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LOW VOLTAGE DIRECT CURRENT IN ELEVATOR ELECTRIFICATION

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ABSTRACT

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The development of low voltage direct current (LVDC) networks is one of the most important ways to make electrical systems increasingly efficient. More efficient power systems are needed to mitigate climate change and promote sustainable development. This thesis examines the applications of the LVDC networks and their benefits for electrical systems. The main goal is to study how LVDC networks can be used in the electrification of elevators and how elevator systems can be made more efficient.

The thesis first examines the structures of LVDC networks and their main development targets, as well as the most significant power electronics converters that have enabled the development of the LVDC networks. The LVDC networks have been extensively tested in electrical distribution networks as well as in its applications such as microgrids. As results of the development of LVDC systems, many different network structures have emerged that have allowed the LVDC networks to be utilized in other applications as well. At the end of the thesis, it is examined how LVDC networks can be utilized in smaller electrical systems.

The thesis shows that the LVDC networks can be utilized in the electrification of elevators in many ways. As in the electrical distribution networks, the electrification of elevators can be implemented, among other things, with various hybrid LVDC solutions, which especially improve the power transmission capacity of long-distance elevators and reduce elevator construction costs. The elevator electrical system also benefits considerably from the fact that the power supply of the elevator is implemented by the LVDC network. As the number of the LVDC distribution networks increases and LVDC technology evolves, it can be noted that LVDC systems have potential for the elevator electrification.

Keywords: LVDC, LVDC network, distribution network, elevator electrification, elevator, efficiency

TIIVISTELMÄ

Topi Jalonen: Pienjännitteisen tasasähkön käyttö hissien sähköistyksessä
Kandidaatintyö, 27 sivua
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Pienjännitteisten tasasähköverkkojen eli LVDC-sähköverkkojen (engl. Low voltage direct current) kehittäminen on yksi merkittävimmistä tavoista tehdä sähköjärjestelmistä yhä tehokkaampia. Perinteisten sähköjärjestelmien tilalle tarvitaan uusia tehokkaampia sähköjärjestelmiä hidastamaan ilmastonmuutosta sekä edistämään kestävää kehitystä. Tässä työssä tarkastellaan erilaisia LVDC-verkkojen sovelluskohteita ja niiden hyötyjä sähköjärjestelmille. Työn päätavoitteena on selvittää, miten LVDC-verkkoja voidaan hyödyntää hissien sähköistyksessä ja miten hissijärjestelmistä saadaan tehokkaampia.

Työn alussa tarkastellaan LVDC-verkkojen eri rakenteita ja niiden tärkeimpiä kehityskohteita. Tämän lisäksi käydään läpi merkittävimpiä tehoelektroniikkamuuntimia, jotka ovat mahdollistaneet LVDC-verkkojen kehittämisen. LVDC-järjestelmiä on ollut laajasti testikäytössä sähkönjakeluverkoissa sekä sen sovelluksissa, kuten mikroverkoissa. LVDC-verkkojen laajan kehityksen seurauksena on muotoutunut monia erilaisia verkkorakenteita. Tämä on mahdollistanut LVDC-verkkojen hyödyntämisen myös muissa sovelluksissa. LVDC-järjestelmien hyödyntämistä pienemmissä sähköjärjestelmissä tutkitaan työn lopussa.

Työ osoittaa, että LVDC-verkkoja voidaan hyödyntää monin tavoin hissien sähköistyksessä. Sähkönjakeluverkkojen tavoin hissien sähköistyksessä voidaan hyödyntää muun muassa erilaisia hybridi LVDC-verkkoja, jotka parantavat erityisesti pitkän ajomatkan hissien tehonsiirtokykyä sekä alentavat hissien rakennuskustannuksia. Hissin sähköjärjestelmä hyötyy myös huomattavasti siitä, että hissin tehonsyöttö toteutetaan LVDC-verkolla. Voidaan todeta, että LVDC-jakeluverkkojen määrän lisääntyessä ja LVDC-tekniikan kehittyessä tullaan LVDC-järjestelmiä näkemään hissien sähköistyksessä.

Avainsanat: Pienjännitteinen tasasähkö, LVDC, LVDC-verkko, sähkönjakeluverkko, hissin sähköistys, hyötysuhde

PREFACE

I wish to thank KONE Corporation for the opportunity to do the Bachelor of Science thesis on an interesting topic. Especially I want to thank my supervisor Juha Panula and also Oskari Perälä for helping in the search for the thesis topic and supporting me during the writing process. I would also like to thank all my colleagues who have helped and supported me during the thesis project. The whole process has taught me a lot of new.

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Tampere, 13.5.2022

Topi Jalonen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
DC	Direct current
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
HVDC	High voltage direct current
LV	Low voltage
LVAC	Low voltage alternating current
LVDC	Low voltage direct current
MV	Medium voltage
MVAC	Medium voltage alternating current
PMSM	Permanent magnet synchronous machine
PV	Photovoltaic

1. INTRODUCTION

The electric power production has been significantly changed in the last decade. Traditionally, most of the electricity has been generated by large centralized units, but nowadays the electricity has been generated even more with renewable energy sources and the power generation is more distributed. Also, energy storages will be needed even more in the future due to distributed generation and because renewable energy sources depend on weather conditions. Because the production of electricity has moved to direct current (DC) and in energy storages is also used a lot of DC, low voltage direct current (LVDC) networks have recently gained a lot of attention [1]. At the end of the 19th century DC power distribution was the first standard electricity distribution system but in 1890s alternating current (AC) power distribution won the war of currents and since then AC electricity distribution system has been the standard distribution system [2]. Hence, DC is not new in the power distributions systems, and nowadays high voltage direct current (HVDC) electricity distribution systems are used to transfer electrical power over long distances [3].

During recent years, DC distribution systems have been extensively studied and modern power electronics has enabled development of the DC distribution systems. In the future, LVDC networks can be used for replacing existing low voltage alternating current (LVAC) distribution networks and can even be used instead of lateral medium voltage (MV) line sections [4]. The protection of LVDC networks has also been improved compared to traditional LVAC networks. Consequently, the entire distribution system is more reliable for end users, and the efficiency and controllability of distribution systems are improved. Even though LVDC networks have been extensively studied, there are only a few practical experiences from implementation of LVDC distribution systems. LVDC testing projects have been implemented in rural areas in South Korea [5] and in Finland [4], for instance. These LVDC power supply distribution networks are not the only development targets. Applications to be developed for LVDC include, for instance, information and communication facilities, future housing, commercial buildings, use in different motor systems such as propulsion systems and charging for electric cars [1].

At the same time when electric power production and distribution systems are undergoing a major change due to climate change and global warming, humanity is also undergoing a major change due to urbanization around the world. Consequently, many companies have begun to invest in sustainable development and energy efficiency and have begun to respond to urbanization. One such company is the Finnish elevator company KONE Corporation. KONE Corporation aims to reduce power losses and increase energy efficiency in its products. At the same time, KONE Corporation aims to make the urban life flow better and make cities and buildings better places to live.

Elevator produces braking energy, when it is braking and that is desired to be supplied to the power grid. Potential energy stored to the elevator car could be more simply supplied into the LVDC power grid through motor drive. Utilization of the LVDC power grid in the elevators is also one of the development targets. The target of the thesis is to find out ways to utilize LVDC power grids in the elevator industry and to improve the energy efficiency of the elevator electrification. The target is also to look at different topologies for elevator electrification and power supply of the motor that utilize LVDC power grids. At the same time, ways in which the elevator could operate as part of the smart grids and ways to integrate elevator electrification system into the power grids of future cities are being considered. This Bachelor of Science thesis is made as an assignment to KONE Corporation and is done as a literature review.

