UiT THE ARCTIC UNIVERSITY OF NORWAY

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DC Distribution systems

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Master thesis in Master of Science, Electrical Engineering

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Foreword

This master thesis is written as finishing work for Master of Science, Elektroteknikk at UiT Narvik. The thesis work started in January, and was to be finished in June. Since "The War of Currents" in the late 1900s, when AC won, DC has been overlooked. However, the research and development of DC technology has been on an uprising. This has opened the possibilities for the subject for thesis. The purpose of the thesis is to carry out a literature study of the DC distribution system. I chose this specific topic, because it introduced me to a new theme, which I had not worked much with earlier. I also saw the potential and possibilities of DC distribution systems, which gave me further motivation to choose this topic as my master thesis.

Through completion of this thesis, I have had great support from various sources. Firstly, I would like to thank my supervisor, from UiT Narvik, Bjarte Hoff. His valuable insight and knowledge has been of great importance, and for much needed guidance through the work of the master thesis. I would also like to thank by family for all the support through the process of this master thesis.

Abstract

In today's distribution system, the dominating type of current used is AC. In newer time, improvements have been done within the field of DC. The developments that are achieved, are in terms of converter efficiency and conversion capabilities. Along with development of DC equipment and technology, the use and development of renewable energy sources has increased, which generates DC power. This has brought up the topic of using DC in the distribution system. A DC distribution system can be a future solution, for higher efficiency and reliability.

This thesis is a literature study of research done on DC distribution system, to assess the current state and feasibility of the DC distribution system. Currently, DC is already in use in several applications, such as data centers, telecommunication systems and electrical vehicles. There are different aspects of the DC distribution system that need to be considered and studied in the future. Several grid solutions are considered, for both low voltage distribution system and medium voltage distribution system. Repurposing of cables is also reviewed, and how the currently laid out cables used in AC can be used in a DC system. Research that is done on efficiency of a DC distribution system has also been described, with the purpose of making an overview and possibilities for the total efficiency of the distribution system. The advantages and disadvantages of the DC distribution system are shown and compared to the AC counterpart in this thesis.

Table of Contents

1 Introduction - Where it all started

It all started in the late 1880s, where the two inventors and engineers Thomas Edison and Nicola Tesla had developed two types of currents. The happenings concerning these two types of currents is today known as "The War of Currents". Thomas Edison developed direct current (DC)[1], where the current that runs continuously in a single direction, for example as in batteries. One big problem Edison had was that in those days converting DC between higher and lower voltages was difficult, because the technology was not developed for it.

Nicola Tesla on the other hand had developed alternating current (AC), which turned out to be the solution that was applicable at that time. The reason for this being that AC could be easily converted between higher and lower voltage levels, using a transformer. Consequently, the events of "the War of currents" shaped the electrical progress into an AC dominated direction for many years. However, research and new implementation possibilities on use of DC has been on an uprising.

The happenings in "The War of Currents" is the baseline for the topic of this master thesis, although there are other motivations to explore the usage of DC in distribution systems. Many applications are based on DC, because they depend on battery based technology. This means that many appliances today could benefit from a change to DC in the distribution system. In addition, renewable energy sources, like solar energy and wind energy, generate DC voltage, where conversion losses can be reduced in a possible DC distribution system. This thesis will explore the feasibility of a transition to a DC distribution system, by conducting a literature study.

Original task text

"The beginning of the electric grids is sometimes referred to "The War of Currents", where AC was competing with DC. AC became the current of choice since the transformer allowed voltage conversion and high voltage long distance transmission. Today, power electronics and DC/DC converters are able to efficiently increase and decrease DC voltage as well. With the realization that most of our devices have built-in rectifiers use DC voltage, the war of currents is again raging. This project should investigate the current state of this war and evaluate the feasibility for such a transition."

Objectives:

- *Literature search to identify the current status for DC distribution grids*
- *Evaluate if the transition is feasible for common electric devices and household appliances*
- *Compare and identify advantages and disadvantages of DC and AC based on today's technology*

2 The electrical grid

In this part I will look at the overall electrical grid. The transmission system both for HVAC and HVDC will be described. The distribution system will also be reviewed, the aspects within it, and the advantages and disadvantages of an AC in the electrical grid will be looked at.

2.1 Transmission system

To understand where the distribution grid fits in, and how it works, we first need to understand the transmission system. The ***transmission system*** is the entire process, network and technologies used, from production of electrical power to delivery of electricity to the consumer.

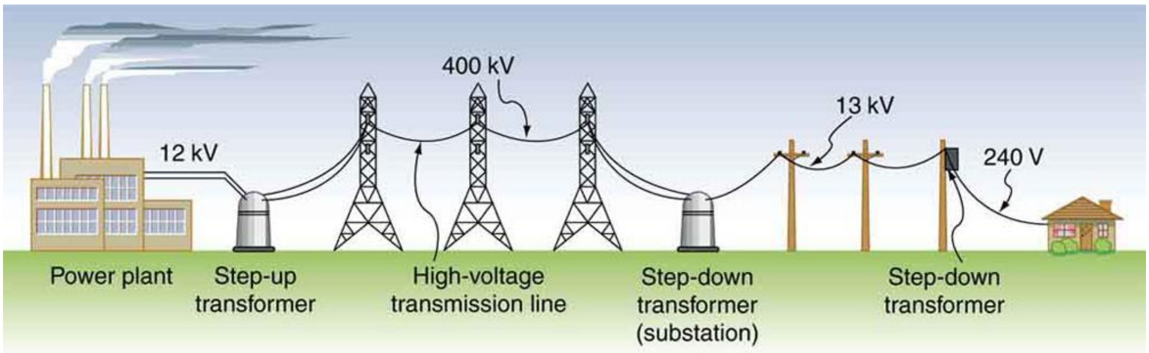


Figure 1 - Overview of a full transmission system

Figure 1 gives an overview of the transmission system, as mentioned earlier, from power production all the way to electricity delivery to the consumer. As we can see, generation plant supplies power at a rated voltage. This power is then fed into a step-up transformer. The voltage is usually increased to much higher level than the original voltage generated in the power plant. The reason for this increase in voltage is because long distance transmission lines have less losses with higher voltage. The high-voltage transmission lines are in practice a lot longer than they seem in the picture, and are classified as ***low-range***, ***medium-range*** or ***long-range*** transmission lines. Low range transmission lines are usually 50 km or less, medium transmission lines are from 50 km to 150 km, long range transmission lines are longer than 150 km.

When power has been transferred through the transmission lines, before it is fed into the distribution grid the voltage must be stepped down. This is done in a distribution substation, where a step-down transformer changes the voltage into the appropriate voltage level. The next step is distribution of power in the distribution grid. This is the process where the power is transferred and reaches the consumers

2.2 Distribution grid

The distribution grid is the final stage of distribution of electrical power from production of power, to delivery of electrical power to the consumer. The goal of the distribution grid is to supply the consumers with power. The first step into to this goal is the distribution substation to transform down the voltage from high voltage, to a voltage appropriate for the distribution grid. The voltage is reduced by using a step-down transformer. For further distribution of power, there are often multiple transformers that reduce the voltage levels, because diverse types of consumers need different amounts of power. This varies from residential homes, buildings and industrial customers.

Here the terms ***primary distribution system*** and ***secondary distribution system*** are introduced. 1. The primary distribution system consists of consumers that use a higher voltage level and have higher power consumption, compared to the low-voltage consumer. The voltage used in the primary distribution system often depends on the power required and the distance to the consumer. These voltage levels vary, but fall into the medium voltage category. In Figure 2 we can see an overview of the primary distribution grid. Where the substation is the connecting point with the transmission lines.

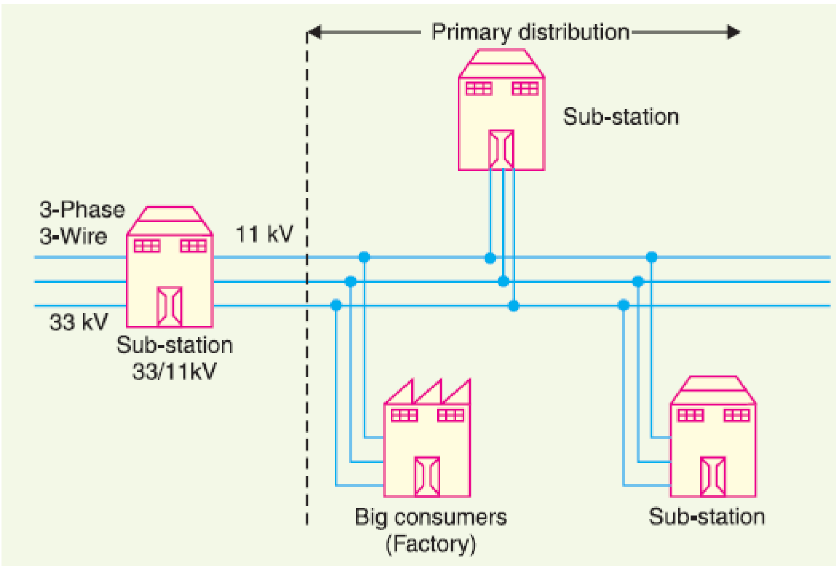


Figure 2 - Distribution grid [2]

2. The secondary distribution system is the low-voltage distribution of power, and is used by regular consumers. The voltage in this system is 230V (or 400V depending on where you live). The voltage is stepped down, using a transformer from the voltage magnitude of the primary distribution grid. These transformers that step-down the voltage to consumer appropriate voltage are usually placed near houses, so that lines do not stretch over long distances.

Distribution grids in populated areas come in two forms. One way of distributing power is by using ***overhead cables***, which are visible. These cables often have a step-down transformer on the top of poles that supply houses with power. This type of solution is not often seen in highly populated areas, like cities. One of the reasons for this is, first, many of these poles in the middle of a city are just not practical, especially in cities with tall buildings. Overhead cables are more oftenly seen in villages, and lone standing houses that need power. Another downside of these overhead cables is the protection of the structure[3]. Falling trees and weather conditions can cause accidents and fall on the lines. If this happens, repairs would have to be done, and that can take longer time than wanted. The issue of icing that is usual in places where there is colder weather, is also a problem. Figure 3 shows a step-down transformer attached to a pole with visible overhead cables.

Figure 3 - Step-down transformer hanging on pole

Another solution, which is also most common in cities where overhead cables are not a practical option, is having ***underground substations*** with a transformer. These transformers are connected to distribution cables that spread underground around in a city. They distribute power to smaller transformers that are usually located outside houses, and have the function to step down the power an additional time to make the voltage level appropriate for households. These underground cables have many advantages. One of these being that the cables are protected from storms, falling objects and cold weather. Underground cabling is also very convenient because it does not stand in the way for other structures, which makes it an excellent fit for populated areas. When considering safety, it is also a better choice since these cables are not in the open for the public.

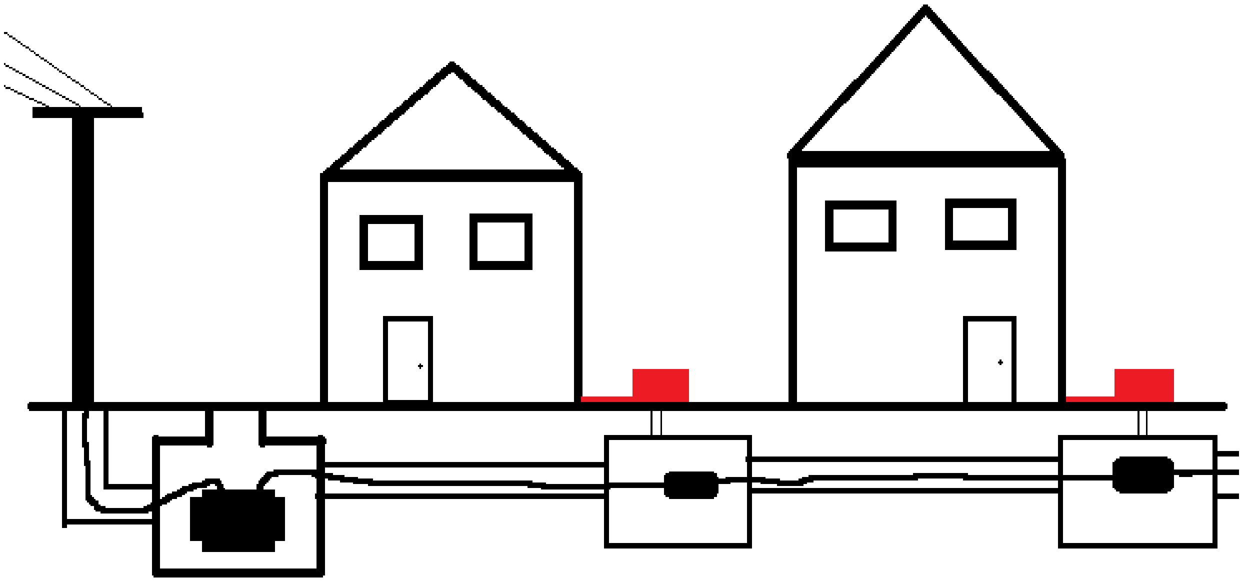


Figure 4 - Simplified overview of underground distribution grid in highly populated areas and cities.

In Figure 4 we can see a simplified version of how power is distributed underground. We can see as mentioned above, the main transformer and the way it distributes power to surrounding households. From the main transformer, cables are connected to smaller transformers that step down the voltage another time to make the voltage-level appropriate for households. Voltage level depends on the country one is in.

2.2.2 Cables used in AC systems

There are different types of cables needed to transmit power in an AC distribution system. This is due to the fact, that there are several voltage levels, and dimensioning of cables will differ, depending of the voltage levels.

For the ***primary distribution system***, the voltage magnitude varies, but is usually around 11kV – 20kV. Nexans, cable producer, has made a cable handbook [4] for their products. Here they describe which types of cables there are, and the areas of usage. While these are possible solutions for which cables to use in a distribution system, the reference is only from one cable producer. However, their assortment of cables is aligned with standards used otherwise by other producers. Nexans was chosen as an example, because they are one of the bigger cable producers in Norway. For the primary distribution system, some of the possible cables that could be used are the “BLL 24kV belagt line” and the “TSLF 12-145kV”.

The BLL 24kV cable is a single conductor, and is suitable for use in overhead power lines. The maximum rated voltage for this type of cable is 24kV. Since it is a single conductor, three cables are needed for an AC system (3-phase). This cable needs also separate grounding, since it is not “built in” the cable. The other variant in the cable handbook from Nexans, is the TSLF 12kV – 145kV cable. This type can be applied in underground structure, both directly in the earth and in tubes/channels and indoor. This type of cable is also a single conductor, which means three cables are needed for AC, and it has grounding in each conductor. These types of cables also have different rated voltages, and can be used for higher voltages than the distribution system voltage level.

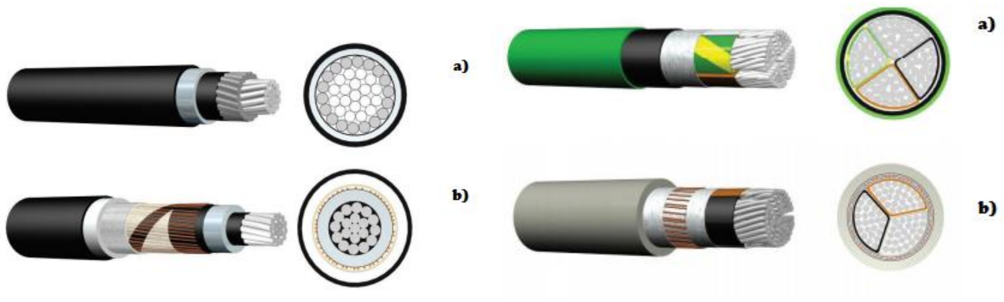


Figure 5 – a) BLL 24kV b) TLSF 12kV – 145kV c) TFXP 1kV d) TFSP 1kV [4]

For the ***secondary distribution*** system, cables with lower rated voltages are usually used. LVAC systems where 1kV is the rated voltage of the distribution system, “TFXP 1kV” and “TFSP 1kV” are commonly used. The TFXP 1kV cable is made for energy distribution, and can be placed underground or in overhead lines. It has 4 conductors, one for grounding and three for each of the phases. It is not suitable for use inside households. The TFSP 1kV on the other hand is suitable for both outdoor and indoor use, and use within buildings and houses. The difference between these are that the TFXP is a much stiffer cable compared to the TFSP, due to the insulation.

2.2.3 AC distribution grid – advantages and disadvantages

As mentioned earlier, when Westinghouse and Tesla won “the War on Currents” AC became the only type used for a long time. The reason for this is that AC was, and still is, very easy to transform and thereby increase or decrease the voltage. Furthermore, it is the easiest way of changing the magnitude of the voltage in transmission lines and adapting this, in order to be able to deliver electricity to consumers.

Transformers, compared to other power electronics, are an economical solution to voltage change and control. Voltage control is achieved by using tap changers, that can control the amount of turns there are around the primary or secondary side of the transformer. In addition, there are also two different types of tap changers, ***On-load*** and ***Off-load*** tap changer[5].

