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Transition to DC distribution grids

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Preface and Acknowledgements

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science at UiT The Arctic University of Norway (Campus Narvik).

I would like to thank my supervisor, Associate Prof. Dr. Bjarte Hoff for his motivation and support during the course of this project work. I say thank you for coming up with such a challenging, but yet very interesting topic, which has broaden my horizon in and outside the field of Electrical Engineering.

I am deeply grateful to my wife, children and my entire family for their love, care and support in seeing me through the years.

Abstract

The war between AC and DC has emerged once again due to the rapid development and advancement of electric power technologies. Nowadays, power electronics and DC/DC converters are able to change voltage levels, which could only be achieved by an AC transformer hundred years ago. Rising trend development of electric vehicle and renewable energy technology have led to an urgency for re-evaluation of which scheme between AC and DC that will provide best solution in terms of economic and technical aspects.

The flexibility that has been offered by AC grid makes AC grid become more favourable since late 19th century. However, the urge in using renewable energies due to environmental issues and concerns has also initiated second state of war between AC and DC. Hence, the re-evaluation of the usage of AC grid distribution in consideration of DC grid distribution.

This project investigates the recent development of DC grid technology, compares AC and DC grids in low voltage distribution system, and evaluates the possibility of transition between HVAC grids into low voltage DC grid.

List of abbreviations

AC	Alternating current
AC μGrids	Alternating current micro grids
CSC	Current source converter
DC	Direct current
DC μGrids	Direct current micro grids
DER	Distributed energy resources
DG	Distributed generation
ESS	Energy storage systems
FACTS	Flexible AC transmission systems
HV	High voltage
HVAC	High voltage alternating current
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistor
LVAC	Low voltage alternating current
LVDC	Low voltage direct current
MV	Medium voltage
PE	Power electronics
PV	Photovoltaic
PMW	Pulse width modulation
RESs	Renewable energy sources
THD	Total harmonic distortion
VSC	Voltage source converter

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1. Introduction

1.1. Project motivation and thesis background

In the early years of electrical power distribution, Direct current (DC) was the standard current. However, due to flaws in Edison's DC system, AC became the current standard due to its ability to step up low voltage into high voltage, and to transmit it over long with the help of the transformer. The battle of standard of current supremacy, which is referred to as "The war of current" began in the late 1880s. [1]

Since then, AC electrical grid has well developed and proven concept due to its development since 19th century. It is able to deliver electric power from power plant to household through substations. It also offers simple and reliable principle that has become the standard over the last century due to, among the previously stated reasons, limited technological advancements. Currently, not only is it being challenged by the aggressive introduction of distributed renewable energy generation, but also under increasing pressure due to growing calls for simple, meshed, low and medium voltage distribution grids as well as high voltage transmission networks. [2]

Moreover, even based on the assumption that all parameters are equal, the very nature of most renewable energy sources (inherently dc) favours DC grid over the ubiquitous AC grid on various accounts. Rising trend development of electric vehicle and the advances in power electronics and the role of DC/DC converters in efficient voltage conversion, brings about the re-evaluation of AC grid.

Based on this project motivation, there are many questions behind this project work and some of them are stated below:

With the existing infrastructure of AC distribution, why should there be a shift to DC distribution?

Will DC distribution grid be more energy efficient, cost effective, and reliable than the present AC distribution grid?

What are the current trends in the low voltage DC distribution?

What are the factors to be put into consideration for the adoption of DC and its transition?

Will the evolution and advancements in power electronics and DC/DC converters only be a game changer for DC and bring a transition change to DC at low voltage distribution?

Even if the potential advantages of DC far outweighs AC, will that be a yardstick to adopt DC distribution?

1.1.1. The war of currents: A historical review

In the 1890's, there was competition between Alternating Current (AC) and Direct Current (DC) electric power system in order to decide which power technology would be employed for electricity transmission and distribution. It was a battle between pioneers of AC and DC. Namely, George Westinghouse alongside Nikola Tesla and Thomas Edison. With the installation of DC generating power plants spaced within hundreds of meters from each other, Thomas Alva Edison used low DC voltage systems to electrify New York City [3].

In 1887, Thomas Edison's company used the DC system to produce 121 power stations in order to produce electricity but could only supply customers within 2.5km from the plant. The problem that Edison faced to transmit DC power over long distances was the power losses on the cables due to high current since Thomas Edison's rival, George Westinghouse, the AC electric power pioneer, transmitted current over hundreds of kilometres. Tesla, who was working with Westinghouse, could solve this problem by stepping up the voltage level when transmitting electricity with the help of AC voltage and transformers. Due to the ease of transmitting electricity from power plants and the use of polyphase induction motors, AC power won the war becoming the standard for electrical power. Thus, making AC grid distribution to become favourite due to its flexibility since late 19th century. [3]

1.1.2. The Second war of current- DC Return

In the beginning of the electric grid when AC was competing against DC, before AC power system could prevail over DC power system, there was decades of research and development. Utilities across the US have developed improved AC distribution systems. For example, there were drawbacks in the several AC distribution schemes that was set up. One of such was that many of the distribution transformers were inefficient to make effective and reliable power supply to the customers. United worked on the perfection of AC distribution and later in the 1920's, power companies replaced the DC distribution with AC radial feeders and other network concepts. Though DC systems have been put in place in major cities across the US, Edison extended the DC system.

However, on the 20th of November 1927, after standardization request and a thorough review of the DC system, it was concluded that the AC network system was more reliable, economically viable and more efficient than the DC system. [3]

This paved way for United's victory.

However, in the past decades, there has been DC application in power generation and transmission. With a vast application of DC, the fact that all electronics runs on DC, and with the fact that well improved power electronic devices are being used on DC grid components, hence the increase in demand for DC power.

Nowadays, with the fact that the power electronic DC/DC converter's ability to efficiently convert voltage, hence, the commencement of the second war of currents.

1.2. Methodology and limitations

The purpose of this project is to evaluate the possibility of shifting to low voltage DC distribution. In doing this, AC and DC are compared based on current technology. The analysis and evaluation of technical and economical aspects are carried out on common electric devices and household appliances to determine the possibility and feasibility of transition to DC.

However, the evaluation of DC distribution grid transition for common electric devices and household appliances will be limited to low (medium and low) DC distribution grids (or systems) for residential sector.

1.3. Thesis outline

This thesis is organized into seven chapters as follows:

Chapter 1 presents the background and main objectives of the thesis, it also presents the scope of the thesis.

Chapter 2 introduces a brief description and literature survey of the concept of electric power systems related to the thesis. In the last section of the chapter, the modern trends for DC distribution grids have been covered and the latest trends/state of arts in the AC grids were also highlighted.

Chapter 3 presents and compares the advantages and disadvantages of both DC and AC based on current technology.

Chapter 4 feasibility studies in form of empirical and theoretical analysis of selected household appliances for efficiency and economic evaluation was performed using four topologies. Results were analysed and compared with other evaluated studies for the feasibility of transition to DC distribution for common electric devices and home appliances.

Chapter 5 further explores the feasibility of DC transition in chapter 4 for technical and environmental evaluation of the DC transition.

Chapter 6 presents a socio-technical perspective of DC transition.

Chapter 7 concludes the thesis and recommendation for future work is give

2. Literature review in electrical distribution systems

2.1. AC electrical power systems

The electrical power system comprises the generating station, transmission and distribution networks. Electrical power is supplied to the consumer from generating stations via transmission lines and distributed networks. Power is transmitted from high voltage of 500kV, 400kV or 132kV or 132KV to medium voltage from 30kV to 1kV and low voltage from 999 to 1V. Such interconnected systems of electric power delivery from generation to distribution is called the Electrical/power Grid. [4]

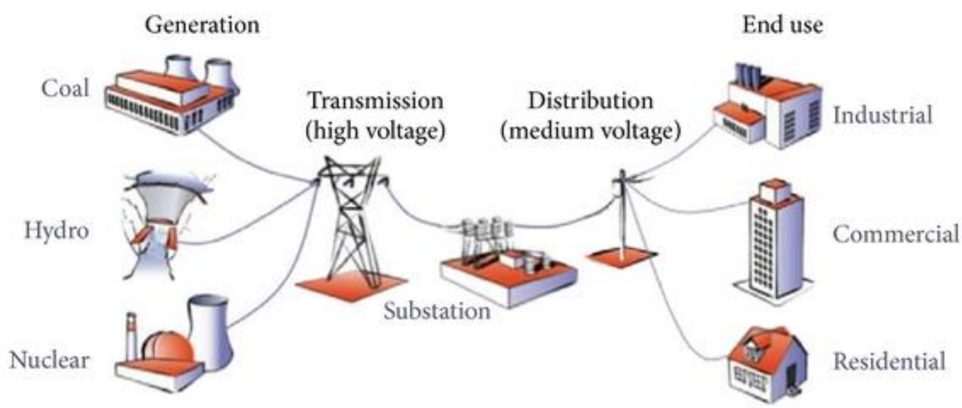


Figure 2.1 : Electric power grid/conventional power generation system [5]

2.1.1. General description of entire power systems

Fig 2.1 shows a typical conventional generation system in which the generating station generates an electrical power at 11kV. The voltage level is thereby increased by a generating step up transformer to 220/230kV, 138kV/230kV depending on the requirements for voltage level. Power is transmitted at long distances with the transmission lines as shown in the figure.

On reaching the receiving substation, the voltage is stepped down with transformers of rating of 220/33kV or 220/22kV, and is further transmitted to the end users. Industrial and commercial sectors are directly supplied via distributors, whereas residential areas are supplied with low voltage level through distribution centers with the help of distribution transformers.

2.1.2. An overview of generation and transmission

The transmission of electric power is done via the electric power grid. AC Electric power transmission system is generally 3-phase, 3-conductor system employed in transmission overhead lines and are generally represented by the one-line diagram shown in figure 2.2. Electric power is delivered from the generating station to the distribution substations. The transmission system comprises of the generation and distribution substations. The former comprises of step up transformers while the latter comprises of step down transformers.

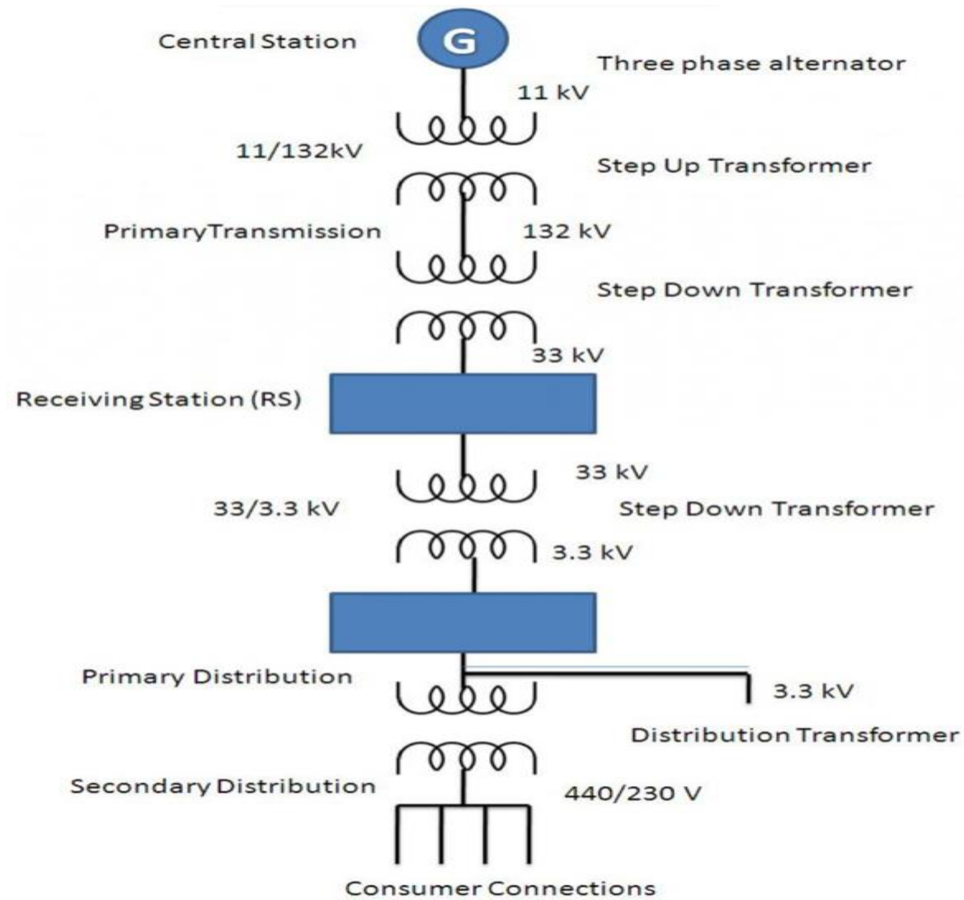


Figure 2.2: One-line diagram of a typical power transmission distribution system [6]

2.1.2.1. HVAC transmission

Worldwide, larger parts of the electric power transmission and distribution employs the use of transmission lines and cables due to the power transformers ability in converting voltage. In exceptional cases, DC transmission lines and cables are utilized in the transmission and distribution of electric power. The operating AC frequency 50/60Hz varies from one country to the other.

2.1.2.2. Grid connected power components

Grid connected power system components/AC distribution components comprises of control electric appliance such as circuit breakers, isolators, etc., measuring appliances such as current transformer, voltage transformer, ammeter, voltmeter, electric meters, protection appliances such as protection relays, fuse and lighting arresters (protectors of very important equipment in the grid), which are also known as secondary equipment, and other equipment such as power cables, bus and current carrying conductors etc., are the main parts of the system.

Transformers are employed for voltage conversion. For long distance transmission, transformers convert electricity from low to high voltage. A step up transformer increases the voltage at the transmission side over high voltage transmission lines while the step down transformer reduces the voltage of power supplied to meet the power needs of the consumers at the distribution end i.e. at homes and other facilities. All the components stated above are required to work in a synchronized and efficient way to avoid breakdown/failure of the power system.