The remainder of the thesis is organized as follows. Chapter 2 presents different LVDC network structures and microgrids. Energy storage technologies, and ways in which intelligence can be used in distribution networks are briefly examined. In addition, advantages of the LVDC distribution systems are briefly studied. In Chapter 3 the main power electronic converters in LVDC distribution systems are presented. The useful lifetime, reliability and power losses of power electronics components are studied and compared with components of the traditional distribution system. Chapter 4 presents different LVDC installations topologies in property electrical systems. High-power load operations as part of the property's electrical systems are also examined. In Chapter 5 LVDC power grids utilization in elevator industry is studied. At first, the electrification of elevators is presented in general. At the end of Chapter 5, LVDC installations and its advantages in elevator electrification are studied and compared with installations of the traditional elevator electrification. Especially, the energy efficiency and power losses of LVDC installations are examined. Finally, Chapter 6 draws conclusions.

2. LVDC DISTRIBUTION SYSTEM

Most of the traditional distribution systems are based on AC power transmission where high voltage level is used for long distance transmission and the voltage level is reduced to a suitable level close to the electricity consumption. Such a network topology minimizes the network power losses. [3] However, this top-down network structure is not the best option for distributed power sources purposes [1]. In addition, HVDC transmission systems are used for long transmission distances. HVDC transmission systems have a high power transmission capacity and unsynchronized AC distribution systems are simpler to interconnect with the HVDC transmission systems [3].

Nowadays, LVDC distribution systems which use lower voltage level compared with HVDC systems have also been studied. The use of LVDC distribution systems increases the power quality and the reliability of the network, and the management of reactive power is also simpler with LVDC systems [3]. In the future, LVAC distribution systems may be replaced by LVDC distribution systems, but lack of standardization has slowed down the deployment and development of LVDC networks [1]. Nevertheless, testing projects have been successfully implemented with various network structures. In this chapter, different LVDC distribution network structures and advantages are reviewed.

2.1 Network structures

Traditional AC electricity distribution has been challenged, as the LVDC distribution systems have proven to be cost-effective in electricity distribution. Because LVDC networks have been developed by many parties around the world, many various structures have emerged for LVDC networks. Different network structures can be divided based on, for instance, voltage levels and the number of conductors in the network. Networks can also be divided according to whether the network uses only DC or whether the network uses both DC and AC in electricity distribution. Implemented network structures are usually based on different combinations of the above features. [6]

As stated above network structures can be divided based on voltage levels. However, in the LVDC distribution systems is desired to use the highest possible voltage level. The maximum low voltage level is defined as $1{,}500\ \mathrm{VDC}$. High voltage levels are used to reduce the transmission losses and maximize the transmission distance of electricity. [3] Lower voltage levels are also used, for instance, in the LVDC distribution in building applications [7]. These applications are reviewed more carefully in Chapter 4.

Regardless of the voltage level, networks can also be classified as single-bus and multi-bus configurations [7]. The simplest topology of the LVDC distribution networks is a unipolar network which is also known as the simplest single-bus configuration. In the unipolar network, only two conductors and one voltage level are used to transfer electricity to consumers as shown in Figure 1. [3]

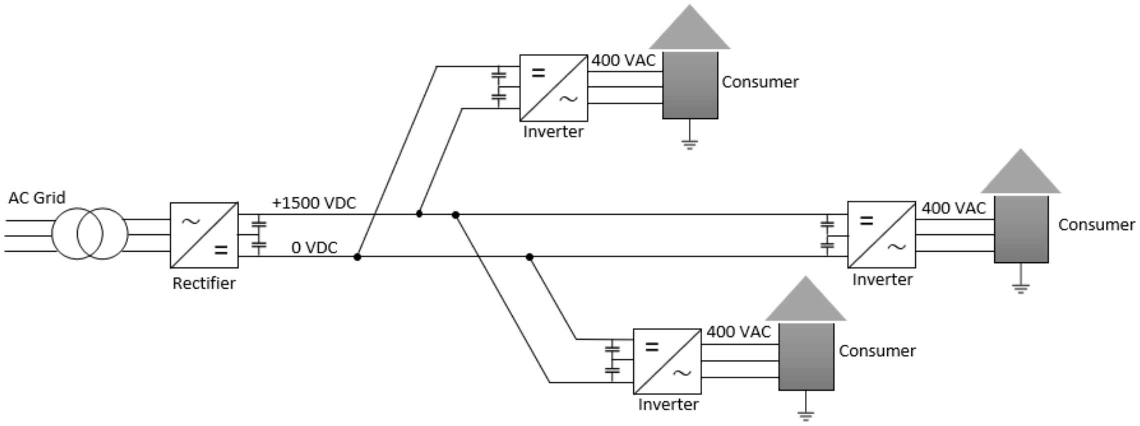

Figure 1. *A schematic of a unipolar hybrid DC-AC distribution network [edited from 3,6,7]*

As can be seen from Figure 1, the rectifier and inverters are connected to $1{,}500\ \mathrm{VDC}$ in the unipolar network. A slightly more complicated version of single-bus configuration is a bipolar network [7]. The bipolar LVDC distribution is made with three conductors and includes voltage levels of $\pm 750\ \mathrm{VDC}$ and the neutral, as illustrated in Figure 2. The bipolar network can also operate like the unipolar network and thus it has higher reliability than the unipolar network. [3]

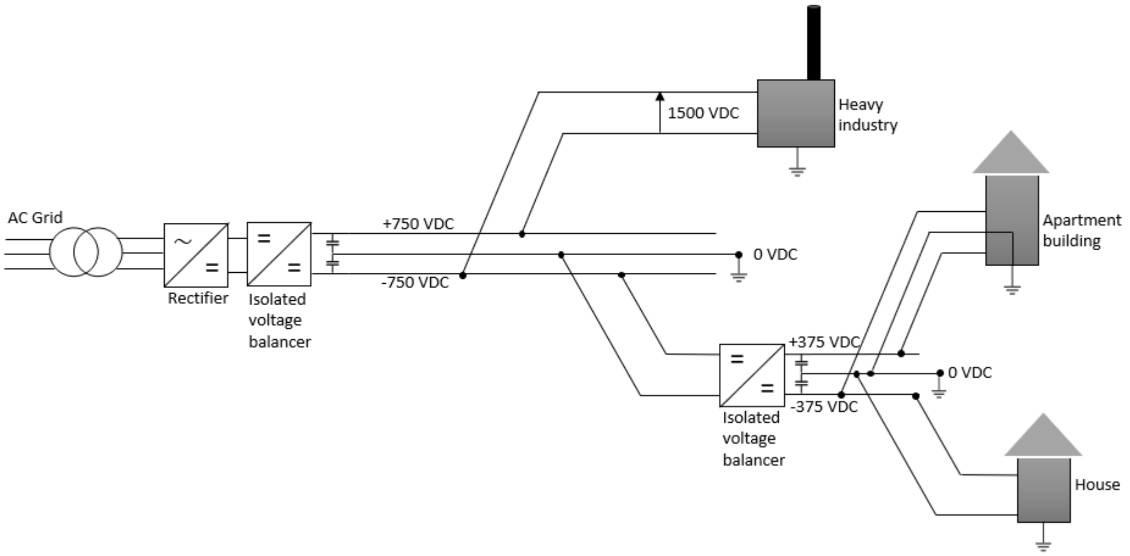

Figure 2. *A schematic of a bipolar full DC distribution network [edited from 3,6,7]*

As can be seen from Figure 2, there are various ways to connect loads to the bipolar network. In the bipolar LVDC distribution, the loads can be connected between the positive and negative terminals, between the positive and negative terminals with the neutral or between the positive or the negative terminal and the neutral. This allows the loads to be connected to the voltage levels that are best suited to them [3].

Multibus configurations are also possible network structures for LVDC networks. Multibus LVDC distribution uses multiple conductors to improve the reliability and availability of the distribution system. These configurations are used, for instance, to interconnect several microgrids where the distribution system requires higher flexibility and reliability. [7] Microgrids are reviewed more carefully in Section 2.2.