The difference between these is that the On-load tap changer can change the amount of turns on either the primary or the secondary side of the transformer (depending on where it is installed). This means that the transformer can change the output voltage while it is connected to load. Generation stations, substations, and distribution substations with a power transformer often have On-load tap changers. The Of-load tap changer can only vary its turns while it is not connected to any load. The ability for easy voltage control is what made AC the preferable choice when it came to choosing between AC or DC in the distribution grid.

The AC technology has been around for so long and, as a result of this, the infrastructure in societies is based on it. In other words, the electrical grid, over the entire world is based on AC and over time AC based technology has been developed, and become a standard. This of course affects the price on equipment used in AC systems compared to DC systems. This includes for example equipment like circuit breaker in AC systems compared to DC systems. AC circuit breakers are much cheaper than DC circuit breakers, because of the different behavior of an alternating current and a direct current, as well as large scale production of the equipment used as standard today.

Although AC in general has its advantages, it also has disadvantages. For instance, one of AC's biggest flaws is that most electrical equipment need a direct current to function properly. This means that every appliance of this sort needs to have a rectifier that converts AC to DC. This conversion also applies to many renewable sources of power, like solar cells (PV cells). Solar cells today generate DC, which needs to be inverted to AC and fed into the grid. This means that power that is generated from solar cells needs to be first converted from DC to AC, and in many cases back to DC again for the energy to be able to power the appliances.

Although AC transmission lines are most commonly used today, they also have disadvantages. Long distance transmission lines have very high voltage, this often has unwanted effects such as "corona effect" and dielectric losses (with high voltages). "Corona effect" is an electric discharge which is caused by ionization of the air surrounding cables. This electric discharge presents itself as waste of energy in high voltage transmission lines. Dielectric losses are losses in specific areas due to heating of the conductor. Another issue with AC transmission lines is the wire size, which is affected by skin effect. Skin effect prevents an alternating current from conducting current through the whole cable, and instead only conducts in the edges of the wire. The result of this is that HVAC transmission lines have a lower capacity for transporting power.

When power is transported from one transmission line to a local grid, one needs to make sure that the frequency is the same when it is fed into the grid. This means that an AC transmission line needs to be synchronized with a new grid.

2.3 High voltage DC transmission lines

In today's electrical grid, high voltage DC (HVDC) transmission lines are one of the most efficient ways of transmitting substantial amounts of power over long distances. HVDC transmission lines are suitable for both overhead lines, underground lines and subsea lines. The use of HVDC in transmission lines proves to be much more efficient compared to HVAC transmission lines[6], in terms of economy and environment.

One of the most appealing causes for the use of HVDC is that it is asynchronous. In other words, it has no frequency. The benefit of not having a frequency is that it can transmit energy between two grids without synchronization. Another benefit of the HVDC transmission line is that it has much lower material costs, and construction costs. HVDC can be transmitted through a single line and ground as return path, also known as a unipolar connection. Alternatively, can we use a bipolar connection as a solution for conducting, and one can uses two conductors instead of three. HVAC on the other hand uses three conductors due to how AC works.

When losses are considered for a HVAC and HVDC transmission line, they increase with increasing distance of the transmission line. This is one of the main speaking points for the use of HVDC in transmission lines. While HVAC has losses in the form of skin effect, resistive losses and reactive losses, the HVDC does not have a reactive component, has only resistive losses.

In [7] [8] authors have done an evaluation of power loss in a HVDC transmission line, and an HVAC transmission line. The results of the evaluation and calculations in [7] show that in short transmission lines (50km range) the loss difference between HVAC and HVDC is minimal. While when length of the transmission line is increased to 100 km and 150 km, the losses in HVAC increase drastically. The HVDC transmission line on the other hand has minimal changes in the total losses regardless of cable length. In Table 1 we can see the total losses in percent for HVAC and HVDC transmission lines depending on lengths.

Length [km]	*HVDC total losses [%]*	*HVAC total losses [%]*
50	4.26	5.3
100	4.73	8.04
150	4.77	19

Table 1 – Calculated [7] losses for different lengths in HVAC and HVDC transmission lines

There are also disadvantages when it comes to development and economy using HVDC transmission lines. Due to the AC dominance in the electrical grid for a long time, development of equipment like high power converters has not come as far. The result of this is that converter technology that is usable in HVDC lines is expensive. These converters also have a problem because they create harmonics which requires that these converters need to have filters.

Although HVDC transmission lines that are in use today, have both advantages and disadvantages, they are well established as a viable solution. The usage of a DC distribution system could prove to have a positive impact on the future distribution systems by increasing reliability, stability and overall efficiency. The knowledge that has come from HVDC structure and research could also be a contributor to the evolution of the DC distribution grid.

3 Converters

In today's transmission system, distribution system and households we have converters of some sort in use. There are several types of converters, with different areas of usage. For example, in long distance transmission lines, DC is an efficient way of transmitting power. On both ends of a DC transmission line cable a converter is in use. The three methods for converting power are:

- AC to DC (rectifier)
- DC to AC (inverter)
- DC to DC (converter)

The way conversions from AC to DC or the other way around are done differ from each of the converter types. In the following sections, we will look at how these converters work.

3.1 AC / DC (rectifiers)

When we are describing the process of supplying a household with power, the line current from a transmission system is alternating current (AC). Although many of our household appliances are just plugged into the socket, DC is the type of current needed for them to work. The purpose of an AC/DC converter is to convert an alternating current input to a direct current output. This process is known as ***rectification***. These rectifiers can be used for many purposes, but are often used as a component in a DC power supply or in high-voltage direct current (DC) transmission systems.

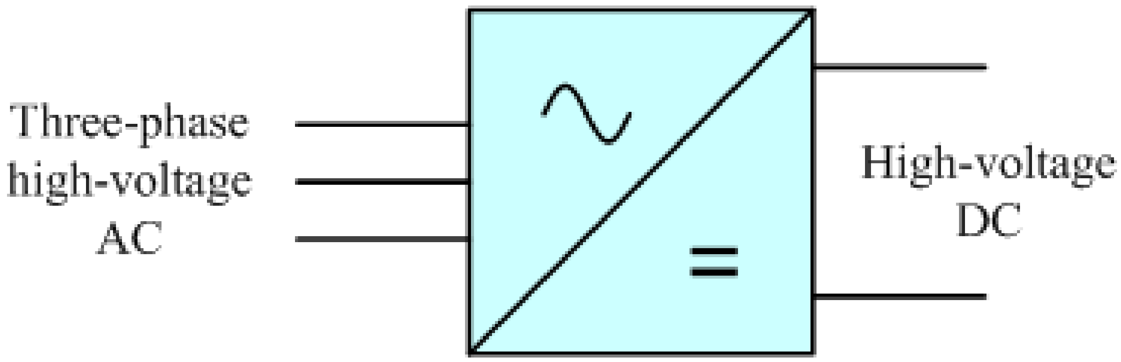


Figure 6 - Symbol for AC/DC converter

3.1.1 6-Pulse bridge rectifier

In high voltage systems, there are different ways of converting from AC to DC. An uncomplicated way off explaining how the current is converted from AC to DC is by using the six-pulse bridge rectifier[9] as an example.

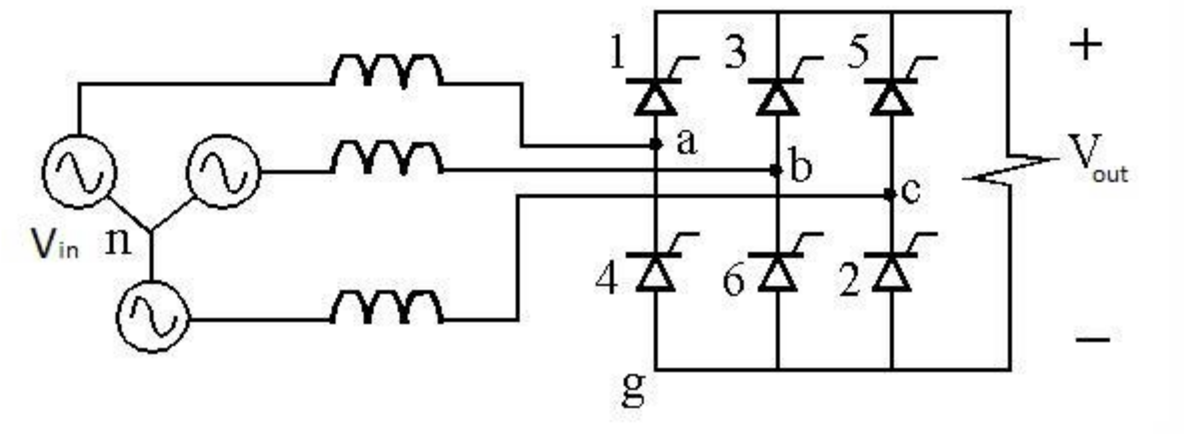


Figure 7 - Six-pulse bridge rectifier [10]

The way this rectifier is converting from AC to DC is by one single phase (a, b, c) conducting current through one of the control units marked with numbers 1-6 in Figure 7. First, phase «a» conducts current through control unit 1 and to output V_{out}. Next, phase «c» conducts current through unit 2 and into V_{out}. And this goes on until it is has gone a full circle through all the control units. The result of this kind of switching between units and phases gives the wanted outcome of a direct current (DC).

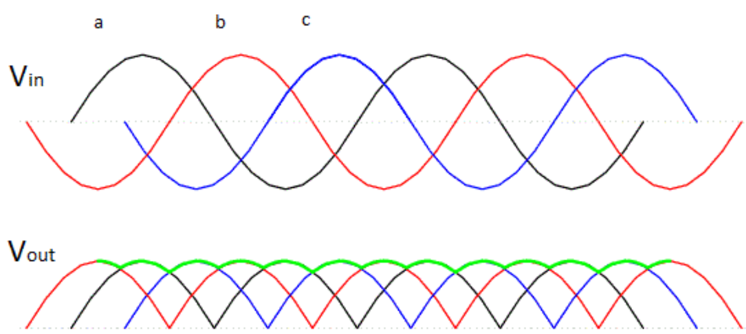


Figure 8 - Illustration of rectifying process in six-pulse bridge [11]

In Figure 8 we can see the AC input with the three phases a, b and c conducting through the control units. Each of the peaks in V_{in}, both positive and negative direction are part of the rectified DC voltage. We can see in the graph for V_{out} that each of the tops for every consecutive phase is the rectified DC voltage. Because of the nature of direct current and that it can only go in one direction the negative AC voltage becomes a positive DC voltage.

3.1.2 12-Pulse bridge rectifier

Next, we have the twelve-pulse bridge rectifier which is commonly used in high power systems. The reason for this being that even though the six-pulse bridge rectifier successfully converts to DC, there is still the possibility for harmonic distortions to occur. A harmonic distortion[12] is an electrical pollution that can cause irregularities and/or malfunctions in the system if it exceeds a certain level. Examples of these uncontrolled harmonics are cables overheating and damage on equipment due to irregular voltage levels.

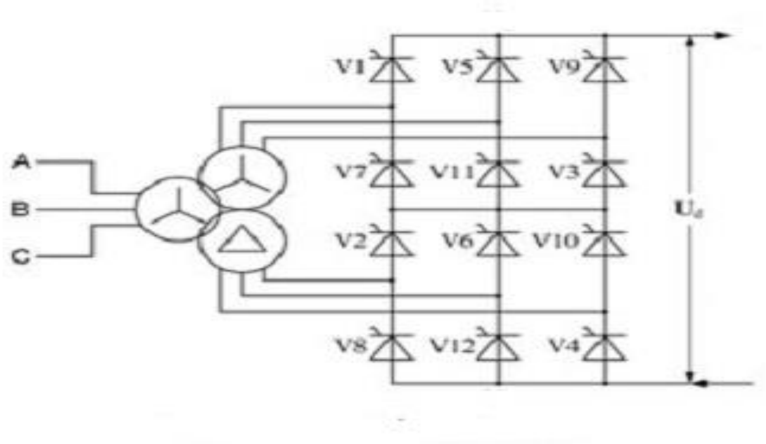


Figure 9 - 12-pulse bridge rectifier has 12 pulses with lower spikes, which ensure a more stable system [13]

The way a 12-pulse bridge rectifier (seen in Figure 9) is connected is by having two 6-pulse bridge rectifiers in parallel which are phase shifted at 30^o. The phase shift is achieved by adding a 3-winding transformer in front of the converter. This transformer as we can see has two secondary windings, where one is connected in Wye, while the other is connected in Delta. These two secondary windings are connected to the two 6-pulse bridge rectifiers, which results in an output that is half of single bridge(6-pulse), while also one peak being phase shifted at 30^o compared to the other. This will, from the primary side of the transformer, also give lower current spikes per phase and less potential for harmonic distortion on the system.

3.2 DC/AC Inverter

DC/AC inverters are in use in different types of applications, and could also be used in a DC distribution grid. Examples of use of inverters, are in DC power supplies (batteries), electric motor speed control and in power grid. The most relevant usage of power inverters described in this thesis is the use of inverters in the power grid. Knowing how an inverter functions and makes DC into AC is important. There are different types of inverters, that create different types of waveforms as an AC output. The two most common types are sine wave and modified sine wave[14].

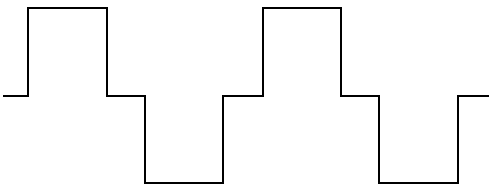


Figure 10 – Illustration of the modified sine wave produced by an inverter

Figure 10 illustrates a modified sine wave, which resembles a square wave. The difference is that it has an extra step that makes it more like the sine wave form. In the modified sine wave inverter, there are three voltage levels of the output waveform; high, zero and low. These three voltage levels are the positive peak, voltage at zero, and the negative peak.

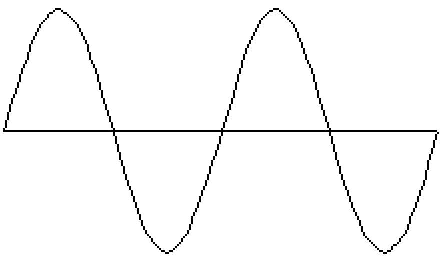


Figure 11 – Illustration of sine wave

Figure 11 illustrates a pure sine wave form which is produced by an inverter. In practice, the "pure" sine waveform produced by an inverter will not be as perfect as shown in Figure 11. It will most likely be more "choppy", although the harmonic distortion will be much lower in a sine wave inverter than a modified sine wave inverter. The difference in harmonic distortions will also vary when comparing high-end sine wave inverters with low-end sine wave inverters.

A basic inverter is a circuit with a DC power source connected to a transformer, with a switch rapidly switching back and forth. The current going through the switches goes in two ends of the primary windings of the transformer, which produces an alternating current in the secondary side of the transformer. The reason the DC is inverted to AC is because the switching of the direct current is conducted into the two paths of the primary side and create a difference in the magnetic field in the primary side. This results in an alternating current on the secondary side.

There are different types of inverters[15], but for a 3-phase system it is necessary to use an inverter made specifically for 3-phase. These are used in high power applications like high-voltage DC power transmission.

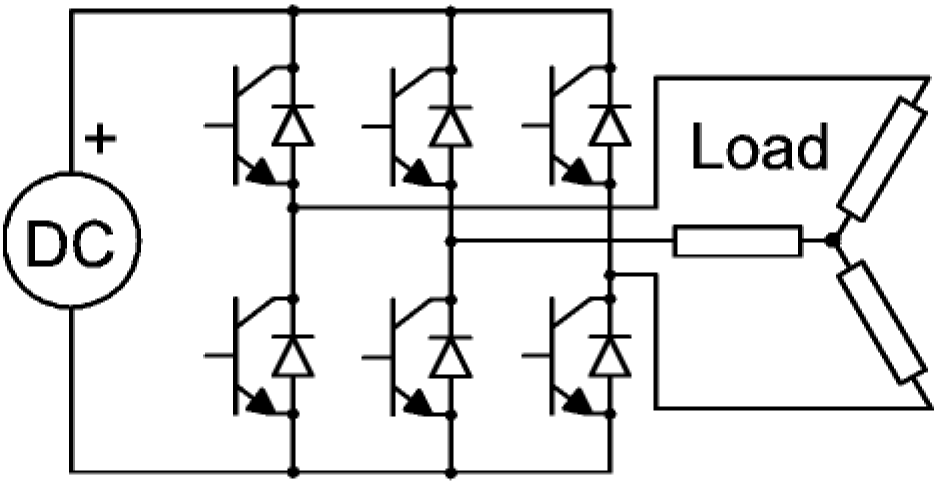


Figure 12 – 3-phase inverter simplified circuit

A 3-phase inverter bridge (as shown in figure 12) is in theory a set of three single-phase inverter switches, which are connected to one of the three output terminals. These switches are controlled so that the output wave form generates a 3-phase AC supply. The 3-phase inverters have to achieve conduction modes,180° mode and 120° mode. The 180° mode of conduction has all switches in conduction state for 180° where three switches are in conduction mode at the same time (with 60° phase shift on each other).
In 120° conduction mode each switch is in a conduction state for 120°, which makes a six-step waveform type. This means that the switches will conduct in pairs to create one phase.

