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A Report on

AN OVERVIEW OF HVDC APPLICATIONS: A STUDY ON MEDIUM VOLTAGE DISTRIBUTION NETWORK

DEPARTMENT OF ELECTRICAL ENGINEERING

UNDER THE GUIDANCE OF PROF.YAKUB KHAN

2020-2021

AFFILIATED TO

UNIVERSITY OF MUMBAI

A PROJECT REPORT
ON
"AN OVERVIEW OF HVDC APPLICATIONS: A STUDY ON MEDIUM VOLTAGE DISTRIBUTION NETWORK"

Submitted to

DEPARTMENT OF
ELECTRICAL ENGINEERING

In partial Fulfilment of the Requirement for the Award of

BACHELOR'S DEGREE IN
ELECTRICAL ENGINEERING BY

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UNDER THE GUIDANCE OF
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CERTIFICATE

This is to certify that the project entitled

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Is a record of bonafide work carried out by them, in the partial fulfilment of the requirement for the award of Degree of Bachelor of Engineering (Electrical Engineering) at ***Anjuman-I-Islam' Kalsekar Technical Campus, New Panvel*** under the University of MUMBAI. This work is done during year 2020-2021, under our guidance.

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Dear Reader

We the students of "Bachelor of Electrical Engineering" assigned with the below mentioned group code are submitting the report entitled **"AN OVERVIEW OF HVDC APPLICATIONS: A STUDY ON MEDIUM VOLTAGE DISTRIBUTION NETWORK"**. This report encompasses various aspects of analytical mechanisms with its key impact and various benefits to the society

This report also highlights some of the ethical and unethical use of the data analysis mechanisms which will help the reader to be aware of how to take the most from this field in a good cause.

Yours Sincerely,

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Abstract

With the continuous increase in demand for power within the last few decades; the need for electricity suppliers has become a great concern along with the usage of renewable energy sources. Electric Power Transmission is the epergne of any power system. Nowadays, HVDC links are considered to be a crucial solution for power transmission as they have various features in comparison with the HVAC. The scope of this research is focused on the applications and development of HVDC, and to study AC and DC distribution networks. This report will present a comparison between HVDC & HVAC links in overhead and cable transmission systems, and a study on Distribution Network.

Declaration

We declare that this written submission represents our ideas in our own words and where others ideas or words have been included; we have adequately cited and referenced the original sources. We also declare that we have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in our submission. We understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Glossary

HVDC: High Voltage Direct Current.

HVAC: High Voltage Alternating Current.

LCC: Line Commutating Converter.

IGBT: insulated gate bipolar transistor.

GTO: Gate Turn-off Thyristors

IGCT: Integrated Gate Commutated Thyristor.

VSC: Voltage Source Converter.

UHVDC: Ultra High Voltage Direct Current.

PWM: Pulse Width Modulation.

CB: Circuit Breaker

CSC: Current Source Converter.

MI: Mass impregnated.

LPOF: Low pressure oil filled.

XLPE: Extruded cross linked polyethylene.

ETO" Emitter Turn Off.

MTDC: Multi Terminal DC systems.

JEPCO: Jordan Electrical Power Company.

AWA: Aluminum Wired Armoured.

PVC: Polymerizing Vinyl Chloride.

FACTS: Flexible Alternating Current Transmission Systems.

THD: Total Harmonic Distortion.

PF: Power Factor.

HP: High Pass.

LP : Low Pass.

PV: Photovoltaic.

Chapter 1: Introduction

- Historical Background

The transmission and distribution of electrical energy started with DC in 1882 by Thomas Edison in New York . Later, in 1954, HVDC became a reality after the establishment of a 20MW HVDC link between the Swedish mainland - Gotland Island in the middle of the Baltic Sea [1]. Afterwards, the Gotland HVDC link was followed by another links. The first major bulk HVDC Transmission link with Overhead lines was the Pacific Intertie link, feeding Los Angeles, which was a record-breaking transmission system, with a 1360 km length and a capacity of 1440 MW. Both of the Gotland and the Pacific Links have been upgraded and are still operational. The current capacity of the Pacific link is 3100 MW. The Itaipu HVDC link in Brazil in 1980s was the HVDC link with the greatest capacity with a total power of 6300 MW, with 600 kV DC levels. It was a back to back system; bringing the 50 Hz generated power of the Itaipu Hydropower plant to feed the Sao Paulo 60 Hz grid. In 2010, the Xiangjiaba-Shanghai link in China broke all the HVDC rating records, with a length of 2071 km, 800 kV DC Voltage transmission level, and power capacity of 6400 MW, feeding the city of Shanghai from the Xiangjiaba hydropower in south west of China [2].

However, due to the invention of the induction motors, which are the backbone of the industry, and the feasibility and easiness of using transformers to change voltage levels, the AC systems took place and become commercially useful. AC transmission system has been preferred in the past 100 years, despite its limitations such as; the transmission capability and inefficiency in long transmission systems, and the impossibility of connecting two Asynchronous systems. However, AC generation, transmission and distribution are still dominant. With the increased demand for electricity and the development and drop of prices of Power Electronics components, HVDC showed that it is the key technique and the only suitable solution for such problems. Its advantages that make it attractive are [1] [3]:

1. Lower energy losses while using HVDC with the same current in the conductor in comparison with the HVAC as shown in Table 1 [4].

AC Cables	DC Cables
Ohmic Losses in Conductor	Ohmic Losses
Induced Losses in Conductor	
Sheath Losses	
Losses in Neighboring Cables	
Charging Current	

Table 1: Energy losses in both HVAC & HVDC.

2. More economical feasibility as they require less conductors and insulation levels.
3. Unlike AC transmission lines, HVDC allows better control over the voltage and power flow, and limits the charging current in long distance transmission lines.
4. Easily allows HVDC links for subsea interconnections.
5. Enhanced controllability and system's stability over the power through the transmission line.
6. The ability of transmitting power in either direction.
7. Allowance for Asynchronous systems interconnections.
8. Provides fully isolation for the system in case of AC faults from one side.
9. HVDC systems enable the use of underground cables over long distances with high power.

Therefore, improving HVDC techniques and components are essential to reduce the HVDC's main disadvantages which can be summarized as follows [3]:

1. High cost and losses of the converter station.
2. Limited operation experience for HVDC conversion techniques.
3. Capacitor banks and harmonics filters on both the AC & DC sides of the converter station, to meet the reactive power demand for AC nodes and the converter itself which can reach 50% of the transmitted active power.

The power electronics components were the roadblock with using HVDC, as they handle the conversion from AC to DC and vice versa. So HVDC applications started to take off after the development of high rated conversion stations "AC/DC and DC/AC "with acceptable costs, performance, and reliability, and the invention of high voltage mercury arc rectifier valves in 1930s [3], this type of HVDC is known as HVDC Classic or HVDC LCC " Line Commutated converter".

Recently, HVDC converter stations are based on the use of semiconductors such as: IGBTs, GTOs, and IGCT, this type is known as HVDC VSC "Voltage Source Control"[3], it has more advantages over classical HVDC. These conversion categories take place at both sending and receiving ends.

- HVDC Recent Research & Projects

Due to the above mentioned advantages, HVDC transmission technology plays a significant key in the development of the current grid, and will be an essential part of the future grid. HVDC has been used in different applications, these applications can be grouped as follows [2]:

1. Large bulk power transmission from remote energy sources.
2. Offshore and remote wind farms.
3. Embedded HVDC links for improving the AC grid performance and enhance the control and the exchange of power among different grids.
4. National or regional interconnections.
5. Underground city centers infeed.
6. Supply of electrical power from shore to oil and gas offshore platforms.

HVDC systems are at the moment being planned and implemented in a bigger and faster way than what was expected, Tables 2,3 show lists of some operating HVDC systems with different technologies [5] [6].