It is likely that in the future traditional AC electricity distribution will be replaced, at least in part, by the LVDC networks. If only MV lines are replaced by the LVDC system and the LVAC system is still used for distribution to consumers as illustrated in Figure 1, then the system is called a hybrid AC-DC system. The hybrid AC-DC topology is also known as a link-type solution. [6] In the hybrid AC-DC distribution system the advantages of both DC and AC transmission can be combined. Often in the hybrid AC-DC distribution systems small scale power generation, such as photovoltaic (PV) arrays and small-scale wind power plants, are connected to DC transmission lines. [8]

If, in addition to the MV branch lines, the LVAC networks are replaced by LVDC systems, the system is called a full DC topology. The full DC distribution system is also known as a network-type solution and its basic principle is shown in Figure 2. [6] As can be seen from Figure 2, in the full DC distribution system, the transmission of electricity to consumers also takes place via LVDC networks.

There are many different structures for LVDC networks, and all of the above topologies and features can be combined. Thus, there is no single standardized network structure for the LVDC distribution, and the topologies illustrated in Figures 1 and 2 are only some of the possible topologies for the distribution systems. These same structures and their combinations can also be utilized in other applications at different voltage levels, such as commercial buildings and elevator electrification. These applications are reviewed more carefully later in this thesis.

2.2 Microgrid

Various LVDC network structures have been developed for different applications and microgrids are one of the applications where LVDC networks are used. Microgrid is an electricity power network that contains a group of distributed power generating sources, energy storage devices and controllable loads as shown in Figure 3 [9]. It normally operates at a low voltage (LV) level and its total installed power capacity ranges from a few kilowatts to megawatts [10]. Microgrids are usually integrated into the main distribution network, for instance, a medium voltage AC (MVAC) network, as shown in Figure 3, but can also be operated in an island mode. In the island mode, microgrids are disconnected from the main network, for instance, if a failure situation occurs in the distribution network [9]. The distributed energy sources, energy storages and controllable loads allow microgrids to operate independently. Network controllability is a key feature for microgrids and is a distinguishing factor between microgrids and traditional distribution systems. This characteristic of microgrid also improve the reliability, electrical safety, and quality of the distribution systems. [10]

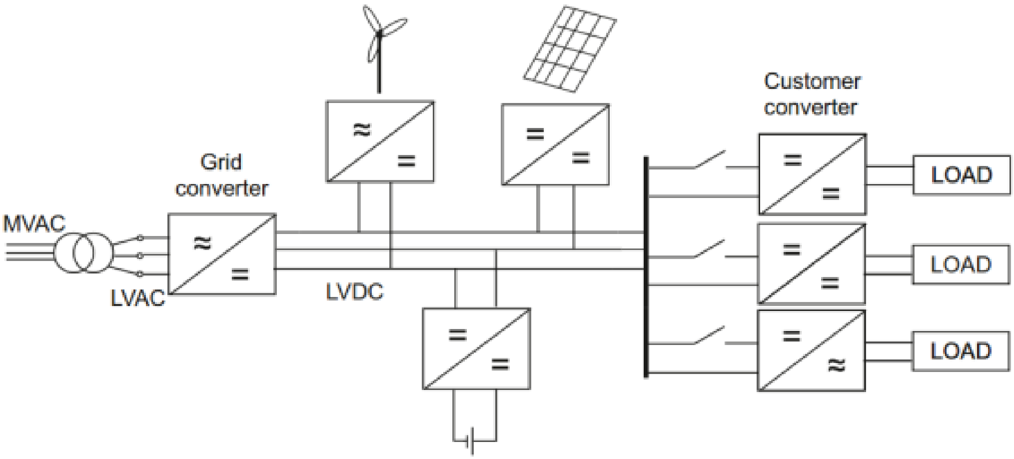

Figure 3. *A typical DC microgrid including various energy sources and consumers [3]*

Figure 3 above illustrates a typical DC microgrid topology, and as can be seen from the figure, microgrids also include, for instance, grid and customer converters in addition to distributed energy sources and controllable loads. In addition to these network components, microgrids often have different controllers, smart meters, smart devices, as well as communication devices. Therefore, the networks of the future are becoming more and more intelligent and such modern intelligent electricity grids are called smart grids. [10] It can also be said that the smart grids are built from many microgrids [9]. Thus, the distribution systems are changing from passive to active networks, allowing bidirectional current flow in the distribution system. At the same time, the roles of network end-users are changing from consumer to both consumer and producer. [10] Such customers are often called prosumers. Such a distribution system or the microgrid where consumers can either sell or buy electricity requires expensive technologies and high-quality communication systems to operate [10].

Like LVDC network structures also the microgrids can be classified into various categories. They can be divided into different categories based on their location or according to the power structure of the microgrid, or in the other words, whether the network uses only DC or only AC, or whether the network uses both DC and AC for electricity distribution. [10] As can be seen from Figure 3, power generation can be based on either AC or DC in the DC microgrid, but AC energy sources are converted to DC for distribution and all power generation and loads are connected to the DC bus via power electronics converters. Unlike in AC systems, the DC microgrid systems voltages of energy sources and frequencies do not need to be synchronized. A great advantage of the DC microgrid systems is also that the power flow direction is bidirectional and thus it is easy to control the power flow of DC microgrid systems. [10] In addition, the quality and reliability of electricity and voltage amplitude can be controlled by customer converters [3].

Micrograms can also operate with AC electricity distribution and a typical AC microgrid topology is shown in Figure 4. It can be seen from Figure 4 that in the AC microgrids all energy sources and consumers are connected to the AC bus by power electronics converters and AC microgrids require several AC/DC/AC conversion stages [3].

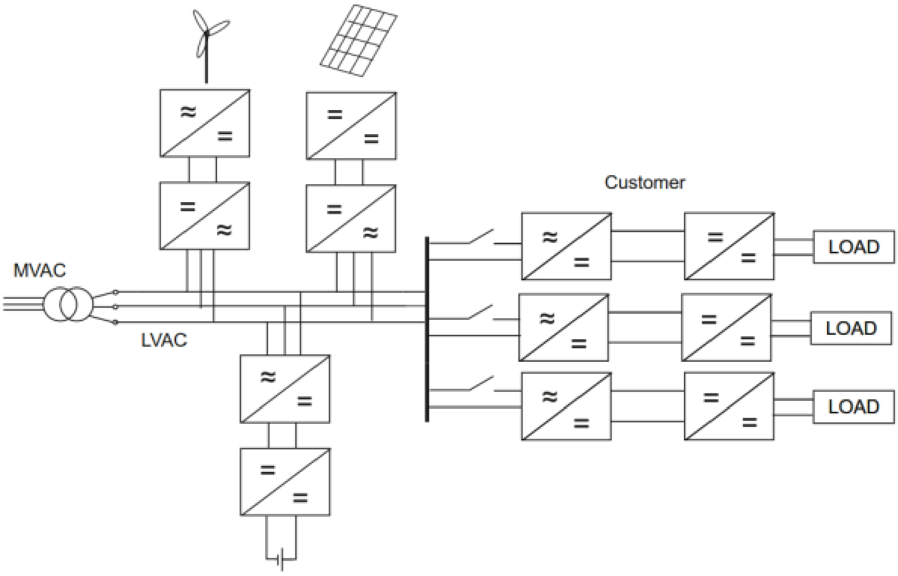

Figure 4. *A typical AC microgrid including various energy sources and consumers [3]*

When comparing Figures 3 and 4, the amount of AC/DC/AC conversion stages is lower in the DC microgrid system compared with the AC microgrid system. Consequently, DC microgrid systems are more efficient because they have lower conversion losses, while the total cost of AC microgrids is higher due to the higher number of the power electronics converters [10].