2.1.2.3. FACTS Technologies and Developments

Flexible AC Transmission Systems (FACTS) have been employed worldwide for reliable long distance AC transmission. These facts are power electronic based technologies, which can be employed to solve current grid issues. Among their capabilities, is its ability to increase the network capacity in transmission, the improvement of system reliability, ease of power flow control with less impact on the environment. [7]

2.1.3. General description of AC distribution grid/system (MV/LV)

In distribution power grids, there are the commercial consumers and the residential consumers. The medium voltage (MV) distribution is applicable to the former while the low voltage (LV) distribution is applicable to the latter.

2.1.3.1. The AC distribution network

The electric power distribution is AC due to the ease of transforming voltages from a higher level to a lower level or vice versa with the help of transformers. In the distribution network, the distribution substation delivers electric power for industrial/commercial operational purposes.

2.1.3.2. Industrial, commercial and residential sector

As it is explained in section 2.1.3.1, power is delivered to the consumers through the distribution substations. This makes electric power distribution possible to the industrial, commercial and residential sector. According to the consumer load type, the residential loads comprise of residential users such as the households, the commercial loads comprises of commercial users such as supermarkets/shops, offices, schools, and other public recreation centers such as hotels and cinemas, while the industrial users are big industries, factories, etc. The industrial, commercial and residential loads makes up the three kinds of loads. 3-phase power is mainly supplied to the industrial sector and such power is designated for various industrial electric motors. On the other hand, only a single phase power is required to power the light of commercial and residential consumers. As already defined in section 2.1.1, the 11KV distribution network supplies electricity to customers via cable or overhead lines and power substations.

2.1.3.3. Grounding and safety

Grounding protects both users and equipment safety against electric hazards. The main hazard from any electrically powered equipment is electric shock. Grounding is done by redirecting fault current to ground by a low resistance path, which separates the user and the equipment.

In AC systems, standards practice has been put in place to ensure safety. However, in DC systems practical experience for grounding is lacking in the residential sector such as in households.

The IEC 60364 international standard for low voltage electrical installations applies to the safety standards for electrical installations. However, in Low voltage DC systems, such safety standard measures is not that applicable due to technical constraints such as the protection of human body.

2.2. DC electrical power systems

2.2.1. HVDC Transmission

In the early days, precisely the 1880s, the HVDC system could not be used to transmit DC power over long distances due to high cost and maintenance. However, in the 1970s, that was possible due to the invention of semiconductor electronics. Several HVDC systems have been installed across the globe since then [8].

HVDC transmission has been utilize for quite a long time now by many countries across the world. Developed countries such as the U.S, China, and some European countries to mention a few have utilized it due to its advantages of lower power losses, lower setup cost etc.

HVDC Developments

Table 2.1 shows some of the various HVDC projects that have been executed around the world. A large number of European HVDC projects employs submarine cables while the Asia HVDC projects employs overhead lines for execution.

For example, the first HVDC transmission project in the world was HVDC Gotland 1 executed by ASEA (a division of ABB group), with a power transmission capacity of 20MW, operating at a DC voltage of ± 100kV and transmission distance of 96km via underwater cable.

However, an HVDC advancement called ultra-high voltage DC (UHVDC) executed by ABB operated at 6400MW with 800kV and transmission distance of 2071km in 2011. It was said to be the highest voltage and longest distance and highest transmission capacity available as at 2011.

Details of more HVDC projects that were executed and still under construction from (2013-2015) can be found in [8]

Table 2.1: Worldwide HVDC projects *[8]*

Project Name	Location	Year	Characteristics		
			MW	kV	km
Gotland	Sweden	1954	20	±100	96
Volgograd-Donbass	Russia	1962	720	±400	473
N. Z. Inter Island	N. Zealand	1965	600	±250	609
Sardinia	Italy	1967	200	200	413
Pacific Intertie	USA	1970	1440	±400	1362
Nelson River	Canada	1973	1854	±463	890
Cahora-Bassa	MZ-ZA	1975	1920	±533	1456
Hokkaido-Honshu	Japan	1979	300	250	167
Itaipu	Brazil	1986	3150	±600	785
Quebec-N. England	Canada-USA	1990	2250	±450	1500
Directlink	Australia	2000	180	±80	59
East-South Intercon.	India	2003	2000	±500	1450
Celilo	USA	2004	3100	±400	1200
Norned	NO-NL	2008	700	±450	580
Yunnan-Guangdong	China	2010	5000	±800	1418
Xiangjiaba-Shanghai	China	2011	6400	800	2071

In July 2016, China awarded a $300 million contract to ABB to build an ultra-high voltage direct current (UHVDC) link with converter transformer technology of 1.100kV, with transmission distance of 3000km and 12GW (Gigawatts) power transmission, making it the first of its kind in terms of highest voltage level, longest distance and highest transmission capacity available so far as at the period of writing this thesis. This has ultimately surpassed the world's first 800kV UHVDC links in operation since the year 2011 [9].

HVDC circuit breaker

The world's first HVDC circuit breaker was developed by ABB in November 2012. The HVDC grid employs a voltage source converter (VSC) based technology. The hybrid HVDC breaker is an advancement of the conventional HVDC breaker. These semiconductor based HVDC breakers are employed to solve the needs of a reliable HVDC grids. The detailed description of the hybrid HVDC breaker and its application is described in [10].

2.2.1.1. DC distribution system applications/Implementation

Due to the increased energy consumption, the quest for power quality improvement in data centres, exceptional and remarkable growth in the IT industry, and the enhancement and advancement of the IT infrastructures, there is the need for DC power and DC distribution system implementation in data centres. The authors in [11] investigated and presented types of power disturbances which can be detrimental to the DC data centre operation in which the most common disturbances are; voltage sags, DC bus faults, load transients (due to server turn on/off and breaker operation). The most common of the AC side disturbance on the DC data centre operation is the voltage sag.

AC data centre architecture

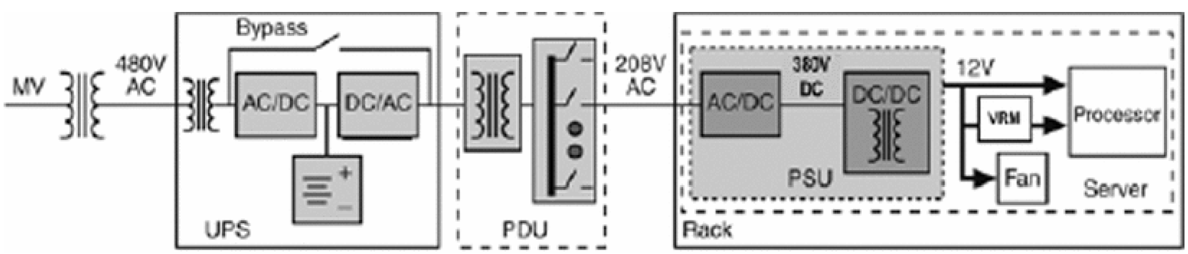


Figure 2.3 : Conventional AC data centre architecture [11]

DC data centre architecture

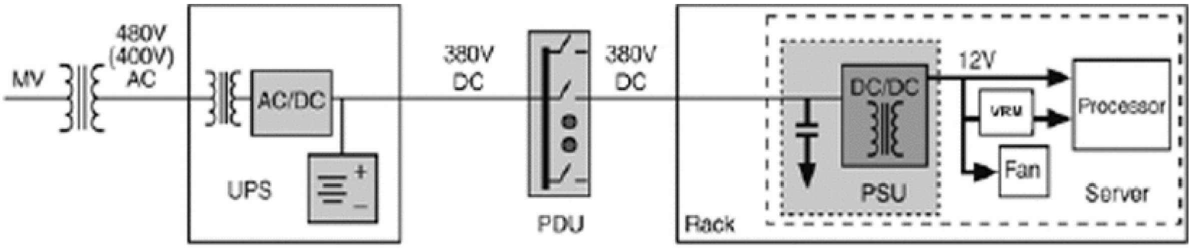


Figure 2.4 : DC data centre architecture [11]

In fig 2.4, the significance of the power quality disturbance is reduced in the DC data centre due to the absence of harmonics and power factor correction (PFC) circuits.

DC power distribution standards for data centres and telecommunication facilities

The Emerge Alliance, an industry consortium advocating the adoption of direct current power distribution standards for buildings announced the release of the Emerge Alliance standard for the use of safe low voltage DC power in commercial buildings. [12].

According to [13] the DC data centres can have 20% energy savings indicating less losses when compared to the AC data centres.

The only applicable DC power distribution system standards applicable to the commercial facilities is the 380VDC distribution system.

The author in [14] analysed the 380Vdc distribution system from a grid to chip perspective and concluded that it is more reliable, more efficient and less complex than the AC topologies.

2.2.1.2. Voltage levels

In the DC systems, voltage level is a vital criterion that can have effects on the safety and performance of the entire system.

Reference [15] investigated DC supply voltages levels for 326V, 230V, 120V, and 48V and suggested the 326Vdc level to be the most suitable to supply power for technical and economic considerations. However, in the same study, voltage levels less than the 120Vdc level investigated was found to be impractical due to voltage drops and current ratings for the particular distribution feeder tested.

On the other hand, the authors in [16] investigated different voltage levels performance for 400Vdc, 325Vdc, 230Vdc, 120Vdc, and 48Vdc and considered the 48Vdc system the most applicable for residential DC systems and the 400Vdc for commercial facilities based on efficiency analysis.

As highlighted earlier in section 2.1.3.3, presently there is no consensus for voltage level in DC distribution networks. Table 2.4 gives a summary of basis for selecting voltage levels.

Table 2.2: Summary of the basis for selecting a voltage level *[17]*

Suggested DC Voltage level	Basis for selection
Vdc $\geq$ 220	Adaptability with existing building's grid
Vdc $\leq$ 238 or 457(phase to phase)	Compatibility with single phase loads
463 < Vdc < 617	Compatibility with 3-phase loads
Maximum possible	Efficiency (use the same equipment)
Vdc $\leq$ 373	Insulation
Vdc $\leq$ 350-450	Component and device matching (rated levels)

MV/LVDC networks criteria

The DC distribution systems connection can take different forms. The two most common connection types of medium and low voltage direct current network can be divided into: unipolar and bipolar system. Fig 2a and b shows the typical DC network topologies for unipolar and bipolar systems.

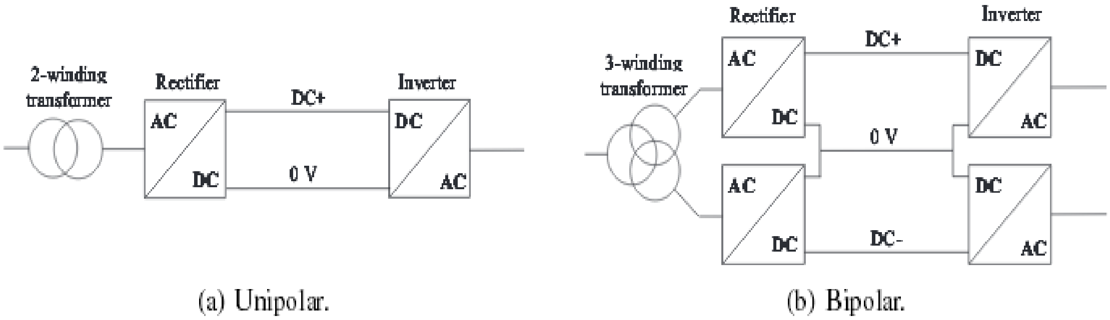


Figure 2.5: DC distribution network connection topologies *[18]*

2.3. Current status of Electrical systems

2.3.1. Current status of AC distribution grids

Due to power quality issues for electrical distribution systems, the AC grids have evolved to comprising of distributed generation systems and loads. The penetration of these renewable energy sources is expected to increase in future. As explained in section 2.1.2.3, FACTS have been employed worldwide for reliable long distance AC transmission and the merits of such application in transmission are also highlighted.

2.3.2. Current status of DC distribution grids

DC has transformed significantly over the years due to many years of in-depth research and its global impacts adapted from [19] and highlighted below:

- The use of HVDC cables in china's grid, China's adoption of the state of the art 750 and 800kV cable in its power grid.

- Adoption of the 380-V for DC power distribution in the commercial sector in North America, Japan and some part in Europe. One of the merits in data centre application is the reduction of losses. Other advantages of this adoption are highlighted in section 2.2.2.1 in this thesis. The EMerge Alliance have made the adoption of the 380Vdc possible.

- DC implantation in hybrid systems by DC pioneers.

DC components + Grid (DCC+G), an European union project for 380-Vdc grids, which commenced in April 2012 and suppose to come to an end in 2015. These 380Vdc distribution systems employs the state of the art and very efficient semiconductor power technologies for implementation.

Direct current B.V also known as (DC=Decent) in conjunction with DC foundation, Joulz and Siemens implemented DC greenhouse. By changing the already AC scheme that had been in place and replacing with DC, implementing distributed generation DG and an energy controlled system, the whole greenhouse is powered by only DC. The purpose of setting such a grid on DC voltage was to demonstrate the potential of a DC grid.

In another perspective, direct current BV is currently involved in another project in which the AC grid instead of updating to DC, is totally converted to DC grid which will be economically viable in terms of equipment installation costs [20].

On the other hand, another project in the Netherlands called the Green Village Project employs a DC grid as a backup while fully powered using renewable energy. Other research projects of the green village is the DC street lighting.

In addition, researches in [21] proved that the data centres could account for up to 10 percent of energy savings by supplying the server racks with DC power rather than AC power. In the same development, it is reported that DC power distribution had been employed in new data centres by Japans telecommunication company, NTT making it a total of five facilities in its capital, Tokyo that is making use of the 380V distribution.

The U.S military, medical facilities and institutions of learning in U.S have employed the use of DC distribution to run their systems in case of failure of the AC power grid.

The authors of [22] developed a LVDC grid lighting system using LED lamps and demonstrated that the energy savings in the LVDC LED system was more in comparison to the conventional AC lighting system.

