University of Strathclyde Engineering

Department of Mechanical and Aerospace Engineering

Power Transmission Options for Offshore Windfarms in Scotland

Author: Sthitadhee Sarkar

Supervisor: Dr. Nick Kelly

A thesis submitted in partial fulfilment for the requirement of the degree
Master of Science
Sustainable Engineering: Renewable Energy Systems and the Environment
2012

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Date: 6th September 2012

Abstract

The United Kingdom has a target of producing 15% of its electricity by the year 2020 through renewable sources. The Scottish Government has set a 100% net renewable target for Scotland by this time. Achieving these targets will involve the commissioning of over 30 GW of offshore wind generating capacity in the UK, 6 GW of which would be in Scotland. The power generated by these offshore windfarms will need to be collected and transmitted to the load centres on the mainland.

This project reviews the policy, legislation and environmental impacts of offshore wind power development in Scotland and different options proposed for it. It further makes an assessment of the options for power transmission from these offshore windfarms onto the mainland and carries out a detailed analysis of them. This is done by a review of available modelling options and constructing a suitable model for this purpose. The model has been used to analyse the various options available. The results have been tabulated and analysed.

One of the key findings of this project is that reactive power management is an extremely important issue to be considered in the planning and design of an offshore windfarm transmission system. Another key finding is that, HVAC is a better technological option for power transmission from offshore windfarms in Scotland, though HVDC is the more suitable options for larger windfarms which are located further away from the coastline.

Acknowledgements

I would like to thank my supervisor, Dr. Nick Kelly for his valuable inputs, guidance and encouragement during the whole course of the project.

Thank you to Dr. Keith Bell for his time and pointers. It would not have been able to complete this project without the significant contributions from Mr. Jeff Fodiak of Xero Energy Ltd. and Mr. Manolis Belivanis, PhD. student, Department of Electronic & Electrical Engineering, University of Strathclyde.

Thank you to my friend, Mr. Dean Drobot for proof reading this report.

Finally, I would like to thank my parents and my sister for their encouragement and support which kept me going.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

AC	Alternating Current
CSC	Current Source Converter
DC	Direct Current
e.g.	For example
EHV	Extra High Voltage
EPR	Ethylene Propylene Rubber
GIS	Gas Insulated Switchgear
HV	High Voltage
IGBT	Integrated Gate Bipolar Transistor
KCL	Kirchoff's Current Law
KVL	Kirchoff's Voltage Law
SCR	Silicon Controlled Rectifier
SLD	Single Line Diagram
$\tan\delta$	Dissipation factor
viz	Videlicet
VSC	Voltage Source Converter
XLPE	Cross-Linked Poly Ethylene
ε_r	Permittivity

Data Units

dm	Decimetre
GW	Gigawatt
kg	Kilogram
kV	Kilovolt
MVA	Megavolt ampere
MW	Megawatt
µm	Micrometre

1.0 Introduction

This section gives an overview of renewable energy in the United Kingdom and Scotland including policy, types, targets, challenges, environmental impacts and proposed infrastructure development.

The United Kingdom Government has set itself a target to achieve 15% of its energy consumption from renewable sources by the year 2020 (Department of Energy & Climate Change, 2011). Of this, 30% electricity, 12% heat and 10% transport fuels are to be obtained from renewable energy sources. Scotland has a target of achieving 100% net electricity production from renewables and 11% renewable heat by this time (The Scottish Government, 2011).

The Scottish Government has planned a timeline for deployment of renewable electricity systems in four different scenarios. These are illustrated in Figure 1-1.

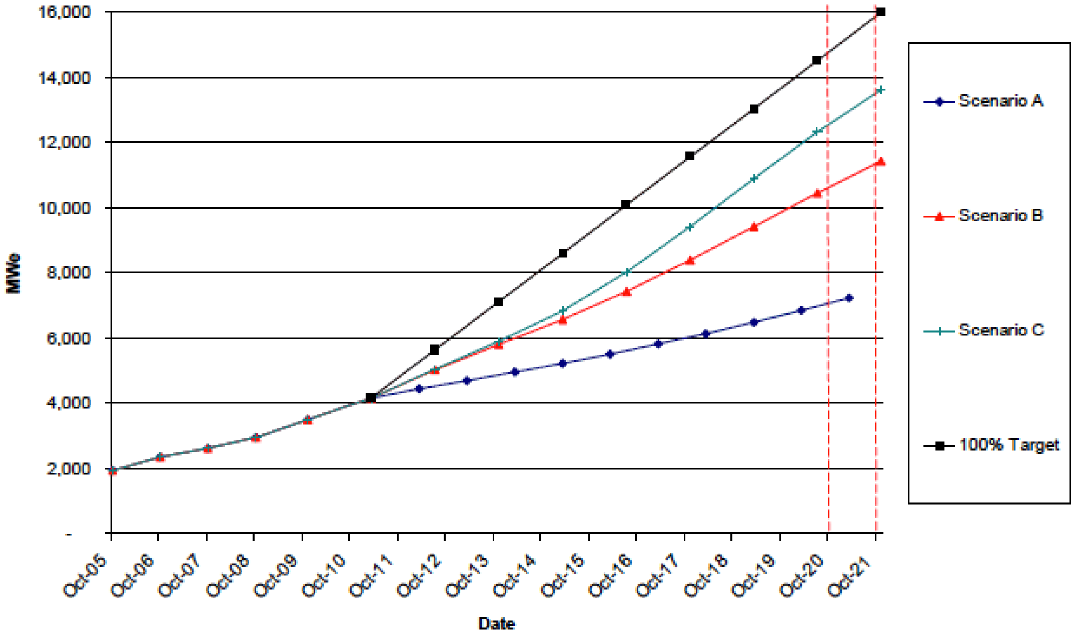


Figure 1-1: Projections of Renewable Electricity Installed Capacity Based on Historical Data (The Scottish Government, 2011)

The scenarios modelled in Figure 1-1 represent:

A. Deployment projection based upon an extrapolation of the annual deployment levels experienced in 2007-08.

B. Deployment projection based upon an extrapolation of the annual deployment levels experienced between 2009 and the start of 2011.

C. Deployment projection, based on Scenario B above, adjusted for the improvements in the planning/consent system that were introduced in recent years but which have not yet impacted upon actual deployment rates.

D. The 100% target line is a straight line extrapolation between current installed capacity and the estimated levels of capacity required to achieve 100% of gross consumption from renewables in 2020. This hypothetical line is incorporated to identify the scale of the challenge. In reality, the rate of deployment will not be linear and would be expected to accelerate towards the latter part of the decade, particularly given the potential magnitude of offshore wind deployment.

1.1 Types of Renewable Technologies Considered

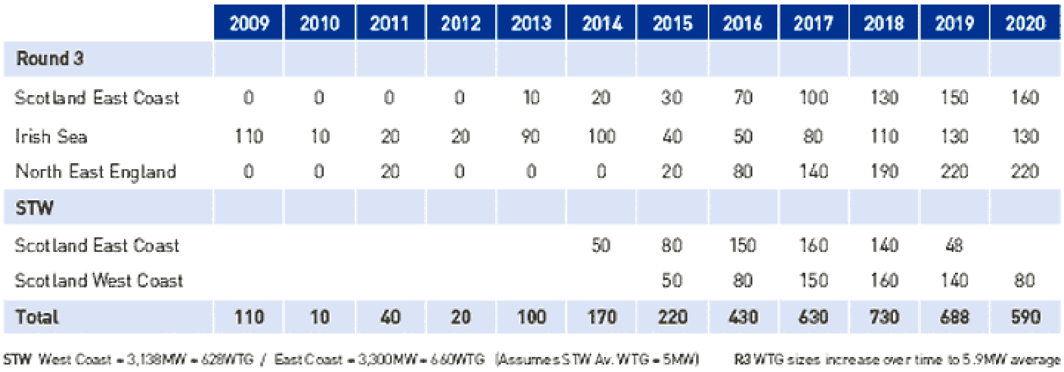
The deployments of the following technologies are being considered by the Scottish Government for achieving the Renewable Energy Targets in Scotland (The Scottish Government, 2011).

- Offshore Wind
- Onshore Wind
- Wave and Tidal Energy
- Renewable Heat
- Bio-energy and Energy from Waste
- Hydropower
- Micro-generation
- Emerging Technology and Energy Storage
- Community Renewables

1.2 Offshore Wind

Deployment of offshore windfarms is being considered as one main means of generation of "Green Electricity". This has been identified as a means of power generation both by the UK and Scottish Governments. The Crown Estate from April 2001 till May 2010 had five rounds of leasing for offshore power generation, resulting in a total of 55 GW installed capacity (National Grid, 2010). Of this, Round 3 itself involved a deployment of 32 GW of offshore wind generation capacity. This is the largest offshore wind deployment project being taken forward in the world (National Grid, 2010). Table 1-1 shows a projection of the number of offshore wind turbines to be installed in the United Kingdom till 2020.

Table 1-1: Number of Turbines Anticipated to be Installed Per Annum (National Grid, 2010)



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Round 3												
Scotland East Coast	0	0	0	0	10	20	30	70	100	130	150	160
Irish Sea	110	10	20	20	90	100	40	50	80	110	130	130
North East England	0	0	20	0	0	0	20	80	140	190	220	220
STW												
Scotland East Coast						50	80	150	160	140	48	
Scotland West Coast							50	80	150	160	140	80
Total	**110**	**10**	**40**	**20**	**100**	**170**	**220**	**430**	**630**	**730**	**688**	**590**

STW West Coast = 3,138MW = 628WTG / East Coast = 3,300MW = 660WTG (Assumes STW Av. WTG = 5MW) R3 WTG sizes increase over time to 5.9MW average

1.3 Offshore Wind in Scotland

Scotland has been declared the windiest country in Europe with an average wind speed of 7.5 metres per second at 50 metres altitude (ScottishPower Renewable Energy Group, 2009). However, this massive potential is still under utilised.

Of the various zones in the Crown Estate Round 3 projects, two of the zones are based in Scotland's Renewable Energy Zone (please refer Appendix III). These will contribute to a total of 4.8 GW of installed capacity of offshore wind generation. These zones are:

- Moray Firth
- Firth of Forth

Also, other than those zones which come under the Crown Estate's Round 3 projects, six areas in Scotland have been identified to have favourable conditions for the deployment of offshore windfarms and would contribute to a total of 5 GW of power generating capacity (The Scottish Government, 2011).