Like the LVDC networks, microgrids can also operate on both DC and AC, and such networks are called a hybrid microgrids. In addition to the grid and customer converters, the hybrid microgrids also have power electronics converters between the DC bus and the AC bus, and both AC system and DC system have their own energy sources and consumers. This allows all power systems and loads to be connected to a system suitable for them and all the advantages and disadvantages of both DC and AC microgrid systems can be included in the hybrid microgrid system. [10]

Microgrids can also be classified into five different categories: remote, military, campus, community, and commercial microgrids based on their location in the power grid [10]. Figures 3 and 4 illustrate one type of commercial microgrids which are normally connected to the main power grid and operate in a grid connected mode. In this case, the price and demand for electricity can be better met. Commercial microgrids are also sometimes called industrial microgrids and these networks are reviewed more carefully in Chapter 4. In the community and campus microgrids, stability and reliability have been able to improve, and in the campus systems, for instance in hospitals microgrids, are often installed to operate independently, so as not to interrupt the transmission of electricity and cause incidents. The military and remote microgrids are usually installed in rural areas where the main power grid is not available or in areas where special security is required. Such networks usually operate in island mode. Depending on the location of these different microgrid configurations, power generation technologies range from diesel generators to solar PV systems. [10]

There are various distributed power generation technologies and as can be seen from the Figures 3 and 4, they can be connected directly to the microgrids using power electronics converters. The power generation units connected to the microgrids are usually called microgeneration units and their output power is rated from some kilowatts up to $50\ \mathrm{MW}$ [10]. These distributed energy sources are normally located at consumers' site in the distribution LV network [9]. Most of the distributed energy sources are renewable, such as solar generation units and wind turbines. It is not always possible to use renewable energy sources, so the microgrids often contain other power sources such as microturbines, fuel cells and diesel generators to ensure the security of supply. [10]

Renewable energy sources depend on environment conditions, in which case they are not always available. Even if weather conditions can be forecasted, electricity must be stored to secure the availability of electricity under any conditions. The operation of microgrid controllability is also based on the energy storages and the microgrids would not be able to operate in the island operation mode without energy storages. The electrical energy can be converted into, for instance, mechanical, chemical, and electromagnetic energy. Most of the storage capacity in the world is in mechanical energy form and the most used mechanical energy storage technology is pumped hydropower storages. Also, electrochemical storage technology, such as batteries, and electromagnetic technology, such as supercapacitors, are used a lot in electrical energy storages. [10]

Future networks will be more intelligent and can connect various technologies together, such as distributed energy sources, consumers, and smart appliances. More and more smart devices are connected to the microgrids which can communicate with the network and each other. One such smart device is an elevator that can be operated as part of the microgrid. Elevators are able to store a small amount of energy, for instance, the potential energy of the elevator car and they are able to supply breaking energy to the network. Elevators may be an increasingly significant part of microgrids in the future thanks to constantly evolving communication systems and intelligence.

2.3 Advantages

Many different advantages for LVDC networks have already been mentioned in the above sections such as the reliability, quality, and safety of the electricity distribution. The same advantages that the LVDC networks have, can be commonly applied to microgrids as the future microgrids are built fully or partially utilizing the LVDC networks. In addition, it is easier to connect renewable energy sources and other microgeneration systems, such as prosumers, to the LVDC networks [8]. At the same time, the amount of voltage level transformations and network converters is lower in the LVDC systems which increases the efficiency of electrical systems [3]. The advantage of LVDC networks is also that DC network generators and smart devices are not necessary to synchronize and power flow can also be bidirectional [10].

LVDC networks make it possible to reduce the length of the entire distribution network and at the same time the number of the protection areas increases. In addition, a local power generation and storage devices allow the LVDC network to operate in the island mode. Consequently, the number of power outages experienced by consumers decreases and transfer security improves. [6] LVDC network transmission capacity is also better than LVAC network and the maximum transmission distance is longer with the LVDC distribution networks [3]. The maximum transmission lengths of AC and DC networks are shown in Figure 5. The maximum allowed voltage drop determines the maximum length and the maximum current of the cable. In the case of Figure 5, the maximum allowed voltage drop is 6 % [3].

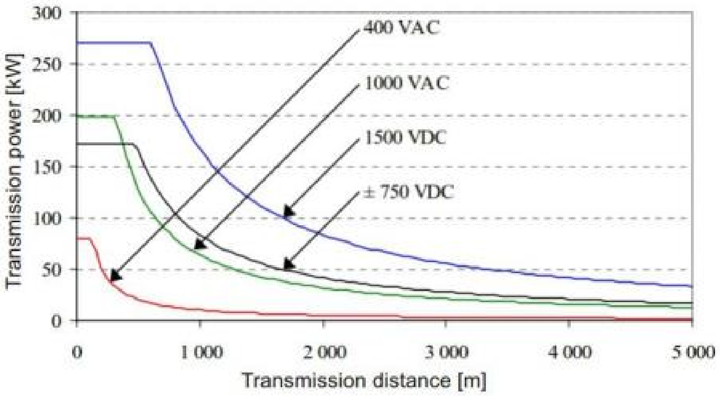

Figure 5. *Maximum transmission distances and powers for AC and DC distribution networks with* $3x35+70\ mm^2$ *LV cable [3]*

As illustrated in Figure 5, the DC distribution networks have much better transmission capacity and longer transmission distance compared with AC distribution networks. Thus, LVDC distribution systems also have lower cable and construction expenses compared with the LVAC distribution systems. When replacing the LVAC networks with the LVDC networks, LVAC network cables can be used for DC distribution if the maximum DC voltage between the bus and earth is up to $900\ \mathrm{VDC}$. [3] LVDC networks also allow the use of a smaller cable with the same current as in LVAC networks [11].

In addition to the advantages, there are also challenges with LVDC networks will need more attention from the researchers in the future. Although the transition from AC systems to DC systems is relatively easy, LV distribution systems require, for instance, new standards for devices and voltage levels. The protection of DC network systems is also more difficult than that of an AC network system. In addition, a grounding of the DC systems is more problematic in comparison with the AC network systems. [11] So there are many challenge areas in LVDC networks that need to be further developed, but the advantages of DC systems are significant compared with AC systems. For this reason, LVDC power systems have been developed and will continue to be developed for various applications, such as elevator electrification and electric car charging.

3. POWER ELECTRONICS IN LVDC NETWORKS

In recent decades, the power electronics components have evolved significantly. Modern power electronics converters have enabled the development of LVDC networks and are the most important part of intelligent DC power systems. The same has been able to be notice in the figures shown in the previous chapter. Power electronics converters allow loads to be controlled and the voltage levels of the loads to be kept at the default range. The voltage ripple ratio can also be kept as low as possible by power electronics converters. [10] In this chapter, the most common converters used in LVDC systems are reviewed. In addition, the power losses of the power electronics converters and their useful lifetime.

3.1 LVDC systems converters

As mentioned above, the power electronics converters are needed to implement the LVDC systems, and the development of power electronics components has improved the applicability of the DC power systems. The LVDC systems require AC/DC, DC/DC, and DC/AC power electronics converters to operate. [10] The purpose of the converters is to keep the DC voltage level constant and make it meet the needs of consumers. The converters are also needed to connect the AC and DC networks together. [3]

In this section various LVDC system converters are studied. The basic structures and operating principles of all these converters are presented. In addition, some of the advantages and uses of these converters are examined.

3.1.1 AC/DC Converters

The AC/DC power electronics converters are required between the main grid and the LVDC system when the DC system operates in the grid connection mode. These converters are also called rectifiers or grid converters, and their function is thus to rectify the AC voltage to DC. [10] When the LVDC system is connected to a three-phase grid, a one-line or two-line rectifier topologies can be utilized in the DC system. The cheapest and simplest AC/DC converter is a diode rectifier which also has high efficient and robust converter topology. The diode rectifiers are only able to provide one-way power flow and their output voltage cannot be controlled. A thyristor rectifier is almost similar and as simple as the diode rectifier, but the output voltage can be controlled. [3] Bidirectional current can be enabled by two-level and three-level AC/DC converters [10]. One type of two-level rectifier is illustrated in Figure 6, and as can be seen from the figure, such AC/DC converters consist of bridge rectifiers and in addition a large filter capacitor.