3. DC Versus AC based on present technology

3.1. DC vs AC power grid

Due to different architectures, voltage levels, and power electronics needed between AC and DC power grid, there are advantages and disadvantages of DC and AC power grid system. There are also challenges and opportunities within the development of DC power grid system. This chapter will discuss about the drawbacks, advantages, challenges and opportunities of DC and AC power grid system development nowadays

3.1.1. Merits of the DC system

The advantages of the DC systems over AC are presented below:

1. Due to the need of multiple levels of DC voltage, a DC system was deemed Superior to an AC system in terms of efficiency (i.e. higher efficiency gains means less energy wasted which means less money is wasted). Even though, the exact value of efficiency gain varies from application to application, the most common and very straightforward gain is in household electronics equipment. Most electronic equipment are DC and normally equipped with two conversion stages for AC power. The two stages are AC to DC and DC to DC. Not only does the removal of the first AC to DC converter increase the efficiency, but also reduces the cost of subsequent current adaptors. other advantages of favoring the DC grid over AC grid is the low copper cost, easy control, meshing simplicity and obtaining different optimized architectures and topologies [23]. The decrease in the required amount of copper in DC grid is mainly due to the use of higher rms voltages, which is equivalent to the peak voltages in ac grids. A more simplified control is obtained from the fact that in a dc grid, only one control parameter is of significance: the voltage. In contrast to AC electrical systems that imposes the same frequency throughout the interconnected system, a DC grid does not have such constraints. This makes the meshing of dc grids relatively easier and more natural.
2. DC power deployment improves stability and increases reliability of the grid
3. More efficient integration of renewable distributed generation.
4. Simpler power electronic interfaces and fewer points of failure.
5. The total losses in DC distribution is less compare to AC. Using solar power to generating electricity, the losses incurred with converting to AC is avoided, with the fact that many household devices runs on DC.
6. Electromagnetic interference (EMI) is lower in DC grids when compared to AC grids.
7. Fewer conductors are required, and there is absence of skin effect (HVDC transmission in this case).
8. In today’s technology, DC is employed in high voltage long distance transmission, which is better in cost when compared to AC system.

Reference [24] investigated the cost of an HVDC system using life cycle cost analysis. In the study, comparison between HVAC and HVDC systems was done using two case studies:

- Between thyristor based HVDC system and high voltage AC system - the overall cost of investment for HVDC converter station were higher than HVAC substations. However, the transmission medium (overhead lines and cables) cost and the operation and maintenance cost were cheaper in HVDC system. Fig. 3.1 shows the losses and cost comparison between HVAC and HVDC systems. The breakeven distance in the figure depends on factors mentioned earlier.

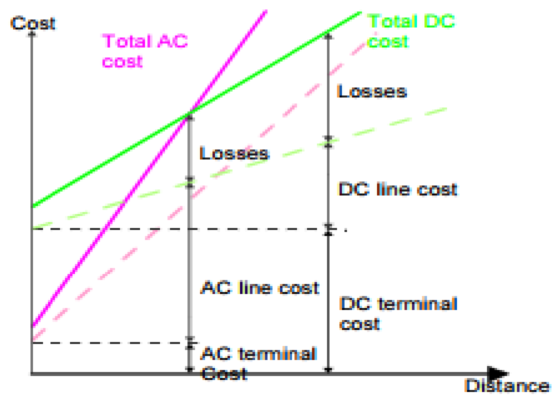


Figure 3.1: Cost and losses comparison of a thyristor based HVDC system vs HVAC system *[24]*.

- VSC based HVDC system versus an HVAC system or load generation source - VSC based HVDC systems are applicable to transmission capacity up to 200MW and short distance transmissions. Fig. 3.2 shows a better advantage of VSC based system over the others in terms of cost considerations.

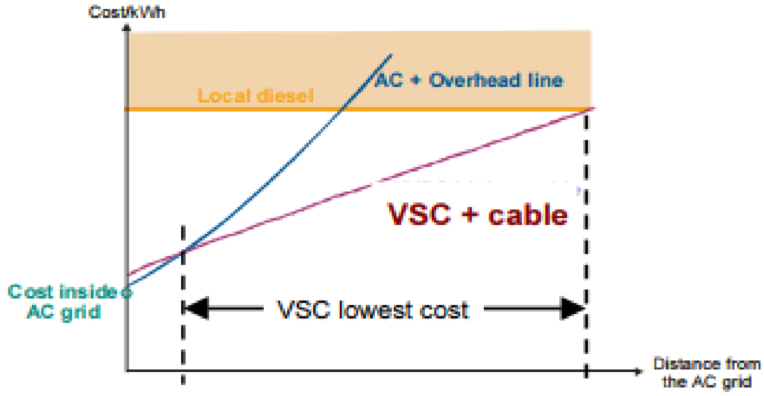


Figure 3.2: Cost comparison with a VSC based HVDC system, HVAC system and a local generation source (diesel source) *[24]*

However, it was highlighted that the advancement in technology has led to the reduction of the HVDC systems cost while environmental impact consideration will account for the increase in costs of the HVAC systems [24].

As stated in the previous section, the DC distribution system has a simple structure from which economical and low energy consumption is presented. Nevertheless, the quality of DC power, and the transmission capacity, is much better compared to the AC technology.

3.1.2. Demerits of the DC system

Some of the disadvantages of the DC system are listed below:

1. DC grid has major disadvantages concerning control and switching actions.

The study of DC grid control has been limited to a traditional hierarchical control approach [25] for both simple systems that are accurately modeled and more complex systems, approximated by simple models. These types of approaches lead to erroneous deductive and inductive reasoning. The main reason for such an approach is mainly due to limited DC grid analyzing tools. Addressing the effect of system components on the dynamics of the whole system is the most common research focus for DC and AC grids. Those components include the various types of sources with their respective converters, electrical loads (constant power loads) and cable parameters.

2. The currently available and researched DC grids and microgrids have sufficient system capacitance. This capacitance is mainly from the terminal capacitors of system converters that imitate the voltage stiff AC grids. System control approach, system architecture, system stability analysis, and fault detection and isolation mechanisms are simply copied

from the traditional AC system.

Also compared to AC, in DC grids, the amount of stored energy in DC grids is determined by the size of the passive components (capacitors and inductors) and storage devices (batteries or super capacitors). Depending on the size of the system capacitance or storage, it can be defined as either high or low energy stored grid. All currently available and researched DC microgrid applications have sufficiently high system capacitance or directly connected storage elements that ensures its voltage stiffness. Capacitance is mainly provided by terminals of system converters for both sources and loads.

3. The main challenge in developing DC grid distribution system technologies is not only the maturity of supporting equipment that available in market but also lack of study about it . In AC grid, there is power transformer which be able to convert the voltage magnitude within the grid system in order to make grid system more flexible while delivering power to the household. However, in DC grid system there has to certain power electronic technology to support DC grid system such as DC – DC converters in order to either increase or decrease the amount of voltage within the grid. This implies that the development of DC grid distribution offers limitless possibilities of the development of electric power technologies itself.

4. Limitation of DC switches and circuit breakers.

One example of technology that might be developed in the future is the development of DC distribution protection system. The common approach that can be taken in developing DC distribution protection system is by employing the same characteristic as AC distribution system and adjust it accordingly [26]. For example, AC distribution systems are traditionally voltage stiff due to the mechanical momentum of the generation mass. Therefore, fault currents are high and protection system need to react fast. In order to emulate same behavior, DC grid system need to have huge capacitance in order to have voltage stiff characteristic same as AC distribution system. Therefore, the adjustment for DC protection distribution technologies will be lessen. The example of DC protection technology is power semiconductor devices (PSD) which are used for solid-state circuit breakers (SSCB) which are arc free. This technology also can interrupt fault current fast and able to detect over current or rate of current rise within DC distribution system

3.1.3. Merits of the AC system

1. Inexpensive transmission is a huge advantage over DC. Since AC can easily and efficiently be converted to another voltage with a transformer.
2. In terms of cost effectiveness and ease of maintainability, AC substations are easy to repair and maintain which makes them even less expensive than DC Substations.
3. Already developed technology and currently accepted technology worldwide.

4. Already developed protection technology compared to the DC distribution protection system.

3.1.4. Demerits of the AC system

1. In terms of cost, AC transmission lines cost more than the DC transmission lines.
2. More inherent losses in AC system due to Skin effect compared to DC.
3. AC systems have problems in reactive power control

Prior researches

In order to shed more light on the advantages of disadvantages of both system, several authors have investigated both systems which is presented below:

The author in [27] has investigated the main advantages of DC multi terminal networks with large number of decentralized power generators. Those advantages are higher efficiency in energy conversion systems, due to the fact that less conversion steps are needed and DC – DC converters can have less losses than 50 Hz transformers, higher power capacity in DC cables, Lower cost in terms of costs of structure in the distribution grid and less material use such as copper and Si-steel in energy conversion systems, less maintenance cost and higher reliability of the decentralized power generators that require otherwise for AC grid side.

In another perspective, reference [28] proposed the concept of DC micro-grid and showed one system configuration and control methods for power converters and generators by conducting several simulations to demonstrate the ability of DC micro-grid to be controlled at constant value. This research has indicated that DC micro-grid gives good effects to the utility grid as well as the customers.

The advantages of DC grid distribution system over AC grid distribution system have been compiled in [29]. These advantages incorporate renewable energy resources, reliability and uninterruptible supplies, voltage stability, fluorescent lighting and electronics, variable-speed drives, power quality, and 60 Hz health concerns.

The authors in [30], [31] have published two publications which shows the concepts and philosophy of voltage weak DC distribution system protection strategies. The review of different DC grid architectures were done by comparing voltage stiff and voltage weak DC distribution grids. The natural behaviors of such systems from a control and a protection perspective are also addressed.

3.2. Power electronics and converters

3.2.1. Role of Power electronics in the power grid

Integration of renewable energy

The role of power electronic converter is continuously rising in the electric power system. Power electronic systems are employed in the integration of renewable energy sources and distribution generation into the electrical grid. [32]. Such integration into the grid is shown in fig 3.3, with the help of power converter and control unit.

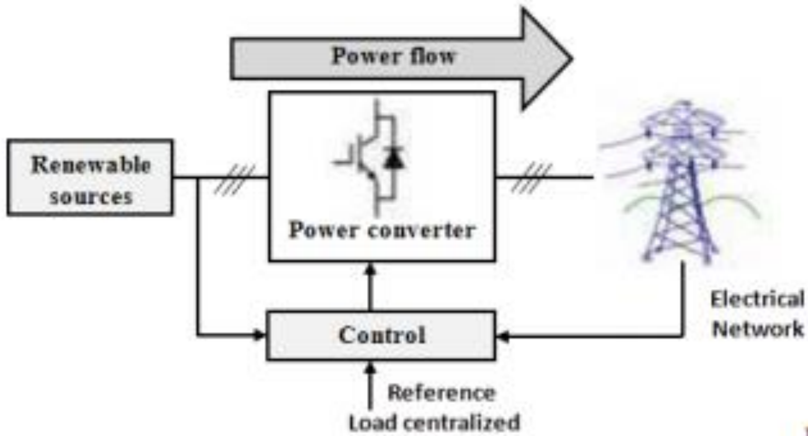


Figure 3.3: Integration of renewable energy to the grid with power electronic system *[32]*

Power electronics are also employed in wind turbine applications since wind energy has a vital role to play in contributing to the production of renewable energy.

Power electronic converters are also employed in the LVDC grids for the integration of renewable energy sources (RES), energy storage sources (ESS), electric vehicles and other loads which employs power. Fig. 3.4 shows the application of a bidirectional AC/DC converter in a low voltage DC (LVDC) grid. A bidirectional AC/DC converter is shown in fig. 2.3. It can be seen from that figure that typical LVDC grid utilizes a lot of power electronics due to the transformation between AC and DC. Distributed generation (DG) such as photovoltaics (PV) system and Energy storage systems (ESS) needs to be connected with the power electronics before its further connected to the power grid, due to the need of ensuring stability and same frequency with the power grid.

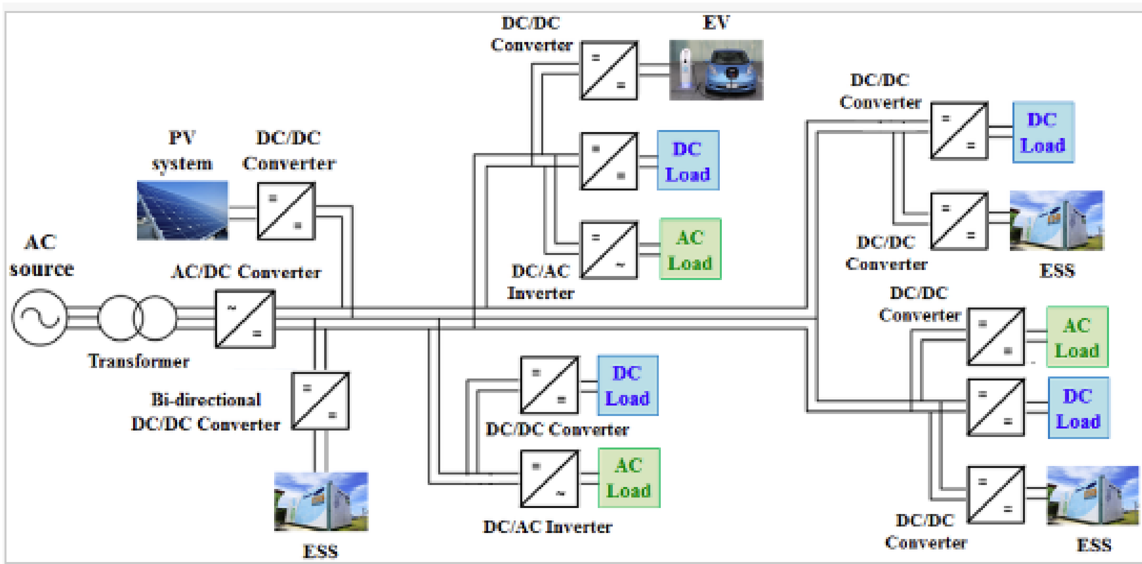


Figure 3.4: A Typical LVDC Grid. *[33]*

Power electronics is implemented in high voltage systems for flexible AC transmission (FACTS) and also in high voltage direct current transmission systems (HVDC). FACTS and HVDC devices are installed to boost the reliability of overloaded networks.

Currently available HVDC technologies are the thyristor based and IGBT based HVDC technologies. For power quality regulation, power electronics devices like STATCOM and VSC's are employed.

