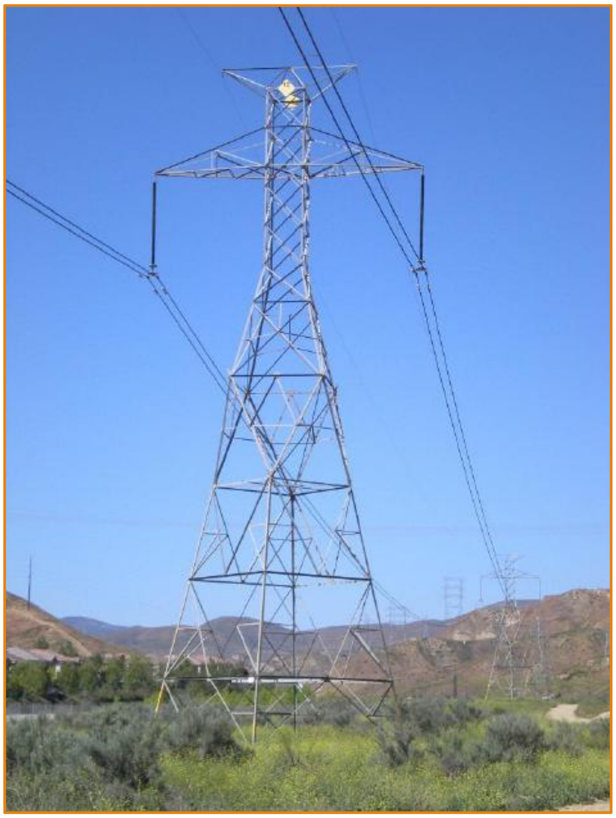

HVDC SYSTEMS

A brief report on the benefits, history and future of High Voltage Direct Current (HVDC) Systems

Submitted in part fulfilment of the requirements for the completion of a Summer Internship at the PowerGrid Corporation of India Limited (PGCIL) during the summer of 2015.

Abhideep Dasgupta

Bachelor of Science, Electrical Engineering

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NO OBJECTION CERTIFICATE

It is certified that **Mr. Abhideep Dasgupta** of the **University of Illinois at Urbana-Champaign, Illinois, U.S.A.** has completed his summer training at **PowerGrid Corporation of India Limited**, Corporate Office, Gurgaon. During his Training, he visited the Badarpur Thermal Power Station (BTPS), managed by National Thermal Power Corporation (NTPC) in Badarpur, New Delhi and the offices of Larsen & Toubro (L&T) in Faridabad, Haryana, while furnishing his theoretical and practical knowledge about the organization and HVDC transmission. We have no objection to his using the content of the report for academic purposes. The contents of this report shall not be copied, modified, lend or made unauthorized use of, in any manner, without the prior consent of the company.

CERTIFICATE

This is to certify that **<u>Mr. Abhideep Dasgupta</u>** has successfully undergone summer training from 1st June, 2015 to 24th July, 2015 (for a period of 8 weeks) at the corporate office of PowerGrid Corporation of India, Gurgaon. His performance during the Training was found to be good.

x *Puneet Tyagi*

Mr. Puneet Tyagi
Asst. General Manager
(Engg – HVDC)

x *vinod k singh*

Mr. V. K. Singh
Dy. General Manager
(HRD)

SUBMISSION

I, **ABHIDEEP DASGUPTA**, student of **Electrical Engineering**, am humbly submitting the report that I have completed during the summer training I have undergone at PowerGrid Corporation of India Ltd. Work, as described in this report, is done by my own skills and study from 1st June, 2015 to 24th July 2015 under the guidance of **Mr. Puneet Tyagi, Asst. General Manager (Engineering – HVDC)** and **Mr. V. K. Singh, Dy. General Manager (HRD)**.

I certify that I have not copied the report or its any appreciable part from any other literature in contravention of academic ethics.

Date:- July 24, 2015 Signature:-

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Abhideep Dasgupta
Electrical Engineering, University of Illinois
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2 ABSTRACT

The War of Currents started more than a hundred years ago, in the 1880s. With the rising popularity of High Voltage Direct Current (HVDC) transmission lines all over the world, the question arises yet again – HVDC or HVAC? So far, we have primarily been using HVAC (High Voltage Alternate Current) or FACTS (Flexible Alternate Current Transmission Systems) technologies, as they have proved to be easier to implement and cheaper in the short run. However, can HVDC technologies replace these in the future? This report has been prepared to evaluate this question by providing a subjective opinion, while also giving a brief overview about the power sector in India.

The common belief today suggests that Smart Grids are the next big thing, the technology that will change the way we look at power systems. This report provides a contextual understanding of the advantages and concerns associated with the usage of a large scale smart grid network, along with the basic theory supporting it.

PowerGrid Corporation is the central power transmission utility in India, and is also India's largest Electric Power Transmission utility. This report also identifies the role of PowerGrid Corporation of India and suggests methods for its implementation of new technology such as HVDCs to service the current state of the power sector in India.

Overall, this report is designed to be a student's perspective on the more modern technology of HVDCs and Smart Grids, and their possible incorporation into future power projects.

3 POWER SYSTEMS IN INDIA

3.1 BRIEF OVERVIEW

The power system in India is governed wholly by the Ministry of Power. The power sector comprises of three pillars, often common worldwide. These pillars are:

- Generation
- Transmission
- Distribution

To make it easier for governance, these – especially Generation – are divided into three further sections in India, namely Central, State and Private. The Central sector constitutes around 30% of the total installed capacity, while the State sector constitutes around 40% and the Private sector constitutes around 30% of the installed capacity. As of April 2015, the total installed capacity of power generated in the country was 271,722 MW.

The PowerGrid Corporation of India (PGCIL) is responsible for the inter-state transmission of electricity and the development of the national grid. India is the sixth largest consumer of power in the world, accounting for approximately 3.4% of the world's power demand. Coincidentally, it is also the sixth largest generator of power. Due to India's large size, the role of the PowerGrid Corporation to provide power to every single inch of this land is much more difficult than one can imagine. Nevertheless, PowerGrid Corporation provides power to India at a system availability of more than 99%.

3.2 CURRENT ISSUES THAT INDIA'S POWER SECTOR IS FACING

India's power sector is growing every year, but it still faces some issues that need to be addressed. For a complete analysis of the power sector in India, a deeper understanding of its major concerns is imperative. A few of the most important concerns have been detailed below[1]. A lot of these concerns are interlinked with one another, but the sub-headings below catalog the broad concerns that we face today.

3.2.1 Losses in Power Lines

India is the seventh largest country in the world, and PowerGrid Corporation of India provides 116625ckm of electric power to every corner of this vast country. Transmission losses from these hundreds of thousands of circuit km of power lines are staggering. In 2008, these losses amounted to 28.44%, while today, they have crossed 30%.

[1] A lot of this information has been obtained from http://indianpowersector.com/home/about/

The total power loss is a sum of T&D (transmission and distribution) losses and AT&C (aggregate technical and commercial) losses. High technical losses in the system are primarily due to inadequate investments over the years for improvement of the existing system, which has resulted in unplanned extensions of the distribution lines, overloading of system elements like transformers and conductors, and lack of adequate 'reactive power' support. Commercial losses are mainly due to low metering efficiency and theft. Large power losses in the connector systems and service connections often lead to premature failure of expensive capital equipment like transformers.

These losses may be minimized by improving metering efficiency, possible addition of feedback systems, proper energy accounting and audit, and improved billing and collection efficiency. Fixing of accountability of the personnel/feeder managers may help considerably in reduction of aggregate technical and commercial losses.

3.2.2 Cross-Subsidization

A system of 'cross-subsidization' is practiced based on the consumer's ability to pay. Typically, the industrial and commercial consumers subsidize the domestic and agricultural consumers. Further, the Government has programs to provide free electricity for farmers, sometimes to gain political favor. Programs such as these have depleted the cash reserves of the government-run electricity-distribution system. As expected, this has led to a financial crippling of the distribution network and its ability to pay for power to meet the demand. In short, the country has the ability to generate enough power for its needs, but power plants refuse to operate and produce at their maximum capacity until they have been paid for the power they generate[2].

3.2.3 Lack of Energy Efficient Buildings

The residential building sector is one of the largest consumers of electricity in India. Being a rapidly developing country, urbanization in India is incessant and the growth of population results in increasing power consumption in buildings. Unfortunately, while experts express the huge potential for energy conservations in this sector, the belief still predominates among stakeholders that energy-efficient buildings are more expensive than conventional buildings; that adversely affects the "greening" of the building sector. New buildings continue to be constructed without any sign of green energy, and power demand keeps increasing.