3.2.1 Modified sine wave vs. Pure sine wave

As we can see, on the illustrations in Figures 10 and 11, there is a clear difference between a modified and pure sine wave. The difference between these two types of AC outputs produced by inverters is that the area of usage is very different. Most common household appliances will be able to run on a modified sine wave, but sensitive electronic and critical equipment do require a more stable AC source.

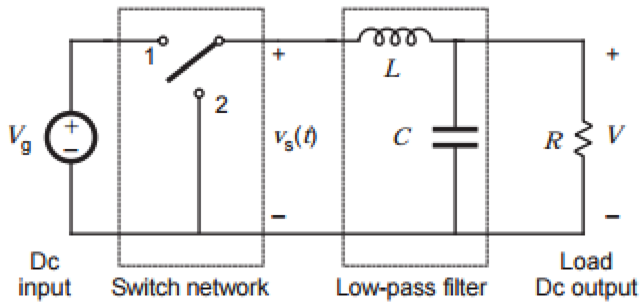
Another difference between the modified- and pure sine wave is the harmonic distortion[16], which is much higher in inverters with a modified sine wave output. This distortion also varies in different types of sine wave inverters, and is stated in data sheets. The efficiency difference in these two types of inverters are also worth noting. An inverter with a modified sine wave output will reduce the energy efficiency of transformers and motors by 10%-20%. These losses are often heat losses and are in the long run damaging for equipment.

3.3 DC/DC converters

The last type of converter reviewed in this thesis is the DC / DC converter[17] . These types of converters are widely used in DC power supplies and DC motor drive applications. The input of these converters is often from a rectified line voltage, which is unregulated. DC/DC converters are therefore often used to regulate a DC voltage to a desired magnitude. There are many types of DC/DC converters, but the more complicated converter topologies are based on these:

- Step-down (buck) converters
- Step-up (boost) converters
- Step-up/step-down (buck – boost) converter

The buck and boost converters have basic topologies, whilst the buck-boost converter is a combination of the two. The buck converter reduces the voltage level, the boost converter increases the voltage while the buck-boost converter can increase and decrease the voltage.



Figur 13 - Step down (buck) converter [17]

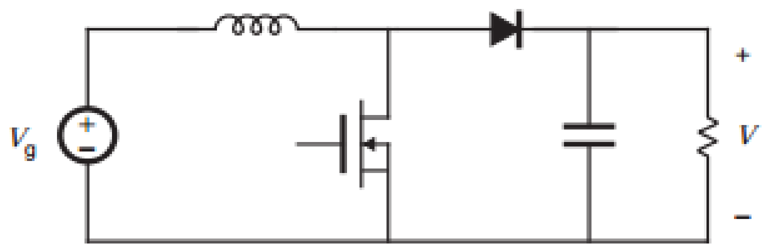
In Figure 13 we can see how a buck converter circuit looks like. The buck converter has an output voltage V equal to V_g when the switch is in position 1 in the switch network, and V equal to zero when in position 2. The result of the switching between position 1 and 2 is a square waveform with a period T_s and duty cycle D. The frequency of the switch equals to $1/T_s$, and is usually in the range of 1kHZ – 1Mhz, where the switching component often is a semiconductor device.

In addition to the switching network, there is also a low-pass filter (LP-filter) connected in the circuit. This is because the desired voltage component, in addition has undesired harmonics due to the switching frequency. These harmonics are removed using the LP-filter. The filter has a corner frequency given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The corner frequency of LP-filter will be chosen to less than the switching frequency so that the filter does not let pass anything else than the DC component of $v_s(t)$ which is made by the switching network. Given that the inductor and capacitor are ideal, there are no losses in the process of removing the harmonics.

The step-up (boost) converter[18] works in the same way, although its topology is a little different. For the converter to be able to boost the voltage up, the inductor is placed before the diode so that when the switch is on, the current flows through the inductor and stores energy by creating a magnetic field. When the switch is off, the energy in the inductor and the original source will be in series. This causes the voltage to increase and charge the capacitor through the diode. The topology of a boost converter is illustrated in Figure 14.



Figur 14 – Step-up (boost) converter topology [17]

4 DC in Distribution grid

In our modern society, a highly reliable power supply is of great importance. The reason for this is that the most critical appliances are dependent on a constant and reliable flow of power such as hospitals, data centers and communication systems. With the current solutions, there is an extensive use of power electronic converters that proves to be highly reliable and easily controllable. However, these power converters also have some efficiency issues, considering there are many conversion steps back and forth. This results in overall system efficiency to be lower than wanted. Because of this, DC power distribution systems have become a research topic that has caught interest. Motivation for the development of DC was first because long-distance transmission of power showed to be more efficient when DC is used. This is because AC has a reactive power-demand which does not exist in DC, this means that only active power is transferred and loss is much lower.

In newer time, renewable energy sources like photovoltaics (PV)[19] and wind have become more relevant. These power sources generate DC, which means a conversion from DC to AC, and synchronization to the grid is necessary to be able to feed this power into the grid. With these types of power sources, a DC distribution grid is an interesting idea which could be relevant for the centralized electrical grid, a microgrid or a nanogrid. Although important for the future, deeper insight on microgrid and nanogrid will not be covered in this thesis, but it is important to note that they may be relevant.

Implementation of DC would cause a reduction in amount of conversions, which would directly influence the overall loss in a grid. These problems also include battery banks and electrical vehicles (EV). To charge an EV it is necessary to have a DC input for the battery, which means conversions from current AC solution. This also includes battery banks, that need conversion and synchronization to be able to be fed to the grid.

For implementation of a DC distribution grid, there are many factors that need to be considered; the grid solutions, how one would distribute power and how the interconnections of the grid will be schemed. This means that it is important to look at practical solutions for where in the grid DC should be used, and how it should branch out all the way to the consumers. What would one do with the current grid that is already established, and is it possible to reuse some of it. Could the already installed AC system and the cables in use be repurposed and used in a future DC. In my opinion it is necessary to establish and set up a system for standardized voltage magnitudes for the distribution system. There are many different suggestions that need to be explored for this voltage, and how it would be solved.

Since one of the speaking points of DC in distribution of power is that it is more efficient. The aspects around the efficiency of DC, how and what makes it more efficient are issues that need more research. Here a comparison between the conversion losses in an AC system and a DC system would be important. As well as comparing the conduction losses in both the AC distribution system and the DC distribution system.

4.1 DC distribution topologies

4.1.1 LVDC distribution system

A DC distribution system starts of the point from when the transmission lines end. The distribution system can be fed by a DC line that uses a DC/DC buck converter to reduce the voltage magnitude. The more likely option is that the distribution system will be fed by an AC line that uses a step-down transformer to reduce the voltage magnitude. For simplicity sake, since distribution grid is the objective, we assume that power through transmission lines is delivered by the means of AC. Different types of structures of DC distribution system will be reviewed here.

4.1.1.1 LVDC Distribution system – AC at consumer level

A low voltage DC (LVDC) distribution system is proposed in [20], where there are to suggestions to how power should be distributed by using DC. In addition to this proposal, other types of DC distribution solutions are to be considered and suggested in other research, which will be considered later in this chapter. In Figure 15 the suggested distribution grid [20] has DC lines from transformer substation that steps down the voltage and rectifies the voltage from AC to DC. The DC line itself goes from the main distribution line and branches out to houses, where it is inverted back to AC using DC/AC inverters. These inverters would be installed in the already existing transformer boxes outside houses.

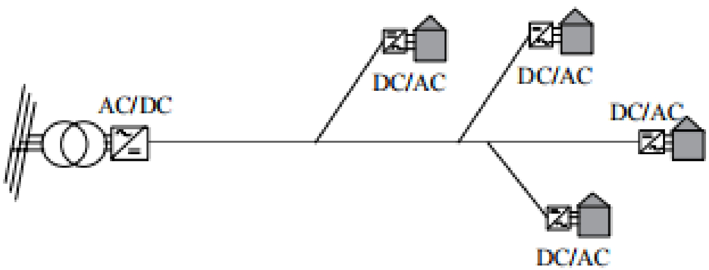


Figure 15 - Suggested LVDC Distribution system extending to residential homes

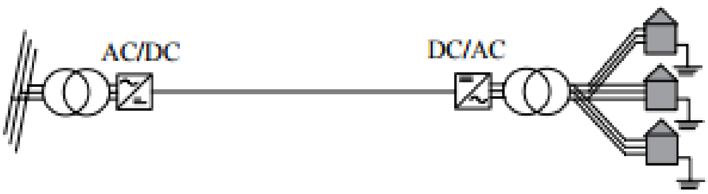


Figure 16 - LVDC distribution with DC distribution line [20]

The second suggestion to how the DC distribution system topology would be constructed shown in Figure 16. This topology consists of two AC systems which are connected with a DC line. The connection to the transmission line is that same as in the previous suggestion, with a step-down transformer and an AC/DC rectifier. The difference is that the DC voltage is converted back to AC and a transformer steps down the voltage again to a magnitude which can be used by consumers. This resembles a standard high voltage DC (HVDC) transmission line, which is most commonly used in long-distance power transmission. This type of structure is called a ***point-to-point*** distribution structure, because power is distributed using DC from a point to another point.

Unipolar structure

These two structure types shown in Figure 15 and 16) are both interesting options for a future DC distribution grid. There are two different ways of connecting a DC line of the kind in Figure 16 ***unipolar*** system and ***bipolar*** system [21] are described, where the difference is number of conductors and the voltage level across the conductors that transmit energy. Here we will look at the first suggested topology, with a unipolar and bipolar system. The unipolar system is shown in Figure 17 [21], it illustrates how customers are connected to the grid. As we can see, consumers are connected to both conductors in the unipolar system, where only one voltage level is available, and the other conductor is neutral. This unipolar type of system has a downside when it comes to reliability. In a fault scenario, if the one conductor transmitting energy suddenly stops conducting due to a fault, it means that all loads connected to this conductor would be without a power supply. Both Figure 17 and Figure 18 are possible structures of the DC distribution system with an inverter supplying AC to households/buildings (as in Figure 15).

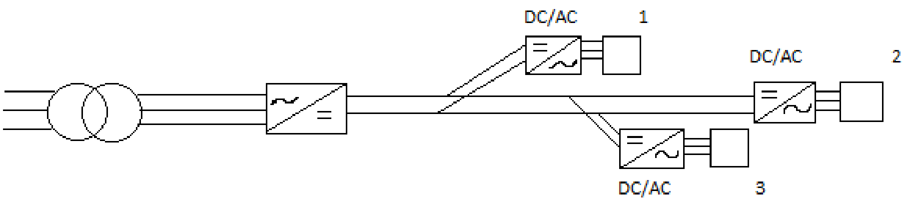


Figure 17 - Unipolar DC structure for LVDC distribution grid

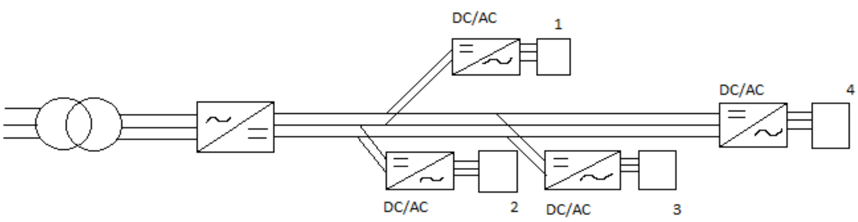


Figure 18 - Bipolar LVDC for distribution grid

Bipolar structure

A bipolar system is very similar to the unipolar, since it means two unipolar systems connected in series. The transformer in the grid can be a two-winding transformer which steps down the voltage to a LVAC magnitude. This is then fed into a single AC/DC converter, which rectifies the voltage. This is the case in the LVDC distribution in Figure 15. Another solution is to use a three-winding transformer which transforms the AC voltage from the grid into two equal voltages. This is then fed into two line converters, that are connected in a unipolar structure, with one positive pole to neutral and one negative pole to neutral.

According to IEC 60038 standard[22] the maximum voltage for a LV system is 1500V DC. For a bipolar DC system like this, the voltage can be chosen to be ±750V DC. This is because the total voltage between the two conductors should be equal to two time the voltage between one conductor and neutral, hence 1500V DC. This lives up to the IEC standard, and is within its imposed laws. A bipolar structure like this has four different methods for distributing power to the consumer level. These four methods are illustrated in Figure 18, and they are as following; positive pole and neutral, negative pole and neutral, between positive and negative pole and between positive and negative pole and neutral.

A distribution system structured like the bipolar LVDC system has better reliability in case of a fault, compared to the unipolar. The reason for this is that the three cables are not reliant on each other to transmit power. The result of this is that if half of the grid is out of order, one can ensure that the rest of the half is in order, and still working. The proposed system in Figure 18 is an actual test subject, that has been tested in the field. At the time of the posting of [21] the system was both installed and preliminary tests were done.

4.1.1.2 LVDC distribution system – DC at consumer level

In a research article on DC distribution system [23] authors have made another proposal for a future DC distribution grid. A model has been made for the LVDC distribution system, as well as an analysis off the system. Simulations have been done for the whole model, including converters, distribution line and the load. An analysis has been performed of voltage and load in a LVDC distribution system. A model of the components used in the LVDC distribution system has been made, but some of those components will not be evaluated in this thesis. In the model in Figure 19a), we can see the proposed model for a unipolar LVDC distribution system, and in Figure 19 b) a bipolar distribution system.

The bipolar distribution system is structured in the same way as in Figure 17. The AC source is connected to a transformer (two winding), with a single AC/DC rectifier. This rectifier is connected to a bipolar LVDC line, which has a negative, positive and neutral pole. As mentioned earlier, this type of structure offers a reliable power supply. The difference between the two proposed structures in Figure 18 and Figure 19 is that the distribution lines are connected to DC/DC converters instead of DC/AC inverters. This means that the households are supplied by a DC source, which is stepped down to a consumer-friendly magnitude.

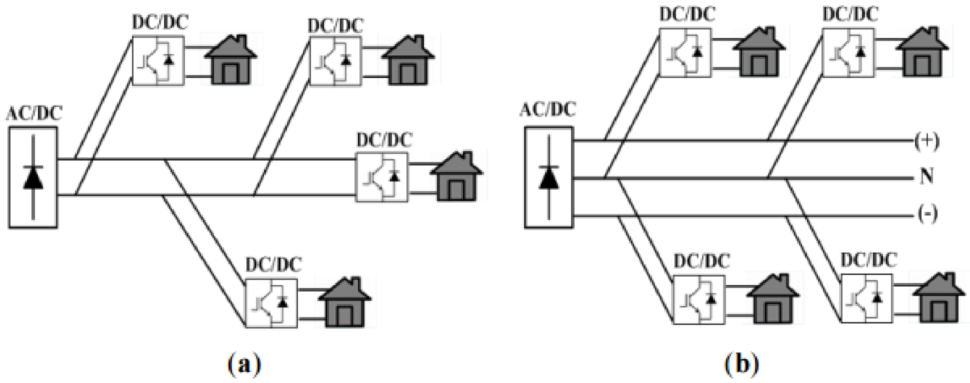
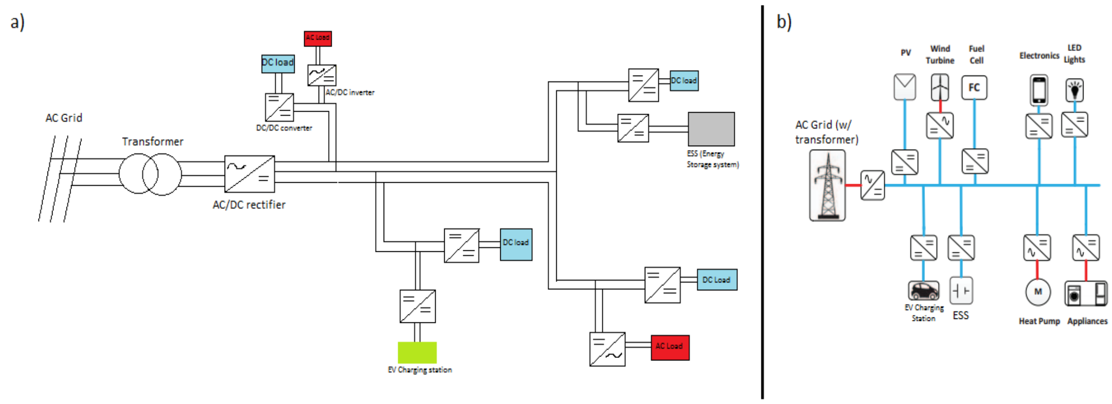


Figure 19 - Components in a LVDC distribution system [23]

In a system with DC supplying homes, one could imagine that the amount of conversions from AC to DC and DC to AC would be lowered within a household. In reference [24] authors research a LVDC distribution system for residential applications. In the article, although residential applications are the focus, a LVDC distribution structure is proposed. The suggestion for LVDC distribution system has many similarities to the one suggested in Figure 18, which makes it relevant for discussion.

In Figure 20 a), a suggested component scheme for a LVDC distribution grid is illustrated. Figure 20 b) shows how the conversion stages between the LVDC grid and loads is done. For some of the components in this structure there would be a reduction in conversions, while others would have to get additional conversions. The difference is that most components run on DC. Fuel cells, photovoltaics, electronics, LED lights, electrical vehicles (charging stations) and energy storage systems are examples of DC based components which are used in residential applications.