- Islay
- Argyll Array
- Beatrice
- Inch Cape
- Neart na Gaoithe
- Forth Array

Offshore wind projects have been deployed for these areas which will sum up to a total of 5.8 GW of increase in offshore wind generation capacity.

1.4 Challenges for Offshore Wind in Scotland

The following challenges may be faced by Scotland in its path of deploying offshore wind generation at such a large scale (The Scottish Government, 2010).

1.4.1 Fit for Purpose Infrastructure

Scotland presently does not have the appropriate infrastructure required for undertaking the offshore wind projects on such a large scale. This includes appropriate roads, ports, manufacturing and fabrication facilities which are required in the development of these projects.

1.4.2 Appropriate Supply Chain

Offshore windfarm projects require appropriate services and skills. Also, this is required within the appropriate timescale. This may be a challenge for the country. Such large scale infrastructure development projects require a strong logistic backbone, which is presently not available in Scotland.

1.4.3 Ongoing Innovation of Technologies and Practices

To incentivise investment and development, there is a need to drive down the costs of projects. This is possible only when a new technology has been used and tested over a period of time in the market. This is still not the case in offshore wind power development and there are new technologies being introduced in the market every day. Older technologies are less expensive, whereas newer ones are not. It is therefore, a difficult task to decide which technology to use.

1.4.4 Regulation of and Access to the Electricity Grid

Large power generation projects require the electricity grid to be developed technologically and geographically to allow the power generated to be transmitted to load centres. The present electricity grid in Scotland is still not developed to that extent and is not having enough capacity for that to be possible.

1.4.5 Managing the Marine Environment

Offshore wind power development will have a significant impact on the diverse marine life in the Scottish waters. Environmental impact assessment will be required to be done and measures taken to minimise impact on marine environment.

1.4.6 Necessary and Available Skills

There is presently a shortage of personnel to work in the development of offshore wind projects in Scotland. There are other established sectors like oil and gas in which professionals prefer to seek employment, keeping in mind the security of jobs. The education sector in Scotland has to produce enough graduates with appropriate skills for them to be able to execute these jobs in the near future and beyond. In this way, Scotland will also be able to set up a skill base, with which it can lead this sector worldwide by offering its expertise to other countries.

1.4.7 Finance

The capital cost of large scale offshore wind projects will require a significant amount of financial investment, which is not feasible through only government and public money. The Scottish government has to incentivise private investment into these projects as well to make them economically viable.

1.4.8 Securing Support of Local Communities

The support of the people of the local communities who live and also make a livelihood out of the sea is an important consideration to be made. They have to be taken into confidence and an awareness of the path which is planned to be followed is to be explained to them. A process of collaborative planning and consultation has to be adopted which will help in making better development.

1.4.9 Competition

There are other UK and European companies who have gained a subsequent amount of experience and established expertise in the development, design and construction of large offshore windfarms. The Scottish companies who are new to this field will be facing fierce competition from these companies and should prepare themselves to compete with them.

1.4.10 Timing

The offshore wind power plan is a major step for Scotland in achieving its 2020 renewable energy target. With all the above possible issues, developing the projects on time to be able to meet the 2020 target is essential. This is a risk in the brave step of going ahead with offshore wind with such tight development schedules.

1.5 Environmental Impacts of Offshore Windfarms

Offshore wind power development is a good way of mitigating greenhouse gas emissions and reducing global warming. This is a strong argument which will help its development and help it emerge as a leading technology for power generation in the coming years (Vella, 2010).

The environmental impacts of offshore windfarms are as under (Danish Energy Authority, 2006).

1.5.1 Marine Life

The foundations built for the offshore wind turbines act as artificial reefs for the fish in the marine area. This increases the fish population in the particular area. The increase in the fish population in turn increases the population of birds in the area. Having a high density of birds within an area causes the collision on birds amongst themselves as well as with the towers or rotors. Therefore, offshore wind turbines have a major effect on the ecology of the surrounding area.

1.5.2 Migrating Birds

Bird strikes with the tower or rotor are also an effect on migrating birds. Having offshore wind turbines can increase this. Apart from collisions, migrating birds also need to spend more energy to navigate around offshore wind turbines. This may cause birds to separate from their flocks while migration. Tower illumination may also be a contributing factor affecting these birds in their orientation and direction.

1.5.3 Interference with Navigation for Endangered and Threatened Species

The high voltage cables carrying power from the offshore wind turbines to the load centres cause electromagnetic fields around them. These produce noise and vibrations in the water surrounding the cables. This is highly threatening for the underwater species and living organisms. Many endangered species may ultimately get extinct because of these vibrations. Therefore, this effect of the cables also has a direct impact on the ecology of the area.

1.5.4 Potential Alteration of Natural Environments

Support structures for the wind turbines, located underwater, anchoring devices and scour protection materials, and electromagnetic devices could cause a reduction in benthic communities, change natural environments and affect migration patterns. This affects the habitats of underwater species.

1.5.5 Marine Traffic, Recreation and other Sea Space uses

Offshore wind turbines may cause disruptions in air traffic control and maritime radars. It may cause interference in communication between the pilots and air traffic control on the ground. Also, sea space which is used for recreational purposes may be affected by offshore wind turbines. Various other sea space uses will also suffer because of offshore wind farms.

1.5.6 Visual Impacts

Turbine towers and turbine rotating blades have a visual impact on the population living on the mainland close to offshore wind farms. Also, aerial warning lights in such wind farms can cause visual discomfort amongst people.

1.5.7 Noise Impacts

Rotating turbine blades may cause noise. This causes discomfort in the people living near such offshore wind farms.

The above mentioned factors are quite threatening to the development of wind energy, keeping in mind the huge potential it has in Scotland. A good balance needs to be reached between the two. Offshore wind is a major factor which will contribute and help Scotland in reaching its 2020 target. On the other hand, it has to be ensured that the offshore wind projects do not have a very harsh effect on the wildlife and ecosystem of the environment. Some changes and adjustments may need to be made in the proposals of certain offshore windfarms if the environmental impact assessment is found to be too large.

2.0 Background Information

This section of the document gives an overview of offshore windfarms and the main components within its power transmission system.

2.1 Overview of an Offshore Windfarm

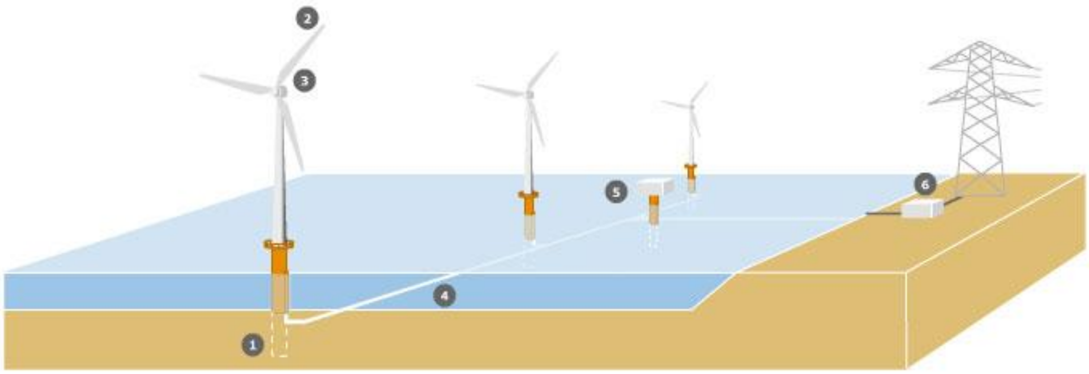


Figure 2-1: Simplified Version of an Offshore Windfarm (Renewable UK, 2012)

The simplified version of an offshore windfarm is shown in Figure 2-1. The various components of the windfarm are as under.

1. Piles: Once a suitable location and position for the turbine is determined, these are driven into the sea bed. Erosion protection, which look similar to sea defences are placed at the base in order to avoid any damage, which may be caused to the sea floor. The top of the foundation is painted with a bright colour in order to enable them to be made visible to passing by ships. Also, an access platform is provided to allow maintenance teams to dock.

2. Blades: There are wind direction and speed sensors fitted on the turbine. These sense and accordingly turn the aerodynamically shaped blades to face the direction of the wind enabling them to collect the maximum possible energy.

3. Nacelle: The blades are connected to a shaft and this enters the nacelle, where other components are housed. The gearbox and generator are two main components within the nacelle. The shaft rotates the generator, which converts mechanical energy into electrical energy.

4. Subsea Cables: These collect power generated by the offshore wind turbines and bring it to the offshore substation. Also, these cables transmit power between the offshore and the onshore grid substation.

5. Offshore Substation: The offshore Substation houses a power transformer, which steps up the voltage of the power generated to higher levels viz. 132, 275 or 400 kV to minimise the losses in transmission.
6. Grid Substation: This is the point where the transmission line, which originates at the offshore substation, connects to the electrical grid on land. The main components of this substation are two bus bars, one for the windfarm side and the other for the grid side and a bus section and bus coupler to give more flexibility to control the power flow.