System	Year Commissioned	System's Capacity [MW]
Gotland	1970	20
Skagerrak	1976	500
Cahora Bassa	1977	1930
Inga-Kolwezi	1982	560
CU Project	1979	1000
Nelson River 2	1985	2000
Itaipu	1984-90	3150
Pacific Intertie	1970	1440
Intermountain	1986	1920
Fenno-Skan	1989	500
Rihand-Delhi	1990	1568
Quebec-New England	1992	2000
New Zealand DC Hybrid Link	1992	560
Baltic Cable	1994	600
Chandrapur-Padghe	1998	1500
SwePol	2000	600
Brazil-Argentina Interconnection 1	2000	1100

Three Gorges-Changzhou	2003	3000
Three Gorges-Guangdong	2004	3000
Norned	2008	700
Xiangjiaba-Shanghai	2010	6400
Hulunbeir-Liaoning	2010	3000
SAPEI	2011	1000
Rio Madeira	2012	3150
Jinping-Sunan	2013	7200
Jinbei-Nanjing	2017	8000
North-East Agra	2017	6000
Jiuquan-Hunan	2017	8000
Changji-Guquan	2017-2018	12000

Table 2: HVDC classic operating and planned projects.

Changji-Guguan HVDC link in China, which will start operating in 2018, is expected to be break every world record in HVDC systems in terms of system's ratings. It is the world's first 1100 kV UHVDC power link with a length of over 3000 km, and 5.5 kA in the conductors.

System	Year Commissioned	System's Capacity [MW]
Hällsjön	1997	3
Gotland	1999	50
Tjaereborg	2000	7.2
Eagle Pass	2000	36
Cross Sound Cable	2002	330
Troll A 1&2	2005	88
Estlink	2006	350
Valhall	2011	78
East West Interconnector	2012	500
Mackinac	2014	200
DolWin1	2015	800
Nordbalt	2015	700
DolWin2	2015	900
Maritme Link	2017	500
Caithness Moray HVDC Link	2018	1200
Johan Sverdrup	2019	100
Kriegers Flak Combined Grid Solutions (KF CGS) HVDC	2019	410
IFA2 HVDC transmission link	2020	1000
Nordlink	2020	1400
NSL	2021	1400

Table 3: HVDC light operating and planned projects.

Chapter 2: HVDC Systems

• HVDC System Components

Each HVDC system consists of at least two terminals and a DC line between them, plenty components can be found in each terminal (converter station) as shown in figure 1. The main components of HVDC system take into account the used conversion technique and the nominal DC voltage. The main components are [6] [7] [8]:

1. The Converters: typically, they constitute of one or more thyristor bridges where each bridge consists of six thyristor valves, which based on the system's size contain numerous individual thyristors.
2. Converter Transformers: there are special types of transformers that designed to withstand high harmonics currents and voltage stress. Also, they will have tap changers to enable the optimization of HVDC operations. It's preferred to connect the transformer in a (WYE-DELTA) connection where the Delta is connected to the DC side in order to eliminate the zero sequence current I_0.
3. Smoothing Reactor: used to protect the converters from overvoltage stress. It prevent step impulsive waves caused by DC fault responses, commutation failure, and dynamic stability. Furthermore, it can be used to smooth the ripples of DC.
4. Reactive Power Compensation: Reactive power demand differ according to the DC power level. Line Commutating converters require capacitive reactive power from the AC system, which is around 50% of the converter's rating.
5. Filters: most HVDC systems use passive AC shunt filters are to satisfy the AC system regarding the harmonics. Moreover, based on the filter design, it supplies part of the reactive power demand as they inject MVAr to the system.
6. DC Capacitors: in addition to AC harmonics, DC voltage and current have harmonics due to the PWM technology in VSC systems, so DC capacitors get rid of the current and voltage ripples.
7. Communication and Control: in order to maintain a stable HVDC system, each terminal will have a control system over its components as well as a well established communication link between the terminals.

8. AC Circuit Breakers: VSC converter cannot interrupt the fault current Therefore the AC CBs are used to disconnect the HVDC system to stop feeding it from the AC side.

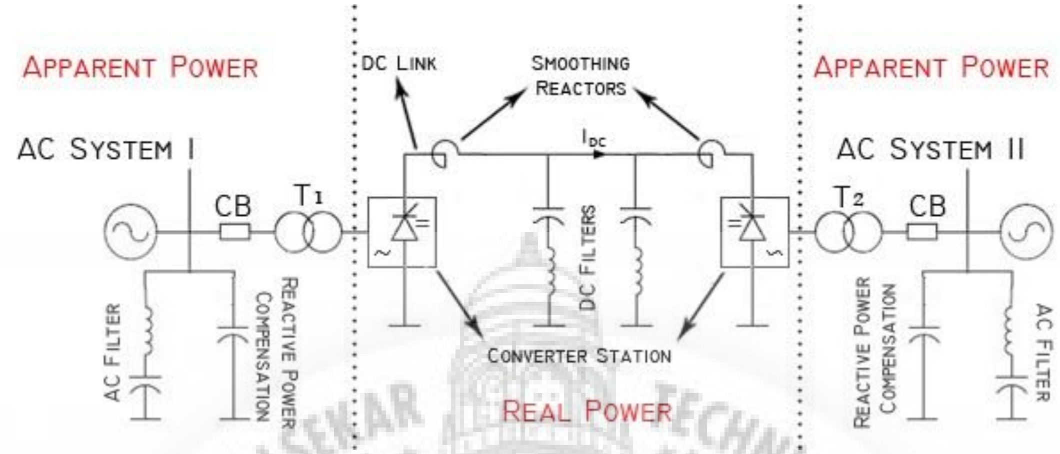

Figure 1: Block diagram of HVDC main components.

- ## HVDC Transmission Configuration

HVDC Transmission systems can be categorized into 1) two terminals and 2) multi-terminal transmission systems. These types differ according to the HVDC application. Figure 2 presents the different HVDC configuration schemes [6].

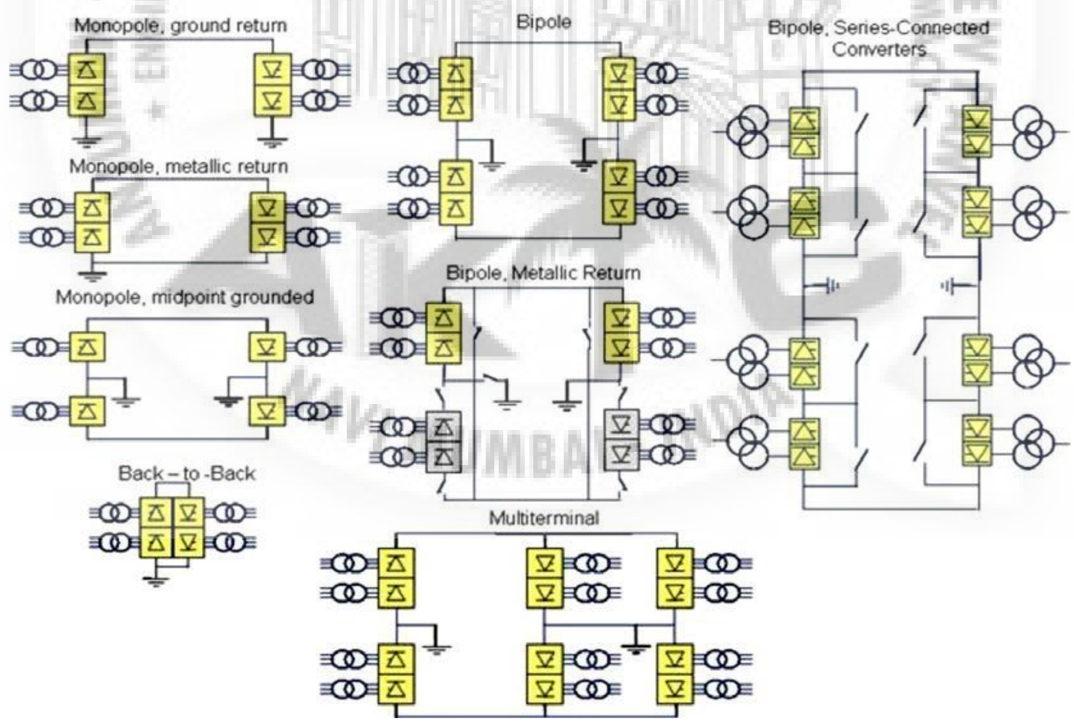

Figure 2: HVDC configuration schemes.