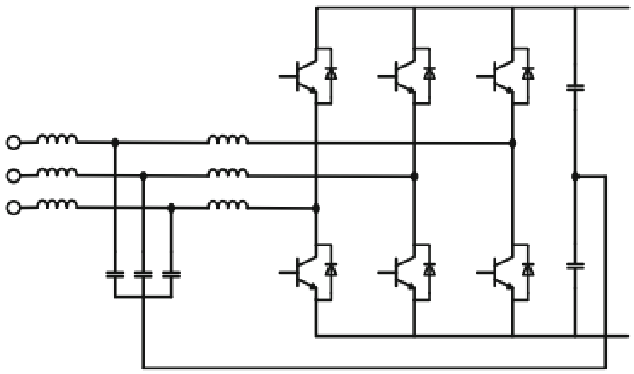

Figure 6. *Three-phase, two-level line AC/DC converter [10]*

In the rectifier seen in Figure 6, fully controlled power semiconductor switches have been used instead of diodes and thyristors. This allows the complete control of the output DC voltage. Thus, voltage variations in the external AC network do not affect the output voltage of a rectifier. Such two-level rectifiers are the most used because they have good controllability and a simple structure. [3] Similar converters are also used in the electrification of elevators.

3.1.2 DC/DC Converters

Distribution of electricity in DC form would be beneficial because most of the devices which are used daily operate with DC electrical energy. However, not all devices operate at the same DC voltage levels. DC/DC power electronics converters are needed to supply the loads to achieve required DC voltage levels. [10] These converters are thus used to convert DC voltage levels and can be used both in distribution networks and in smaller electrical systems such as elevator electrification.

There are many various types of the DC/DC converters that are suitable for different purposes. Some converter topologies are designed for higher loads than others. There are converters that increase the input voltage and those that reduce the input voltage at the output. Some converters are also combinations of the above converters where the input voltage level can be both increased and decreased. Such a converter is, for instance, a buck-boost converter, while a voltage reducing converter is, for instance, a buck converter. [10] Converters that can increase the input voltage level at the output are called boost-type converters and one such DC/DC boost converter is shown in Figure 7.

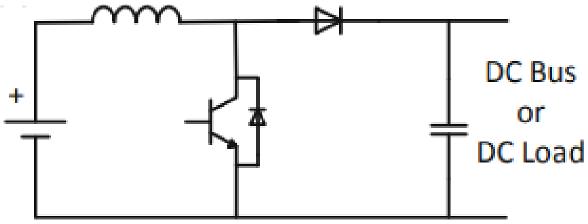

Figure 7. *Conventional DC/DC boost converter [10]*

Figure 7 above shows the topology of the most conventional boost converter. However, the various converters mentioned above are not the only topologies of the DC/DC converters. Isolated DC/DC converters are another structure type for these converters. One type of the isolated DC/DC converter is a flyback converter which is used for low-power applications. [10] Similar converters as the flyback converters are used, for instance, in the electrification of elevators.

3.1.3 DC/AC Converters

DC/AC power electronics converters are called inverters, and they are required when AC loads are fed from a DC electrical system. They are used to converting the DC voltage form into the AC form. The DC/AC converters can be either three-phase or single-phase converters depending on the consumer requirements. In addition, inverters can also be used to full-bridge or half-bridge topologies. [3] The half-bridge is the simplest structure but requires more passive circuit components for filtering than the full-bridge structure. However, full-bridge structure includes more active circuit components and thus has a more complex structure than the half-bridge structure. [10] In Figure 8 a three-phase two-level half-bridge inverter is shown.

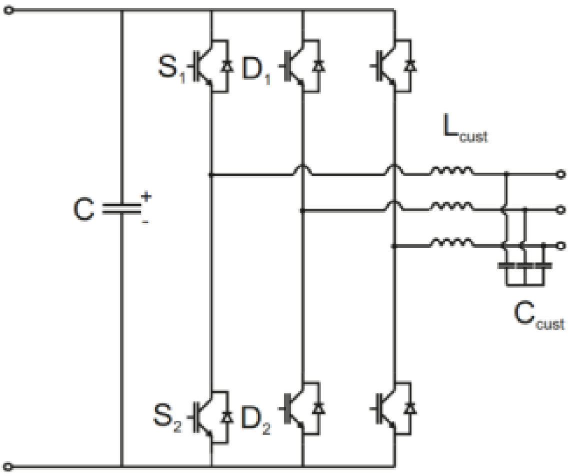

Figure 8. *Three-phase two-level DC/AC power electronics converter [3]*

The inverter in Figure 8 is one of the simplest DC/AC converter topologies and similar inverters are also used in hoisting machine inputs in the electrification of elevators. As can also be seen from the figure, the DC side capacitor is required to compensate for voltage fluctuations. In addition to being simpler in structure than full-bridge inverters, half-bridge converters also have lower costs and are easier to control. However, the challenge with all types of inverters is the harmonic production, which is attempted to be eliminated by many different methods. [10] This makes the structure of inverters more complicated and at the same time increases their costs.

3.2 Power losses and useful lifetime

Power electronics components incur many various costs during their lifecycle such as construction and replacement costs. In addition, power losses take place in these components. Power losses occur whenever current flows through a resistive material such as semiconductor switches, inductors, and wires. Thus, the power losses occur not only in the power electronics components, but also in passive components such as filters. For instance, power losses cause voltage drop in circuit and heating of the components.

The power losses of the converters can be divided to switching and conduction losses. The switching losses include turn-off and turn-on losses of the power semiconductor switches and reverse recovery losses of diodes. In addition, the conduction losses happen in both semiconductor switches and diodes. The power loss is also affected by the power level of the converter at which the converter operates. [3] Some power electronics converters also produce low frequency harmonics to the networks which cause additional losses in capacitors, transformers, and inductors. These harmonics components also cause electromagnetic interference (EMI) and dielectric stresses. [10]

In addition to the power losses of the converters, the construction and replacement of components also incur costs. The average useful lifetime of the power electronics converters is very short, only 5-10 years, while the average useful lifetime of components in the existing distribution networks is, for instance, from 30 to 50 years. However, a good maintenance program can slightly extend the life of the converters. In this case, a lifespan of about 15 years is possible. The useful lifetime of the converters is also affected by their installation environment, such as operating temperature and load characteristics. [12] It can be said that the fewer converters can be used in electrical systems, the less they incur costs.

4. LVDC INSTALLATIONS IN PROPERTY ELECTRICAL SYSTEMS

As already mentioned above, there are many different applications for the LVDC electrical systems. One application is LVDC installations in building electrical systems where, the advantages of different voltage levels can be utilized. This chapter reviews the different LVDC installation topologies for property electrical systems and how to connect high-power loads to them.

4.1 Installation topologies

The property electrical system installations can be carried out in the same ways as the distribution networks. LVDC distribution systems for building applications can thus be implemented, for instance, as hybrid, bipolar or unipolar network. In the near future may be seen hybrid AC/DC distribution systems for buildings, because many devices today require AC electricity to operate, so it does not make sense to convert the entire distribution system to the LVDC system. [7] Figure 9 shows one possible topology for such a system.