Photovoltaics and energy storage systems would benefit a lot from such a distribution system. The reason for this is that PVs and ESS would not have to convert the DC generated/stored to AC and synchronize it with the grid, directly in to it. Many household appliances, electronics and EV charging stations would also avoid this conversion stage from AC to DC, instead only DC/DC converters would have to adjust the voltage magnitude to appropriate levels for the different types of applications.



Figur 20 - LVDC distribution grid a) with a bipolar structure b) showing components and power electronics needed [24]

4.1.2 MVDC distribution system

In addition to LVDC distribution system, there are proposals suggesting use of medium-voltage DC (MVDC) distribution systems. The MVDC distribution system is part of the primary distribution system, which transmits power from the high voltage transmission lines, to the low voltage (secondary) distribution lines. In a research [25] authors employed at RWTH Aachen University have explored the possibilities of a small scale MVDC distribution system for a new campus site. The MVDC distribution system was made to supply several research facilities at the new campus. The distribution lines are structured to be bipolar, so that the voltage is across the negative and positive pole equals to two times the pole to neutral voltage. The voltage is chosen by considering typical voltage source converters and their DC outputs. A converter with U_{AC} = 6kV gives an U_{DC} = 10kV. Converters with lower voltage inputs tend to have much higher currents, which increases heat loss. With a converter supplying the grid with 10kV DC the bipolar structure has a U_{pos} = 5kV and U_{neg} = 5kV voltages in the positive and negative poles.

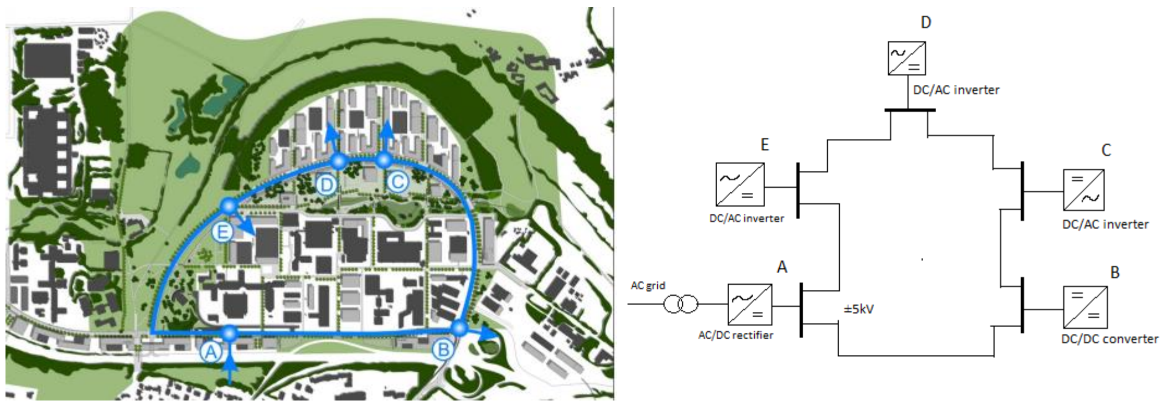


Figure 21 - a) Map of campus and proposed MVDC system [25] b) ring bus MVDC distribution system

In Figure 21 a), we can see a map of area for the new MVDC distribution system. The points with given letters (B-E) are connections to specific research labs and in general for the low-voltage distribution system. Point A on the map is the connection between the grid and the MVDC system. The system gives several options when it comes to distribution of power, two proposals were made between a single feeder and a ring bus for the system.

A similar consideration is also made in reference [26] on suggestions for different structures. A single feeder distribution line could work for this system, but it has some negative aspects to it that are important to note. For the single feeder to be able to supply all loads when at full load, the conductor would have to have a very big cross section. In addition to this a fault, a point A, (where the AC/DC rectifier is located) the entire system would have to be switched off. This means there would be no DC supply to the MVDC distribution system.

The other alternative for structure of the system is a ring bus as seen in Figure 21 b) [25]. This type of connection offers a more reliable system, with advantages that the single feeder system cannot. The inverters in the distribution buses (C-E) are connected to different types of loads, and B is connected to bi-directional DC/DC converter that charges a battery energy storage system (BESS). The reason this type of distribution system is advantageous is in case of a fault in one of the lines between the loads, a full system shutdown is not necessarily needed. With a system like this in place, and a topology like this one would be able to distribute power from transmission lines to the low voltage part of the distribution grid with much lower losses. This is in terms of both heating losses and conversion losses, which increases the overall efficiency of the distribution system.

There are different ways of utilizing DC in a MVDC distribution system. In the proposal above, the whole medium voltage distribution grid utilizes DC. Authors in [27] suggest a different usage of DC in the medium voltage distribution system, shown in Figure 22. The infrastructure of the grid is interconnected so that two medium voltage AC (MVAC) systems are supplied by a high voltage transmission line. The MVDC distribution grid is connected between the two MVAC systems, as a link. The MVDC line also supplies a DC power to LVDC loads, which can be residential houses or buildings. These loads have a DC/DC converter, which steps down the DC voltage to a low voltage level appropriate for consumer use.

For the MVDC grid to be able to be fed into the MVAC grid, inverters need to convert the DC to AC. As for the PVs and windmill connected to the MVDC grid, it can easily be fed into the distribution grid for extra power which can be distributed, or even stored in an energy storage system. A distribution line like this can be advantageous, not only because it uses DC to distribute power. It also contributes to an overall more reliability in the two AC systems that are linked together by the MVDC system.

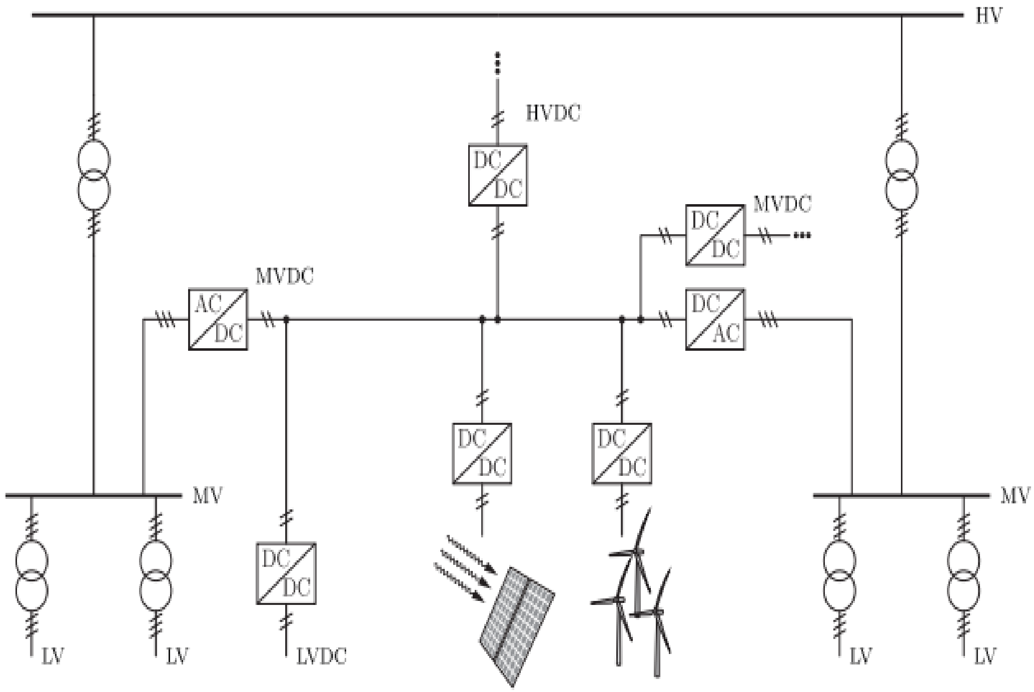


Figure 22 - MVDC distribution system linked between two MVAC systems [27]

The solutions presented for the structure of a DC distribution grid, for both low voltage and medium voltage, are a contribution to give overview of the possibilities that have been researched. To make a better assessment for what the best choice is, other considerations need to be done, such as:

- Voltage standards already established
- Converters usage in a DC system
- Cables: can cables that already are in use be utilized in a DC distribution system
- Efficiency: Discover the efficiency the use of DC, compared to AC in the distribution system

4.1.3 LVDC within households/buildings

An important part of the considered DC distribution system is how households and residential buildings are to be connected. There are two options for structure, one where the load is based on today's solutions, where AC is supplied to households/buildings. The other possibility is to supply the households/buildings with DC. This solution is a viable possibility because many appliances require DC, and not AC. Authors in [28] describe a LVDC system for households where DC goes through the wiring. The reason this kind of proposal is suggested is because the number of applications that use DC in a household/building seem to outweigh the number of AC applications.

Kitchen appliances, LED lights, computers, other low power electronics all rely on DC to work. Although the supplied DC voltage might be too high for many of these applications, a DC/DC converter can be used to secure power supply. This type of structure also makes EV charging stations and energy storage systems (ESS) easier to connect and with less conversions. Here a simple DC/DC buck converter would be used to step down the voltage, and charge both ESS and EV charging station. Figure 23 [28] shows how a possible household or building would look with DC supplied power, and DC/DC buck converters stepping down the voltage to supply low power loads. Voltage supplied to high power loads is directly from grid supply.

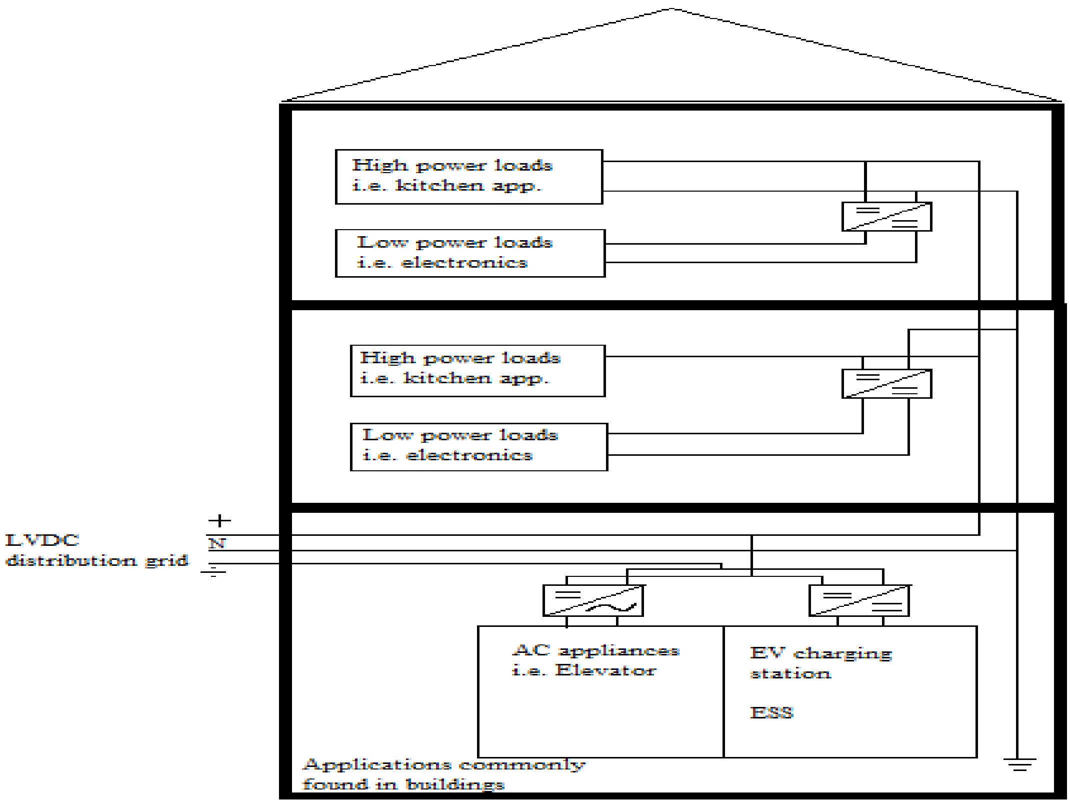


Figure 23 – LVDC household/building distribution

4.1.4 LVDC distribution system – Test pilot

The proposals and suggestions for both MVDC and LVDC distribution systems are needed to contribute to increased development of the DC distribution system. While these suggestions and proposals are positive in research and in minor scale, real life test pilots of such a system are even more helpful. Due to increased requirements for reliability in Finland a test pilot for a unipolar point-to-point LVDC system [29] was implemented by ABB and distribution system operator Elenia Oy in 2014. This was implemented to get further experience within the DC distribution systems field. The structure of the system is like the structure in Figure 16. Where the rectifier converts the voltage from 400V AC to 570V DC, which is then boosted to 750V DC, to reduce the current.

In Figure 24 we can see how the LVDC distribution line was laid out, and where the conversions occur. In this system, ABB also supplies technical support by the means of data analysis sent from the converter cabinets on each point. Here data is collected, and is plotted through a web page, and fault monitoring can also be done through this tech support.

The most interesting part of this pilot test is to see how consumers have been affected, and if there were any disturbances or annoyances for the consumers. Through the implementation of this system, consumers were only disconnected temporarily, while the swap between MVAC and LVDC was done. No faults were detected, and if a fault would happen an energy storage system was in place for supply as back up.

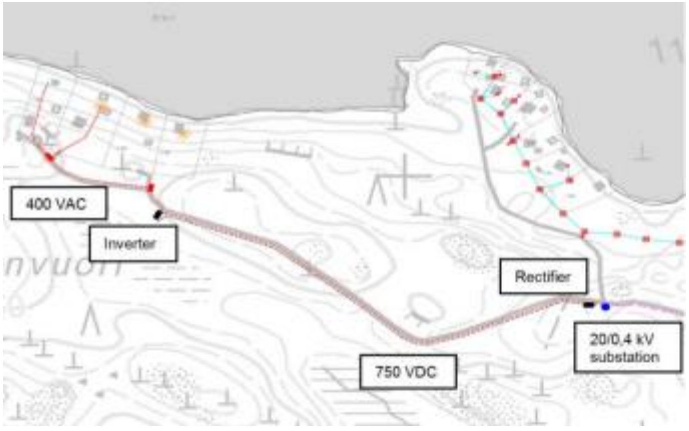


Figure 24 – Map overview of the pilot tested LVDC distribution system

4.2 Voltage levels in DC distribution systems

Before discussing converters, cables and the efficiency of DC distribution grid, it is necessary to consider what voltage levels should be used in in a DC distribution grid and in residential houses and buildings. Through the different grid solutions proposed previouslys, different voltage levels have been mentioned and discussed. In reference [28, 30] voltage-level for a DC distribution system is described and discussed.

Voltage Level of Applications [V DC]	**Applications**
1500V	PV systems, traction systems
750V	Tram power systems
400V	Electric Vehicles
380V	Data centers
48V	Telecom, small PV systems
24V	Lighting systems (LED)
12V	Lighting
5V	Microprocessors and Electronics

Table 2 - Voltage usage for different applications

Table 2 [28] shows what type of different voltage levels are needed to power several types of applications. The voltage usage of these different appliances is shown because this offers an insight in what kind of appliances DC distribution can be used for. This also means that voltage standardizations should be adapted to be suitable for these applications to be able to utilize the DC distribution system.

For the LVDC distribution grid considered in Figure 18 and Figure 19, a 1500V DC voltage level is proposed for a bipolar connection, which makes the voltage between negative/positive pole and neutral to be 750V. As mentioned, this upholds the requirements of the IEC standards for low voltage systems. The difference would be that the one in Figure 17 would use a DC/AC inverter to supply households with AC, while the one in Figure 19 would convert it using a DC/DC buck converter to lower the voltage level. The advantage of such a high voltage, even in a LV system, is that the losses are lowered due to lower current which results in lower conduction losses.

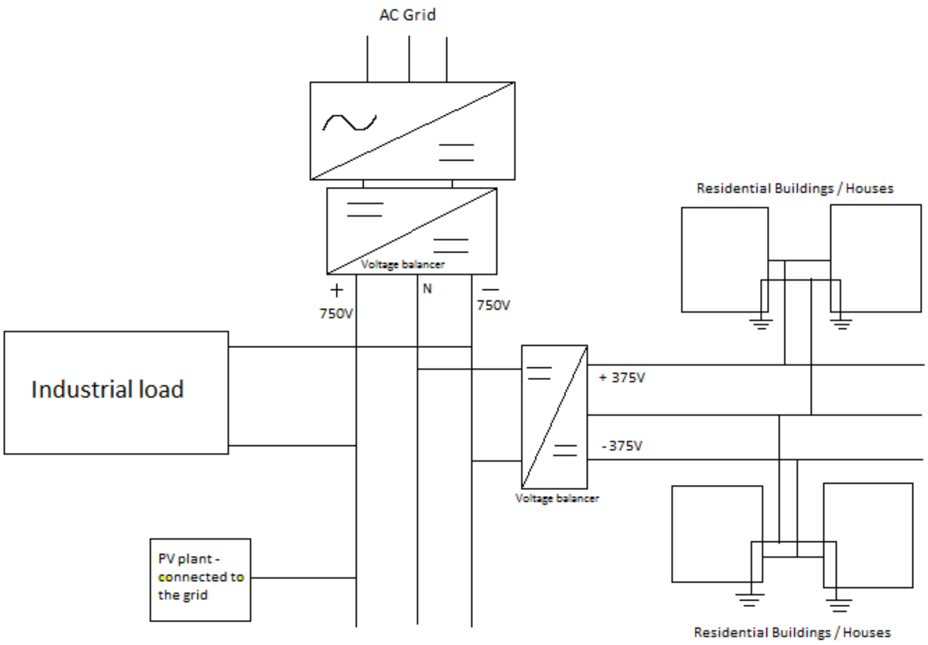


Figure 25 - LVDC distribution system with connection to residential buildings/homes

In Figure 25 we can see LVDC systems, with both the LVDC distribution system and supply of residential buildings/houses which is proposed in [28]. This type of system is very similar and could also be applicable to a system structured like Figure 18 and Figure 19. The main distribution line is using a 1500V DC (±750V DC) grid with a unipolar structure. This main line can branch out and extract a bipolar 750V DC (±375V DC) line that supplies households and buildings. If one were to apply this type of structure like shown in Figure 18, then it would be that an inverter would have to be implemented at some point to supply the house. This type of hybrid AC/DC could be an easier approach considering ACs foothold in the power grid we have today.

