSOs. As well as installing this for resolving capacity related issues a possibility is also to install the branch as a precaution in new development, if future power increase is expected to take place.

An important aspect to take into consideration when studying the financials related to construction of a new branch of the network is the surrounding costs related to the cable or line. Only about one fourth of the installation cost for a new cable deployment is the cable itself, the rest are labour, machine and civil engineering costs. An overview of cost related to deployment of cables is presented in table 4.1.

4.2.3 Single and Multi-conductor Cables

When installing underground cables, several different options exist such as type of cable (PEX or PVC), diameter, single or multi conductor and type of placement in the ground. The 240 mm^2 cable is often chosen in both 400 V and 10/20 kV installations due to its commonly availability and price. PEX insulated cables dominates the market due to its many benefits over PVC insulated cables.

When designing and installing the cable a decision must be made over to choose single or multi conductor. Where the main benefit of the multi conductor cable being easier to install over the single conductor cable, due to only one physical object have to be placed in the ground. This also means less machinery is needed for installing. From the survey by the different DSOs the majority answered they choose the multi conductor cable in favour of single conductor. As an exception did one of the DSO answer that they use the single conductor alternative in most cases, where the main reason is that the small cost increment is justified with the possible decreased risk of failures and higher current capabilities.

One example of a decreased potential failure risk by using single conductor cables is the quality of the cable joints as any type of phase-to-phase risks are eliminated, joints are also generally easier to achieve when not bundling them together with other conductors which is the case in multi conductor cables. Comparing the cost for installation of a 240 mm^2 PEX single over multi conductor cable using EBR's statistics reviles, that there is about 7 % more expensive to install multi conductor cables [28]. The EBR cost is presented in table 4.1 in thousand Swedish krona per kilometre. No further research has been made where the decreased risk of failures in single conductor cables can be verified.

Table 4.1: Comparison of cable installation cost for PEX insulated 12 kV and 24 kV with single and multi-conductor [28].

Type	Labour (tkr/km)	Material (tkr/km)	Machine (tkr/km)	Other (tkr/km)	Total (tkr/km)
PEX 3x240 12 kV	316.94	233.28	107.62	535.87	1193.72
PEX 3x1x240 12 kV	319.52	311.41	104.93	535.87	1271.73
PEX 3x240 24 kV	314.49	264.41	101.58	535.87	1216.34
PEX 3x1x240 24 kV	319.52	345.51	104.93	535.87	1305.83

4.2.4 1 kV AC Network

A possible alternative voltage level in the distribution network is the intermediate 1 kV level. The intended use case for this technology is to upgrade whole or parts of an 400 V branch with 1 kV. From a market perspective a common type of application is to step up the voltage using a 0.4/1 kV transformer in the sending end and stepping down the voltage in the customers end via a 1/0.4 kV transformer. Other possible implementations are to step down the voltage directly from a 10 or 20 kV network down to 1 kV. Another possibility is to step down the voltage directly from the regional network and completely skipping the 10 or 20 kV level [30].

Installations of this kind have been done in Sweden, although it is unknown how many projects have been delivered and their overall performance. In the customer orientated magazine Volt produced by the Swedish wholesaler Elektroskandia, a 1 kV network installation on the island Gräsö in the Stockholm archipelago is presented as a solution to enable new customers in an already existing 400 V network to be installed [31]. Due to capacity limits in the 400 V branch and the long distance the 1 kV network was implemented as a compromise instead of installing a new high voltage 10 or 20 kV branch. This enabled the installation to use already existing infrastructure such as the poles for the overhead line. The system in general consists of a 0.4/1 kV transformer in one end and another 1/0.4 kV transformer at the customers end, making the solution transparent to the end-user.

The advantage of this technology is that many low voltage components and cables are already rated for 1 kV, enabling cost effective equipment to be sourced. The main advantage from a technical point of view is that this technology allows higher power transfer as well as decreased loop impedance compared to a 400 V system. In theory, the power capacity is increased by a factor of 2.5 times by using 1 kV instead of 400 V. A typical implementation of this from a DSOs perspective is to strengthening the electrical system for users located in weak networks, for example end-users located at the end of long line on the countryside. A bonus with the technology is the possibility to use dry transformers, making installations easier in an environmental perspective as no precaution to risk of oil leak has to be taken.

