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Offshore Power Transmission
Submarine high voltage transmission alternatives

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Submission date: June 2009
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Problem Description

Offshore power transmission involves transmission of power over long distances using cables. Typical applications are power transmissions from shore to offshore installations such as oil platforms or power from an offshore wind park to shore. Offshore wind parks are a highly interesting alternative to onshore wind parks. The challenge, however, transmitting the power to shore in a cost-effective and reliable manner.

Initially the project set out to look at the challenges related to offshore power transmission using alternating (AC) or direct current (DC) solutions. Here the possibilities were vast and could include: investigate theoretical and practical/economical outer limits of AC cable lengths, investigate the criteria involved in deciding whether AC or DC transmission is the best solution, develop a guideline for selection of design topology and technology solutions for various cases.

Assignment given: 20. January 2009
Supervisor: Tore Marvin Undeland, ELKRAFT

Preface

This thesis has been written at the Department of Electric Power Engineering at the Norwegian University of Science and Technology in cooperation with ABB.

The main objective of this study was to develop a guideline for offshore power transmission. Due to a vast subject with many approaches, some energy was put into finding the correct course. There was also a strong incentive for doing an analysis of the electrification of a specific offshore installation. This was attempted, but due to lack of good planning this was not completed. I hope to take the lessons learned and the valuable experiences with me, to improve future work and especially utilize the opportunities presented to their full extent.

I would like to thank Professor Tore M. Undeland for his supervision. In relation to the project I was given the opportunity of working at ABB Oil and Gas in Oslo the summer of 2008. At ABB I would like to thank Tor Eivind Moen and Roald Sporild for their help and advice, and for making me feel like part of the team.

Many thanks goes to my classmates, for the ever so frequent coffee and cake breaks, help, advice and support. I would also like to thank Helen-Sophie for her cheerful mood and her need of supporting me throughout this period, being there for me and reading through my report. Without her I do not think I would ever have finished in time.
Also, a great thanks to my parents for believing in me.

Trondheim, June 2009

Ragnar Ulsund

Abstract

Offshore power transmission is becoming an increasingly important issue. To moderate climate change, world leaders have set environmental goals that will be very difficult to reach without renewable power production and the removal of production units with high emissions. Wind power and electrification have been the focus in this report. Plans for the expensive wind power are already moving offshore.

This report has made an attempt at suggesting a guideline for well-suited transmission systems, for wind power projects located at a distance in order to make them more economically attractive. Another emphasis has been to find the most suitable transmission system for gas turbines at offshore installations.

As expected, the use of alternating current is best suited at shorter distances. At longer distances this system is still feasible up to 350 km, but losses will be high and there will be limited power available. A conventional thyristor-based direct current system will therefore be an attractive option for high power ratings and long distances. On the other hand, direct current based on voltage-source converters is considered more expensive, but has an improved control of reactive power and is therefore preferable to the conventional direct current system. To determine which system has the best design, one has to consider each case individually.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Electricity access is almost synonymous with standard of living. Increasing people's standard of living will also increase the electricity demand. Those already connected find new uses and increase their electricity demand. At the same time, the world increase its emissions, which is causing climate change.

Time is changing, and polluting and inefficient gas turbines are not the best possible solution for electricity at offshore installations anymore. There is an increasing awareness of the crude oil and gas producers; there is a need for cleaner energy. It is not only a environmental issue anymore, there are financial powers in effect as well.

Many world leaders have already accepted the challenge and are trying to take necessary measures. Strategies for preventing climate change, delaying global warming and increasing overall standards of living should be implemented.

Offshore power transmission involves transmission of power over long distances using cables. Typical applications are power transmissions from shore to offshore installations such as oil platforms or power from an offshore wind farm to shore. Offshore wind farms are highly interesting alternatives to onshore wind farms. The challenge, however, is transmitting the power to shore in a cost-effective and reliable manner. Offshore power transmission and installations are increasingly attractive options for oil companies. These reduce the need for offshore turbine generators, frees up valuable space on the installations for process equipment, reduces maintenance costs, and has environmental benefits with respect to fuel efficiency and CO_2 and NO_X emissions. Initially the project set out to look at the challenges related to offshore power transmission using alternating (AC) or direct current (DC) solutions. Here the possibilities were vast and could include: investigating theoretical, practical and economical outer limits of AC cable lengths, investigating the criteria involved in deciding whether AC or DC transmission is the best solution, and developing a guideline for selection of design topology and technology solutions for various cases.

The main focus of this paper will therefore be investigating what types of offshore power transmission solutions are best, with regards to the new production from renewable energy, and the shift from the most polluting power sources, such as gas turbines at offshore installations, to electricity from shore.

Chapter 2

Renewable energy and petroleum - hand in hand towards the future

The climate settlement is an official agreement between most of the Norwegian political parties, stating that Norway will reduce its emissions and try to take sustainable responsibility for future generations. It was meant as a long term policy that could remain even if future governments change, and opposition takes power. The settlement present some goals that Norway hopes to reach:

- A goal of becoming carbon neutral ambitiously within 2030 (the previous goal was set to 2050).
- A goal of reducing CO_2 emissions equivalent to 15-17 million tons.

One of the points that the political parties agreed upon was that two thirds of the reduction of emissions had to be in Norwegian territory. To achieve these goals, encouraging policies were suggested such as funds to renewable energy research and discouraging policies like an increase of tax on petrol. Offshore wind power gets 150 million NOK with other inexperienced technologies for demonstration program [2].

In figure 2.1 below from [1] there is shown a possible development in the North Sea, where the circles are representing the existing oil and gas platform of today and maybe tomorrow's. There are still new findings, but they are smaller ones. The big oil and gas fields are already found and almost all of them are over their peak production. If the incentive is strong enough they could be electrified from shore to reduce offshore gas turbine emissions. Then, as production slows down there would eventually be available infrastructure for offshore wind power. Wind turbines would not be in anyones backyard and Norway could still be an energy exporter, if an offensive is made before it is too late.

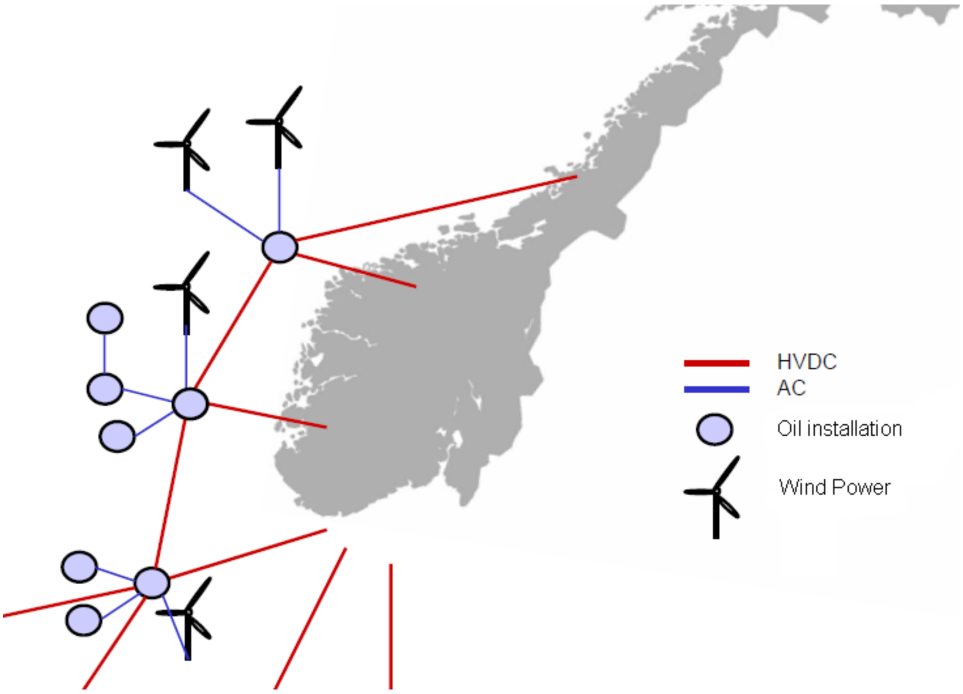


Figure 2.1: Future North Sea

2.1 Wind power and other Renewables

Offshore Wind Farms

Wind Power is a beautiful energy source, but only appreciated by people who understand why, and it has become more attractive to remove it out of sight. A wind turbine consists of many components and there is usually a lot of thought put into each and the location of them.