I. Two Terminals HVDC:

HVDC systems are divided into transmission systems and interconnection systems, where the HVDC transmission systems can be either Monopolar or Bipolar. In the two terminal type there will be two converter stations in the transmission system, where one will act as a rectifier while the other will act as an inverter. Both stations have the same circuit configuration and equipment's. However, they may differ in the matter of AC filter design and reactive power compensation [7]. There are three different configurations which are [4]:

1. Monopolar:
They are the simplest and least expensive system since only one cable is needed to connect both ends of the converter stations "rectifier & inverter". They have been used with low voltage electrode lines and sea electrodes to carry the return current or a dedicated cable can be employed. Monopolar HVDC is typically used for smaller systems

2. Bipolar:
It is a combination of 2 poles which share a common ground or return. This gives two independent circuits each with half of the system's capability; meaning that it can operate at half power if one DC cable is out of service and ground return would be used for ground current. It's highly preferred in case of frequent single pole failure as half of the power may still available.

3. Back-to-Back:
From the expression itself, it indicates that both the rectifier and inverter are located in the same site linked via a short DC link, and might need a smoothing reactor for the case of DC line fault. They are used to provide interconnection and controllable power transfer between two AC Asynchronous networks.
As the DC link is short, Back to Back systems are designed at low voltage in order to reduce the station's cost

II. Multi Terminals HVDC:

Multi-terminal HVDC transmission systems are used to connect several AC systems or to divide an AC system to multiple isolated subsystems. In this configuration, there are more than two sets of converter stations, which can be connected in series or parallel as shown in figure 3.

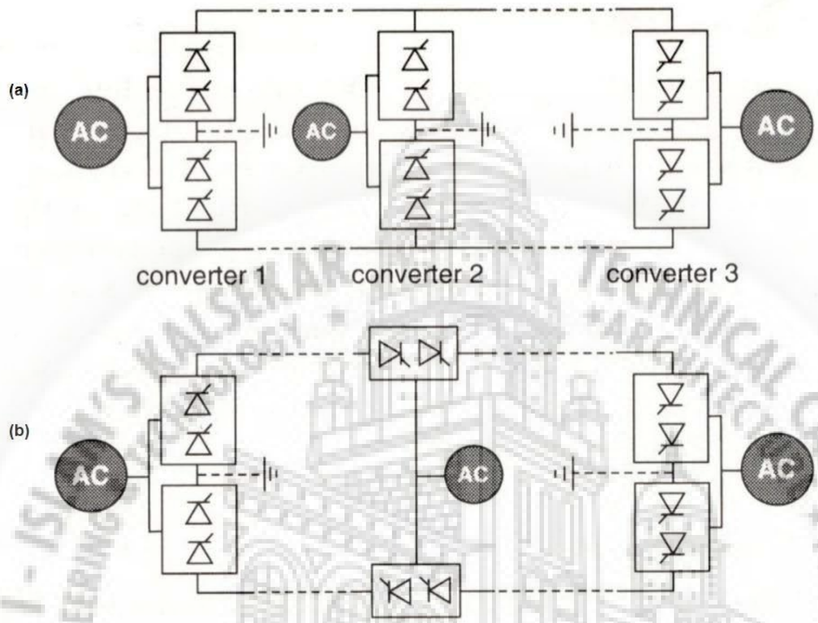

Figure 3: parallel (a) and series (b) connected configurations.

In both parallel and series connections, the regulation and distribution of active power depend on the direct voltage variation which can be maintained by controlling the firing angle or the transformer tap-changer [7].

Chapter 3: HVDC Converter Station

• Line Commutated Converter

Most HVDC systems that are in service now are of the LCC types [6], also referred as Current Source Converter CSC or HVDC Classic. It is a thyristor based technology where the mercury arc valves are replaced with thyristor valves, and the converter's commutation is done by the AC system itself. The thyristors are a silicon semiconductor devices with four layers of N and P type, acting as a bi-stable switches, and is triggered into the on state by applying a pulse of positive gate. Once the thyristors are on, they cannot be turned off by the gate signal itself, but only when the anode current tries to go negative and the current will therefore go to zero and turn the thyristor off [9], this will limit the LCC active and reactive power control. Due to the thyristors high ratings, the LCC technology is well established for high power transmission with robust voltage and power levels among all other converter technologies [10].

The converter absorbs reactive power (50% ~ 60% of the transmitted active power) from the surrounding systems resulting low order harmonics generation. So passive filters and reactive compensation units must be provided to maintain stable performance [11]. However, when connected to weak AC system, converter commutation failure may occur. Therefore, additional commutating capacitor will be needed to operate the converter.

• Voltage Source Converter

Voltage Source Converters VSC, also known as Self Commutated Converter or HVDC Light, has been in use since 1997 with the start of Hällsjön Project, Sweden, with total power of 3MW, 10 kV DC voltage level. The losses back then were around 3% per converter station [12].

HVDC VSC uses self commutating switches, typically insulated gate bipolar transistor IGBT, or gate turn-off thyristors GTO The development of VSC technology focused on reducing the converter losses and increasing the voltage and power levels. These self commutation devices have the ability to turn on or off at any time independent of the AC system. Thus allowing the application of high frequency pulse width modulation techniques PWM.

This difference in construction offers many advantages over HVDC LCC., these advantages can be summarized as follows [6] [8] [9]:

1. Due to the usage of self commutating devices, VSC will avert the system from commutation failures.

2. VSC doesn't require reactive power compensators and have independent and full control over the active and reactive power. This will lead to a better system's stability and enhance the market transactions and power trading.
3. Harmonics level are at higher frequencies and as a result the filter size, losses and cost is lower.
4. VSC has the ability to support weak AC systems when there is no active power being transmitted.
5. Instantaneous power flow reversal without the need of reversing the voltage polarities, thus lowering the cables cross section.
6. Excellent response to AC faults and black start capability.

Despite the VSC advantages and due to the IGBT relatively lower ratings and the higher converter losses, HVDC VSC has not been able to make much edge over LCC. Recently, a lot of research is being done to overcome these limitations. The main VSC disadvantages are summarized as follows [8]:

1. Increased losses in the converter due to the high frequency switching losses.
2. Higher costs than LCC converters as they require much more semiconductor devices to withstand the voltage and power levels.
3. Larger footprint as the IGBT's have lower power and current overloading capabilities than thyristors.
4. Require very fast AC Circuit Breakers in the case of DC faults as the VSC converter acts like an uncontrolled thyristor and feeds the fault.

Table 4 summarizes the difference and presents a comparison between HVDC LCC and VSC technologies.

	LCC	VSC
Switching device	Thyristors	IGBT
Switching Losses	No Losses	Low
Station Size	Large	Small (around 50% of LCC)
Reactive Power Demand	High (around 50%)	Not required
Active and Reactive Power Control	Limited Control	Continuous and inherent
Power Levels	Very High (up to 12 GW)	Moderate (up to 1400 MW)
AC Filters	Large and expensive	No need
DC Filters	Might be used	No need
DC Cable	Expensive and high cross sectional areas.	Less expensive and smaller
Commutation Failure	Present for AC disturbances	No
AC Fault-Ride Through	Possible	Excellent and fast

Table 4: General comparison between HVDC LCC and VSC.

- Converter Station Losses

The Losses in any HVDC system will basically be divided into converter station losses and DC cables losses. HVDC converter stations consist of a number of various equipments, each of them contribute to the converter's total losses, with different method to precisely determine the losses in each. However, it has become an accepted practice to sum the losses from each and every component in the converter station as calculated from computed calculations [15].

In HVDC transmission systems, the converter is responsible for the greatest amount of losses, nearly 80% of the system's overall losses [16]. The station losses depend on the system size, the voltage level, and the configuration. Typically, HVDC LCC converter station losses vary between 0.5-1% of the rated power transfer. Figure 4 shows a typical LCC converter station losses [8].

The main converter station losses for both LCC and VSC can be categorized as follows [17]:

1. Switching Losses
2. Semiconductor conduction losses.
3. Converter valves.
4. DC capacitor/reactor Losses.
5. Turn-on and off losses.
6. AC harmonic filters.

