UNIVERSIDAD PONTIFICIA DE COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERIA (ICAI)

Grado en INGENIERÍA ELECTROMECÁNICA

Especialidad ELÉCTRICA

CORRIENTE CONTINUA EN ALTA TENSIÓN

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Madrid

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Resumen

El consumo de energía eléctrica durante las próximas tres décadas aumentará a un ritmo de un 2% anual. Se espera que en el año 2040 el consumo de electricidad se haya doblado respecto a 2010. La actual red de distribución y transporte eléctrico no está preparada para recibir este constante aumento, ya que son redes antiguas cerca de su máxima capacidad.

Por primera vez desde 1880, la corriente continua vuelve a aparecer en proyectos y redes de distribución. Hasta ahora había estado limitado su uso a práctica experimental, ya que el paso de alterna a continua necesitaba del desarrollo de la electrónica de potencia.

En las últimas dos décadas, la electrónica de potencia, junto con la electrónica de radiofrecuencia ha vivido un avance espectacular, centrándose sobre todo en equipos que pueden trabajar a mayor frecuencia, y sobre todo, capaces de soportar mayores potencias.

Este proyecto intenta dar respuesta a las preguntas planteadas sobre la viabilidad y coherencia de la instalación de granjas eólicas offshore. Se estudia una conexión HVDC entre un molino eólico que se encuentra situado en mitad del mar y la red eléctrica continental de un país europeo.

La turbina eólica tiene una potencia instalada de 5MW, producida gracias a un generador asíncrono de tensión alterna de salida trifásica línea-línea de 900V y una corriente nominal de 3200A. La conexión HVDC tiene una tensión de 150KV. Para aumentar la tensión a la salida del generador, se utiliza un transformador, de relación 110KV/900V. Después se une este transformador a la estación de conversión a continua mediante una línea eléctrica alterna de 1km.

Los convertidores entre corriente continua y corriente alterna son convertidores controlados por tensión o VSC (Voltage-Sourced Converter). El desarrollo de estos convertidores ha sido posible gracias al desarrollo de los transistores bipolares de puerta aislada, o IGBT (Insulated-Gate Bipolar Transistor).

El paso de corriente continua se realizará a través de un cable XLPE para valores de tensión máxima 150KV y una distancia estimada entre estaciones HVDC de 250 km. Este cable tendrá un polo más el retorno en neutro. A su vez, un cable de corriente alterna de longitud 1 km unirá la turbina a la estación HVDC. Este cable trifásico tendrá las mismas características que el cable de corriente continua.

Tras la conversión de nuevo a corriente alterna, el modelo será conectado a una carga o resistencia que hará las veces de red eléctrica. Esta solución ha sido tomada ya que los modelos necesarios para sincronizar y unir dos redes trifásicas alternas son dignos por si solos de un proyecto aparte.

Pero esta solución no es del todo satisfactoria, ya que para obtener una correcta señal sinusoidal es necesario disponer de una red trifásica de referencia. Es por ello, y por la ausencia de filtros de harmónicos que las corrientes de salida no son perfectamente sinusoidales.

Aun así, los resultados obtenidos en las simulaciones muestran que la corriente continua tiene menores perdidas que la corriente alterna. Además la tecnología HVDC permite transporta mayor cantidad de energía que la HVAC, ya que el voltaje es constante, al igual que la corriente, transmitiendo siempre el máximo de potencia disponible.

Faltaría estudiar el efecto que tiene filtros de paso bajo, para frecuencias de producción de la energía eléctrica (50-60Hz). Es importante recordar que estos filtros ayudan no solo a emitir una onda correcta sinusoidal, sino también a mejorar el factor de potencia de la red a la que esté conectada la granja eólica.

Teniendo en cuenta todas las ventajas enumeradas, es pregunta obligada por qué el desarrollo del transporte eléctrico no ha sido realizado en HVDC hasta hace relativamente poco. Cabe decir como respuesta que el coste de los convertidores es muy alto, ya que necesitan de tecnología avanzada y solo se han obtenido componentes fiables en los últimos tiempos. Este coste en la mayoría de las veces no compensa las mayores pérdidas de una línea HVAC.

No obstante la distancia entre costes se reduce cada día más, ya que el avance constante de la electrónica de potencia ha reducido los costes de las estaciones, aumentando su competitividad en distancias más cortas. De manera general, para líneas aéreas, la intersección entre el coste de HVDC y HVAC se encuentra alrededor de 400 km de distancia entre el punto de generación y el punto de consumo.

Para caso de líneas submarinas, esta distancia se reduce debido a la mayor inductancia existente en los cables submarinos por haber una capa mayor de aislante. La distancia queda fijada a 80km, que es una distancia inferior a la mayoría de las conexiones importantes bajo estudio (Irlanda-Inglaterra-Europa Continental) o que ya han sido realizadas (Península Ibérica-Menorca).

Este estudio quiere poner de relieve la importancia que tienen y tendrán las líneas HVDC en el futuro próximo de la energía eléctrica. Nuevas conexiones que ayudarán a estabilizar y mejorar el sistema eléctrico mundial están bajo estudio. También ayudarán a controlar e integrar el desarrollo de las energías renovables, que no tienen una producción estable ni son predecibles en periodos largos de tiempo.

La política europea de energía ya ha comenzado a hablar de una red internacional que conectaría Europa, el norte de África y los futuros parques eólicos que se están instalando en la costa irlandesa y en el mar del Norte.

La tecnología en corriente continua en alta tensión permite que todas estas conexiones sean ser reversibles, fácilmente controlables y de alta capacidad. Son capaces de transportar la capacidad de generación de granjas eólicas o solares en largas y muy largas distancias, sin sufrir excesivas pérdidas ni de potencia ni de tensión.

Se puede resumir que la tecnología de Corriente Continua en Alto Voltaje puede ayudar a alcanzar el sueño del autoabastecimiento energético de Europa, y la independencia de los países productores de petróleo o gas.

Este último punto entra en relieve si se echa la vista atrás, a las últimas crisis energéticas acaecidas en los últimos meses como son el desafío de Rusia en Ucrania, los brotes de guerra civil en Irak, y el avance del Estado Islámico de Irak y el Levante, que puede afectar a la producción de petróleo en Oriente Medio y Próximo.

Abstrat

The energy consumption for the next three decades will increase at a rate of 2% per year. It is expected that in 2040 electricity consumption has doubled over 2010's. Current electrical transport and distribution network are not ready for this steady increase, as older networks are near their maximum capacity.

For the first time since 1880, direct current reappears in projects and transport networks. Until now, direct current has been limited to experimental use. The passage from AC to DC needed for the development of power electronics.

In the past two decades, power electronics, along with radio frequency electronics have seen an important improvement, focusing especially on equipment and transistors that can operate at higher frequency, and above all, equipment that are able to withstand higher powers.

This project attempts to answer the questions raised about the feasibility and consistency of the installation of offshore wind farms. A HVDC connection between a wind turbine that is located in the middle of the sea and the continental power grid is studied.

The wind turbine has an installed capacity of 5 MW, produced by an asynchronous generator with three phase output AC voltage of 900V line-line and a nominal current of 3200A. HVDC connection has a voltage of 150KV. To increase the output voltage of the generator, a transformer is used with 110KV/900V relationship. Transformer output is attached to the conversion station by a 1km AC power line.

Converters between direct current and alternating current are controlled by voltage and Pulse Width Modulation, named VSC (Voltage-Sourced Converters). The development of these converters has been possible thanks to research of insulated gate bipolar transistor or IGBT.

The current transport is performed through a XLPE cable for high voltage (150KV). Between HVDC stations the length is 250 km. This cable will have one pole and a neutral return. Also a 1km AC three-phase cable connects the HVDC station and the transformer.

After the conversion back to AC power, the model will be connected to a load or resistance that will act as the three-phase national grid. This solution has been taken as the

models needed to synchronize and merge two alternating phase networks are by themselves worthy of a separate project.

But this solution is not entirely satisfactory, since part of the needs for the correct operation of the converters is to provide a reference phase network. Therefore, the absence of harmonic filters avoids the output currents to be perfectly sinusoidal.

Even so, the results of the simulations show that DC has lower losses than AC. After more, HVDC technology allows to transport more power, as the voltage and the current are constant, so the power transport is maximized.

Missing the study of the effect of low-pass filters for electricity production frequencies (50-60Hz), it is important to remember that these filters not only help to issue a proper sine wave, but to improve power factor of the network.

Considering all the advantages listed, we must ask why the development of electric transport has not been done in HVDC until relatively recently. It must be said in response that the cost of the converters is very high as they need advanced technology and it has been reliable only in recent times. This cost does not offset the higher losses of HVAC line in short lines.

But the gap between costs is reduced every day, due to constant advancement of power electronics, which has reduced the cost of these stations, increasing its competitiveness at shorter distances. Generally, for terrestrial power lines, the intersection between the cost of HVDC and HVAC is about 400 km from the point of generation to the point of consumption.

For the case of submarine lines, this distance is reduced due to the effect of the inductance of the cable. Subsea cables need greater insulation. The distance is fixed at 80km, a distance less than the most important connections under study (Ireland-England-Continental Europe) or that have already been built (Menorca-Spain).

This study aims to highlight the importance HVDC lines will have in the near future of electricity. New connections to help stabilize and improve the global electricity system are under study. Also they will help to control and integrate the development of renewable energy, which has an unstable and unpredictable long-time production.

The European energy policy has already begun to speak of an international network that would connect Europe, North Africa, and future wind farms being installed in both the Irish coast and North Sea.

HVDC allows that the different connections would be reversible, easily controllable and with high capacity. They are therefore capable of carrying the power generates by wind or solar farms. Long distances would not be a problem, not suffering excessive losses of power or voltage.

Therefore it can be summarized that High Voltage Direct Current can help achieve the dream of energy self-sufficiency and the independence of petrol producers.

This last point comes embossed with latest energy crises in recent months such as the challenge of Russia in Ukraine, outbreaks of civil war in Iraq, and the advancement of the Islamic State of Iraq and the Levant, which may affect the oil production in the Middle and Near East.

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Chapter 1.- Introduction and project planning

Last three decades, we have assisted to an important increase in world energy consumption. Developed countries have not raised significantly their consumption. On the contrary, the developing countries, especially the Asian countries, have lived an important period of industrialization, led by China and India, that has increased energy need.

World energy consumption increases from 524 quadrillion Btu in 2010 to 630 quadrillion Btu in 2020 and 820 quadrillion Btu in 2040, a 30-year increase of 56 percent (Fig. 1). More than 85 percent of the increase in global energy demand from 2010 to 2040 occurs among the developing nations outside the Organization for Economic Cooperation and Development (non-OECD), driven by strong economic growth and expanding populations. In contrast OECD member countries are, for the most part, already more mature energy consumers. [USEI13]

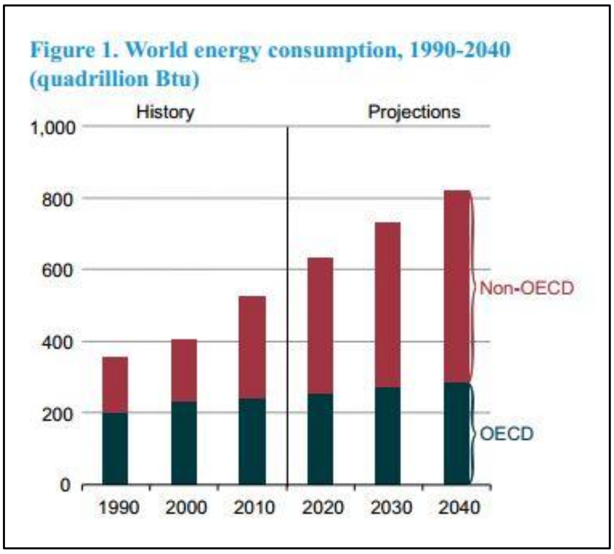


Figure 1. World Energy Consumption

OECD member countries as of September 1, 2012, are the United States, Canada, Mexico, Austria, Belgium, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom, Japan, South Korea, Australia, and New Zealand.

Renewable energy and nuclear power are the world's fastest-growing energy sources, each increasing by 2.5 percent per year. However, fossil fuels continue to supply almost 80 percent of world energy use through 2040.

World net electricity generation prevision increases by 93%, from 20.2 trillion kilowatthours in 2010 to 39.0 trillion kilowatthours in 2040. Electricity supplies an increasing share of the world's total energy demand and is the world's fastest-growing form of delivered energy (Fig. 2). Table 1 shows the net electricity generation by energy source in the OECD and non-OECD countries.

Region	2010	2020	2030	2040	Average annual percent change, 2010-2040
OECD					
Liquids	0,3	0,2	0,2	0,2	-1,1
Natural Gas	2,4	2,9	3,5	4,3	2
Coal	3,5	3,3	3,3	3,3	-0,2
Nuclear	2,2	2,4	2,7	2,7	0,7
Renewables	1,9	2,8	3,2	3,7	2,2
Total OECD	**10,3**	**11,6**	**12,9**	**14,2**	**1,1**
Non-OECD					
Liquids	0,6	0,6	0,5	0,5	-0,9
Natural Gas	2,1	2,6	3,7	5	3
Coal	4,6	6,9	9	10,6	2,9
Nuclear	0,4	1,3	2,1	2,8	6,3
Renewables	2,2	3,7	4,7	5,9	3,3
Total non-OECD	**9,9**	**15,1**	**20**	**24,8**	**3,1**
World					
Liquids	0,9	0,8	0,7	0,7	-1
Natural Gas	4,5	5,5	7,2	9,4	2,5
Coal	8,1	10,1	12,3	13,9	1,8
Nuclear	2,6	3,6	4,8	5,5	2,5
Renewables	4,2	6,5	7,9	9,6	2,8
Total World	**20,3**	**26,5**	**32,9**	**39,1**	**2,2**

Table 1. OECD and non-OECD net electricity generation by energy source, 2010-2040 (trillion kilowatthours)

The irruption of the renewables energies, as consequence of high fossil fuels prices in combination with concerns about the environmental consequences of greenhouse gas emissions resulted in interest in developing alternatives to fossil fuels for generation. Renewable energy sources are the fastest-growing sources of electricity generation, with annual increases averaging 2.8 percent per year from 2010 to 2040 (Table 1). Especially it is important the growth in wind energy and hydroelectric, which account 80 percent of the increase.

Wind energy has grown swiftly over the past decade, a trend that continues in the projections, what will not be achieved by the hydroelectric. In the OECD nations, most of the hydroelectric resources have been exploited. On the opposite, the predominant source of renewable electricity growth in non-OECD countries will be hydroelectric power.

The growth in the electrical market not just affects the generation party, but the transport and the distribution. New lines will be developed and built in the developing countries to achieve the goals and improve the grid to their populations.

Current grid dates from 30-to-40 years ago. They are not updated to support the changing flow from renewable energies and international connexions among cross-border grids. Today's power grid was designed to deal with a power delivery paradigm, for a one-way flow of energy from large centralized sources of supply to large and somewhat distributed locations of consumption. [VADA13]

But nowadays, every consumers could become a producer. Installation of photovoltaic panels, and the sell of the excess electricity to the electrical companies is a more common habit each day. Distribution grid has to be able to control this new input to the grid, a grid that is not prepared to small and distributed inputs. Also, the existing electrical transmission networks are already used at their limits, appearing bottleneck and overloads.

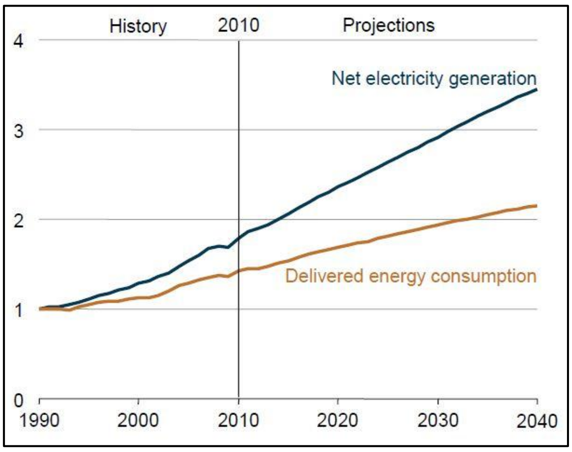


Figure 2. Growth in world total electricity generation and total delivered energy consumption (index, 1990 = 1)

In the next years and decades, the electrical networks will have to meet the increasing consumer demand, follow the deregulation directives, allowing the access to all market players. All types of generation will have to be delivered with high flexibility, ensuring free energy trading, taking into account that the power flow, as it has been saying, has become bi-directional.

The new network will have to prevent from "black-out" and interruption of service. Moreover, due to the international connexions, the network will face bigger voltage drops, frequency variations and different frequencies (50-60 Hz). To improve the transmission and not force the different lines, the reactive power will have to be compensated and controlled.

Two important options appear to control the new situation that has appeared in the network: FACTS (Flexible AC Transmission System) and HVDC (High Voltage Direct Current).

FACTS helps to improve the quality of the transmission in alternative current lines, reducing losses and improving power factor. FACTS shunt devices dynamically provide reactive power at a particular point of an AC network to support the voltage along the AC transmission line.

Also they are used to improve the stability and prevent from cascading disturbances. Last point is very important because current grids could go down if one point gets off. It happens due to the necessity to consume all the electricity inserted in the grid. If the electricity cannot travel down a path, it will search the next node. Paths, to be economically profitable, work near full capacity, and if more energy is added, the nodes will shut down themselves to preserve their integrity. [AG__14]

However, FACTS does not help to improve the capacity, but to control the distribution to improve the performance, and to avoid mayor failures that could tear down the electric systems.

Then, scientists and electrical transport companies have come back to first steps of electricity and, above all, the first big electric network installed in New York in 1885 by Thomas Edison. Thomas Edison was able to built the first direct current distribution grid in New York City. Later, after the electric war won by Westinghouse (helped by Nicolas Tesla), the alternative current was the model to follow for all the transport lines.

However, last 40 years have lived the power electronics' development, with higher voltages and more performance lines. Nowadays, HVDC systems could transport more energy that similar HVAC lines with the same infrastructures, and losses in long distances are lower than traditional alternative current lines.

Technically speaking, the DC current loads only one time the capacitances of the lines, whereas that AC loads and unloads two times each cycle the capacitances.

Moreover, HVDC is easy to control, because the power electronics allow to control the power, the voltage and output current would be a perfect sinusoidal. Also, two networks at different frequencies could be connected, stabilizing the international grid.

Besides, with the irruption of the renewables energies, HVDC could transport the power in both sides; reducing the error rate and the failure probability. Smart Grids, and the future network need flexible elements that allow updating and several configurations.

Nevertheless, one main reason HVDC will be a must-to-be next years, is the off-shore wind farm. Wind energy has been in continued grown, due to its performance, its on time production and the smaller environmental impact it has. Better and more constant wind speeds are available offshore compared to on land, and the opposition of residents to receive the visual impact is lower.

Fig. 3 shows us the prediction in following years for the European Union.

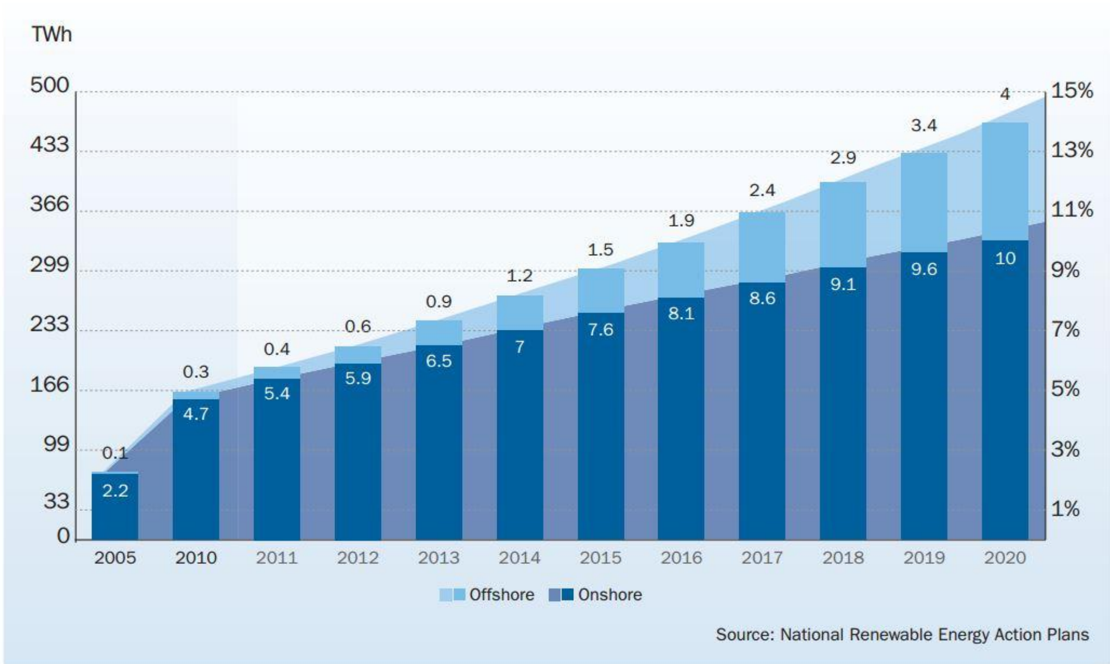


Figure 3. Power Cumulative Productive from Offshore/Onshore Wind in the EU 2000-2030 [MOCC11]

Offshore wind farms will spread around seas and oceans next years, and a new need, to distribute their power production, has appeared. Alternative current submarines lines are already in used. But they have an important disadvantage, the special insulator that protects it from water corrosion, raises inductance and capacitance of the line.

Europe is a world leader in offshore wind power, and important projects are under study to transform the North Sea from a fossil fuel reserve to an enormous wind farm that could supply Europe of cheap, renewable electricity.

Offshore wind farms will need to transport the electricity to onshore grid, and is under study a HVDC grid that would interconnect the European countries and the regions around. It would different renewable sources in different positions to improve the stability of the grid. Photovoltaic energy would be exported from the Sahara, and wind farm would be installed all around the European and African Atlantic coasts.

The following project will take this problem and will propose a better solution that alternative current. As many projects that are under study right now, HVDC shows important advantages that could be used to increase the transported power, reduce losses and fix the stability of the grid.

Moreover, it is important to understand how HVDC converters work, because next decades we will live an important increase in the use of HVDC and converters. Electric car batteries and computers, servers work with DC current, and it could not be crazy to think about a direct link between producers and consumers.

The following chapters in this project are organized as follows:

- Chapter 2 give a overview of the state-of-arts of HVDC transmission, power electronics and wind turbines, with explication of the different used technologies. A special emphasis in HVDC has been done.
- Chapter 3 reviews the different simulation models that are going to be used to analyze an HVDC submarine line. The data used in the analysis, the algorithms and the numerical implantation will be added.
- Chapter 4 makes the analysis of obtained data and a sensibility analysis that would help to understand if HVDC is interesting or not economically talking.
- Chapter 5 saves the conclusions that have been discovered during the project. Results and methodology would be analyse.
- Chapter 6 resumes all the sources that been used to understand and write this project.
- Chapter 7 or Annexes includes images of the different Simulink Blocks, that are too large to be disposed in the middle of this work.

Chapter 2.- State-of-the-Art

1. Introduction

High-voltage direct current electric power transmission system uses direct current for the transmission of electrical power, in contrast with the more common alternating current (AC) systems.

For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be warranted, due to other benefits of direct current links.

HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power.

HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

The use of High Voltage Direct Current Transmission (HVDC) actually started at the same time that first electricity was developed. Thomas Alva Edison obtained an electricity network with a capacity of 6 x 100kW for a power of 1200 kW using DC light bulbs in 1882. At their earlier development, Edison's experiments with DC systems were unable to compete with the AC systems proposed by Westinghouse and Tesla.

More than 70 years later, the DC transmission system came into use again after finding a mercury-arc tube at the end of the 1920s. A commercial HVDC project was first built in 1950 using a submarine cable to link Sweden with P. Gotland with a capacity of 20MW at 100kV voltaje[ARRIL98].

HVDC technology started to be used again because the mercury-arc tube was already well established. Power converters could be made, something that could not be achieved in the 1880s and that resulted in the defeat of Edison's DC system over Westinghouse's AC system. Mercury-arc tube technology itself only lasted about 20 years until the invention of the thyristor in 1970.

The thyristor is the basis of the rapid development of HVDC technology because it can be made for the purposes of power.

In the last decade, the development of IGBT technology allows the use of IGBTs for HVDC converters (Fig. 4), although its capacity is smaller than HVDC systems using thyristor converters.