There are several options for selection of the voltage magnitude in a DC distribution grid. One of the main problems with selection of a voltage level is that there are no specifically defined standards at present time. This makes it more of a theoretical selection, then a practical one, which could be implemented in the real world. One specific voltage level that is researched though, is for data center distribution systems. In [31-33] research shows that data centers have an increased efficiency when using 380-400V DC. The research and work done within this department of knowledge could be also a contribution towards developing a safe, reliable and efficient DC distribution system.

4.3 Converters in DC distribution systems

It has been pointed out that the usage of converters in both current AC distribution system, and a possible DC distribution system is extensive. There are three types of converters that are in use in a DC distribution system, depending on the structure of the DC distribution system. AC/DC rectifiers, DC/AC inverters and DC/DC converters. These converters would have to be installed at different points of the system to manipulate the voltage into either AC or DC depending on what is needed.

Seen from a DC distribution perspective, the converters also have different usages. AC/DC rectifiers are mostly used to rectify the AC grid voltage into DC voltage, which is fed into the DC system. The purpose of the DC/AC inverter is to invert the voltage from DC to AC, given that the system is structured like in Figure 15.

In a DC distribution system that is structured like Figure 19, where DC goes all the way to the consumer, DC/AC inverters would still be utilized. This is because many applications within households, buildings and industry still rely on an AC supply. This means that DC/AC inverter would still be used, just within residential buildings or industry. DC/DC converters would be the most used component in a DC distribution system that is structured like the one illustrated in Figure 19. The DC/DC converter reduces the voltage magnitude to appropriate levels, both for consumers and industry.

Distributed generation (DG) would also need DC/DC converters, such that power could be supplied to the grid. Energy storage systems would need a bi-directional DC/DC convert, which enables it to let power flow in both directions, so that it can supply the grid and store energy “for a rainy day”.

For a MVDC system, the number of converters depends on how many distribution lines are connected. Even if the number of converters varies, the types are still the same. AC/DC rectifiers are used to convert the supplied voltage from the transmission lines. Then either DC/AC inverters or DC/DC converters are used depending on whether the branches require AC or DC, or a combination of both. Obviously, the difference between the converters in a MVDC distribution system will require higher voltage levels than the converters used in a LVDC.

4.3.1 DC/DC converter - Neutral-Point Clamped

The research and modeling done in reference [21] also presents a proposal for which types of AC/DC converters to choose for rectification of an AC voltage supplied from then medium voltage system. It is also proposed that a DC/AC inverter for the conversion of voltage is supplied to the households. These converters have not only been simulated, but also installed and tested on a real distribution line. Hence these are very real, and relevant converters for a possible DC distribution system.

As for the DC/AC inverter, a Neutral-Point Clamped (NPC) converter is suggested. Simulations are done for both a single-phase and three-phase converter, that give somewhat similar output voltages. Each of the phases in a NPC converter has its own leg of switches. The NPC converter power circuit most commonly use IGBTs with anti-parallel diodes as switches. In Figure 26 a) we can see the three-phase NPC converter circuit. The results of the converter simulations in Figure 26 b) show that with a 750V DC input from the DC lines, the converters give 230V AC (RMS value) output voltage for the three-phase two-level and three-level converters. The three-level converter gives a more sinusoidal output. This means that the filter size can be smaller, while staying within the harmonic distortion (THD) requirements.

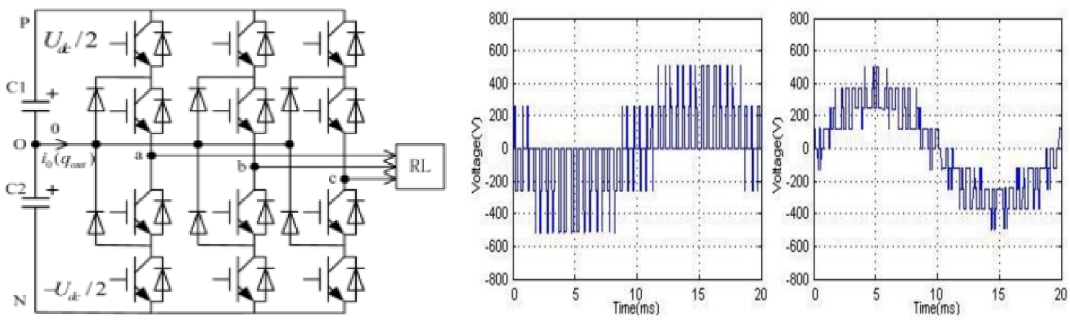


Figure 26 – a) Three-level NPC converter topology [34] b) Simulation results of NPC converter for two-level and three-level converter. [21]

3.3.2 AC/DC Vienna rectifier

The Vienna rectifier is a unidirectional three-level three phase rectifier, which means it can only convert from AC to DC and not the other way around. The rectifier has 18 diodes and 3 IGBTs switches, one switch in each leg connected to one of three phases. The outputs of the Vienna rectifier can connect to three conductors which is the positive pole, negative pole and neutral. These conductors have three voltage potentials: U_{dc}, 0 and -U_{dc}. The converter topology is illustrated in Figure 27. One of the reasons one can use this type of rectifier is that it is possible to control the harmonic distortions that occurs.

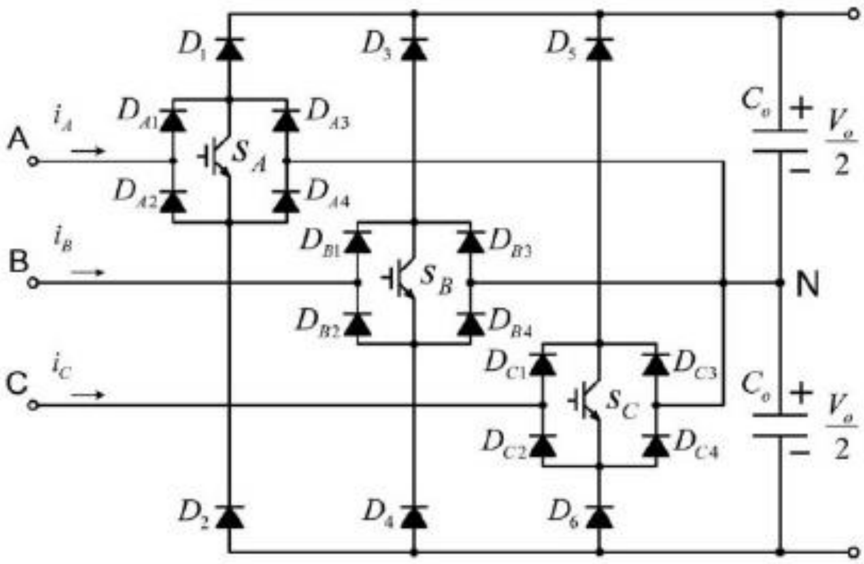


Figure 27 – Vienna rectifier topology [35]

4.4 Cables in DC distribution

For a DC distribution system to be set in place, cables that are already in use in the distribution system need to be evaluated and further use considered. As seen earlier, when constructing a DC structure, one can choose to have a bipolar or unipolar structure. This means that the number of conductors in the two structures are different. DC has some challenges when it comes to implementation, one of them being that the whole structure of the electrical grid is made for AC. This means that either new cables need to be installed, or already existing cables can beused. There are several considerations to be made when it comes to challenges on cable use in a DC distribution system.

In [23, 36, 37] the authors discuss conductor solutions considering a transition from AC to DC distribution systems. Existing AC networks with two-wire, three-wire and four-wire cable systems are considered used for underground line. This means that one cable has two, three or four wires within one cable that transmit power. For AC distribution systems, most cables consist of three phases and a neutral for four-wire cables. For three-wire cables there are only the three phases with a separate ground. Two-wire cables can also be used in AC, but only in low voltage system.

For standard cables, maximum voltages are often given as pole to ground voltage and a pole to pole voltage (phase-ground, phase-phase). This voltage is RMS-voltage, which means that the maximum voltage the cables can take is $\sqrt{2} * V_{AC}$ which is the peak AC voltage, and the equivalent DC voltage. For instance, a cable which is rated at 600/1000V, the phase to ground voltage is 600V and the phase to phase voltage is 1000V.

The equivalent maximum DC voltage for this cable can be assumed to be:
$\sqrt{2} * V_{AC} = V_{DC}$
$V_{DC} = \sqrt{2} * 1000 = 1414V$ DC for phase-to-phase
$V_{DC} = \sqrt{2} * 600 = 848.5V$ DC for phase-to-neutral

For a repurposed AC line with DC supply, this means that the voltage limit for the cables is higher for DC than for AC. Article [37] elaborates on the different interconnections one can make with a different number of wires, with a unipolar and bipolar DC distribution structure. It shows that both unipolar and bipolar structures have options for re-cabling. Although a unipolar structure is possible, bipolar structure with both three-wire and four-fire conductors shows to have a greater ability to carry power. In Figure 28 we illustrate how different connections for different numbers of wires, two-, three- and four-wire cables look like. The four-wire cable structure distributes power to consumers through two of the four cables. Consumers are evenly distributed across the four cables.

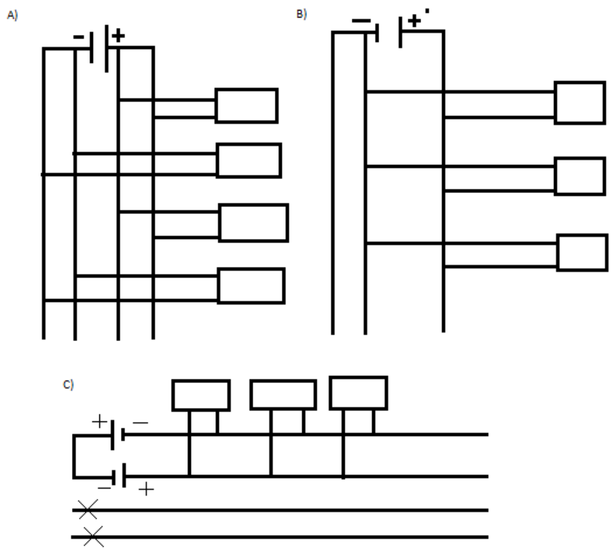


Figure 28 – A) Four-wire cable with unipolar structure B) Three-wire cable with bipolar structure C) Two-wire cable with bipolar connection

There is a proposed concept for both overhead and underground lines, which utilizes the already existing AC cables. Figures 29 and 30 illustrate repurposing of an AC overhead line and underground line [23] As is marked in the figure, the three phases are replaced by the positive, negative and neutral pole. Simulation on the use of DC in existing AC line is done, using a 100 mm^2 outdoor weatherproof PVC insulated wire.

In Table 3 parameters for both overhead lines and underground lines are presented. Simulation results show that with a source voltage at ±750V DC, the voltage of the modelled distribution line is 734.04V DC. There is obviously a voltage drop, due to line impedance and due to conductor resistance. Despite this an assumption can be drawn that the existing conductors used in AC lines are sufficient for DC to be applied on the line.

Type	Dimension (mm^2)	Core Diameter (mm)	Sheath layer (mm)	Conductor resistance (Ω/km)
Overhead Line	100	13	16	0.185
Underground Line	240	18.3	2.6	0.0754

Table 2 – Cable parameter

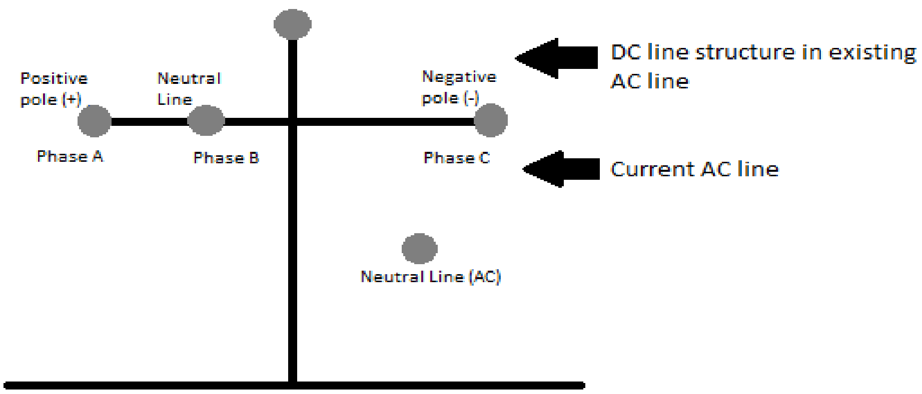


Figure 29 – Overhead line cable configuration for DC

Underground cables also have the same possibilities for utilizations of direct current. In Figure 30 we can see how an underground cable would be repurposed from 3-phase AC to a bipolar DC structure. The setup is similar as for the overhead lines, with phase-A, phase-B, phase-C being repurposed into a positive pole, neutral and a negative pole. For the simulations, cross-link polyethylene vinyl sheath cables were used.

As for the simulations, results showed to be much like the ones done for the overhead lines. With a 750V DC source, the voltage across the cable was 746.7V, which indicates a small voltage drop. This voltage drop is much smaller than the one in overhead lines, due to the conductor resistance being much smaller. As with the overhead lines, the simulations indicate that the old AC cables can be used for a newly implemented DC distribution system.

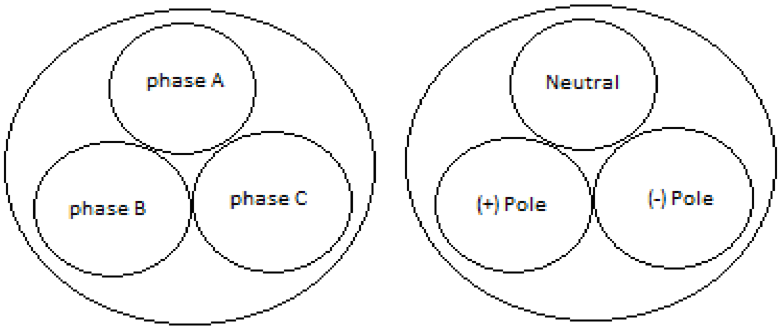


Figure 30 – Underground cable configuration for DC

The results of the simulations in addition to the research concerning cable repurposing shows that there are many solutions for how to transition from AC to DC distribution system, without having to lay new cables. The voltage tolerance of the cables can be assumed to be higher for DC distribution system than the given voltage for AC distribution system. This is because the voltage magnitude for AC cables are given as a RMS value, which is lower than the peak value of the AC voltage. This means that the existing cables are capable of handling the peak voltage. Since DC is a constant value, one can set the DC voltage at a higher magnitude.

4.5 Efficiency – conversion and conduction

Efficiency of distribution system is one of the most important traits that need to be enhanced and sustained. The way efficiency is calculated is by determining the losses of equipment, such as converter and cables. These losses occur due to various reasons. Converters consist of wires and switches, which cause both conduction losses and switching losses. Cables have conductor resistance which vary depending on the cross-sectional area of the cable and length, which also causes losses. In addition, for AC distribution system, transformers also cause losses. The formulas required to calculate losses in AC systems, are not included, although the results have been included in this section.

The efficiency of equipment can be calculated by looking at the input values and the output values of a given component. Efficiency is calculated by following formula [38]:

$$\eta = P_{out} / P_{out} \quad (1)$$

Where the basic calculations of losses with a specific efficiency is given by:

$$P_{loss} = (P_{out} / \eta) - P_{out} \quad (2)$$

The two different main losses are cable losses and transformation/conversion losses. In a DC distribution grid, these cable losses are in cables that are transmitting power from a transformer station and all the way down to consumer level. Cable losses can be calculated, by first finding the current, which is given by power consumption of a cable:

$$\boldsymbol{I = \frac{P}{U}} \quad \textbf{where } \mathbf{I = I_{dc}} \textbf{ and } \mathbf{U = U_{dc}} \tag{3}$$

With a given I_{dc}, calculating the power losses of a cable is given by:

$$\boldsymbol{\Delta P_{dc} = 2 * rL * I_{dc} = 2 * rL * \frac{P^2}{U^2}} \tag{4}$$

Where r is the cable resistance (Ω/km), L is the length of the cable, U = U_{dc} which is the DC voltage, which can be given by $\sqrt{2} * V_{AC} = V_{DC}$ if only an AC voltage is available, and ensuring that cables will not be damaged.