3.2.4 Implementation Challenges

India's power sector faces various implementation challenges that hinder the process of starting up new projects and/or enhancing or reconstructing existing projects. A few of these implementation challenges include – management and execution of new projects, ensuring availability of adequate quantities and

[2] Information obtained from Employee at National Thermal Power Corporation power plant at Badarpur, Delhi.

optimal qualities of fuel, lack of initiative to develop large coal and natural gas resources available in India, acquisition of land, environmental clearances at both the state and central government levels, and training of skilled manpower to prevent talent shortages for operating latest technology plants.

3.2.5 Shortage of fuel

Despite abundant reserves of coal, India is facing a shortage of coal. The country is not producing enough to feed its power plants. Some plants do not have reserve coal supplies to last even one day of operations. India's monopoly coal producer – state-controlled Coal India – is constrained by primitive mining techniques. Poor coal transport infrastructure has exacerbated these problems. To expand its coal production capacity, Coal India needs to mine new deposits. However, most of India's coal lies under protected forests or designated tribal lands. Any mining activity or land acquisition for infrastructure in these coal-rich areas of India has been rife with political demonstrations, social activism and public interest litigations.

3.2.6 Poor pipeline connectivity

India has a large supply of coal bed methane and shale gas, but the lack of suitable infrastructure, especially poor pipeline connectivity prevents the country from harnessing these enormous resources and living up to its actual potential.

3.2.7 Less Natural Gas than Predicted

India faces a shortage of natural gas – one of its most important fuels. One of the most recent offshore natural gas fields (Krishna Godavari Basin) has delivered less fuel than projected. This has also caused more concern over future such natural gas projects, slowing down the rate of growth in this sector.

3.2.8 Delayed HEP projects

Recent Hydro-Electric Power (HEP) projects in India have been held up for various reasons. Most of these projects started in the Northern and North Eastern regions of the country. Environmental difficulties have been prevalent in these regions for many years. In addition to this, the government also faced some rehabilitation controversies, coupled with public interest litigations. These led to the ultimate slowing down of these HEP projects.

3.2.9 Theft of power

Theft of power is one of India’s largest concerns, but is also the most difficult to regulate. There are various ways in which power can be acquired illegally. Some of the ways power theft takes place are listed below:

- Direct hooking from power lines (overhead/ground cables) past the energy meter
- Bypassing the energy meter by short circuiting its input and output terminals
- Inserting foreign materials into the meter to manipulate its readings
- Physical obstruction of electromechanical meters causing the disk to rotate more slowly

Each of these methods of power theft can easily go unnoticed by officials, and can easily be covered up. These add up to the AT&C losses of the country. In a vast country like India, it is difficult to verify every electric connection in every home for theft of power. This leads to large losses on the government side. Additionally, many overhead lines in India are not insulated, facilitating illegal hook ups[3]. In recent years, power theft has only been increasing as many people from poverty stricken lands of India realize it is much cheaper to steal electricity than to pay the government's relatively high rates for electricity.

3.2.10 Political Factors

India's nuclear power generation potential has been stymied by political activism since the Fukushima disaster in Japan. Political parties have a strong influence on the growth of the power sector in India. They try to work in favor of the public just before election periods to gain public trust and eventually win the elections. They allow power theft, thwart major government plans, and oppose projects that will affect a minor portion of the public. Due to other problems such as illiteracy and overpopulation in India, political parties can tend to be extremely influential when it comes to major projects such as power plants. They easily acquire the support of the public and start large scale movements.

3.2.11 Outreach

As we know, India is a huge country. Of the 1.2 billion or more citizens of this vast subcontinent, over 300 million have no access to electricity. Of those who do, many find the supply of electricity intermittent and unreliable. Due to its size and often irregular terrain, it is difficult to expect the power grid to cover every inch of the nation. This has always been a cause for concern for the Government and PowerGrid Corporation. The government is committed to providing uninterrupted power to each and every household and is taking several steps to fulfill its promise to the people of India.

3.2.12 Lack of clean and reliable energy sources

For generations, India has lacked clean and reliable energy sources of electricity. This, in part, causes a large population of the country (around 800 million) to continue using traditional biomass energy sources – namely fuel wood, agricultural waste and livestock dung – for cooking, water heating and other domestic needs. Traditional fuel combustion is the primary source of indoor air pollution in India, causing between 300,000 to 400,000 deaths per year and other chronic health issues.

3.2.13 Increasing Power Demand

Power Demand is constantly increasing in the nation. As the population increases, the number of residences and office spaces increases, and power supply does not decrease. In today's growing digital age, we use less paper and more technology, all of which requires power. The country's power supply

[3] Information obtained from http://www.projectguru.in/publications/power-theft-in-india/

needs to meet this growing demand, but fails to keep up with it. The electrical energy demand for 2021–22 is expected to be at least 1,915 Terawatt Hours, with a peak electric demand of 298 GW[4].

3.2.14 Interruptions in supply

As previously mentioned, PowerGrid Corporation provides power to the country at more than 99% system availability. However, there are still numerous reports of widespread blackouts, dips in voltage, interruptions in supply, and "load shedding" all over the country. This has always been one of India's primary power concerns, and will continue to be an issue until the main power grid spans every inch of the country.

3.2.15 Dated power plants

India's coal-fired, oil-fired and natural gas-fired thermal power plants are not as efficient as they should be, and offer significant potential for greenhouse gas (CO_2) emission reduction through better technology. Compared to the average emissions from coal-fired, oil-fired and natural gas-fired thermal power plants in European Union countries, India's thermal power plants emit 50% to 120% more CO_2 per kWh produced.

[4] Information obtained from https://en.wikipedia.org/wiki/Electricity_sector_in_India#Demand

4 POWERGRID CORPORATION OF INDIA

4.1 BRIEF OVERVIEW

The PowerGrid Corporation of India Limited (PGCIL) is the Central transmission utility of India. It is a public sector organization (PSU), and is India's largest Electric Power transmission utility. The role of PGCIL in India is divided into three broad sections, namely:

- Transmission
- Consultancy
- Telecom

Each of these sections has been discussed in some detail in the following sub-sections[5]. The Corporate Office of PowerGrid is located in Gurgaon, Haryana, near the border of New Delhi. It is from here that all of PowerGrid's systems are controlled. The vision of the country is clearly defined as:

World Class, Integrated, Global Transmission Company with Dominant Leadership in Emerging Power Markets Ensuring Reliability, Safety and Economy.

PowerGrid emphasizes on the overall development of areas and communities around its establishments. It undertakes various community development schemes through provision of facilities like health, education and drinking water in addition to infrastructure such as roads and community centers.

4.1.1 Transmission

PowerGrid currently services 116625 ckm of Transmission lines all over India. It operates almost 200 sub stations in the country, and provides a total capacity of approximately 234700 MVA of power. Of this, it has an inter-regional capacity of approximately 46450 MW.

The main aim of the company is to ensure compliance with prescribed standards as well as to achieve high availability of the system for uninterrupted power supply to customers. PowerGrid also continues Grid Management through its 100% subsidiary company POSOCO (Power System Operation Corporation Limited). Grid management in India is carried out regionally.

4.1.2 Consultancy

PGCIL provides transmission related consultancy to more than 150 domestic clients. The Corporation also has numerous global connections as it has more than 25 international clients in 18 countries outside India. The company uses its in-house expertise to provide this consultation. It has also planned and undertaken

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[5] Information obtained from official PowerGrid website at http://www.powergridindia.com/, and is up to date as of 31st May 2015.

Capacity Building Assignments for clients. The company completes system engineering and feasibility studies, environment and social impact assessments, provides contract services and provides consultancy on design and engineering related issues, amongst many other things.

4.1.3 Telecom

The PowerGrid Corporation of India also owns and operates around 33240 km of Telecom Network, also known as PowerTel. It has points of presence (PoP) in more than 350 locations all over India. The Corporation also has intra-city networks in more than 100 cities all over India. This telecommunications business initially stemmed from the already existent transmission network and assets of the company, and later turned out to be a profitable business of its own. In a lot of places, the telecom antennae have been placed on transmission line towers. It is the only utility in the country to have an optic fibre network using Optical Ground Wires (OPGW). Underground optic fibre cables have been used where transmission line towers are unavailable. These optic fibres allow for higher grade long distance telecommunication of a much higher capacity than standard cables. Due to this convenient interdependence of the two networks, PGCIL has found it easy to access areas of India with rough terrains such as Jammu and Kashmir, where other telecom providers cannot easily provide services. This telecom network also provides a useful means for the coordination and control of PowerGrid's own grid networks.