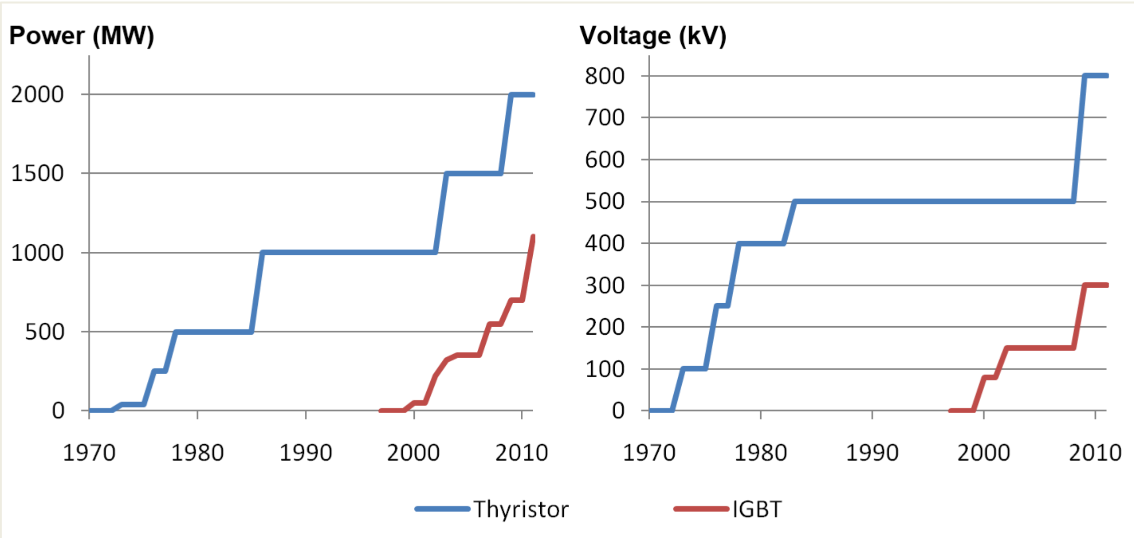


Figure 4. Development Thyristor vs IGBT

Starting with a 20MW system in Sweden, now there are more than 100 active HVDC transmission lines in the world with a total capacity of more than 80GW (Fig. 5). Starting from a voltage of 100 kV up to now reachs the 500kV, and systems of 800kV are under construction.

Some projects are quite famous among HVDC: Gotland in Sweden in addition to being the first HVDC system it was also the first HVDC thryristor used; HVDC Itaipu in Brazil (2 x 3150MW, +/- 500kV, 800 km) which is the biggest current HVDC system, Kii- Channel HVDC in Japan (1400MV, +/- 250kV), which uses light-triggered thyristors 8kV - 3500A.

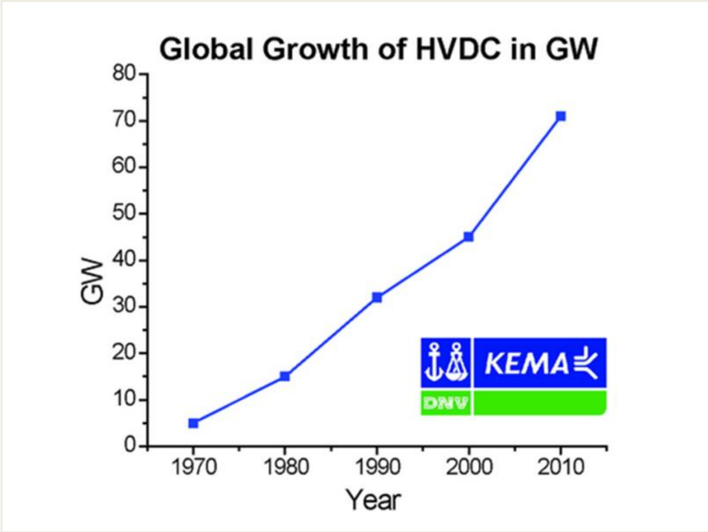


Figure 5. Total Transport HVDC Capacity

2. HVDC Technology

There are two kinds of converter technology from AC to DC (rectifier) and DC to AC (inverter) used in HVDC systems at this time: Line Commutate Converter (LCC), commutation meshes using thyristors, and Voltage Source Converter (VSC) that uses IGBT.

2.1. Line Commutate Converter Based HVDC

Most HVDC schemes in commercial operation today employ line commutated thyristor valves converters. In a line commutated converter, the commutation is carried out by the AC system voltage. LCC HVDC will continue to be used for bulk power HVDC transmission over several hundred MW, because this mature technology provides efficient, reliable and cost effective power transmission for many applications.

LCC HDVC was introduced in the USSR in 1950 (Kashira-Moscow) and in Sweden in 1954 (Gotland). Both systems used mercury arc valves. The first application of thyristors valves was to the Eel River scheme in Canada in 1972.

The use of thyristors initiated a rapid increase in the installed capacity of HVDC systems because of the superior reliability improvements and compact design with large capacity thyristors that have arrive to up to 8.5 kV, 4 kA.

LCC HVDC technology has been very well established for very large power converters. For the purposes of high power (1000MW) this technology seems the only option at this time. HVDC Itaipu HVDC system is currently the largest commercial operation using the LL-HVDC. The LL-biggest HVDC project that is being built now is Xiangjiaba - Shanghai HVDC 6400MW which transmits power at 800kV for 2071 km.

Commutated meshes are one of the weaknesses that exist in the LCC. It requires a high AC current in the sending and the receiving end. Fig. 6 shows the LCC HVDC scheme.

An LCC transmission system consists mainly of the following components [LAZA05]:

- AC filters
- DC filters
- Converter transformer
- Thyristor valves

- Smoothing reactor
- STATCOM or capacitor banks
- DC cable and return path
- Auxiliary power set

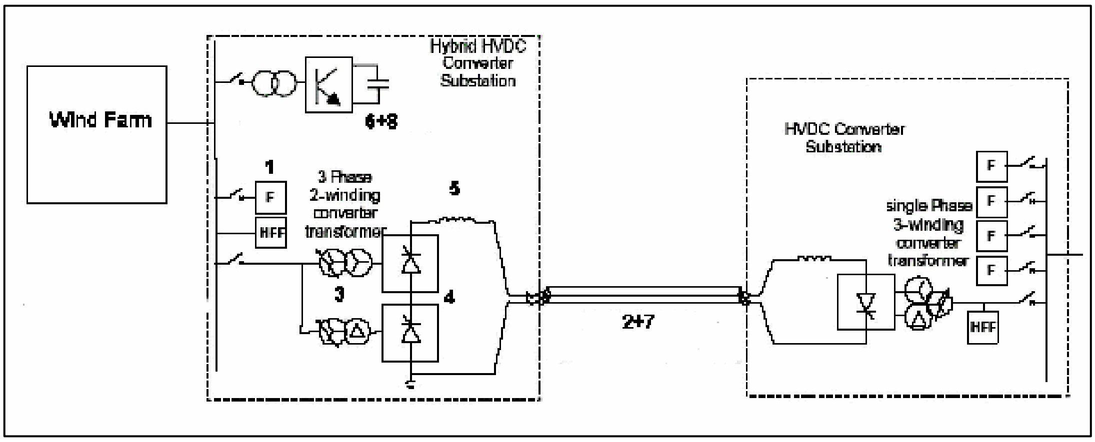


Figure 6. Configuration of a wind farm using LCC HVDC transmission system

2.1.1. *Filters*

AC filters are used in order to absorb harmonic currents generated by the HVDC converter and to reduce the impact of the harmonics on the connected AC system. AC filters also supply reactive power to the converter station.

DC filters are used to avoid that the harmonic voltage in the DC side will cause an AC current superimposed on the DC current in the transmission line.

2.1.2. *Converter Transformer*

In LCC transmission systems two converter transformers are required (one offshore and one onshore). Their configuration (Fig. 6) is to have the secondary offshore and the primary onshore with one star and one delta connection. This way several harmonics are cancelled and a significant reduction of filters is achieved.

The overall design of a converter transformer for HVDC LCC transmission is more complicated than it is for ordinary transformers. The insulation has to withstand the AC component of the voltage plus the DC component coming from the thyristor valves.

2.1.3. Thyristor Valves

The thyristor valves are the most important component in the converter station, since they operate the conversion from AC to DC and vice versa. The available technology today gives thyristors characterized by silicon wafer of diameter up to 125 mm, blocking voltages up to 8 kV and current carrying capacities up to 4kV DC.

With these characteristics it is possible to convert up to 1000 MW for land connections and up to 500 MW for submarine transmissions. In order to operate the thyristor valves require reactive power. For this reason filters and capacitor banks are used, but the usage of STATCOMs is also considered. (Fig. 7)

2.1.4. Smoothing Reactors

Smoothing reactors are large inductances connected in series with each pole. They prevent the current interruption at minimum load, limit the DC fault current, prevent resonances in the DC circuit and reduce the harmonic current caused by interferences from the overhead lines.

Figure 7. Thryristor Valves Hall

2.1.5. *Capacitor Banks and STATCOMs (Static Synchronous Compensator)*

Since the valves in the converters require reactive power, it is necessary to include in the design of the converter station capacitor banks or STATCOMs. This way the control of the reactive power balance is achieved. Capacitor banks consist of a series of capacitors connected in parallel to the transformer.

A static synchronous compensator (STATCOM) is a member of the FACTS (Flexible Alternating Current Transmission System) family of devices. STATCOMs are designed with VSC technology and they improve the operation of the whole converter station due to their function to generate or consume reactive power.

2.1.6. *DC Cables and Return Path*

Two cables technologies have been developed until now:

- Mass-impregnated cables
- Oil-filled cables

2.1.7. *Auxiliary Power Set*

The purpose of the auxiliary power set is to supply power to the valves when they are fired at the beginning of the transmission. It also provides power to the cooling, control and protection devices when the wind farm is disconnected from the main grid.

2.1.8. *Offshore Substation*

As it has been mentioned before, there has never been a construction of an offshore platform to host a LCC converter and all of its components. It is important to notice that the overall size of a converter station using LCC technology is several times the size of a transformer station (used in HVAC transmission schemes). Thus, the size and apparently the cost of an offshore platform for HVDC LCC converter will be significantly bigger.

2.2. Voltage Source Converter

HVDC transmission based on VSC devices is a relatively new technology, since it has been developed after the evolution of IGBTs (Insulated Gate Bipolar Transistors). The first system was installed by ABB in Hellsjön, Sweden in 1997. It was a small transmission system (3 MW at 10 kV), installed mainly to test the reliability of the technology. Since then many HVDC VSC links have been constructed throughout the world, some of which include submarine cables.

HVDC VSC configurations are capturing more and more attention due to some expected advantages, which extend the possibility of uses of this system.

- Independent control of active and reactive power in each converter station. This allows controlling the transmitted power in the system. In the offshore station reactive power can be generated to supply wind turbines and the injection of active power in the transmission system can be control. In the onshore station, reactive and active power can be varied in order to control voltage and frequency variations in the AC network. In other words the system can operate in all four quadrants of the PQ-plane.
- Connection of the system to a weak AC grid since active and reactive power can be controlled. A wind farm can create problems if it is connected to weak grids due to the variations of the wind and the produced power. These problems can be solved when the control of active and reactive power is achieved.
- No risk of commutation failure as in LCC systems
- Decoupling of the connected AC networks.
- Possible function as a STATCOM supplying or consuming reactive power without absorption or generation of active power. This feature can be useful if the voltage level must be controlled at one end of the transmission system for stability reasons.
- Easier implementation of multiterminal schemes since the polarity on the DC side is the same in both the inverter and rectifier mode.
- The system is easier to design and more compact than a LCC station since fewer components are required. There is no need for STATCOMs or capacitor banks and fewer filters are installed in VSC converters. For this reason the size of the offshore platform that will be required to host the VSC converter station is smaller compared to LCC solutions. (Fig. 9)

A basic configuration of a transmission link from an offshore wind farm using HVDC VSC technology can be seen in Fig. 8.

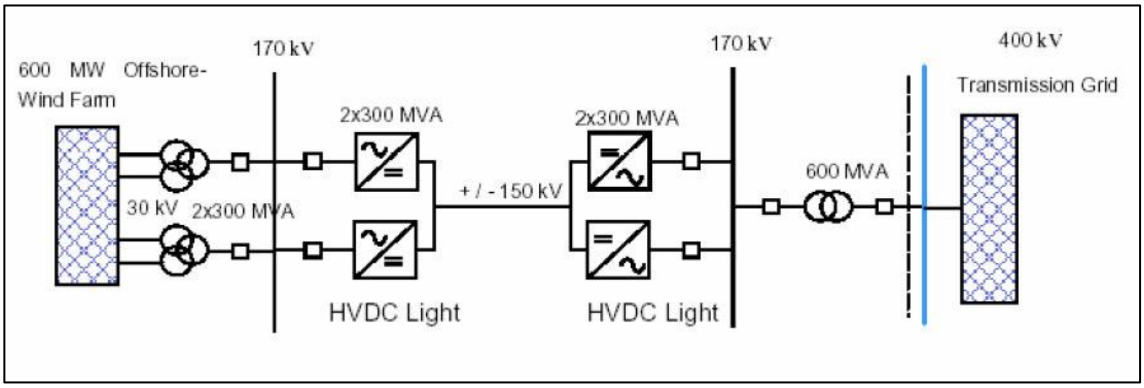
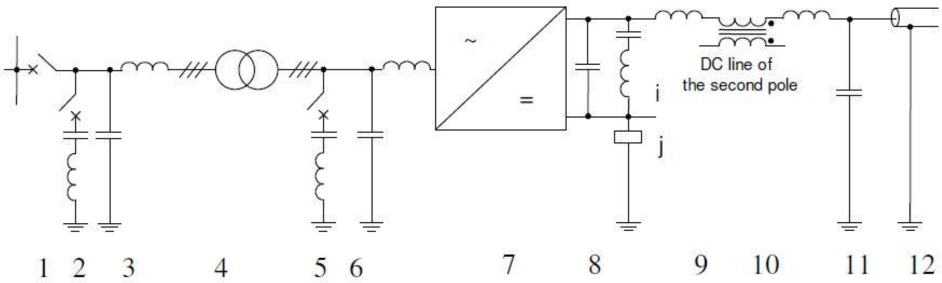


Figure 8. Wind farm connection in HVDC

Figure 9. HVDC Offshore Platform Hel Win1

The main components of an HVDC VSC based transmission for offshore wind farms line are:

- Converter stations (both offshore and onshore)
- Transformer
- Phase Reactor
- AC Filter
- DC-link Capacitor
- Cable pair (polymeric extruded cables)



1) VSC converter station circuit breaker
2) System side harmonic filter
3) AC side Radio Frequency Interference filter
4) Interface transformer
5) Converter side harmonic filter
6) HF-blocking filter/phase reactor
filter [b)]
7) VSC unit
line[b)]

8) VSC dc capacitor
9) DC harmonic filter
10) Neutral point grounding branch[a)]
11) DC reactor [b)]
12) Common mode blocking reactor [b)]
13) DC side Radio Frequency Interference
14) DC cable or overhead transmission

[a)] The location of the neutral point grounding branch may be different depending on the design of the VSC unit.
[b)] Not normally applicable for Back-to-Back systems.

Figure 10. HVDC VSC Main Components

2.2.1. HVDC VSC Conversion Station

The principle scheme of a VSC system converter station is shown in Fig. 10 including a list of its main components. The most important component of the converter station is the VSC unit. It is in this unit where the AC to DC (and vice versa) conversion takes place.

The device is based on IGBT components and it can reach high levels of converted power due to evolution of this semiconductor type. The switching frequency of the converter is of great importance. High value of switching frequency can reduce the number of harmonics and thus the number of filters but it increases the power losses and the inefficiency of the system. Existing VSC HVDC systems are designed with switching frequency between 1300 Hz (Cross Sound Cable) and 2000 Hz (Tjaereborg with wind power transmission).

A transformer connects the AC system to the converter in order to step up the voltage level for conversion in the VSC device. The interface transformer also provides reactance between the AC system and VSC system and prevents zero frequency currents from flowing between the AC system and the converter.

A number of filters are used both on the DC and AC side. These filters are mainly used to decrease the influence of harmonics induced in the system and to improve the overall performance of the converter.

The presence of auxiliary power equipment is necessary in the offshore converter substation in order to provide power to some components (cooling system, air conditioning system, control and protection devices), when the windfarm is disconnected.

2.2.2. Transformer

Transformers are used to interconnect the VSC with the AC network. The main function of the transformers is to adapt the voltage level of the AC network to a voltage suitable to the converter, or the opposite. This voltage level can be controlled using a tap changer, which will maximize the reactive power flow.

2.2.3. Phase Reactor

The phase reactors, known also as converter reactors are used to continuously control the active and reactive flow. According to [STAN10], the phase reactors have three main functions:

- to provide low-pass filtering of the PWM (pulse-width modulation) pattern to provide the desired fundamental frequency voltage;
- to provide active and reactive power control;
- to limit the short-circuit currents.

2.2.4. AC Filter

AC filters are used to eliminate the harmonic content of the output AC voltage. Otherwise, malfunctioning in the AC grid will appear.

Depending on the desired filter performances or requirements, the filter configuration is varying. In a typical HVDC scheme, the filter consists of two or three grounded / ungrounded tuned filter branches.

2.2.5. *DC-link Capacitor*

There are two capacitors stacks of the same power rating. The main goal is to provide a low-inductance path for the turned-off current. Moreover, the DC capacitor serves as an energy store and it reduces the harmonics ripple on the DC voltage.

Depending on the size of the DC side capacitor, DC voltage variations caused by disturbances in the system (AC faults) can be limited.

2.2.6. *DC Cables*

The cables used in VSC transmission systems are based on the extruded polymeric insulation technology. This solution has better thermal characteristics compared oil filled or mass impregnated cables. It also requires less auxiliary components and its maintenance is much simpler. Extruded cable presents good mechanical flexibility and strength and it can be installed also at high depth in submarine applications.

2.3. Reactive Power Consumption LCC and VSC

An HVDC converter converts electric power from high voltage alternating current (AC) to high-voltage direct current (HVDC), or vice-versa. HVDC is used as an alternative to AC for transmitting electrical energy over long distances or between AC power systems of different frequencies [HEYM12].

HVDC converters capable of converting up to 2000 megawatts (MW)[DAVI10] and with voltage ratings of up to 900 kilovolts [SKOG10] have been built, and even higher ratings are technically feasible. A complete converter station may contain several such converters in series and/or parallel.

Almost all HVDC converters are inherently bi-directional; they can convert either from AC to DC (rectification) or from DC to AC (inversion). A complete HVDC system always includes at least one converter operating as a rectifier (converting AC to DC) and at least one operating as an inverter (converting DC to AC).

Some HVDC systems take full advantage of this bi-directional property (for example, those designed for cross-border power trading, such as the Cross-Channel link between England and France).[ROWE87] (Fig. 11)

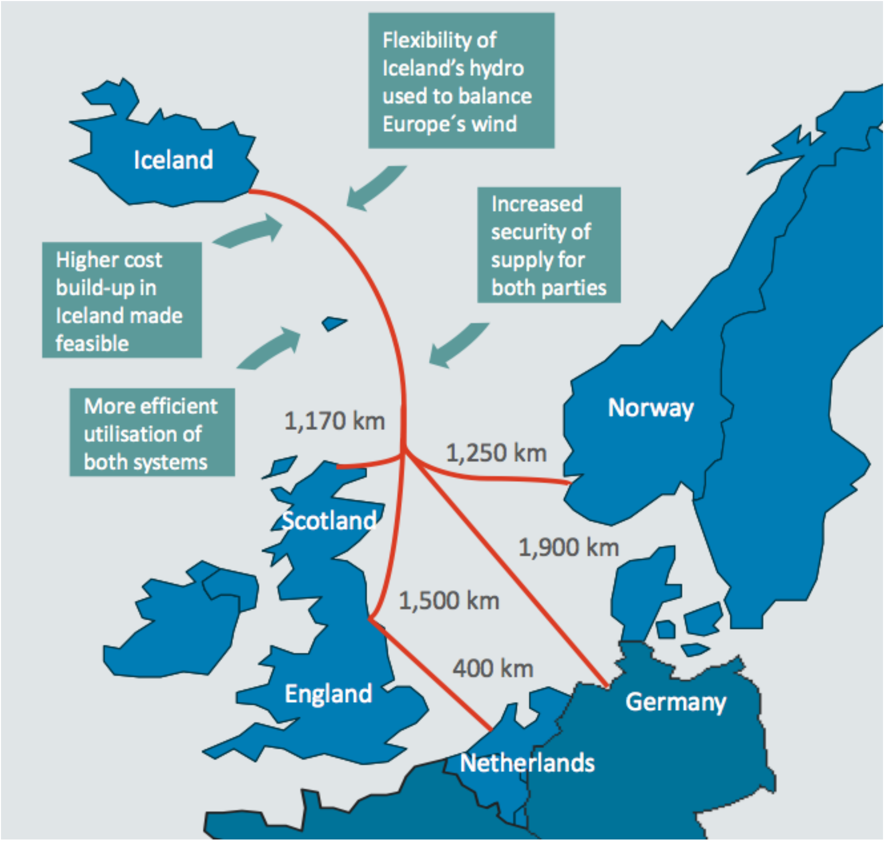


Figure 11. North Sea Planned HVDC Submarine Lines

Others, for example those designed to export power from a remote power station such as the Itaipu scheme in Brazil may be optimised for power flow in only one preferred direction [PRAÇ96]. In such schemes, power flow in the non-preferred direction may have a reduced capacity or poorer efficiency.

HVDC converters can take several different forms. Early HVDC systems, built until the 1930s, were effectively rotary converters and used electromechanical conversion with motor-generator sets connected in series on the DC side and in parallel on the AC side[PEAK09]. However, all HVDC systems built since the 1940s have used electronic (static) converters.

As of 2012, both the line-commutated and voltage-source technologies are important, with line-commutated converters used mainly where very high capacity and efficiency are needed, and voltage-source converters used mainly for interconnecting weak AC systems, for connecting large-scale wind power to the grid or for HVDC interconnections that are likely to be expanded to become Multi-terminal HVDC systems in future. The market for VSC HVDC is growing fast, driven partly by the surge in investment in offshore wind power, with one particular type of converter, the Modular Multi-Level Converter (MMC)[LESN03] emerging as a front-runner.

2.3.1. LCC (Line-commutated converters)

With this classical technology it is possible to control the opening (depending on the phase shift α) of the thyristors but not the closing. That means that we can control the active power P but not the reactive power Q.

Q is in function of P, α and d (loss of relative inductive tension).

$$Q = P.\tan(cos^{-1}(\cos(\alpha - d))) \quad (1.1)$$

These results into a Q consumed between 30 and 55 % of P for real simulation. When we are working with back-to-back systems, in order to connect two systems with different frequency; we can use just one converter to do the two conversions. The Graëtz bridge will work as a rectifier with an angle α between 0 and 90 degrees and it will work as an inverter with an α between 90 and 180 degrees.

2.3.2. VSC (Voltage-sourced converters)

In order to have an independent control of the active power P and the reactive power Q the VSC technology has been developed. [ASPL98]

The equivalent circuit one line diagram of the system is in Fig. 12. The steady-state phasor diagram of the system is shown in Fig. 13.