2.2 **The Wind Turbine**

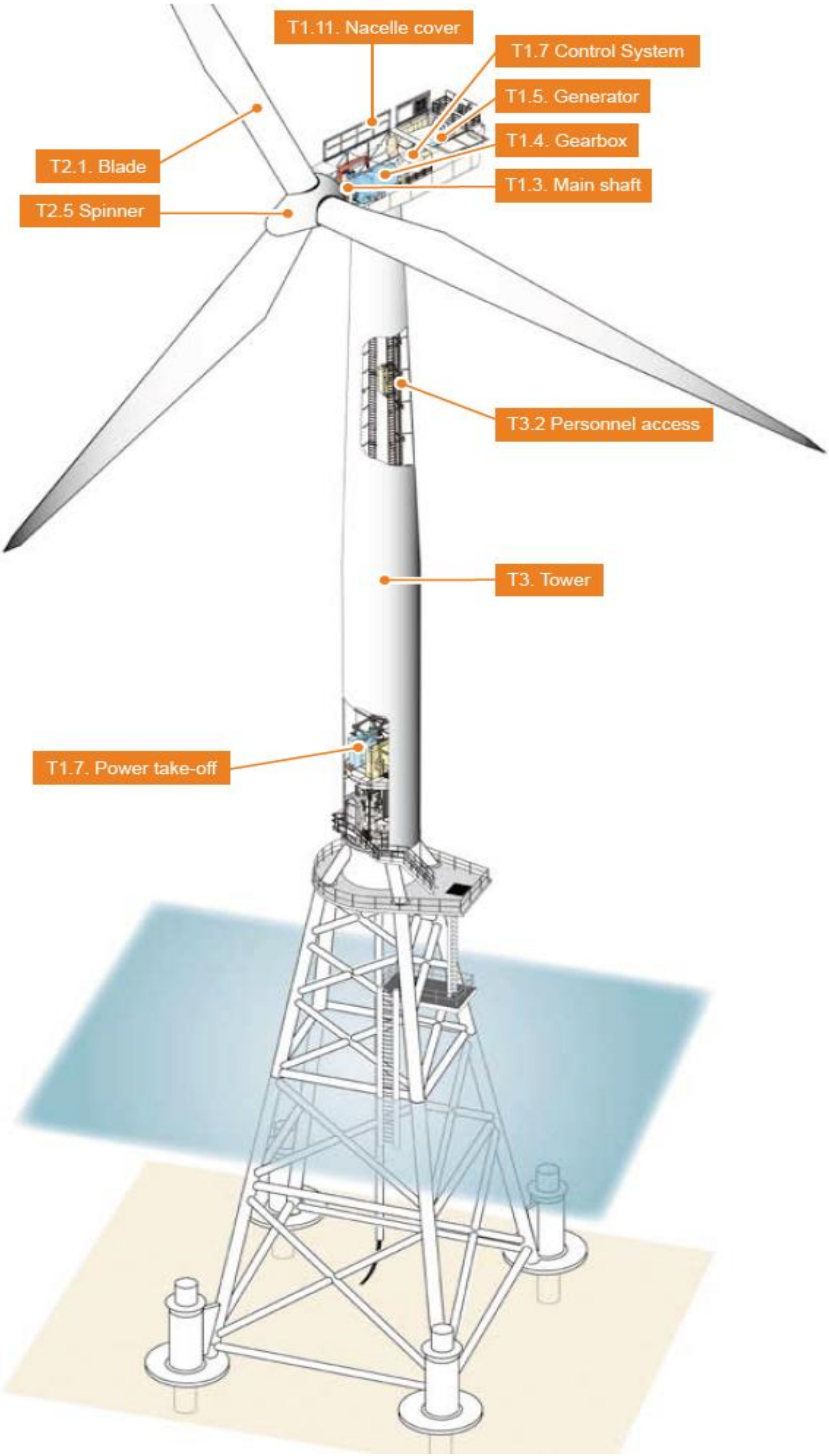


Figure 2-2: An Offshore Wind Turbine (The Crown Estate, 2011)

A typical offshore wind turbine is shown in Figure 2-2. This is the part of the system which collects wind energy through its aerodynamically designed blades and transmits the kinetic energy of wind onto the shaft through the spinner. This kinetic energy is further converted into electrical energy by the generator in the nacelle box. Figure 2-3 shows a detailed view of the components within the nacelle box.

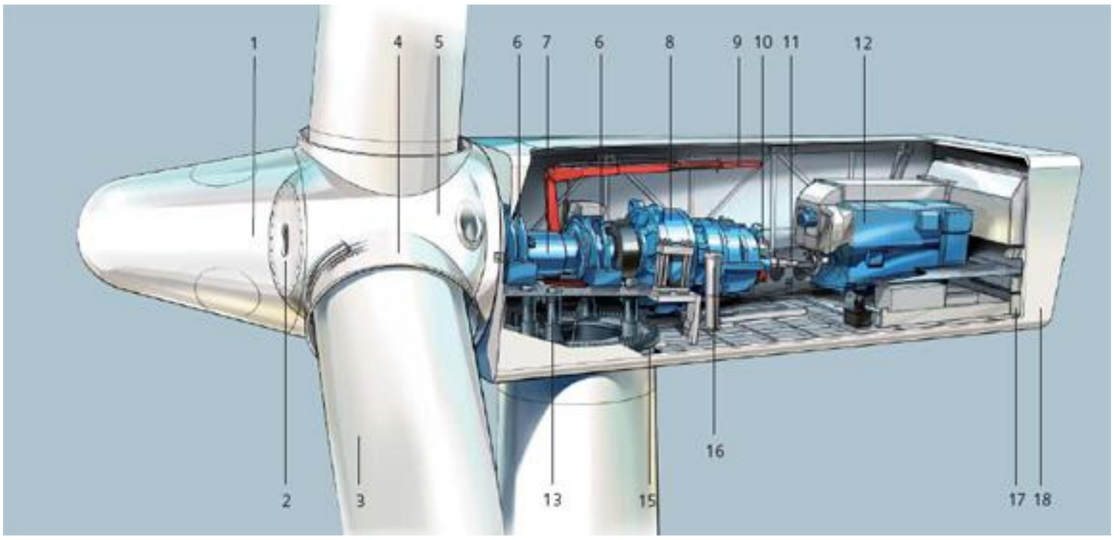


Figure 2-3: Nacelle Arrangement (Siemens Wind Power, 2012)

Table 2-1 lists the components contained within the Nacelle Arrangement.

Table 2-1: Components of the Nacelle Arrangement (Siemens Wind Power, 2012)

Label Number	Name of Component
1	Spinner
2	Spinner bracket
3	Blade
4	Pitch bearing
5	Rotor hub
6	Main bearing
7	Main shaft
8	Gearbox
9	Service crane
10	Brake disc
11	Coupling
12	Generator
13	Yaw gear

14	Tower
15	Yaw ring
16	Oil filter
17	Generator fan
18	Canopy

2.3 Subsea Cables

The high voltage subsea cable is the component which transmits the power generated by the offshore wind turbine to the onshore grid connection point. This is a very important component of the system as the entire power generated reaches the grid connection point through this.

Submarine cables are classified on the type of insulating material which they have. Some of the different types of submarine power cables are listed as under (Worzyk, 2009).

2.3.1 Polyethylene Cables

Polyethylene is a hydrocarbon consisting of long chains of CH_3-$(CH_2)_n$-CH_3 molecules. The only components are carbon and hydrogen either in branched or non-branched chains. It is a non-polar and semi-crystalline material. It is thermoplastic and can be re-melted. It is available in different density ranges such as LDPE (Low Density), MDPE (Medium Density) or HDPE (high Density). The densities vary in between 0.9-0.97 g/cm^3. PE has a lower dissipation factor and lower dielectric loss than paper insulation.

2.3.2 Cross-Linked Polyethylene (XLPE) Cables

Cross-linked polyethylene has been used for submarine cables since 1973 and for underground land cables even before. XLPE is made by cross linking chains of LDPE to form three dimensional networks. The cross linking is an irreversible process and gives the polymer a higher melting point. PE is thermoplastic and melts along with deforming its shape at temperatures between 80-110°C. XLPE on the other hand performs better at higher temperatures. It can allow the conductor to be loaded until the conductor attains a temperature of 90°C. XLPE is destroyed by pyrolysis at 300°C.

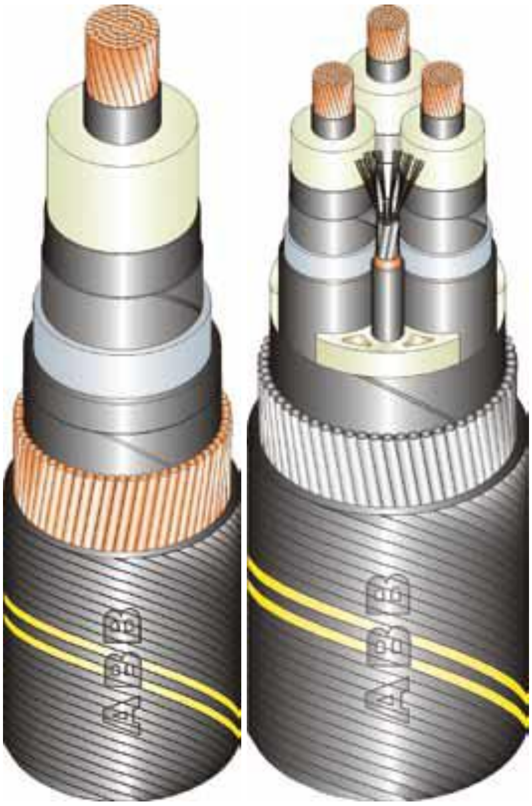


Figure 2-4: ABB Single Core and 3-Core Submarine Cable with Lead Sheath, Wire Armour and Optic Fibres (ABB, 2012)

2.3.3 Extruded HVDC Cables

The space charge phenomenon makes standard XLPE unsuitable for HVDC applications. Under the application of direct voltage, the space charge accumulates at certain places in the insulation wall. These accumulations create undesired peaks of electric field in the insulation. This effect makes XLPE unsuitable for HVDC applications.

Advanced XLPE extrusions have been developed which are suitable for use in HVDC applications. The mechanical strength achieved by extruded materials makes it highly suitable for submarine installation and operation. Figure 2-5 shows a typical extruded HVDC cable.

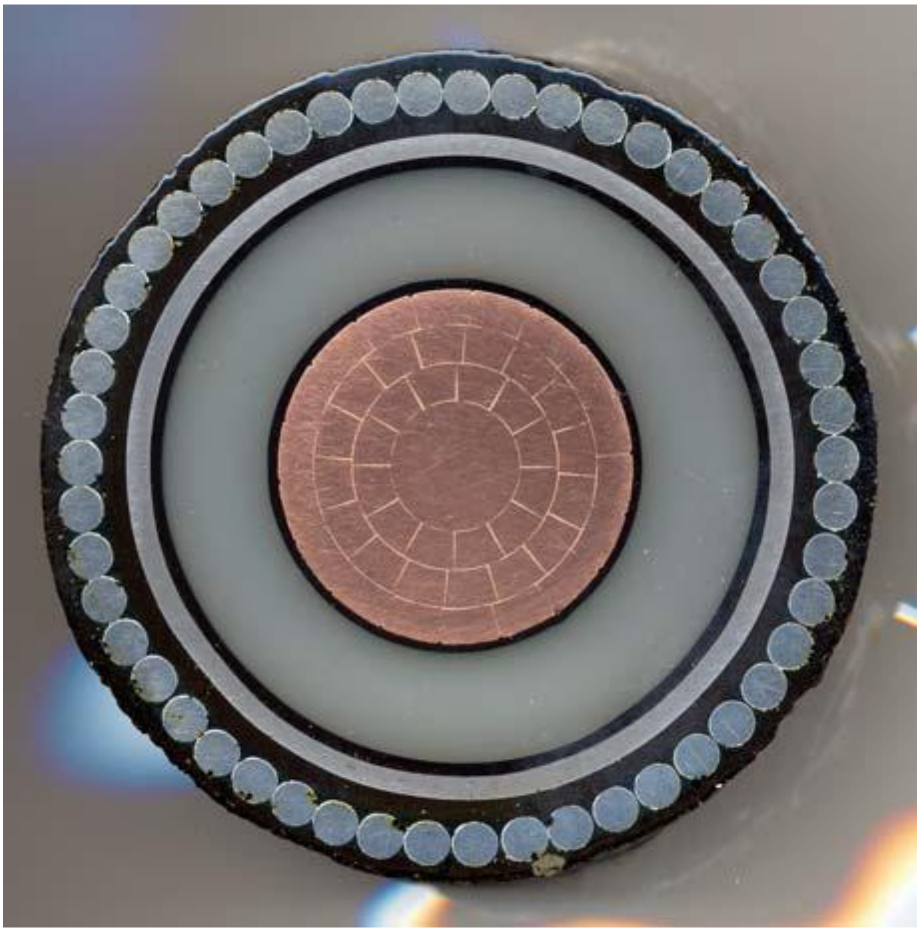


Figure 2-5: HVDC Cable with Extruded Insulation used for Submarine applications (Worzyk, 2009)