Other advantages with 1 kV networks are that standards and installation guidelines already exist, which makes system design and installations easier compared to untested and uncertified systems. No active protection or relay control is necessary for a 1 kV network as fuses are approved as a protection device. The market for 1 kV approved fuses is however more limited compared to the high current fuses used in 400 V systems.

The disadvantage of this implementation is mainly related to the cost of the transformers which approximately are the same for an equivalent 10/0.4 kV or 20/0.4 kV transformer [28]. The implementation of replacing parts of a 400 V branch will need two separate transformers, making the cost for this type of implementation even higher. Also, the fact that a 1 kV network only delivers 10 % of the power transfer capacity compared to a 10 kV, limits the technology feasibility to retrofitting existing installations for users in rural 400 V networks. For using this on an already existing branch requires that the existing cable or line is rated for 1 kV operation which may not always be the case. Another important factor to consider related to this sort of installation is that by installing more equipment to the network, the potential risk of failures and cost related to maintenance increase.

Possible future development of this technology can be to use adjustable tap changers on the 1 kV transformers to effectively regulate voltage in networks where much load variation can be expected, such as areas with many vacation properties or PV and EV installations located in rural areas.

4.2.5 Line Voltage Regulator

A possible device to use for voltage control in distribution networks are Line Voltage Regulators. The main functionality of this type of device, is by the help of a transformer and power electronics to actively regulate the voltage on the secondary side. Operation can be done in both boost or buck-mode, therefore it is possible to both raise and lower the voltage. The technique used in these devices is not a new design, instead it is based on research from the 1980s [32].

In recent years with increased PV installations around the world, voltage stability issues in the distribution networks has become problematic in some networks where both over and under-voltage can exist. As PV generation output can experience fast changes due to changing weather conditions over the day, meaning the power output will change correspondingly. Since PV installations in one specific area in most cases are connected to the same distribution network, meaning the power output response will affect the voltage level in the whole network. In for example weak networks, this behaviour can cause issues. In most cases the PV inverter will shut itself off due to the over or under-voltage, this results in the DSO not fulfilling their responsibility to deliver a stable connection to the electrical network.

By today most of the Line Voltage Regulators operate independently in terms that the control equipment within the device measures the voltage and adjust it accordingly. By introducing some outside data variables, such as weather telemetries and installed PV capacity in one branch the response time and overall response performance of this type of device can be improved.

4.2.6 Flexibility Markets

With the renewable energy transition taking place around the globe new challenges in the electricity market are introduced as large, centralized power production is shifted to decentralized renewable power production. This shift and the fact that the electricity usage is expected to grow has resulted in regulations expecting utilization of the electric infrastructure and generation to be done more effectively. A relatively new and proposed solution to address this is the introduction of flexibility markets where the European Commission promotes this idea to help the EU meet the goal of becoming climate neutral by 2050 [33], [11].

This flexibility market is supposed to integrate in all parts of the electrical network, from bidirectional exchange between countries on a TSO level to individual customers on a DSO level. The main principle of the flexibility system is to use the fact that end-users in many cases have or are willing to exchange their power flexibility for an economic value. A typical example of this is heating in households where this is today controlled by thermostats which switch on and off accordingly, independently of the situation in the electrical network. With the flexibility market initiative, household would instead shift their electrical usage to other periods of the day and by doing this they would get compensated in terms of trading electricity to a lower cost. As a result migrating the congestion in the electrical grid. This do not only apply to individual household heating, rather it can be applied to a variety of grid connected technologies like EVs, heavy-industries and so on. The main idea is to allow more capacity in the existing system by introducing and encourage a flexible usage by enabling trading on a flexibility market.