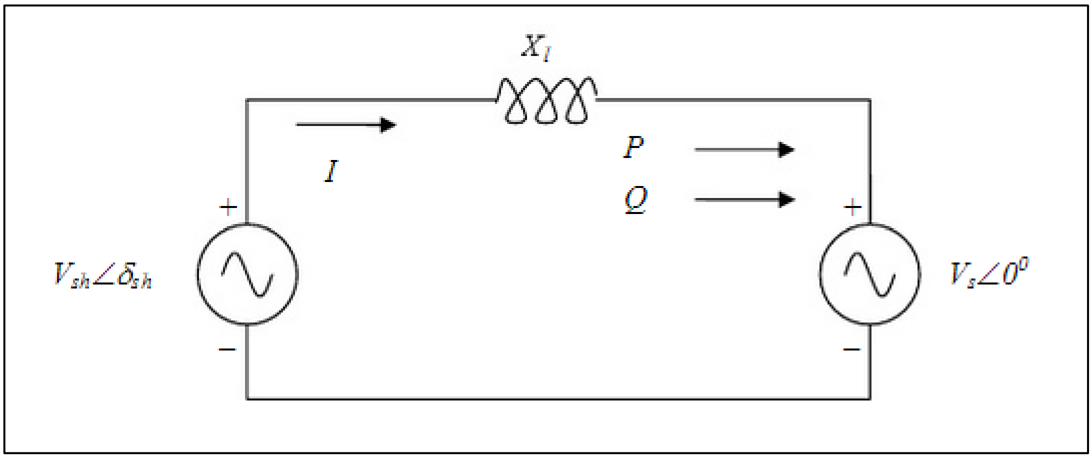


Figure 12. VSC schema with a lossless reactor

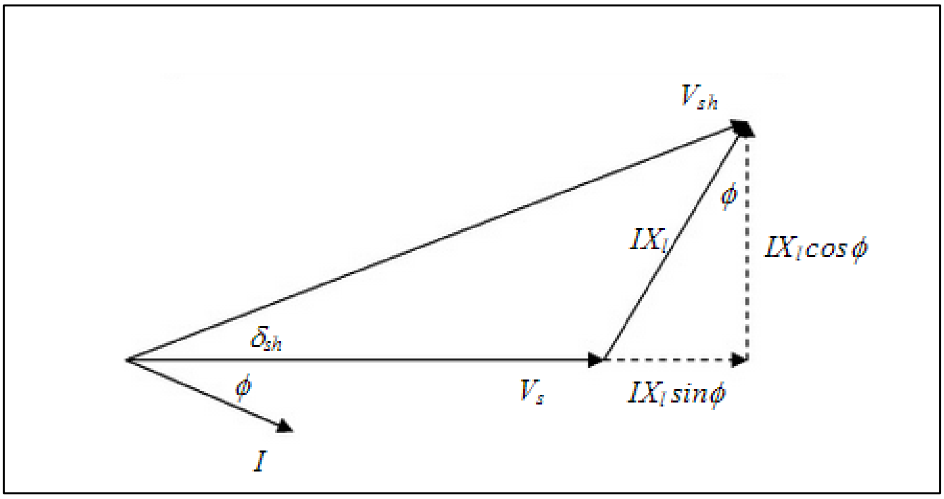


Figure 13. Steady-state phasor diagram of a VSC connected to an AC system

The active and reactive components of the complex power injected at the AC system can be expressed as:

$$P = VI\cos\theta \quad (1.2)$$

$$Q = VI\sin\theta \quad (1.3)$$

According to the phasor diagram; the following equations can be derived:

$$IX_l\cos\theta = V_{sh}\sin\delta_{sh} \quad (1.4)$$

$$IX_l\sin\theta = V_{sh}\cos\delta_{sh} - V_s \quad (1.5)$$

Therefore,

$$I\cos\theta = \frac{V_{sh}\sin\delta_{sh}}{X_l} \quad (1.6)$$

$$I\sin\theta = \frac{V_{sh}\cos\delta_{sh} - V_s}{X_l} \quad (1.7)$$

Substituting equations:

$$P = \frac{V_{sh}V_s\sin\delta_{sh}}{X_l} \quad (1.8)$$

$$Q = \frac{V_{sh}V_s\sin\delta_{sh}}{X_l} - \frac{{V_s}^2}{X_l} \quad (1.9)$$

Where

V_{sh}	VSC source voltage
V_s	AC system voltage
Φ	Phase angle of the current flowing from a VSC to an AC system
X_l	Reactance of the series capacitor compensated transmission line
X_l	Current flowing from a VSC to an AC system
δ_{sh}	Phase angle of the VSC source voltage

Table 2. Elements equation number

Realizing that we can independently control the phase shift angle α and the amplitude of the tension the generator-inductance side V_{sh} l, it is possible to control independently at each instant P and Q:

$$P = f(\delta_{sh}) \ (1.10)$$

$$Q = f(Amplitude\ of\ V_{sh}) \ (1.11)$$

All of this is possible because now we use IGBTs instead of thyristors so we can control the closing and opening of the device. Furthermore the IGBTs have much less loses than the thyristors due to the low power control needed for a MOSFET gate

The control of the signals is done due to the technic of PWM (Pulse Width Modulation) which consists in the generation and filtering of a signal in high frequency, so we can obtain a signal at the output of the filter at the requested frequency (50 Hz).

The signal at the output of the converter has always the same amplitude but its pulse change its duration, which means that we have a signal with an average tension that varies depending on the pulse width.

2.4. Conclusion between HVDC technologies: VSC vs LCC

Nowadays VSC technology has a lower price (€/KW) than LCC technology (Fig. 14). In addition, it has better performances (until 300 MW). The most important facts are:

- VSC has a maximum power of 350 MW and a voltage of 150 KV.
- VSC is a bipolar system while LCC allows monopolar systems.
- VSC allows to control P and Q independently while in LCC we can just control P and Q is a function of P.
- The LCC converters need big filters due to its high consume of reactive power while VSC needs much littler filters.
- VSC allows controlling the frequency and voltage independent from the AC network. The short-circuit current and the reactive power are not such a decisive factors.
- The modularity of VSC makes it very easy to be implemented.

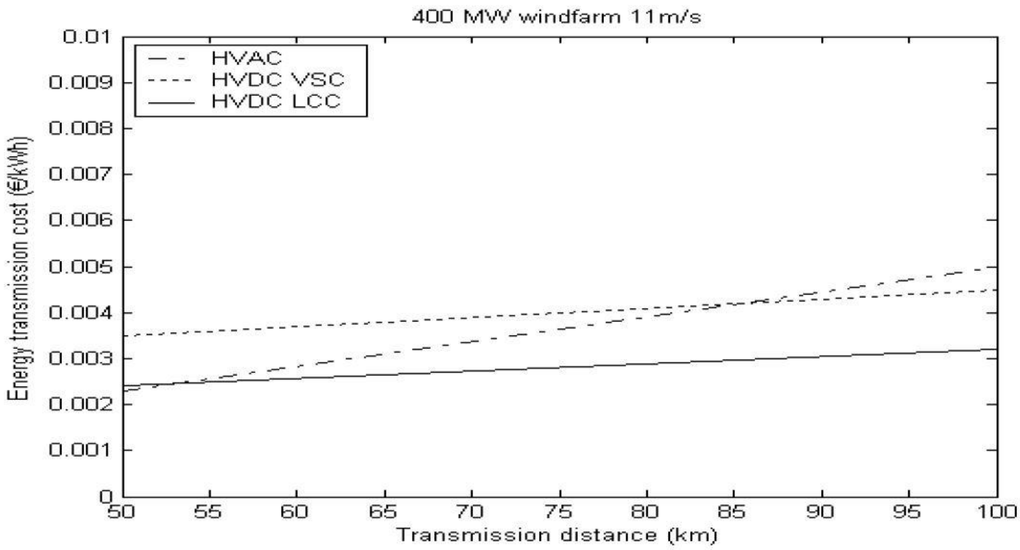


Figure 14. HVAC vs HVDC LCC vs HVDC VSC Costs

3. HVDC Poles

The system configuration strongly depends on local conditions, objectives, and economic factors. Both VSC and LCC can use the same configuration, and modifications can be made depending on local conditions.

HVDC converter bridges and lines or cables can be arranged into a number of configurations for effective utilization. The connexion of the converter bridges maybe be arranged either monopolar or bipolar as shown in Fig. 15 and are described as follow.

3.1. Monopolar/Bipolar HVDC systems

3.1.1. Monopolar HVDC System

In monopolar links, two converters are used, separated by a single pole line and a positive or a negative DC voltage is used. In Fig. 15(a) there is only one insulated transmission conductor installed and the ground is used for the return current. Instead of using the ground as a return path, a metallic return conductor may be used. For instance, the Konti-Skan (1965) project and Sardinia-Italy (mainland) (1967) project use monopolar links.

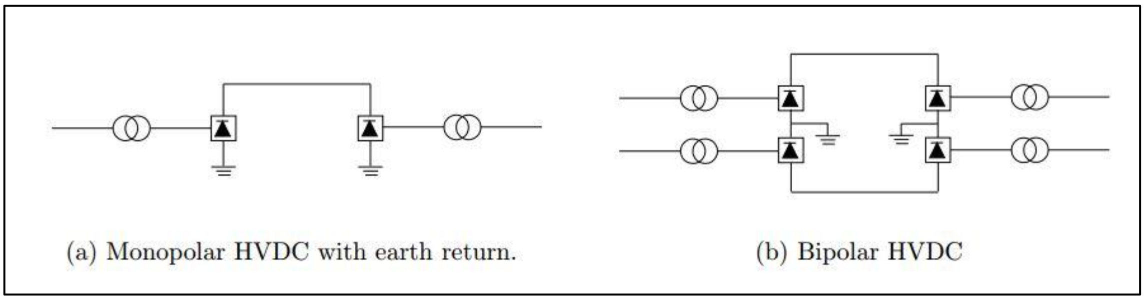


Figure 15. Monopolar and bipolar connection of HVDC converter bridges

3.1.2. Bipolar HVDC System

This is the most commonly used configuration of HVDC power transmission systems. The bipolar circuit link, shown in Fig. 15(b), has two insulated conductors used as plus and minus poles. The two poles can be used independently if both neutrals are grounded. It increases power transfer capacity.

Under normal operation, the currents flowing in each pole are equal, and there is no ground current. In case of failure of one pole or the ground line, power transmission can continue on the other pole or between poles, so its reliability is high.

3.2. HVDC Configurations

The selection of configurations of HVDC system depends on the function and location of the converter stations. Various schemes and configurations of HVDC systems are shown in Fig. 16:

3.2.1. Back-to-back HVDC systems

The two converter stations are located at the same site and no transmission line or cable is required (Fig. 16(a)). The two AC systems interconnected may have the same or different nominal frequency, i.e. 50Hz and 60Hz.

The back-to-back link can be used to transmit power between two neighbouring non-synchronous systems. Other use of this configuration could be to filter a sinusoidal from a noisy network, and send a proper sinusoidal current.

The DC voltage in this case in quite low (i.e. 50kV-150kV) and the converter does not have to be optimized with respect to the DC bus voltage and the associated distance to reduce costs, etc.

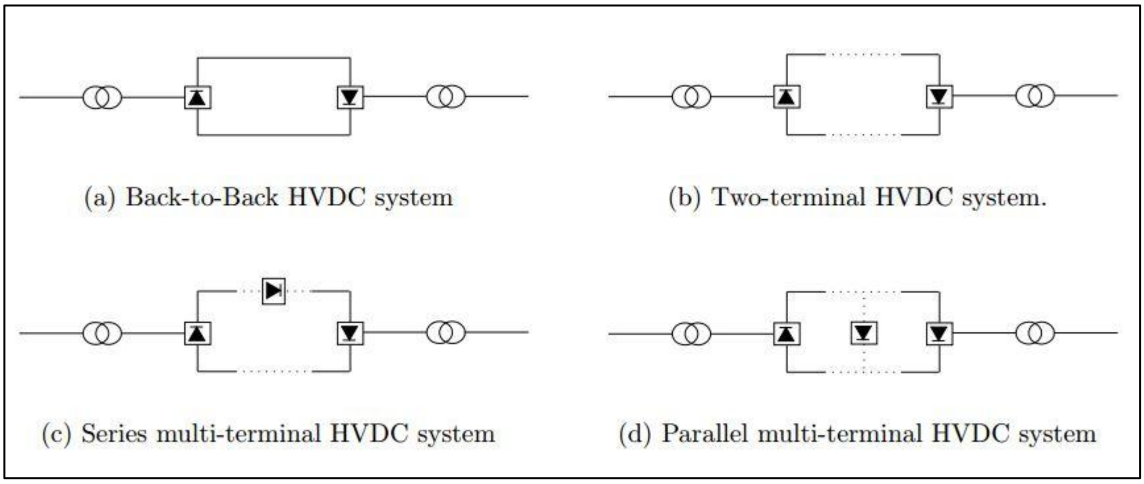


Figure 16. Arrangements of HVDC systems.

3.2.2. Transmission between two substations.

When it is economical to transfer electric power through DC transmission from one geographical location to another, a two-terminal or point-to-point HVDC transmission system, shown in Fig. 16(b), is used. In other words, DC power from a DC rectifier terminal is transported to the other terminal operating as an inverter.

This is typical of most HVDC transmissions systems. The link may connect two non-synchronous systems (e.g. between Sweden and Denmark) or connect two substations within one interconnected system (e.g. between Three-Gorges to Shanghai link in China).

3.2.3. Multi-terminal HVDC transmission system.

When three or more HVDC substations are geographically separated with interconnecting transmission lines or cables, the HVDC transmission system is multi-terminal. If all substations are connected to the same voltage then the system is parallel multi-terminal DC, shown in Fig. 16(c). If one or more converter bridges are added in series in one or both poles, then the system is series multi-terminal DC shown in Fig. 16(d).

A combination of parallel and series connections of converter bridges is a hybrid multi-terminal system. Multi-terminal DC systems are more difficult to justify economically because of the cost of the additional substations. Examples of multi-terminal HVDC were implemented in the connection Sardinia-Corsica-Italy and the connection Hydro Quebec-New England Hydro from Canada to the US.

4. Use of HVDC

AC transmission systems are still the most used due to a more competitive price advantage. But a HVDC system will be considered more profitable than the AC system at some particular application.

4.1. Transmission distance

In large power transmission over long distances, HVDC provide an economically competitive alternative to the system over AC transmission. Apart from the additional loss due to the use of the converter compared to the AC system, the channel loss on HVDC transmission can be smaller (30 to 50%) than the equivalent AC channel at the same distance. At a great distance, transmission systems require AC substations in the middle of the channel as well as reactive compensation, whereas DC transmission does not require intermediate substations. A typical distance which the use of HVDC will benefit economically is 500 km and above.

4.2. The use of cable

In cases where the use of cables is needed, such as the transmission through oceans, or underground transmission designs, the use of HVDC is more economically beneficial than the use of AC cables. Another issue on the use of wires with an AC system is the reduction of cable capacity due to long distances because of high reactive power. This is because of the characteristics of the cable, which has a larger capacitance and the inductance is less than the equivalent air conductor.

4.3. Interconnection frequency

Interconnection between 2 areas of different frequencies can only be done by using the HVDC to ensure continuity of reliable operation. An example is the Shin-Shinano substation of 600 MW which connects western Japan (Japanese-frequency is 60 Hz) with the eastern part, whose frequency is 50 Hz. Not only in cases like Shin-Shinano are frequencies different between the two terminals. There are several other cases like connecting two different power companies using HVDC frequency converters.

4.4. HVDC versus HVAC transmission

Modern high voltage direct current (HVDC) systems can transmit up to five times more power across the same pylons and wires as AC systems and are the technology of choice for bulk transmission over long distances. Moreover, given the increasing difficulties in obtaining permissions for new power lines in both urban and rural areas, HVDC is often the only solution for increasing capacity over shorter distances.

In order to minimise environmental impacts, we can replace offshore gas turbines by either AC or DC transmission to link offshore platforms with onshore electrical networks. This ensures high performance while optimising the use of the plant and reducing the gas emissions associated with power generation.

HVDC is also the technology of choice for underwater cables, such as those linking offshore platforms to the grid. Over a certain distance, the reactive power produced by an AC submarine cable would take up the entire current carrying capacity of the conductor, so no usable power would be transmitted [CANE10].

AC current has become the most used, but there is still a problem for transmission lines of long distance. So HVDC is needed for some projects.

Obviously, for a high voltage transmission line the main limit is the voltage. The other important factor is the current. Another factor that reduces the useful current carrying ability of AC lines is the skin effect, which causes a non-uniform distribution of current over the cross-sectional area of the conductor. Transmission line conductors operating with HVDC current do not suffer from either of these constraints. Therefore, for the same conductor losses (or heating effect), a given conductor can carry more current to the load when operating with DC than AC.

Furthermore, the switching surges are the serious transient over voltages for the high voltage transmission line, in the case of AC transmission the peak values are two or three times normal crest voltage but for DC transmission it is 1.7 times normal voltage. HVDC transmission has less corona and radio interference than that of HVAC transmission line. The total power loss due to corona is less than 5 MW for a ± 450 kV and 895 kilometres HVDC transmission line. [BATE69, MORR79].

The long HVAC overhead lines produce and consume the reactive power, which is a serious problem. If the transmission line has a series inductance L and shunt capacitance C per unit of length and operating voltage V and current I, the reactive power produced by the line is:

$$Q_C = \omega.C.V^2 \quad (2.1)$$

Consumer reactive power per unit length

$$Q_L = \omega.L.I^2 \quad (2.2)$$

If $Q_c = Q_L$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_S \quad (2.3)$$

Where Z_S is surge impedance of the line. The power in the line is

$$P_N = V.I = \frac{V^2}{Z_S} \quad (2.4)$$

It is called natural load. So the power carried by the line depends on the operating voltage and the surge impedance of the line. Table I shows the typical values of a three phase overhead lines [].

Voltage (KV)	132	230	345	500	700
Natural load (MW)	43	130	300	830	1600

Table 3. Voltage Rating and Power Capacity

The power flow in an AC system and the power transfer in a transmission line can be expressed:

$$P = \frac{E_1 E_2}{X} \sin \delta \quad (2.5)$$

Where E_1 and E_2 are the two terminal voltages, δ is the phase difference of these voltages, and X is the series reactance. Maximum power transfer occurs at $\delta = 90^{\circ}$.

P_{max} is the steady-state stability limit. For a long distance transmission system the line has the most of the reactance and very small part is in the two terminal systems, consisting of machines, transformers, and local lines.

The inductive reactance of a single-circuit 60 Hz overhead line with single conductor is about 0.5Ω/km; with double conductor is about 3/4 as greater. The reactance of the line is proportional to the length of the line, and thus power per circuit of an operating voltage is limited by steady-state stability, which is inversely proportional to length of line. For the reason of stability the load angle is kept at relatively low value under normal operating condition (about 30°) because power flow disturbances affect the load-angle very quickly.

In an uncompensated line the phase angle varies with the distance when the line operating at natural loads and puts a limit on the distance. For 30° phase angle the distance is 258 mi at 60 Hz. The line distance can be increased using series capacitor, whose reactance compensates a part of series inductive reactance of the line, but the maximum part that can be compensated has not been determined yet.

On the other hand D.C transmission has no reactance problem, no stability problem, and hence no distance limitation.

5. Advantages and disadvantages of HVDC

In many cases, projects are justified on a combination of benefits from the two groups. Today environmental aspects are becoming more important and have to be take into account.

HVDC is in that respect favourable in many cases, as the environmental impact is less than with AC. This is due to the fact that an HVDC transmission line is much smaller and needs less space than AC lines for the same power capacity.

The system characteristics of an HVDC link differ a lot from AC transmissions. One of the most important differences is related to the possibility to accurately control the active power transmitted on a HVDC line. This is in contrast to AC lines, where the power flow cannot be controlled in the same direct way.

The controllability of the HVDC power is often used to improve the operating conditions of the AC networks where the converter stations are located.

Other important property of an HVDC transmission is that it is asynchronous. This allows the interconnection of non-synchronous networks [ABB__2].

5.1. Advantages

The most common reason for choosing HVDC over AC transmission is that HVDC is more economic than AC for transmitting large amounts of power point-to-point over long distances. A long distance, high power HVDC transmission scheme generally has lower capital costs and lower losses than an AC transmission link.

Even though HVDC conversion equipment at the terminal stations is costly, overall savings in capital cost may arise because of significantly reduced transmission line costs over long distance routes.

HVDC needs fewer conductors than an AC line, as there is no need to support three phases. Also, thinner conductors can be used since HVDC does not suffer from the skin effect. These factors can lead to large reductions in transmission line cost for a long distance HVDC scheme.

Depending on voltage level and construction details, HVDC transmission losses are quoted as about 3.5% per 1,000 km, which is less than typical losses in an AC transmission system [SIEM11]. (Fig. 17)

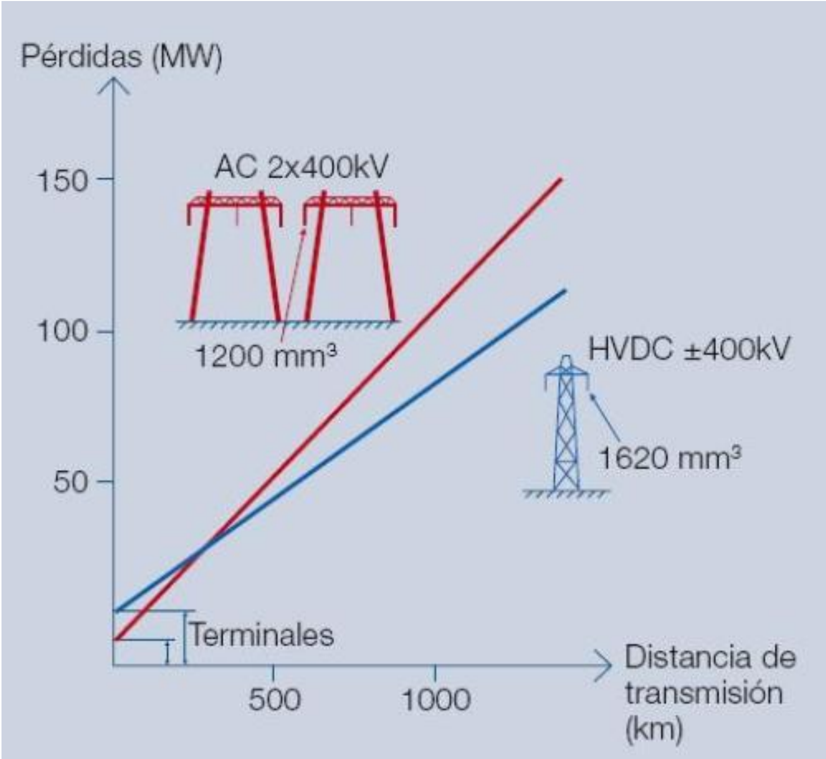


Figure 17. Losses vs Distance

HVDC transmission may also be selected because of other technical benefits that it provides for the power system. HVDC schemes can transfer power between separate AC networks. HVDC powerflow between separate AC systems can be automatically controlled to provide support for either network during transient conditions, but without the risk that a major power system collapse in one network will lead to a collapse in the second.

The combined economic and technical benefits of HVDC transmission can make it a suitable choice for connecting energy sources that are located remote from the main load centres.

Specific applications where HVDC transmission technology provides benefits include:

1. Undersea cables transmission schemes (e.g., 250 km Baltic Cable between Sweden and Germany[SIEM11], the 580 km NorNed cable between Norway and the Netherlands[20], and 290 km Basslink between the Australian mainland and Tasmania[SKOG10]).

2. Endpoint-to-endpoint long-haul bulk power transmission without intermediate 'taps', for example, in remote areas, usually to connect a remote generating plant to the main grid, for example the Nelson River DC Transmission System.

3. Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.

4. Power transmission and stabilization between unsynchronised AC networks, with an extreme example being the ability to transfer power between different countries that use AC at differing frequencies. Since such transfer can occur in either direction, it increases the stability of both networks by allowing them to draw on each other in emergencies and failures.

5. Stabilizing a predominantly AC power-grid, without increasing prospective short circuit current.

5.1.1. Undersea/Underground Cables Systems

Long undersea/underground high voltage cables have a high electrical capacitance compared with overhead transmission lines, since the live conductors within the cable are surrounded by a relatively thin layer of insulation (the dielectric), and a metal sheath. The geometry is that of a long co-axial capacitor.

The total capacitance increases with the length of the cable. This capacitance appears in parallel with the load. Where alternating current is used for cable transmission, additional current must flow in the cable to charge the cable capacitance. This current flow causes energy loss via dissipation of heat in the conductors of the cable. Additional energy losses occur as a result of dielectric loss in the cable insulation.

However, when direct current is used, the cable capacitance is charged only when the cable is first energized or when the voltage is changed; there is no steady-state additional current required. For a long AC undersea cable, the entire current-carrying capacity of the conductor could be used to supply the charging current alone. The cable capacitance issue limits the length and power carrying capacity of AC cables.

DC cables have no such limitation, and are essentially bound by only Ohm's Law. Although some DC leakage current continues to flow through the dielectric insulators, this is very small compared to the cable rating and much less than with AC transmission cables.

5.1.2. Overhead line systems / Skin Effect

The capacitive effect of long underground or undersea cables in AC transmission applications also applies to AC overhead lines, although to a much lesser extent. Nevertheless, for a long AC overhead transmission line, the current flowing just to charge the line capacitance can be significant, and this reduces the capability of the line to carry useful current to the load at the remote end.

Another factor that reduces the useful current carrying ability of AC lines is the skin effect, which causes a non-uniform distribution of current over the cross-sectional area of the conductor. Transmission line conductors operating with HVDC current do not suffer from either of these constraints. Therefore, for the same conductor losses (or heating effect), a given conductor can carry more current to the load when operating with HVDC than AC.