2.3.4 Ethylene Propylene Rubber (EPR)

Some manufacturers use Ethylene Propylene Rubber (EPR) in place of XLPE for submarine cables. EPR has a higher tan δ and ε_r values than XLPE. This makes it unsuitable for use in higher voltages as in XLPE. EPR insulated submarine cables are more suitable for use in medium voltage applications.

2.3.5 Paper Insulated Oil Filled Cables

This type of submarine cable is filled with low viscosity oil. This type of cable is known by several names, some of which are:

- LPOF – Low Pressure Oil Filled
- SCFF – Self Contained Fluid Filled
- SCOF – Self Contained Oil Filled

High pressure oil filled cables are unsuitable for submarine applications. The insulation paper is made from conifer pulp (kraft paper). In order to improve dielectric losses for EHV AC applications, the pulp is washed with de-ionised water. Paper with a low density, of the order of 0.7-0.8 kg/dm^3 is used to keep the dielectric losses low and permeability for oil flow high. The insulation is formed by paper tapes of thickness between 50 and 180 μm. Thin paper, with higher dielectric strength is used closer to the conductor as electric stress is higher at this part of the cable. The electric stress is lower in the outer parts of the cable and can be achieved with lesser layers of thicker paper tapes. The stacked paper tapes in the insulation wall also provide greater mechanical strength.

2.3.6 Paper Mass Insulated HVDC Cables

Paper mass insulation is widely used for HVDC applications and has been used for several years now. These types of cables have been used in the past for medium voltage AC applications, but are presently used only for HVDC applications. Mass impregnated cables are available for applications up to 500 kV DC and are the best possible option for DC at such high voltages. Also, another advantage of these types of cables is that they can be used for very long lengths and are highly suitable for such applications.

Figure 2-6: Mass Impregnated HVDC Cables (Worzyk, 2009)

Mass impregnated HVDC cables are shown in Figure 2-6. These cables require a different type of paper for insulation than that used in oil filled cables for HVAC applications. As there is no problem of dielectric losses in DC cables, a higher density paper may be chosen with a density of the order of around 1.0 kg/dm^3 to achieve maximum dielectric strength. The paper used in these cables is also made from kraft paper. Sometimes, different paper thickness is used in order to achieve better mechanical flexibility in the cable.

2.3.7 Gas Filled Cables

Lapped cable insulation with a gas filling in place of an oil filling was developed by C. J. Beaver and E. L. Davey of W. T. Glover & Co in 1937. The design elements were kept the same as a standard oil filled cable and the cable insulation was developed by pre-impregnated paper tapes. After its installation, the cable was vacuum treated and pressurised with nitrogen from both ends. The pressurised nitrogen filled the band gaps in between the paper tapes, suppressing the formation of partial discharges. Despite voids present in the insulation, this type of cable can be used for both AC and DC applications.

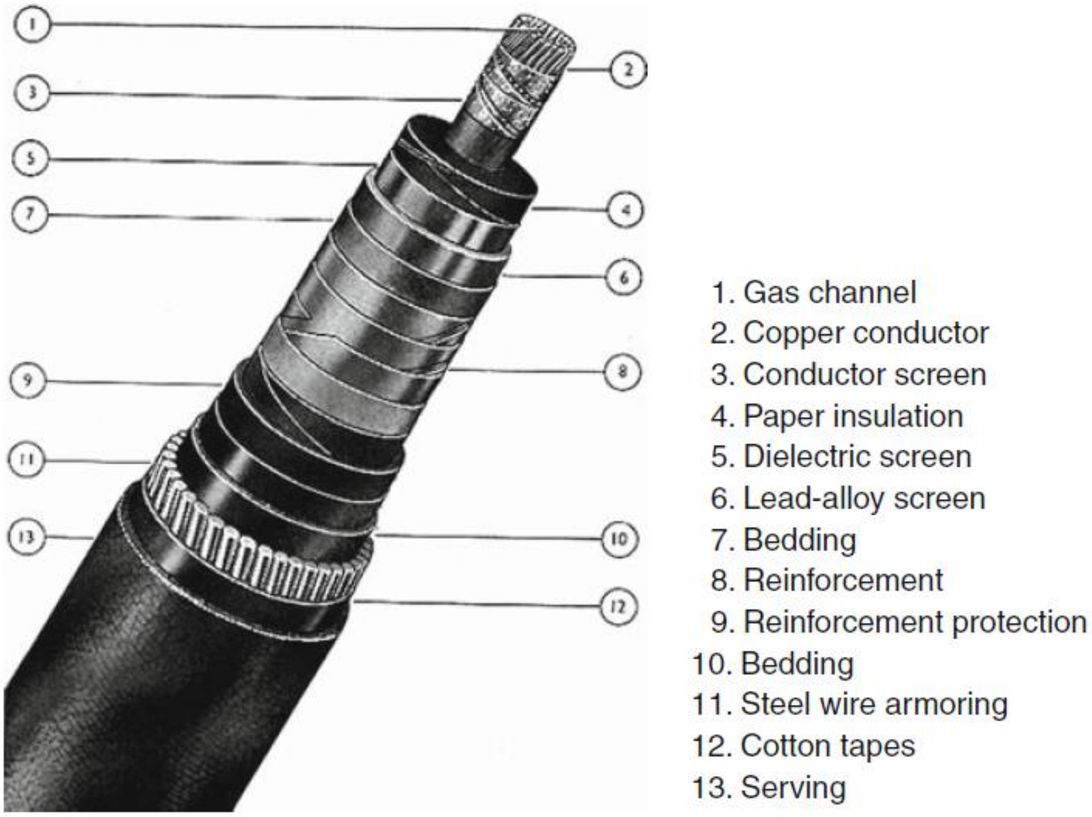


Figure 2-7: A Gas Filled Cable and its Various Components (Worzyk, 2009)

2.4 Substations

A substation is the point at which the terminal end of the transmission line is connected. A typical Single Line Diagram (SLD) for an offshore windfarm is shown in Figure 2-8.

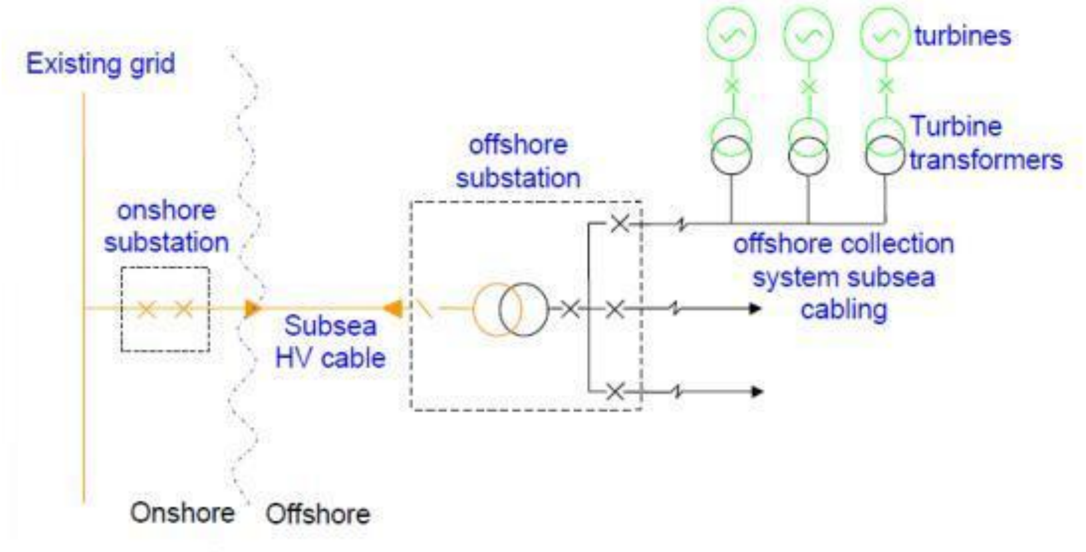


Figure 2-8: Typical Single Line Diagram of an Offshore Windfarm (Gardner, 2009)

2.4.1 Offshore Substation

The offshore substation is where the cables carrying the power produced by the offshore wind turbines terminate. The turbines are connected to turbine transformers. The turbine generators generate power typically at voltages of 6.6 or 11 kV. The voltage level is stepped up to 33 kV in the turbine transformers (Siemens Wind Power, 2012). The submarine cables then carry power from individual turbine transformers to the offshore substation. These cables terminate on the bus bar of the substation. There are large power transformers at the substation, which further step up the voltage to typical levels of 132, 275 or 400 kV. The power is then transmitted through the submarine HV cables to the onshore substation and terminates on the receiving bus bar of the onshore substation.

2.4.2 Onshore Substation

The onshore substation is the grid connection point of the offshore windfarm. This is where the connection is made with the existing high voltage electricity grid. The submarine transmission cables which originated from the offshore substation terminate on the bus section in the substation. The bus section is connected to the grid side bus bar through a bus coupler.

2.5 Transformers

Transformers are a major component of the offshore substation and also placed within each turbine. Both are step up transformers, which are used to step up the voltage level of the electricity generated by the wind turbines. Figure 2-9 shows a typical substation transformer, used in offshore substations.