The interest for wind power is increasing, this is no surprise considering the enormous theoretical potential, both on land and offshore. Offshore has a higher potential, better conditions and higher wind speeds. Europe in total has a theoretical potential somewhere between 2.8-3.2 and 8.5 PWh, and compared to Norway's consumption of 0.125 PWh it is very high. Today, the experience is limited and wind power is expensive, and off shore it would cost at least twice as much as the land based wind power. Nevertheless, there is a shift towards offshore wind farms. As the saying goes: bigger is better. Wind farms are becoming popular and large farms have been built, with over 150 MW installed, like Horns Rev and Nysted.

2.2 Energy on the Norwegian Shelf

In 2006, the petroleum industry in Norway represented approximately 25 % of the total greenhouse gas emissions and has also been the only sector that has had a steady increase of emissions compared with other sectors, that seem to have stagnated. There are 170 turbines that amount to approximately 3000 MW of installed power on the Norwegian shelf. Of them, 60 have waste heat recovery units reaching approximately 1000 MW. There are 100 gas turbines (780 MW) that drives electric generators and 70 gas turbines (962 MW) that drives machines using mechanical energy. It is the electric generators that are the easiest to power from shore, while the mechanical energy requires much more adaptation and thus a higher cost. Compared to rest of the world, the Norwegian shelf is relatively energy efficient. Decent maintenance and few old turbines make sure of this. Average efficiency is around 31 %, and varies from 22-37 %. Adding to the total efficency are done by waste heat recovery units, where efficency can be as high as 60 %. This gives a total efficiency of approximately 40 % [19].

Electrification on the agenda

The Norwegian Petroleum Directorate (NPD), the Norwegian Water Resources and Energy Administration (NVE), the Norwegian Pollution Control Authority (SFT) and the Petroleum Safety Authority Norway (Ptil) was given the task by the Ministry of Petroleum and Energy to prepare an up-to-date analysis of the *Cost of Measure* (2.1) with regards to power from land/emission-free power to petroleum activities. This report presented an estimated cost of measure in 2007 around 1600 NOK for each ton reduction in CO_2 emissions. Cost of measures was for part electrification, because a whole electrification is not economically feasible. In total the petroleum industry released over 12 million tons CO_2 in 2006, part electrification measures would reduce this with 4 million tons.

$$\text{Cost of Measure} = \text{Cost of Abatement} \tag{2.1}$$

Where *Cost of Abatement* is all cost with regards to investment, operation, sales, resources and emissions divided by the net CO_2 savings [19].

The reservoirs are finite. To maximize the emission reduction, electrification must start as soon as possible, meaning 2012 and finishing 2015 at the earliest.

Future scenarios of cost estimation

In the report mentioned above the Norwegian shelf is divided in four areas and no new installations are considered. Power production is important. Would an increase in power production onshore reduce the CO_2 emissions, and in what quantity? Here, three different scenarios were considered.

1. Scenario *Dedicated power production:* This scenario considers power directly from gas power plants with CO_2 management dedicated only to offshore installations. Cost of this scenario comes from gas power, capture and storage. Here emissions would be the physical ones and power price will not be relevant, because the production is dedicated to the shelf.

2. Scenario *Power from market - physical powers:* Here the driving forces of the energy market dictates the power price. This scenario's quota are excluded and there will be no incentives for low emissions. Emissions would be an average of power productions.

3. Scenario *Power from market - with restricted emission and trade quota:* Increased consumption in Norway would result in increased import of power. This scenario uses the same driving forces as scenario 2, but the assumption here is active international policy that is based on committed CO_2 emissions reduction. This meaning that trade quota is functional and will take care of emissions on its own, and also give a higher market price.[18]

Chapter 3

Electrical installations offshore

The diversity of offshore units is significant, this chapter will give a description of some of them with the focus on installations located at longer distances. Typical installations will be introduced, first for offshore production like wind power, then offshore platforms with its production and consumption.

3.1 Offshore energy production

Humans have enjoyed the power of wind for a long time, from the drying of clothes, sailing and now producing electricity. This section will briefly explain how wind energy is converted to electricity and where to locate the wind parks.

Wind energy

A simple way of describing wind energy is by saying that, wind blows making the blades rotate. The rotating force is transferred to the generator which makes electricity for us to use. With a simple concept like this and its enormous potential, it is almost strange there are not wind turbines everywhere. The obvious reason why is that they are expensive to build and maintain. This is why it is important to find the best suited locations for wind power.

Energy conversion in steady state from wind through blades to mechanical power can be described by equations 3.1 and 3.2 below [3].

$$P_{mec} = \frac{\pi \rho \omega_s^3 (\frac{D_r}{2})^2}{2} C_p(\lambda, \beta) \tag{3.1}$$

$$\lambda = \frac{\omega_t D_r}{2\omega_s} \tag{3.2}$$

Where:

P_{mec} = mechanical power
ρ = air density = 1.225 kg/m^3
ω_s = wind speed [m/s]
D_r = rotor diameter [m]
$C_p(\lambda, \beta)$ = aerodynamic efficiency
λ = tip speed ratio
β = pitch angle
ω_t = turbine rotor speed [rad/s]

As seen from equation 3.1 power is highly dependent on wind speed, so when finding a suitable site for a wind farm one should look for high wind speeds. Measurements must be accurate when designing the wind farm. For example if there is an error of three percent in wind measurements this will result in an error of nine percent in power.

From [4] “Wind resource estimation – an overview” methods vary from folklore and measure-correlate-predict (MCP) to combined meso and micro scale modeling. MCP uses measurements for a short time period, and correlates with an overlapping of climatologically representative time series as a reference station. For a larger farm there should at least be on site mast measurements for one year, with a decent reference station in the vicinity, preferably with a 30 year history data. If there is little correlation, one could use on site measurements as input. When this potential is found, micro-siting with models such as WAsP, MS-Micro, Raptor or computational fluid dynamics (CFD) could be employed. CFD is expected to enhance prediction, especially with complex terrain.

Care must be taken when choosing methods of measurement and modeling to produce applicable power curves for turbine design and siting of turbines [4].

Turbine technologies

Wind turbines usually operate at a medium voltage level of 690 V. The voltage is often transformed at the base of the turbine to produce a more suitable voltage level. Typical turbine design:

- Fixed speed, stall
- Fixed speed, pitch
- Adjustable slip
- Double fed induction generator
- Full converter, gear or direct driven

Figure 3.1: Wind turbine.