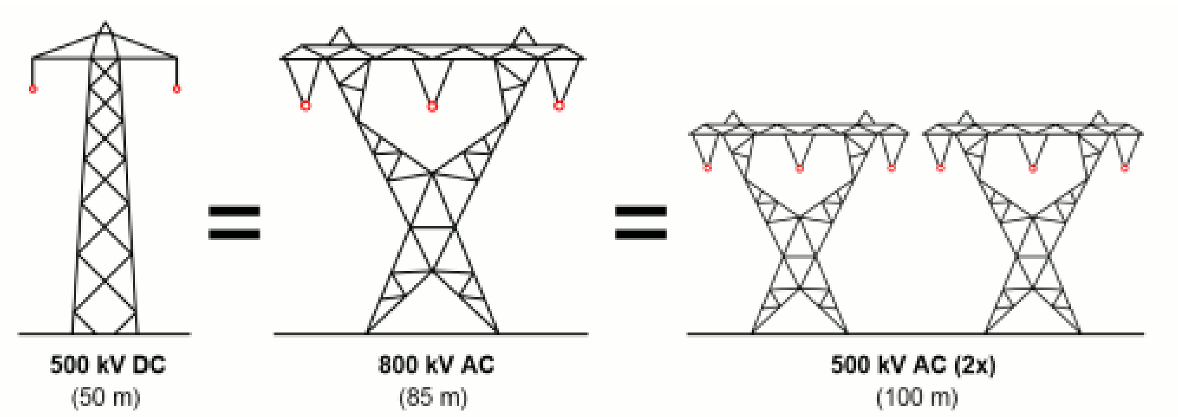


Figure 18. Three high-voltage configurations with 2 GW capacity.

As Fig. 18 shows, this means that a DC power line will be significantly smaller than its AC equivalent, roughly by a factor of two. Since AC and DC use roughly the same types of cables, this translates into reduced line costs and reduced tower costs. In addition, the ground clearance required is reduced considerably. In regions where land is expensive and regulations are strict, obtaining a contiguous strip of ground can be as much of a challenge as putting up the lines themselves – and DC is 40-50% cheaper in this respect. DC was chosen in the Rihand-Delhi project (India) and the Queensland project (Australia) in part because the towers were more compact.

Finally, depending upon the environmental conditions and the performance of overhead line insulation operating with HVDC, it may be possible for a given transmission line to operate with a constant HVDC voltage that is approximately the same as the peak AC voltage for which it is designed and insulated. The power delivered in an AC system is defined by the root mean square (RMS) of an AC voltage, but RMS is only about 71% of the peak voltage.

Therefore, if the HVDC line can operate continuously with an HVDC voltage that is the same as the peak voltage of the AC equivalent line, then for a given current (where HVDC current is the same as the RMS current in the AC line), the power transmission capability when operating with HVDC is approximately 140% of the capability when operating with AC.

5.1.3. Asynchronous connections

Because HVDC allows power transmission between unsynchronized AC distribution systems, it can help increase system stability, by preventing cascading failures from propagating from one part of a wider power transmission grid to another.

Changes in load that would cause portions of an AC network to become unsynchronized and separate would not similarly affect a DC link, and the power flow through the DC link would tend to stabilize the AC network.

The magnitude and direction of power flow through a DC link can be directly commanded, and changed as needed to support the AC networks at either end of the DC link. This has caused many power system operators to contemplate wider use of HVDC technology for its stability benefits alone.

5.2. Disadvantages

The disadvantages of HVDC are in conversion, switching, control, availability and maintenance.

HVDC is less reliable and has lower availability than alternating current (AC) systems, mainly due to the extra conversion equipment. Single-pole systems have availability of about 98.5%, with about a third of the downtime unscheduled due to faults. Fault-tolerant bipole systems provide high availability for 50% of the link capacity, but availability of the full capacity is about 97% to 98%. [BENN12]

The required converter stations are expensive and have limited overload capacity. At smaller transmission distances, the losses in the converter stations may be bigger than in an AC transmission line. The cost of the converters may not be offset by reductions in line construction cost and lower line loss.

Operating a HVDC scheme requires many spare parts to be kept, often exclusively for one system, as HVDC systems are less standardized than AC systems and technology changes faster.

In contrast to AC systems, realizing multiterminal systems is complex (especially with line commutated converters), as is expanding existing schemes to multiterminal systems. Controlling power flow in a multiterminal DC system requires good communication between all the terminals; power flow must be actively regulated by the converter control system instead of the inherent impedance and phase angle properties of the transmission line.[LEEL07].

Multi-terminal systems are rare. On 2012 only two are in service: the Hydro Québec – New England transmission between Radisson, Sandy Pond, and Nicolet[NEPO08] and the Sardinia–mainland Italy link which was modified in 1989 to also provide power to the island of Corsica.[BILL89]

HVDC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching. In November 2012, ABB announced development of the world's first HVDC circuit breaker.[CALL12][27]

The ABB breaker contains four switching elements, two mechanical (one high-speed and one low-speed) and two semiconductor (one high-voltage and one low-voltage). Normally, power flows through the low-speed mechanical switch, the high-speed mechanical switch, and the low-voltage semiconductor switch. The last two switches are paralleled by the high-voltage semiconductor switch.

Initially, all switches are closed (on). Because the high-voltage semiconductor switch has much greater resistance than the mechanical switch plus the low-voltage semiconductor switch, current flow through it is low. To disconnect, first the low-voltage semiconductor switch opens. This diverts the current through the high-voltage semiconductor switch. Because of its relatively high resistance, it begins heating very rapidly.

Then the high-speed mechanical switch is opened. Unlike the low-voltage semiconductor switch, which is only capable of standing off the voltage drop of the closed high-voltage semiconductor switch, this is capable of standing off the full voltage. Because no current is flowing through this switch when it opens, it is not damaged by arcing.

Then, the high-voltage semiconductor switch is opened. This actually cuts the power. However, it only cuts power to a very low level; it is not quite 100% off. A final low-speed mechanical switch disconnects the residual current.[27]

5.2.1. Economical Aspect

Bulk power could be transferred using HVDC or HVAC transmission system from a remote generating station to the load centre. Direct cost comparisons between AC and DC alternatives should be conducted before making a decision. In order to compare the cost, all main system elements must be taken into consideration.

For the DC alternative, capital cost for the converter terminals, AC input/output equipment, filters, the interconnecting transmission line must be accounted. For the AC alternative, capital cost for the step-up/step-down transformer, the overhead line, light load compensation if required, reactive power compensation, circuit breaker, building should be evaluated. Control system cost need to be considered for the both case. Table 4 shows generic cost comparison elements [BOWL90, CPIU12].

For the preliminary planning stage, the capital cost for the terminals and transmission line are the main concern. For example, Nelson River HVDC Transmission line Bipole 1 is considered here for economic analysis.

AC station costs

Alternating current switching and substation plant may include the cost of following major items:

- power circuit breakers
- power transformer
- disconnect switches
- reactors
- shunt capacitors
- static capacitors
- synchronous compensators
- series capacitors
- bus work
- protection and control systems
- structures
- control houses

Estimate the costs is not a straight forward calculation, because the equipment's' costs are always varying and also it varies from place to place and company to company. For this calculation, the installed cost of each of these items includes cost of materials or equipment, construction, land, material handling, surveys and usually overhead charges.

At the beginning of the survey several transmission arrangements were investigated for the Bipole 1, but preliminary examination narrowed down to 500 AC or ± 450 DC. The cost comparison between them is discussed here. Installed costs for 500 kV AC substation for the Nelson River Bipole 1 is shown in Table 4.

The estimate cost for the circuit breaker and transformer include the approximate cost of related control and protection, bus work, disconnect switches, related structures, and control houses. Total cost for the sending and receiving end AC stations is $37.69 million. All costs are calculated on the basis of year 1985.

The cost of electrical and electronic equipments varies time to time; naturally the cost goes down with newer technology. The HVDC and HVAC system consist of not only the equipment cost but also the labor cost, which goes up with the time. If both costs compensate each other, the present cost would be the same as 1985's cost. By taking inflation into account, the costs in 1985 can be converted to the present equivalent cost, and the multiplying factor is 1.73 [18].

Type of equipment	Cost ($)
Circuit breaker	1500000.00
Transformer	1534500.00
Shunt Capacitor	1787500.00
Series Capacitor	2200000.00
Sialic var system	8250000.00
Shunt reactors	3575000.00

Table 4. AC Substation costs for Bipole I

AC transmission line costs

AC transmission line ROW needs bigger space and more construction cost than those of DC transmission for the same power capability and comparable reliability. AC transmission line has 3 power carrying conductors whereas DC transmission has only two and theses reasons increase the AC transmission line costs significantly. A typical cost for 500 kV AC line is $955/kV-mile. Nelson River Bipole 1 is 895 km (556.2 miles); total transmission line cost is 265.6 million dollars. Total cost for the Nelson River Bipole 1 if AC transmission would be used is 303.29 million dollars.

DC station cost and line cost

The main equipment of the D.C station is converters and more than 50% costs of HVDC transmission system are related to the converters. The converter stations are the key component to make an economical comparison between DC and AC transmission system. For an AC system the line costs predominate and station costs are small and for the DC system stations costs predominate and line costs are small. Table 5 shows the percentage of each main component cost relative to the total station cost for DC system [28-29].

Equipment	Percentage of total cost
Converter transformers	20-25
Valves	20-30
Filters and var supply	5-20
Miscellaneous	5-15
Engineering	2-5
Civil work and site installation	15-30

Table 5. DC System Costs as a percentage of Total Project Costs

5.2.2. *Environmental aspect*

The purpose of the power transmission line is to carry energy from generation stations to urban or industrial places. To satisfy the growing need of the energy the transmission line capacity has been increased rapidly recent years, and this trend is continuing. The typical high voltage transmission line range is 400-1000 kV and this huge voltage has to cross all kinds of terrain - urban area, village, water, desert, and mountain.

The effect of high voltage on the environment and human being is a topical and even controversial issue in recent year. This section discusses HVDC transmission effects on the environment in the context of Nelson River transmission system. The common effects of high voltage transmission systems are magnetic fields, electric fields, RF interference, corona effects, electromagnetic interference, electrodes, acoustic noise and visual impact. [SCHM96]

5.2.3. *Magnetic field*

The magnetic field around a conductor depends on the current flowing through the conductor and the distance from the conductor. The magnetic flux density is inversely proportional to the distance from the conductor. For ± 450 kV DC transmission line the flux density is about 25 μT, where the Earth's natural magnetic field is 40 μT [19].

5.2.4. *Electric field*

Electric field is produced by the potential difference between the overhead conductor and the earth and the space-charge clouds produced by conductor corona. Directly under the conductor has the highest electric field and is approximately 20 kV/m for a ± 450 kV transmission line. The electric field may change with the weather, seasonal variation and relative humidity.

DC has less electric field problem than that of AC because of the lack of steady-state displacement current; thus HVDC require much less right-ofway (ROW) than horizontal AC configuration and less height than the AC delta configuration of HVAC transmission of comparable rating.

The potential difference between land electrode and line conductor is termed as step voltage, can cause shock current. The typical human body resistance of 1000 ohms, a limit value of 5 mA current can flow through the human body safely and DC has the less electric current density, which is 70 nA/m2 for ± 450 kV transmission line.

5.2.5. Corona effect

Corona effects on the surface of high voltage overhead power transmission lines are the principal source of radiated noise. The ion and corona effects on the DC transmission lines lead to a small contribution of ozone production.

The natural concentration of ozone in the clean air is approximately 50 ppb (parts per billion) and in the city area this value may reach 150 ppb. The limiting values for persons risk is around 180-200 ppb. The HVDC overhead transmission line produces 10 ppb as compared with naturally occurring concentration.

5.2.6. Radio, TV and telephone interference

The switching process of the thyristor valves of the electronic converters causes fast current commutations and voltage changes, which produces parasitic current. The parasitic current and operational harmonics cause disturbances in the kilohertz and megahertz region of the radio-frequency spectrum.

These high frequencies propagate to the overhead line through the converter transformers. Radio interference radiation can be reduced by electromagnetic shielding of the valve hall. The radio-interference level of an HVDC overhead transmission line is lower than that of HVAC overhead transmission line. For the HVDC it is 40 dB (μV/m) for 0.5 MHz, 300 meter from the conductor, for the 380 kV HVAC overhead transmission line the value is 50 dB (μV/m).

The fair weather corona-generated line radio interference is about 35 dB at 30 m and 40 dB at 15 m from the outer conductor at ± 450 kV.

The power line carrier frequency interference can occur at the frequency band 30-400 kHz. The thyristor operation produces the harmonics, and this harmonic current induces potentials in the lines as results of their electromagnetic fields. These potentials can interfere with the telecommunication systems electrically and magnetically. This interference can be reduced using appropriate filter circuits.

5.2.7. Acoustic noise

The main sources of acoustic noise are the road and rail traffic, and very small portion come from the industrial plant like power plant. The subjective perceptions of acoustic noise nuisance are dependent on the amplitude, frequency and duration of the noise.

The accepted limit of the acoustic noise for the industrial plant depends on the local conditions but is generally between 35 and 45 dB (A). The HVDC transmission system contains numbers of subassemblies and components which cause noise. The transformer is the principle source of noise, and its noise mainly depends on the core flux density. The no load operational noises are 10 to 20 dB (A) higher than that of the rated load operation.

With converter transformers, on the other hand the sum of all load noises is approximately 10 dB (A) higher than the no load noises, and the frequency content of the emitted noise is evenly spread over 300 to 3000 Hz. The noise can be controlled or reduced using high quality low noise equipments, enclosure of equipment to attenuate noise emission, shielding room or separating the noisy equipment by distance. For a typical HVDC station has a noise intensity of less than 10 dB(A) at a distance of 350 m. [MARU82]

The HVDC transmission line has less width for the rightof-way compare to HVAC transmission line and hence, DC transmission has less visual impact.

In general, from all environmental aspect, the audible noise could only be the limiting factor for HVDC line in meeting existing or future regulations.

5.3. Conclusion

Long distances are technically unreachable by HVAC line without intermediate reactive compensations. The frequency and the intermediate reactive components cause stability problems in AC line. On the other hand HVDC transmission does not have the stability problem because of absence of the frequency, and thus, no distance limitation.

The cost per unit length of a HVDC line lower than that of HVAC line of the same power capability and comparable reliability, but the cost of the terminal equipment of a HVDC line is much higher than that of the HVAC line. The breakeven distance of overhead lines between AC and DC line is range from 500 km (310 miles) to 800 km (497 miles) for onshore transmission lines. The HVDC has less effect on the human and the natural environment in general, which makes the HVDC friendlier to environment.

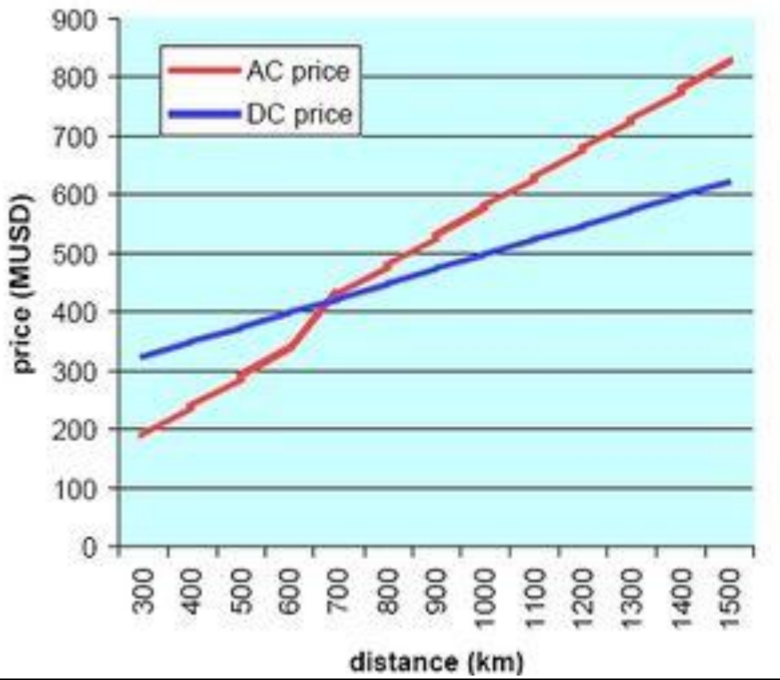


Figure 19. Intersection Point for Cost

6. Thrysistor, Power MOSFET and IGBT

The HVDC needs transistors to convert the alternative to direct current or, on the contrary, to alternative from direct current. As we have seen there are two technologies that are vastly used today: IGBT and thyristors. Also power MOSFET ares used in applications that use low voltage. Each one has different characteristics, qualities and disadvantage.

6.1. Thyristor

The thyristor is a two-to four-lead solid-state semiconductor device with four layers of alternating N and P-type material. They act as bistable switches, conducting when their gates receives a current trigger, and continue to conduct while they are forward biased (that, is while the voltage across the device is not reversed.

Figure 20. Thyristors Stack (Manitoba Hydro-Bipole)

A three-lead thyristor is designed to control the larger current of its two leads by combining that current with the smaller current or voltage of its control lead. On the other hand, a two-lead thyristor is designed to “switch on” if the potential difference between its leads is sufficiently large –a value representing its breakdown voltage.

They can control a relatively large amount of power and voltage, for that characteristic is a very good choice for HVDC. It could be used in power-switching circuits, relay-replacement circuits, inverter circuits, oscillator circuits, etc.

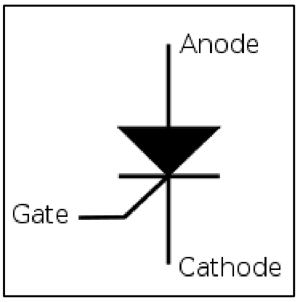


Figure 21. Thyristor circuit symbol

Originally thyristors relied on current reversal to turn them off, making them difficult to apply for direct current; newer devices types can be turned on and off trough the control gate signal. A tryristor is not a transistor, because it is not a proportional device. A tryristor can only be fully on or off, while a transistor can lie in between, being the characteristic that makes the tryristor a good switch.

Modern thyristors can switch power on the scale of megawatts, they have become the heart of HVDC converters, either to or from alternating current (Fig. 22). There are two kinds, electrically triggered (ETT) and light triggered (LTT) thyristors.

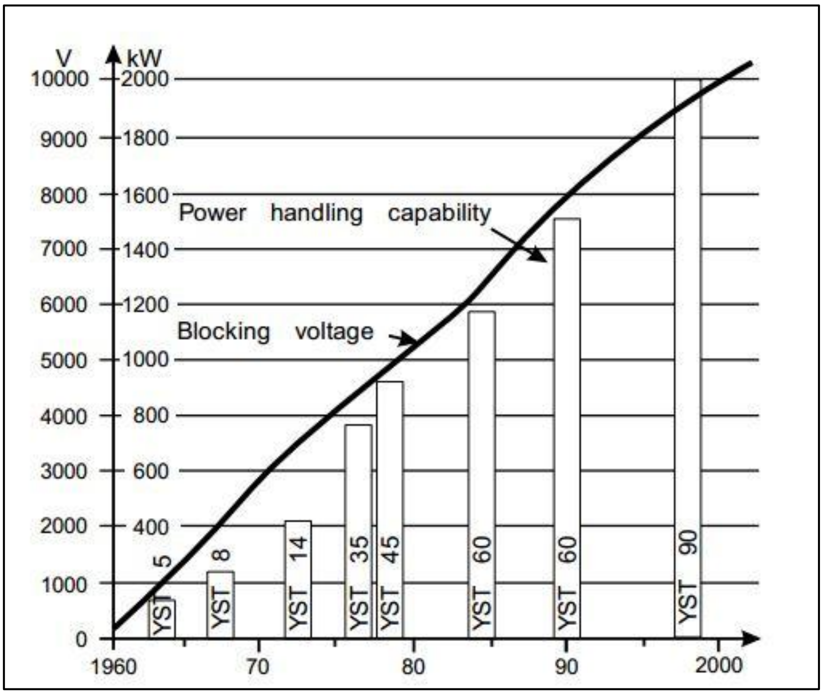


Figure 22. Thyristor blocking voltage and power handling capability

The valves are arranged in stacks usually suspended from the ceiling of a transmission building called a valve hall. Thyristors are arranged into a diode bridge circuit and to reduce harmonics are connected in series to from a 12 pulse converter. The entire arrangement becomes one of multiple identical modules forming a layer in a multilayer valve stack called a *quadruple valve*. Three suck stacks are typically mounted on the floor. (Fig. 20)

Cooling of the thyristors is achieved by heat sinks, designed to reduce the thermal resistance between thyristors wafer and the cooling medium to a minimum. The increased power handling capability of the devices means higher on-state losses, and consequently the thermal resistance becomes an increasingly important parameter as the impact on the cooling system design is large.

The functional drawback of a thyristors is that it only conducts in one direction. A TRIAC (Triode for Alternanting Current) could be used, because it is bidirectional and current can flow in either direction (Fig. 23). TRIAC current flow can be enabled by either a positive or negative current applied to its gate electrode. But reactive loads can cause TRIAC to fail to turn off during the zero-voltage instants of the AC power cycle.

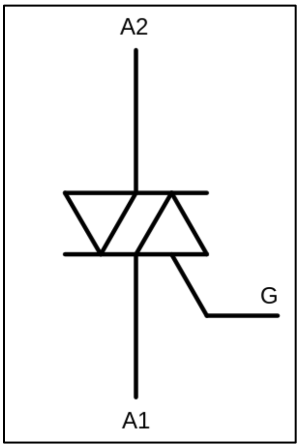


Figure 23. TRIAC schematic symbol

SCR (Silicon-Controlled Rectifier) is the old name for the thyristors. It's possible to use inverse parallel SCRs, because each SCR in the pair has an entire half-cycle of reverse polarity applied to it, they are sure to turn off. It adds complexity of two separate but essentially identical gating.

6.2. Power MOSFET

The MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is a four-terminal device, with source (S), gate (G), drain (D) and body (B) terminals, but the body is often connected to the source, making a three-terminal device. Both terminals are short-circuited internally. A power MOSFET is a specific type of MOSFET designed to handle significant power levels. Its main advantages are high commutation speed and good efficiency at low voltages. It shares with the IGBT an isolated gate that makes it easy to drive.

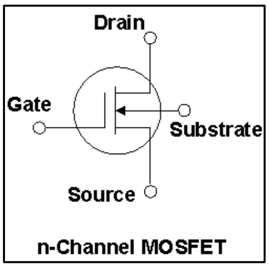


Figure 24. MOSFET Circuit Symbol

Analog circuits spend most of their time inside the switching region, depending on the linearity of response in this region. MOSFET is used for its advantages in scaling. The characteristics and performance of many analog circuits can be scaled up or down by changing the sizes (length and width) of the MOSFETs used. Also, their ideal characteristics regarding gate current (zero) and drain-source offset voltage (zero) make them nearly ideal switch elements, and also make switched capacitor analog circuits practical. In their linear region they can be used as precision resistors, with high control.

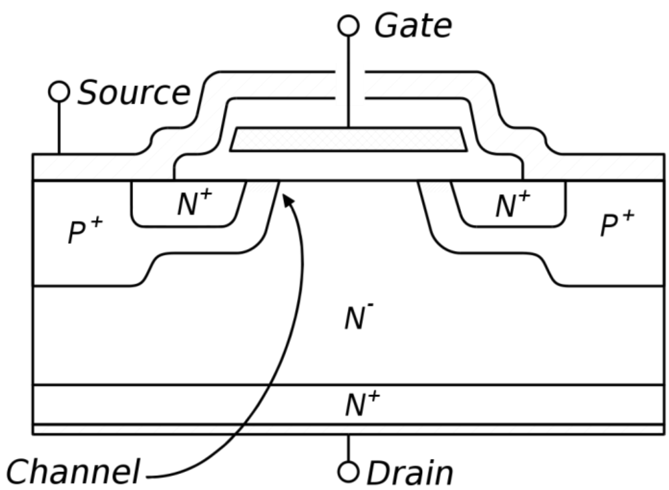


Figure 25. Power Vertical Diffussed MOSFET Cross Section

The actual power MOSFET are call Vertical Diffused MOS. As it can be seen in the Fig. 25, that shows the "verticality" of the device, the source electrode is placed over the drain, resulting in a current mainly vertical when the transistor is in the on-state. With a vertical structure, the voltage rating of the transistor is a function of the doping and thickness of the N epitaxial layer, while the current rating is a function of the channel width. That makes possible for the transistor to sustain both high blocking voltage and high current within a compact piece of silicon.

In an electronic popular planar structure, the current and breakdown voltage ratings are functions of the channel dimensions, resulting in inefficient use of the "silicon estate".

The power MOSFET can switch at very high speed. The only intrinsic limitation in commutation speed is due to the internal capacitances. These capacitances must be charged or discharged when the transistor switches, what is a relatively slow process because the current that flows through the gate capacitances is limited by the external driver circuit.

In the case of HVDC, with analog and high power circuits, MOSFETs have the advantage of not suffering from thermal runaway. Thermal runaway refers to a situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature, often leading to a destructive result.

Power MOSFETs usually increase their on-resistance with temperature. (positive temperature coefficient). Under some circumstances, power dissipated in this resistance causes more heating on the junction, which further increases the junction temperature, in a positive feedback loop. However, the increase of on-resistance with temperature helps balance current across multiple MOSFETs connected in parallel, so current hogging does not occur. If a MOSFET transistor produces more heat than the heatsink can dissipate, then thermal runaway can still destroy the transistors.