Figure 2-9: A Typical Substation Step-Up Transformer (ABB, 2012)

2.5.1 Turbine Transformers

The turbine transformers are located at the bottom of each offshore wind turbine. These transformers step up voltage from the typical generating voltage of 6.6 or 11 kV to 33 kV. These are transformers of capacity which match the generator capacity of the turbine so that when the turbine is generating maximum electricity, the maximum electricity can be stepped up in voltage. Also, when designing these transformers, sufficient capacity has to be considered in order to ensure that the transformer does not get overloaded at any time. There is a control system present in the turbine, which controls these transformers.

2.5.2 Substation Transformers

The substation transformers are rather large transformers located on the offshore substation platform. These transformers are loaded and switched on/off according to the power being generated by the offshore windfarm. The transformers step up the voltage from 33 kV to the voltage at the grid connection point, which is 132, 275 or 400 kV.

2.6 Switchgear

Switchgear is that part of the electrical system which helps in connecting and also disconnecting parts of the power system in the event of a fault (Chakrabarti et al., 2006). The main components of switchgear are as under.

2.6.1 Circuit Breaker

The circuit breaker is an important component of the switchgear. Whenever there is a fault, the circuit breaker helps in disconnecting the circuit on load and breaking the fault current. Circuit breakers have a medium for arc extinction and this is what distinguishes them from isolators. Isolators also have a similar working mechanism like circuit breakers, the only difference being the presence of additional arc extinction medium in them. This arc extinction medium helps circuit breakers to operate on load, whereas isolators can be operated only off load. Circuit breakers are usually rated on their short circuit current capacity, which is the amount of current they are capable to break on load. Circuit breakers are classified on many different parameters, but one important and the most common classification of them is based in the arc interruption medium that they use. Some different types of circuit brekers based on this type of classification are as under.

- Oil Circuit Breaker (OCB)
- Minimum Oil Circuit Breaker (MOCB)
- Air-Blast Circuit Breaker (ACB)

- Vacuum Circuit Breaker (VCB)
- Gas Insulated Circuit Breaker (GCB)

Sulphur-hexafluoride (SF_6) is the most commonly used arc interruption medium in GCBs and the corresponding switchgear is called Gas Insulated Switchgear (GIS).

2.6.2 Protective Relays

Relays are the devices that detect abnormal conditions in electrical circuits by constantly measuring the electrical quantities, which are different under normal and fault conditions (Chakrabarti et al., 2006). The relays sense abnormal conditions and send out a signal to the circuit breakers to trip. When the circuit breakers trip, the fault current is interrupted and therefore, saves the equipment from any further damage. Relay setting is extremely important for the tripping of the circuit to occur as desired and therefore, it should be ensured that this is done with extreme precision. Traditionally, electromechanical relays were used for power system protection. Presently, they have been replaced by digital microprocessor and microcontroller based relays.

2.6.3 Instrument Transformers

The two main types of instrument transformers used in switchgear are:

- Current Transformers (CT)
- Voltage Transformers (VT)

The values of current and voltage in transmission systems are generally extremely large and these need to be monitored carefully. If measuring instruments for measuring such large values would need to be designed, they would be extremely large in size and also very expensive. Therefore, instrument transformers are used to proportionally step down the values to lower ranges to enable measuring instruments to monitor them carefully. In this case, a very high level of precision is required to be maintained as relays are connected to the secondary side of the instrument transformer and in case of any abnormal condition; it sends a signal to the circuit breakers to trip the circuit. Therefore, the design and installation of the instrument transformer is very important for the proper operation of the power system.

2.6.4 Measuring Instruments

The main two types of measuring instruments in the power system are as under.

- Ammeter
- Voltmeter

The measuring instruments measure the circuit parameters constantly. The ammeter is used to measure the current in the system, whereas the voltmeter is used for measuring the voltage. These instruments actually measure the secondary levels of the instrument transformers and display the readings accordingly. The ammeter is used to measure current, whereas the voltmeter is used to measure voltage. Apart from this, there are other measuring instruments, including watt meters and power factor meters.

2.6.5 Bus Bar

The bus bar is the component of the switchgear which is the connection point. The incoming and outgoing feeders originate and terminate onto the bus bar. It is usually made of copper and is meant to have low impedance. The bus bar also has a separate protection system and is separately protected, in case of any faults occurring on it.

2.7 DC Converter Stations

The original motivations, which lead to the development in HVDC power transmission was to reduce the large amount of losses being experienced in the AC power transmission systems. HVDC systems are known to have lower losses as they are free from effects like Ferranti Effect, susceptance, skin effect, corona, etc. (Arrillaga et al., 2007). Also, the amount of power that is transferred through the same amount of copper conductor in HVDC systems is much larger for HVDC transmission systems.

The voltage of DC power cannot be either stepped up or stepped down. For this purpose, it needs to be converted into AC. Converter stations are built on both ends of the HVDC transmission line for conversion from AC to DC and vice-versa. There are two types of HVDC converter stations described as under.

2.7.1 Current Source Converter (CSC) Stations

This is a thyristor based converter station, which uses a silicon controlled rectifier (SCR) for AC to DC conversions. This is the traditional type of technology which has been used for HVDC converter stations. The limitations of CSCs are listed as under.

- There is a requirement of an AC power source.
- A static synchronous compensator or rotating electrical machine is required.
- Managing harmonics caused by the AC power source is an issue.

2.7.2 Voltage Source Converter (VSC) Stations

The CSC technology has been recently replaced by voltage source converters (VSC). The VSC technology uses an Integrated Gate Bipolar Transistor (IGBT) in place of a SCR. This type of converter station is becoming popular very rapidly and is being used in HVDC transmission systems worldwide. Some of the advantages of VSCs are listed as under.

- These are independent voltage sources that can either supply or absorb reactive power.
- These are much smaller in size than traditional CSCs. The small size makes it easier to install in offshore locations and design and construct structures for them.

However, one limitation of VSCs is that they have reduced power capacity as compared to CSCs. Scientists are carrying out research to address this shortcoming and improve this technology.

2.8 HVAC Shunt Reactors

Figure 2-10: Air-Core HVAC Shunt Reactors (National Grid, 2010)

There are primarily two types of HVAC shunt reactors, as under.

2.8.1 Air-Core Shunt Reactor

Figure 2-10 shows an air-core HVAC shunt reactor. These are relatively larger in size, but quieter and require lesser maintenance. They do not have non-liner cores and are therefore, not subject to core saturation effects. These are less expensive than iron-core reactors. These are normally available up to operation voltages of 72 kV and 100 MVAr. Higher capacities are possible to be made available, but require exclusive design. A disadvantage of air-core reactors is that they have a strong magnetic field, which usually extends beyond the reactor surface. Therefore, any metallic loops must be avoided, where circulating currents may flow close to these reactors.

2.8.2 Gapped Iron-Core Shunt Reactor

An iron-core reactor has a similar construction to that of a power transformer and is immersed in an oil tank. The gapped iron core provides a higher reluctance and hence, allows higher magnetising current to flow. These reactors are available upto operation voltages of 800 kV and 250 MVAr. These reactors do not have any magnetic fields extending beyond their surfaces, are well protected from the environment and are hence, more suitable for offshore applications.

A shunt reactor is used for reactive power compensation in submarine power cables. These cables tend to have a large amount of capacitive reactive power and this causes the current in cables to increase beyond the designed capacity at certain points within them. This limits the length of cables in HVAC transmission systems. Also, the voltage in the cable is stabilised through these shunt reactors. Reactive power cannot travel through long distances and therefore, this reactive compensation has to be applied locally at points throughout the transmission line. Reactive compensation may be applied at the offshore substation, onshore grid connection point and also intermediate points within the submarine cable by constructing offshore platforms (National Grid, 2010). Shunt reactors may be connected either on the tertiary winding of the power transformer or the HV bus bar of the substation switchgear for operational switching.

If the length of the transmission line is limited, it implies the inability of planning new offshore windfarms for greater distances from the onshore grid connection point. This makes reactive power and its management and extremely important aspect to address with regard to offshore windfarms.

3.0 Aims and Objectives

This section of the document lists the aims and objectives of this project.

3.1 Aims

This project will make a techno-economic analysis of the HVAC and HVDC power transmission options for proposed offshore windfarms in Scotland and conclude which option would be most viable.

3.2 Objectives

The objectives to be addressed in the study, which will lead to the results and conclusions, are as under.

- To assess the development plans for transmission networks for offshore wind power in Scotland.
- To review different modelling options available for power transmission lines.
- To develop a suitable model to represent an offshore power transmission network.
- To validate the power transmission line model.
- To make sensitivity study and control reactive power issues in long submarine power transmission lines.
- To make a techno-economical analysis and recommend the most feasible option for offshore wind power transmission in Scotland.

4.0 Literature Review

This section of the document presents a review of existing literature available on the subject. Existing transmission line modelling approaches and methods have been discussed.

4.1 Transmission Line Modelling Basics

A transmission line transmits power from one location to another. Transmission lines are usually modelled and analysed by parameterisation with passive components. Some of the components used are resistors, inductors and capacitors. The orientation and magnitude of the parameters depend upon the type of conductor or cable in use and its electrical properties. The series components represent the characteristics of the conductor itself, whereas the shunt components represent the characteristics which are induced as a result of its interaction with other parameters such as electrical earth or other conductors. Additionally, other inherited characteristics may be represented such as mutual inductance or coupling of transmission lines, which are phenomena observed in case of multi phase systems (Grainger & Stevenson, 1994).

In this project, a sinusoidal steady state analysis of the transmission line is performed. No transient studies are done. The steady state behaviour of transmission lines are analysed. There are two available methods of modelling transmission lines through two different types of parameters (Bergen & Vittal, 2000).

- Distributed Parameters
- Lumped Parameters

The lumped parameter method is a further simplification of the distributed parameter method. The next sections explain the above methods in greater detail. In this thesis, lower case letters will be used for distributed parameters and upper case letters will be used for lumped parameters.

4.2 Distributed Transmission Line Parameters

As the name suggests, distributed transmission line parameters imply that the line parameters are distributed equally along the transmission line (Glover et al., 2012). The parameters are specified per unit length and are additive in nature along the length of the transmission line. For a transmission line, quantities such as voltage, current and power are studied. The power flow and losses can be determined from these distributed line parameters. Figure 4-1 shows a transmission line model with distributed line parameters. The model consists of a series impedance and shunt admittance. The summation of all these line segments gives the overall distributed line model.