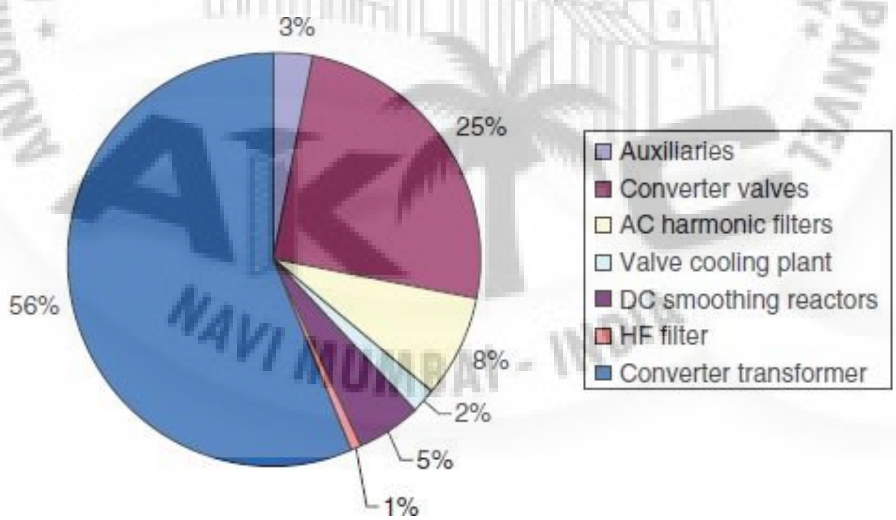

Figure 4: Breakdown of LCC converter station losses.

- PWM

Pulse Width Modulation (PWM) is a voltage signal that is used to control power electronics circuits. This can be achieved by controlling the duty cycle of the switch at high frequency and high efficiency switching procedure. PWM generated signals can be formed into various waveforms and duty cycles depending on the generation technique and the width of the input pulse. A standard PWM generation method, known as carrier-based PWM, compares a reference DC control voltage to a triangular wave (carrier) as shown in figure 5.

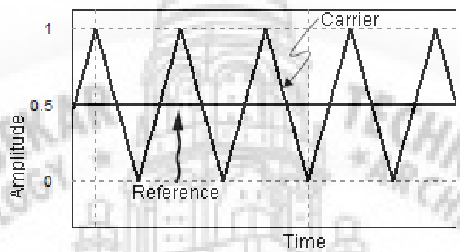

Figure 5: PWM modulation with 50% duty cycle.

Recently, most VSC HVDC systems use the IGBT as the base of their converters. As these modern devices can be turned on and off depending on the control signal, PWM is one of the best control techniques to maintain switching in VSC HVDC systems [18]. PWM offers many benefits to the HVDC system, these benefits are summarized as follows [19]:

1. Enlarged operation region due to the independent control of power flow as shown in figure 6, along with rapid voltage control over the converter bus.

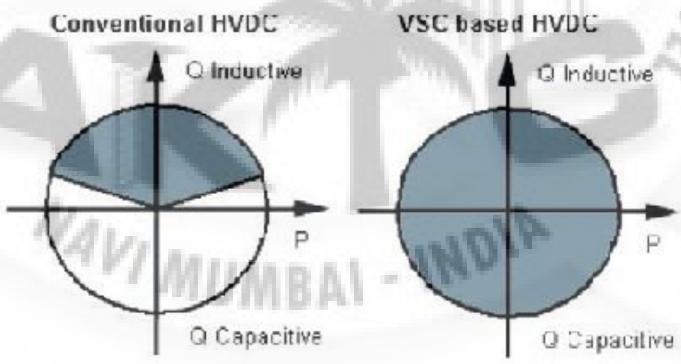

Figure 6: active and reactive power control among different HVDC systems.

2. Easiness and simplicity of reversing the power flow.
3. Supply remote loads and enable the grid connection of distributed generation or renewable energy sources.
4. Offers a solution for harmonic filters by reducing of current and voltage harmonics.
5. Elimination of commutation failures.

Chapter 4: HVDC Overhead Lines & Cables

- HVDC Overhead Lines

HVAC has been used for high power transmission with three cables, one for each phase, where only one pair of cables is needed for HVDC. In comparison with HVAC, these HVDC cables have the ability to carry power with two conductors as AC lines with three conductors of the same size [20]. As well, they have lower weight and losses at the same power level. For a given cable cross section, the line losses with HVDC is nearly about half of the losses of HVAC [21]. Furthermore, monopolar HVDC lines costs are about 45 percent less than the AC links as the DC links require only two thirds of the cables insulators [20].

HVDC is well fit for long distance transmission where HVAC need extra design considerations as a result of high charging current in the cable [4] [19]. This extremely limits the usage of HVAC especially at high power levels, putting HVDC to be the only possible solution. HVAC suffers from various limitations at overhead transmission links or underground cables, these limitations can be summarized as follows [22]:

1. Thermal Limits: The amount of power that can be sent through an AC link is limited as a result of the conductor's thermal limits. These limits increase with increasing the line's length, resulting in an increase in insulation levels and the transformer's cost.

2. Charging Current: HVAC suffers from capacity drop with long distances as shown in figure 7. This is a result of the cable's reactive components and the high value of the charging current which increases with the cable length.

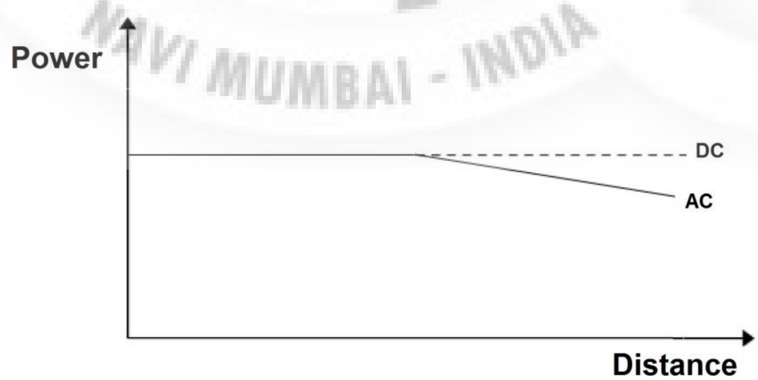

Figure 7: Power capacity for HVAC & HVDC versus distance.

3. Corona Losses: considered to be the major system's loss along with the copper losses. Unclean climate conditions dramatically increase the corona losses which may result in a grid failure in case of bad weather.

4. Skin Effect: The electric current tends to flow through the skin of the conductor, causing the effective resistance of the conductor to increase with the system's fundamental frequency and therefore increasing the losses.

5. Ferranti Effect: it is a rise in the voltage at the sending end of the line due to the absence of the load or with a very light load. This effect increases with the link's length and voltage level. It can be much more crucial at underground cables even in short distances.

6. Economics of Transmission: HVDC requires less right of way (ROW), simpler and cheaper towers and reduced conductor and insulation costs. The power losses are also reduced as fewer conductors are used in HVDC, not to mention the absence of the skin effect in DC links.

- ## Under Ground Cables and Break-even Distance

The concept of Break-even distance arises whenever transmission systems are discussed, it implies that the savings from HVDC lines cost overweight the initial high cost of converter station. For overhead lines, the break-even distance is in the range of 500-800 km while for underground cables it's around 20-40 Km [23]. the variation of break-even distance is due to a number of other factors as the voltage/power levels, elements cost, Right of way (ROW) cost, and operational costs. Figure 8 shows comparison between AC and DC links costs where station costs, line costs, and the value of losses is considered [8].

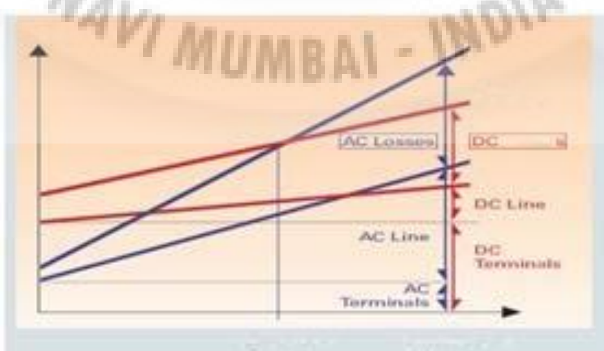

Figure 8: Cost comparison and Break-even distance for HVDC & HVAC.

As a result of different market demands and due to the difference of applications for both HVDC technologies, LCC has been used for overhead transmission lines while VSC is used for submarine and underground cables [24].

The most common cable technologies that have been developed and used in HVDC systems are [8]:

1. Mass impregnated (MI) cables.
2. Low pressure oil filled (LPOF) cables.
3. Extruded cross linked polyethylene (XLPE) cables.

As for the structure difference between AC and DC extruded cables, it can be neglected and hardly detected visually, and the same structural components are required to enable power transmission using HVDC and HVAC extruded cables [21].