MOSFET usually includes a diode, whose more important utility is prevent destructive feedback in switched current systems. It's called damper

6.3. IGBT (Insulated Gate Bipolar Transistor)

The IGBT is a three-terminal power semiconductor device that combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation –voltage capability of bipolar transistors. The IGBT combines an isolated gate FET for the control input, and a bipolar power transistor as a switch.

They apparition was due to the industrial necessity of high current (>100A). The IGBT is usually used in medium-to-high-power applications, where IGBT modules consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000V, equating to hundreds of kilowatts.

The IGBT-birth was caused but the research of an improvement of the high-voltage MOSFET low-efficiency. The improvement was the bipolarity and the conductivity modulation but with a speed loss.

The first-generation devices of the 1980s and early 1990s were prone to failure through such modes like latchup (device will not turn off as long as current is flowing, a power cycle is required to correct this situation) and secondary breakdown. The current third-generation is better, with speed rivalling MOSFETs, and excellent ruggedness and tolerance of overloads.

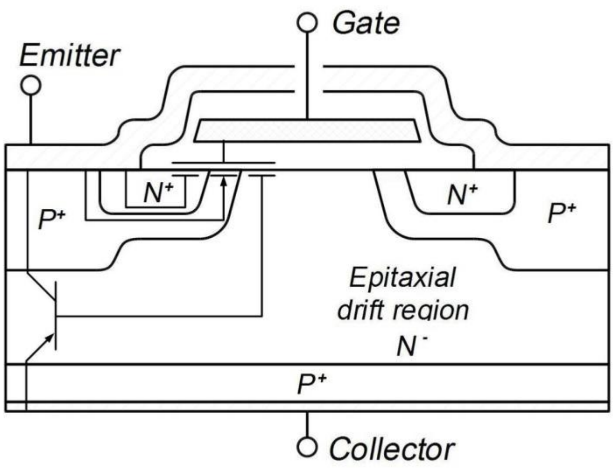


Figure 26. IGBT Cross Section

An IGBT cell is constructed similarly to an n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor. This p+ region creates a cascade connection of a PNP bipolar junction transistor with the surface n-channel. The role of the p+ part is injecting minority carriers and they will adapt the resistance.

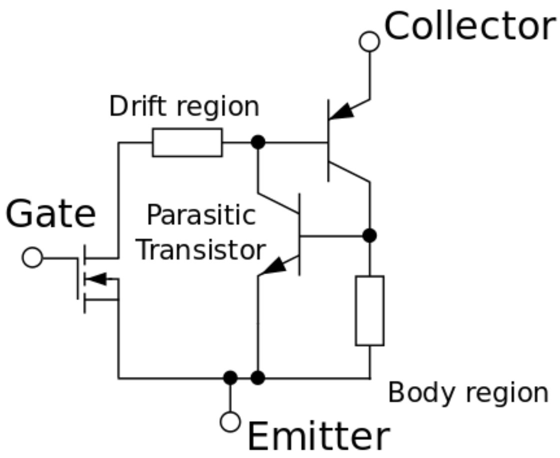


Figure 27. Equivalent Circuit for IGBTs

The IGBT transistor cannot conduct in the reverse direction. In bridge circuits where reverse current flow is needed (if an AC-DC converter wants to be used in both sense) and additional diode (freewheeling diode) is placed in parallel with the IGBT to conduct current in the opposite direction.

For applications where the circuit applies a reverse voltage to the IGBT, an additional series diode must be used. And IGBTs has longer switching time and hence higher switching loos compared to a power MOSFET because minority carriers injected into the N-drift region take time to enter an exit.

6.4. Power MOSFET vs IGBT

IGBT is transistor that combines the characteristics of MOSFET and bipolar. Both technologies have advantages and disadvantages that affect efficiency, commutation speed, maximum current, power losses and control ease.

The first important different is the breakdown point. IGBT technology is the device of choice for breakdown voltages above 1000V, while the MOSFET is certainly the device of choice for device breakdown voltages below 250V. Between 250 to 1000V, there are many technical papers available from manufacturers of these devices.

The choices depends also of the frequency, being the IGBT preferred for low frequencies (<20kHz) and the MOSFET for very high frequencies (>200kHz). For the intermediate position there are other technologies that use in the different sectors. [BLAK03]

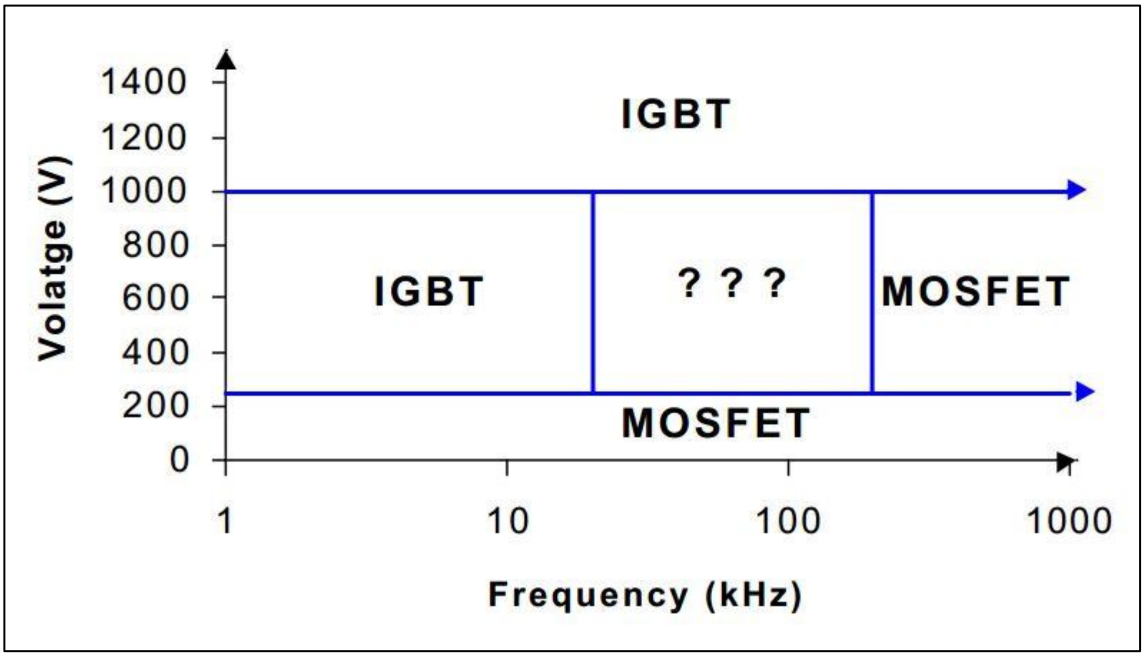


Figure 28. MOSFET vs IGBT (Frequency, Voltage)

7. Cables for HVDC Power Transmision

HV land and submarine cables systems are the backbone of all power transmission networks. The greater and ever-increasing demand for power, the need for larger bulks of power and for the transmission of such bulks over longer distances, the localization of the sufficient or even exceeding existing power generation capacity far from the requiring use and consumption centers are the main reasons for the realization of interconnections among power networks of various and different types.

Offshore wind farms are the kind of projects that involves more HVDC. Alternative submarine current cables have the disadvantage of causing losses because of the great capacity they have.

Part 5 is going to study the different cables that have been developed and why HVDC is convenience for its utilization in offshore applications.

7.1. Insulated HVAC cable system

For submarine distribution, to provide more space for active current to flow, the reactive current has to be distributed evenly at both ends of the cables. Thyristor Controlled Reactors (TCR) is used to provide compensation. Compensation has to be provided because of the higher capacity cables have due to the submarine insulation.

In a study by Joan Todorovic, he compared three levels of transmission voltage: 132 kV, 220 kV and 400 kV. Three types of HVAC cables are being considered.:

- For 132 kV transmission systems: three-core TKVA 145kV 3x1x1000 mm^2 KQ. The cable is XLPE insulated and has a nominal current of 1055 A.
- For 220 kV transmission systems: three-core TKVA 245 kV 3x1x1000 mm2 KQ. The cable is XLPE insulated and has a nominal current of 1055 A.
- For 400 kV transmission systems: three single core XLPE 400 kV cables in trefoil formation.

The number of cables that are required for the transmission of the power onshore depends on the rated power of the windfarm and the transmission distance. The transmission capacity of the three cables mentioned before is presented with respect to the transmission distance. (Fig. 29)

The voltage of the grid within the windfarm is 33 kV while the voltage level of the onshore main grid is 400 kV. For this reason no onshore transformers are required when a transmission voltage of 400 kV is selected.

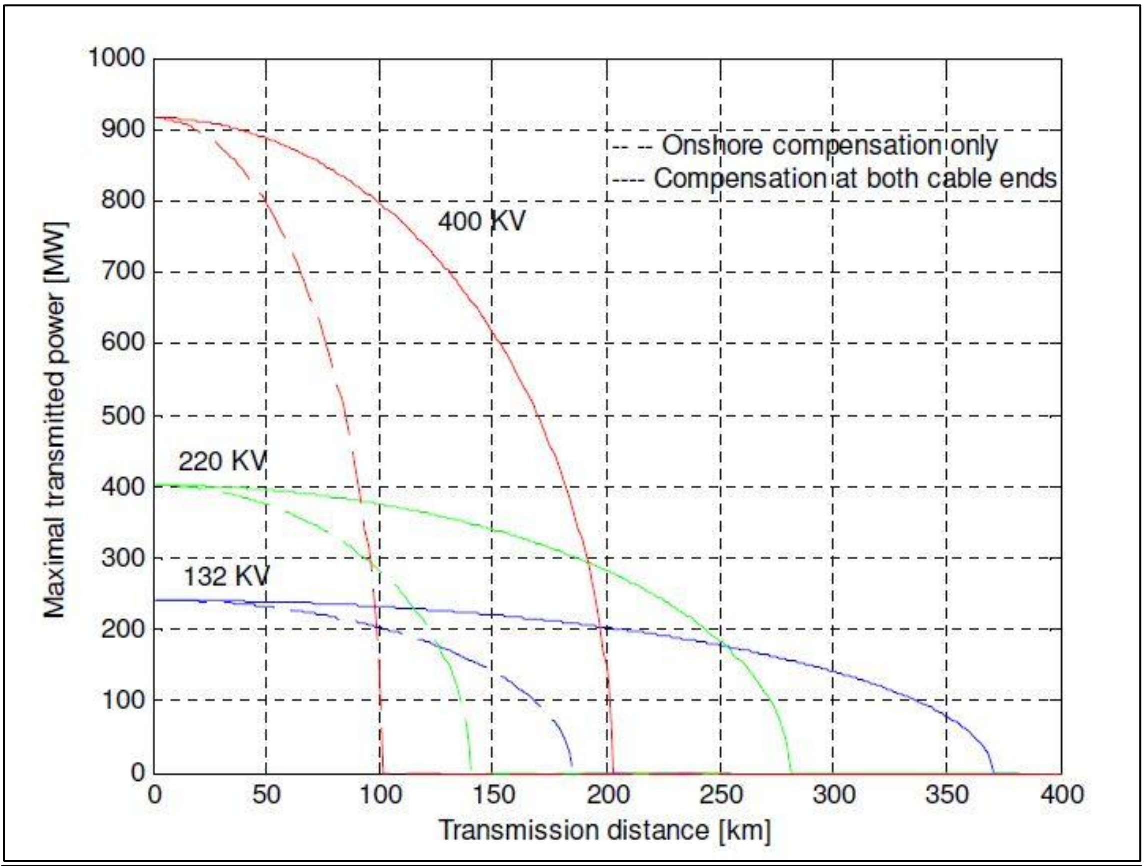


Figure 29. Limits of cables transmission capacity HVAC

As it is possible to notice, the 220 kV cable is not able to transmit any active power over 280 km and the 400 kV cable above 200 km.

For this study, the transmission systems, or some of their components, have rated power extremely higher than the required. Choosing overrated components in a transmission system is often suggested in order to increase the reliability and to improve the overall performance. Assumptions are made in order to have a more realistic approach. In some cases transformers with less rated power are used while it is assumed that the losses of the transmission system remain the same. It is not thought possible to make the same assumption for the cables since a change in their characteristics will effect the entire losses model significantly.

7.2. Cables for HVDC

7.2.1. Mass-impregnated cables

Mass-impregnated cables (MI) consist of a conductor, built on stranding copper layers on segments around a central circular rod, and oil and resin-impregnated papers which cover the conductor; the inner layers are of carbon-loaded papers and the outer layers is made of copper-woven fabrics.

The cables are then covered with sheaths, jackets, anti-corrosion protections and armors in order to protect the cable from the environmental. The available technology for these cables is for voltages up to 500 kV and transmission capacity up to 800 MW for monopole solution, but 600 kV and 1000 MW solutions are under development.

These cables can be installed at sea depths up to 1000 m under the sea level and with nearly unlimited transmission length. The capacity of this system is limited by the conductor temperature, which can reduce overload capabilities. [WEND11]

7.2.2. Oil-filled cables

Oil-filled cables (OF) are insulated with paper impregnated with a low viscosity oil under an overpressure of some bars and incorporated in a longitudinal duct to permit oil flow along the cable. These cables have been developed later compared with the previous type and the available technology today ensures voltages up to 600 kV and capabilities up to 1000 MW for monopole solution for land installation.

Problems of this cable regard the length, since, due to the required oil flow along the cable, the cable length is limited to 100 km. Besides, the risk of oil leakage must be taken into account for environmental issues.

7.2.3. Cross-linked polyethylene insulator cables

Some other solutions are under development: one considering a cross-linked polyethylene insulator (XLPE) that ensures high temperature of working during the transmission, and one using a lapped non-impregnated thin PP film insulator that should ensure very long and deep submarine installation due to the increase of the electrical stresses in operation.

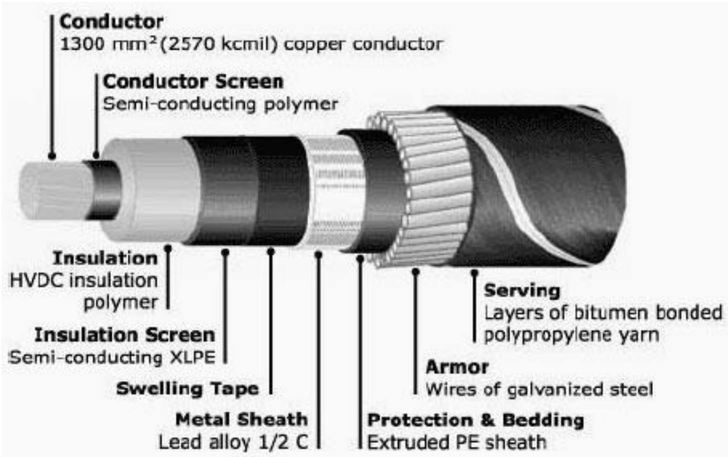


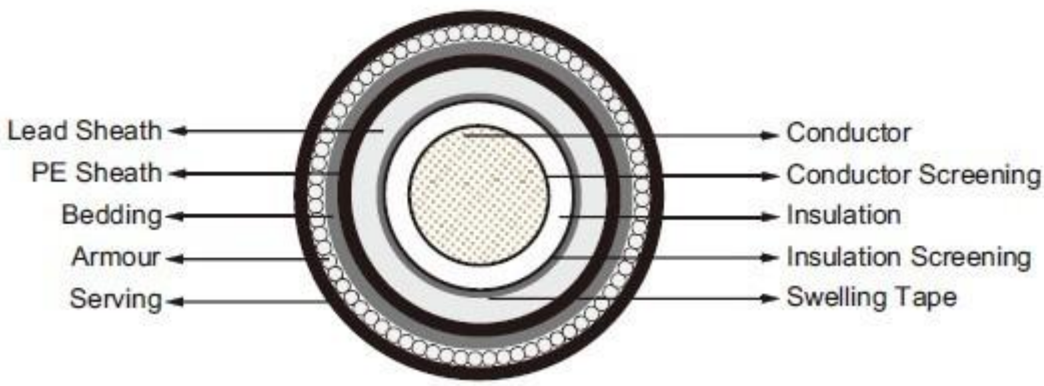
Figure 30. Section of a XLPE cable

7.2.4. *Return patch cables*

For the return path of the current, earth electrode, metallic return conductor as a part of the DC cable or an AC cable with low voltage level can be chosen. The choice of one of the solution above depends on environmental conditions and restrictions of the site where the cable has to be installed. For example some problems can be present if the site is a natural park and thus an earth electrode is not suitable for the return path purposes.

7.3. Submarine Lines

The geometric of HVDC cable for a submarine use is shown in Fig. 30.



The following components can be recognized [BERH13]:

1. Conductor: copper and aluminum are widely used for the conductor.
2. Conductor screening: a semi-conducting layer which maintains a uniform electric field and minimizes electrostatic stresses.
3. Insulation: insulation material separates the current carrying conductor from the ground potential.
4. Insulation screening: it is a semi- conductive layer which maintains a uniform electric field and minimizes electrostatic stresses.
5. Lead sheath: is used as a path for fault current during external cable damage and water barrier.
6. Lead Sheath
7. PE Sheath: it is used to provide a bedding for the armor wires.
8. Optical fiber or Bedding: it is inserted for cable monitoring and communication purpose.
9. Wire armor: it is used with the lead sheath as a buried cable where moisture is a concern.
10. Serving: it is the final propylene sheath used as outer protective layer against corrosion and mechanical damage.

8. Offshore Wind Turbine

Most wind turbines are horizontal axis, versus vertical axis turbines. Vertical axis is a kind of wind turbine that has not had success due to its lower energy production (10-30% of the wind power) and increased maintenance. [ROGE08].

8.1. Historical Evolution and Background

Table 6 shows the evolution in the time of the wind turbine. Current horizontal axis with three blades achieves the best use of wind energy. [SCHU12]

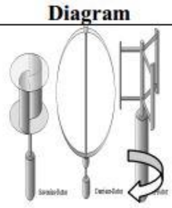
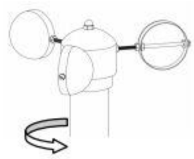
Ref No.	Design	Orientation	Use	Propulsion	* Peak Efficiency	Diagram
1	Savonius rotor	VAWT	Historic Persian windmill to modern day ventilation	Drag	16%	
2	Cup	VAWT	Modern day cup anemometer	Drag	8%	
3	American farm windmill	HAWT	18th century to present day, farm use for Pumping water, grinding wheat, generating electricity	Lift	31%	
4	Dutch Windmill	HAWT	16th Century, used for grinding wheat.	Lift	27%	
5	Darrieus Rotor (egg beater)	VAWT	20th century, electricity generation	Lift	40%	
6	Modern Wind Turbine	HAWT	20th century, electricity generation	Lift	Blade Qty / efficiency 1 / 43% 2 / 47% 3 / 50%	

Table 6. Modern and historical rotors

Wind energy is not something that has been recently discovered. Humans have tried to harness the wind throughout human history. Lot of designs of early windmills can be found with respect to the application, the technology and the culture.

However, the integration of wind power into the industrial environment, as a reliable source of large-scale electrical energy production, is rather recent. The awareness that fossil fuel deposits are becoming shorter and the increasing environmental concerns, in combination with technological maturity pushed the development of wind power systems. Today wind power is considered to be one of the fastest growing forms of electrical energy production.

The wind power industry will flourish creating many employment opportunities and the large amount of investments planned can create the perfect environment for further evolution of the technology surrounding wind power. However, one can point out several drawbacks.

First, wind power is a variable energy; its production depends on the wind. As electricity is not a storable energy, wind power is not easy to integrate in the network. Then wind farms deteriorate landscape and make noise, most of people want wind turbines but not near them.

Also, some scientists believe that wind turbines create interferences with waves. Finally, wind turbines do not have a good power above surface ratio. It cannot be the only source of power.

8.2. Horizontal Axis Wind Turbines

Horizontal axis wind turbines harness the power of the wind and use it to generate electricity. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity

A typical wind turbine consists of the following components [ENER13] (Fig. 30):

- **Anemometer:** Measures the wind speed data and transmits it to the controller.
- **Blades**: Lifts and rotates when wind is blown over them, causing the rotor to spin. Most turbines have either two or three blades.
- **Brake**: Stops the rotor mechanically, electrically, or hydraulically, in emergencies.

- **Controller**: Starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they may be damaged by the high winds.
- **Gear box**: Connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30-60 rotations per minute (rpm), to about 1,000-1,800 rpm; this is the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.
- **Generator**: Produces (50-60Hz) AC electricity; it is usually an off-the-shelf induction generator.
- **High-speed shaft**: Drives the generator.
- **Low-speed shaft**: Turns the low-speed shaft at about 30-60 rpm.
- **Nacelle**: Sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.
- **Pitch**: Turns (or pitches) blades out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or too low to produce electricity.
- **Rotor**: Wind turbines can have from one to three rotor blades, made of fibreglass-reinforced polyester or wood-epoxy. The blades are usually between 30 and 80 metres in diameter. The longer the blades, the greater the energy output. They rotate at 10-30 revolutions per minute at constant speed, although an increasing number of machines operate at a variable speed. The blades can be rotated to change the pitch angle and modify power output.
- **Tower**: Made from tubular steel, concrete, or steel lattice. It support the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.
- **Wind direction**: Determines the design of the turbine. Upwind turbines—like the one shown here—face into the wind while downwind turbines face away.
- Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

- **Yaw drive**: Orients upwind turbines to keep them facing the wind when the direction changes. Downwind turbines don't require a yaw drive because the wind manually blows the rotor away from it.
- **Yaw motor**: Powers the yaw drive.

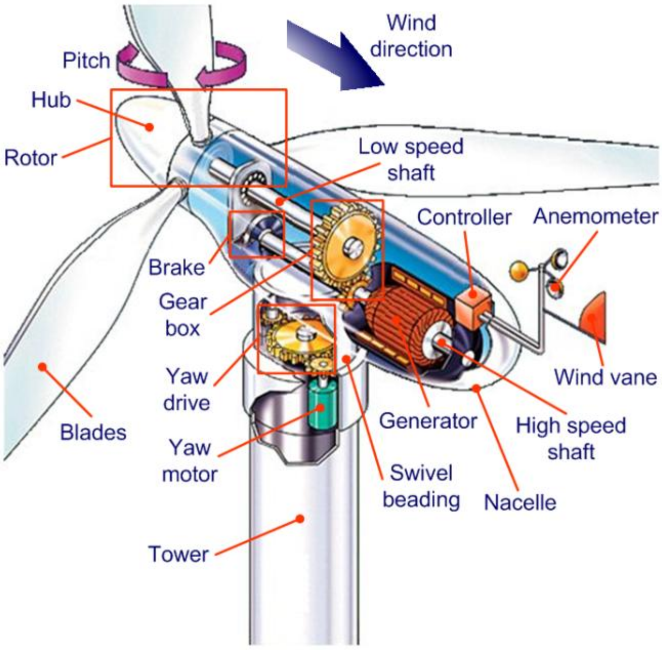


Figure 31. Wind Turbine Components

These are the step to converts the kinetic energy in the wind to electrical energy.

1. The wind turns the blades.
2. The blade turns a shaft inside the nacelle (the box at the top of the turbine).
3. The shaft goes into a gearbox, which increases the rotation speed.
4. The generator converts the rotational energy into electrical energy.
5. The transformer converts the electricity from around 700 Volts (V) to the right voltage for distribution, typically 33,000V.
6. The National Grid transmits the power around the country.

8.3. Offshore Wind Turbines

The differences between offshore and onshore turbines are the tower and the blades. Moreover, it is important to reduce the number of rotating and wear-prone parts, due to the maintenance difficulties. In the sea the tower has to endure the power of the wind, but also the wave stake, the corrosion due to seawater and a hypothetical boat crash.