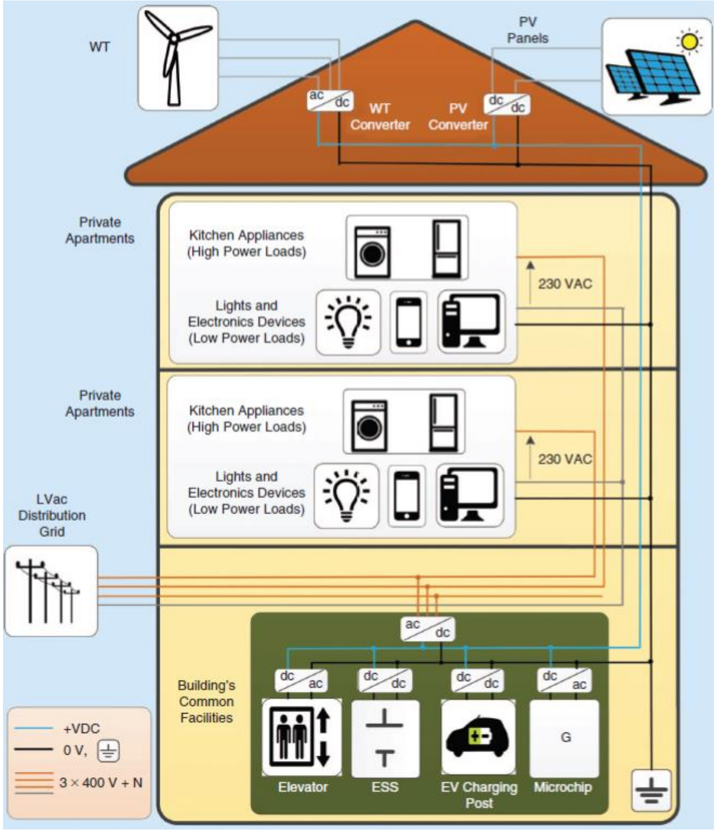

Figure 9. *A topology of hybrid distribution system for property applications [7]*

As can be seen from Figure 9, the LVDC system can be used to connect the renewable energy sources, energy storage systems and common loads in buildings such as elevators and lightning systems. In such system, electricity is still distributed through the traditional LVAC network, eliminating the need for consumers to change their electrical equipment. However, the AC and DC systems are interconnected by a bidirectional AC/DC converter as shown in Figure 9.

In the future can be seen distribution system applications in buildings that operate fully with the LVDC. In this case, the distribution is made more efficient, because it is possible to utilize several voltage levels. However, the choice of the optimal voltage level is not as straightforward for these building electrification systems as for the LVDC distribution systems. The choice of voltage level depends on the features of the power system and the size of the power loads connected to it. For instance, for low-power loads such as computers and televisions, a much lower voltage level is sufficient than for medium power elements such as stoves and washing machines. [7] However, it is desired to distribute electricity to different loads at the most optimal voltage level possible, so there may be many various voltage levels inside the same building.

4.2 High power load installations

As mentioned in Section 4.1, different power loads require different voltage levels. High-power elements, such as elevators and electric vehicle charging posts, require the highest voltage level in the building electrical systems, as can also be seen in Figure 9. The high-power elements also include, among others, distributed generation and energy storage systems. [7] In the full DC distribution system, the high-power elements can be connected directly to the distribution network, while in the hybrid LVDC system, the high-power elements can be connected to their own DC network that is interconnected to the main grid, as shown in Figure 9. These connection methods make it possible to reduce the conversion stages. [12]

Many high-power loads require different converters to operate and connect to the network. Today, for instance, many motors, such as the elevator hoisting machine, are controlled by a frequency converter, and DC/DC converters are often used in the electric vehicle charging posts. When applying the LVDC distribution networks in buildings, the structure of frequency converters is simplified and the amount of voltage conversion stages is reduced. [12] This significantly improves energy efficiency and encourages the use of LVDC distribution networks in smaller electrical systems as well.

5. LVDC IN ELEVATOR INDUSTRY

More and more people are moving to cities and in the future most of the humanity will be living in cities. This phenomenon is called urbanization and elevator company KONE Corporation has begun to respond to it by developing increasingly efficient and sustainable ways to move people from one place to another. In the future, the use of elevators and escalators will increase, and KONE Corporation is a pioneer in the development of new elevator and escalator technology ideas [13]. This chapter examines how LVDC networks could be utilized for the electrification of elevators. Before that, the structure and electrification of the elevator are generally undergone.

5.1 Elevators in general

The main function of elevators is to move people and goods from one floor to another as safely and reliably as possible, but at the same time as environmentally friendly and smoothly as possible. In Figure 10 are shown the main components of a long-distance elevator, and as can be seen from the figure, the elevator operates exclusively in a shaft built for the elevator. These long-distance elevators are called High Rise elevators. There are car guide rails on the walls of the shaft along which elevator car and car sling run. The car is a part of the elevator where people and goods can be moved safely from one floor to another. As can be seen from Figure 10, the hoisting ropes carry all the load in the car and are attached to the car sling and counterweights. The purpose of the counterweights is to balance the load on the elevator and thus reduce the lifting work done by the hoisting machine [14].

Elevators have evolved much from the first elevators and different elevator structures and technologies have emerged over the years. For instance, various types of elevators have been developed for different distances. In addition to the High Rise elevators in Figure 10, medium and short distance elevators i.e. Mid Rise and Low Rise elevators have been developed. Different elevators are also capable of operating at different speeds, but in general it can be said that High Rise elevators travel faster than other types of elevators. Elevators can also be classified as elevators with machine room and elevators without machine room. The elevator shown in Figure 10 is a machine room elevator, in the other words, it has a separate space for the hoisting machine. Elevators without a machine room are also possible. In them, the hoisting machine is mounted on the wall of the shaft, so there is no need for a separate machine room.