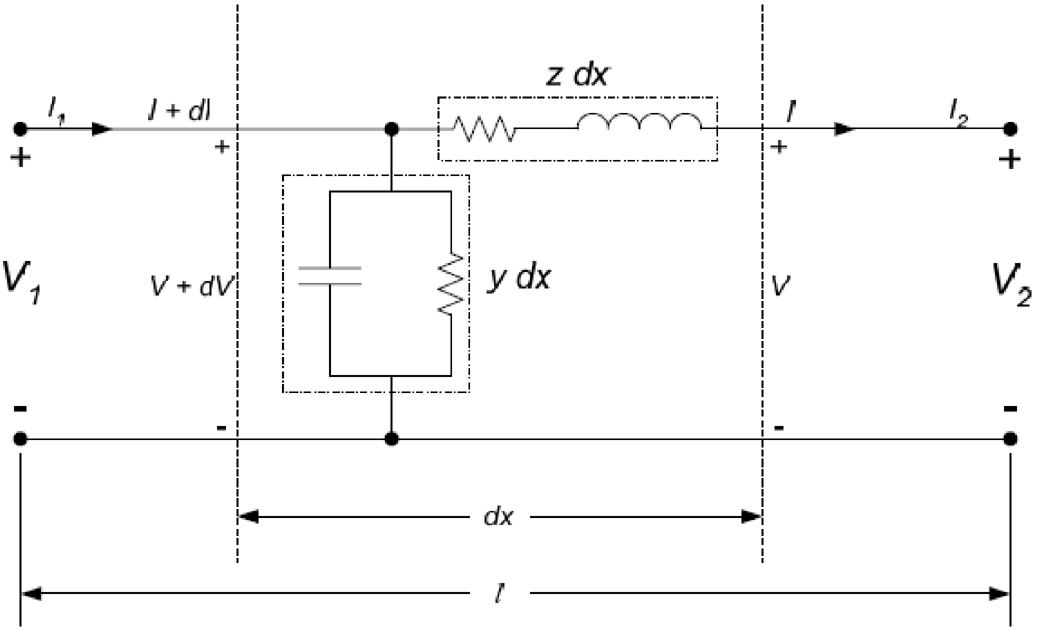


Figure 4-1: Distributed Parameter Transmission Line Model (Glover et al., 2012)

The line series impedance is represented by a resistance in series with an inductance. This is quantified per unit length as under.

$$z = r + j\omega l \tag{4-1}$$

The series resistance is quantified in ohms per unit length and the series inductance is quantified in henrys per unit length. Ω represents the operational angular frequency of the AC power system in radians per second. The impedance of the inductor is a function of the frequency of the AC power system. The shunt element of the model consists of a resistance in parallel with a capacitance. The admittance of this element is quantified as under.

$$y = g + j\omega c \tag{4-2}$$

The admittance of the capacitor is also a function of the frequency of the AC power system.

As shown in Figure 4-1, the total length of the line is denoted by *l* and that of the differential element is denoted by *dx*. The impedance across a series section is *zdx* and that across a shunt segment is *ydx*. At the sending end, $x = 0$ and the voltage and current are denoted by V_1 and I_1 respectively. At the receiving end, $x = l$ and the voltage and current are V_2 and I_2 respectively. A voltage drop of dV appears across the series element of the line and a current dI flows through the shunt element. The voltage drop and current loss in the line can be represented by the first order differential equations 4-3 and 4-4 (Grainger & Stevenson, 1994).

$$\frac{dV}{dx} = zI \qquad \textbf{4-3}$$

$$\frac{dI}{dx} = yV \qquad \textbf{4-4}$$

Similar behaviour can be characterised by second order differential equations 4-5 and 4-6.

$$\frac{d^2V}{dx^2} = yzV = \gamma^2V \qquad \textbf{4-5}$$

$$\frac{d^2I}{dx^2} = yzI = \gamma^2I \qquad \textbf{4-6}$$

γ represents the propagation constant (Grainger & Stevenson, 1994). Solving the differential equations give the below solution in equations 4-7 and 4-8.

$$V = V_2 \cos h\,(\gamma x) + Z_c I_2 \sin h\,(\gamma x) \qquad \textbf{4-7}$$

$$I = I_2 \cos h\,(\gamma x) + \frac{V_2}{Z_c} \sin h\,(\gamma x) \qquad \textbf{4-8}$$

The voltage and current at any point along the transmission line can be determined from these equations by substituting the appropriate value of x. Z_c is the characteristic impedance of the line. This is given by equation 4-9.

$$Z_c = \sqrt{z/y} \tag{4-9}$$

At the terminals, x=l and the terminal currents and voltages can be given by equations 4-10 and 4-11.

$$V = V_2 \cos h\,(\gamma l) + Z_c I_2 \sin h\,(\gamma l) \tag{4-10}$$

$$I = I_2 \cos h\,(\gamma l) + \frac{V_2}{Z_c} \sin h\,(\gamma l) \tag{4-11}$$

4.3 Lumped Transmission Line Parameters

The lumped transmission line parameter model is a simplified version of the distributed parameter model. It has been derived from equations 4-10 and 4-11 (Glover et al., 2012). The model cannot give values of voltage and current at different points along the transmission line. This information is useful in many studies, but where it is not required; the lumped parameter model may be used.

In most studies, engineers are more interested in the values of voltage and current at the terminal ends of the transmission lines (Glover et al., 2012). The propagation is neglected and lumped transmission line parameter model is adopted for power flow studies. To develop the lumped parameter transmission line model, equations 4-10 and 4-11 can be put into the form as follows (Glover et al., 2012).

$$V_1 = AV_2 + BI_2 \tag{4-12}$$

$$I_1 = CV_2 + DI_2 \tag{4-13}$$

Where,

$$A = \cos \mathrm{h}(\gamma l) \tag{4-14}$$

$$B = Z_c \sin h\,(\gamma l) \tag{4-15}$$

$$C = \frac{1}{Z_c} \sin h\,(\gamma l) \tag{4-16}$$

$$D = \cos \mathrm{h}(\gamma l) \tag{4-17}$$

The lumped parameter transmission model holds the appropriate terminal behaviour as in equations 4-12 and 4-13. A π-equivalent circuit for this is shown in.

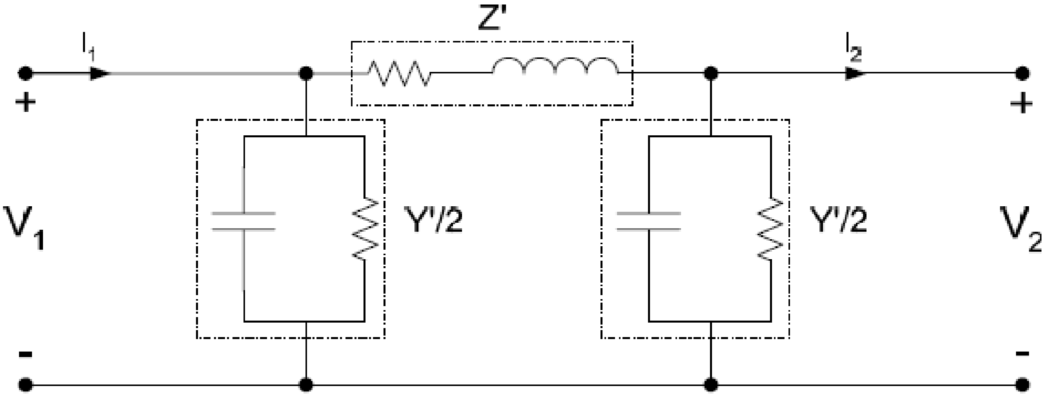


Figure 4-2: π-Equivalent Circuit of Lumped Parameter Transmission Line (Glover et al., 2012)

The series and shunt elements of this model are also represented by passive elements. The total impact of the distributed elements along the whole length of the transmission line is lumped together in ohms. They are proportional to the length of the line, but are not expressed in terms of quantity per unit length. By proper calculation of the values of Z' and $Y'/2$, the same impact of the passive elements on the transmission line can be represented. By Kirchoff's voltage law (KVL) and Kirchoff's current law (KCL) in Figure 4-2, the following equations are derived.

$$\begin{aligned} V_1 &= V_2 + Z'\left(I_2 + \frac{Y'}{2} V_2\right) \\ &= \left(1 + \frac{Z'Y'}{2}\right) V_2 + Z' I_2 \end{aligned} \tag{4-18}$$

$$\begin{aligned} I_1 &= \frac{Y'}{2} V_1 + \frac{Y'}{2} V_2 + I_2 \\ &= Y'\left(1 + \frac{Z'Y'}{4}\right) V_2 + \left(1 + \frac{Z'Y'}{2}\right) I_2 \end{aligned} \tag{4-19}$$

Comparing equations 4-18 and 4-19 to equations 4-12 and 4-13 respectively, we can obtain the values of *A*, *B*, *C* and *D* lumped parameters as under.

$$A = \left(1 + \frac{Z'Y'}{2}\right) \tag{4-20}$$

$$B = Z' \tag{4-21}$$

$$C = Y'\left(1 + \frac{Z'Y'}{4}\right) \tag{4-22}$$

$$D = \left(1 + \frac{Z'Y'}{2}\right) \tag{4-23}$$

Solving for Z' and ${}^{Y'}/_{2}$ in Figure 4-2,

$$Z' = Z_c \sin h\,(\gamma l) \tag{4-24}$$

$$\frac{Y'}{2} = \frac{1}{Z_c} \tan h\left(\frac{\gamma l}{2}\right) \tag{4-25}$$

The above process which allows the determination of parameters is a lumped π-equivalent model with variable length, characteristic impedance and propagation constant of the line. The resistor, capacitor and inductor elements are sized by equations 4-24 and 4-25. The RLC circuit thus obtained will maintain appropriate behaviour at the terminal ends. Similarly, a T-equivalent circuit may be constructed with two series and a shunt impedance element. This is a transformation of the π-equivalent model, which holds the same terminal relationship. The relationship may be simplified for a line of a shorter length.

4.4 Lumped Parameter Transmission Line Models

For lines which are not particularly long, $|\gamma l| \ll 1$ (Grainger & Stevenson, 1994). In this case, an approximation may be made to equations 4-24 and 4-25, without any severe impact on the accuracy. This section explains how the simplification may be made and also about the omission of certain passive elements, which further simplifies the lumped parameter transmission line model.