Power electronics is also used in fuel cell applications. Block diagram of a grid connected fuel cell system, which also employs power electronics can be found in section 3.3.2.4.

Pulse Width Modulation (PWM)

PWM is a technique employed to control power converters. PWM controls the switching period of the power semiconductors (e.g. IGBTs and thyristors) in the converters at a certain switching frequency.

3.2.2. Energy efficiency of power converters

The author [34] investigated efficiency of MV/LV DC grid and AC/DC grid with a DC-DC converter with a full-bridge isolated boost converter type. The loss comparison are described in section/chapter 5.1.

3.3. AC vs DC distributed generation

Due to the increasing demands of environmental protection and energy structure adjustment the grid-connection of distributed renewable energy attracted more and more attention with the trend of smart grid development. New energy includes wind power, solar power, fuel cells, tidal power etc. Mainly, there are two methods of grid-connection of these energies, one is inversing the DC current to AC with power electronic device to achieve the connection of distributed generation to the grid, but there will be decrement of power quality that cause unbalance of three-phase and flow reversed to the power grid caused by distribution generation which is characteristic of randomness and fluctuations

The other is constructing the micro-grid with energy storage device and energy conversion device. Micro-grid is expensive and there are no authoritative standards so it cannot be widely applied at present. A combination of both AC and DC power distribution network .AC has been proposed to solve the connection of distributed power into distribution network. However, this technology has a critical bottleneck that the transformer will enter into the core saturation caused by the injected DC current, so an intelligent inductive filtering technique and zigzag transformer applied in distributed network superposed AC and DC is proposed for this problem.

3.3.1. DC Grid Integration of distributed generation and loads

The integration of Distributed generation integration is safe, and covering part of the household DC loads, losses can avoided due to AC/DC power conversion.

Fig. 3.3-3.5 shows the three different structures employed in the DC distribution grid. The three structures have merits and demerits due to their structure type. For example, the radial type in Fig. 3.3 has a simple structure making the flow calculation, fault recognition and the protection control to be uncomplicated but its disadvantage is in its low reliability of generation. Nonetheless, its structure is more implemented in many distribution systems. On the other hand, the ring and the mesh structure type, have a complex structure making the flow calculation, the fault recognition and protection control to be complicated. However, both structures (ring and mesh) have high reliability of distribution [35].

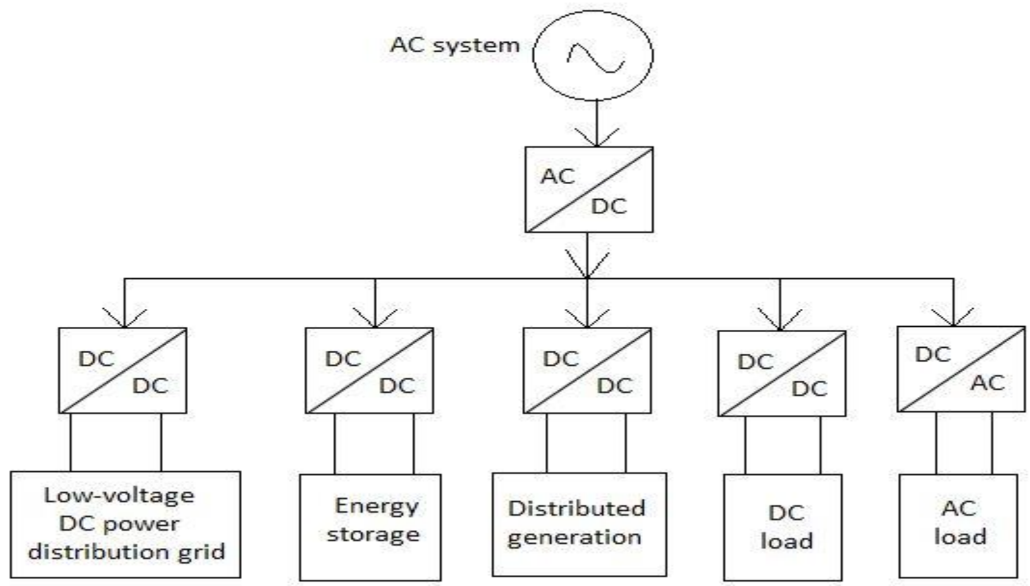


Figure 3.5: Radial structure for DC distribution grid with DG *[35]*

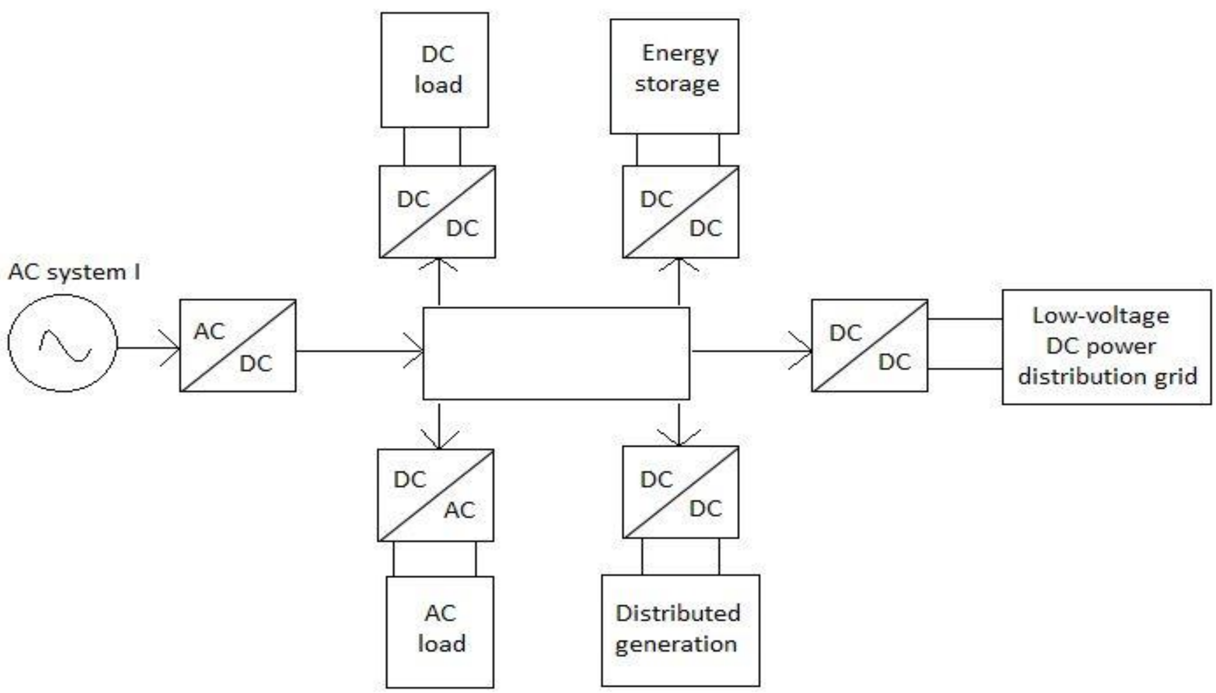


Figure 3.6 Ring structure for DC distribution grid with DG *[35]*

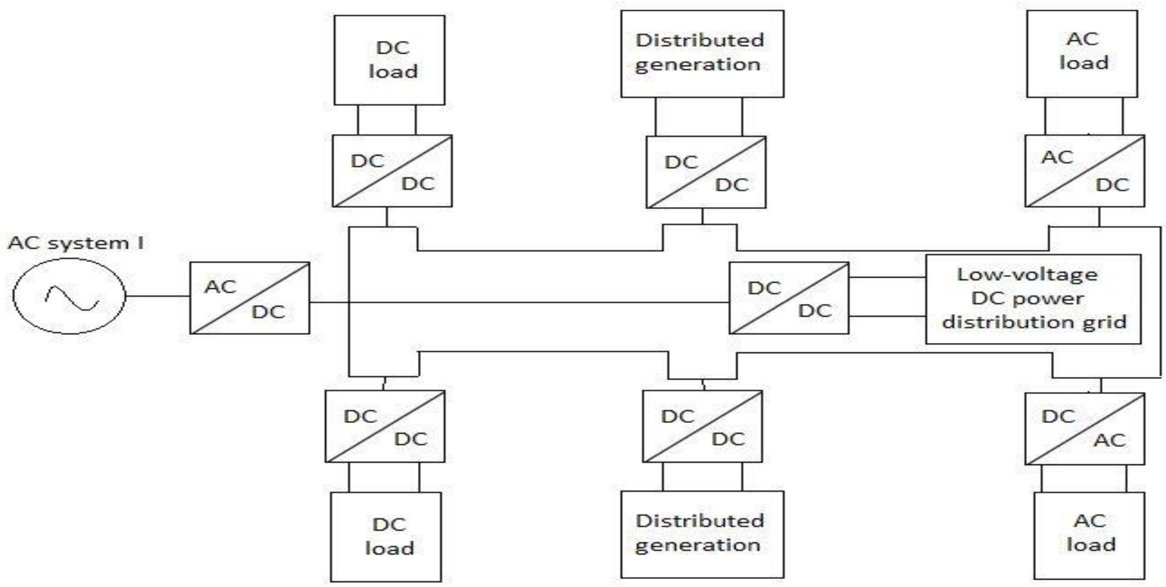


Figure 3.7: Mesh structure for DC distribution grid with DG *[35]*

3.3.2. DC microgrids and distributed generated sources

3.3.2.1. AC microgrids versus DC microgrids (overview)

Microgrids are designed to operate independently. However, during normal operating conditions, they are connected to the utility grid at a point of common coupling (PCC), where the loads are supplied by the utility grid and other local sources. They are known to improve power quality, increase energy efficiency, they also reduce emissions, power losses and network congestion. Another advantage of the microgrid is its ability to sell power back to the grid. [36]

AC microgrids

In AC microgrids, an AC bus connects all distributed energy resources (DERs) and loads. Fig. 3.8 shows the structure of the AC microgrid in which three phase DC/AC inverters are needed to connect DC distributed generations (DGs) to the common bus, and three phase AC/DC rectifiers are needed to supply DC loads. As compared to DC microgrids, it also employs a transformer and a point of common coupling switch inorder to connect the microgrid to the utility grid.

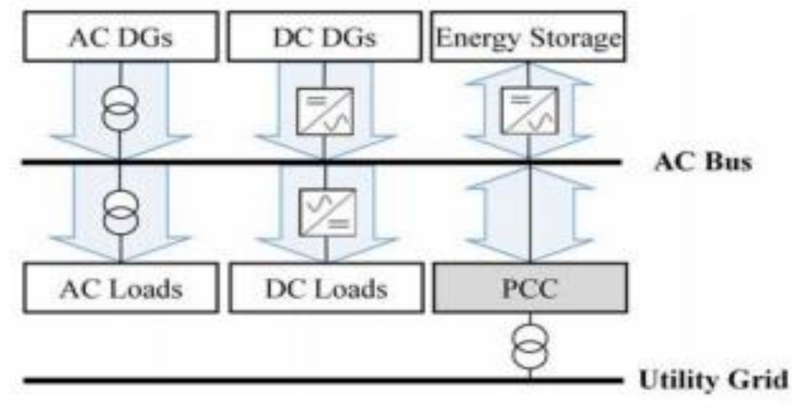


Figure 3.8: Structure of AC microgrid *[36]*

DC microgrids

In DC microgrids, AC/DC rectifiers are employed for connecting AC distributed generations (ACDG) and DC/AC inverters are employed for supplying AC loads through a common DC bus.

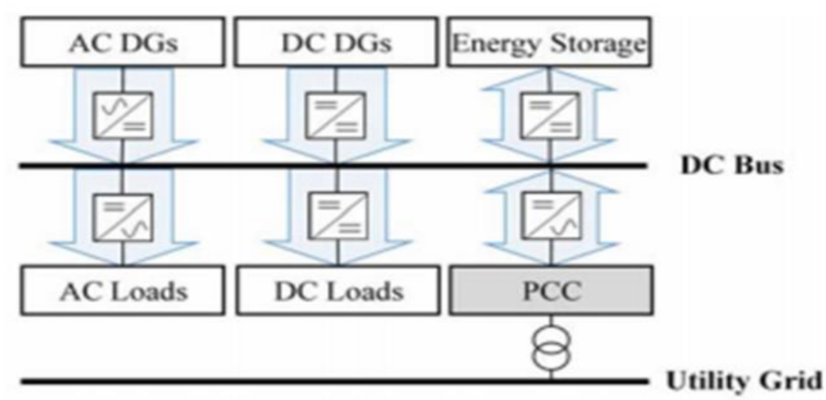


Figure 3.9: Structure of DC microgrid *[36]*

DC microgrids are employed in the integration of renewable energy sources which primarily generates DC. A DC micro grid is well suited to integrate a range of distributed energy resources (DER) units. Considering existing technologies, connection to a DC grid requires fewer stages of power conversion resulting in a less complex interface and lower losses. The application of DC microgrids is in the data centres. The structure of DC microgrid is shown in fig. 3.9 where three phase AC/DC rectifiers and transformers connects AC distributed generations (ACDGs) to the common bus, also single and three phase DC/AC inverters are required for supplying AC loads, and a three phase DC/AC-AC/DC converter a transformer, and a coupling switch are needed for connecting the microgrid to the utility grid.

In DC microgrids, the common bus would be used for DC voltages and currents. While in the AC microgrids, the common bus would be used for AC currents and voltages.

3.3.2.2. Battery/Fuel cell/PV energy sources

Storage technologies such as batteries are vital components of the microgrids.

Fuel cells are DG sources, which is employed in distributed generation applications. Comparing its merits to traditional/conventional power plants, they are highly efficient and have zero or very low emission of carbon. They are also very useful in microgrid applications. However, one of the demerits of the fuel cells is that their slow response to electrical load transients is due to the slow internal electrochemical and thermodynamics characteristics [37].