Extruded polyethylene (XLPE) cables have showed significant advantages over other HVDC cable types, and recently, have seen a very fast development. They are less expensive compared to other HVDC cable types. Their construction is simpler as they allow a lower bending radius, easily transported and installed, with faster manufacturing process and more environmental benefits [26]. Figure 9 shows a cross sectional view of XLPE HVDC cable.

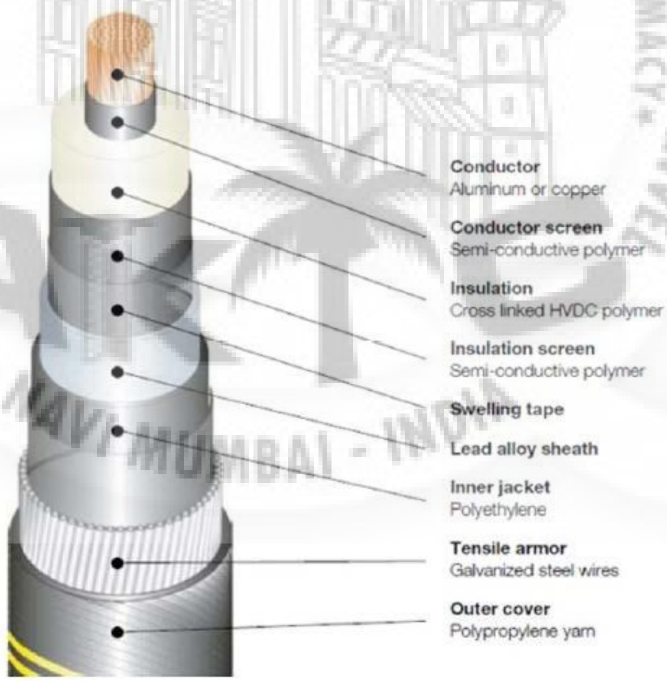

Figure 9: Cross sectional view of XLPE cable, ABB.

Chapter 5: HVDC Protection

- HVDC Faults

Despite of all HVDC advantages, it doesn't have the availability of fast, reliable, and efficient Circuit Breakers (CB). The problem is that DC doesn't have natural zeros which leads to a more complicated protection system. As well, the amount of energy that needs to be damped during arc in case of DC fault is very high compared to one with AC fault [26]. Furthermore, HVDC VSC converter acts like an uncontrolled thyristor in case of DC fault and feeds the faulted area [8].

When a fault occurs on the DC side of VSC-HVDC system, the IGBT's lose control of the power flow and the freewheeling diodes feed the fault [27]. The different DC faults that may occur are [6] [7] [27] :

1. Positive/Negative Line to Ground (Line to Ground):
   Both Line to Ground faults occur when one of the lines gets shorted to the ground, or get struck by lightning in the case of overhead lines. It may occur in case of objects falling onto the line. Furthermore, cable insulation can cause line faults due to improper installation.

2. Positive Line to Negative Line (Line to Line):
   Besides the previous Line to Ground fault reasons that also may lead to a Line to Line fault, Line to Line fault can occur due to switching fault, which will cause the positive bus to short the negative bus inside the converter.

3. Overcurrent (OC):
   Overcurrent protection is necessary in case of line faults where the fault current is almost twice the full rated current. Another essential use of OC protection is in case of overloading the HVDC system. Mainly, it appears in multi-terminal HVDC systems as one of the terminals is out due to a fault.

4. Overvoltage (OV):
   Commonly, Overvoltage is considered an issue when Line to Ground faults occur, where the DC link capacitor discharges immediately, causing the voltage on the non-faulted pole to increase to twice the rated voltage. Moreover, Overvoltage can occur in the case of inverter/converter loss as it charges the DC link capacitors causing voltage rises.

- HVDC Protection Devices

DC lines can be protected using conventional AC devices; as CB or Fuses or DC devices; as IGBT CB, Converter Embedded Devices. Both protection devices have various features, AC devices have shorter lead time, they are less expensive, and most importantly mature & familiar with wide previous operation experience [27]. On the other hand, DC devices act faster than AC and allow unfaulted lines to remain operating but it's a new technology with limited operation experience. Different protection devices are discussed in [27] and summarized as follows:

I. **Circuit Breakers** are the most economical device to protect DC systems. They are common, available and can be replaced and repaired in a short time. However, their interruption time can be a restriction as they need a long time to interrupt faults. The best interruption time for conventional Circuit Breakers is two cycles. DC capacitor's voltage & line current will fed in a standard over current/voltage relay to sense any unusual state. When a fault occurs, the capacitor discharges and results the voltage to decrease and the line current to increase over the rated value. The relay will sense one of these conditions and trip the breaker until the fault is cleared and the line is back to normal operation.

Another relay that can be used to protect the converter is the differential relay. The main function of the differential relay, as shown in figure 10, is to measure the current before and after the converter and trip the AC breaker if both of the currents don't match.

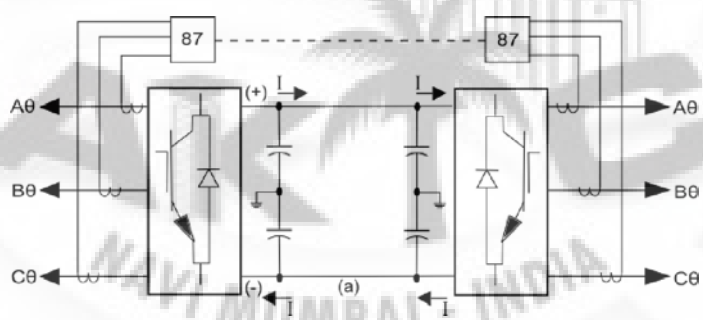

Figure 10: Differential relay scheme for HVDC systems.

II. **Fuses** are thermal devices that can only be used once over its life time, they interrupt the fault whenever it occurs regardless the state of the fault whether it is permanent or temporary. The main throwback in using fuses for DC protection is that the impossibility of restoring the line without physical change of the fuse after the fault is cleared. Therefore, fuses are not widely used as a prime device for protection system for the HVDC but as a backup for other protection devices failure.

III. **IGBT CB** rely on the IGBT blocking capability, it consists of solid state device alongside with anti-parallel diode. This configuration makes current flow through the IGBT CB unidirectional; this will result in lack of protection coverage for the system's components. Figure 11 shows different scenarios for IGBT CB blocking capability used in monopolar lines.

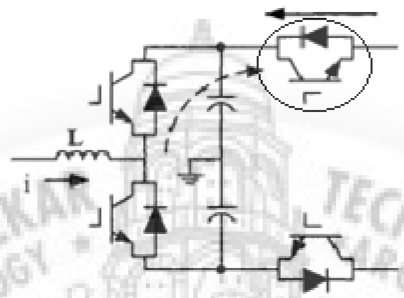

Figure 11: IGBT CB blocking capability.

When a fault occurs in the DC line, the IGBT-CB "represented in the circle" will block the fault current and protect the converter station. However, when the fault occurs in the station itself, the anti-parallel diode will conduct and allow the fault current to flow. Therefore, in this scenario the protection of the system will rely on the converter's IGBT blocking capability.

For two terminal systems, one IGBT CB will be connected to each terminal to block the current and isolate the faulted line. This will be synchronized with a fast acting DC switch to sense the line's voltage and current then determine the system's state in order to trip the breaker. This is considered to be an advantage for IGBT CB, where in case of a ground fault the system will continue running using one terminal to transmit the power "monopolar configuration". As well, this IGBT CB can operate in a fewer time compared to AC devices.

IV. **Converter Embedded Devices** are active protection devices, such as Emitter Turn Off (ETO), that are installed within the VSC converter, which will reduce the station size as well as its cost. This type of active devices has higher voltage and current ratings, and will replace the IGBT to maintain switching and protection. As a result, a redesign procedure is a required.

Figure 12 shows an illustration of ETO based converter. In normal operation, the X leg of the ETO will conduct and take on the switching process where the Y leg will act as an anti-parallel diode. In case of fault, the X leg will be blocked and the Y leg will feed the fault until the identifying the state of the fault, if it’s permanent the Y leg will be turned off.