Sections 4.2 and 4.3 explained distributed and lumped parameter transmission line modelling. The lumped parameter model, as explained is a π-equivalent circuit, which contains series resistive and inductive elements along with shunt resistive and capacitive elements. Certain assumptions are made on this model to further simplify it. In this way, four different models are presented, on the basis of line length. As the line becomes shorter and shorter, certain assumptions are made and certain parameters are neglected (Glover et al., 2012).

4.4.1 Long Transmission Line Model

For a long transmission line (l > 250 km), no approximations are made (Glover et al., 2012). The passive elements of the π-equivalent circuit are calculated using equations 4-24 and 4-25. For this π-equivalent circuit, the characteristic impedance and propagation constant are given as under.

$$\begin{aligned}\gamma &= \sqrt{yz} = \sqrt{(g + j\omega c)(r + j\omega l)} \\ &= \sqrt{gr - \omega^2 cl + j(\omega cr + \omega gl)}\end{aligned} \qquad \textbf{\textit{4-26}}$$

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{r + j\omega l}{g + j\omega c}} \qquad \textbf{\textit{4-27}}$$

The values of Z' and $^{Y'}/_2$ are computed from ω and Z_c. The circuit elements of the passive elements are then calculated for the equivalent circuit as shown in Figure 4-3. This representation is called the long transmission line model (Glover et al., 2012).

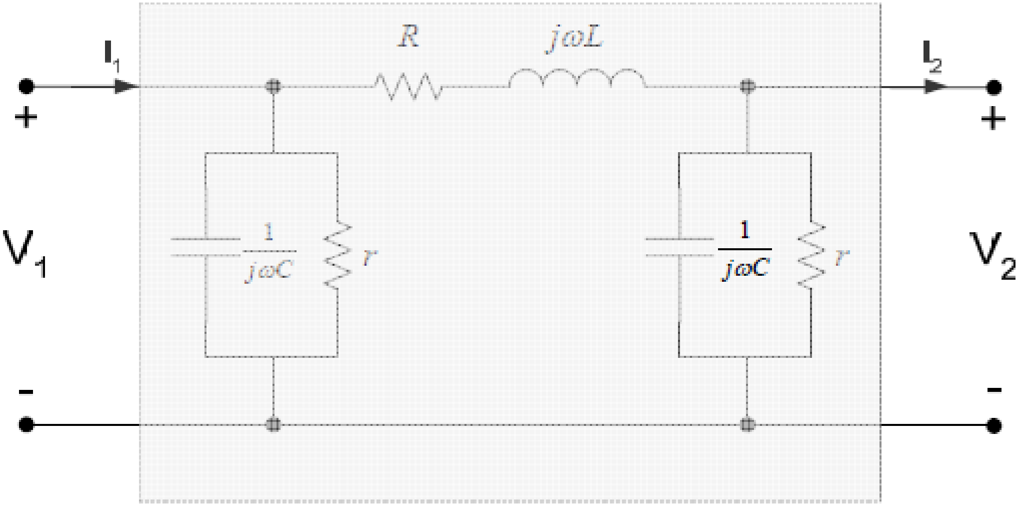


Figure 4-3: Long Transmission Line Model (Glover et al., 2012)

Where,

$$Z' = R + j\omega L \qquad \textbf{4-28}$$

$$\frac{Y'}{2} = \frac{1}{r} + j\omega C \qquad \textbf{4-29}^{1}$$

4.4.2 Medium Transmission Line Model

The shunt resistive element may be neglected if the length of the transmission line is lesser than 250 km. This is defined as a medium transmission line (Glover et al., 2012).

The current that flows through the resistive shunt element of the transmission line is very small and is proportional to the magnitude of the terminal voltage. The impact of this element is significant only in the case of high voltage long transmission lines. This element is neglected in medium length transmission lines with negligible impact of the accuracy of results. The corresponding equivalent circuit thus obtained is shown in Figure 4-4.

---

[1] r in 4-29 is a lumped parameter. It has been represented in lower case in order to differentiate it from the series resistive element.

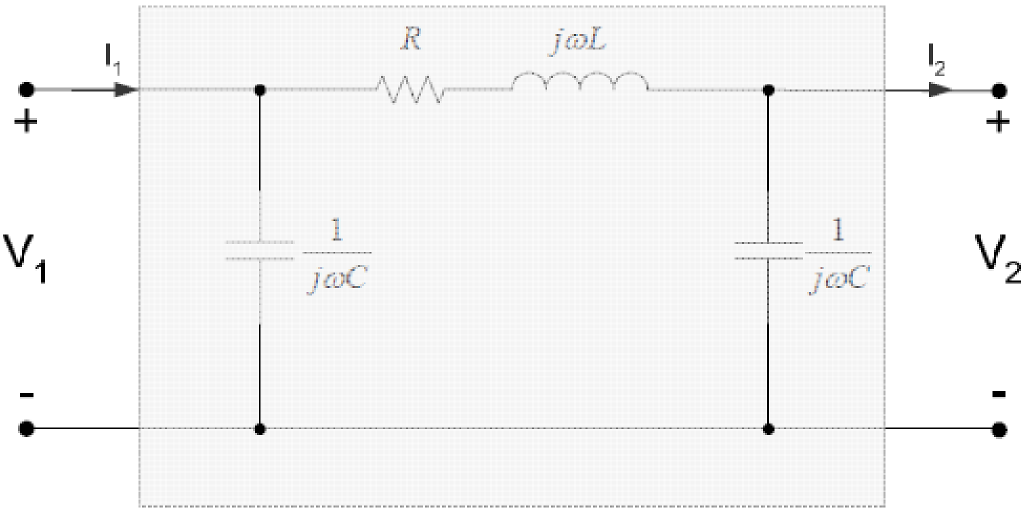


Figure 4-4: Medium Length Transmission Line (Glover et al., 2012)

Further approximations are made on this model. The propagation constant and characteristic impedances are no longer used to calculate the RLC elements for the lumped parameter transmission line model. The approximations made are as under.

$$Z' \approx Z = zl = R + j\omega L \tag{4-30}$$

$$\frac{Y'}{2} \approx \frac{Y}{2} = yl = -j\omega C \tag{4-31}$$

This computation is simpler than that of the long transmission line model. The values of the elements in this model can be determined from the line length and parameters in per unit length. There is no requirement of any hyperbolic functions.

4.4.3 Short Transmission Line Model

Further simplifications to the medium transmission line model are made for the short transmission line model. A short transmission line is defined as that which is lesser than 80 km in length (Glover et al., 2012).

For a short transmission line, the shunt elements are all neglected. The shunt charging caused by shunt capacitance is negligibly small in magnitude in short transmission lines and hence, neglecting this element has a negligible impact on the result. Further, there are two types of short transmission line models as under.

- Short Lossy Transmission Line Model
- Short Lossless Transmission Line Model

The lossy model has a series resistor as well as series inductor component, as shown in Figure 4-5. The term lossy is taken from the fact of the presence of I^2R real power losses in the model. Small approximations in angles are used and the elements of this model are calculated from equation 4-30.

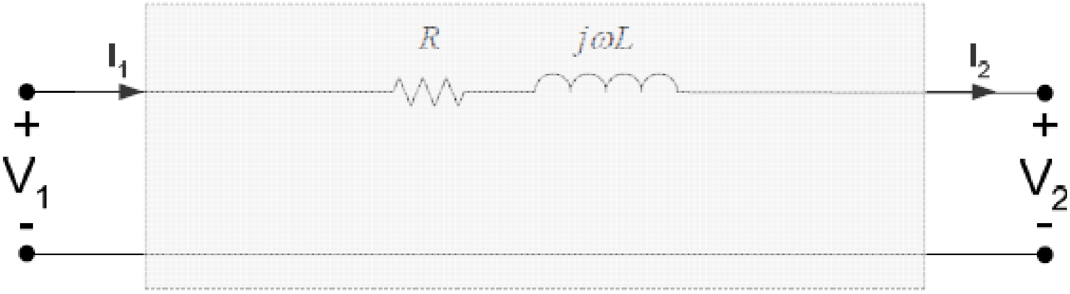


Figure 4-5: Short Lossy Transmission Line Model (Glover et al., 2012)

The other short transmission line model available is the short lossless transmission line model. This is the most simplified model and is more often used in power distribution systems or very short transmission lines. This model is widely used in power flow solvers to simplify and speed up calculations. The model only consists of a series inductor, as shown in Figure 4-6, and has no resistive component, which would represent the real power loss. Therefore, it is called a lossless transmission line model.

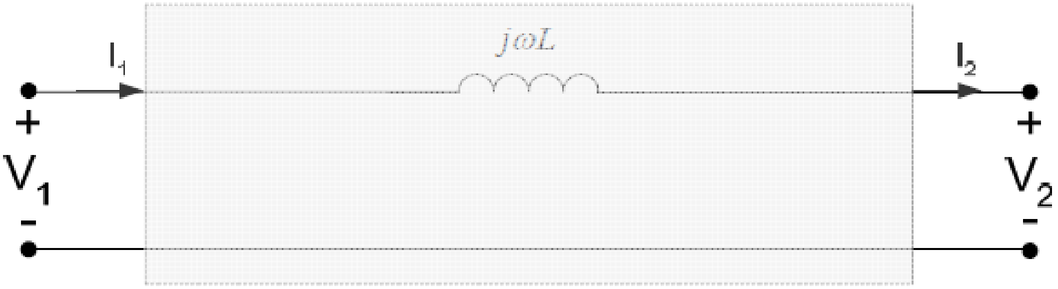


Figure 4-6: Short Lossless Transmission Line Model (Glover et al., 2012)

The inductor sizing calculation for this model is done as under.

$$Z = j\omega L \tag{4-32}$$

Four different transmission line models have been presented based on the length of the respective transmission lines. It should be ensured that the appropriate model is used to avoid any errors in the results obtained. The guidelines of using these models is summarised in Table 4-1 (Glover et al., 2012). It may be inferred from the other models that the short lossless transmission line model may be used in those instances only where the transmission line length is much lesser than 80 km.

Table 4-1: Summary of Lumped Parameter Transmission Line Models (Glover et al., 2012).

Line Model	Transmission Line Length	Recommended Lumped Transmission Line Model	Assumptions
A	$l \ll 80\ km$	Short Lossless	All shunt elements neglected Series resistance neglected $Z' \approx Z$
B	$l < 80\ km$	Short Lossy	All shunt elements neglected $Z' \approx Z$
C	$80 \leq l < 250\ km$	Medium	Shunt resistance neglected $Z' \approx Z$ $\frac{Y'}{2} \approx \frac{Y}{2}$
D	$l \geq 250\ km$	Long	None

5.0 Modelling

This section explains the steps involved in the modelling of an offshore windfarm transmission line. The overview, methodology and assumptions in this project are explained in detail.