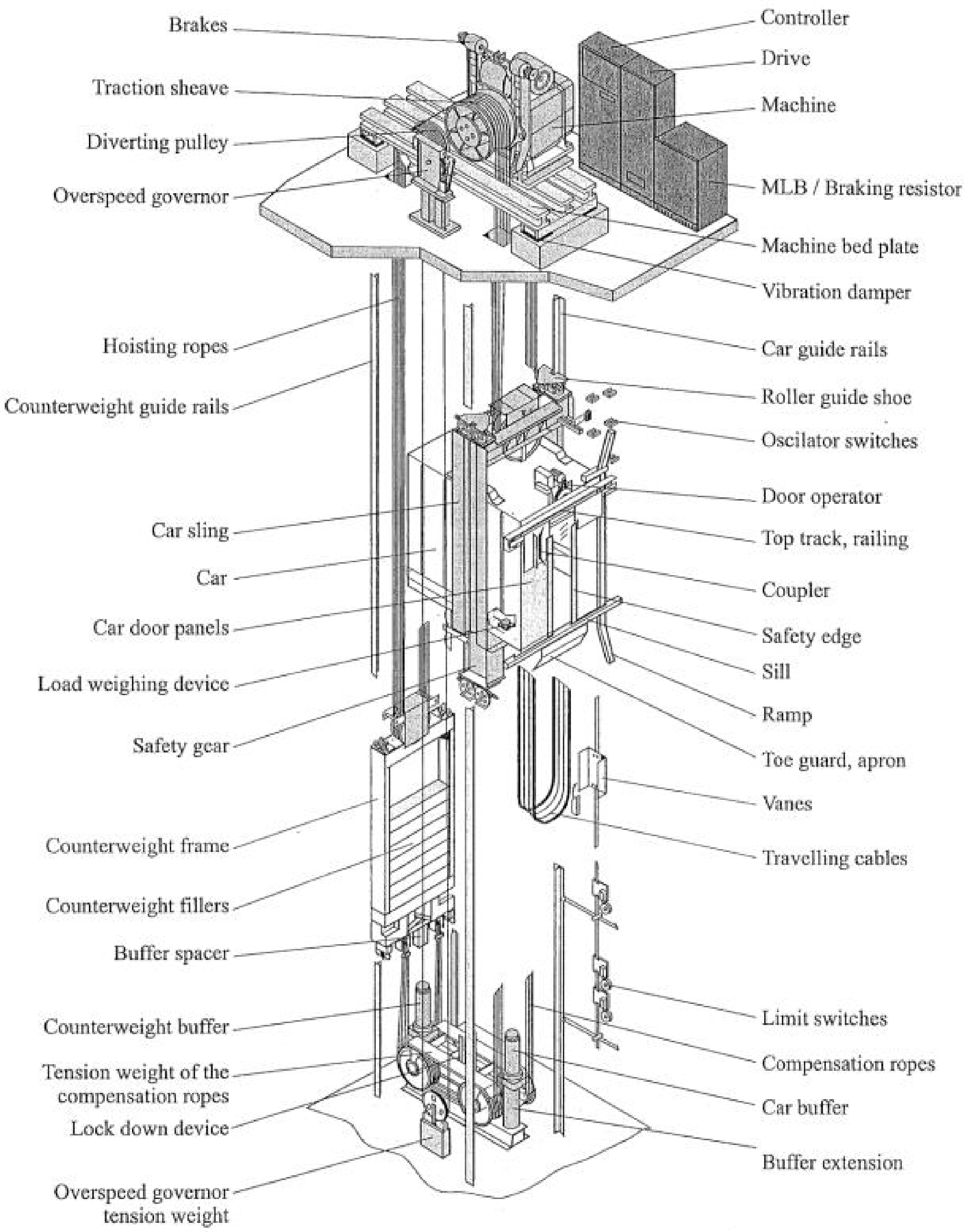

Figure 10. *The main components of the machine room elevator system [14]*

The structure of the elevators has therefore changed a lot over the years and its mechanical components have been improved. For instance, the weight of the ropes has been reduced with KONE UltraRope hoisting ropes. Carbon fiber is used as a material for the UltraRope ropes, and they have enabled the development of longer distance elevators [15]. Consequently, by developing mechanical parts of the elevator, it is also possible to intensify the operation of the elevator.

5.2 Electrification of elevators in general

Electrification of elevators is based on two main components: controller and frequency converter i.e., drive. In the Low Rise elevators, these components can also be integrated together. In elevators with machine room, the controller unit, and the drive are installed in the machine room, while in elevators without machine room the drive is located in the shaft. [14] However, in the elevators without machine room the controller may be located either in the shaft or outside the shaft at a landing, depending on the controller unit model.

There are various types of drives for elevators and their operating principles differ slightly. Although there are different types of drives, the main principle of all drives is to feed power to the elevator machinery. [14] Figure 11 shows a schematic diagram of one type of elevator drive and how some components of the elevator, such as the controller unit, are in contact with it.

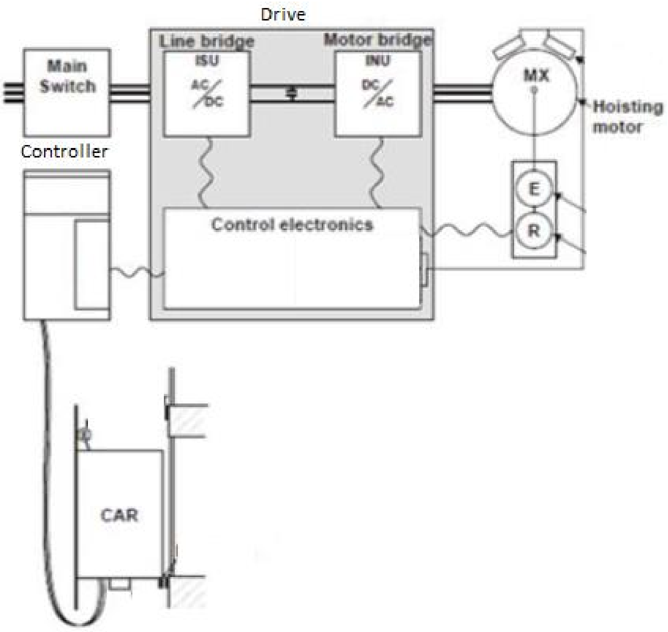

Figure 11. *A schematic of a one type of elevator drive and the devices that work with it [edited from 14]*

As can be seen from Figure 11, the hoisting machine is connected to the drive. The drive feeds the hoisting machine with varying voltage and varying frequency depending on how much torque is needed and what the desired elevator speed is [14]. As can also be seen from Figure 11, the drive includes, among other things, a line bridge that converts the AC electrical power into the DC voltage and a motor bridge that converts the constant DC voltage into the AC power to run the hoisting machine. The drive can also be used to reduce the rotating speed of the hoisting machine. This is called line braking and during this the motor operates like a generator. Often the electrical energy produced by the motor can be fed back to the network. However, it is not always possible to feed electricity back to the network, whereby the electrical energy is converted into thermal energy by power resistors. [14]

The drives are used to control the hoisting machines. The hoisting machines used by KONE are permanent magnet synchronous machines (PMSM) with an axial flux structure. This means that the magnetization of the motors is implemented with permanent magnets and its magnetic field is parallel to the axis of the motor. Such a hoisting machine structure saves a considerable amount of space, which makes it possible to install the hoisting machines in the shaft as well. [15] Figure 12 shows KONE’s EcoDisc hoisting machine installed on the shaft wall.

Figure 12. *PMSM hoisting machine mounted on the elevator shaft wall [15]*

As can be seen from Figure 12, the PMSM hoisting machines have made it possible that machine rooms are not always required. Another advantage of the PMSM hoisting machines is that they are gearless because they are controlled with drives [14]. However, there are many different types of the hoisting machines and, for instance, the motor structure of the High Rise elevators are different from that shown in Figure 12.

Depending on the drive, they sometimes feed other control units in addition to the hoisting machines. The control units can also get their input directly from the network. The controller contains the most important operating logics of the elevator system, and it handles the car calls and signalization as well as commands the drive, for instance. As can also be seen from Figure 11, the elevator car is connected to the control system by the travelling cable. The travelling cable allows all electrical devices of the car to be connected to the control system and the car to continuously transmits information to the controller. The electrification of the elevator also includes the electrification of the shaft lighting in addition to the devices mentioned above. It usually comes from a separate electrical centre, so that the electricity can be cut off from the elevator during maintenance without the shaft losing its lighting. [14]

5.3 LVDC installations in elevator electrification

The utilization of the LVDC systems in the electrification of elevators can be studied in a few different ways. For instance, it can be studied how the electrification of an elevator benefits from being fed from the LVDC network or how LVDC technology can be utilized in the elevator electrification. In the electrification of elevator, most of the power required by the elevator is transmitted through the AC power transmission system. For instance, it will be possible to improve the efficiency of the system if these transmission system parts were replaced either completely or partially by the LVDC system.

As described in Section 5.2, the travelling cable is used to transfer the power to the car it requires to operate. Especially in the long-distance elevators, the length of the travelling cable increases considerably. In this case, the size of the traditional AC supply cable should be increased to avoid overheating of the cable and voltage drop. It would also increase the construction costs and cable weight. However, this can be avoided, for instance, by applying the hybrid AC-DC distribution network described in Chapter 2 to the electrification of elevator. As in the hybrid distribution networks, part of the AC transmission system can also be replaced by the LVDC system in the elevator electrification, as shown in Figure 13.

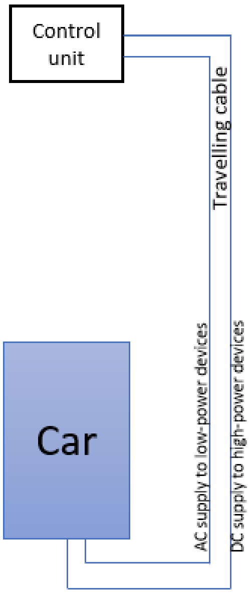

Figure 13. *Hybrid AC-DC power system in the elevator electrification*

In the hybrid network of Figure 13, high-power devices are fed with the LVDC distribution network while low-power devices are fed with the traditional AC network. Its structure is quite similar to the hybrid distribution system of the building in Section 4.1. In this way, it is avoided that the size of the cables needs to be increased, because as already mentioned in Chapter 2, LVDC systems are able to transmit more power than the traditional AC network with same cable size.