Stall is when the wing loses its ability to maintain the lift, similar to a plane trying to climb to fast without enough speed. At optimal tip speed ratio, stall regulated turbines have a fixed revolution speed, but when wind increases stalling will occur and turbine power is reduced. Tip speed ratio is the relation between wind speed and rotational speed. For stall regulated turbines with variable revolution speed, power electronics are used to control the torque for the generator. Then it can operate with a wider range of wind speeds.

Pitch is the ability to twist the blades and always have the optimal angle of attack. A turbine with variable rotational speed wants the optimal tip speed ratio in parts of the operating time. Under turbulent conditions and gusts, pitch control can keep the power constant. This is also the case when the generator the fully loaded.

Active stall regulation is the opposite of pitch regulating. While pitch regulates the blades, minimizing the angle of attack to decrease lift coefficient, active stall will on the other hand increase the angle of attack to decrease the lift.

Off shore the wake effect is larger than on land, because of the smooth surface of the ocean. Luckily, the ocean is fairly large so it is easy to place the turbines further apart. This is one of the many aspects that are economically optimized.

3.2 Oil and Gas Consumption

According to what is done with respect to offshore installation the electrical power supply will vary. However, it is regarded as an auxiliary system, designed to supply the platform with necessary electric power throughout its lifetime, with sufficient reliability and availability. This has often been divided in three parts [14]:

- Main Power system
- Essential power supply
- Emergency power system

Main Power system

The electric power needed for the daily operation of an installation is covered by the main power system, usually consisting of 2-4 identical gas powered generators with ratings approximately up to 35 MW. Keeping the short circuit current within its limits is very important when designing generators. Typical values are 40 kA and 50 kA for high voltage and low voltage distribution, respectively. Other criteria are redundancy, load scenarios, cost optimization, flexibility and environmental considerations.

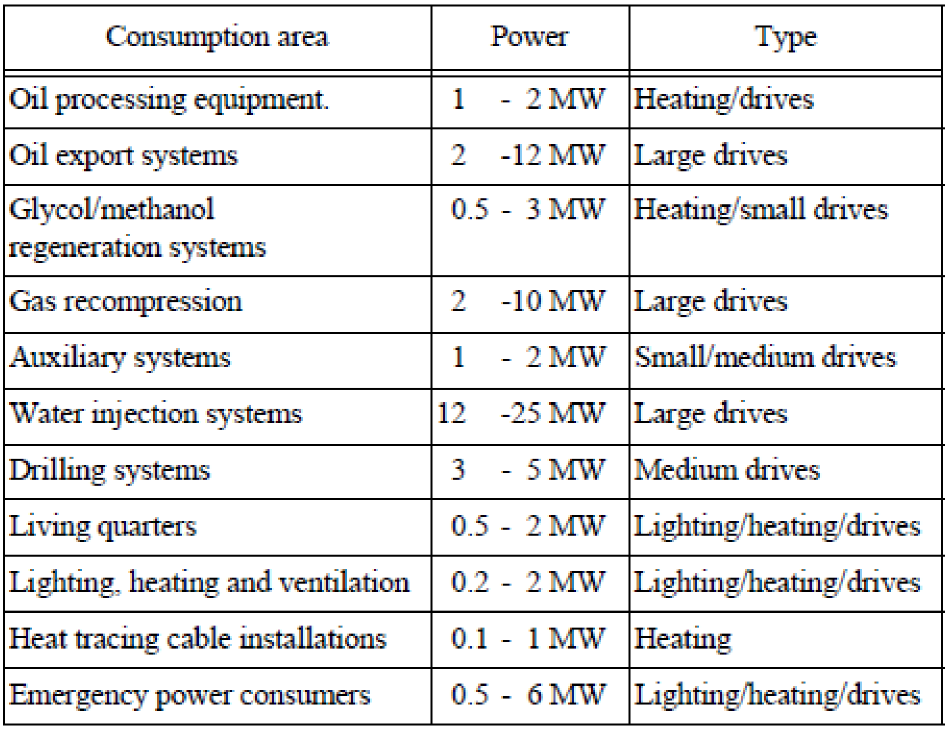
There are many different electrical loads on offshore oil and gas installations. Typical components is found in table 3.1.

Essential power supply

Essential power supply is a separate power supply that is necessary during commissioning of a new platform and in the drilling period before production. The system can also be a backup for the main power system during serious faults and maintenance. It is usually a part of the normal distribution and on large platforms have a rating up to 2x4 MW. As newer installations have more reliable main power systems, tendency is to leave out the essential power supply category and cover the need under commissioning with temporary diesel generators or supply from adjacent vessels and platforms.

Emergency power systems

These exist for safety reasons and should be completely independent from the main power system. They supply necessary power for emergency equipment, fire fighting, lighting, cooling and initiate when the main power system fails. Emergency systems should supply power up to 24 hours with ratings that



Consumption area	Power	Type
Oil processing equipment.	1 - 2 MW	Heating/drives
Oil export systems	2 -12 MW	Large drives
Glycol/methanol regeneration systems	0.5 - 3 MW	Heating/small drives
Gas recompression	2 -10 MW	Large drives
Auxiliary systems	1 - 2 MW	Small/medium drives
Water injection systems	12 -25 MW	Large drives
Drilling systems	3 - 5 MW	Medium drives
Living quarters	0.5 - 2 MW	Lighting/heating/drives
Lighting, heating and ventilation	0.2 - 2 MW	Lighting/heating/drives
Heat tracing cable installations	0.1 - 1 MW	Heating
Emergency power consumers	0.5 - 6 MW	Lighting/heating/drives

Table 3.1: Main power consumption areas on an oil production platform.

vary, but these usually are between 0.5 MW and 1.5 MW. For the Norwegian continental shelf all installations must comply in accordance with regulations set by the Norwegian Petroleum Directorate (NPD) [14].

Chapter 4

Three main types of transmission

In this chapter an overview of components in offshore transmission systems will be presented, and how they link in order to transfer power.

- HVAC High Voltage Alternating Current
- HVDC LCC based on Line-Commutated Current Source Converter
- HVDC VSC based on Self-Commutated Voltage Source Converter

4.1 High voltage alternating current (HVAC) transmission

HVAC is the most straight forward technical solution for offshore power transmission. Therefore it is also the most used and experienced. Existing offshore wind farms are connected with HVAC power transmission. From figure 4.1 below, main components could be [9]:

- AC based collector system within the wind farm.
- Offshore station that includes transformer and reactive compensation.
- Three core XLPE (cross linked polyethylene insulation) HVAC cable
- Onshore transformer station and compensators

Today the biggest wind offshore farms are Danish Horns Rev and Nysted, with total power of 160 MW and 165.6 MW, respectively installed. Both are located fairly close to shore and HVAC transmission were the optimal solution.