Fig. 3.10 shows a block diagram of a grid connected fuel cell system which employs power electronics i.e. boost DC/DC converters and PWM (pulse width modulation) inverter in order to connect to the power grid. The super capacitor or battery banks shown in the fig acts as an energy storage device to improve the fuel cell system performance during transient interruption. The LC bandpass filter employed in the power system is used to eradicate unwanted harmonics

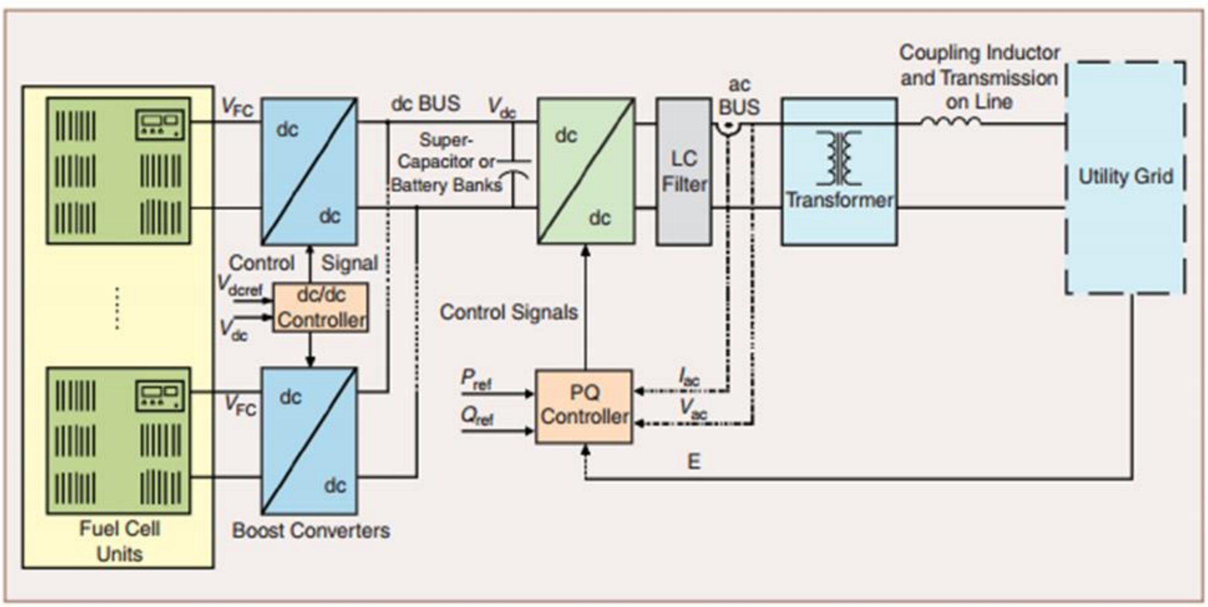


Figure 3.10 : Block diagram of a grid connected fuel cell power system [37].

3.3.3. The Impact of distributed generation

Impact of DG on Voltage Regulation

The radial distribution system regulates the transformer voltage in the substation, using load tap changing (LTC) transformer additionally by the line regulator on the distribution feeder and the shunt capacitor on the feeder or along the line. The voltage setting is based on a one-way power flow where the regulator is equipped with line drop compensation. The DG connection may cause a change in the voltage profile along the feeder by changing the direction and magnitude of the real and reactive power flow. However, the impact of DG on voltage regulation can be positive or negative depending on the distribution system and the characteristics of the distributed generator as well as DG location [38]

Impact of DG on Losses

One of the main impacts of distributed generation (DG) is on feeder losses. Finding DG units is an important criterion that needs to be analyzed in order to achieve better system reliability by reducing losses.

Finding a DG unit to minimize losses equals finding a bank of capacitors to reduce losses. The capacitor bank will only contributes to the reactive power flow (Q).

Impact of DG on Harmonics

Harmonics are always present in the power system to some extent. They can be caused by, for example: non-linearity on the impedance or an exciting transformer load like a fluorescent lamp, AC to DC conversion equipment, variable speed drives, switch electrical appliances, etc. In the case of an inverter, its contribution to harmonic current is partly due to a Silicon Controlled-Rectifier (SCR) power inverter that produces a high-level harmonic current. Currently, the inverter is designed with an Insulated Gate Bipolar Transistor (IGBT) technology that uses pulse width modulation to produce an injected "pure" sinusoidal wave. This new technology produces cleaner output with less harmonics that must meet IEEE 1547-2003 standards.

Impact of DG on Short Circuit Levels of the Network

The short-circuit level of the network has a direct influence of the presence of DG within the network itself. This creates an increase in cesarean current when compared to normal conditions where no DG is installed in the network. The error contribution of a single small DG is not large. However, an increase in cesarean current will occur. In the case of many small units, or several large units, the level of short circuits can be altered enough to cause coordination between protective devices, such as fuses or relays.

3.3.4. The role of electric vehicles in the grid

The automobile industry has evolved from the manufacture of vehicles using conventional fuels to the production of electric vehicles (EVs). Plug in hybrid and EVs are a technology for solving the effect of greenhouse gas emissions from the transportation sectors. According to the analysis conducted by the International Energy Agency (IEA) based on the submissions of the Electric Vehicle Initiative (EVI), comprising of a 16 member countries, caught across the globe, electric vehicles are projected to reach a total of 20 million by the year 2020 [39].

The extensive use of these vehicles will help in transferring these emitted greenhouse gases back to the electric power sector from the transportation sector. The key challenges are identifying which generating technology will charge the vehicles, the need to boost the transmission and distribution systems inorder to meet up with increased power demand, and the prospects of using charge batteries for distributed storage purposes. However, apart from the roles it plays in the environment as carbon free emitters to the environment, since these vehicles are charged at home or public charging stations, the choice of charging if uncoordinated will have an impact on the distribution grid which leads to power losses and voltage deviations [40].

The authors in [40] analysed the role of charging plug in hybrid electric vehicles by carrying out load flow analysis in order to determine the deviations in voltage and losses in power. The authors analysed the impact using three case studies: without PHEV's, uncoordinated charging and coordinated charging. It was found out that the uncoordinated charging had an impact of the distribution grid in terms of power losses and for the coordinated charging case, it was found out that the power losses was drastically reduced which was almost the same case without plug in hybrid electric vehicles (PHEVs). This resulted to power quality improvement for these aforementioned two cases.

4. DC transition for household appliances and common electrical devices

4.1. Types of loads in household appliances

Household appliances can be grouped into major appliances, small appliances, and consumer electronics. Major appliances are used for cooking, washing and food preservation purposes. While the small appliances categories are smaller when compared to the major appliances. Examples of them are microwave ovens, coffee makers, blenders, electric kettles, etc.

4.1.1. General loads

Categories of these are major household appliance. Examples of such are dishwashers, washing machines, dryers, air conditioners, oven, refrigerators, to mention a few.

4.1.2. Sensitive loads

Sensitive electronic loads are commonly found in office buildings with digital computers and in data and communication centres and these are nonlinear in nature. Other examples of these modern appliances are consumer electronics products, such as TV's, DVD players, mobile phones, game consoles, home entertainment centres, etc, which are used in households, business

Reference [41] described the use of LVDC distribution system for sensitive electronic loads in office buildings using four different loads, which includes a fluorescent lamp, a compact fluorescent lamp, a computer and a coffee maker, using AC and DC system for evaluation and comparison purposes. Experimental results showed less losses when the load was supplied with the DC system compared to the conventional AC UPS (uninterrupted power supply) system.

4.2. Emerging DC technology appliances (tech in house appliances and offices)

There are numerous energy efficient products that are internally compactible with DC. These DC appliances utilize DC power internally. Among these products are the LED lights and many electronic loads such as DC refrigerators, 12V DC blenders, heaters and hair dryers. Some of these products are also compactible for use on car batteries.

4.3. Energy efficiency analysis with household appliances (Comparison between different types of household appliances)

Consumer electronics devices consume over half the power in any typical home. Such devices includes: electric water heaters, electric heating devices, air conditions, etc.

In reference [42], the energy efficiency analysis of DC products was analysed operating with AC for AC and DC voltage supply. Comparison was made for DC and AC products using DC lamps, air conditioners, refrigerator/freezers and it was observed that the DC products were more energy efficient that the AC products based on available data. However, in this study, it was concluded that the DC refrigerators were of higher efficiency but they were more costly than the AC products with the same size and volume because of the technological advances, which was used to reduce their energy use.

In comparison to other work, reference [42] investigated energy efficiencies of household appliances in connection to DC systems. From Fig. 4.1, it was found out that there was a 14% energy savings if AC/DC conversions are avoided and 33% gain shifting to DC. The 14% in energy savings is reported in table 5.1 in section 5.

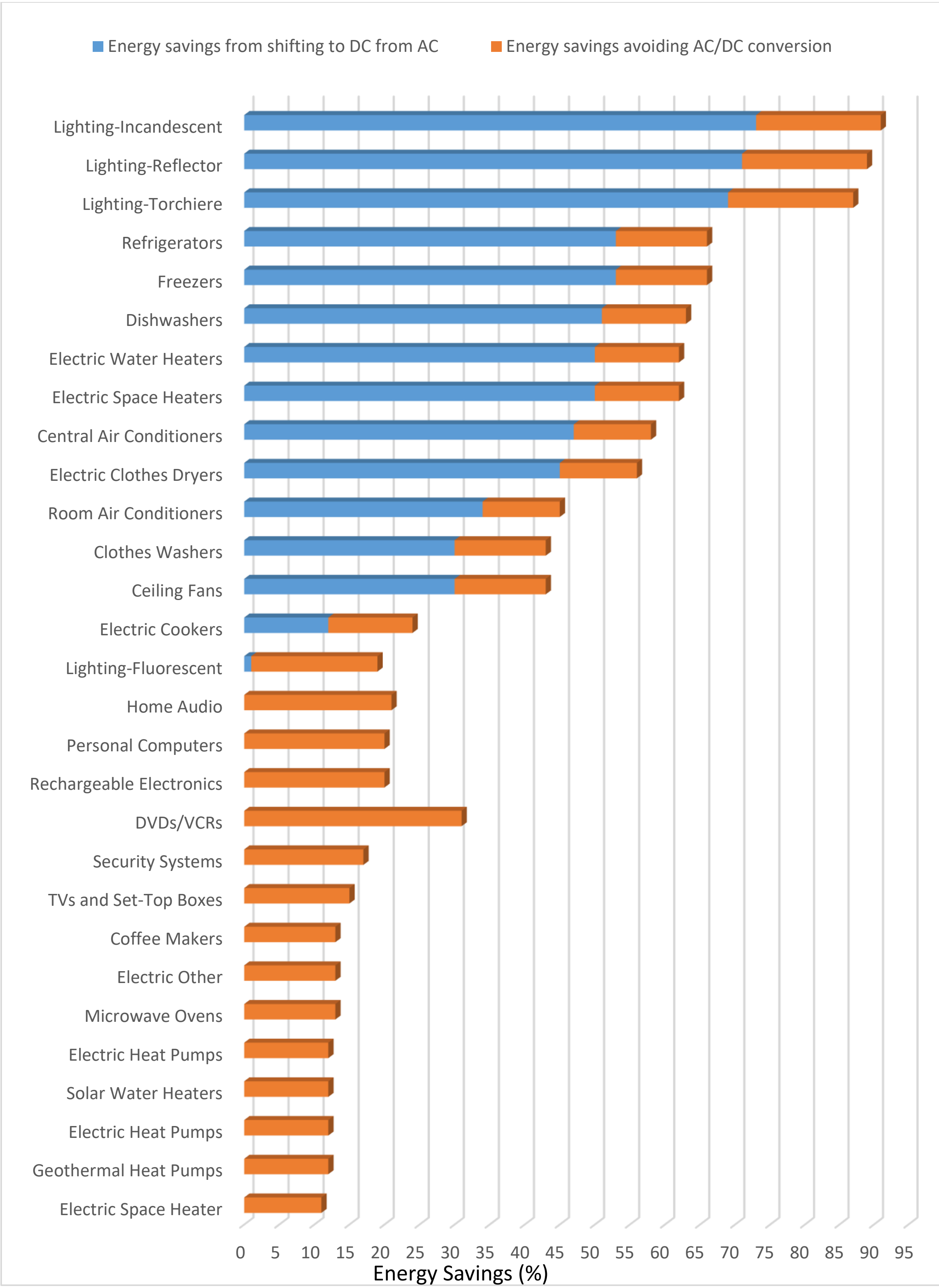


Figure 4.1: Potential of energy savings by shifting to DC appliances and avoiding AC to DC conversions *[42]*

4.4. Feasibility Study of Low Voltage DC Network for Household Appliances

In this section, the feasibility study to determine the best scheme of Low Voltage DC (LVDC) grid to be implemented for household appliances is presented. To conduct a feasibility study, it is important to define the voltage levels of Low Voltage DC grid that will be used in feasibility study in this study.

I. Voltage Levels

There is a variety of voltage levels in DC that can be used to be voltage level of LVDC. However, thorough study needs to be done to choose the amount of voltage level for LVDC. There are several studies that have examined the amount of voltage suitable for LVDC grid. Table 4.1 shows list of voltage levels recommended for LVDC based on prior researches and studies.

Table 4.1: list of voltage levels recommended for LVDC**.**

Authors	**Voltage Levels recommended**
Pellis [43]	< 120 V
Williamson [44]	24 V < V < 48 V
Li [45]	< 120 V
Sannino [46]	< 326 V
Anand [47]	48 V
Pang [48]	400 V

Based on the aforemented table, it can be concluded that there are variety voltage levels that has been recommended by several authors. Pellis and Li et al has recommended voltage level below 120 V to be implemented in LVDC grid. However, Sannino et al found that voltage below 120 V is not recommended to be implemented in LVDC grid because it is too low to be basis voltage in LVDC grid or LVDC bus. Too low voltage on DC bus or DC grid will cause huge power losses before it is even distributed. In this study, we use Norwegian grid standard is used as reference, which is 230 V / 50 Hz. The voltage level between phase to phase is 398 V. Therefore, in this study, the median value between the recommendation voltage levels from Pang et al and Sannino et al that comply the IEC 60038 and BS7671:2008 standards which are 400 V and 800 V is chosen. This is due to the need to choose suitable amount of voltage DC which is applicable to be used in DC grid and also stepped down before it is connected with household appliances which is working on relatively low voltage.