For calculating the conversion losses there are some elements we need to have in mind. If a DC distribution system that supplies DC to households is considered, there are losses in the AC/DC rectifier (voltage source converter) and the DC/DC converters between two lines. The losses come in the form of conduction losses and switching losses. Calculating conduction losses in a converter can be difficult because of the switching components in the converter. The expression in (5) can be used to calculate the conduction losses per phase leg. I = I_{rms} which is the RMS value of the current through the converter leg, r_{on} is the on-state resistance of the switching component, and V_{on} is the voltage drop of on-state.

$$\boldsymbol{\Delta P_{conduction} = \frac{2\sqrt{2} * V * I}{\pi} + r_{on} * I} \tag{5}$$

For each switch in the switching component (i.e. IGBT) there is a loss, which makes it necessary to calculate the total switching losses of converters. E_{on} and E_{off} is the energy loss during switching, and E_{RR} is the reverse recovery energy. The frequency of the switching f_{sw} directly affects the switching losses. The expression for calculating the switching losses is as following:

$$\boldsymbol{\Delta P_{switching} = \frac{2\sqrt{2}}{\pi} * I_{rms} / I_{nom} * (E_{on} + E_{off}) * f_{sw} + E_{RR} * f_{sw}} \tag{6}$$

With these expressions in mind, a full-scale calculation for a DC distribution system can be made. This would be useful to see the total efficiency of DC distribution system, and for it to be compared to an AC distribution system. This would contribute to the development and state of the DC distribution grid.

For the next section of this paper I will focus on calculations done in [38] for analyzing the efficiency in LVDC and MVDC distribution system. The calculations above have been used to find the η (efficiency) of three different types of distribution systems. These calculations are done for the lines and the conversions points in the distribution system. This means that the conversions within the households, buildings and industry is not included here. There are three distribution systems that have been looked into, they are as following:

- AC distribution system: MVAC and LVAC structure
- Mixed AC-DC distribution system: MVAC and LVDC structure
- DC distribution system: MVDC and LVDC structure

4.5.1 Efficiency of AC and AC-DC distribution system

In research article [38] three types of systems are studied and calculations are implemented to find the efficiency of the system. In these calculations, the distribution system for both MV and LV have been considered, and the converters and transformers that are used in this type of system. The losses and efficiency for a household is not considered here, and the calculations for converters and lines are not optimized and could be more accurate.

For each of the three systems, the parameters of the systems are changed to have an overview of different scenarios. L_s and L_{LV} are parameters for distances, L_{LV} being the distance between substation distribution transformer and low voltage feeders. L_s is the distance of the medium voltage line to the distribution transformers in substations. The transformer short-circuit impedance that is in the transformer, is also used for the efficiency calculations of the system and is expressed by k_{T1} and k_{T2}.

A simplified circuit scheme is shown in Figure 31 for the components used in the calculations for an AC system and AC-DC mixed distribution system. The reason calculations are done for AC distribution system is to compare this with the two other solutions even though it is not the center of discussion for this thesis. For each of the systems, there are different cases where the parameters of the system vary to show how the systems react to different scenarios.

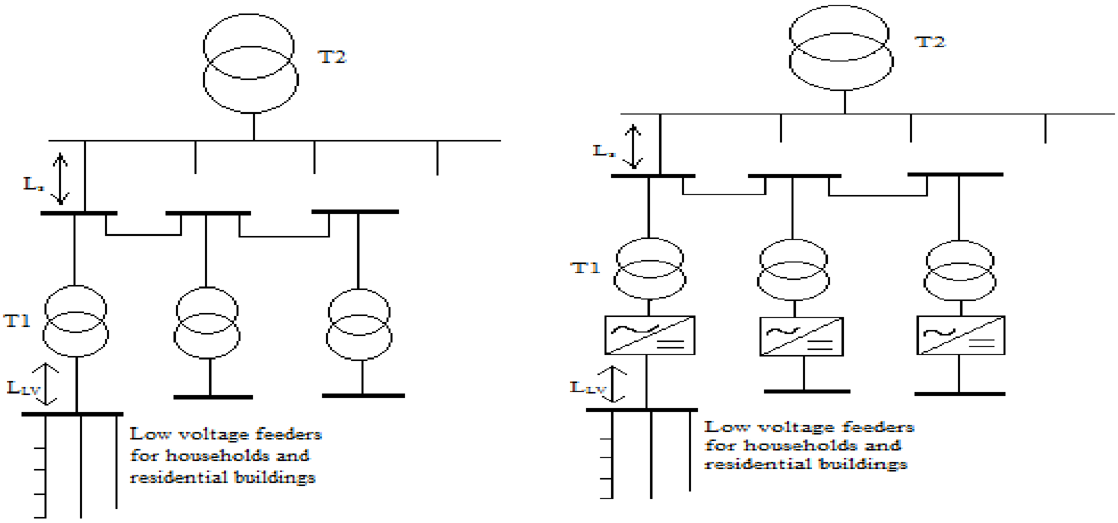


Figure 31 – a) AC system overview with components of the AC system b) Mixed AC-DC system

Case	L_{LV} [m]	L_S [km]	k_{T1} [pu]	k_{T2} [pu]	**η** [%]
1	20	2	1	1	97.3
2	50	2	1	1	96.5
3	20	4	1	1	97.0
4	20	2	2	1	96.4
5	20	2	1	2	96.6

Table 4 - Results of efficiency calculations for AC distribution system [38]

As we can see, the calculations have been done for different cases where the parameters of the cable lengths in both MV and LV part of the system, and the transformer values have also been changed. When the length of the LV feeders is changed, the efficiency of the system drops by 0.8% compared to case 1. This is because to the increase in length of a cable carrying low voltages increases the current and conduction losses in the cable. One can see a clear difference between the increased length of LV feeders compared to the increased length of the MV feeders, and that the conduction losses aren't as great. The increase of cable length for MV line in case 3 only has a 0.3% efficiency drop. Here same reasoning is applied. Expression (4) also confirms that if length of cables is increased the conduction losses will also increase.

The mixed AC-DC system in Figure 31 b), which is in practice a MVAC distribution system connected to a LVDC distribution system has also been considered in these efficiency calculations. Here the transformer T1 is connected to an AC/DC rectifier, which feeds the LVDC distribution system. In a system like this, the parameters for the length of cables and transformer short-circuit impedance are included. The difference is that converter losses also need to be included, which means that switching frequency f_{sw} and the losses for the switching component (here an IGBT) which is used in high power applications. K_{IGBT} is the total converter losses factor.

Case	L_{LV} [m]	L_S [km]	k_{T1} [pu]	k_{T2} [pu]	f_{sw} [Hz]	K_{IGBT} [pu]	η [%]
1	20	2	1	1	1500	1	96.4
2	50	2	1	1	1500	1	94.9
3	20	4	1	1	1500	1	96.3
4	20	2	2	1	1500	1	95.9
5	20	2	1	2	1500	1	96.0
6	20	2	1	1	2500	1	96.1
7	20	2	1	1	1500	0.5	97.0
8	20	2	1	1	2500	0.5	96.8

Table 5 – Calculation results of AC-DC system[38]

Table 5 contains the efficiency of an AC/DC system, and the parameters that affect the efficiency. The length, as in the AC system, has a bigger efficiency loss when the length of

LVDC cables are increased than the MVAC cables. With a mixed AC/DC grid, the converter must be introduced in the power loss calculations. As mentioned earlier, the switching losses are directly related to the switching frequency, which can be seen by the efficiency changes when f_{sw} is changed. As we can see, the efficiency of the whole system is reduced by 0.3% with a change in f_{sw} from 1500 Hz to 2500 Hz. We can also see that even if the semiconductor losses (IGBT) are reduced with half, the efficiency of the system is only increased by 0.6%. With this compared to the AC system, the efficiency is at best 0.3% lower in the AC/DC mixed distribution system.

4.5.2 Efficiency of DC distribution system

In the DC distribution system used for efficiency calculations there is both a MVDC and LVDC distribution system, i.e. multilevel DC system [38] as seen in Figure 32. A transformer in the substation steps down the voltage, which is then rectified in an AC/DC converter to the MVDC system. This is then spread into the medium voltage feeders, which are connected to the LVDC system. This is then stepped down using a DC/DC buck converter, that feeds the low voltage feeders and spreads to households and buildings. For this system, compared to the two others already discussed, the DC/DC converter has taken the place of the distribution transformer. This means that another type of conversion has been added to the total power loss of the system. I_{IGBT} is the nominal converter current, which is seen in Table 6.

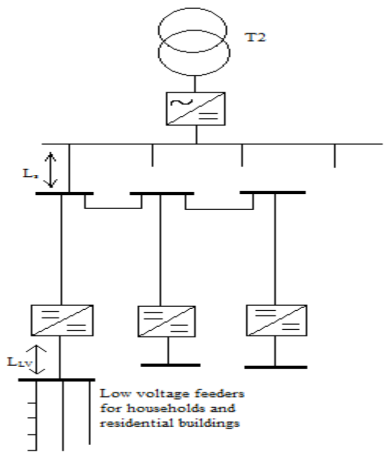


Figure 32 – Multilevel DC distribution system used in efficiency calculations

From the calculation results seen in Table 6, we can see that increased cable length and switching frequency reduces the efficiency of the system like in aforementioned systems. When the rated voltage in the medium voltage system is reduced, we can also see a 0.4% efficiency reduction. This might be due to less voltage, which means that the current increases, and higher current leads to higher conduction loss. The difference between choosing a converter with high nominal current through IGBT proves to have minimal effect and change. A reduction of converter losses by half, K_{IGBT}, shows to have a very positive effect on the overall efficiency, and even increases it to the best efficiency solution than AC systems.

We can also note that two new values have been added in Table 6 which are the utilization factor of the transformer (v_{T2}) and DC/DC converter ($v_{dc\text{-}dc}$). A utilization factor is the percentage of maximum possible work these two components can give. These values are included in this table because they are much lower than in AC systems and AC/DC mixed systems. The transformer has an average 67.1625% utilization factor, which means that on average this transformer would never be used at full power. The same goes for the DC/DC converter, only that the average percentage is even lower. For the MV portion, this means that the amount of MV feeders could be increased, so that T2 utilization reached 100%. The same goes for the DC/DC converter, the number of LV feeders could be increased.

Case	L_{LV} [m]	L_S [km]	U_{dc} [kV]	f_{sw} [Hz]	K_{IGBT} [pu]	I_{IGBT} [pu]	η [%]	$v_{dc\text{-}dc}$ [%]	v_{T2} [%]
1	20	2	32	1500	1	25	96.8	51.3	67.1
2	50	2	32	1500	1	25	95.2	52.2	68.2
3	20	4	32	1500	1	25	96.7	51.3	67.2
4	20	2	32	2500	1	25	96.7	51.4	67.1
5	20	2	32	1500	0.5	25	97.5	51.3	66.6
6	20	2	32	2500	0.5	25	97.5	51.3	66.6
7	20	2	16	1500	1	25	96.4	51.4	67.4
8	20	2	32	1500	1	75	96.8	51.4	67.1

Table 6 – Efficiency calculations of multilevel DC distribution system [38]

Although the calculations in [38] are helpful when considering the efficiency of a DC distribution system compared to AC, they are still not sufficient. The overall loss calculation of converters and cables can be more specified, and this is a general calculation for converters and cables. Some parts of the losses are not considered, like for example the many conversions done within the household. The total power consumption of a system is also not considered. This is crucial because even though the losses in a system might be higher, the overall consumption of the loads can also be increased as seen in Table 6.

As mentioned before, DGs can be connected directly to the grid without any conversion stages by using DC in the distribution system. DG conversion losses are not considered either, and are a contributor to the total efficiency of a distribution system. Conversions within the households, like appliances running on DC and charging stations for EVs do not need the conversion stage with DC supplied to a household. This specific analysis gives an overview of the efficiency, but represents also very general calculations.

Other research has also been done on the efficiency and comparison of AC distribution system and DC distribution system in [39]. Here different voltage levels are considered with different efficiencies of converters in the system. In [30, 40] research has been done for specifically this purpose, to find out the losses and the efficiency of applications used in a household. Household appliances with different voltage levels that have been considered, both AC supplied and DC supplied. Here the distribution grid itself is not considered, but it is important to look at the consumer level because it is the ultimate goal for power distribution. Therefore, looking at the consumption and losses in AC and DC systems on the consumer level is also very important. The results of the simulations in the article are shown in Figure 33. Here we can see that the overall consumption when AC is in use is higher than DC. The converter losses are also much higher in an AC system than in a DC system. The reason for this is that a household using AC has many more conversions than a DC system. This is due to the fact that many applications are already using DC, which means that many conversion steps are avoided. For an AC system, these applications would need rectifiers which have conversion losses because the efficiency of rectifiers not being even close to 100%.

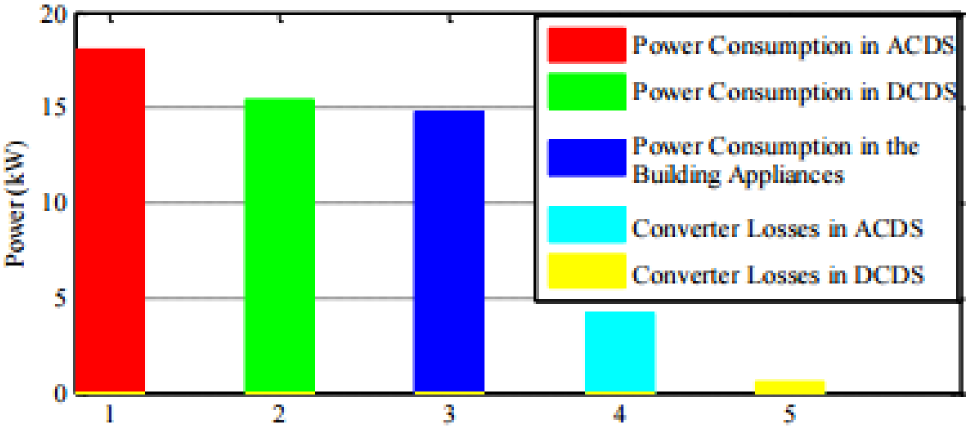


Figure 33 – Power consumption and converter losses in residential DC systems [30]

In research paper [27] a cost calculation and consumption calculation with losses has been conducted for a MVDC system compared with MVAC/LVAC in urban areas. Here the cost of converters, transformers, and energy is included. The investment cost, and operation costs are computed to show an overall comparison of AC and DC in distribution system. The total results shown in Figure 34, where the total investment and operational costs of a LVAC, MVAC and MVDC system is shown. The operational costs of both a MVAC and MVDC system are very small, but the investment costs of a MVDC system is significantly lower than the MVAC system. The LVAC system has high operational costs, but similar investment costs as the MVDC system. The results of the loss calculations are shown in MWh, and are higher for MVAC (0.27 MWh) system than MVDC (0.24 MWh). These results show that the investment and operational costs of a MVDC system in urban areas is feasible.

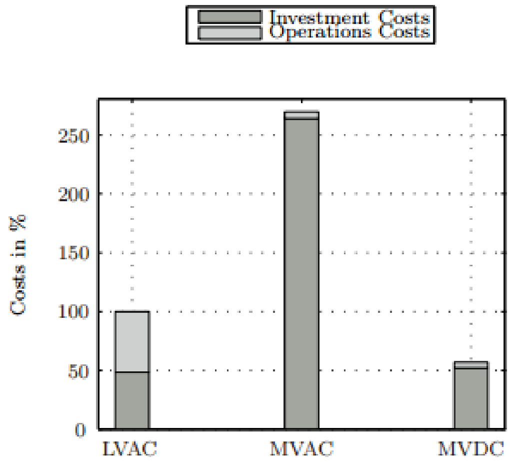


Figure 34 – Investment and Operational costs of LVAC, MVAC and MVDC distribution systems [27]

5 Experiment – Household appliances with DC supply

5.1 Purpose of the experiment

The main goal for this experiment is to explore the results of supplying DC to everyday household appliances. By conducting this experiment, it will give an insight to the viability of having DC directly into the intake for the socket. As well as general insight in how AC/DC rectifier can manage having direct current conducted through the circuit. This is because most household appliances today are dependent on a direct current to work. This also includes equipment and everyday items that are based on power supply from batteries. The question at hand is if AC/DC rectifiers in these appliances will be able to conduct current through the rectifier. If so, will it be able to supply the object with the full power it needs, or will it have losses going through the rectifier. Another possible outcome could be that the rectifier simply cannot conduct DC through its circuit, and will not work at all.