Horns Rev was constructed in 2002 outside the west coast of Denmark. It supplies approximately 150,000 Danish households, compared with Nysted

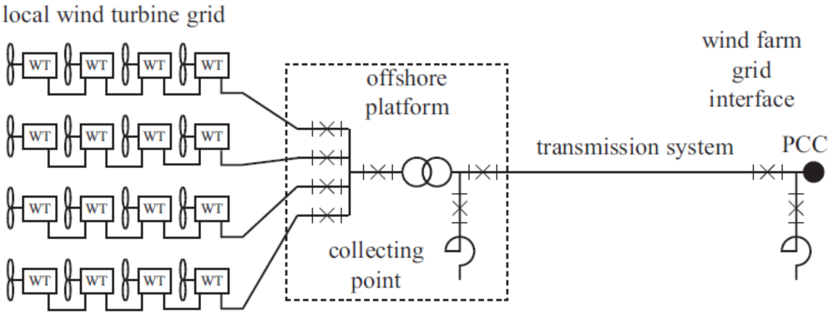


Figure 4.1: The electrical system for a large AC wind farm

that supplies 145,000 households with more power installed but with somewhat poorer wind conditions. Inside the Horns Rev wind farm the voltage level is 36 kV. Voltage level is raised to 150 kV offshore, before feeding to the 15 km cable to shore. The substation is a tripod construction with the following technical installation:

- 36 kV switch gear
- 36/150 kV transformer
- 150 kV switch gear
- a control and instrumentation system, as well as communication unit
- an emergency diesel generator, including 2 times 50 ton of fuel
- sea-water-based fire-extinguishing equipment
- staff and service facilities
- helipad, crawler cran and a Man-Overboard-Boat

The Danish Nysted offshore wind farm uses a voltage level of 33 kV within the farm, a substation with 33/132 kV transformer and a 10 km cable to shore. These offshore substations are rather unique, and will provide information for future offshore transmission projects. [6]

HVAC is the most economical solution for short distances. The main difference from HVDC cables and overhead lines is the capacitance. A cable with a an outer semi-conducting sheath can be modeled as a coaxial cable. Capacitance per unit length is defined as shown in equation 4.1.

$$C = \frac{q}{v} = \frac{2\pi\epsilon_0\epsilon_r}{\ln(\frac{r_y}{r_i})} \tag{4.1}$$

Figure 4.2: The Horns Rev offshore transformer

where r_y and r_i denotes the outer and inner radius of the insulation, respectively. ϵ_r is the relative permeability of the insulation, for XLPE ϵ_r ≈2.3-2.6. For polymeric insulation permittivity is temperature dependent. Finding capacitance without outer screen can be done by FEM-software [10]. Other insulation as high-pressure pipe-type, or gas-filled with paper and low-pressure oil-filled with paper insulation will not be considered in this report, due to that XLPE has the overall the most attractive qualities for long offshore power transmission.

Capacitance is both a curse and a blessing for long cables. It maintains the voltage across the entire cable. It causes a charging current to flow along the length of the cable. Charging current, I_C is defined as shown in equation 4.2:

$$I_C = 2\pi f C E \tag{4.2}$$

where the charging current is dependent of f - frequency 50 or 60 Hz, C - capacitance and E - voltage. I_C reduces the available cable capacity to carry useful load current I_P:

$$I_P^2 = I_T^2 - I_C^2 \tag{4.3}$$

where I_T is cable rated ampacity. As DC transmission frequency is zero which gives leads to no charging current, there will not be any reduction of ampacity, $I_P^2 = I_T^2$.

Cable parameters are distributed, which means that charging current is flowing unevenly along the cable. If a sending end has to supply all of I_C, the sending end absorbs reactive power. Along the cable there is production of reactive power. Maximum value of I_C is found at sending end, and maximum voltage would be found in the other end.

If both ends are supplying I_C, both ends will absorb reactive power, and I_C would be at its maximum at both ends. There will be a voltage increase at the center of cable, V_{max} at half of cable length.

Losses in AC cables could also be the limiting factor. HVAC submarine cable loss have four components:

- Dielectric losses. This type of loss is relatively small.
- I^2R losses in the conductor core. These are the most significant losses.
- I^2R losses in the metallic sheath, generated by induction of the main core current. This loss can be up to one third of the core losses.
- I^2R losses in the steel wire armour, also generated by induction of the main core current. This loss can be up to one half of the core losses.

Other factors that should be considered is that capacitance can produce overvoltages that eventually can cause breakdowns, high harmonic currents and undesirable resonance. Longer cable increases the difficulty to obtain a reliable system design. Transmission capacity in any cable is eventually restrained by reactive power production due to capacitance [12]. Figure 4.3 below gives an overview of the effects of different power transmission capacities .

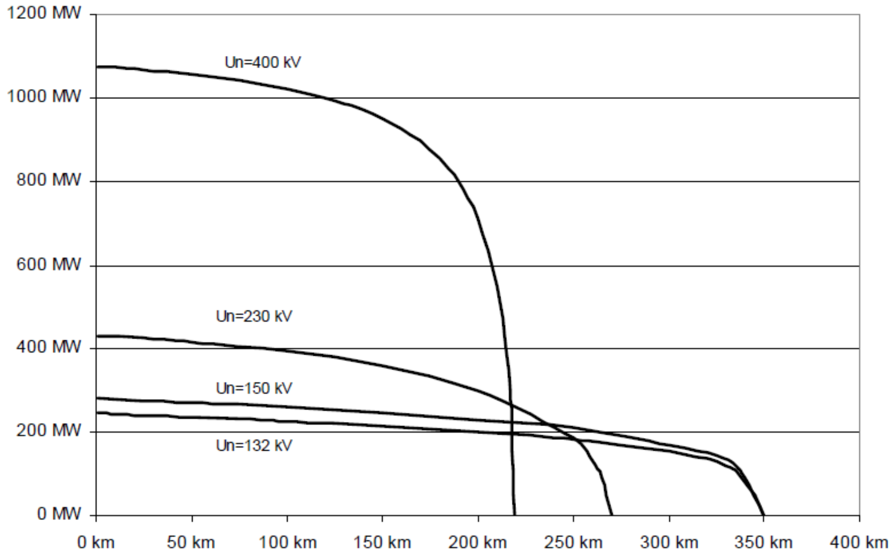


Figure 4.3: Power transmission capacity vs distance

4.2 High voltage direct current line commutated converter(HVDC LCC)

Interest of HVDC transmission sparked the development of mercury arc converters as early as the 1930s, and made way for the first commercial HVDC link to the island of Gotland, Sweden. The mercury arc converters were slowly made obsolete by thyristor semiconductor converters that today are considered mature technology. Principally HVDC LCC is two converter stations, one rectifier and one inverter. The rectifier terminal takes electric power from the grid, transmitting it by a DC link to the inverter terminal that converts the electric power back to AC, for distribution in a new grid. The main components are:

- Converter transformer: the main purpose is increasing transmission voltage, but if properly designed they could also reduce harmonics. One onshore and one offshore, usually both star and delta connections for 12-pulse converter as in figure 4.4 from [12]. 12-pulse converter cancel harmonics and reduce filters.

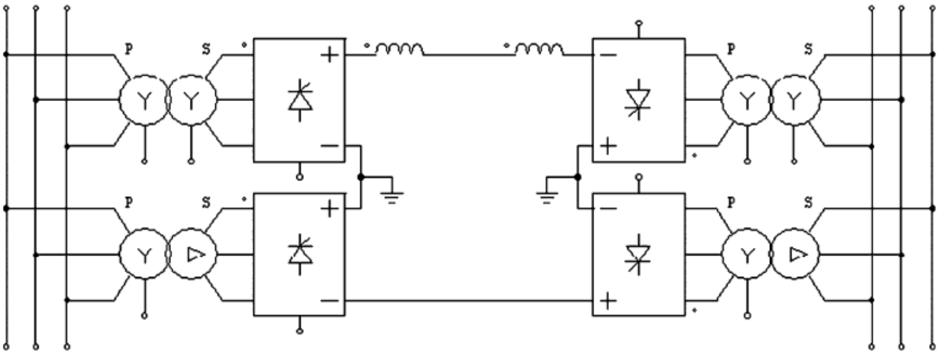


Figure 4.4: HVDC LCC transmission system

- LCC power converter based on thyristors: the thyristor valves are the most important components because they operate the conversion of AC and DC. In order to operate, the thyristor valves require reactive power. For this reason filters and capacitor banks are used, also static synchronous compensator (STATCOM) can be considered (see below). 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 [13].