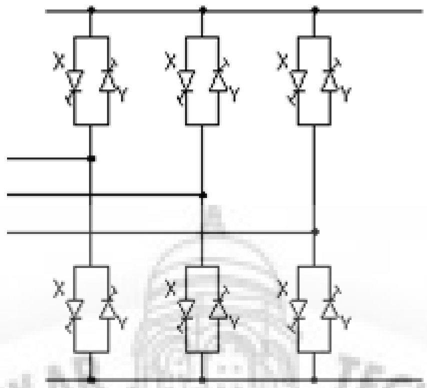

Figure 12: ETO based VSC.

Currently, many protection methods has replaced the typical IGBT CB. One of the solutions can be done by implementing an additional circuit that presents an artificial zero in case of fault [26]. Another method is a combinational circuit that uses switches and press-pack thyristors to protect the converter from failures as it can withstand higher current ratings[28].

One more method is proposed and explained in [29] for Multi Terminal DC systems (MTDC) is the handshake method, which rely in the use of VSC side AC CBs and fast DC switches to clear and isolate the DC line faults.

Chapter 6: System Design

- AC system

Power systems modeling can be done by representing the system's components by either a steady state model (Static models), or a changing models (Dynamic models). This study facilitates the steady state of the electrical distribution network, which may represent a good approach to understand the system behavior under different load conditions.

The electrical system of the main campus at The German Jordanian University consists of different 6 loads, each one is connected via an 11-0.4 kV transformer, all the transformer are then fed from the main station's 33-11 kV transformer via 11kV XLPE standard copper conductors, to the local distribution grid JEPCO. Table 5 shows the system's overall electrical data.

Transformers		
Voltage Level	Quantity	Ratings
11-0.4 kV Step Down Transformer	6	1500 kVA
33-11 kV Step Down Transformer	1	10 MVA
Cables		
Cable Type	Length	
11 kV XLPE Standard Aluminum Conductor	3 Km	
0.4 kV XLPE/AWA/PVC Standard Copper Conductor	20 Km	
Busses		
Voltage Level	Quantity	
33 kV Bus	1	
11 kV Bus	12	
0.4 kV Bus	6	

Table 5: GJU electrical components' electrical data.

The existed AC system was as shown in figure 13.

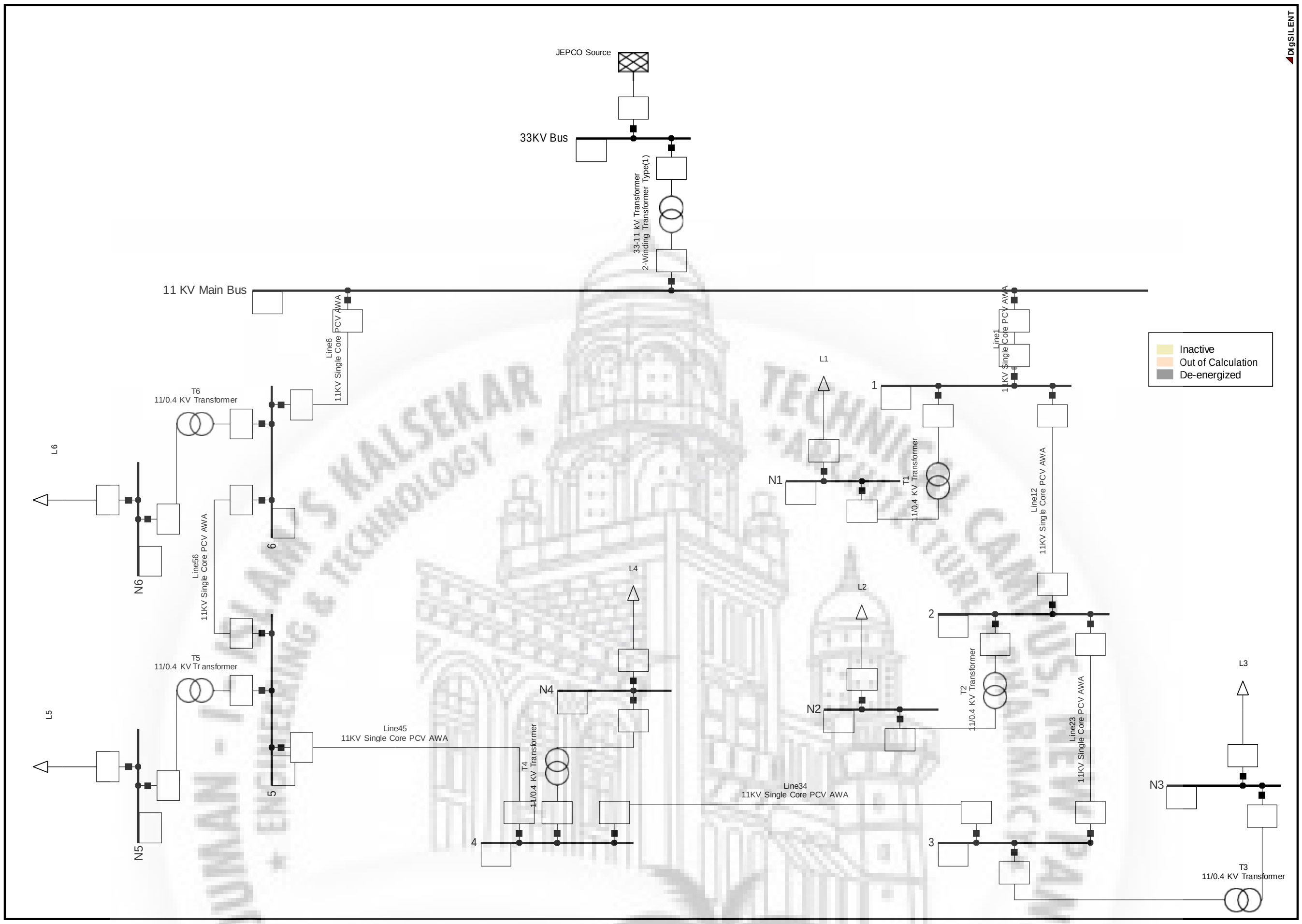

Figure 13: AC system

- Conversion from AC to DC lines

As AC lines suffer from various limitations which made HVDC to become attractive due to its wide benefits to the system performance. For bulk power transmission, increasing the system's overall capacity is a challenge as it require costly line upgrades, series compensation or installing FACT devices. For power trading, AC systems control are very complicated due to the existence of frequency and phase angels and the AC load flow is unpredicted. However, DC control is much simpler as the DC is a linear system. Furthermore, VSC technologies can fully control both active and reactive power flows which increases the system flexibility for adding DC connection points, and improves the voltage stability of the AC system [30].

• DC System

With maintaining the same AC system parameters, the design of the DC system is shown in figure 14. A main 6 pulse AC-DC converter station was added to the campus so that all the 6 loads will have approximately equal distance, thus lowering the cables requirement.

To meet the AC system requirements, 6 inverters were added at each load along with a smoothing reactor. Furthermore, AC harmonics filters, Reactive power compensators were added to maintain the system stable performance and meet the Jordanian grid standards for the THD and the PF [31].

Detailed description of the design of the main DC system components is discussed below.