Research is going on within this area, especially within the EU where many research projects are founded by the Horizon2020 initiative. Much research performed is within the TSO level and how nations should cope with the flexibility markets. On the DSO and low voltage networks this potential change has many different challenges and benefits where it could enable the network to be used much more efficient than what it is today. In some areas can the dynamic tariffs which are introduced by some DSOs be seen as an introduction into enabling the flexibility for individual household customers, by allowing them to transfer power on the DSOs network at lower rate depending on time on the day [25].

To sort financial compensation for the end-user and to push them to control their behaviour, a solution often presented to facilitate this is to introduce aggregators who serve the purpose to collect and aggregate or control the behaviour of a group of end-users. These aggregators can then exchange this with the players on the electricity market, these players are mainly the electricity producer and network owners. At the end, this will both benefit the end-users in terms of lower electricity costs and benefit the market players in terms of flexibility services, which can enable them to operate their production or network in a more effective way. The aggregators will not only enable the end customer to buy but also to sell electricity in a more effective way. Therefore, driving the incentive for more installation of renewable energy sources such as wind and PV.

An example of how this can work is that an aggregator has aggregated a group of users with a total capacity of 50 MW. If for example the national TSO is expecting a potential congestion in the network feeding a specific area, it can then ask the aggregator market to exclude this load under the period this congestion is expected to take place. By doing this the TSO will not be required to expand their network in an inefficient way and at the same time the end-user will be financially awarded for their flexibility by moving their load to another time.

Test of aggregation and flexibility markets has recently started in Sweden in the Stockholm metropolitan area under the project sthlmflex which is a research initiative by Svenska Kraftnät, Ellevio and Vattenfall [34].

As well as including the national TSO networks the DSOs must be included in the flexibility market where they have the possibility to operate on similar commercial permissions as the others, meaning they should be able to get some kind of return from the flexibility market. As a result of the European Commission new energy policy framework "Clean Energy For All Europeans" (proposed in 2016 and completed in 2019) that aims to meet the EU's climate goal of becoming climate neutral by 2050 [11], the Swedish Energy Markets Inspectorate published in 2020 a new proposal with the purpose to meet these new requirements [35]. This new proposal aims to provide new regulations especially applicable for the DSOs and how they should behave in the new flexibility market.

These new regulations do not define exactly how the DSOs should implement this into their distribution network, which is not the case as the Swedish Energy Markets Inspectorate is a government agency whose purpose is to regulate the market and not to provide technical system solutions. One of the larger challenges this regulation will require from the DSOs are services that enable a flexibility market to operate in an efficient manner in their network [35].

A possible ethical concern with the introduction of flexibility markets is that this solution will require the end user to understand and be more active on the electricity market. For individuals that are not familiar or find electricity and the electricity market difficult, this kind of shift might lead to this group of users being forced outside this market. At the end it may result in these users paying a higher price which in some sense can be seen as a discriminatory behaviour, which limits this group access to electricity in the same way as everyone else. At the same time, it must be weighed for the possibility to open the whole electrical grid to become more effective and efficient. A possible solution to this might be to have a system in place that automatically protect this group of users by placing these users in a default aggregator group. Sort of similar to how the Swedish pension system works.

4.2.7 Electrical Meters

Electrical meters has historically mainly been used to bill the end customer its active power usage. In the beginning this was done using an analog electromechanical meters where the data manually had to be reported to the DSO. This only gave the end customer the possibility to be billed over a long period of time, typically only a few times every year. This resulted in the customers got billed a preliminary consumption every month.

About 10 years ago where the DSOs forced to discontinue all meters that did not have the capability to report on a monthly basis, this effectively removed all analog meters and instead introduced digital meters with remote billing capabilities. The main motivation for this requirement was to enable the end customer to be billed on a monthly basis and to be able to participate in the electricity market [36]. This also led to less administration for the DSOs as billing got more automated.

In 2018, the Swedish Energy Markets Inspectorate lunched new technical requirement for smart meters and by 2025 all existing meters should be replaced with meters fulfilling the new directive set by the European Commission. The main difference from previous requirements is that the meters shall be able to remotely report at a minimum of 15-minute interval, report power outages and other faults as well as enable the end-user an open connecting point to the meter for them to connect their own equipment [37].