Current AC voltage levels that is used in household varies between 220 – 230 V AC. Therefore, it is worth to consider that the amount of DC grid need to be at least higher than that to minimize power losses and provides flexibility for household user. This is because the household appliances working in different voltage levels but mostly not more than 220 – 230 VAC. Table 4.2 shows several typical power ratings(in kilowatts) for several household appliances selected to investigate the feasibility [49].

Table 4.2: Several rated power of several household appliances [41]

Appliance	**Rated Power (kW)**
Refrigerator	1.67
Kettle	2
TV	0.083
Desktop Computer	0.15
Oven	2.4
Lighting	0.1

The ampacity of cable manufacturers and the maximum voltage levels needs to be considered to ensure it is suitable for cable characteristics and thermal limits of the insulation. Table 4.3 indicates the amount of voltage that is applicable for DC according IEC 60038 – standard voltage

Table 4.3: Maximum voltage levels for DC according to IEC 60038

Grounding type	Voltage to earth (V)	Voltage between conductors (V)
TN system	900	1500
Ungrounded IT	N/A	1500

Table 4.4**:** Ampacity of Copper conductors according to NEC (USA)

AWG	Area (mm^2)	Ampacity (A) at 75°C
13	2.62	20
14	2.08	20
15	1.65	16
16	1.31	16

Table 4.4 demonstrates ampacity of copper conductors according to NEC (USA).

After the voltage level is determined based on prior researches and recommendation, it is important to conduct empirical study to choose voltage levels for LVDC grid between 350 V and 700 V. For the empirical study, voltage drop in DC can be calculated according to [50]

$$V_{drop} = 2(P_{rated}/V)L(R/1000) \quad (1)$$

On other hand, to calculate voltage drop in AC three phases, (2) is used as shown:

$$V_{drop} = 0.866\ x\ (P_{rated}/V)\ x\ 2\ x\ L\ x\ R/1000 \quad (2)$$

For the forthcoming calculation, there are several assumptions that are used

1. AC system is using three phase three wire system
2. The distance is 50 meter
3. Wire diameter size is 13 AWG
4. Wire type is Copper
5. Conductor temperature is 80°C

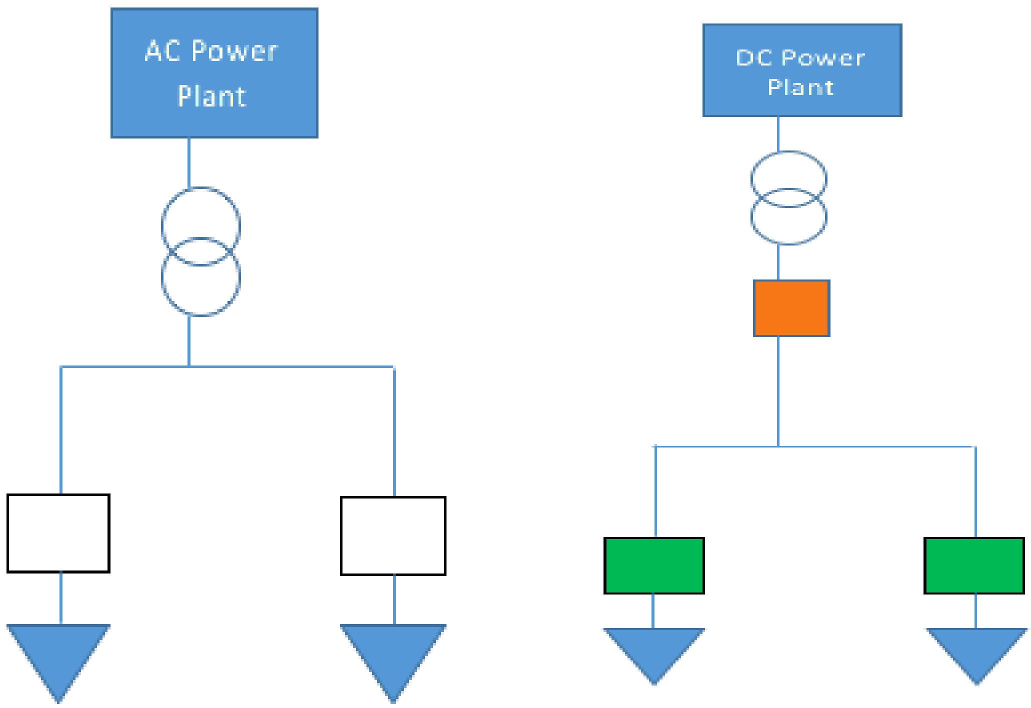
Table 4.5: Voltage drop calculations

Appliance	**Rated Power (kW)**	**DC Voltage drop (400 V DC) (%)**	**DC Voltage drop (800 V DC) (%)**	**AC Voltage drop (%)**
Refrigerator	1.67	0.848	0.21	2.2
Kettle	2	1	0.25	2.66
TV	0.083	0.0422	0.01	0.11
Desktop Computer	0.15	0.0762	0.1524	0.1989
Oven	2.4	1.2	0.3	3.19
Lighting	0.1	0.05	0.0127	0.13

Based on calculations in table 4.5, it can be stated that overall DC grid provides less voltage drop than AC grid. Voltage levels at 800 V provides best solution among other voltage levels (400 V DC and 230 V AC). Further investigation with regards to safety and power losses needs to be done in order to choose the best architecture among others.

II. Architecture

In this feasibility study, radial structure is used. Fig. 4.2 shows the topologies of radial structure between AC and DC grid that is used in this study.



(a) AC Grid architecture (b) DC grid architecture

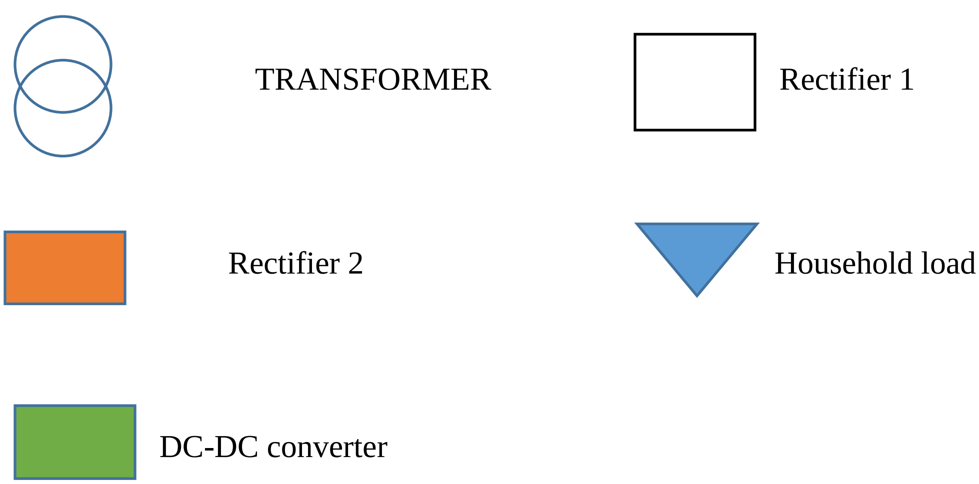


Figure 4.2: AC and DC grid architecture

In figure 4.2, there is differences between rectifier 1 in AC grid architecture and rectifier 2 in DC grid architecture. Rectifier 1 is the rectifier that is in built in the charger of household appliances. On the other hand, rectifier 2 is the rectifier that converts AC voltage to DC voltage that is not small enough to be connected to the household appliances. This rectifier plays major role as the converter that standardize the voltage that comes to the household before it is step-down again with the DC – DC converter.

From figure 4.2, it can be seen that DC grid architecture needs more power electronics more than AC grid architecture. But the analysis of power losses due to power electronics needed will be discussed more in power losses section.

When considering the architecture of DC grid, the number of conductor used needs to be considered as well. There are two topologies for DC grid which are monopolar and bipolar. Monopolar is the topology that has one energized conductor and one zero voltage conductor. On the other hand, bipolar is the topology that has both two conductors energized with the same voltage but different polarity. A monopolar might be convenient compare to bipolar due to less number of conductor needed. However, in terms of safety and protection, bipolar link can have a midpoint high-resistance ground point that reduces the fault current, thus reducing the risk of electric shocks. However, small fault currents might be difficult to detect and additional equipment might be necessary.

Furthermore, a bipolar link might provide flexibility to transmit half the power in case of faulty Operation [51]. In addition, the use of a bipolar link provides flexibility to connect loads to either one pole or two poles. By doing so, different loads can be accommodated and careful long-term planning of future installations becomes possible. Therefore, in this study, bipolar topology is used.

In this study, four architectures are investigated. These are:

1. AC grid – AC household appliances
2. AC grid – DC household appliances
3. DC grid – DC household appliances
4. DC grid – AC household appliances

First, to analyze the architecture stated above, the household appliances would be broken down into two categories, which are AC and DC. Toaster, Oven, Hair dryer and refrigerator use AC voltage. The rest household appliances mentioned use DC voltage. Therefore, for forthcoming analysis, AC household appliances will refer to toaster, oven, hair dryer and refrigerator while DC household appliances will refer to the rest of household appliances except those appliances.

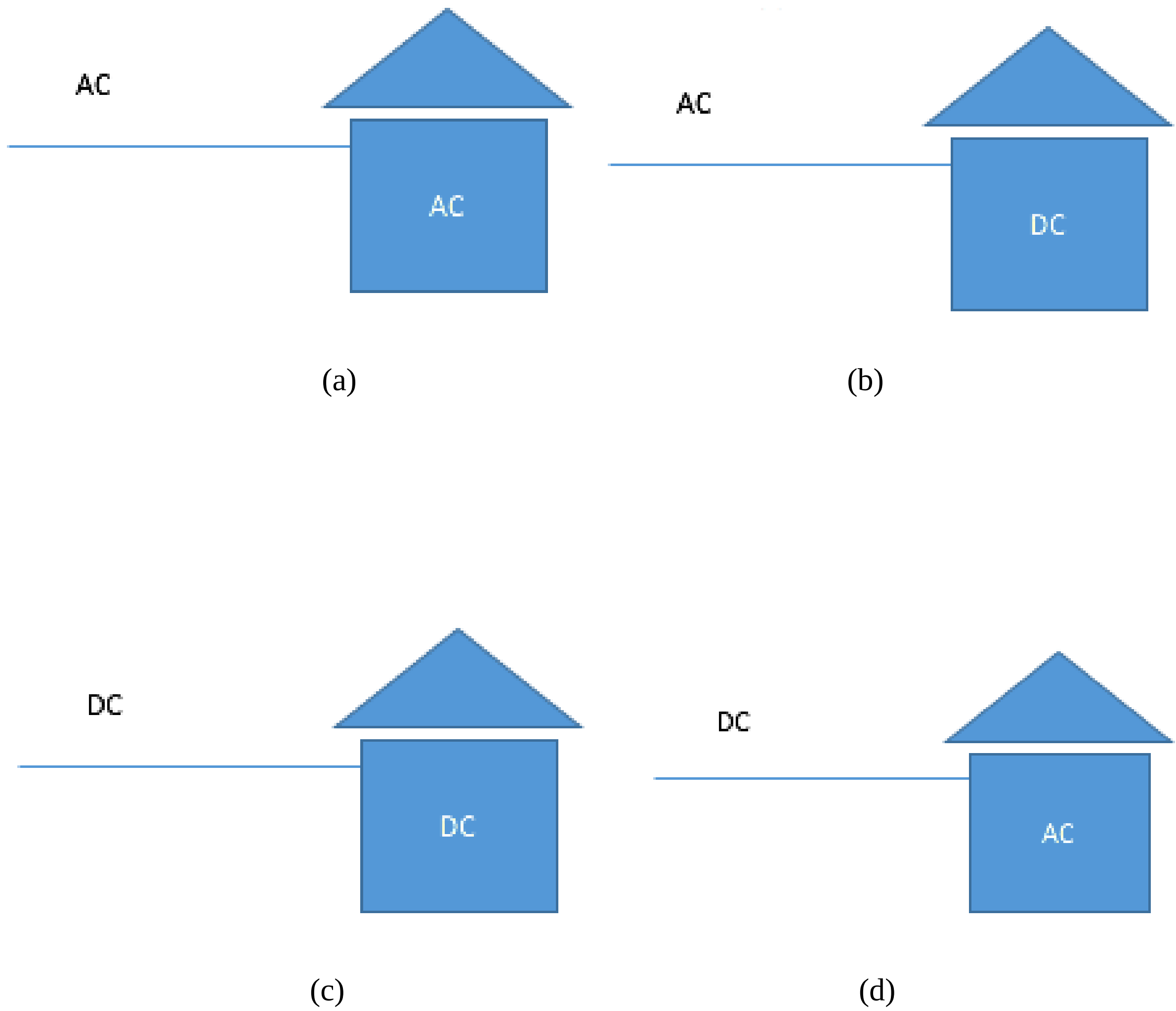


Figure 4.3: (a) AC grid - AC household appliances (b) AC grid - DC household appliances (c) DC grid - DC household appliances (d) DC grid - AC household appliances

Figure 4.3 describes four different scheme between AC/DC grid with AC/DC household appliances. The evaluation between these four architectures will be presented in power loses section.

III. Power losses

In this section, there will be two categories of power losses which are converter losses and conductor losses. For converter losses, there will be three main power electronics that will be used which is described in table 4.6.

Table 4.6: Typical efficiency of different power electronics [52]

Items	Typical efficiency
Rectifier	99%
Inverter	95%
DC – DC converter	90%

Based on voltage levels analysis, 800 V provides best efficiency in terms of voltage drop. Therefore, for forthcoming analysis of power losses to compare different topologies, 800 V will be used as voltage level of LVDC grid. To calculate the power losses in LVDC and LVAC, (3) and (4) are used:

$$P_{DC\ losses} = V_{drop}^2 / R \quad (3)$$

$$P_{AC\ losses} = V_{drop}^2 / Z \quad (4)$$

To calculate R, equation 5 below is used:

$$R = \rho L / A \quad (5)$$

For the forthcoming calculation, the resistivity of copper at 20°C is taken as 1.68 x 10^{-8} (Ωm). Cables cross-sections are 1.5mm^2 according to common engineering practice in AC. However, because the conductor's temperature rises, a resistivity at 80° C will be used. ρ_{80} is calculated according to the IEC 60287-1 - Electric cables - Calculation of the current rating.

$$\rho_T = \rho_{20}\, x\, (\theta_T - \theta_{20}) x\, \alpha_{20} + \rho_{20} \quad (6)$$

Where

- α is the temperature coefficient of the conductor material per K at 20° C (4.29×10^{-3}).
- θ_T is the temperature of conductor.