4.2 POWERGRID AND HVDC SYSTEMS IN INDIA

PowerGrid Corporation has initiated India's advent into the advancing world of HVDC technologies. In 2014, PGCIL was nominated for building the largest transmission link in India, connecting Raigarh, Chattisgarh in Northern-Central India and Pugalur, Tamil Nadu in South India[6].

Recently, PowerGrid selected ABB to develop the world's first multi terminal UHVDC link between Agra in North India to Biswanath Chariali in Eastern India, covering a distance of approximately 1728km. There is a converter station in Alipurduar, in North Eastern India. This UHVDC link has a converter capacity of 8000MW, and will operate at a DC voltage of ±800kV. The image on the next page illustrates the sheer size of this project, connecting two far ends of India, the 7th largest country in the world[7]. It also gives an idea of the locations of the three converter stations.

[6] News about this nomination available on http://www.business-standard.com/article/economy-policy/power-grid-corp-nominated-for-largest-transmission-line-114121701006_1.html

[7] By size. Data taken from https://simple.wikipedia.org/wiki/List_of_countries_by_area

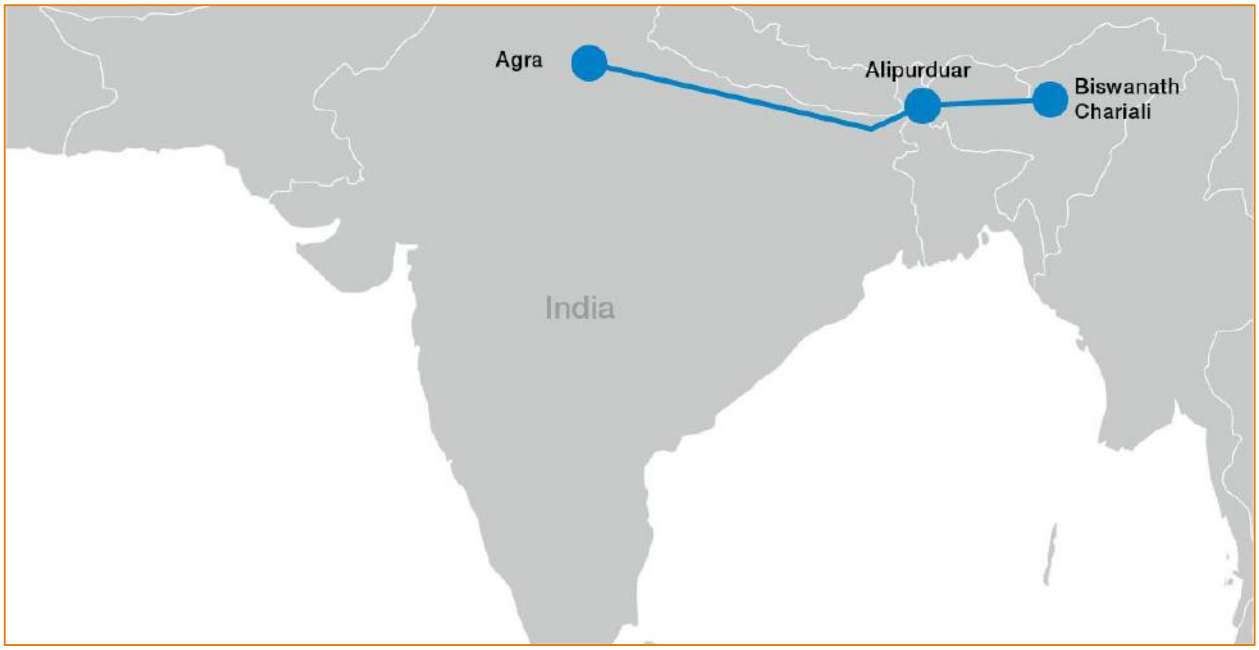

Image 1: PowerGrid Corporation's new HVDC line in Agra[8]

4.3 FUTURE PLANS

PowerGrid Corporation recognizes the importance of smart grids and HVDC systems in today's age. The company has taken pioneering steps in bringing the smart grid technology to all facets of a power supply value chain and has developed a pilot smart grid project at Puducherry (formerly known as Pondicherry) through open collaboration covering all attributes of a smart grid in the distribution of power. PGCIL has many plans for the future. The company plans to explore many new business opportunities. Some of them are listed below:

- Smart Grid/Smart City Projects
- Green Energy Corridors
- Energy Efficiency
- Dedicated Transmission System for bulk users like the Indian Railways
- Strengthening of Intra-State Transmission
- Desert Power
- Electric Vehicles
- Distribution of wires

[8] Image obtained from http://www07.abb.com/images/default-source/p-s-hvdc/maps/asia/l_north-east-agra.jpg?sfvrsn=2

5 HVDC SYSTEMS

5.1 THEORY

"HVDC" or "High Voltage Direct Current" is the new age alternative to "HVAC" (High Voltage Alternating Current) or "FACTS" (Flexible Alternating Current Transmission System) systems that have been used for years. As the names state, an HVDC power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems.

5.1.1 Components

Some of the main components of HVDC systems include thyristor valves, converter transformers, smoothing reactors, harmonic filters (AC, DC and "Active" filters), surge arresters and control and protection technology in addition to the main DC transmission circuit – consisting of the DC transmission line, the DC cable, the high speed DC switches and the Earth electrode. These elements have been described in some detail and their roles in an HVDC transmission system have been detailed below[9].

Thyristor valves make the conversion of current from AC to DC. They are the central component of any HVDC station. They can also be used as a kind of switch to control the valve. The converter transformers then transform the voltage of the AC busbar to the required entry voltage of the converter. The smoothing reactor is an important part of the system that helps prevent intermittent current, limits the DC fault currents and helps prevent resonance in the DC circuit.

A harmonic filter is required on the AC side of an HVDC converter system to absorb harmonic currents generated by the converter and thus to reduce the impact of the harmonics on the connected AC systems. It also supplies reactive power to compensate the demand of the converter station. There are AC, DC and Active harmonic filters. Active filters can be used on both the AC and DC sides of the converter. A surge arrester simply prevents damage to equipment due to overvoltages. During normal operation, it has absolutely no effect on the power system.

The most important and prominent component of the system is the DC transmission circuit itself. The DC transmission line consists of the towers, cabling and insulation. Cables can be of various types, some examples being mass-impregnated and oil filled. XLPE cables and lapped thin film insulated cables are also slowly becoming popular. There is also a system of circuit breakers (or high speed switches) to prevent sudden disruption of network and crash of the entire system.

The next section describes the two main types of HVDC systems.

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[9] Information about components of a DC network obtained from http://www.energy.siemens.com/us/pool/hq/power-transmission/HVDC/HVDC_Proven_Technology.pdf

5.1.2 Two types of HVDC Systems

There are two main classes of HVDC systems, one of which is an older and more traditional technology, while the other is a new system that is slowly proving extremely advantageous. Both systems use Direct Current and display all or most of the advantages of HVDC systems detailed in the next section. The two types of HVDC systems are:

- LCC based systems (classical)
- VSC based systems

A brief description of both systems is provided in the sub-sections below, with illustrations of their differences. Globally, the application of HVDC systems into existent power grids has only been increasing at a rapid rate. The graph in Section 8.2 on page 29 shows the global growth of HVDC systems.

5.1.2.1 Classical (LCC) HVDC Systems

"LCC" or "Line Commutated Converter" based HVDC systems make use of thyristors (a particular kind of valve or switch that conduct when their gate receives a current feedback). These have been in use for a long time, in some cases over 50 years. However, these systems cannot create an AC voltage at the terminal of the receiving end. These are currently available up to 800kV/6400MW, but 1000kV/10000MW systems are being studied and will soon be available.

5.1.2.2 VSC based HVDC Systems

"VSC" or "Voltage Source Converter" based HVDC systems make use of transistors. This technology is relatively new, and is capable of creating an AC voltage at the terminals of the receiving end. This makes this VSC technology very useful for creating back-to-back networks to connect two existing AC grids. This technology is currently only available up to 350kV/500MW but ratings are quickly expected to rise due to the level of research being done in this field. Some of the biggest companies have come up with fully tested versions of these VSC based HVDC systems. ABB has a technology called HVDC Light™ (in addition to their traditional HVDC Classic™ system), Siemens has introduced HVDC Plus™ (as opposed to their traditional HVDC Classic™ system), and Alstom has named its VSC system HVDC MaxSine™. Each of these new products are aimed at smaller loads for the time being, even remote loads like islands that require relatively less power. This will be expanded to a larger scale once research into this technology provides us with the ability to have higher voltage/current level VSC based HVDC systems.