These smart meters are often described as a keystone in the flexibility markets which in some aspect can be described as a part of the smart grid concept. The main purpose of the smart meters, are according to the European Commission to enable the end-user to participate in the digitalisation of the new evolving energy markets via "several different functions" [38]. The Swedish Energy Markets Inspectorate presented in 2017 a proposal of seven functional requirements for the new smart meters that are required to be installed before the end of 2025 [37].

These seven functional requirements are:

- Extended measurement data - Measurements shall be done per phase where voltage, current, active and reactive power is measured. Furthermore, shall the meter be able to measure input and output power.
- Open customer interface - The end-user shall be able to connect via an interface to the meter and access the measurement data in close to real time.
- Remote reporting - The meter shall apart from remotely report the power consumption also remotely report measurement data and network interruptions.
- Hourly reporting of amount of transferred active energy - Reporting of active power shall be reported every hour with the possibility to reporting at a minimum of 15 minutes.
- Registration of interruptions - The meter shall be able to register interruptions longer than three minutes in one or more phases.
- Remote Upgrades - The DSOs shall be able to remotely upgrade the firmware and configuration of the meter.
- Remote activation and deactivation of customer - The DSOs shall be able to activate and deactivate the electricity for customers remotely.

An important factor to take into consideration with the deployment and usage of smarter electrical meters is the personal integrity for the individual end-users and households. By today the reporting and information exchange is limited where mainly billing of electrical consumption is made.

With a more frequent and regular reporting, down to 15 minutes or possible even close to realtime in the future, it is important that the information from the meters is treated in an ethical and secure way. This because it is possible to use the information collected from the electrical meters to monitor the behaviour of the users, such as when reaching home or in some cases what appliances the end user is using. This information would traditionally only be used by the DSOs but with the introduction of flexibility markets and aggregators some information might be necessary to share for the system to operate. In such case it is important that regulations are in place to limit what information is exchanged, and that the information that is exchanged only provides information that is necessary. It is also of importance that the data that is necessary to exchange is shared in a way that limits the amount of personal data and at the same time fulfils the data requirement needed.

4.2.8 Usage of Big Data from Meters

With the introduction of the new meters many new opportunities emerges for the DSOs regarding the possibility to use data. From the interview study conducted with the different DSO, the main opinion is that they see great opportunity in this, but do not have the capacity and capabilities to develop tools themselves to utilize this data. The capabilities that the DSO already utilize from the new meters are mainly related to monitoring faults at the end-user, such as loss of connection or fault due to loss of neutral conductor.

There are many possibilities to develop methods and products to further use this data, especially if the big data concept is considered in the distribution network. For the DSOs network infrastructure it opens up several new features by using this data to find potential bottlenecks or troubleshooting faults.

A possible implementation of the massive data the DSO has at their disposal, is combining the geographic information system (GIS) data which describes the physical layout of the electrical network, electrical specification of components in the network such as cables and transformers and metering data from the end-user's smart meter. As all variables of the network are then known and easily accessible in a database or similar structure, and the fact that the new electrical meters can report detailed electrical data such as individual current and voltage magnitudes, active and reactive-power and more. By then combining all this data and performing calculations it is possible to create a system that can give very detailed information for each component in the network, such as loading in an individual cable or phase currents in a specific cable cabinet at a specific location.

A challenge for such a system is that the network topology can change significantly in different parts of the network, meaning simple Kirchhoff's circuit laws cannot be used. But as electrical data in many points in the network are known, a machine learning algorithm should be able to handle these calculations where it automatically can compensate for errors by using the massive data available. Other measurement points can if necessary complement the electrical meters at the end-users, such as meters in the transformation stations. In the end, this kind of implementation will not require a massive installation of measurement devices in all parts of the network, instead it will use already existing infrastructure meaning investment in new hardware will be limited.