- AC and DC filters: filters are used to absorb the high content of lower harmonic currents generated by the converter in order to minimize the impact on connected grid. AC filters also supply reactive power to the converter station. DC filters hinder the generation of circulating AC currents in transmission cable.

- Smoothing reactors: are used to avoid current interruption with minimum load, limit DC fault currents, reduce harmonics and prevent resonance.

- STATCOM or capacitor banks: is necessary because valves in converter need reactive power to operate functionally. Capacitor banks consist of a series of capacitors connected in parallel to the transformer. STATCOM is expensive, but would improve the overall operation of the converter station, due to the ability to consume and generate reactive power.

- DC cables

Figure 4.4 below illustrates a HVDC LCC transmission system. Figure 4.5 from [11] below shows the most commom system configurations. The simplest and cheapest HVDC transmission system for moderate power transfers are monopolar configurations. Only one cable and two converters are required, these systems have been used with low-voltage electrode lines and sea electrodes to carry the return current in submarine cable crossings. This might not be preferred in heavily congested areas, fresh water cable crossing or areas with high earth resistivity.

HVDC LCC also requires an auxiliary power set to supply valve when they are fired at the beginning of transmission.

4.3 High voltage direct current voltage source converter (HVDC VSC)

The evolution of the insulated gate bipolar transistors (IGBT) has lead to development of products like HVDC Light and HVDC Plus, ABB and Siemens products respectively. ABB installed their first HVDC VSC transmission in Hellsjön, Sweden in 1997. Since this first small installation proved its reliability, there has been many constructed HVDC VSC links all over the world. High power IGBTs have allowed VSC in HVDC systems to operate in the range of 1-2 kHz, giving significantly less harmonic distortion. They are commercially available and ranges up to 1100 MW and ± 300 kV. Compared to converter station losses for the HVDC LCC 1-2%, HVDC VSC has a higher power loss 4-5%, but there are a couple benefits that the LCC cannot match.

HVDC VSC systems can independently control active and reactive power at each terminal, and the transmission could be controlled with great flexibility. It can even start with a dead grid. Its main components are [11, 12, 13]:

- HVDC VSC substations onshore and offshore: These stations are smaller than conventional HVDC and thus better suited on a offshore installation.
- Transformers.
- Smoothing reactor: Will be smaller, because of a higher switching frequency.
- AC and DC filters: also smaller and no need for reactive compensation.
- Cable pair, polymeric extruded cables.

Figure 4.6 illustrates a HVDC VSC system.

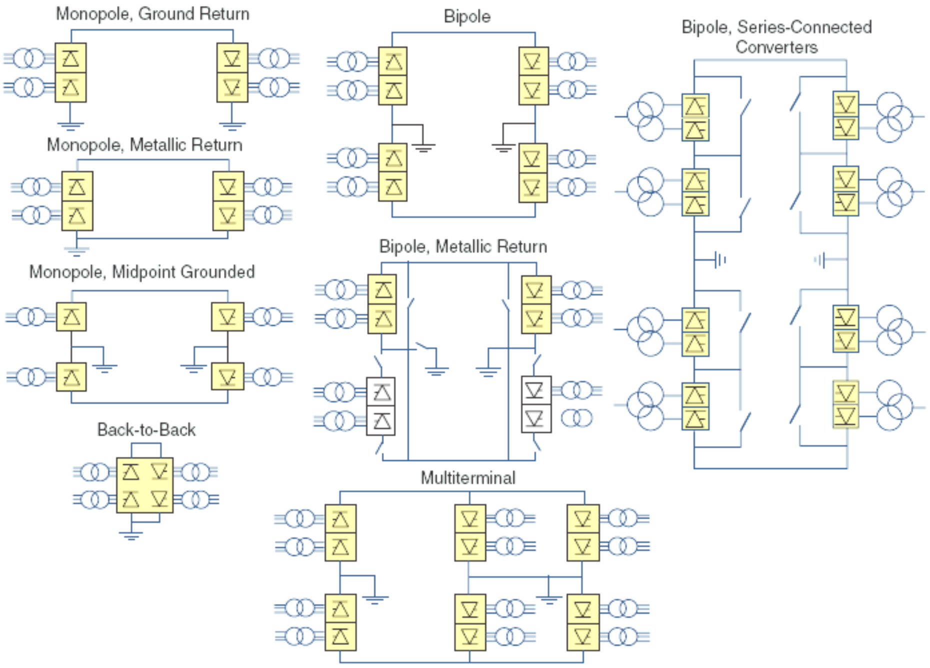


Figure 4.5: HVDC configurations and operating modes

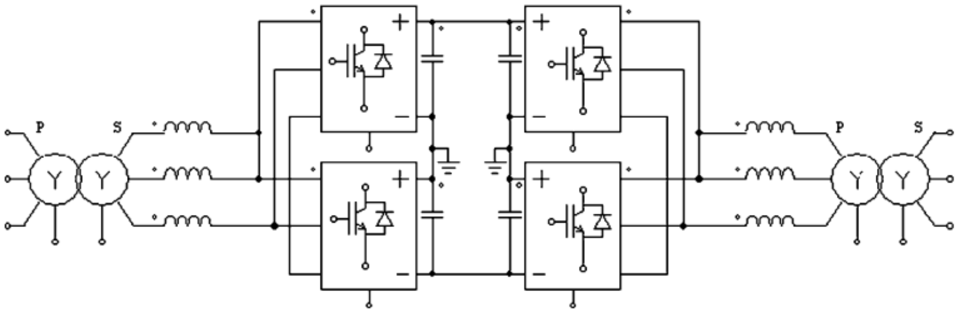


Figure 4.6: HVDC VSC transmission system

Chapter 5

Discussion

When establishing a guideline for offshore power transmission and selecting design of topology and technology, there are many aspects that have to be considered. This chapter will present these aspects and a guideline for typical solutions. Clarifying the different aspects determining what type of system topology should be selected. Focusing on both large offshore wind farms and the offshore petroleum industry. In the end it is often a financial decision whether topology will be of AC or DC design.

The selection will always be very dependent on the specific case, but from earlier projects and comparing other studies, it is possible to do estimations. Here is one figure from Aker Kværner[15] (see figure 5.1) that shows the two most determining factors, distance and power.

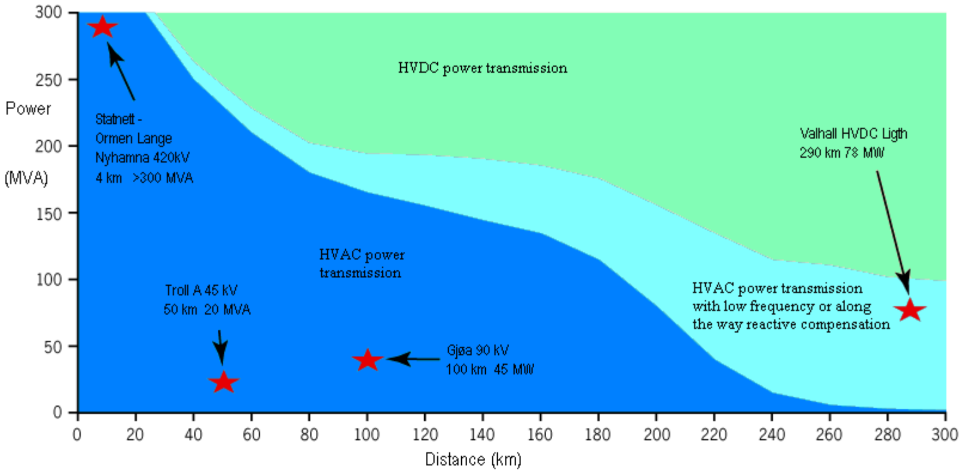


Figure 5.1: Indication of transmission capacity as a function of cable length.