5.2 COMPARISON WITH OTHER METHODS

HVDC systems are most often compared with the existing HVAC/FACTS systems, as these are the two most widely used methods even today. There are numerous parameters that can be compared when it comes to these two common systems of transmission. Some of the most significant ones have been detailed below. Section 8.1 on page 25 of the appendix contains illustrations of four simple, common applications of HVDC transmission networks.

5.2.1 Effective Power Transmitted

AC transmission lines need to be designed to handle the peak voltage of the AC sine wave. However, since AC is a sine wave, the effective power that can be transmitted through the line is related to the root mean squared (RMS) value of the voltage, which for a sine wave is only 0.7 times the peak value. This means that for the same size wire and same insulation on standoffs and other equipment, a DC line can carry 1.4 times as much power as an AC line.

5.2.2 Underwater Cabling

HVDC cables are extensively used in sub sea level conditions. This is because, for underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For such underwater transmission systems, the line losses due to capacitance are much greater, which makes HVDC economically advantageous at a much shorter distance than on land. One such example of an underwater cable is NorNed. NorNed is a 580km long HVDC submarine cable between Norway and Netherlands, which connects the two countries' electricity grids. It is a bipolar 450kV, 700MW cable. The image below shows its location in the North Sea in Europe.

Image 2: The NorNed HVDC cable in Europe, connecting Feda, Norway to Eemshaven, Netherlands[10]

[10] Image obtained from http://new.abb.com/systems/hvdc/references/norned

5.2.3 Loss of Power

Power losses are comparatively much lower in HVDC systems as compared to HVAC systems. The loss of power has been tested to be lower at each of the levels – generation, transmission and distribution. One main reason for this low level of power loss is the cyclical nature of alternating current. AC charges and discharges every cycle, therefore there are losses every half cycle. DC charges and discharges only once, with absolutely nothing to do with cycles. This causes the losses at the transmission level to be greatly reduced, especially due to the large distances traversed.

5.2.4 Costs

As compared to the general HVAC used throughout the country, HVDC has a much higher set up cost but a far lower average long run cost per meter. The power losses are much lower in HVDC systems, which is a very important factor in power generation, transmission and distribution. The image below shows how total long run costs are much lower for DC systems as compared to AC systems even if the initial set up cost is higher.

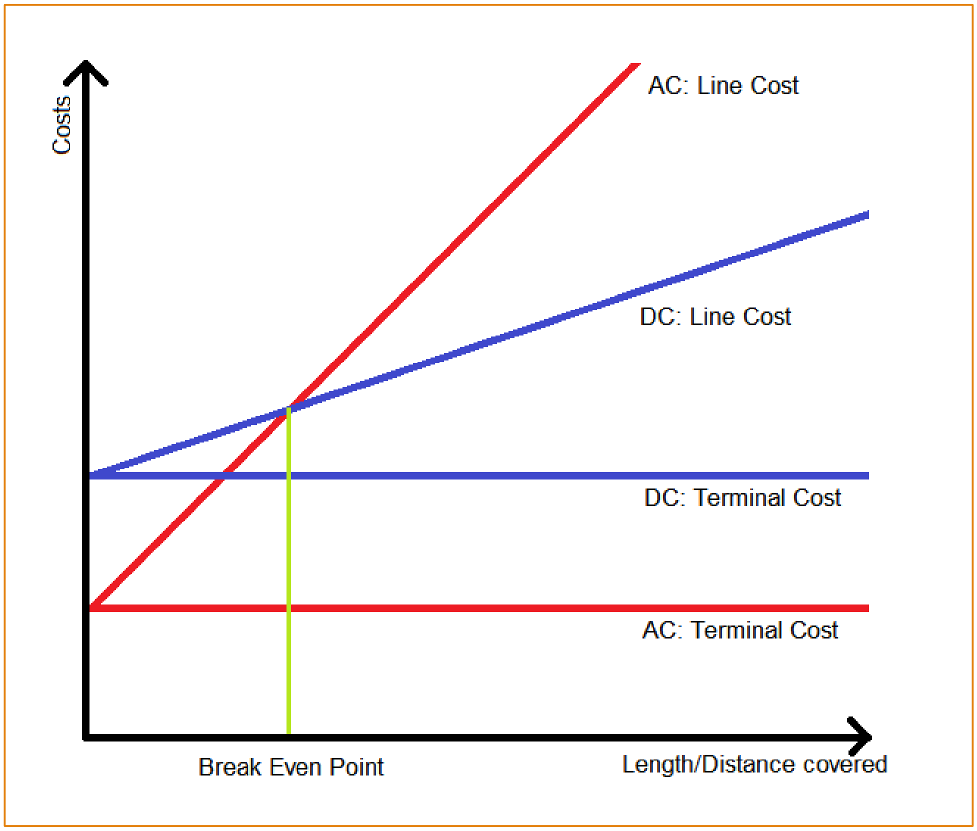


Image 3: A comparison of long term costs for High Voltage AC and DC transmission lines[11]

[11] Self-generated image. Image not to scale.

5.2.5 Right of Way regulations (Wayleave usage)

The image below shows how the same wayleave can be used much more economically as part of a DC system as compared to an AC system. Alternatively, this means that smaller wayleaves could be used for the same amount of power transmission in DC networks rather than AC networks. This is more beneficial than one might imagine. Smaller wayleaves allow for reduced right of way (ROW) requirements. This means that less land will be used in the construction and implementation of each wayleave, and more land will be available for general use. This also reduces the cost of each wayleave. Another huge advantage is the reduced visual impact. In some places, people tend to object to tall wayleaves as they ruin the natural appearance of the location, and prove to be eyesores. With HVDC wayleaves, more power can be achieved from the same tower, and the same power can be achieved from a smaller tower.

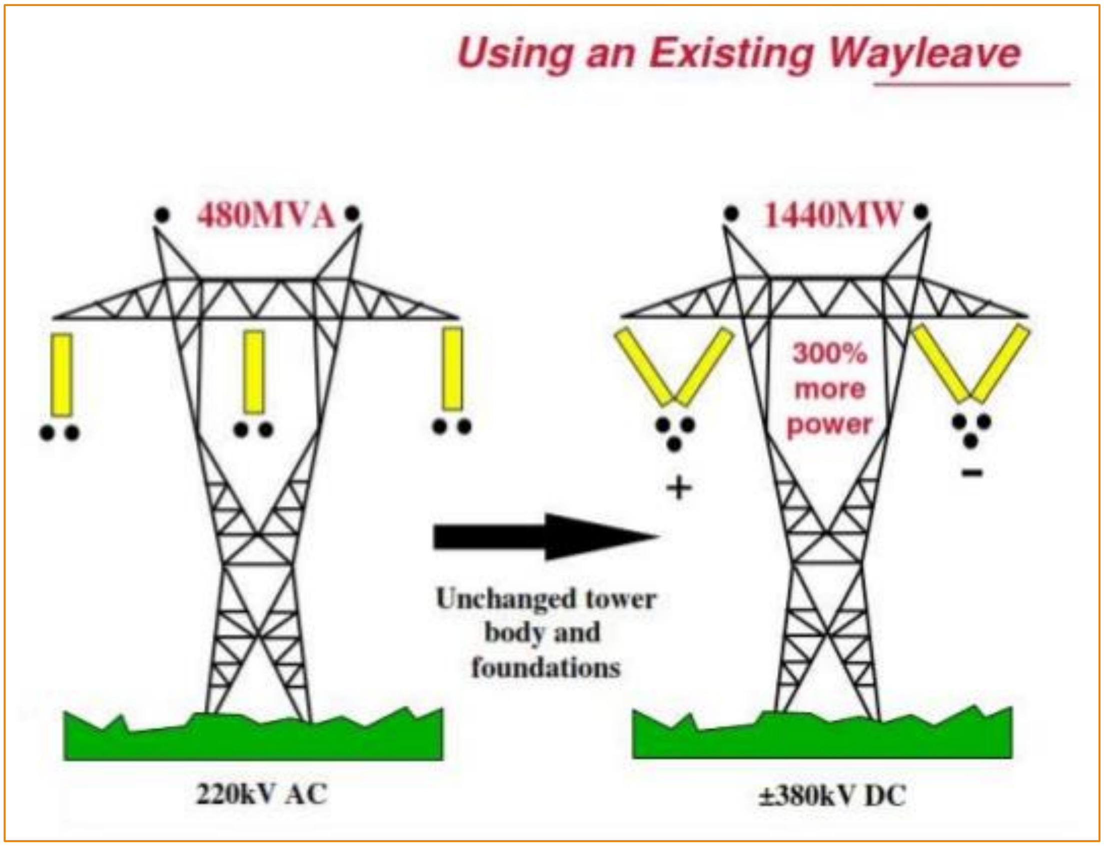


Image 4: Comparison of an existing wayleave's usage in AC and DC configurations[12]

As the above image clearly shows, much more power (300%, in this case) can be obtained from the same wayleave when it is used in a DC configuration instead of the standard AC configuration.