5.2 Execution of experiment

Equipment	*Lab code/number*	*Settings*	*Usage*
Oscilloscope	EL 1531		Measurement tool
A/V – converter (current measurement)	E-1093/11	Input 1 & 3 - 1A = 1V	Used as current measurement input for oscilloscope
V/V converter (voltage measurement)	EL-1076/9	U = 10-500V	Used as voltage measurement instrument for oscilloscope
DC power supply	Model number: Chroma 62012P-600-8	Range: 0-600V	Supplies DC for execution of experiment
Outlet power strip	None		Used to connect to DC supply such that measurement is possible

Table 7 – Equipment list

Alarm clock w/ radio - Memory	*230V AC – 50Hz*
Internet router – Speedtouch multimodem	100-240V AC 50-60Hz, 0.5A

Table 8 – Tested object

As the first part of the experiment, connecting the equipment into a working circuit was the first step. Full list of equipment used can be seen in table 1. The full circuit looks as following:

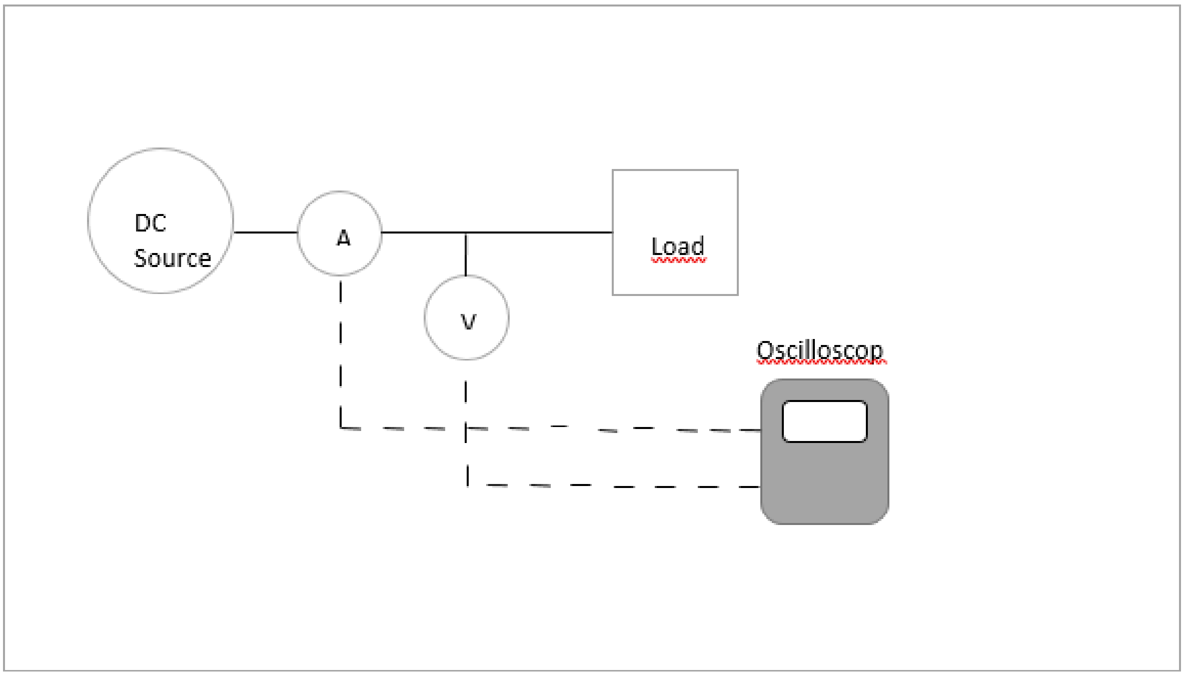


Figure 35 - Electrical scheme of the circuit built for the experiment

Since DC voltage is not something that you can normally get out of the intake, for this experiment to be feasible, there is a need for a DC supply. UiT has a DC power supply at hand for students to use. This power supply has a range of 0-600V which is a suitable fit for measurements on household appliances that usually use 230V AC. This DC power supplier has some settings that need to be adjusted, such as a voltage limit and current limit. If 250V DC is wanted, setting the voltage limit to 250V is needed. Default for both these are zero, and the load will try to draw as much power as needed but will be blocked because of the limit set, such that the current and voltage with drop.

The oscilloscope computes the measurements given from the A/V converter and the V/V converter. The V/V converter transforms the voltage to a lower level, and computes the measurement as a graph. While the oscilloscope can "read" the input from the V/V converter without a problem, it cannot measure a current. Therefore, the A/V converter converts the current measured into a voltage signal, which the oscilloscope can compute into a graph.

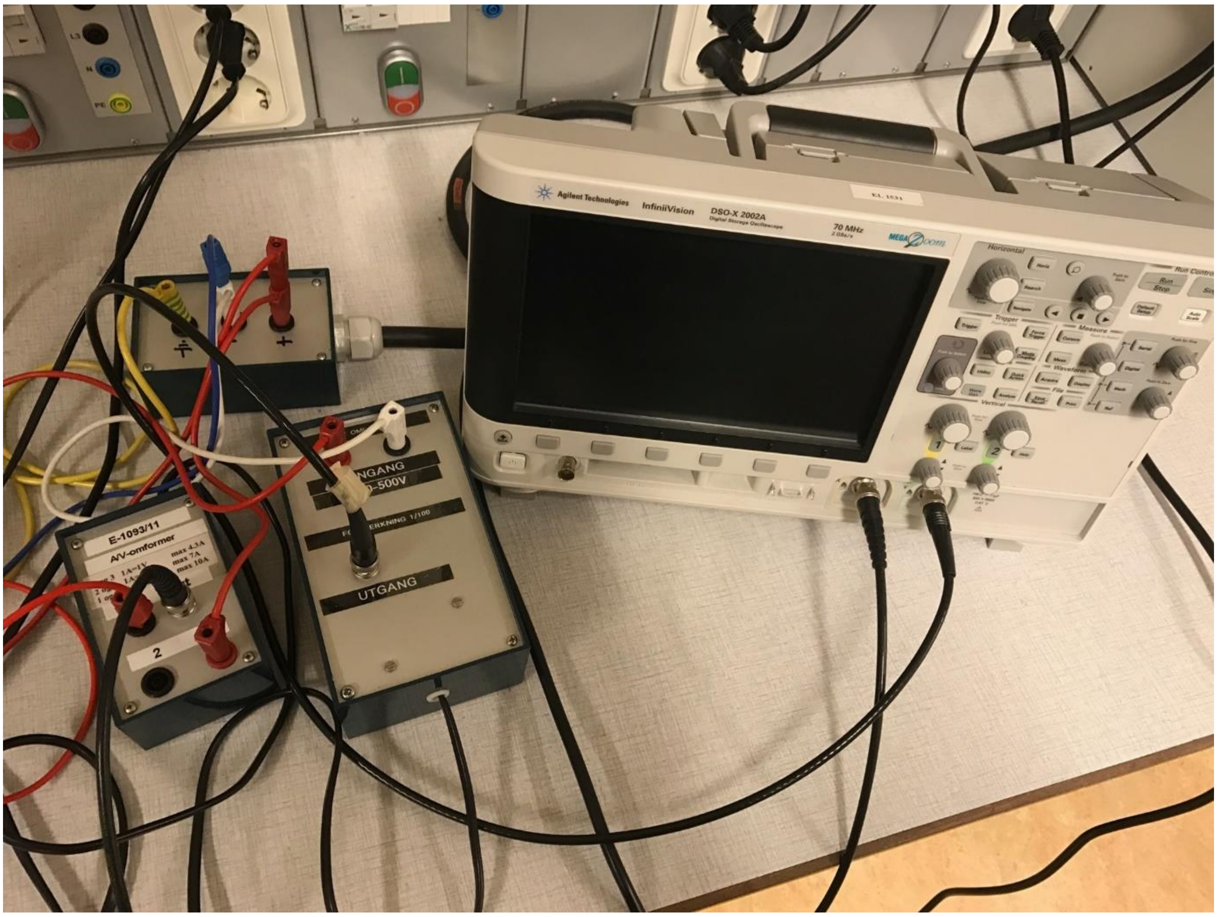


Figure 36 - Measurement equipment and how it looked in the lab

When the circuit was finished and ready for use, the next step was connecting the tested object to the circuit. Figure 36 shows the equipment we used in the experiment, with a few parts not in the picture, like DC power supply which has its own fixed location. The experiment was tested on multiple household appliances, to get a broad perspective and explore a variety of results. With this in mind, testing was done using an alarm clock w/radio and internet router as seen in table 8.

5.3 Results of experiment

To ensure that the tests would go smooth and without any damaging failures, all the test objects were first tried with 230V AC. This is because appliances with a transformer inside cannot use DC, and will more than likely end up frying its circuit. So, the first object on the list for testing was the alarm clock w/ radio.

5.3.1 Alarm clock w/ radio

The measurement circuit was connected to 230V AC source to explore the properties of the alarm clock and if it is capable of being supplied a DC voltage.

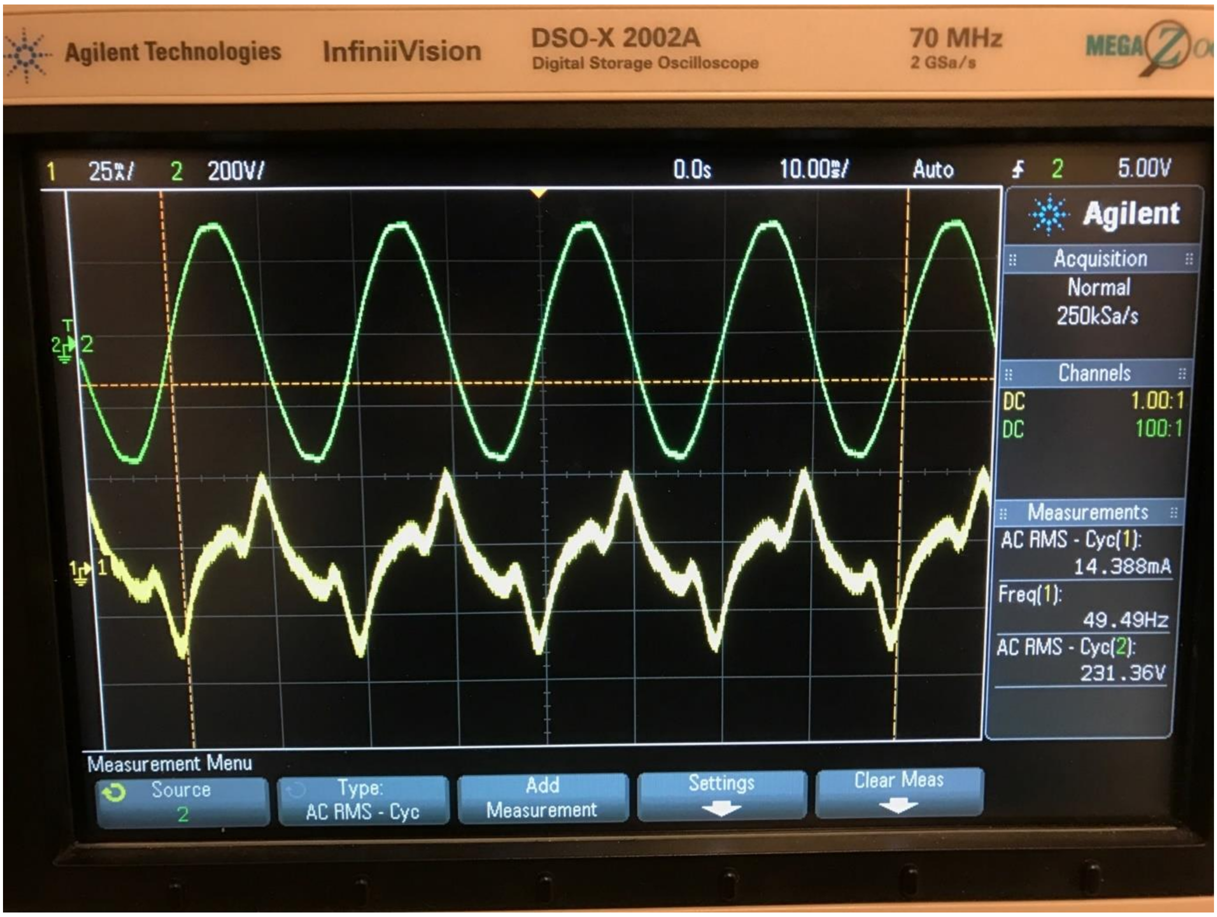


Figure 37 – Oscilloscope measurement of the alarm clock running on 230V AC

As we can see in Figure 37 the voltage is displayed on the upper graph. The values are correct considering it measured 230V AC, and has a frequency of 50Hz. The problem with this alarm clock is that the current is alternating, not a perfect AC sine wave but still alternating. What this means is that the alarm clock most probably has a transformer inside which steps down the voltage and drives an alternating current through the circuit of the alarm clock.

There may be some rectifier inside as well, but as long as there is a transformer ahead of the other components this will be an issue. This means that a direct current through this circuit would most likely end up in destroying the circuit and the alarm clock.

5.3.2 Internet router

Next appliance for testing was the internet router. The reason I chose a router for testing was because it is something most people in the modern world have in their house. Just like the alarm clock. Connecting it to the measurement circuit was just plugging the socket into the intake of the circuit. Firstly, it was tested with 230V AC, just to see what kind of equipment was inside the router and if there was any in doing the experiment with DC. The AC results given by the oscilloscope looked as following.

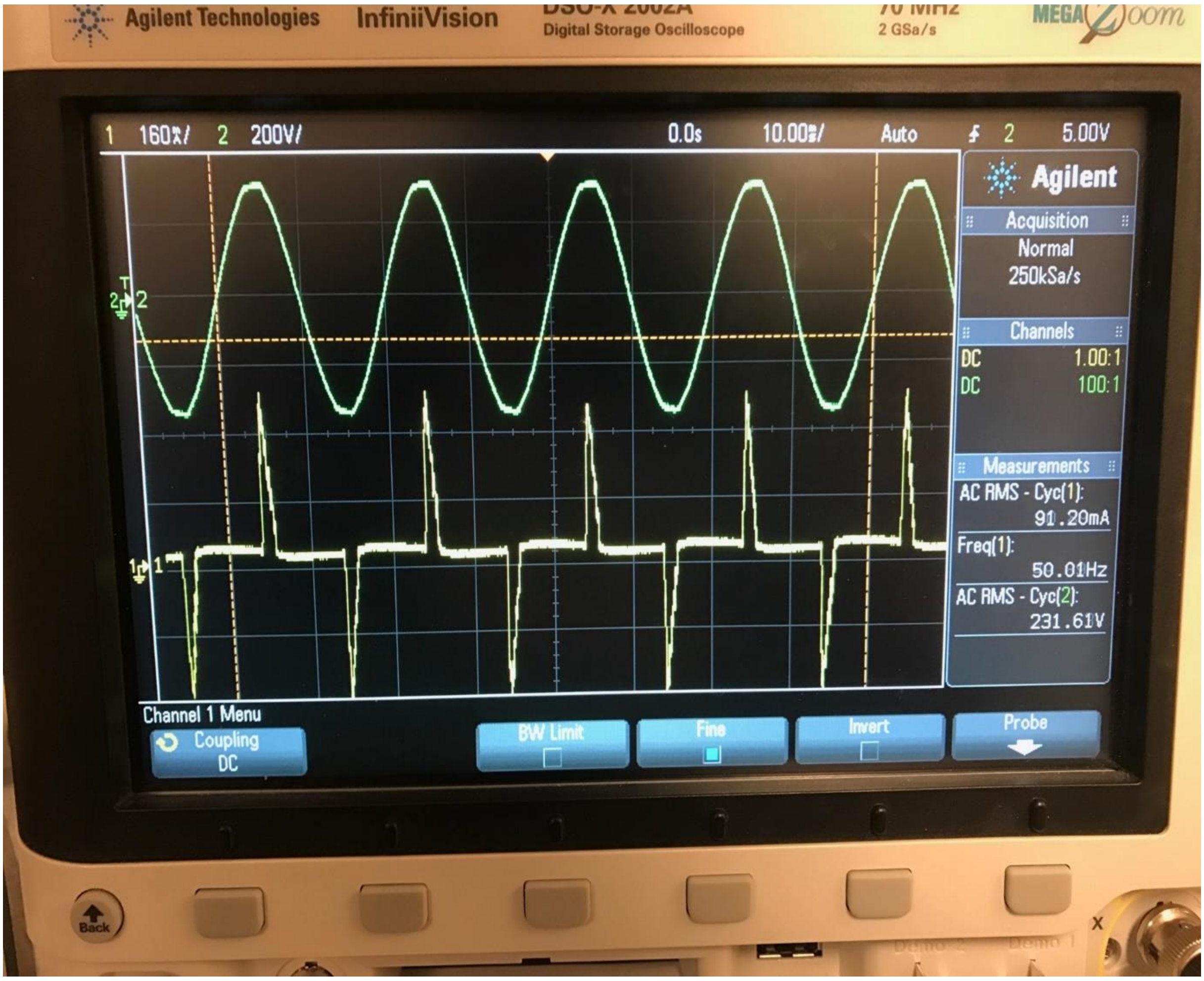


Figure 38 – Oscilloscope measurements of internet router running on 230V AC

As we can see, the oscilloscope results in Figure 38 from the router is not the same as for the alarm clock when looking at the current waveform. This waveform which is more or less straight with these spikes indicates that there is an AC/DC rectifier. With an AC/DC rectifier in the circuit the assumption is that it could also handle a direct current applied to the router. The result is shown in Figure 39.