5.1 Electrification of the Norwegian continental shelf

Topology selection

Generally there are many requirements influencing choice of topology for oil platforms, according to Unitech these are paramount for the Norwegian continental shelf:

- A 60 Hz distribution on offshore installation would require converting, then generally HVDC transmission is selected because of the easy adaptation. An alternative were to remove existing gas turbines and install an electric motor with generation capability, taking 50 Hz in and 60 Hz out. A rebuilding offshore without the possibility of factory assembly and tests, were considered complicated and unproven. Electric motor implies a larger concentrated load, as well as larger dimensions compared to the removed gas turbines and the measure would transfer cost from the transmission system to the platform.

- HVDC power transmission requires a new platform, a substation. The substations will carry converter switchgear, transformer and distribution facility. Substation design would depend on equipment dimensions, weight and water depth. Designated substations would make cost more predictable compared with removing existing structures. Optimal design would be easier. Installation and testing could be done at yards for demanding offshore operations.

- A 50 Hz distribution on offshore installation, HVAC would be the preferable solution unless power rating and distance for the AC transmission is exceeded. One should place emphasis on the cost of an extra substation against(or possible removal of existing structure) the cost of AC versus DC at a given site. At certain sites optimal design is not clear, and more than one concept of topology must be considered. Power capability and practical distance of HVAC transmission is of grave importance [16].

Power and distances for Unitech projects

Below are some examples of relevant reference projects for HVAC transmission that have undergone Unitech studies that are feasible.

- Ormen Lange, sub sea future pressure support: 120 km, 110 kV, 60 MW. Main motors are frequency converter driven [16].

- Gjøa: 110 km, 40 MW. Direct on-line start of 2.5 MW motors[16]. Also evaluated 100 km, 90 kV, 70 MW [17].

- Yme: 140 km, 25 MW with reserve up to 40 MW. Direct on-line start of 3.5 MW motors. Project is not determined pursued [16]. Also evaluated 110 km, 80 kV, 25 MW [17].

Voltage stability

Variations in the stationary voltage must stay within a level that can be compensated by transformer tap changer. In principal, the Unitech projects have a transformer at the supply/sending end that regulates the voltage at the primary side of the transformer at the receiving/consuming end. Transformer at the receiving end compensate voltage at the intermediate level.

With regards to resonance frequency, transmission systems have to avoid the fundamental frequency (50 Hz or 60 Hz) with decent margins.

Direct-on-line motor starting

Starting of large motors is a large disturbance on an electrical installation. The worst and the cheapest way to start a motor is direct-on-line. According to the IEC61892 standard, under special conditions of short duration such as motor starting, higher voltage drops may be accepted provided the installation is capable of withstanding the effects of these higher voltage transients. Up to 20 % variation of nominal voltage is allowed [20]. Many installations at the NCS were built before IEC61982, and they should operate according to standards such as IEC60092 and FEA-M 92 that only allow transient voltages of ± 15% compared to its nominal value.

Of 50 Hz installations at the NCS, most asynchronous motors with direct-on-line start range up to approximately 5 MW. In the study of Yme, motors with a rating up to 4 MW was qualified for direct-on-line starting at the distance of 140 km. This kind of initiation generally requires that the transformer at the installation is properly dimensioned. The receiving transformer should have a low enough series reactance suited for this purpose. When comparing a 170 km HVAC cable with series reactance of 0.12 Ω/km, to a transformer of 50 MVA with 12 % reactance, and refer this to 132 kV, the series reactance of the cable would still only be half the size of the transformer reactance. Long HVAC cables will be compensated by extra transformer performance to handle dynamic voltage variations. Higher transformer performance leads to increased size and weight, but not nearly the size and weight of a total HVDC substation. Performance of the receiving transformer increases, or the series reactance which usually is at 10-12 % per unit, is reduced. Reducing the transformer reactance leads to less ability to withstand large short circuit currents [16].

Redundancy

As mentioned earlier in 3.1, wind power is still very expensive so one of the main point is to keep the costs down. Redundancy for the wind farms must be considered: even if expected faults are very rare, the cost of a fault can result in a lot of lost revenue. Redundancy can be achieved by having different cable routes, or having an open switch between two feeders in normal operation and if a feeder cannot be operated. The switch closes and there is still full operation. A drawback would be that all dimensions must be able to handle both feeders wind turbines. No wind farm developers consider redundancy, and there is still experience to be gained [6].

The petroleum industry has an even higher cost of unavailability than wind power, but there is no suggested redundancy from Unitech, for part electrification. It is assumed that a monopolar solution with one concentric cable is used for low power HVDC transmissions. On the other hand, utilizing two single-core cables for larger loads has been proposed. The latter solution presents the possibility of reduced capacity if a fault occurs in one of the transmissions. Three single-core cables as seen to the left in figure 5.2 below, having shared reinforcements and cap - a rather conventional solution - is assumed used with regards to AC cables. A solution of four separate single-core cables and redundancy is not considered suitable in this case. The series reactance will increase due to the distance between the single-core cables, and transmission over longer distances will therefore be out of question. In other words, one has to lay extra cables to obtain redundancy. The costs of this will be extremely high and has to be weighed with the risk of becoming damaged by trawl, anchors or similar objects [16].

5.2 Transmission cost estimations

This section will present cost estimations for marine high voltage transmission. There has been violent market fluctuations the last 12 months. Making cost estimation difficult. Here prices and cost will be presented in Norwegian kroner, with reasonable estimations from Googles currency converter. One possible simplification of total cost of equipment was presented by Olsen, in a masters thesis from 2008[8]. There are few HVDC projects that are comparable with regards to cost and volume. From a comparison could be made, even if some were older and during this time technology has evolved. Taking this into account and assuming that HVDC VSC is somewhat more expensive than the HVDC LCC, a correlation fitting was done.

$$\text{HVDC cable cost } = 6 \text{ MNOK / km} \quad \text{Additional costs } = 800 \text{ MNOK} \tag{5.1}$$

The cost were estimations for the HVDC VSC transmission is for a minimum power of 500 MW over 50 km distance. Over these values, the additional

Figure 5.2: Submarine cables.

costs increases 10 percent for each 100 MW over 500 MW. However, relative to itself the cable cost becomes 3% less expensive for each additional 100 km.

$$\text{HVAC cable cost } = 12 \text{ MNOK / km} \quad \text{Additional costs } = 50 \text{ MNOK} \tag{5.2}$$

The cost estimations for HVAC transmission is for a minimum power of 100 MW and 50 km distance. The additional costs increases 10 percent for each 100 MW over 100 MW. Calculating the investment cost from these equations 5.2 and 5.1 was done through a small script, which takes care of the appropriate adaptation with regards to power and distance. They were fitted towards actual cost of high voltage transmission projects and gives estimations in range of 50-200 km and up to 1200 MW. These calculations were used as basis for an technical economical optimizations for large offshore wind power farms in Norway, and for transmitting the power to Europe [8].