[12] Image obtained from http://image.slidesharecdn.com/factspresentation-141027091054-conversion-gate02/95/hvdc-facts-20-638.jpg?cb=1414401846

5.2.6 Connection to existing networks

An HVDC system can be used to connect two different HVAC networks of different frequencies. This sort of a connection is called a "back-to-back" network. In such a network, power flow can be controlled in both magnitude and direction, either by the operator or with the help of an automated response. Voltage and frequency in both AC networks can be controlled, independently of each other. This method can be used to assist one or both of the networks to respond quickly in times of system fault or disturbances. This is mostly automated because operator does not have enough time to respond to these faults quick enough. The automated systems today are capable of preventing large scale outages in an interval close to 10ms.

5.2.7 Connections to a Smart Grid system

In today's age of automation and digitalization, smart grids are the newest, most efficient ways to manage large scale power grids. HVDC systems are much more easily compatible with these smart grids as compared to the sinusoidal HVACs. The conversion of AC to DC for use in an extensive smart grid also leads to a huge amount of power loss. Hence, HVDCs seem to be the more logical solution for smarter grids of the future.

5.2.8 Reactive Power Losses

AC power transmission has the need for reactive power compensation due to the natural capacitance and inductive properties of a wire. This is minimized in DC power, as DC transmission lines do not suffer reactive losses. The only losses in a DC transmission line are the resistive losses, which are present in AC lines as well. Therefore, HVDC systems cut down on an even larger amount of power losses.

5.2.9 UHVDC systems

UHVDC systems – ultra high voltage direct current system – comprise more modern technology that is being currently developed. As of now, 600kV, 800kV, 1000kV and 1100kV systems are available, but even higher kV systems are being researched. Anything above 600kV currently qualifies as a UHVDC system. These modern day transmission lines require even less right of way (ROW) as compared to the standard HVDC systems. They provide extremely effective and cost efficient transmission of very high levels of power to loads very far from the generation sites. As the name suggests, this is HVDC on a larger scale. Hydro Electric Power plants or Nuclear power generation plants that are situated away from densely populated areas will be able to benefit from this technology.

Driven by economic growth, demand for power and the need to efficiently integrate renewable power generation, it is clear from developments in AC networks that UHVDC will have a major role to play as power systems evolve. The expansion of this role is also clear from the interest in extending the capabilities of UHVDC transmission in the recent years. Given UHVDC's very high ratings, it is essential that these valuable assets operate safely, reliably and efficiently[13].

Companies like ABB, Alstom and Siemens have the proven tools and expertise needed to design and manufacture reliable UHVDC converter transformers. This solid technology background ensures that even in the fast-developing UHVDC area, customers can be sure that the equipment is designed, tested and built to the highest standards of operational stability.[14]

In India, there are already 176kV, 200kV, 500kV and 600kV lines, and 800kV lines are already being set up in the new Agra-Biswanath line in North India. In 2015, India will also have 1100kV lines set up.

The following image is an illustration of ABB's latest 800kV UHVDC transformer and its size with relation to a mid-size sedan.

Image 5: The size of a typical 800kV UHVDC transformer with relation to a mid-size sedan

[13] Analysis acquired from http://tdworld.com/sponsored-articles/uhvdc
[14] This information is up to date as of 3rd April, 2014

5.2.10 Additional Advantages

HVDC systems have been proven to be brilliant solutions for endpoint to endpoint bulk transmission over large distances with no intermediate taps. A possible application of this is to transmit energy from a remote power generating plant to the main power grid.

For similar reasons, HVDC transmission lines are also the optimal method for connecting remote loads, like islands. Underwater HVDC cabling can be used, as well as back-to-back interconnections to connect the major grid to the minor grid.

A lot of modern Electric Vehicle (EV) Charging is now done with light HVDC cables, because vehicles require DC power. If AC cables were used, a rectifier would be required to convert the power to DC power. But, there is a limit to the amount of power a rectifier can handle. Largescale commercial EVs require high power, so DC cables need to be used.

6 SMART GRIDS

6.1 WHAT IS A SMART GRID?

According to Oxford Dictionaries, a smart grid is – in short – an "electricity supply network that uses digital communications technology to detect and react to local changes in usage"[15].

A smart grid makes use of technologies such as state estimation that can improve the detection of faults in the system and facilitate self-healing of the network without the need for external intervention. This ensures a much more reliable supply of electricity as well as a reduced vulnerability to natural disasters or attack.

In essence, a "smart grid" computerizes the entire system. This is comparable to the case of mobile phones and new age smart phones. Smart phones have a much more advanced computer inside them, which enables input, output, feedback, communication and many other extra features. Similarly, a smart grid would comprise a standard power grid that would be completely computerized, centrally controlled, easy to track, and far easier to manage.

The availability of feedback systems from every point in the system would make error detection and repair possible with the touch of a button. Smart grids reduce the amount of man power necessary by making good use of these user-response structures.

According to PowerGrid Corporation, a Smart Grid facilitates efficient and reliable end-to-end intelligent two-way delivery system from the source to the sink through integration of renewable energy sources, smart transmission and distribution. In this way, smart grid technology shall bring efficiency and sustainability in meeting the growing electricity demand with reliability and quality.

As we have learnt, a smart grid enables real time monitoring and control of power systems. In addition to this, it helps greatly in the reduction of AT&C losses and demand response. Overall management in terms of demand, quality of power and outages is made much easier. At a more local level, this allows smart home energy systems as well. Smart grids can act as a backbone infrastructure to enable new business models like smart cities, electric vehicles and smart communities.

As mentioned before, HVDCs are a good solution to a future involving smarter grids, as they integrate well with the digital, computerized systems, as compared to older HVAC technologies. The next section briefly describes some of the advantages of new age smart grid technology.

[15] Definition acquired from http://www.oxforddictionaries.com/definition/english/smart-grid

6.2 ADVANTAGES OF A SMART GRID

A smart grid is expected to provide benefits to utilities, consumers as well as societies in multiple extents. Some of them have been described below[16]:

6.2.1 Benefits to Utilities

Smart grids come with far reduced operation and capital costs for utilities providing power. They are much safer for employees working in the field, and are expected to typically bring in a higher revenue. They have also been tested to provide higher customer satisfaction than the traditional power grids. Overall, employee productivity will rise due to better O&M techniques too.

As we have explored, theft of power is usually reduced in the case of a smart grid. This leads to increased revenues for utilities. Additionally, the flatter load profile of the smart grid will reduce operating and maintenance (O&M) costs. Power losses along the line are lower, at both the transmission and distribution levels.

Utilities can also benefit from increased asset utilization and extended life of system assets through improved asset health management. The system will have improved load forecasting capabilities that enable more accurate predictions on when new capital investments are required.

Few smart grid networks have dual functions. This incorporates advanced metering infrastructure systems which, when combined with different software can be utilized to recognize power theft and by way of elimination, identify where equipment failures have occurred. These are in addition to their key functions of measuring the time-of-use of electricity and doing away with the requirement for human meter reading. They also come with integrated abilities to support electric vehicles, thereby helping the entire society one step at a time.

6.2.2 Benefits to Consumers

Consumers benefit from an improved level of service, facing fewer inconveniences. They have reduced costs to incur because the loss of power is relatively less, so their energy bills are not as high. The systems help consumers reduce consumption of electricity too, by preventing wastage and directing them on how to utilize low-priority electronic devices when prices are lower.

Consumers will have the opportunity to interact with electricity markets through home area networks and smart meter connectivity. There will also be the possibility of a completely new concept of consumers selling self-produced electricity back to the grid. Consumers will have an increased opportunity to purchase energy from clean sources, further creating a demand for the shift form a carbon based economy to a green economy.

[16] Information acquired from Power Grid Corporation website

Additionally, as mentioned before, the use of smart grids in today's world gives customers the opportunity to reduce transportation costs by using electric vehicles in lieu of conventional vehicles.

6.2.3 Benefits to Society

Smart grids help to virtually eliminate blackouts, helping the entire society. The reduction in overall cost helps keeping the prices of goods and services lower. The advanced infrastructure is also very important for boosting economic growth and development. Smart Grids have significantly reduced CO_2 emissions as compared to current technologies, but as discussed later, they have RF emissions that take the place of CO_2. However, public health is expected to greatly improve if Smart grids are implemented due to low CO_2 emissions. The quality of air in the area is improved and the carbon footprint is reduced.