An example of offshore wind turbine is Siemens 6.0 MW Offshore Wind Turbine, with a maximal power of 6.0MW, above most of the land turbines. It has 50% fewer moving parts than comparable geared machines, because the main shaft, gearbox and high-speed generator have been replaced by a low-speed generator. They have to be lighter, to offers cost benefits in terms of substructure requirements, shipping and installation. [SIEM11]

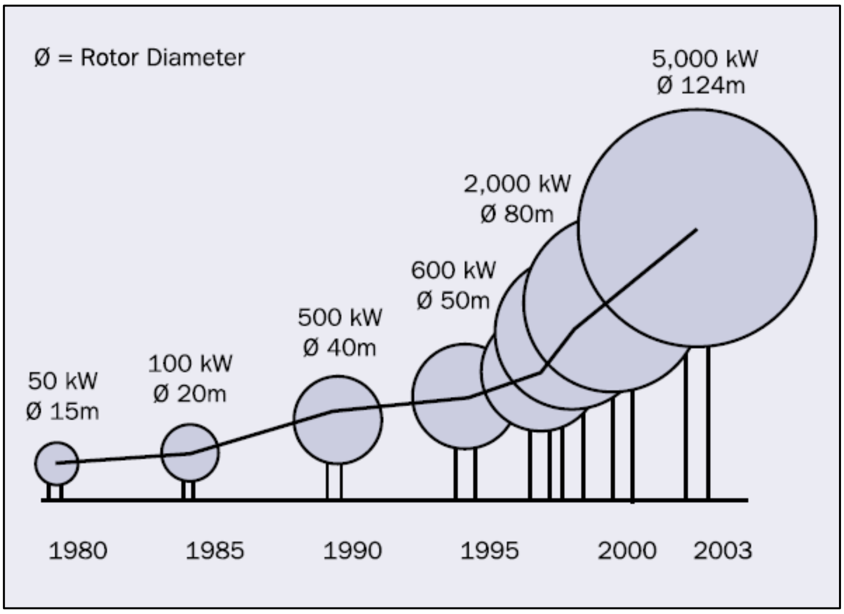


Figure 32. Growth of commercial wind turbines

All the external surfaces and systems feature offshore-grade corrosion protection, and a completely enclosed nacelle, fitted with internal climate control. Also, the nacelle forms a self-contained unit delivering medium voltage. As a result the turbine can be fully pre-commissioned onshore, leaving only final connections.

Larger blades mean more power, and as the Fig. 31 shows there have had a constant evolution that has led to bigger and composite-materials blade. To help warranting the corrosive protection, the blades are usually made from just one piece, so there are no glue joins with could expose the blades to cracking and lightning damage.

Usually, offshore wind power turbines are right off the coast, with wind turbines placed on concrete platforms. This situation could only appear in the continental shelf, where depth is lower and the possibility to make a solid platform could be solve with the current technologies. Depth is limited to water shallower than 150 m. Environmental problems could appear in this area because continental shelves teem with life.

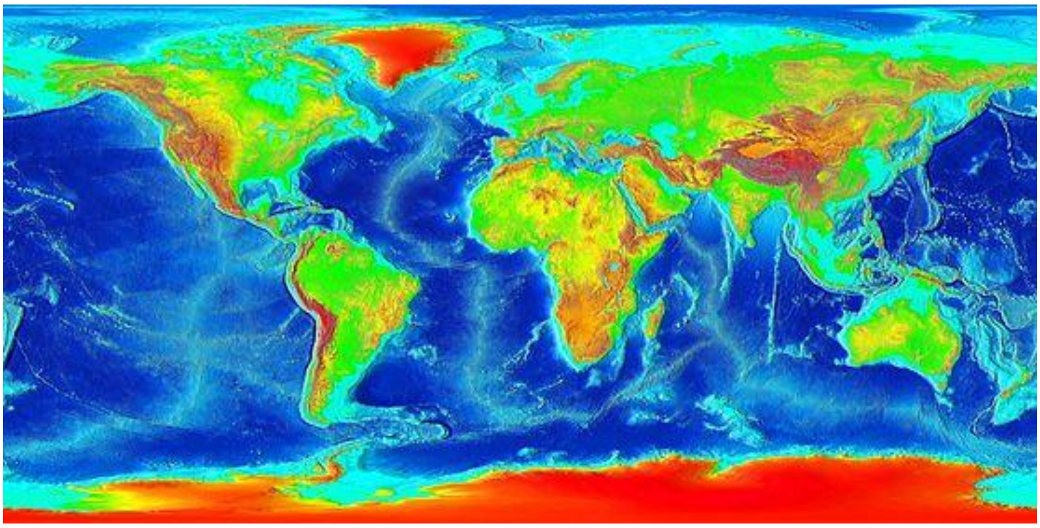


Figure 33. Continental Shelf in cyan

Fig. 32 highlighted the continental shelf. It is remarkable that seas where offshore wind energy is more present have a vast continental platform (North Sea, Finland, Norway coast).

Further out in the sea, the offshore wind turbines appear in floating platforms. The current limit to start using floating platforms is around 50 meters depth. The platform is anchored to the seabed in 3-4 points, to control the position. But it can sway with the waves and the difference in height of the tides. (Fig. 33)

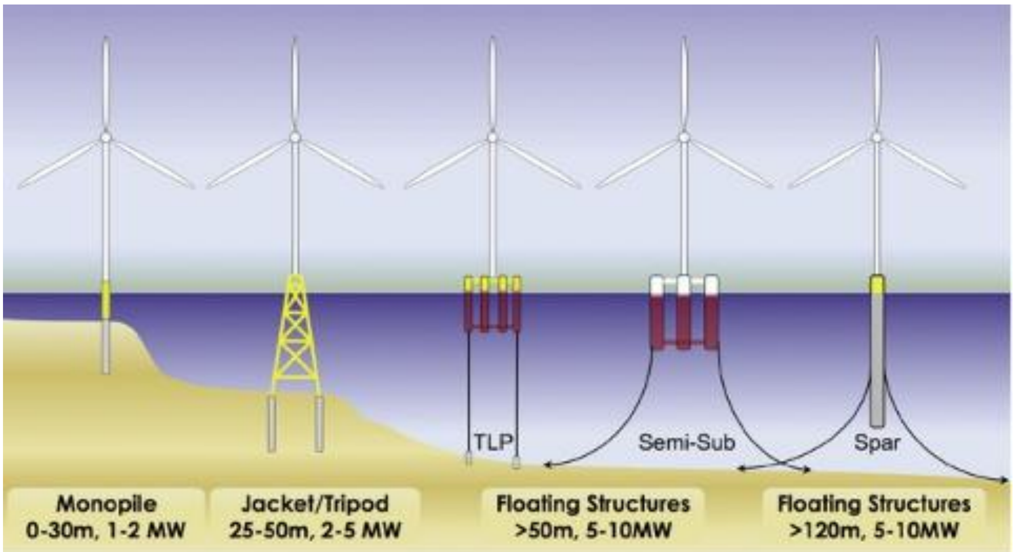


Figure 34. Offshore Wind Turbines Platforms

Chapter 3.- Description of the developed model

1. Targets and Specifications

The main objective of this project is to study the connection of an offshore wind turbine to the national onshore grid of the country, through a HVDC link.

A study of voltages, currents and power will be done. The choice for the converter will be a VSC converter, because is smaller, easier to control and it needs less components.

Losses, improvements, use of constant speed rotor and other consideration will be discussed by a Matlab / Simulink simulation. The special library SimPowerSimulation includes most of the blocks uses in this project. Also the explanations to understand the correct way to work with them and the different magnitudes that could be used are included in this library.

Specifications are the following;

- Wind Turbine with asynchronous generator:
  - Nominal Power: 5MW
  - Nominal Phase-Phase Voltage: 900V
  - Nominal Line Current: 3200A
  - Nominal Wind Speed: 12m/s
- Weather Conditions:
  - Mean Wind Speed: 12m/s
  - Direction: Not important
  - Temperature: 20ºC
- HVDC Line
  - Maximum Voltage: 150kV
  - Maximum Power 100MW (if it would be a wind farm of 20 wind turbines)
  - Distance: 250km
- AC Onshore Network
  - Voltage: 110kV
  - Frequency: 50Hz

These specifications are settled specified by the study of the current conditions of the North Sea wind farm in development.

Wind turbines for offshore conditions have more power than onshore one. In the sea they can be larger, with more area face to the wind and the wind is more constant.

2. Models of the Components

2.1. Wind Turbine

The model used of the wind turbine is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation.

$$P_m = \frac{c_p(\lambda, \beta) \cdot \rho \cdot A \cdot v_{wind}^3}{2}$$

- P_m : Mechanical output power of the turbine (W)
- C_p : Coefficient of Power coefficient of the turbine
- ϱ : Air density (kg/m^3)
- A : Turbine swept area (m^2)
- V_{wind} : Wind speed (m/s)
- λ : Tip speed ratio of the rotor blade tip speed to wind speed
- β : Blade pitch angle (deg)

Tip speed ratio or TSR is the ratio between the tangential speed of the tip of a blade and the current velocity of the wind. TSR is related to efficiency, with the optimum varying with blade design. [RAGH14]

$$TSR = \lambda = \frac{speed\ of\ rotor\ tip}{wind\ speed} = \frac{\omega \cdot r}{v_{wind}}$$

Where:

- ω : Rotor Angular Velocity (rad/s)
- r : Rotor radius (m)

The optimal tip speed ratio for maximum power extraction is inferred by relating the time taken for the disturbed wind to reestablish itself t_w to the time taken for a rotor blade of rotational frequency ω to move into the position occupied by its predecessor t_s.

For an *n* bladed rotor, t_s is given by:

$$t_s = \frac{2\pi}{n\omega}$$

If the length of the strongly disturbed air stream upwind and downwind of the rotor is s, t_w is given by:

$$t_w = \frac{s}{v_{wind}}$$

The maximum power extraction occurs when these two time periods are about equal, from which the optimal rotational frequency is:

$$\omega_{opt} \approx \frac{2\pi v_{wind}}{ns}$$

Consequently, for optimal power extraction, the rotor blade must rotate at a rotational frequency that is related to the speed of the incoming wind, the radius of the rotor and the number of blades.

$$\lambda_{opt} \approx \frac{2\pi}{n}\frac{r}{s}$$

Coefficient of power of wind turbine is a measurement of how efficiently the wind turbine converts the energy in the wind into electricity. Coefficient of power at a given wind speed is electricity produced divided by total energy available in the wind at that speed.

$$C_p = \frac{Electricity\ produced\ by\ wind\ turbine}{Total\ Energy\ available\ in\ the\ wind}$$

Total energy available in the wind can be expressed as:

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v_{wind}^3$$

Wind turbines extract energy by slowing down the wind. Therefore, for a wind turbine to be 100% efficient it would need to stop 100% of the wind - but then the rotor would have to be a solid disk.

Theorical limit of the coefficient of power is calculated by the Betz's law to be 59.3% of the kinetic energy in the wind. The factor 16/27 (0.593) is known as Betz's coefficient. However current practical utility-scale wind turbines achieve at peak 75% to 80% of the Betz limit.(Fig. 34)

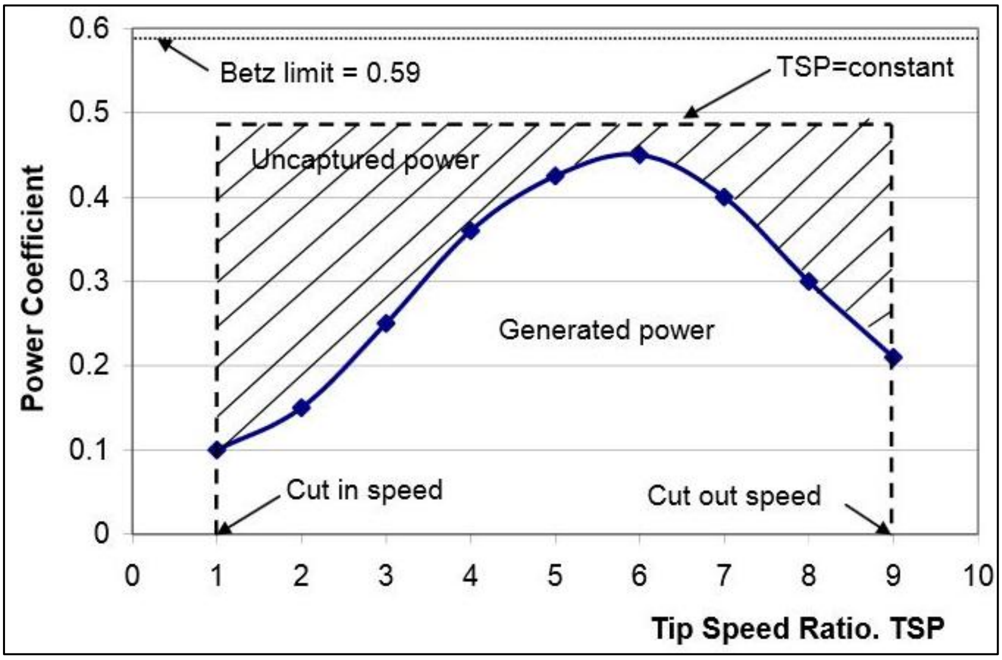


Figure 35. Power Coefficient vs TSR

A generic equation is used to model $C_p(\lambda,\beta)$. This equation, based on the modeling turbine characteristics is:

$$c_p(\lambda,\beta) = c_1\left({}^{c_2}/_{\lambda_i} - c_3\cdot\beta - c_4\cdot\lambda\right)e^{-{}^{c_4}/_{\lambda_i}} + c_6\cdot\lambda$$

There is a model for Simulink where the inputs are generator speed, wind speed and pitch angle. The output of the wind turbine is the torque. The torque turns a synchronous machine used as a generator, which supplies the transmission line with a phase AC voltage. The speed of this generator affects the wind turbine due to its resistance.

For the special application of offshore wind turbine the turbine will be low speed, reducing the number of moving parts, as has been concluded before. Images from the design could be seen in Annex . The area of the blades could be chosen and the different parameters that affect the power will be chosen.

2.2. Rectifier / Inverter

A HVDC link needs two substations to convert from alternative current to direct current and inversely. Current production and consumption of high power is made in alternative because synchronous and asynchronous motors are very effective machines, with little maintenance, compare to the DC motor. Also, alternative current has the advantage of use of two tensions with the same transport line, phase-neutral and phase-phase.

Both stations have similar schemas because an IGBT converter is reversible and could be use from both AC to DC and DC to AC. IGBT transistors with diodes in parallel have been choose to control the converter. Controlling the moment of the sinusoidal signal when transistors turn on and turn off, the HVDC link would be bidirectional. In this special case could be interesting to give power to the turbine when it is starting up and, for most of the time, receive power from the offshore farm.

The rectifier (Fig. 35) is made with a Graetz bridge with diodes (Graetz bridge). A capacitor is placed at the output of the rectifier in order to filter high frequencies and get a proper signal. The use of diodes is better in this application than IGBT because the quality of the direct current output has less noise. If the input is off the rectifier AC with a phase-to-phase voltage of U, the output will be:

$$V = \frac{3 \cdot \sqrt{2} \cdot U}{\pi}$$

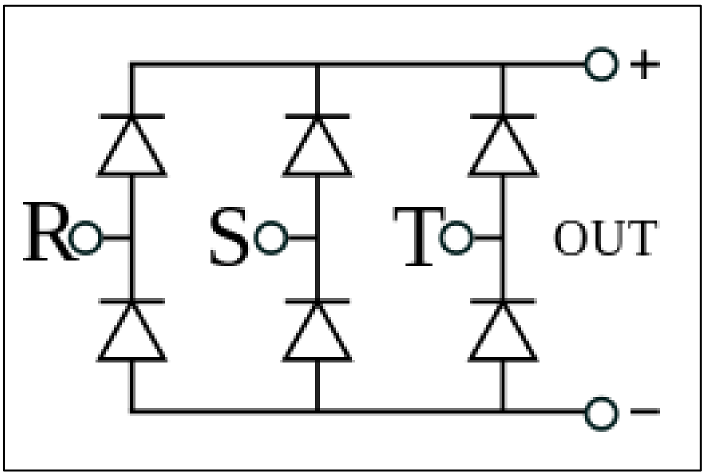


Figure 36. Diodes Bridge

The Inverter (Fig. 36) is a universal bridge with IGBT/diodes (Graetz bridge). It transforms a DC voltage into a three-phase AC voltage. IGBT are controlled by a pulse width modulation. If the voltage of the DC input is U, the average output will be:

$$U_m = \frac{3 \cdot \sqrt{2} \cdot U}{\pi} \cdot \cos(\alpha)$$

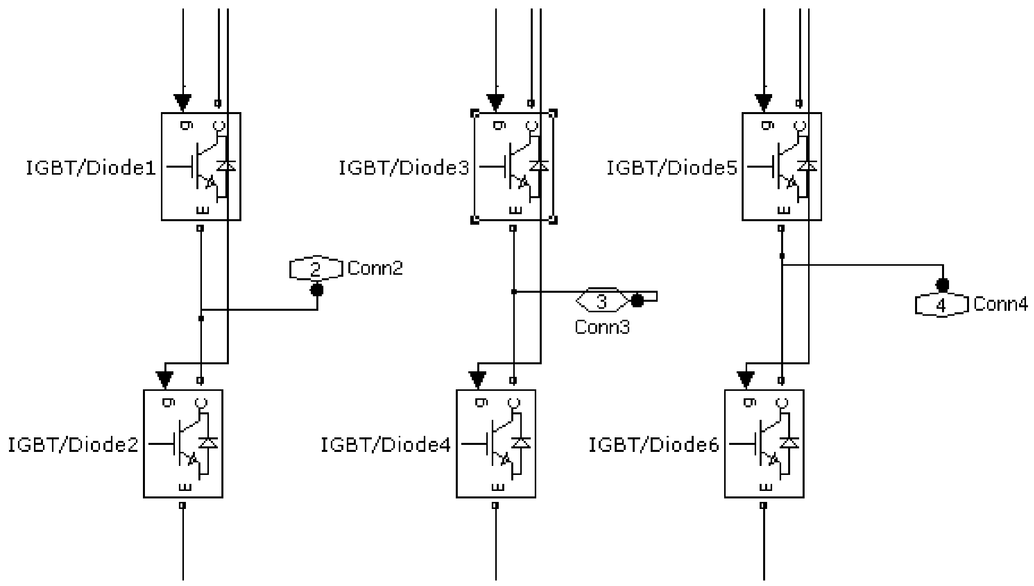


Figure 37. Inverter - IGBT/Diodes Bridge

There are different options to control the tension that goes to the transistors: Full-wave; Half-wave; and Pulse Width Modulation.

The pulse width modulation (PWN) is more appropriate to our problem because Full-wave and Half-wave controls are not well adapted because of these reasons:

- The height of the filter for harmonics
- Loss in components
- High costs

PWN allows to change the waveform by modifying the switch command. The goal of such a command is to have a coefficient to set the amplitude of the fundamental and to repel harmonics from the fundamental. Main advantages of PWN are:

- The height of the filter is reduced because harmonics are repeled from the fundamental.
- PWN allows setting the frequency and the amplitude of the signal.

The PWN used in the model is the intersective one. The command signal is obtained thanks to a triangular signal compared with a sinewave signal (Fig. 37). The comparison of these two signal leads to a logical signal (0 or 1).

A sinusoidal voltage V of frequency f is compared with a triangular voltage V_p of frequency of frequency f_p, where V_p is said carrier voltage and both frequencies are directly dependant by a integer factor. [ITEE03]

PWN is a way to delivering energy through a succession of pulses rather than a continuously varying (analog) signal. This fact reduced the consumption of the converter and sets a lower temperature in working situations.

For PWN being applied it is necessary to control the cutoff of transistors. Last need remarks the interest of using IGBT against thyristors. Also, as it has been studied, IGBTs have lower consumption, due to its control in voltage.

By increasing or decreasing pulse width, the controller regulates energy flow to the converter. The converter's own inductance acts like a filter, storing energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal. In other words, energy flows into the load not so much the switching frequency, but at the reference frequency. Thanks to m and λ, the output signal can be set as wanted.

$$m = \frac{f_S}{f_T}$$

$$\lambda = \frac{V_S}{V_T}$$

m = modulation coefficient
f_S = frequence of the sinewave signal
f_T = frequence of the tringular signal
λ = setting coefficient
V_S = amplitude ofthe sinewave signal
V_T = amplitude ofthe tringular signal

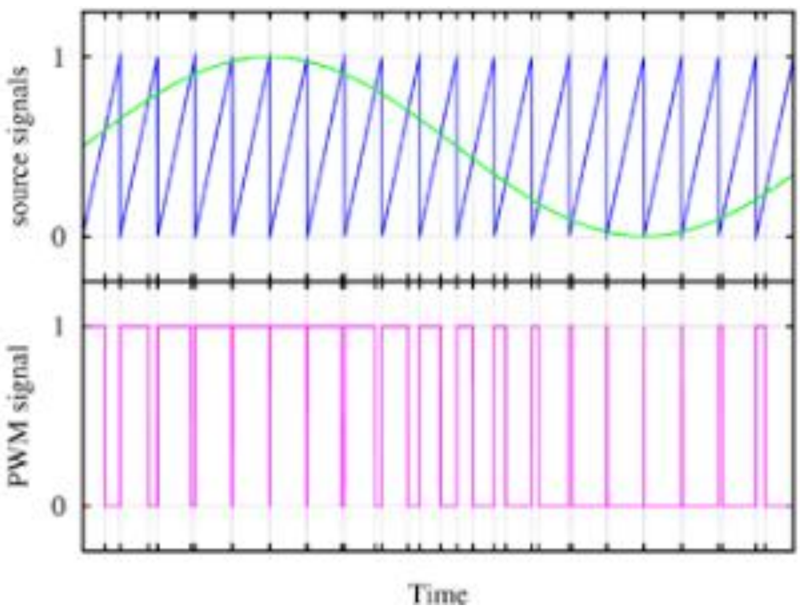


Figure 27. Pulse width modulation

2.3. HVDC Line

The line is modeled by a PI section line (Fig. 28). We shall represent lines as a "pi" section with lumped parameters. There are three cases: short, medium and long lines.

In the short line model (under 50 miles), we assume the shunt capacitance (the legs of the π) are so small that they are open circuit (i.e. neglected). This leaves only the series RL branch.

In the medium line model (50 to 250 miles), we assume that the capacitance may be represented as two capacitors (legs of the π) each equal to half the line capacitance. This is known as the nominal π model.

In the long line model (over 250 miles), we assume the line has distributed parameters instead of lumped parameters. This yields exact results.

After finding the exact model, an equivalent π is found. This is called the equivalent π model because it has lumped parameters, which are adjusted so that they are equivalent to the exact distributed parameters model. [EMAD03]

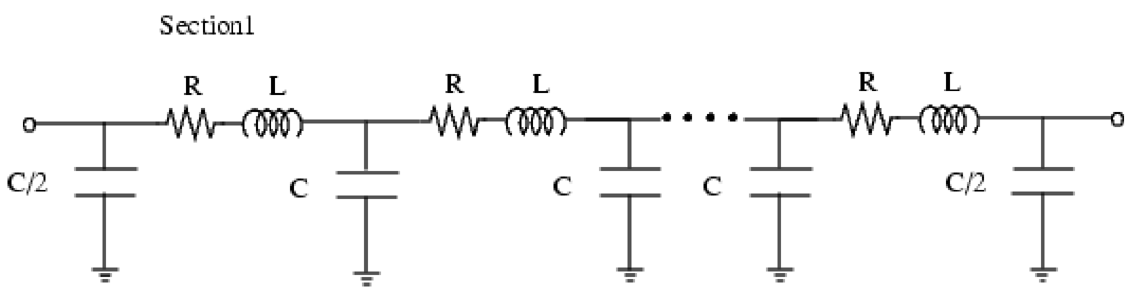


Figure 28. PI section

The study is made in the steady-state, so for losses calculation in the line, all the capacitances and inductances will not be taken into account, because the line would be always charged. The capacitance would be as an open circuit, and the inductance as a short circuit.

3. Data

Data uses try to increase the realism of a computerized simulation. It would try to copy the operating regime of a offshore wind farm that is located in the North Sea, with a HVDC link to the United Kingdom.

Wind is usually measured by stations fixed in the ocean. Common unit is knots and the Beaufort scale (B), that goes from 0 to 12. It sets a level for the conditions of the sea. Common equations in wind study are:

$$v_{wind} = 0{,}837 \cdot B^{\frac{3}{2}} \ (m/s)$$

$$1 \ knots = 1{,}852 \ km/h$$

The conditions of wind during a full year are in the next table /Table 7):

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Full year
Average Wind Speed (kts)	21	21	18	17	16	15	14	15	19	18	20	21	17
Average Wind Speed (km/h)	38,9	38,9	33,3	31,5	29,6	27,8	25,9	27,8	35,2	33,3	37	38,9	31,5

Table 7. Average Wind North Sea

The average wind speed of the year is 31.5 km/h or 8.7 m/s. The simulation of wind has been prepared for higher speed, 12 m/s to take into account that wind in the highest part of the blade is faster.

Air density at 20ºC, at the sea level is 1.2 kg/m^3.

For the wind turbine, the coefficients that would define C_β are:

- $c_1 = 0.5176$
- $c_2 = 116$
- $c_3 = 0.4$
- $c_4 = 5$
- $c_5 = 21$
- $c_6 = 0.0068$

The maximum active power of the wind turbine is 5MW at 900V, in line with most wind turbines specifications, taking into account the maximum limit of efficacy. For the reactive power the value is 1.3 MVar. The nominal current of the wind turbine is 3200A. Wind turbines consume reactive power.

A transformer that will rise the voltage from 900V to 120KV is used, to reduce the Joule losses in the line.