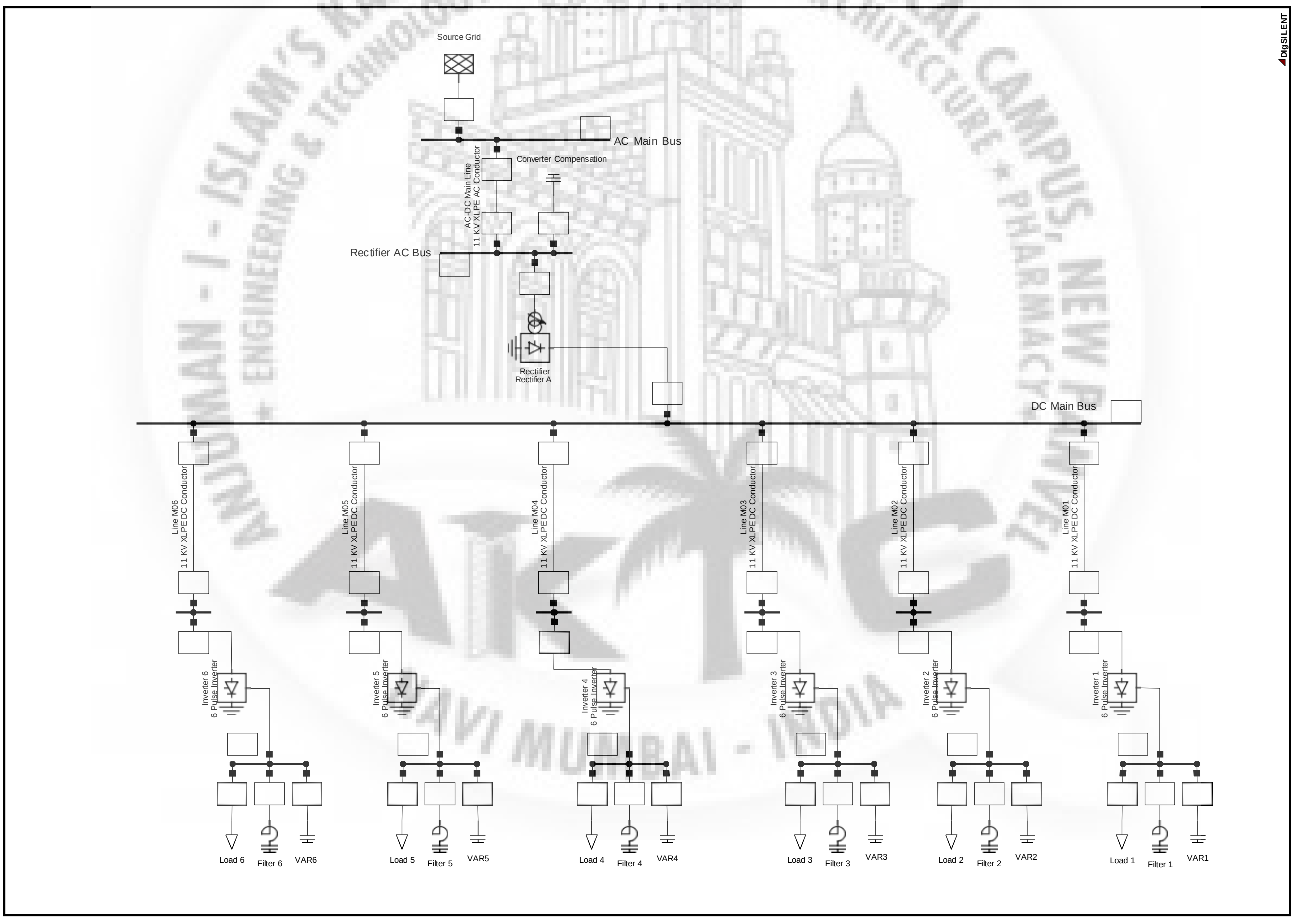

Figure 14: Proposed DC network.

I. Six Pulse Line Commutating Converter

The campus is fed from a 33/11 kV transformer as shown in figure 15. The optimum AC voltage to be connected through the AC side of the converter station is 11kV; as the price of the converter is relatively high for the 33kV AC voltage level and the current will be relatively higher if the connection point was through the 0.4 kV AC voltage level, thus increasing the line losses.

Figure 15 shows the main components of a six pulse line commutating converter (LCC), the converter scheme was designed using PSIM V9.0. The desired DC output voltage will be calculated as follows:

$$V_{DC} = \frac{s * q}{\pi} * \sin(\frac{\pi}{q}) * \frac{\sqrt{2}}{\sqrt{3}} * \sin\ (\alpha) * V_{AC} = 1.35 * cos\,(\alpha) * V_{AC}$$

where:

V_{DC} : The DC output voltage of the converter.

V_{AC} : The line to line AC input voltage of the converter.

α : The firing (ignition) angle; Alpha.

s=2, q=3.

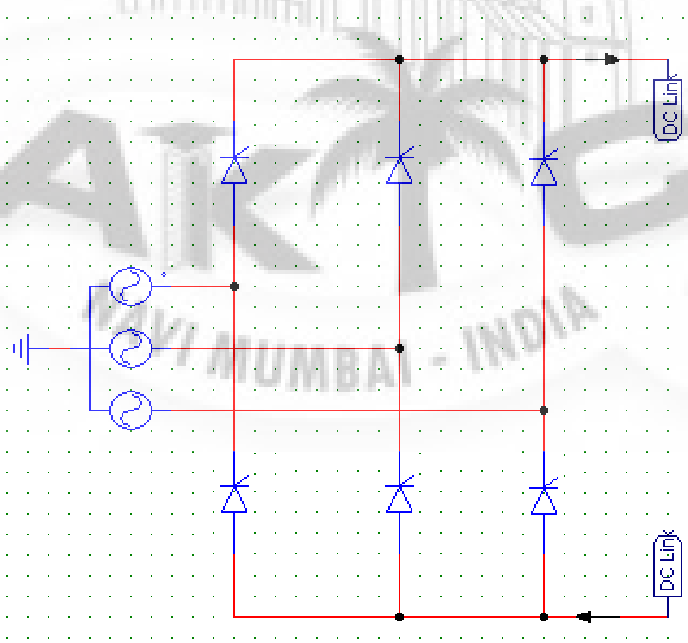

Figure 15: 6 Pulse LCC circuit.

II. DC Cables

Using the same AC cables would be acceptable in this case as the DC content of the cable rated current (rms value) would be nearly 70% of the AC rated current value. The 630 mm^2 single core armoured 11 kV XLPE standard copper conductor, shown in figure 16, has a maximum current rating of 760 Amps while being laid in ground, which means that it can withstand nearly 540 DC Amps. Typically, shifting from AC to DC wouldn't require changing the conductors type rather than upgrading the insulation [8]. It's worth to mention that the DC insulation level is only 87% for the same AC line [20], but the upgrading of the insulation type is done so that the line can operate with DC current.

Figure 16: Single core armoured 11 kV XLPE Copper conductor.

III. HP and LP Filters

At each HVDC terminal there will be a passive AC filter to mitigate the total harmonic distortion to an accepted limit, the maximum limit is specified by the Jordanian Grid Code by 6.5% [31]. most LCC systems use shunt filters but some also use a combination of both shunt and series filters. HP and LP filters are designed so that the gain of the filter is at its lowest value at low order harmonics. Furthermore, they also support part of the reactive power requirement of the system [7]. These harmonics are found in the system due to the switching procedure in the converter stations (Thyristors or IGBTs).

The design of HP and LP passive filters was done on PSIM V9.0, and their frequency response are shown in figure 17 and 18.

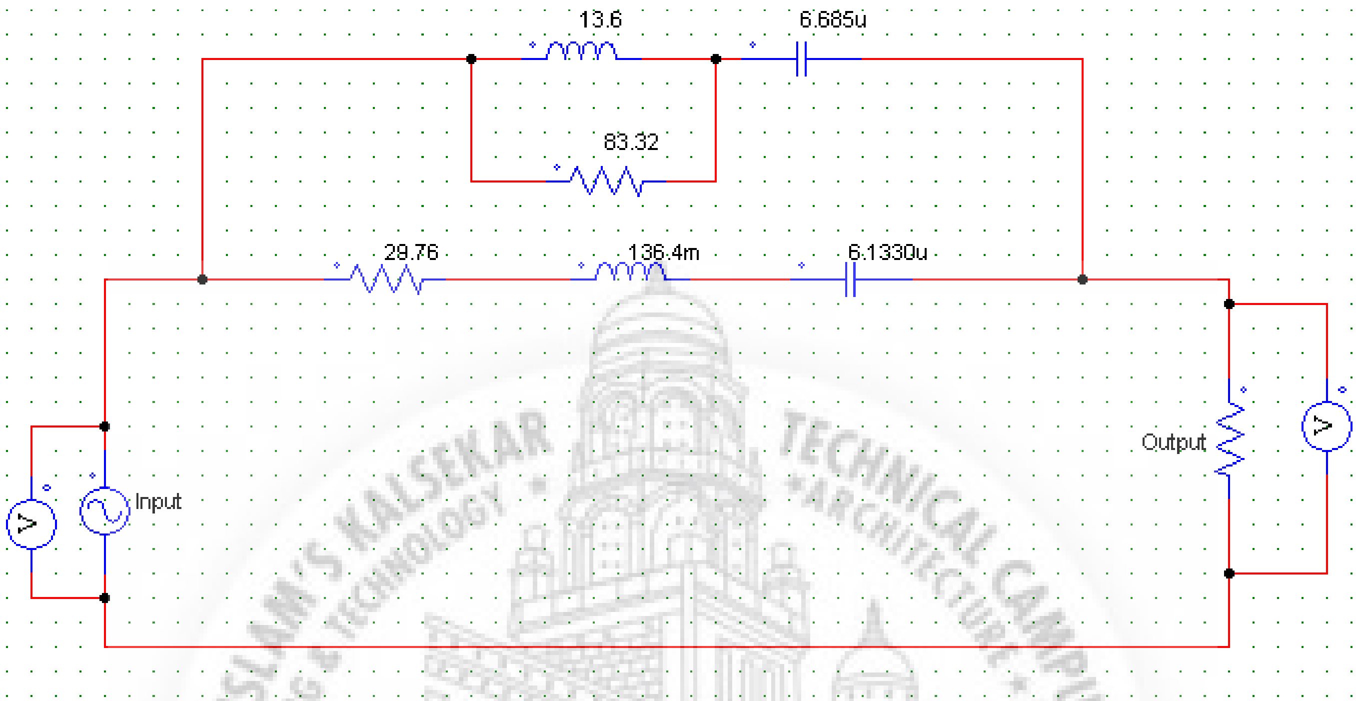

Figure 17: High pass and RLC damped filters design.