A more robust transmission grid will also accommodate larger increases in green energy such as wind and solar generation. The smart grid will also enable the creation of new electricity markets. It will enable society to offer its electricity resources to the market and create the opportunity to earn a steady revenue stream on such investments as demand response, distributed generation, and storage of power.

Smart grids are designed to reinstate electricity flow much more quickly following a disturbance of power supply. Currently, an electricity disruption like a blackout, can result in a domino effect – a sequence of failures that can impact banking, traffic, security, and communications. In cold countries, this is a specific cause for concern in winter, when homeowners may be left without heat. A smarter, two way interactive grid would contribute resiliency to our electrical power system and ensure it is better prepared to tackle emergencies such as earthquakes, severe storms, terrorist attacks and huge solar flares.

Should there be a power outage, smart grid technologies would identify and isolate the outages, restraining them before they take the shape of large-scale blackouts. The new technologies would also assist with ensuring that electricity recovery starts quickly and strategically following an emergency-routing electricity quickly. The combination of these energy resources would help a community ensure operation of its vital services such as its police department, health center, phone system, grocery store and traffic lights during emergencies.

6.3 CONCERNS

Even though smart grids seem like a logical, effective solution for grid management in the future, they come with many concerns. Some of the biggest ones are discussed below:

6.3.1 Privacy/Security

Privacy is one of the largest concerns with smart grids. Users do not want their usage details available to the utility. Digitization of the grid means that everything at the local level will be computerized too, and this implies that all the data will be shared with the utility and/or the system. Many users see this as a violation of privacy and do not like sharing all the information with the utility. Cybercrime has become a large issue in today's modern age of technology. Utilities could be afraid of misuse of these centralized systems by anti-social elements like terrorists etc.

6.3.2 "Fair" availability of electricity

Users might define the fairness of availability of electricity differently than the utility does. There will always be conflict as to how the electricity is distributed in times of a shortage.

6.3.3 Unclear fare rate

Consumers worry that complex rate systems (such as variable rates) do away with accountability and clarity, enabling the supplier to take advantage of the customer. However, this may also be beneficial to users at times, as the system suggests ways to use the power to reduce electricity bills.

6.3.4 Kill switch

The centralization of the power grid will make it very easy to cut off power for someone who has defaulted on the payment (or someone with a similar case). Users are obviously not happy with this choice of a kill switch for every power connection, even though it is viewed as a huge benefit for power utilities.

6.3.5 RF emissions from Smart Meters

Smart Meters will be installed regularly to be able to monitor the data in real time. However, these meters will all be emitting radio frequency, which is far worse than any emissions from traditional power grids.

6.3.6 Losses due to Theft of Power

Anyone who is skilled beyond a particular level in Electrical or Electronics Engineering might be able to program the RF meters to display a different reading than normal and will be able to steal power from the digital grid. Theft of power might become easier in some ways but also more difficult in some ways.

7 WAY FORWARD

The advent of HVDC technologies into the modern age of power systems has provided us with an extensive range of possibilities to explore in the present and the future. Ultra High Voltage Direct Current technologies are already available at 600kV and 800kV levels, and are already being developed at 1100kV levels, ready to be in use by 2015. PowerGrid Corporation has taken up an 800kV UHVDC project that connects Agra (in Central North India) to the easternmost parts of India. This HVDC system will also be ready in 2015.

Due to the existing grid of HVAC and FACTS systems, however, we must look at future HVDC systems that are capable of matching these older systems. They must also be efficient when it comes to expanding these systems. A possible answer to this challenge is the new technology that many companies are now developing – the “light” HVDC solutions, running on VSC based technologies. ABB has developed HVDC Light™, Siemens has come up with HVDC Plus™, and Alstom has manufactured HVDC MaxSine™. Simply put, it is a ‘lighter’, cheaper, smaller scale HVDC solution for areas requiring less than normal amounts of power transferred over a lower distance. This technology makes use of VSC based HVDCs rather than the common LCC systems. It is appropriate for lighter loads, or even remote loads – like an island – as compared to the Standard HVDC solutions, which are for higher loads and more major projects. Other large companies also have similar projects, and many more will soon come up. This will make HVDC systems a slightly cheaper option for the future than predicted.

The greatly reduced transmission losses coupled with the lower long run total costs make HVDCs seem like the most viable solution for the future. As the age of digital technology dawns upon us, our power grids will soon need to be connected to Smart Grids, and a newly developed HVDC system will easily form a part of such a smart network with an effective feedback system for faster fault detection and restoration.

Section 8.2 of the appendix on page 29 contains a graph that clearly shows the growth of HVDCs in the last 35 years, providing a reasonable understanding of its advent into the future as well.

However, as discussed previously, HVAC has been the technology that has majorly been used in the past. So, in future we cannot completely do away with this technology, but rather we will have to build upon it. This is also possible, because as we have seen, it is not too arduous a task to connect new age HVDC technology with HVAC technology of the past. With a simple converter station, new lines can be added to the existing grid.

HVDC technologies can be linked with many more secondary sources of power than HVAC systems. In today’s age, researchers and scientists are constantly trying to find new renewable sources of energy as we expect an energy crisis in the near future. Solar and wind power are the most prevalent of the current large scale renewable energy sources, and every attempt is being made worldwide to increase their relevance in power grids across the globe. Of these, solar cells – as the name rightly suggests – store power in DC format, and therefore make it much easier to connect a solar power generating field to an HVDC grid. Most other forms of renewable energy work on the basis of turbines (or anything rotating, really), which all generate AC power. However due to the DC nature of the power generated in solar power plants, this becomes HVDC's closest complementary energy source.

In India, Shri Narendra Modi initiated a Canal Project while he was the Chief Minister of the state of Gujarat. This was a huge benefit in many ways, but failed to catch on in the expected way. Projects such as this one will slowly but surely add to the power potential of the country. The canal project essentially covered up some of the existing water canals in Gujarat with solar cells. This way, the water did not evaporate as quickly into the atmosphere, and a large amount of electricity was generated from those solar cells, powering all the nearby villages. However, the government cannot be expected to take on multiple projects like this as it will become a huge financial burden on them.

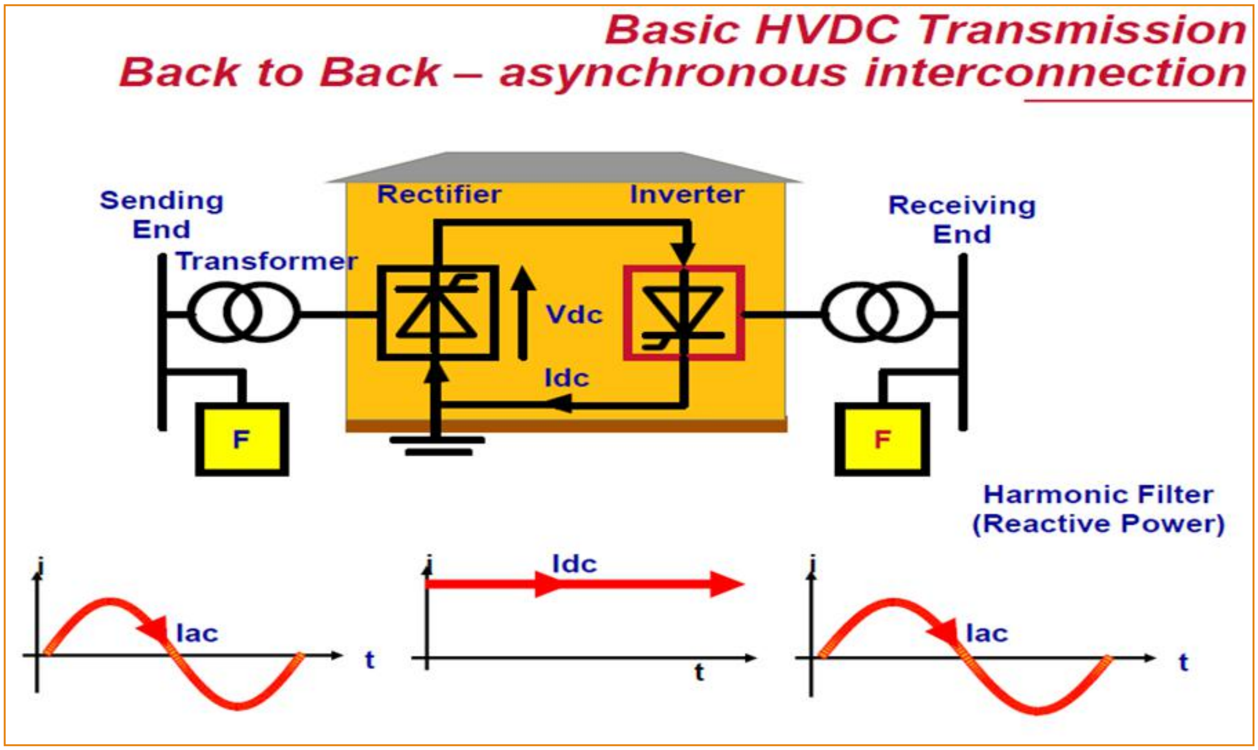
Another interesting case that could be taken up is the simple concept of desert power. By the technical definition of a desert, 33% of the earth's surface is covered with deserts. Some of the traditional deserts are cold deserts, but most of them are hot deserts. The solar power potential of these hot deserts is simply colossal, and if tapped, could benefit people and power utilities all over the world. Some desert power projects have been initiated, some are already in progress, but many more will be required to make a difference.