For the IGBT converter and the Pulse Width Modulation generator the values are:

- Triangular frequency: 2000 Hz
- Modulation coefficient: 1

The length of the line would be 250 km, to better understand the advantages of these connections in long distances. The line is prepared for a direct voltage of 150KV. The parameters are:

- Resistance: 0.0326 Ω/km
- Inductance: 0.42 mH/km
- Capacitance: 0.24 μF/km

4. Algorithms

The software Simulink, a part of Matlab allows to choose different algorithms to resolve the problems. In this project the option chosen is ***"ode23tb"***, specially designed to solver stiff differential equations, being a low order method.

The parameters that have been used are:

- Variable step
- Maximum step size: 1/50, it's said, the maximum is one period, with a frequency for the electric grid of 50 Hz.
- Minimun step size: auto
- Relative tolerance: 10^{-4}
- Absolute tolerance: 10^{-3}
- * In some case, to obtain longer simulation, the value ***"Number of consecutive zero crossings"*** has been risen.

These specifications are used in different examples of the power systems Simulink Examples area.

5. Numerical Implantation

First part to be calculated is the maximum wind power that the wind turbine would give with the conditions that have been set. Output voltage is defined to be 575V and wind speed to 12m/s, so the total power is:

$$P_{wind} = 5MW \cdot 0.9 = 4.5MW$$

Current can be calculated applying the Ohm law for triphasic systems.

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos(\emptyset)$$

As the reactive power is 1.3MVar, it is possible to calculate the $\cos(\emptyset)$ to be able to calculate the current through the line.

$$\cos(\emptyset) = \frac{S}{P} = 0.96$$

Where the apparent power is equal to:

$$S = \sqrt[2]{P^2 + Q^2}$$

The current obtained is close to the nominal current.

$$I \approx 3000\, A$$

A transformer with m=120 has been placed between the wind turbine and the rectifier, to raise the voltage and reduce the losses. This transformer is taken as ideal, so there is no losses. The change in the voltage and the current is written in the following equations:

$$V_{out} = V_{in} \cdot n = 108kV$$

$$I_{out} = \frac{I_{turbine}}{n} \approx 25\, A$$

The three-phase line between the transformer and the HVDC transformation center has losses that could be calculated taking into account that is 1km long and the resistance. The drop of voltages produces in the line is easy to calculate.

$$V_{losses} = I \cdot R = 0.815V$$

The total real power loss is calculated with real power line-neutral equation:

$$P_{loss} = 3 \cdot V_{loss} \cdot I \cdot \cos(\emptyset) \approx 60W$$

As described in the model, the rectifier output voltage is equal to :

$$V_{out} = \frac{3 \cdot \sqrt{2} \cdot U}{\pi} \approx 145kV$$

The rectifier is taken to be perfect, and not losses are studied, when the current go through it to become a direct current systems. So it is possible to apply the equality of power before and after the rectifier. Later, as the voltage is known, the current can be cleared.

$$P_{AC} - P_{loss} = I_{DC} \cdot V = P_{DC}$$

$$I_{DC} = 31A$$

To calculate the losses in the line, applying the steady state, the voltage drop along the line is the voltage drop due to the resistance of the line.

$$R_{Tot} = R_{\Omega/km} \cdot L_{km} = 8.15\Omega$$

$$P_{Losses} = {I_{DC}}^2 \cdot R_{Tot} = 7832W$$

The inverter, with IGBT technology, would reconvert the electricity in three-phase alternative current that will be directly connected to the grid. But first, the currents are filtered to make appear the purest sinusoidal signal, to reduce losses and improve the quality of the signal.

Chapter 4.- Results Analysis

1. Results of the base case

Base case in this project is a single offshore wind turbine connects to continental grid with a HVDC link. IGBT converters are used for the electronic power section. For the calculation part in the chapter 3, the converters have been taken as no-losses.

Simulink allows including in the calculations the losses of both the transformers and the converters. The results from Simulink are going to be studied in the next pages, to get the real value of losses, the quality of the signal, and the interest of this application. An image of the Simulink Block of all the project it is in the Annexe B.

The important measures in this model are current and voltages. As it will be shown, the AC signals are periodical of period 1/50, as the European grid works in 50Hz. A correct cycle will be 0.02s. Simulation period has been set to 0.05 second maximum, because the Phase-Width Modulation requires big quantities of memory, and long simulations have led to memory errors.

Due to problems with the calculation capability of my computer, there are errors with the voltages and currents calculation, because for high voltage they present problems of approximation. For that situation, voltages has to be multiplied by 100 and currents divided by 10.

HVDC transformation station cost forces to build one station for the wind farm. So a link between each turbine and the transformation station is needs. If voltage trough the link is output voltage of the wind turbine (900V), losses would be important. With a 3000A current, the losses in 1 km are big enough to take care of them.

If there would not be a transformer to rise the voltage, the losses calculations would be for a 1km line:

$$V_{drop} = R \cdot I = 0.0326 \cdot 3000 = 97.8V$$

The voltage drop is around 10% of the nominal line-line wind turbine voltage (900V). Joule losses are calculated in the next equation. The voltage drop is taken to be a line-neutral because it affects each line in a individual way.

$$P_{loss} = 3 \cdot V_{drop} \cdot I \cdot \cos(\emptyset) = 844992 \approx 0.85MW$$

0.85MW is 17% of total power given by the turbine. This quantity will suppose already losses close to 20% in the line for just 1km. It is the demonstration of the interest in rising the voltage in transportation lines.

However, if a transformer is introduced between the turbine and the HVDC station, tha situation changes. As it has been calculated in the Chapter 3, transformer reduces the losses to 60W, or 0.001% of total power.

The transformer voltages and currents look like sinusoidal signals. But there are some interference due to the AC generator. Harmonics signals appear, and the transformer helps to reduce them for later steps (Fig. 38 and Fig. 39). The interest of placing a low pass filter after the transformer has to be studied. Harmonics reduces the power capacity and could be the cause of breakdowns due to overvoltage.

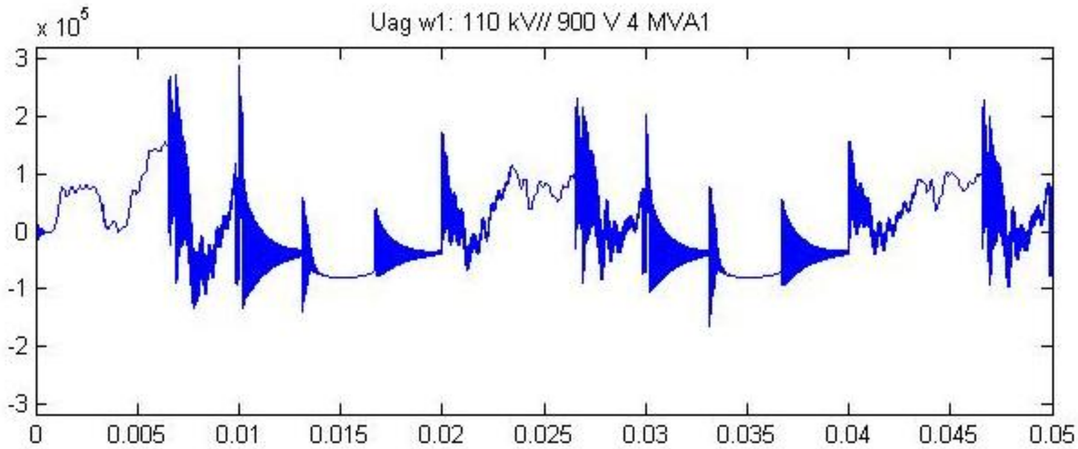


Figure 38. Transformer 110KV Winding Voltage

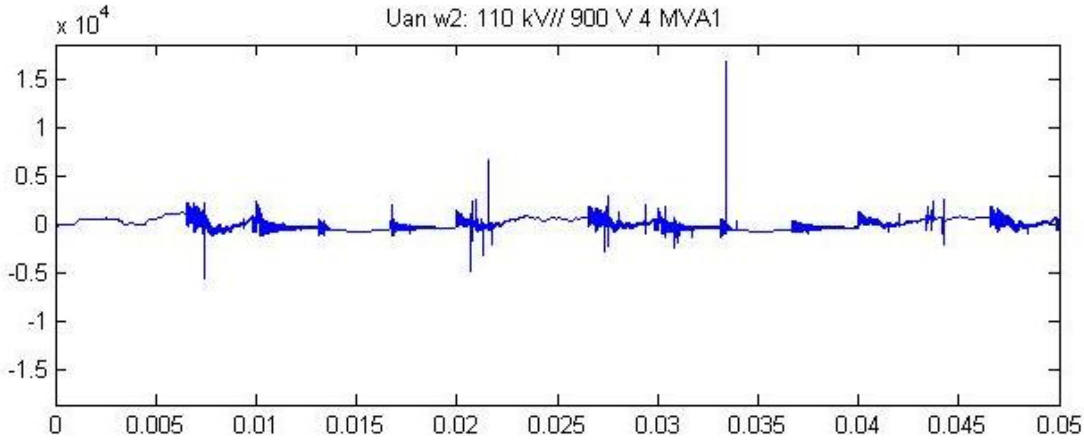


Figure 39. Transformer 900V Winding Voltage

The converter from alternative current to direct current uses IGBT transistors, a technology controlled by voltage. The use of voltage reduces the losses in the converter, and allows a better control. Fig. 40 shows the voltages that the each transistor sees from gate to collector. When they are up or on, there is not current that is going through the transistor, (OFF period). Then the transistor sees 0 or close to zero, it is open, and there is current going through.

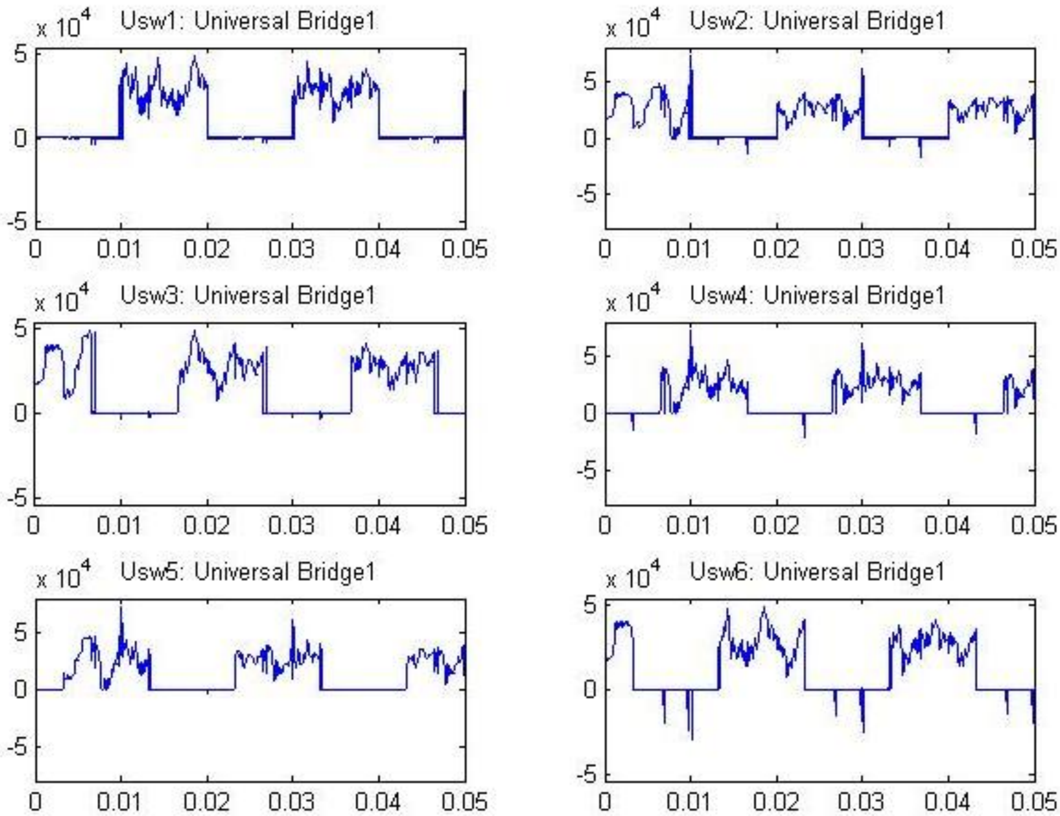


Figure 40. IGBT Bridges Voltages

The converter has been studied to generate a direct current voltage around 150kV, reducing losses, and close to the maximum voltage of the IGBT transistors and VSC model.

Also, the Pulse Width Modulation generator is a Matlab block. As the converter is three-bridges converter, is said, two transistors for each phase, six different signals are necessary. Thanks to the speed to commute of the IGBT transistors, the frequency has been settle to 2kHz, because of limitations of Matlab calculation and memory.

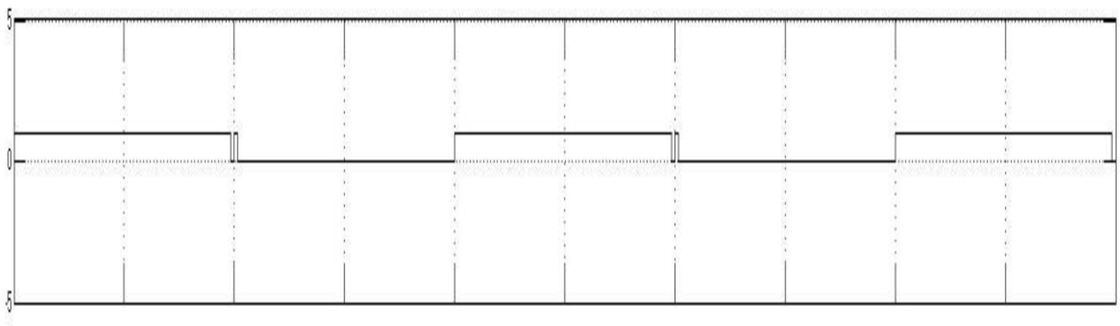


Figure 41. PWM Signal

The DC current has to go through one line, and to return from the other. Both lines has a low resistance in DC. For a frequency of 50Hz the big problem would be the extra insulation. The extra insulation raises the inductance of the cable, increasing the losses. The current in the line and the voltage are closed to a DC current behavior. The necessity of a filter is well-understood, to eliminate the ripple of the current.

Other converter is placed to go from DC to AC. The goal of this converter is to deliver an sinusoidal output voltage, to directly connect to the grid. But different filters, capacitances and control would be necessary to obtain a perfect transmission to the electric grid.

The load receives the power from the wind turbine. The signal looks like a sinusoidal, although a filter would reduce the harmonics. A STATCOM would do its work in this situation. It is important to remark that the current has a similar shape. The voltage from all the load are in the Annexe C.

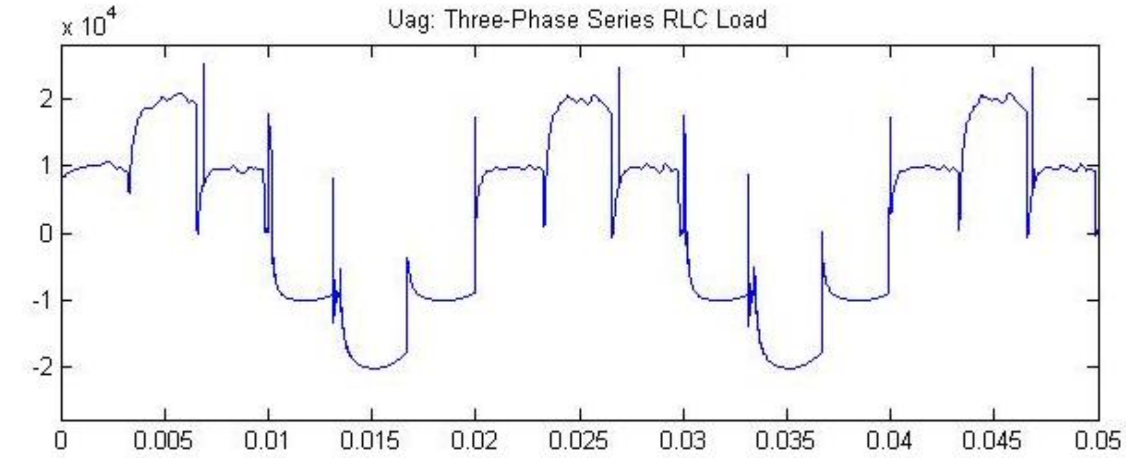


Figure 42. Load Voltage

With the current, it is possible to approximate the power that the wind turbine is giving to the load. Effective voltage is the maximum power divides square root 2. (Fig. 42 and 43)

$$V_{RMS} = \frac{V_{peak}}{\sqrt[2]{2}} = 1414V$$

$$I_{RMS} = \frac{I_{peak}}{\sqrt[2]{2}} = 14.1A$$

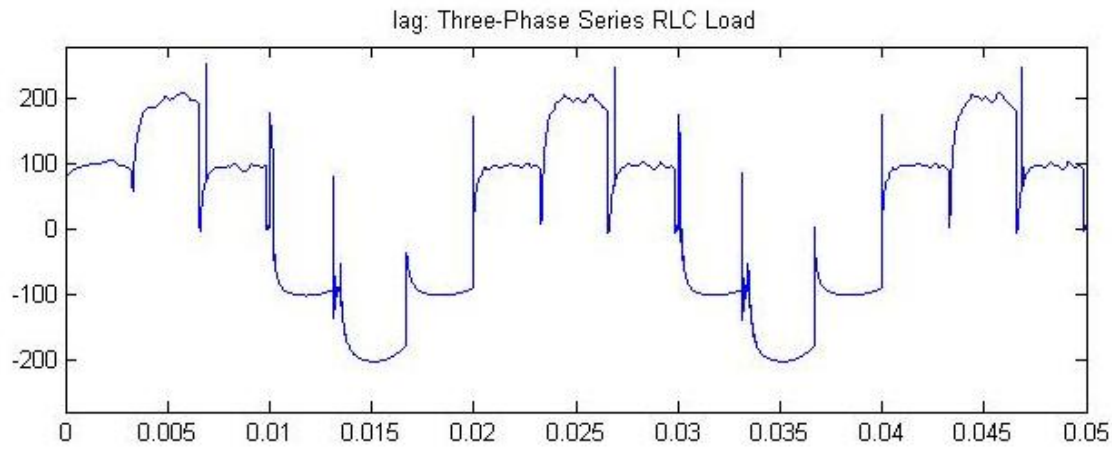


Figure 43. Load Current

Total power given to the load is dependent of the line-ground voltage.

$$P = 3 \cdot V \cdot I \cdot \cos(\emptyset) \approx 4MW$$

The total losses are 0.5MW,so around 11% of losses of the produced power. This value is around the value attended for HVDC. HVAC lines, in distances of two hundred kilometers would have losses around 20% of the generated power.

Chapter 5.- Conclusions

1. Methodology Conclusions

The study has tried to understand every important component that is used in HVDC links, giving special importance to components that are exclusive of this kind of electric transportation.

IGBT converters, transformers, Pulse Width Modulation generator, asynchronous generator, Direct Current cables and offshore wind turbines have been studied and simulated in a simple way. But for they specifications, are products very sensitive to little variations and different input voltages, currents or frequencies.

For this application, high power calculation, because the use of medium-high frequencies (20kHz) implies lot of cycles in a 0.05s calculation. At least 1000 iterations would be done.

Nevertheless, lots of different models are able in Matlab and Simulink programs. A necessary study of the conditions, options and parameters has to be done, as it has been done in this project. The choice of correct values, and the simulation under constant conditions would help to reduce the calculations and the simulation times.

Constant values have been used, but it is important to remember that this application would work under incontrollable situations, which are usually difficult to anticipate and predict. Wind conditions could be study but physical changes (wind speed, temperature and natural events) or human catastrophic events could lead to unattended conditions.

However, last affirmation does not undervalue the quality of the obtained results. Results help to understand the advantages that HVDC has against HVAC. Moreover it is a general explication of the technology under HVDC that would introduce the reader to a really updated and high-level technology.

HVDC technology is changing all days, with new products, converters and power capacity. There is several real examples that have been built all around the world. VSC converters are relatively newborn, what has complicate the research of implemented examples, but thank to currently development of offshore wind farm, examples start to be ready.

The use of a reactive power source has complicated the simulation and the results. The study of a STATCOM option or a capacitor bank would have help to reduce the harmonics, providing at the same time the reactive power the wind turbine needs to work.

Moreover, to simulate the electric grid with a simple reactive load it is not the proper way, but adapt the output of a HVDC conversion station to the three-phase sinusoidal grid is an study that would need a unique project alone for it.

2. Results Conclusion

Results have complicated the analysis due to the difficulty to set a perfect Matlab simulation. Memory errors, overflows and mandatory use of different voltages to get results have made a complicate study.

From the results the first important result that is possible to take into account is the necessity to transform the low voltage to high voltage. Turbines are prepared to work in a low nominal voltage (550-900V) and relatively high current (2000-3000A). If there is not a transformer to raise the voltage, the Joule losses are really important in short length. 20% of the energy produced would be lost in the 1km link between the turbine and the HVDC conversion station.

The HVDC converters, controlled by Pulse Width Modulation have been a difficult study to do. They produce a sinusoidal-like signal, but lot of filtration is necessary. The PWN generator has to be correctly calibrated to give a proper signal to all the transistors. It is important to remark that PWM is not a perfect solution.

In a theoretical situation, each transistor would be off and on in a complementary way, controlled by the angle, but in real PWM, a way to attain the perfect operation point, IGBT is on in periods it should be off, and vice versa. That operation help to the appearance of harmonics, and this is the explanation of big filters closed to HVDC station.

It is important to remark that HVDC needs smaller transmission lines to carry the same power than similar AC lines. This is due to the fact that direct current transports always maximum power and alternative current depends of the point in the period. This is an important advantage for subsea lines because smaller lines are necessary, so the cost to tender a power line.

Subsea HVDC lines presents the advantage to have less inductance that similar HVAC lines. The extra insulant due to be in the sea, to avoid corrosion and the contact between electricity and the water raises the inductance. This inductance is charged at the beginning of the use of DC (first transient), but in AC it has to be charged every period, two times, one in the positive side, and other in the negative one.

Economically, this inconvenience for AC lines compensates the fact that HVDC converters are expensive, and transform the alternative current to direct one only compensate in subsea applications for distance longer than 80 km. In overlines, the distance is 400km or more, depending of the technology: LCC is cheaper than VSC.

Environmental taking, it is important to understand that the noise of the HVDC station could be important. In the middle of the sea, the platform should be acoustically isolated from the seabed, to reduce impact in the species that could leave close to the station.

3. Recommendation for future studies

For future studies I highly recommend to understand properly the different technologies that are proposed. Later, taking into account the application and the power, a choice has to be done.

Also, an important choice would be the simulation software. You have to take into account the time simulation is going to have, and it is impossible to go forward just testing if each component work.

I have firstly study the behavior of each of the converter in an individual way with a voltage source, testing the different answer to direct and alternative current. Later I have join the HVDC link, and start to obtain the results.

However, my biggest problem has been to give to the turbine and the asynchronous generator the reactive power it needs to work. That needs hard calculation, and is not easy to install a capacitance bank without affecting the normal working operation.