As in the property application mentioned in Section 4.1, also the electrification of the elevators could be built almost exclusively from the LVDC networks. In this case, the use of different voltage levels enables power transmission as efficiently as possible. However, when designing such a structure, it should be considered that unnecessary conversion stages are not created.

Lighting for the elevator shaft can also be implemented with the LVDC system. It enables the minimization of cable size and at the same time more efficient transmission because the DC voltage is the native operating voltage to the modern lightning systems such as led lights.

Both bipolar and unipolar networks can be used in the elevator electrification system, but a simpler unipolar network will already increase the power transmission capacity considerably compared with the traditional AC network. However, if extended capacity is required, a slightly more complex bipolar network can also be used, but at the same time, for instance, it increases construction costs compared with the unipolar network. In addition to being more efficient and saving on construction costs, the LVDC networks ensure higher power quality and a regular output voltage. For that reason, other devices can also be designed to operate at the optimal point. Also, because the native operating voltage of many modern electrical devices is DC, it is more efficient to transfer power to them with the LVDC networks.

As the LVDC networks will become more common in the future, both in the distribution networks and in smaller distribution applications such as building and marine applications [16], it is very likely that elevators will be fed from the LVDC networks. In this case, the structure of the frequency converter can be simplified and additional voltage conversions stages can be eliminated [12]. Figure 14 shows an example from a small-scale industry. Figure 14a shows a controlled motor system fed by the traditional LVAC network, while Figure 14b shows a system fed by the LVDC network. As can be seen from the figures, the drive rectifier can be removed when the system is fed from the LVDC network. For this reason, one conversion stage is avoided, making the system more efficient and cheaper.

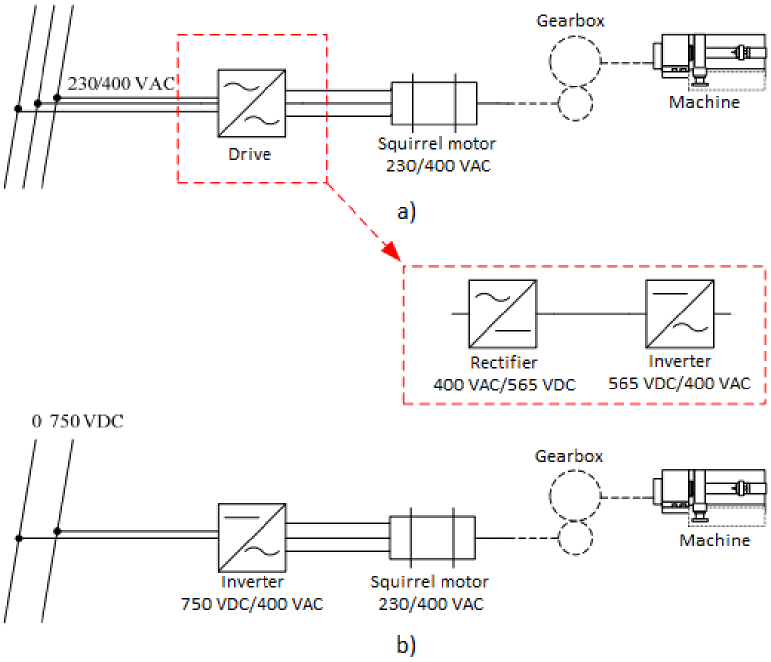

Figure 14. *The power supply of the machines via a) the traditional LVAC network and b) the future LVDC network [edited from 12]*

As in Figure 14, the rectifier stage could be removed from the elevator drive if the elevator is fed from the LVDC network. In this case, when the elevator is fed from the LVDC network, it is also more natural and efficient for elevator electrification to consist of LVDC networks. In addition, when the elevator brakes and produces electrical energy, it is easier to transfer back to the LVDC grid. The elevator is therefore easier to operate as part of the rest of the grid thanks to the LVDC system. The benefits of the LVDC networks for the elevator systems are quite significant, so the LVDC systems will certainly be seen in the electrification of the elevators as well.

6. CONCLUSIONS

Climate change and the limited quantity of fossil fuels has guided many companies to develop their operating practices and investment targets. Many companies are investing in sustainable development and more efficient final products. At the same time, electronic devices are also evolving, and their operating voltages have undergone changes from AC voltage to DC voltage. In addition, the amount of renewable energy sources has grown significantly, and power generation is more and more distributed. Consequently, new LVDC network technology has been developed, especially for electricity distribution networks.

LVDC networks have thus been developed mainly for electricity distribution networks and its applications such as microgrids. Many different types of networks have emerged when developing networks, each with its own pros and cons. The LVDC networks have also enabled the faster development of the smart grids as the LVDC networks enable better control of distributed power generation, energy storages and consumers. In this case, consumers, and other individual high-power loads such as elevators will be able to operate more efficiently and easily as part of the rest of the power network. The LVDC networks also provide more diverse voltage levels, which has allowed the development of smaller LVDC systems such as the building electrification applications.

The LVDC networks therefore bring a lot of different benefits. In addition to the above benefits, few important advantages need to be highlighted such as improved electricity quality, reduced power losses and increased transmission capacity. The benefits and the development of the LVDC networks have been made possible by the rapid development of power electronics components. With the help of the power electronics converters, voltages can be converted from one form to another and provide higher quality and more regular electricity. Components are still being further developed to be more and more efficient, allowing the converters and LVDC systems to become even more efficient.

Like many other equipment, elevators and their electrification are also being developed to be more efficient. Due to the versatility of LVDC network structures and different voltage levels, the LVDC networks would enable even more efficient electrification of elevators. Similar network structures used in the electricity distribution networks can also be utilized in the elevator electrification. With the LVDC networks, especially in long-distance elevators, it is possible to reduce power losses and increase the power capacity of the travelling cable. This also avoids increasing the size of the travelling cable, thereby significantly reducing the weight of the travelling cable and the costs of the construction. LVDC networks thus provide considerable advantages over traditionally AC electrification.

The fact that elevators would be fed from the LVDC distribution networks would also bring considerable benefits. In this case, at least one voltage conversion stage would be avoided in the elevator drive. In addition, the elevator system is easier to operate as part of the main grid and, for instance, it is easier to supply electrical energy back to the LVDC distribution network. With LVDC networks, the elevator could operate even more versatile as part of the distribution system, such as acting as energy storage in LVDC building application.

In the future, the number of LVDC networks will increase significantly around the world, especially in countries where the electricity network is still under construction. The LVDC networks will become more common both in the distribution networks and in other distribution applications such as building distribution systems and marine electrification systems. For this reason, the LVDC networks will also be seen in other applications such as elevator electrification. However, this thesis did not examine, for instance, the protection of the LVDC networks or disadvantages such as electromagnetic compatibility (EMC) problems that LVDC networks can cause to elevator electrification. Solving these problems, as well as finding the right LVDC network structure, is a key part of the development of the elevator electrification.

The first parts of the thesis examined at what the LVDC networks are and why they have been developed. In addition, the main development targets of the LVDC networks and their greatest benefits compared with the traditional LVAC networks were studied. This was followed by a review of the major power electronics converters, which are the most important components of the LVDC networks. Smaller applications of the LVDC networks, such as building and elevator electrification systems, were examined in the final parts of the thesis. The main goal of the study was to find out how LVDC technology can be utilized in the electrification of elevator. The thesis showed that elevators would benefit significantly from the LVDC networks and could be utilized in a variety of ways in the elevator electrification. Consequently, thanks to significant advantages and ever evolving technology, LVDC networks will also be seen in the electrification of elevators.

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