As we mentioned before, smart grids will form a large part of the future of power systems. However, it is not just Smart Grids, but Micro Grids that will actually make a huge difference. Micro grids are self-sustaining smaller scale grids that do not require long transmission cables from other sources. These reduce the need for HVAC and HVDC cables everywhere. This system is essential for long term dependability on these networks. A lot of the power in a micro grid is usually sustained from sources such as wind and photovoltaic (PV) solar cells. This concept is very similar to that of a net zero energy building, but on a much larger scale. Possible options for implementing a micro grid strategy are small cities, towns, universities and/or communities, amongst many others.

8 APPENDIX

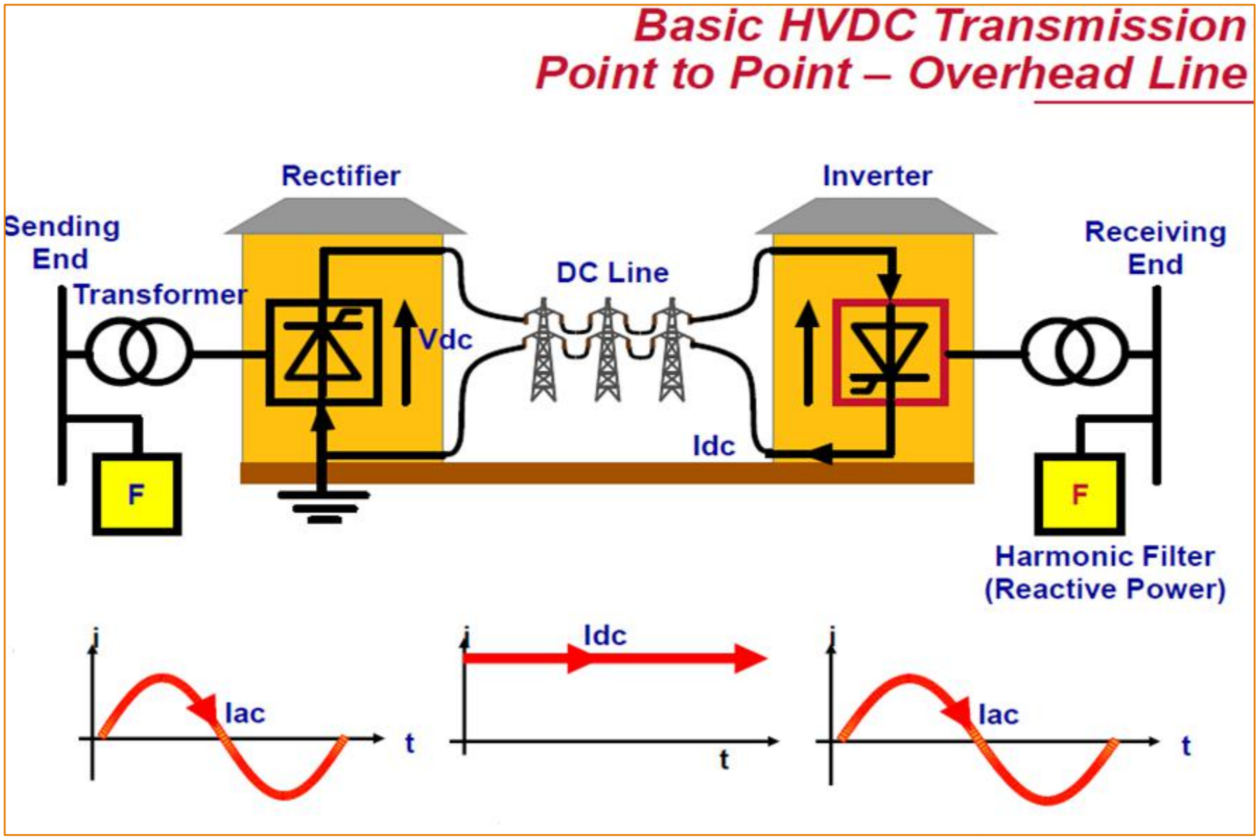
8.1 ILLUSTRATIONS OF HVDC TRANSMISSION NETWORKS IN THEIR SIMPLEST APPLICATIONS

8.1.1 Back to Back – Asynchronous Interconnection



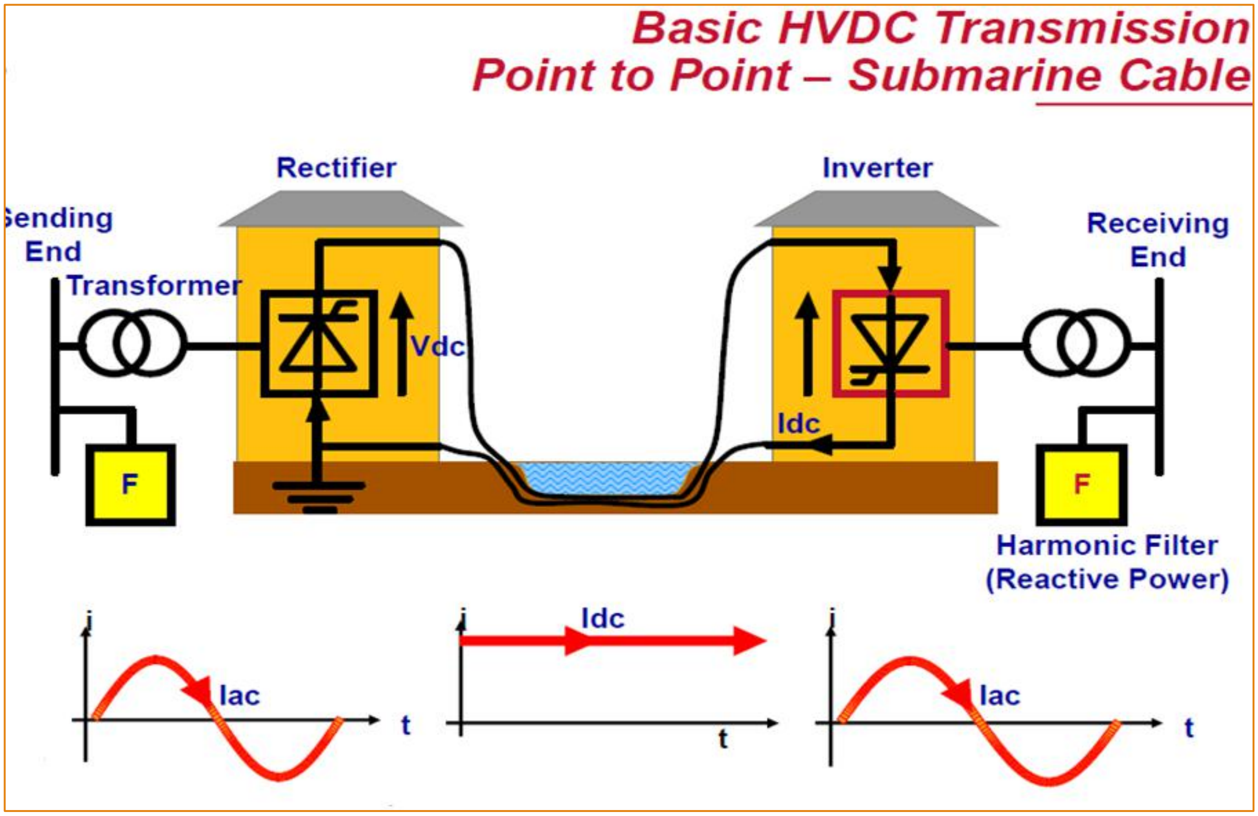
Here, choice of voltage is set by manufacturer to minimize number of semiconductors in series.