There are as mentioned many approximations and uncertainties with regards to cost. To have a better foundation of knowledge, another ones conclusions are also presented. In [13] there is a more detailed description of the different transmission system and their components' cost. Here it is also mentioned that costs are the most difficult part of investigating different transmission technologies. The reason is that the related industry regard the information as confidential, because it could give a competitive edge for smart manufacturers.

HVAC transmission cost

In 4.1 there were presented many of the components necessary for the alternative current transmission. From [13] the costs of following components were treated:

- Transformers
- Compensators
- 132 kV, 220 kV and 400 kV three-core, XLPE submarine cables
- Switch gear

Transformer cost

Table 5.1 is an excerpt of different transformer cost based of its rated power. These values were used to establish an equation 5.3 for transformer cost C_t in NOK, with regards to different power rating P.

$$C_t = 296000 * P^(0.7513) \tag{5.3}$$

Rated power (MVA)	Cost (NOK)
800	45 000 000
630	37 700 000
300	21 700 000
125	11 200 000
40	4 730 000

Table 5.1: Cost of transformers according to their rated power

Reactive compensation

Cost of reactive compensator is assumed to be two thirds of the cost for a transformer at the same rated power.

HVAC cable cost

The three-core XLPE cables cost of voltage level 132 kV and 220 kV C_132 equation 5.4, C_220 equation 5.5 is is based on [9], while cost for the 400 kV cable C_400 equation 5.6 is an educated guess from [13].

$$C_132 = 13400000 NOK/km \tag{5.4}$$

$$C_220 = 14700000 NOK/km \tag{5.5}$$

$$C_400 = 17400000 NOK/km \tag{5.6}$$

Assuming only laying single cable

$$C_install = 892000 NOK/km \tag{5.7}$$

Switchgear voltage

Cost of switch gear also from Lundberg [9] can be found in table 5.2.

Voltage level (kV)	Cost (NOK)
400	2 700 000
220	1 600 000
132	1 100 000
33	518 000

Table 5.2: Cost of switch gear according to their rated voltage level

HVDC LCC

Equation 5.8 can be linearized from table 5.3 [13]. Where C cost is given in NOK/km according to P the power capacity of the cable in MW.

$$C = 10000 * P + 1400000 \tag{5.8}$$

Cable rated power MW	Project name	Cost in 2004 (NOK/km)
600	SwePol link	8 000 000
550	Iceland link	6 500 000
500	ItalGre link	6 250 000
440	Skagerakk 3	6 250 000

Table 5.3: DC cable cost according to power capacity

HVDC VSC

Equation 5.9, where C (cost) is given in NOK/km according to P the power capacity of the cable in MW. Installation is twice that of the HVAC, and system cost is 0.98 NOK/VA. The cost of Cross-Sound HVDC VSC transmission system(330 MW, 40 km and 150kV) was 1 billion NOK [12].

$$C = 0.273 * P + 0.0093 \tag{5.9}$$

Unitech assumption for cost

Unitech has also done an assessment of the Norwegian petroleum sector. There are many similarities to their approaches, as gathering available data and extrapolating linear relation. Conditions for cost estimations are [16]:

- The cost of cables is based on estimates from manufacturer and data from previous projects.
- HVDC VSC based on ABB's HVDC Light was the only transmission considered. Data collected from Valhall project and manufacturer estimations have been used to determine a linear correlation between power and cost.
- The cost of AC cables and laying is based on collected numbers and experience made during Troll A laying and installation.
- The cost estimation for an eventual substation platform is included converter and distribution facilities. Substation is adapted to its purpose. Fixed platforms will use J-pipes for cables, while floaters will need dynamic cable entry.
- Long AC transmission will have compensation units. [16]

5.3 The general characteristics for selecting HVDC over HVAC

- Investment cost, DC cables are smaller than ac, while dc terminals cost more than AC terminals, see section 5.2

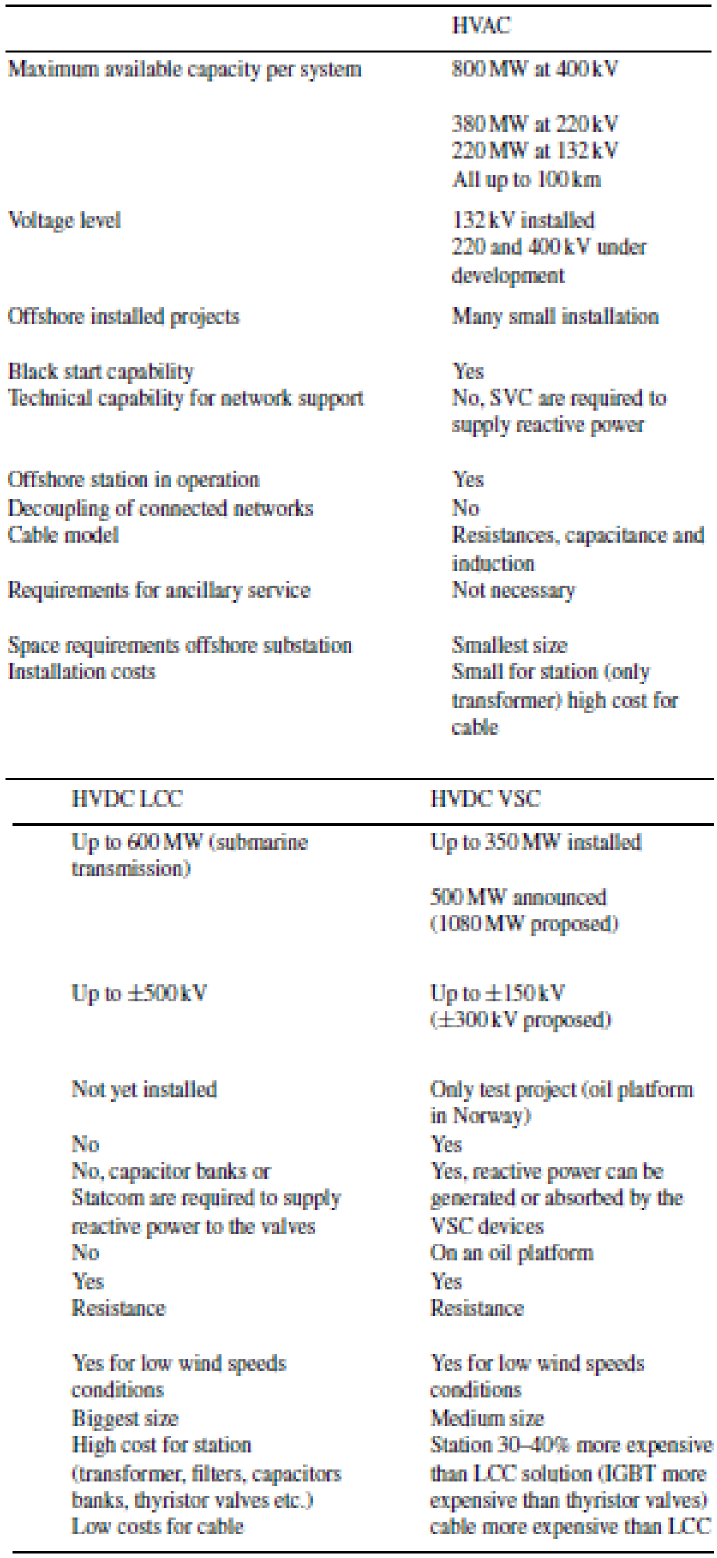
- Reactive power flow only in AC, see section 4.1.
- Lower losses more of it in AC, see section 4.1.
- Asynchronous connection separated networks, AC is not an option without extra equipment.
- Controllability, DC provides better control
- Limit short circuit currents, DC does not contribute to short circuit current of interconnected AC system.