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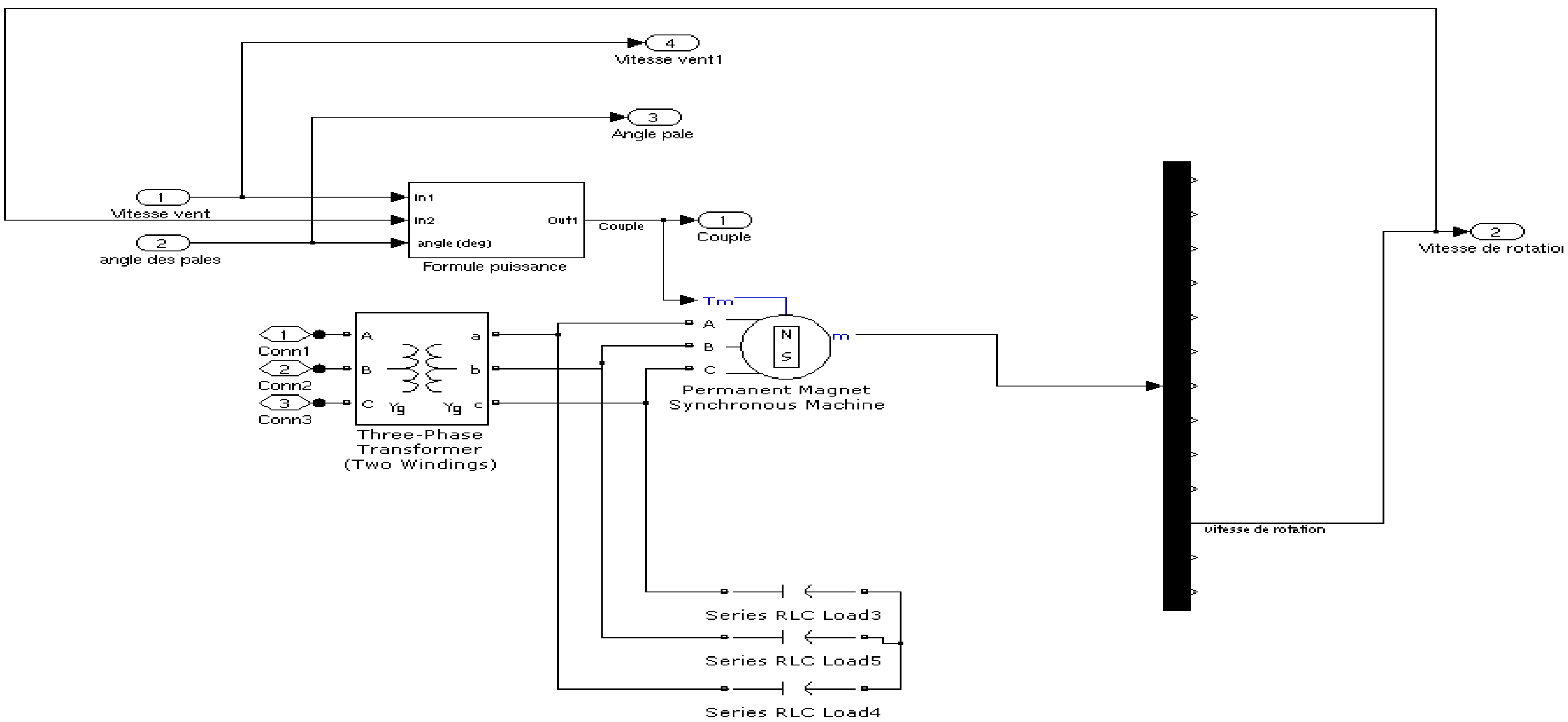
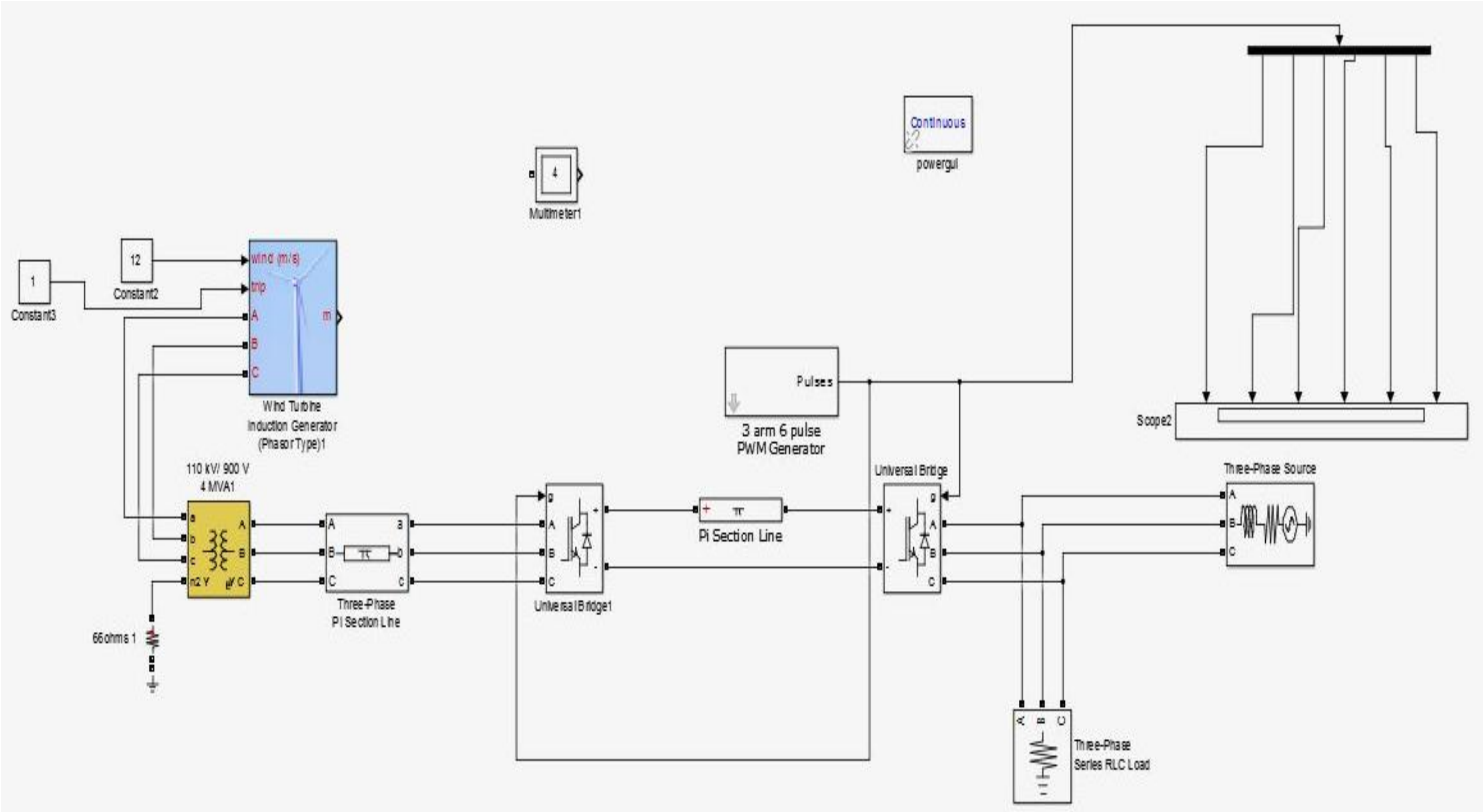
Chapter 7.- Annexes

Annexe A – Wind turbine Simulink model



Annexe B – Offshore Wind turbine + HVDC Simulink model



Annexe C – Voltage and Current from the Components

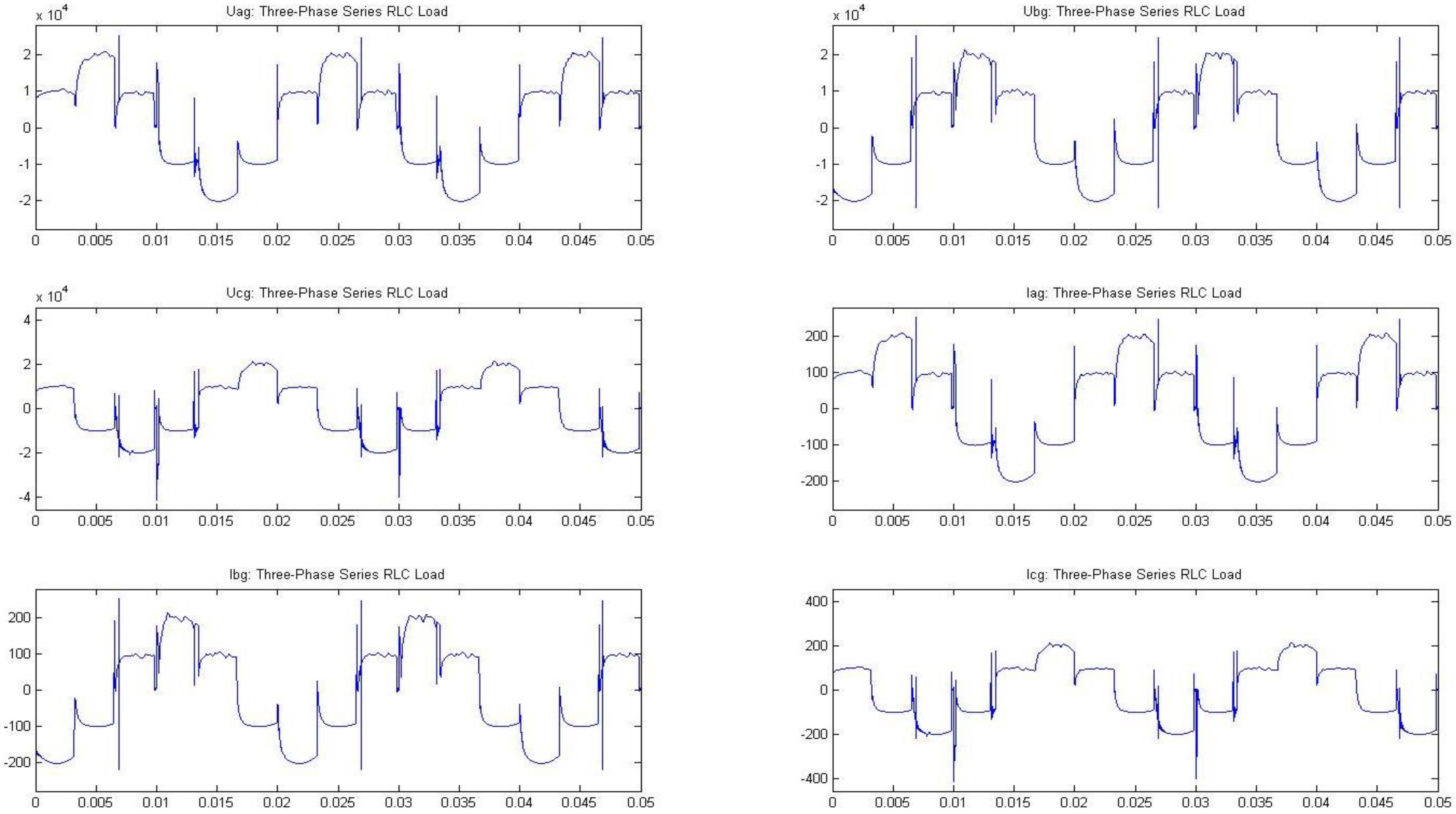


Figure 44. Voltages/Currents Load

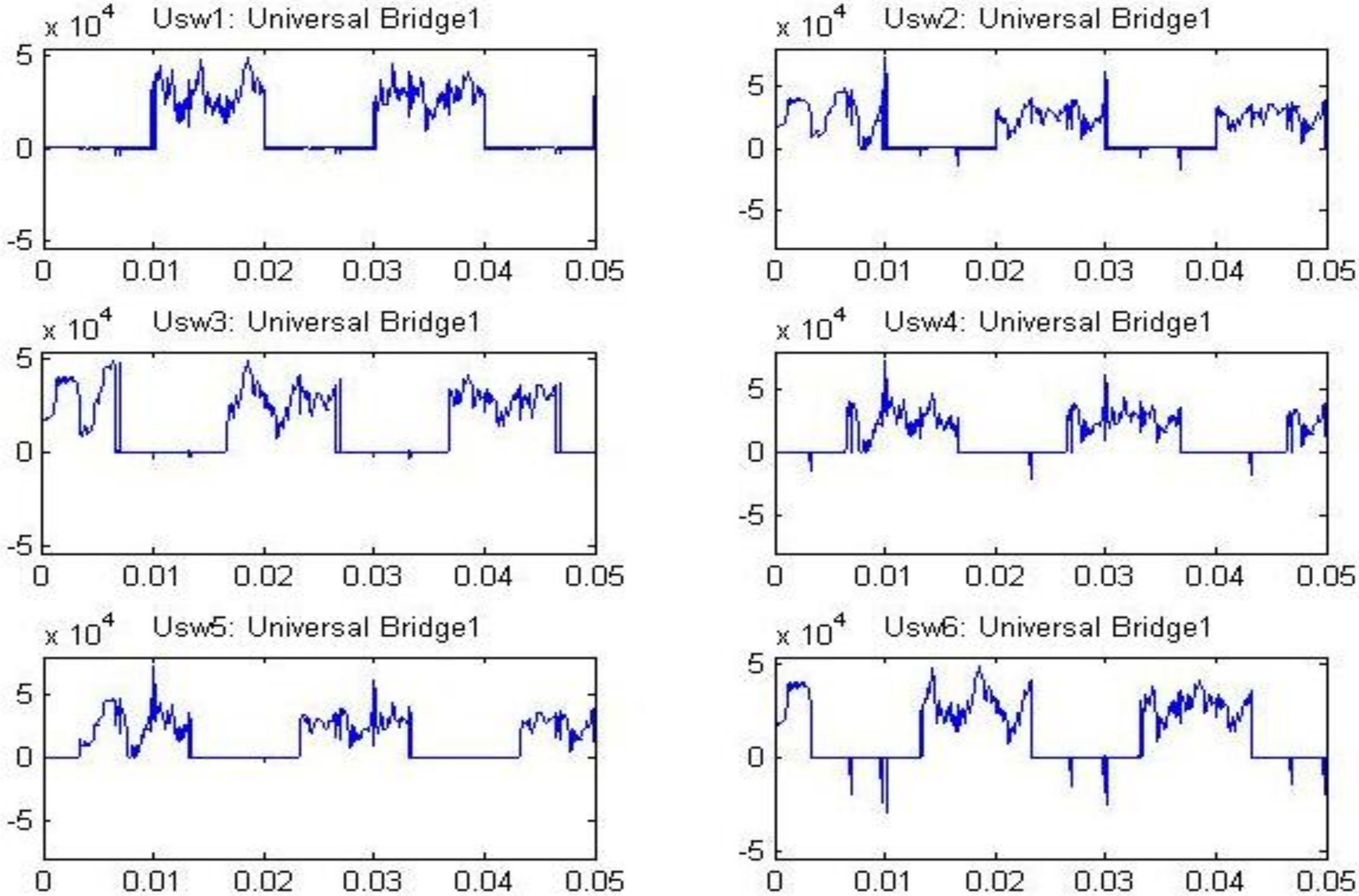


Figure 45. Transistor Individual Voltage

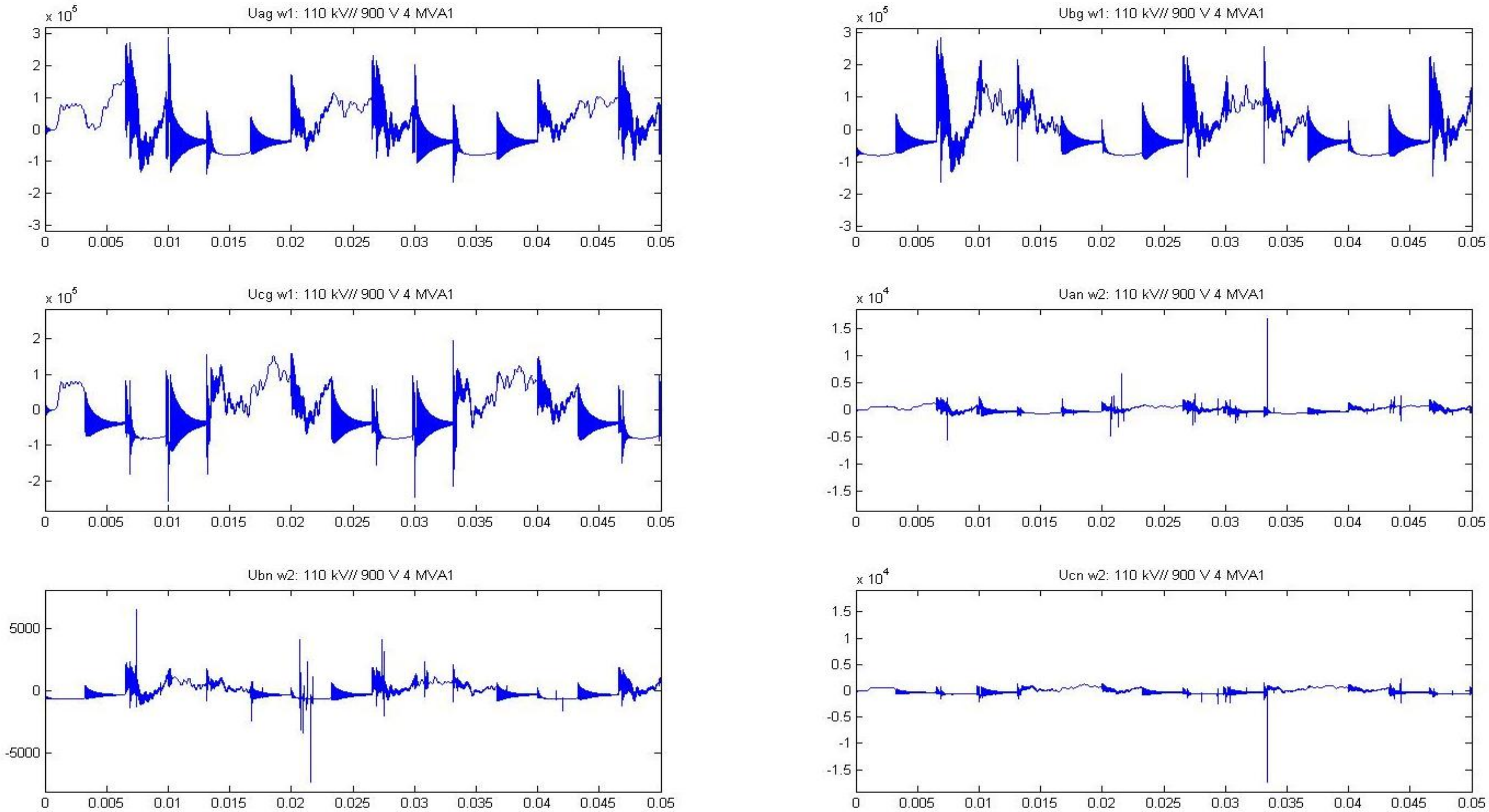


Figure 46. Transformer Windings Voltages

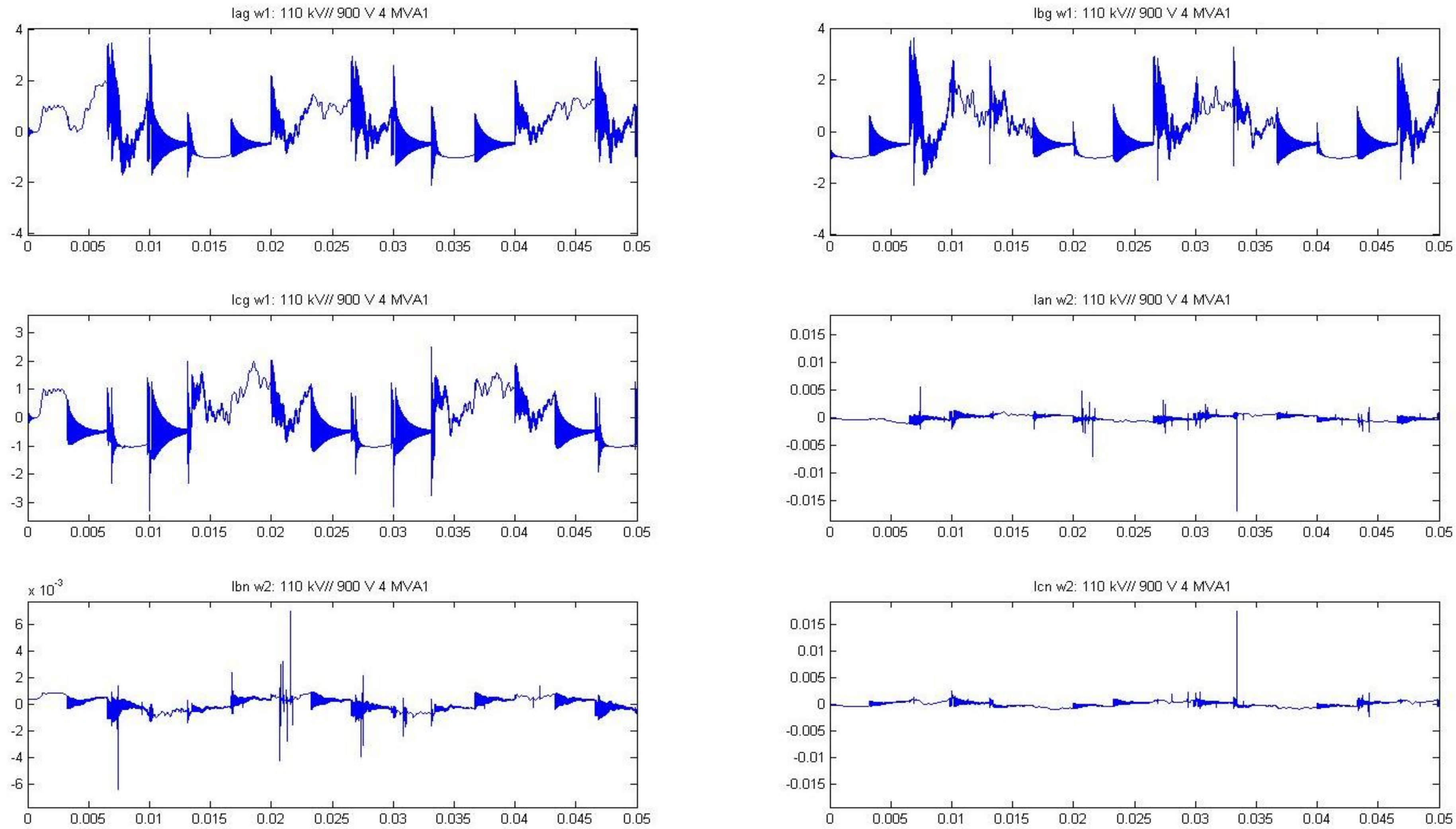


Figure 47. Transformer Windings Currents

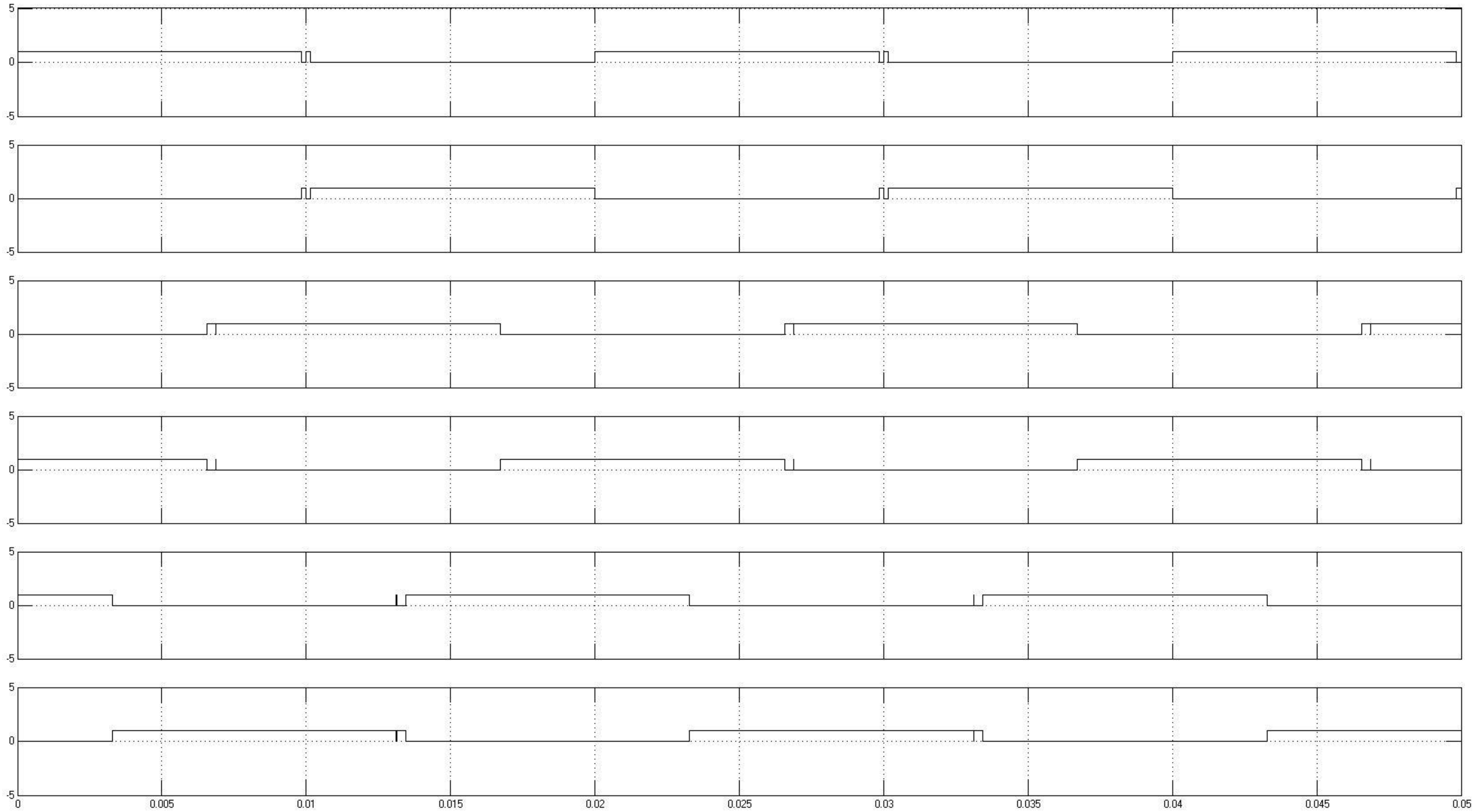


Figure 48. Pulse Width Modulation Generator