8.1.2 Point to Point – Overhead Line



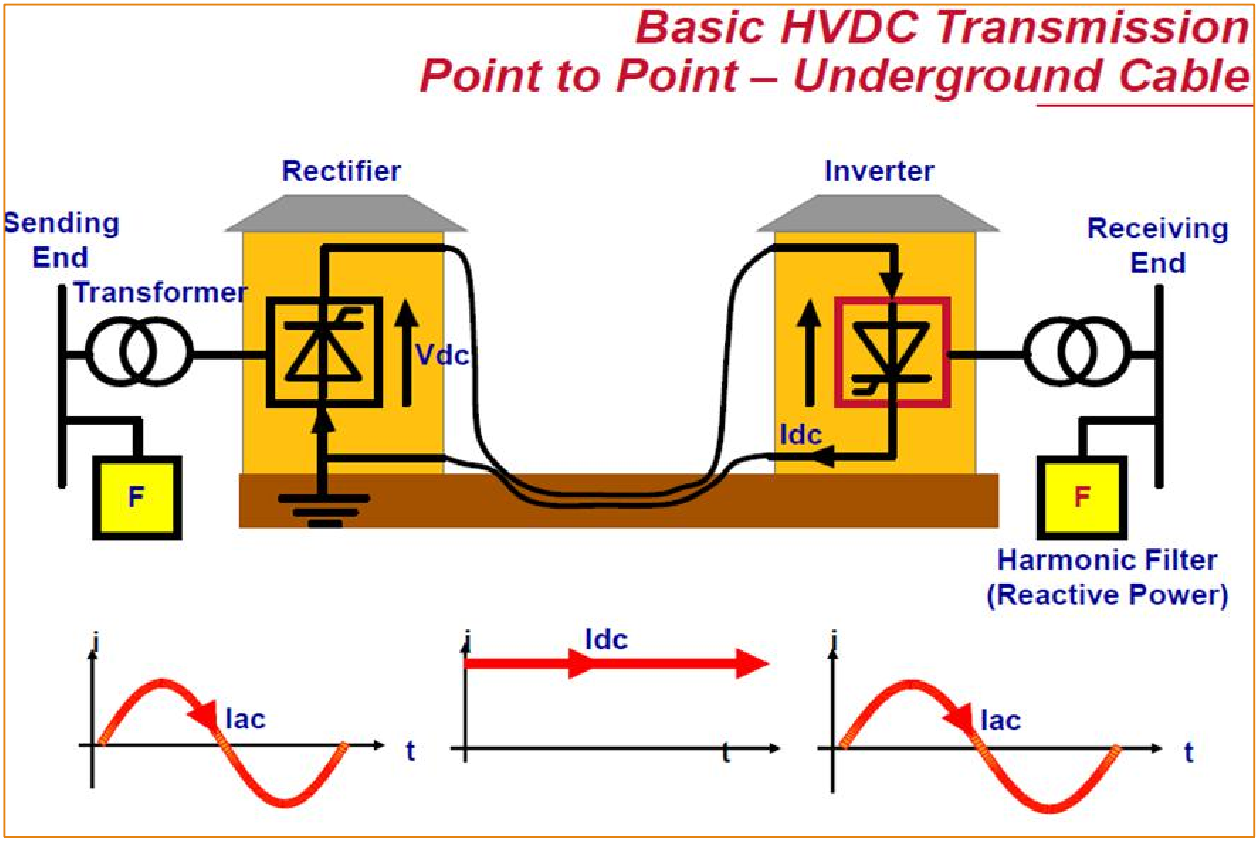
Here, choice of DC voltage is set by the cable to the highest possible voltage to minimize losses and cost.

8.1.3 Point to point – Submarine Cable



Here, choice of DC voltage is set by the cable to the highest possible voltage to minimize losses and cost.

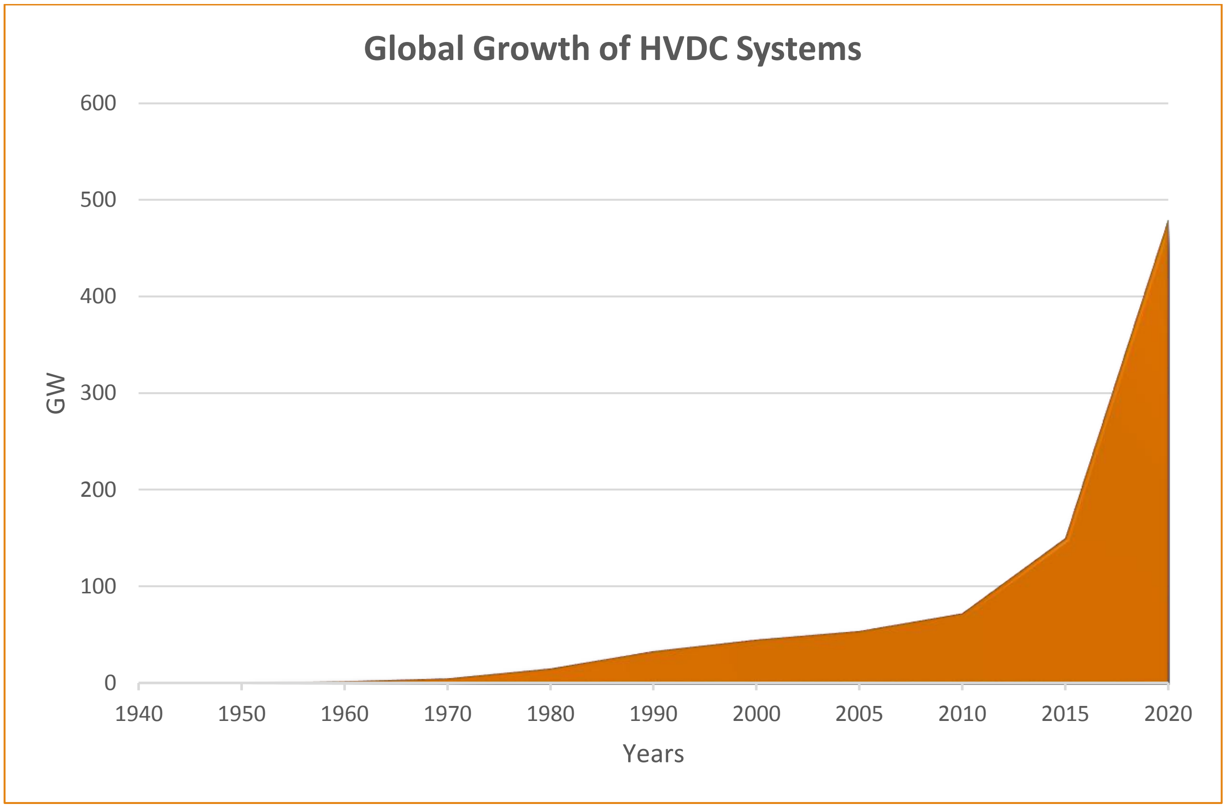
8.1.4 Point to point – Underground Cable



Here, choice of DC voltage is set by the cable to the highest possible voltage to minimize losses and cost.

8.2 GROWTH OF HVDC SYSTEMS

The graph below clearly shows the surely rising growth of HVDC systems in the world since the inception of its technology in the 1930s. IT is predicted that over 330GW of HVDC systems will be developed in the next 5 years[17].



[17] Graph created with help from IEEE report at http://smartgrid.ieee.org/questions-and-answers/902-ieee-smart-grid-experts-roundup-ac-vs-dc-power

8.3 LIST OF HVDC PROJECTS IN INDIA

The following table is a list of the current HVDC projects in India with some important details about each of them[18].

Sr No	Name	Converter station 1	Converter station 2	Total Length	Volt (kV)	Power (MW)	Year	Type	Supplier
1	Sileru-Barsoor	Sileru	Barsoor	196	200	100	1989	Thyr	BHEL
2	Rihand-Delhi	Rihand	Dadri	814	500	1500	1990	Thyr	ABB, BHEL
3	Chandrapur-Padghe	Chandrapur	Padghe	752	500	1500	1999	Thyr	ABB
4	Talcher-Kolar	Talcher	Kolar	1450	500	2000	2003	Thyr	Siemens
5	Ballia - Bhiwadi	Ballia	Bhiwadi	800	500	2500	2010	Thyr	Siemens
6	Mundra - Haryana	Mundra	Mohindergarh	960	500	2500	2012	Thyr	Siemens
7	North-East Agra	Agra	Biswanath	1728	800	6000	2016 (exp)	Thyr	ABB
	(Multi terminal bipole UHVDC)	Converter Station at Alipurduar							

[18] Data for table obtained from https://en.wikipedia.org/wiki/List_of_HVDC_projects#Asia

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