By using (6) resistivity of copper at 80°C is 2.11×10^{-8} Ωm. Then, by using (6) and (5), resistance of cable is 0.68. While Z is obtained using (7):

$$Z = \sqrt{R^2 + X^2} \quad (7)$$

Reactance X is calculated by using specific reactance which is 0.1 Ω/km. Since the distance is 50 m, the reactance is 0.0005 Ω. Due to low value of reactance, it is neglected. Thereby, making the value of impedance the same as the value of resistance. Table 4.7 shows conduction losses calculations in AC and DC.

Table 4.7: Conduction losses calculations

Appliance	**DC Power losses (400 V DC) (%)**	**DC Power losses (800 V DC) (%)**	**AC Power losses (%)**
Refrigerator	1.01	0.25	2.25
Kettle	1.18	0.29	2.75
TV	0.05	0.01	0.11
Desktop Computer	0.09	1.46	0.21
Oven	1.41	0.35	3.30
Lighting	0.06	0.02	0.13

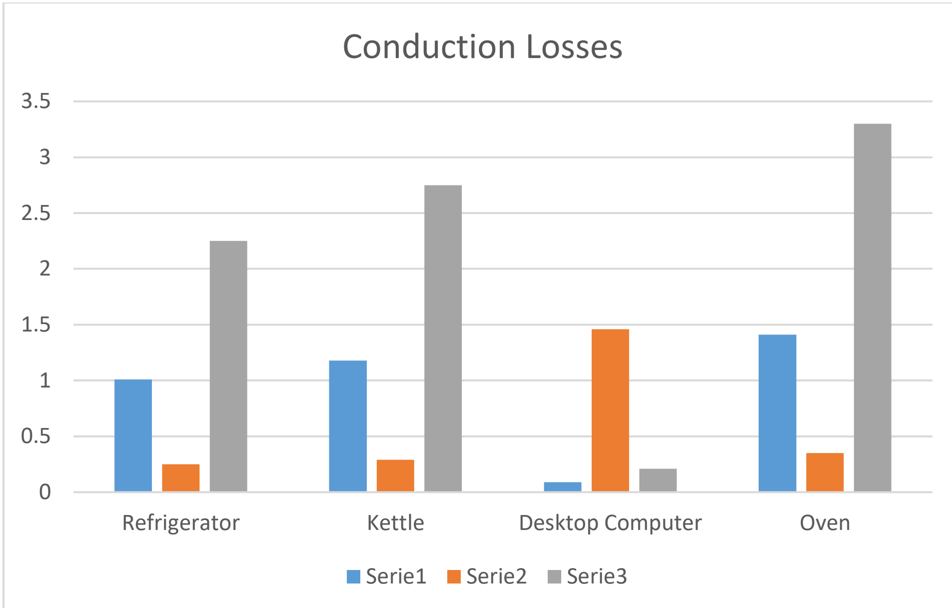


Figure 4.4: Conduction Losses Diagram

Fig. 4.4 shows conduction losses diagram. In this figure, telephone, TV and lighting were neglected due to small percentage value. Based on table 4.7 and Fig. 4.4 above, 800 V demonstrates best performances in terms of delivering power through electricity grid compared to others. On the other hand, AC grid have highest power losses when compared to others.

Table 4.8: Power electronics scheme on four different topologies

Topology	**Power electronics scheme**	**Converter losses / efficiency (%)**
AC grid – AC household appliances	N/A	0/100
AC grid – DC household appliances	Rectifier – DC/DC converter	10.9/89.1
DC grid – DC household appliances	DC/DC converter	10/90
DC grid – AC household appliances	Inverter – Rectifier – DC/DC converter	15.355/84.645

There are three power electronics used in this study, which are rectifier, inverter, and DC/DC converter. DC/DC converter was used to step down voltage from high voltage DC to low voltage DC, Inverter was used to convert DC power to AC power, while rectifier was used to convert AC power to DC power. From table 4.8, it can be shown that scheme "DC grid – AC household appliances" use more power electronics than other topologies and has lowest efficiency among others. It is because although AC household appliances use AC to operate, its circuit is powered with DC. For example, in households nowadays, when the TV is connected to AC source/grid, it converts AC power to DC power to power up its circuit inside in order to operate well.

Table 4.9: Overall losses calculations

Appliance	**AC - AC (%)**	**AC - DC (%)**	**DC - DC (%)**	**DC – AC (%)**
Refrigerator	2.25	12.905	10.225	15.567
Kettle	2.75	18.919	10.9	16.201
TV	0.11	24.933	11.575	16.836
Desktop Computer	0.21	26.938	11.8	17.048
Oven	3.30	28.943	12.025	17.259
Lighting	0.13	30.948	12.25	17.471
Overall losses	**1.558**	**21.926**	**11.238**	**16.519**

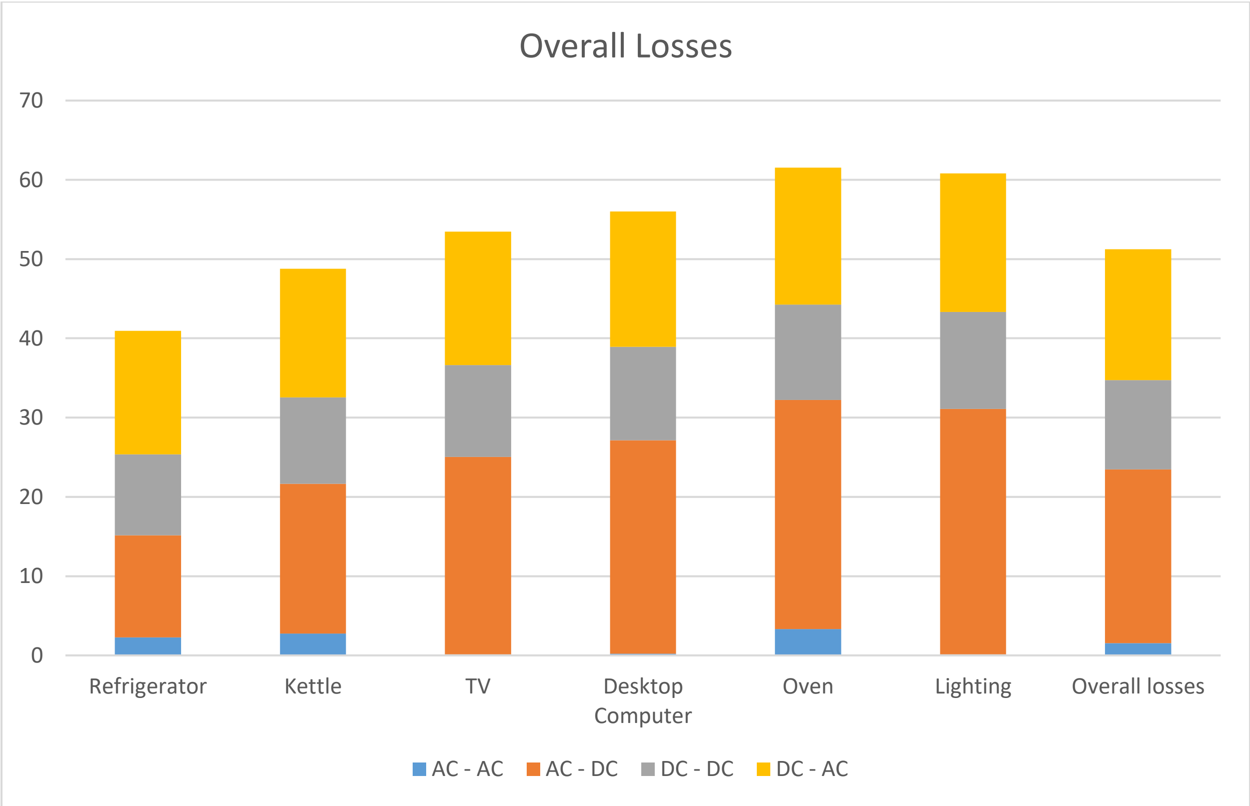


Figure 4.5: Overall Losses Diagram

Table 4.9 and Fig. 4.5 shows the result of overall losses calculations between four different topologies. It can be deduced that AC grid – AC household appliances topology shows best performance among others in terms of overall losses.

4.4.1. Economical aspect evaluation/Analysis

In this section, economic analysis was conducted to provide an analysis about how power losses will affect the cost of electricity per year. Data of average yearly consumption per household was taken from [53]. Data Øre/kWh also taken from [54] which stipulates the cost of electricity to be 34.3 Øre/kWh. Table 4.10 shows average yearly consumption in Norway in different appliance.

Table 4.10 Average yearly consumption of appliances in Norway

Appliance	**Average yearly consumption (kWh/household)**
Refrigerator	247
Kettle	12
TV	163
Desktop Computer	154
Oven	269
Lighting	1000

By multiplying average yearly consumption and cost of electricity in Norway along with power losses at different topologies, the cost of losses per appliance in Norway at different topologies was acquired as shown in Table 4.11 below.

Table 4.11: Average yearly cost of losses per appliances for different topologies

Appliance	**AC - AC (NOK/household)**	**AC - DC (NOK/household)**	**DC - DC (NOK/household)**	**DC – AC (NOK/household)**
Refrigerator	190.622	1093.303	866.272	1318.819
Kettle	11.319	77.871	44.864	66.685
TV	6.149	1393.993	647.147	941.299
Desktop Computer	11.093	1422.919	623.299	900.504
Oven	304.481	2670.461	1109.511	1592.483
Lighting	44.59	10614.993	4201.75	5992.596

Total losses	**568.255**	**17273.539**	**7492.844**	**10812.388**

Based on table 4.11 above, it can be seen that AC grid – AC household become best topology in terms of cost of losses per appliances by providing cheapest cost of losses compare to others. On the other hand, AC grid – DC household become worst topology in terms of cost of losses per appliances with the amount of cost of losses 17273 NOK/household per year.

IV. Conclusions

Theoretical and empirical studies have been conducted to investigate the feasibility of transition from LVAC grid to LVDC grid. The results show that the transition is feasible in terms of technical aspect. However, LVDC grid demonstrates poor efficiency than LVAC grid with the topology, AC grid – AC household. The Voltage level that most suitable for LVDC grid is 800 V DC. Among other topologies, AC grid – AC household appliances demonstrates best efficiency in terms of conduction losses and converter losses. AC grid – AC household also offer least cost of losses compare to other topologies by costing every household per year in Norway around 568.25 NOK. On the other hand, AC grid – DC household become the most unfavorable topology among other topologies by costing huge amount of money which amounted to 17273 NOK/household per year. This follows from earlier empirical study performed, that AC grid – DC household have highest overall losses among other which is 21.9%.

5. Feasibility of DC transition

In this chapter, the challenges of the transition to DC is analysed. This is divided into three main parts namely, sustainability, safety, stability and reliability, and affordability of the power systems. Sustainability entails the reduction of the impact of CO2 emissions from the power generation as low as possible and affordability in terms of enabling efficiency in the power sector/systems network during the transition to the low-carbon transformation.

5.1. Technical aspect evaluation

Efficiency analysis of DC distribution systems

Table 5.1: Reported results on LVDC distribution system *[50]*

Voltage [Vdc]	System Size	Reported energy savings [%]	Source
< 120V	Single-family dwelling	Very low	Pellis (1997)
326V	Single dwelling	Very low	Engelen et al. (2006)
326V	Residential	-2% to +2.8%	Hammerstrom (2007)
326V	Residential	+2% to +5%	Waeckerlé (2011)
±750V	Residential	Up to +4.88%	Paajanen et al. (2009)
±200V	Residential complex + PV	+15%	Kakigano et al. (2010)
24V/380V	Residential & PV	+5% to +14%	Garbesi et al. (2011a)
22kV/325V	Large-residential	+2.5%	Dastgeer and Kalam (2009)
-	-	+10% to +35%	George (2006)
48V	1000 racks datacentre	+20%	George (2006)
380V	Data centre	-3% to +25%	Johnson (2012)
300V	Data centre	14.8% to 15.5%	Kim (2012)
380V	Data centre	+28% a)	Electric Power Research Institute (2010)
380V	Data centre	+1.25% b)	Rasmussen (2007)
13.8kV/2.4kV	~35MVA/32MW	~-80% (100% AC load) / ~+40% (100% DC load)	Starke (2008)
32kV/325V	Test feeder	~1%	Nilsson and Sannino (2004)
N/A	Residential, Commercial, Manufacturing, Data centres	+19% to +25.32%	Savage et al. (2010)
28V	University library computers	+14% + 47% for appliance change to DC	Williamson (2011)

Table 5.1 shows the summary of results for LVDC distribution system for commercial and residential applications carried out by different authors for analysis and evaluation of different DC systems in comparison to the AC system. From the table, it can be seen in the first group that the results varies for each studies and system sizes. In the residential system category, efficiencies

between -2% (energy losses) and 14% have been claimed. In this same group, the highest energy savings of 15% was claimed with a residential complex having photovoltaic (PV) system. The fact that each system having a PV system, accounted for this high percentage in energy savings, making the total amount of losses of the DC systems lower than that of the AC system within a year duration. In the first group, the reported energy savings claimed by different authors will have to depend on different factors such as: the system size, the use of PV systems, the assumed converter efficiencies and voltage levels.

For the second group, the data centre, energy efficiencies of up to 35% was reported. However, in a different case study for the same application, energy loss of -3% and an infinitesimal gain of +1.25% was claimed. The inconsistencies in these energy savings reported for this group depends on the efficiencies of the power converters and the UPS that were used in the evaluation and analysis.