This can further be developed into many useful applications such as heat maps for the whole network where the DSOs easily can see current and potential issues based on the real actual network rather than relying on manual simulations which do not include individual measurement data from end-users. This information can also be used as a valuable resource when the DSOs design new networks, or in the case of capacity related issues give information what branch the capacity problem is located at.

Another possible function with this type of system is to perform electrical calculations in close to real time, where the limitation will be the possible 15-minute delay from the electrical meters. Performing close to real time measurement and calculations would enable the DSOs to use this kind of system not only for diagnostics purposes but also as a complement to the ordinary operational control of the network where faults can be predicted before they occur.

As the DSOs are regulated to operate the network as efficient as possible this sort of system would make sense in an investment perspective as it can reduce unnecessary costs related to inefficient design caused by over dimensions in the network. It may also help the DSOs to faster react to possible issues and therefore reduce the amount of costly customer interruptions.

Another factor to take into consideration is that this kind of system does not have to be developed as a critical application for the network operation. This means cheaper non-critical sensors can complement the system, such as temperature sensors on transformers. This can then enable more applications to integrate into this kind of system. For example, shift scheduled maintenance and replacement to condition-based on the components in the network. In the end this could enable a more circular economy with savings in both costs and environment.

4.2.9 Energy Storage

The interest in different energy storage solutions has in recent year witnessed an upsurge in interest, mostly due to the technical developments in battery technology which has resulted in higher capacity batteries at a lower cost. This have for example contributed (or is contributed by) to the rapid expansion of EVs. Batteries have also gained interest in the electrical networks as an energy storage solution, which by some means is not a completely new technology as energy storage has existed in the hydroelectric industry for a very long time. The revolutionary aspect is that they, as many other technologies in the electrical network, can be decentralized. It is already today possible for individual users to buy battery storage system to tie into their own household.

The EU research project BATSTORM estimated in a report from 2018 that it is not unlikely to see a price reduction of up to 50 % in lithium-ion batteries until 2030. The report furthermore estimates a rapid grow in installed distributed energy storage devices in the EU. From about 200 MW installed in 2018 to 5000 MW in 2026 [39].

This price reduction in battery technology has already today increased the interest in investing in battery systems as energy storage. There are today many commercially available battery storage systems from different manufactures designed for individual households. A lot of research is going on in this area as well as industries who are commissioning full scale installations. An example of this is the Swedish company Vattenfall who in late 2020 finished installation of a pilot project of the largest battery storage system in Sweden (by today). The primary aim of this installation other than providing useful research is to help with the local increased shortage of capacity in the Uppsala region. The total capacity of this specific installation is approximately 5 MW and the total energy is approximately 20 MWh [40]. Another aspect to take into consideration regarding especially larger battery installations is that they do not require any time consuming and complicated concession rights for installation, which is otherwise a challenge for construction of new power lines.

The Swedish regulation by today state that a DSO is not allowed to produce or trade electricity, except if the purpose is to cover its own network losses or to temporary produce electricity to provide electricity in case of an interruption in its own network [12]. As a result of this the DSOs are limited in terms of what capabilities they have to operate an energy storage in this potential growing market. The European Commission further specifies this in a directive from 2019 regarding the internal electricity market, where the commission specifies that "System operators should not own, develop, manage or operate energy storage facilities", instead they should be "market-based and competitive". The European Commission also specifies some exceptions which mainly relates to the same exceptions as the Swedish regulations [10].

Another usage of different energy storage solutions is to integrate them into a microgrid system, for which in recent years has gained much attention in the industry as a concept that could function in the real world. Many different implementations of the microgrid structure exists already for different use cases and applications. An interesting layout especially for the low voltage distribution network is to integrate microgrids with an energy storage solution. This in order to reduce capacity related issues and allow more renewable production to be integrated into an already existing network. Microgrids can also work in island operation, meaning off-grid solutions is possible [41]. Vattenfall is currently installing a test pilot on the Swedish island Arholma in the Stockholm archipelago. The aim of this installation is to increase the quality in terms of stable and reliable delivery of electricity, and at the same time enabling more renewable power production to take place on the island [42].