The small AC wind park was best for short transmission distances (up to approximately 20km) and the AC/DC wind park was best for long distances (above approximately 130km). The large AC wind park is best in between the small AC and the AC/DC wind park [3].

According to de Alegrìa's article (2008) "(...) the cost of HVDC system is mainly set by semiconductor cost and HVDC will be cost competitive with HVAC at any distance in the year 2011 [12]." Even with uncertainties, the comparison made by Barberis (2005) shown in table 5.4 below, a very reference guideline for a transmission system for an offshore wind farm [21].

With oil and gas platforms emphasis on all of the energy consumption, especially oil platforms where much heat is needed then a solution with both gas turbines and power from shore can most economic. Similar to the Gjøa platform where a long AC connection optimized at 90 kV for 40 MW, which is under half of the total power demand. The rest is taken care of by offshore generation.

Troll A the largest man moved construction, is impressive in itself, with Katie Meluha even having had a concert 300 m below sea level here and Richard Hammond's Engineering Connections shows that Troll A has never been a stranger to novel experiences or setting records. The focus here however is that it is the first offshore gas platform with HVDC transmission system, designed to operate an electric drive system. Using ABB technology, voltage source converter HVDC Light and cable wound motor Very High Voltage Motorformer. Troll A also have a HVAC cable connected, which shows that flexibility is important, and that there is not a given transmission system for a given platform.



	HVAC	HVDC LCC	HVDC VSC
Maximum available capacity per system	800 MW at 400 kV 380 MW at 220 kV 220 MW at 132 kV All up to 100 km	Up to 600 MW (submarine transmission)	Up to 350 MW installed 500 MW announced (1080 MW proposed)
Voltage level	132 kV installed 220 and 400 kV under development	Up to ±500 kV	Up to ±150 kV (±300 kV proposed)
Offshore installed projects	Many small installation	Not yet installed	Only test project (oil platform in Norway)
Black start capability	Yes	No	Yes
Technical capability for network support	No, SVC are required to supply reactive power	No, capacitor banks or Statcom are required to supply reactive power to the valves	Yes, reactive power can be generated or absorbed by the VSC devices
Offshore station in operation	Yes	No	On an oil platform
Decoupling of connected networks	No	Yes	Yes
Cable model	Resistances, capacitance and induction	Resistance	Resistance
Requirements for ancillary service	Not necessary	Yes for low wind speeds conditions	Yes for low wind speeds conditions
Space requirements offshore substation	Smallest size	Biggest size	Medium size
Installation costs	Small for station (only transformer) high cost for cable	High cost for station (transformer, filters, capacitors banks, thyristor valves etc.) Low costs for cable	Station 30–40% more expensive than LCC solution (IGBT more expensive than thyristor valves) cable more expensive than LCC

Table 5.4: Guideline of HVAC and HVDC transmission systems.

5.4 Conclusion

After considering different point of views around cost and feasibility of submarine high voltage power transmission, establishing a general guideline for marine transmission is not possible. If one was established, the uncertainty would be too great. However, there is a consensus that 50 km is the break-even point at high power ratings. Since offshore space, though limited, HVAC will more often be preferable at longer distances due to its smaller size and cost offshore. Thus it is very case to case sensitive, on the longer HVAC transmission there is less flexibility for any incidents that could occur and the it would be far a more complex system analysis, than with short transmission length.

Bibliography

[1] Odd Håkon Hoelsæter, *Nytten av et offshore kraftnett* http://www.regjeringen.no/Upload/OED/Vedlegg/Energir%E5det/121107/statnett.pdf, 12. november 2007

[2] Press release, 17.01.2008, http://www.regjeringen.no/en/dep/md/press-centre/Press-releases/2008/enighet-om-nasjonal-klimadugnad.html

[3] Lundberg S., *Wind Farm Configuration and Energy Efficiency Studies – Series DC Versus AC Layouts*, Thesis for the Degree of Doctor of Philosophy, Chalmers University of Technology, Göteborg, 2006

[4] Landberg, L., Myllerup, L., Rathman, O., Petersen, E.L., Jorgensen, B.H., Badger, J. and Mortensen, N.G., *Wind resource estimation—an overview.* Wind Energy. 6 3, pp. 261–271, 2003

[5] Mclean R., *Electrical System Design for the Proposed One Gigawatt Beatrice Offshore Wind Farm*, Master Thesis, Department Energy Systems and the Environment, University of Strathclyde, UK, 2004

[6] Ackermann T., *Wind Power in Power Systems*, John Wiley and Sons, 2005

[7] http://www.windpower.org/ *Danish wind industry association*

[8] Olsen J., *Offshore vindkraft - Tekniske og økonomiske vurderinger for utbygging og tilkobling*, Master of Science Thesis in Energy and Environment, Department of Electric Power Engineering, NTNU, 2008

[9] Lundberg S., *Configuration study of large wind parks*, Thesis for the degree of licentiate engineering, Chalmers University of Technology, Göteborg, 2003

[10] Prof. Nysveen A., *Maritime and offshore power systems - Subsea Power Systems*, Department of electric power engineering, NTNU, 2008

[11] Bahrman M.P.,Johnson B.K. , *The ABCs of HVDC transmission technology - An Overview of High Voltage Direct Current Systems and Applications*, IEEE Power & Energy Magazine, March/April Vol. 5 No. 2, 2007

[12] de Alegrìa, I.M. et al., *Transmission alternatives for offshore electrical power*, Renew Sustain Energy Rev (2008), doi:10.1016/j.rser.2008.03.009

[13] Lazaridis L., *Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under the Special Consideration of Reliability* Master Thesis, KTH Stockholm, Sweden, 2005

[14] Myhre J., *Electrical Power Supply to Offshore Oil Installations by High Voltage Direct Current Transmission*, Fakultet for informasjonsteknologi, matematikk og elektroteknikk, Dr. ingeniøravhandling, NTNU, 2001

[15] Aker Kværner Engineering and Technology, *Elektrifisering: Kraft fra land og Samkjøring mellom innretninger*, Rev.3, 19.01.2008, http://www.sft.no/

[16] Unitech Power Systems, *Elektrifisering av Norsk sokkel – Transmisjonssystem fra land og distribusjon til plattformer*, Rev. 2, 29.11.2007, http://www.npd.no/

[17] Unitech, *Real time simulation for industry and utility power systems*, http://www.ieee.no/

[18] OD, NVE, Ptil and SFT, *Kraft fra land til norsk sokkel* , http://www.npd.no/

[19] Abrahamsen, E., Oljedirektoratet *Elektrifisering av sokkelen*, IFEA-seminar 28-29 april 2009

[20] IEC 61892, *Mobile and fixed offshore units – Electrical installations*

[21] Barberis N., *Evaluation of Losses of HVDC Solutions for Large Offshore Wind Farms* , Master Thesis, Department of Electrical Engineering, KTH, Stockholm, Sweden, 2005

[22] Todorovic J., *Losses Evaluation of HVAC Connection for Large Offshore Wind Farms*, Master Thesis, Department of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, 2004

[23] Ned Mohan, Tore M. Undeland, William P. Robbins *Power Electronics*, John Wiley and Sons, 2003