The authors in [34] analysed the power losses when AC is replaced with DC for efficiency analysis. The losses are evaluated as stated below:

1. <u>Losses in AC grid system</u>
   The losses were calculated in the AC system with a 150/20KV transformer rated at 10MVA which supplies a number of MV feeders at a nominal voltage of 20KV and found the system efficiency to be 97.3% with losses not more than 1% between 5 different cases investigated. The 1% in energy savings is reported in table 5.1 above. However, when the length of the cable changes (doubled) in one of the cases, the efficiency of the system was 96.5% (still within the 1% loss range).
2. <u>Losses in DC grid system</u> by replacing the MV/LV transformers with DC-DC converters, i.e. using DC for both MV and LV levels, the authors calculated the losses in the system and the system efficiency was found to be 96.8%. However, with the changes in the cable length in one of the cases examined, the efficiency reduced to 95.2% and with the changes in the switching frequency in the cases examined, for the DC-DC converters, resulted to 0.1% increase in losses.
3. <u>Losses in AC-DC grid systems</u> The losses in the AC/DC grid system was calculated and found the system efficiency to be 96.4%. However, when the length of the three phase LV cable was increased in one of the cases evaluated, efficiency reduced to 94.9%.

In reference [55], the power efficiency for AC and DC loads in LVDC distribution system was analysed. Different power converters and both AC and DC loads were analysed by modelling and simulation. Fig 5.1 shows the efficiency results of both types of loads. It can be seen that the efficiency for the AC load is much lower compared to the DC load due to less power conversion process due to the less power converted used. However, the author pointed out that the adoption of LVDC system will depend on two factors, which are:

- To boost efficiency, all AC loads needs to be substituted for DC loads.
- A more thorough research and detail analysis of the LVDC distribution system must be carried out.

Load	Component	Factor(Location)	Value
AC Load	Diode Rectifier	Voltage(A)	220V
		Current(A)	0.0953A
		Power(A)	20.97W
		Efficiency	75.08%
	DC/DC Buck converter	Voltage(B)	178.91V
		Current(B)	0.088A
		Power(B)	15.744W
		Efficiency	91.46%
	Total efficiency		68.67%
DC Load	DC/DC Buck converter	Voltage(C)	380
		Current(C)	0.045A
		Power(C)	15.465W
		Efficiency	90.44%

Figure 5.1: Load efficiency analysis in LVDC distribution system *[55]*

5.2. Environmental aspect evaluation

Nowadays, the preservation and protection of the environment has been an international phenomenon and a major global concern. There are so many factors that lead to environmental problems such as population growth, leading to loss of diversity and ecosystem degradation, ocean pollution, deforestation, atmospheric ozone depletion, air pollution and global warming.

Although all environmental aspects are important, global warming, air pollution and ozone depletion are considered/relevant for this thesis.

The society now rely more on a reliable and stable power supply. This reliance is said to increase as low carbon technologies of power generation are developed and deployed for the decarbonisation of economies.

According to the International Energy Agency (IEA), “maintaining reliable and secure electricity services while seeking to rapidly decarbonize power systems is a key challenge for countries throughout the world”.

5.2.1. Environmental impacts of wind power technology

The greenhouse gas emissions and air pollution from the construction of wind power farm/station is minimal and is declining. Its operation is emission and pollution free. Nowadays, wind turbine designs have so far reduced the noise levels from turbines. In this case, causing a reduction in energy losses and output. Although there might be some risks associated with wind turbine technology, and one of such is the risk to animals like birds striking wind turbine towers or the turbine blades.

5.2.2. Environmental impacts of solar power technology

Photovoltaics are known to be safe when compared to other power generation technologies. Photovoltaic systems are noise and pollution free during their operation. Compared to others types of electric sources, they have lower environmental risks. However, the chemicals used in the PV (photovoltaic) cells, at the manufacturing plant, the installation site or recycling plant, could be released to the air or water causing an environmental risk.

5.2.3. Environmental impacts of hydroelectric power technology

Hydropower is an old form/conventional source of power generation. Hydroelectric power is a form of renewable energy source which generates power that is less air polluting compared to fossil fuels and gas, inexpensive to operate and maintain, etc. It is the cheapest form of power generation today. However, its construction and operation is detrimental to river ecosystem (fishes inclusive) and wildlife conservation. The construction of the dam also results in the reduction of water quality and flooding. Globally, the negative effect is also felt in humans too as humans have been displaced physically over years due to its construction [56].

5.2.4. Greenhouse gas emission impact of various power generation methods

Power production based on fossil fuel e.g coal, oil and natural gas, as the main energy sources lead to global greenhouse gas emissions and possess great threat to the environment. The burning of fossil fuels (coal burning power plants) for the generation of power is the largest source of pollution. (Case study, U.S). Another second largest contribution of carbon pollution is in the transportation sector in which a large quantity of CO_2 is emitted yearly (U.S as case study which generates up to 1.7billion tons of CO_2 emissions yearly.) [57].

China comes first then U.S followed by the European Union, India, the Russian federation and japan which are the top CO_2 emitters. The use of alternative sources to fossil fuel burning should be adopted worldwide in reducing the carbon pollution, which results in greenhouse effect. As new energy efficient technology is being developed, cleaner fuels are being used and scientists and Engineers come up with latest ways of developing/modernizing the power plant systems, reducing the impact of green gas emission is reduced.

5.3. Environmental impact analysis of power electronics.

In order to know the environmental implication of the different power converters employed to the grid, several authors have investigated this implication to ecology/ecosystems as part of curbing the implications of global environmental damage.

The studies in [50] have estimated ecological damage on a 1kW DC/DC converter using life cycle assessment approach, an approach for investigating the environmental impacts of products and services. In this study, the author compared AC and DC distribution technology for environmental impact assessments using the same equipment in comparison for both systems and found out that the PCB, power devices, electronics and heat sinks contributed majorly to the environmental impact. However, author argued that if an AC alternative makes use of rectifiers and Power factor correction (PFC), with 50% of PCB space, then, the DC/DC converter devices were considered more environmental friendly.

In another context, reference [58] investigated two power electronic converters and their component parts using the Life Cycle Assessment (LCA) described earlier.by doing so, the author analyses its product life cycle, which includes: the advantages of energy savings, energy invested in the fabrication and construction of power electronics and its end of life. According to the LCA performed, the energy payback time for power electronics was shorter, in the range of a few months. The payback time was even compared to other renewable energy sources such as wind turbine having an energy payback time of 6-8years, and photovoltaics systems having a payback time of 1-3 years.

6. Socio-technical challenges of DC technologies and transition

In this chapter, an in depth analysis of issues affecting the transition to DC is presented, i.e the events that can happen outside the electrical system that might hinder the transition. It also highlights on the necessary collaborations and cooperation needed in the transition to DC.

6.1. Perception and acceptance of DC technologies

There should be thirst for clean energy as there are benefits associated to these types of energy. This type of green energy must be reliable, affordable, economically viable, socially acceptable and environmentally friendly. For there to be a transition, then the type of transition must be able to meet the already stated qualities. DC technologies has been been for a long time known to have all these characteristics, however, there are factors that must be looked into which might hinder DC technology and the transition to DC generally.

6.2. Role of stakeholders, institutions, and networks in the transition to DC

Stakeholders, institutions, networks are further divided into the below:

Users/consumers perception

User here does not only mean the consumers but also private entities such as engineers, technicians and even electricians and they have a role to play too. It is not only by supporting the DC transition or DC products, but they themselves

The author in [20] has been playing a role of becoming a vital knowledge partner in the field of DC by making and providing teaching materials for higher institutions to enlighten them about DC technology so that they can also promote the technology for its future advancement. The student's response and acceptability of the technology so far has been tremendous. This is to show the importance of public awareness and enlightenment.

Public policy and public acceptance of power electronics/Energy efficiency awareness

The role of power electronics is vast particularly its role in improving the efficiency of energy conversion. These roles has been discussed in section 3. There is the need to quantify the value of power electronics and promoting it to the policy makers in a way they can understand and accept. The author in [58] highlighted further that the renewable energy sources (wind turbines and PV systems) were much more prominent to the entire populace due to their green nature but that few people knew of the energy savings potential of power electronics. Fig 6.1 shows the merits of employing power electronics for different system configuration. It can be shown that the application of such to PV systems has a lesser energy payback time when compared to others. The author highlighted further that fig 6.1 can serve as an awareness tool to policy makers and the entire general public for the awareness of power electronics and its potential in sustainable energy future. By so doing, power electronics will go through rapid phases of in-depth research advancements and also the conventional means of generation highlighted in section 5.3 will have to be replaced which will reduce environmental impacts.

	PV system with no power optimisers HID lamps with magnetic ballasts	PV system with no power optimisers HID lamps with electronic ballasts	PV system with power optimisers HID lamps with magnetic ballasts	PV system with power optimisers HID lamps with electronic ballasts
Sustainable energy balance [years]	3.7	2.2	2	1.5

Figure 6.1: Sustainable energy balance for different system configurations: case studies [58]

The role of government and NGO's in the transition

For any transition to happen in an economy, the government have a very important role to play. Their perspective view of such a transition and their contribution of adequate funding for advanced technologies by research is very vital for the transition. As a case study, as it has been highlighted earlier in section 5.4, about Direct current BV, the Netherlands have always been on the forefront in the recognition of the role the DC grid will play in the economy by giving it full support in terms of recommendation and massive support for projects.

The role of environmental agencies

Federal environmental agencies in many countries of the world has a nonchalant attitude towards the role that energy efficiencies and renewables will play in their prospective economies. Taking the U.S as a case study, those agencies are guided by the government and any decision to be taken concerning these issue will have to be a top to bottom approach. Failure to impose high prices on carbon and other green house gas (GHG) emissions, which will result to high price of fossil fuels, and in turn which is expected to make the renewable generation more cost effective.

The role of technology providers, consultants, researchers/expertise

According to [21] in the past years, the potential in energy savings for DC power has been the topic for discussion in several conferences, in which the service providers and consultants have indicated inconsiderable interest in DC distribution. However, things have changed due to technological advances.

For any transition to happen, researches and expertize play a vital role in technological advancement. Research grants have to me made available to the researchers for innovative research

and development for technological advancement. However, if support for research and development is not fully in place, then no transition can happen. This is where the government and financial institution have to play their role in the transition.

Research bodies and funding bodies too have a role to play in the transition. If research bodies comes up with novel innovative ideas, then there would be ease of collaboration and cooperation between these two important institutions. These are ideas that can sell easily to the populace without both parties loosing at the end.

The role of market institutions, suppliers and product manufacturers in the transition

The market institutions, suppliers and product manufacturers have role to play in the transition. There has to be a supply network for any DC electrical system to be supplied. This network comprises of the manufacturers, wholesalers, distributors, retailers and even the electrical installers. This means that the development of a market for DC products will entail the full cooperation of everyone in this supply network.

The role of utilities

Utilities has a role to play in the transition to DC. They have a role in making DC power available to end users which must have to be cost effective as possible. Their active participation in summits, symposiums, exhibitions and workshops related to the power grid should be highly embraced. In this case they join forces with other stakeholders to discuss and debate on the current best practices and create a platform for solving the potential roadblocks to electric power transformation.

The role of higher institutions of learning

Institutions of learning are a main source of research and have to cooperate with the power network companies for innovative technology research within the power field.

Role of companies

Companies both public and private also have their prospective role to play in the transition by their corporate responsibility to the environment and not only social responsibility. As it is already pointed out earlier in section 2.3.2 about Direct Current BV implementation of DC in greenhouse, they were recently nominated for the European business awards for the environment 2016-2017 award to be precise. This is an European commission environmental award which has not only made Direct current BV to be recognized globally, it has also made the Netherlands to be in the forefront of tackling the global phenomenon of climate change using sustainable innovations. The theme, "DC grid, the missing link to a sustainable future" found its place to the top for final selection [59].

The author in [59] believe that DC is the bedrock of sustainable energy and one of their goals is the transition to sustainable DC world from current AC world. As it has already been highlighted in section 2.3.2, they are actively involved in projects that deals with transition to DC from AC grid.

ABB, a global power specialist has has always been a proponent for DC distribution even through their products, as they continue to invest in direct current (DC) power technology for power distribution systems in data centres. Apart from the data centres, one of their anticipated breakthrough of their product is the HVDC circuit breaker, earlier emphasized on, in section 2.2.1. Apart from this, they play other roles by collaborating with other DC proponents to make DC power a full functional reality (21).

7. Conclusions and Recommendation for future work

In the very past, DC was championed as a better means of electricity supply than AC but eventually such changed due to its flaws and AC has become standard ever since, even till today. However, along the line, HVDC has so far till today been employed in long distance transmissions due to technological advances in power electronics due to its merit when compared to AC, already discussed in this thesis, in subsequent sections. So presently, DC current is being employed in the power grid as a backbone to the current grid. Apart from that, standard bodies such as Emerge Alliance, advocates for DC power in commercial and telecommunication centres, such as data centres, and must have to also make the case for DC distribution standards in residential applications apart from data centres. Other standards bodies and DC proponents must cooperate with in-depth research to make the transition to DC happen.

This project has evaluated the DC grid as vital for meeting the ever-growing demand for electric power due to various environmental concerns such as climate change, power systems security, energy efficiency, e.t.c. In addition, both AC and DC systems have been evaluated thoroughly, the current state of arts of both systems has been identified, also technical, economic, environmental and socio-technical feasibility evaluation has been carried out,

However, there are questions that lingers in the minds of individuals towards the transition to DC. Questions like: why should such a transition to DC take place? Who will promote such a transition? How will the transition to DC take place, and when will the transition happen?

All the answers to these questions have already been dealt with in this thesis. These are people of all occupations, which have been discussed in section 6 that have an impact for this transition to happen. DC grids has great potentials but a major pitfall is the unavailability of standards, although such standards are championed for in data centres and telecommunication centres, but the residential/households aspects is lacking.

It is a fact that before a transition can happen, it will have to overcome obstacles to changes.

If the electrical power system is sociotechnical, then an extensive transition, such as DC transition will require comprehensive changes across the entire institutions earlier discussed. However, there would have to be hindrance to the changes that needs to be put in place for the transition to happen.

Moreover, general acceptance of DC technology and DC transition would not just happen instantly. A whole lot of measures will have to be put in place. Impediments to the transition and rapid deployment of this technology has to be tackled.

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Appendices