An important factor to take into consideration with more energy storage solutions and especially battery storage solutions is the material used in the battery cells. There are already today some rare earth materials used in different type of battery chemistry. With the potential growth in the battery sector there is a possibility other material will become problematic in the future, due to limited availability or difficult processing. Which may result in unfair working conditions or high negative environmental impact.

As a result of new regulations from the European Commission, new laws regarding conflict minerals in the EU came in full force as of January 2021 [43]. Although these regulations mainly affect importing of tin, tantalum, tungsten and gold for the distributors, these sorts of regulations might also expand to other rare materials used specifically for different types of batteries. This might impact the deployment rate as installations of large scale battery storage solutions might not only depend on the price, but also on materials being gathered in a sustainable and fair way.

5
Conclusion

The energy sector's shift towards using more renewable sources have resulted in a high interest in electrical networks as they will play an important role in the conversion to a more sustainable future. The importance of especially flexibility in the electrical distribution industry is therefore crucial to allow new technologies and solutions to be implemented to accelerate this conversion. Key factors that must be addressed are technical development, digitalisation and regulations.

The development of technical solutions mainly relates to appliances that will enable a smarter utilization of already existing infrastructure and new products that will allow a more effective usage to be implemented. It is not unlikely that combinations of these technologies will exist, such as hybrid networks consisting of micro grids working in conjunction with existing distribution networks. The development of traditional products must adopt its equipment to function in a future network with a high amount of renewable penetration, meaning product requirements have to take flexibility and digitalisation into consideration. This can for example be sensors or methods used to measure the lifetime of a component based on condition rather than age and therefore contribute to a more circular economy.

The importance of introducing digital solutions to the distribution network relates mainly to enable a more total efficient usage of already existing and future equipment. This can lead to less investment in capital intense applications such as an extra transformer where a digital platform can monitor the whole network and making this sort of investment unnecessary, resulting in a more efficient network. As distributed renewable power production is introduced to the distribution networks, flexibility is going to play a key role where the DSOs digital systems must integrate with the end-users and electrical market in a more dynamic way. This for them to keep up in both a technical and economical way in the new evolving electricity market.

At last, the regulations that are in place today must adopt to allow future technology to operate on the monopoly market and at the same time ensure its fundamental purpose, which is to deliver electricity to consumers in an efficient, cost-effective and reliable way. Many of the current regulations in the EU are already today in the investigation phase to enable a smooth introduction of more renewable energy, both in production and consumption. Regulations regarding flexibility markets must clearly define what purpose and position the future DSOs will have in the electrical network. The regulations for the DSOs investment profile related to the capital base have to become more flexible to ensure and stimulate the operators to invest in solutions that will gain all parts of the electricity market.

5.1 Future Work

From this thesis several future challenges and solutions for the low voltage distribution network have been presented. Many of these will require further investigation, especially those regarding new products and services. Listed below are topics this work has touched upon and found to be interesting for further research.

- Study the impact from more active equipment in the network in terms of voltage stability and harmonics. Preferably by performing simulations or measurement in parts of the network where this sort of products are already installed.
- Investigate what more flexible behaviour in the network will result in. How will the utilization look like? What purpose should the future DSO serve? How should the business model for DSOs look like?
- What impact will microgrids have on the electricity market? What purpose should the surrounding networks and DSOs serve? Who should be operating and allowed to operate a microgrid?
- The big data concept should further be analysed where an investigation should be made if the idea regarding the data from the electrical meters proposed in this report is possible to achieve. Depending on the outcome from this, can a possible functional model be presented?
- Investigate if the self-healing network concept is possible to implement with the current hardware installed in the low voltage distribution network? If not, what potential investment must be made to enable this? Can this be combined with the big data concept?
- Analyse the future for 1 kV networks. Is it possible to optimize the cost of technology to make it more attractive to the market? Is it possible to replace the transformer with power electronics? Can the voltage be controlled in a more dynamic way with digital communication in each end?
- Investigate the electrical safety aspect in a network with more distributed generation. Study possible fault scenarios with simulations and present solutions to address these.

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