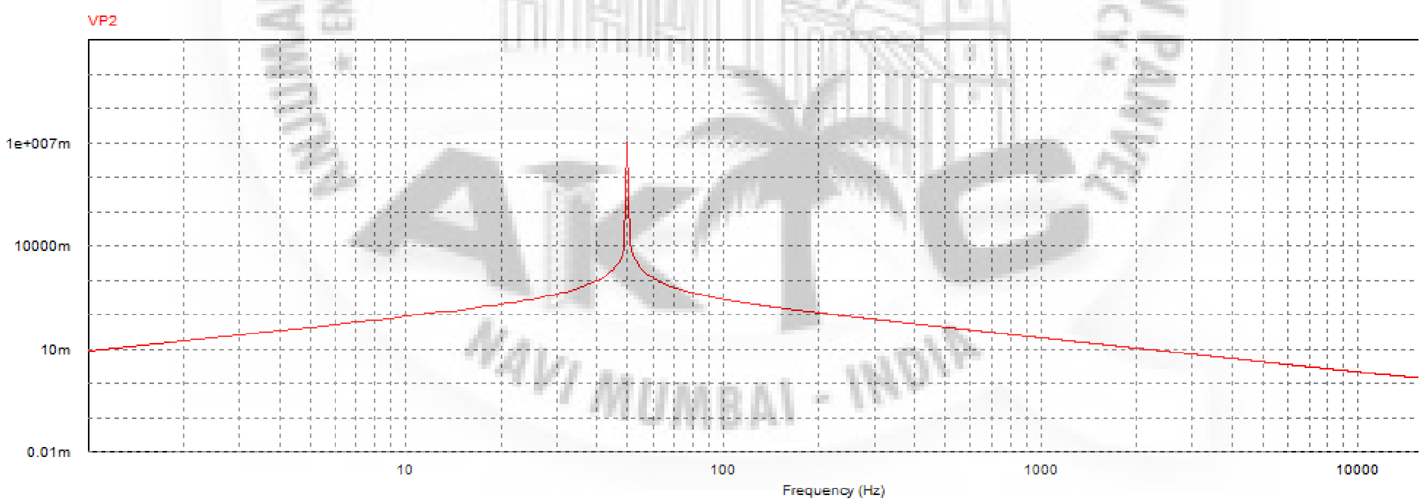

Figure 18: Frequency response of the designed filters.

IV. Reactive Power Compensation

AC voltage depends on the active and reactive power of the converter, so in order to maintain the system stability and minimize the voltage fluctuations, the reactive power consumption of the converter must be covered. This reactive power consumption is a result of commutance reactance in the thyristors. Reactive power compensators provided several benefits to the system such as: meeting the 0.9 power factor requirement of the Jordanian Grid Code [31] as shown in figure 19 , balancing the drawn active power, eliminating current harmonics, and most importantly supporting the voltage and decreasing the voltage sags hence improving the stability.

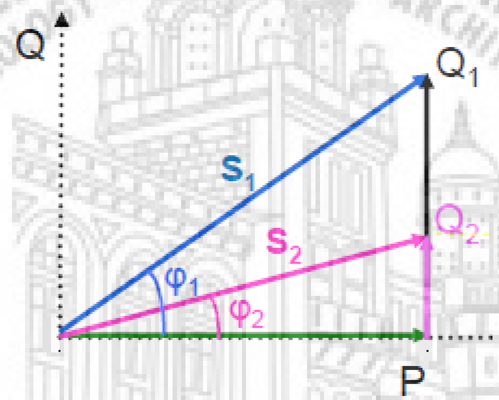

Figure 19: Power Factor improvement with the installation of VAR compensators.

Reactive Power Compensators can be done using several techniques [7], such as Capacitor Banks, Static VAR Compensators, or Synchronous Compensators. These different techniques differ based on the HVDC application, the amount of compensation, speed of reactive power regulating, and the strength of AC system.

The following equation is used to calculate the amount of compensation required by the converter:

$$QQ = 2\pi\pi\pi * V^2 * C$$

For each converter in the system, the amount of reactive power compensation was 0.3 MVar, and 0.5 MVar for the rectifier.

Table 6 shows the equivalent DC system electrical components.

Converter Station		
Voltage Level	Quantity	Ratings
33 kV	1	10 MVA
11 kV	6	1500 kVA
Cables		
Cable Type	Length	
11 kV XLPE Standard Aluminum Conductor	1.2 Km	
0.4 kV XLPE/AWA/PVC Standard Copper Conductor	20 Km	
Busses		
Voltage Level	Quantity	
33 AC kV Bus	1	
14 DC kV Bus	1	
0.4 AC kV Bus	6	
Reactive Power Compensation		
Ratings	Quantity	
0.1 Mvar Capacitor Bank	6	
Filters		
Type	Quantity	
HP Damped Filter	7	
RLC Filter	7	

Table 6: Proposed DC electrical components

Chapter 7: Conclusion, Recommendations and Future Work

The load flow analysis of both of the AC and DC systems showed significant difference in the losses. As it can be shown from table 8, the knee point; where this difference started to become larger is nearly around 70% of the nominal loading value; as the current started to become higher. The cables losses can be computed by the following equation:

$$S = I^2 * Z$$

Where:

S : The complex power losses in MVA.

I : The current flowing in the conductor.

Z : The impedance of the conductor.

Conductors impedance contains real (resistive) and imaginary (reactance) components, these impedance values are used to calculate voltage drop, power flow, and line losses. Typically, the reactance part of the impedance dominates the impedance of the conductor [32]. So in the case of DC network, the imaginary components (inductive part) will not be considered as a part of the conductor as the inductors will act as a short circuit for DC current. Moreover, this will eliminate the reactive power losses (Q) and thus reducing the system's overall losses.

The losses in the DC system were nearly 5% of the losses at the AC system at the same power transfer, this is a result of three key parameters which are:

1. The DC losses are only real power losses (active) and the conductors have a relatively low resistance values compared to the reactance values.
2. The current in each DC line (94 A) were about 70% of those at AC lines (126 A) at the same power level.
3. The existence of high reactive power losses in the AC line, where it's zero Mvar in the DC lines.

As the university is still developing, increasing the load in the future will lead to a saving percentage of around 9%.

Due to the lack of information regarding the DC network models and prices, cost analysis study nor contingency analysis weren't implemented in this research.

As mentioned earlier, the DC current was nearly 70% of the AC current, this will significantly reduce the amount of insulation level for the conductors, and thus reducing the cables cost.

Regarding the harmonics, DC distribution networks will cancel out the effect of harmonics as there're no alternating current in the system, and used filters will eliminate the switching harmonics. Therefore, this will increase the potential of installing solar PV power stations at the campus and charging stations without affecting the grid nor needing high cost harmonics filters; leading to a more stable and reliable system.

However, future work can be made concerning the short circuit analysis, contingency analysis, and cost analysis to ensure and clarify the benefits and the feasibility of using a DC distribution grid for the customers and the grid operators.

This technology is under continuous development, the author believes that it will enhance the integration of renewable energy resources for low scale users, and as most commercial applications are DC, this will make the DC distribution networks the backbone of the future grids. Moreover, it will open up a wide research area to develop power electronics devices for medium voltage applications.

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