Figure 39– DC supply on router

As shown in figure 39 one can see that the yellow signal is the current, and the green is the voltage. With the DC power supply set to supplying 250V DC the current is 30.4mA. The interesting thing about this is that the router works just as fine with a DC supply as with a AC supply. The current is more or less clean, with spikes which are due to noise in the measurement equipment. For reference, this test was tried out on the router with different voltage levels since the equivalent DC voltage for 230V AC[41] is:

$$V_{DC} = \sqrt{2} * V_{AC}$$
$$230V * \sqrt{2} = 325.3V\ DC$$

Hence, a test was done of two other voltage levels. 285V and 325V which is equivalent voltage level compared to a 230V AC, just to see how the router would deal with different levels of voltage. The result is shown in Figure 39 and Figure 40.

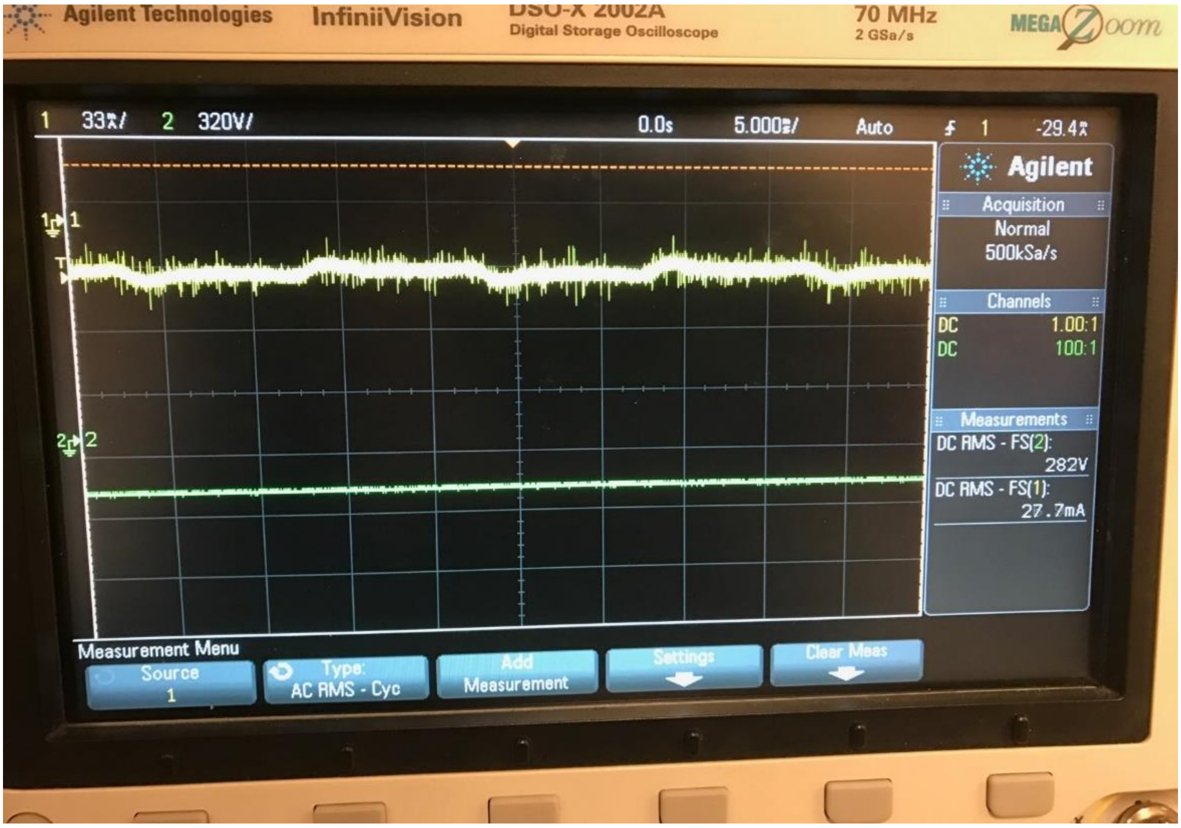


Figure 39 – 285V DC supplied to router

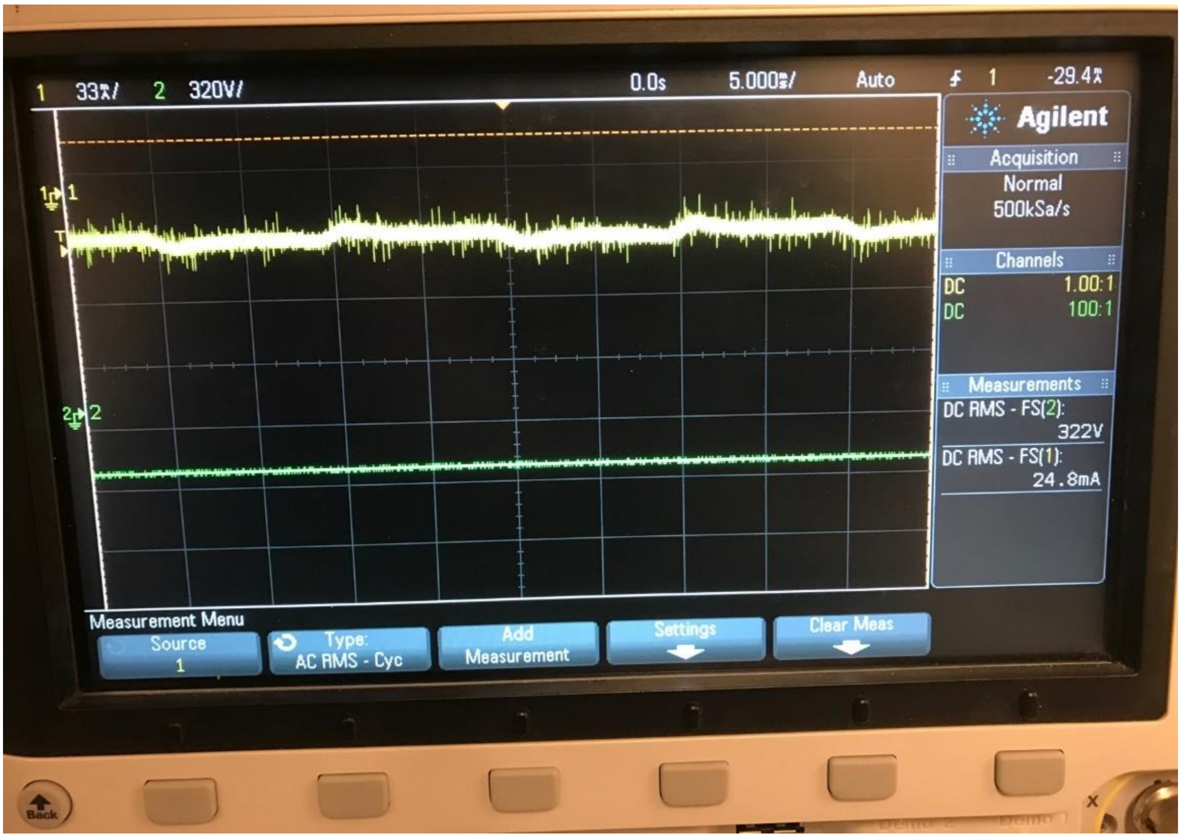


Figure 40 – 325V DC supplied to router

As we can see, there is minimal difference in the voltage and current graphs given by the oscilloscope.

Voltage limit – DC power supply	*Voltage measured in oscilloscope*	*Current*
250	246V	30.4 mA
285V	282V	27.7 mA
325V	322V	24.8 mA

Table 9 – Voltage levels

Here we can see that for each of the three voltage levels set on power, supply is more or less equal to the voltage measured in the oscilloscope. The current values are as expected, whereas the expectation for the current was that it would decrease when the voltage was increased. The reason the current decreases when the voltage is increased is because the power need for the router is constant. Hence, if voltage is increased, and the current must to be lower to maintain the constant power.

5.4 Conclusion of experiment

From the two highly regular and much used household appliances, we got two different outcomes. The alarm clock did not work with a DC power supply. This is as mentioned earlier, because it most probably needs a transformer as a part of the circuit, and without that it is impossible to conduct a direct current through it. This could be seen from the results on the oscilloscope when a 230V AC was used to power the alarm clock. If a direct current would have been tested the result would be frying the transformer and possibly rest of the circuit as well and destroying the alarm clock.

While the alarm clock was less of a successful test, the internet router had the opposite outcome. Since the first test with regular 230V AC gave a signal that resembles the output of a AC/DC rectifier it was known that the router runs on DC. Due to this, an educated decision was made to test the router with three different voltage levels. As expected, the router was fine with both with testing 250V, 285V and 325V supplied from the DC power supply.

As we have seen, transformer based household appliances would be a problem in a possible DC distribution grid which stretches all the way into households. One simply could not use these given that there was DC coming out of the intake in households. On the other hand, many appliances also use the same technology as used in the router. For those appliances using DC directly from the intake would not be a problem. Adaptation to different types of appliances would be needed if a future DC grid is to be implemented. To have a bigger overview of what equipment could handle of change like this, an experiment like this would need to be done, but on a bigger scale.

6 Discussion – Is DC in distribution grid feasible?

When looking in to the feasibility of a DC distribution system, there are many considerations and aspects that need to be brought to light. As seen in the research review I have done, there are many proposed solutions to the infrastructure of both a MVDC and LVDC distribution grid. Structure of conductors is also proposed and needs to be considered. Voltage levels in the DC distribution system is something that needs to be evaluated.

According to research that I have looked in to, there are few to no rules on the voltage standardization for a DC distribution system. Some rules are set for low voltage system, such as the 1500V pole to pole and 900V pole to ground. For medium distribution systems, there is even less requirements, and only proposed options for voltage. A standardization would be an effective way of establishing the DC distribution system, and would be much easier way to establish if rules and requirements were set within electro engineering in general.

In MVDC distribution system the infrastructure is simpler, and has less interconnection than a LVDC system. This is because the MVDC system is a link between the high voltage system, and low voltage system. In a MVDC distribution system, the voltage can be increased to higher voltage levels than in the MVAC system. This means that the current in the conductors would be lower than in MVAC system, and it would have lower conduction losses. While such a MVDC distribution grid can by itself have a positive effect on the distribution system in terms of efficiency and reliability, it would be even more efficient in a system where PVs and windfarm power is generated. This would enable direct connection of PVs/windfarms to the grid. It would be very advantageous because several conversion stages, done in AC system today, cause energy loss, and would be e avoided. The same advantages apply for energy storage systems. For industries that utilize medium voltage DC, it would also be an advantage with a solution like this, because the power capacity could be increased. MVDC distribution systems can also be connected as a link between two systems, to contribute to an overall increased reliability and stability of a system.

As for the LVDC distribution system, several proposals have been made. The biggest difference between them are that one supplies the load with AC, while the other supplies the load with DC. For simplicities sake, we name the AC solution for “method 1” and the DC solution will be called “method 2”. The infrastructure could be built in very similar ways. For both method 1 and method 2, a rectifier would have to be installed on the low voltage side (secondary side) of the distribution transformer to convert from AC to DC. The cables going from the rectifier to the households would have to be adapted so that DC voltage could be conducted.

It has been shown in my studies that cables used in the current AC distribution system can be repurposed and used in a DC distribution. If the already existing cables could handle DC voltage at the rated voltage, one would have to rewire and adjust for DC. However further research is needed to certain if repurposing of AC cables is possible. If the already existing cables are not sufficient or appropriate for DC to be supplied, new cables would have to be laid out, which would prolong this process.

At the consumer end, a DC/AC inverter would have to be installed to supply the load with AC for method 1. Method 2 would require a DC/DC converter at consumer end. Implementation of method 1 should be much easier than method 2, from an infrastructural point of view. It requires installation of converter for AC/DC rectifying and a DC/AC inverter that converts back to AC that is then supplied to households or buildings. Although it may be an easier method, it is also the more likely solution to be implemented because it still offers higher reliability and stability then the traditional AC structure.

Method 2 on the other hand supplies residential buildings with DC. Since houses today have an infrastructure that is accustomed for AC, this means that an assessment would have to be done. The goal would be to find out how much of the current wiring in households and buildings could be repurposed for DC use, if any. In a realistic world, I would assume that the cost efficiency of rewiring a whole house to be adapted to DC is not good enough. Appliances with transformers within the circuit are a problem, because DC supply is not able to power them. This is because inverters would be needed for all the appliances that need AC supply. Method 2 would require many changes within a household/building already standing. For houses/buildings that are under construction planning this would be much easier to realize.

From the efficiency research, we have seen that losses in a DC distribution system compared to an AC distribution system are minimal. The difference between the two systems is that DC distribution system is not running on full capacity. This means that the distribution system can supply more power while using the same amount of transformers/converts as the AC distribution system.

Higher system reliability is also implied, because there is less chance for an overload of the system. From an economical point of view, having to use less equipment and components to supply even more power to consumers means it more economically efficient than a AC distribution system.

It has also been shown in research I have reviewed that in a residential building the total losses and consumption is higher with LVAC than in a residential building with LVDC. The reason residential houses/buildings are included in this discussion is because this is where the power transmitted through the distribution system eventually ends up. Since DC has higher efficiency in residential buildings, it is also desirable to have a DC distribution system that supplies DC to houses. As discussed, this might turn out to be a problem if the necessity for total rework of wiring process in a household/building.

The pilot test on a LVDC distribution system is an effective way on increasing the experience and further improvement and the development of the DC distribution system. With such a pilot test, it is easy to gather data that can contribute to setting standards for DC distribution systems.

Test pilots like this also work as a guide for other possible pilot tests in the future and as basis for larger scale trials.

There are also socioeconomic issues that need to be addressed if such a transition is to be done on a large-scale level. For method 1, there will be few to no changes for the end consumer. The actual complexity of the installation of components for a DC distribution system might affect the society. In case of method 2 the changes would be much bigger, and it would affect different aspects of our lives. If a DC distribution system on a larger scale is realized, and households are supplied with DC this would affect much of today's household appliances and technology. This means that all sockets for chargers, and supplies that are in use today would be rendered useless, unless a solution was to be developed.

On a household scale, the ***costs*** can be assumed to be not that high. Although on a large scale, for example an entire city that goes through this transition to DC distribution system (method 2), one can assume that the costs would be much higher. However, research today sets focus on future energy sources and how to use existing energy sources in an efficient manner. Additionally, focus is set on energy sources that would substitute oil fuels to preserve the environment and hence the increased use of for example electrical cars.

Seen from a current perspective, EVs and battery based technology have become increasingly popular. A DC distribution system would benefit the charging stations for EVs, since the amount of conversions is reduced to only stepping down the voltage to the magnitude that is needed for a charging station. If the EV market keeps rising in the future, the implementation of a DC distribution grid will be even more desirable, because more charging stations will be needed.

As a conclusion, I believe that a transition to DC in the distribution system is feasible. Although more research is needed on calculation of cost-benefit. In this thesis, different proposed structures for both MVDC and LVDC have been reviewed, and some of the proposed structures are even implemented in the real world. Although efficiency research shows that DC distribution system is more efficient when using method 2, it is also the harder method to implement into today's AC dominated market.

Method 1 for LVDC or MVDC distribution system is still a viable option for a distribution system, because it offers less operational costs of the system and lower conduction losses, as seen in pervious chapter. As for applications that are originally made for systems that supply AC, we have seen through the experiment that some will work and some will not. If DC would be supplied to households in the future, an overview of which applications could and could not work with DC would have to be made. In addition, a solution would have to be made for the appliances that cannot work with DC supplied.

A transition to DC in the distribution system is not something that could happen overnight. Thus, some measures would have to be made in order to transition the distribution system to DC over time. A step towards the implementation of DC distribution system is by setting a requirement for producers to have hybrid technology that is compatible for both AC and DC. This would in terms of commercialized applications make it possible for a transition to DC distribution system in the future. This is because new equipment that is bought would be usable with DC, and in the long run all equipment would be usable with DC.

Another possible solution would be to implement a hybrid AC-DC supply for existing households. This would open up for using both DC and AC, and transitioning to only using DC seen from a long-term perspective. With a hybrid system like this, consumers would have the option to use either DC or AC, while also getting the benefits of having DC supplied to the house i.e. charging stations for EVs without the conversions stages. In terms of applications already existing in the household, a transition like this would make it possible for them to still be in use. In addition to having a requirement set for producers to have equipment that is compatible for both DC and AC, it would result in all equipment being usable with DC over time. After a while, this would transition into only DC equipment being used, and resulting in a smooth transition to DC distribution system and DC supply to houses.

6.1 Further work

To further develop and research the DC distribution system, there are several steps that can be taken and other considerations that have not been made in this thesis. These steps are in terms of realizing the DC distribution system as a contender for a spot in the standardized distribution system. Some of these steps are as following:

- Further research and simulation of grid solutions and structures
- Increased amount of pilot testing, for increased experience within the field
- Finding a solution to how to implement DC in households/buildings, for overall distribution system efficiency
- In depth research and calculation of losses and efficiency in a DC distribution system
- Research into repurposing of cables that results in a standardization
- Further development of high efficiency converters
- Setting requirements and rules, to enable the standardization DC distribution system
- Research on breakers for DC distribution system, can AC breakers be repurposed
- Fault analysis of DC distribution system, to ensure high reliability and stability

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