5.1 Overview

The approach towards offshore transmission line modelling followed in this project is summarised as:

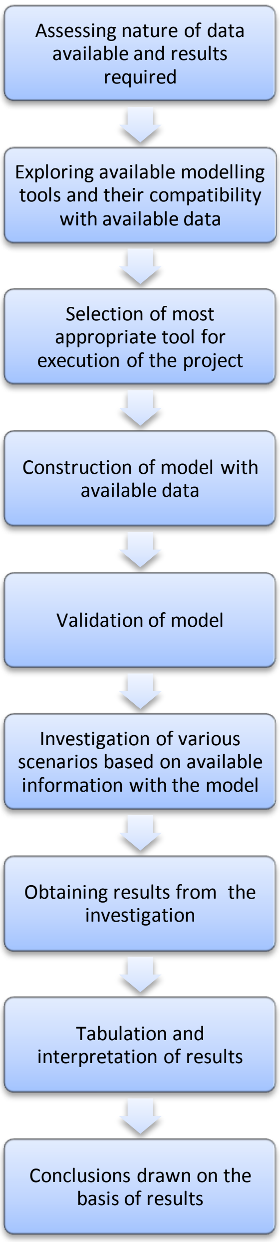


Figure 5-1: Modelling Approach of the Project

As shown in Figure 5-1, the modelling approach for the project involves several steps of equal importance. A further detail of the methodology followed is explained in the next section.

5.2 Methodology

The modelling in the project involved several steps. Each of these steps is discussed in greater detail as under.

5.2.1 Collection of Information and Data

The project involved collection of various types of information and data from various sources. The different kinds of information required to perform this study are listed as under.

- Review of renewable energy targets of the United Kingdom and Scotland.
- Proposed methods of achieving these renewable energy targets.
- Various scenarios described with different rates of working towards these targets and the corresponding economic impacts of these plans.
- Policy on offshore wind in the United Kingdom and Scotland.
- Environmental impacts of offshore windfarms.
- Proposed offshore windfarms in Scotland.
- Distance of the proposed offshore windfarms from the existing onshore electricity grid.
- List of equipment required in execution of offshore windfarm projects.
- Types of cables being used in proposed offshore windfarm projects.
- Cable parameters for such cables being used in offshore windfarm projects.
- Cost of various components in offshore windfarm projects.

5.2.2 Exploring Modelling Options

The various options for modelling of the transmission lines of offshore windfarms were considered. Several software packages for modelling were found. Some of these are listed as under.

- OpenDSS: An open source software package available for download from the internet free of cost. Good recommendations and reputations from other users along with a good user interface. However, more suitable for power distribution systems, rather than transmission systems.

- DIgSILENT PowerFactory: A professional software package with full Graphical User Interface (GUI). It is increasingly becoming popular among utilities and engineering design consultancies. It is licensed software which is very powerful. However, relatively difficult to learn and grasp within a short time period.

- PSS®E: A professional software package from Siemens AG. Powerful and being used by several engineering design consultancies worldwide. A licensed software and also relatively difficult to learn in a short period of time.

- IPSA+: A professional software package developed by IPSA Power. Licensed software, but a trial version available for free download.

- PowerWorld Simulator: A software package developed by PowerWorld Corporation. A limited version is available for free download from the internet. It has a good user interface and is frequently used by students and academicians for studies. It is also used by some engineering design consultancies.

5.2.3 Selection of Appropriate Tool

Considering the various pros and cons of the options of software packages available as mentioned above, the PowerWorld simulator was chosen. The following features of PowerWorld simulator made it the most viable option for use in this project.

- Licensed software which can be downloaded from the internet. Hence, there are no issues regarding the availability.

- Available free of cost. Hence, no cost involved in obtaining software.

- The evaluation can handle up to 12 buses. This is adequate for the nature of study to be performed and the required results.

- In case any issues faced in the evaluation version, the full version is available in the computer laboratory of the Department of Electrical and Electronic Engineering at the University of Strathclyde, which is accessible.
- Good Graphical User Interface (GUI).
- Relatively easy to learn and use in a short period of time.
- Widely used by students and academicians for transmission line and power system load flow studies.

5.2.4 Model Construction

On selection of the appropriate software, the model was constructed using the PowerWorld Simulator. The model was created with the following data, as shown in Table 5-1.

Table 5-1: Data Used in Offshore Windfarm Model

Parameter	Value	Source
Offshore Windfarm Generation Capacity	2000 MW	Scotland's Offshore Wind Route Map: Developing Scotland's Offshore Wind Industry to 2020 (The Scottish Government)
Transmission Voltage	400 kV	Round 3 Offshore Windfarm Connection Study (The Crown Estate)
Transmission Line Parameters	X : 0.119 Ω/km R : 0.027 Ω/km C : 0.19 μF/km	Offshore Development Information Statement – September 2010 (National Grid)
Distance of Offshore Windfarm from Onshore Grid Connection Point	50 to 200 km	Round 3 Offshore Windfarm Connection Study (The Crown Estate)
Distance between Joints in Cable Section	500 m	XLPE Submarine Cable Systems (ABB, Sweden)

Of the proposed windfarms in the Scottish Territorial Waters and National Grid Round 3 zones, the capacity varies between 280 MW to 3465 MW (The Scottish Government, 2011). Most proposed offshore windfarms were of up to 2000 MW, with only the Firth of Forth windfarm being greater. Therefore, a value of 2000 MW was used for the installed capacity of the offshore wind generation in the model.

The present power transmission grid in Scotland operates at a voltage level of 132 kV and 275 kV. The offshore windfarms are proposed to be connected to the 400 kV supergrid (The Crown Estate, 2011). The supergrid in Scotland is also being developed for this reason. Therefore, a transmission voltage of 400 kV was selected for the model.

Contracts for the supply of cables for the connection of Round 3 offshore windfarms have been awarded to a few submarine cable manufacturers. The bulk of it has been awarded to ABB Cable Systems, Sweden (National Grid, 2010). The cable design parameters which have been published by ABB Cable Systems have been used in the model for constructing the offshore transmission line model.

The distance of the proposed windfarms from the onshore grid connection points in Round 3 projects varies widely from around 50 km up to 200 km (The Crown Estate, 2011). Therefore, these values have been used to investigate different scenarios with the model and what implications the length of the transmission line has on the offshore windfarm.

The distance between cable joints in the submarine transmission line cable is an important consideration as there is a significant amount of power loss due to the resistance in these joints (SVOMA et al., 2007). The lengths of the cable drums in which submarine cables were supplied were considered and joints were put onto the cable at these distances.

The model thus constructed is a model with lumped transmission line parameters. The PowerWorld simulator automatically selects the most appropriate lumped parameter model to be used for the length of the transmission line. Hence, depending on that parameter, a long, medium, short lossy or short lossless transmission line lumped parameter model is used.

On appropriately assigning these parameters to the PowerWorld Simulator, the model is constructed and is ready for use in analysis of different scenarios.

5.2.5 Model Validation

Once the model is constructed, its validity was determined. The validation technique was by comparing results generated by the model with already validated results.

The real power transfer for a 500 MW offshore windfarm for different splits of offshore reactive compensation was investigated. The split of reactive compensation implies the distribution of reactive compensation between offshore and onshore locations. Three different scenarios were analysed as under.

- 100/0 Split: The scenario in which the entire reactive compensation applied to the cable was onshore only. There was no offshore reactive compensation applied. This meant that the reactive compensation was applied on only one end of the cable.
- 50/50 Split: The scenario in which there was an equal distribution between the reactive compensation applied of the cable. This meant that the reactive compensation was not only applied on a single end of the cable.
- 70/30 Split: The scenario in which there was a 70% to 30% split in the reactive compensation applied to the cable. This meant that 70% of the reactive compensation applied was onshore, whereas 30% of that was offshore.

The results obtained were similar to that already published in a similar study. The graphical representation of the results in both scenarios is shown in Figure 5-2 and Figure 5-3.

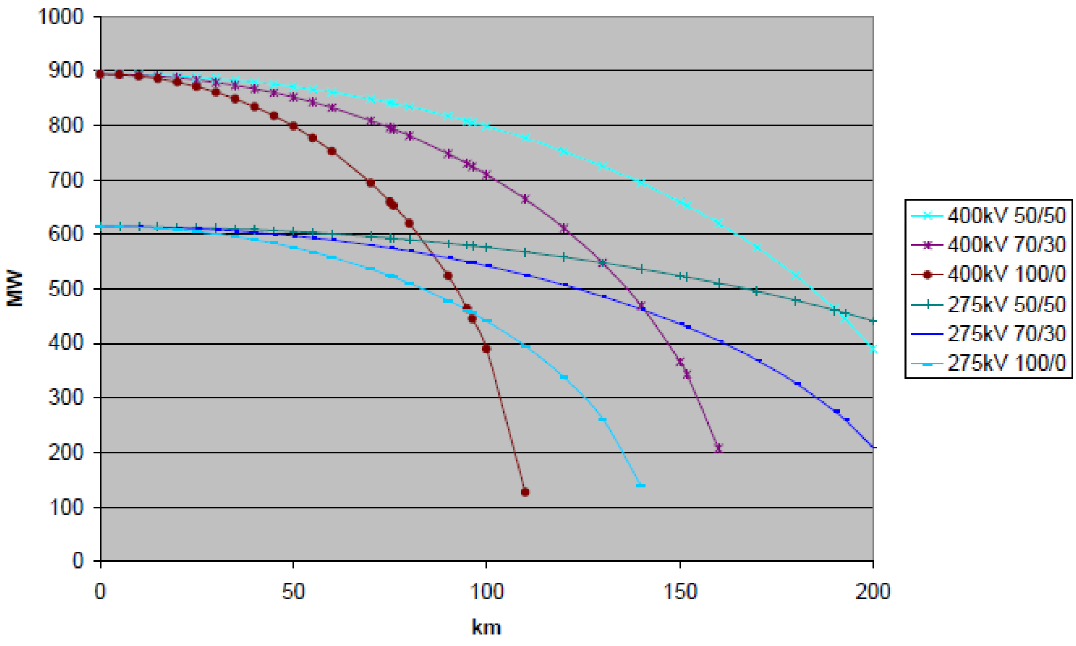


Figure 5-2: Graphical Representation of Results Obtained in a Previous Study (National Grid, 2010)

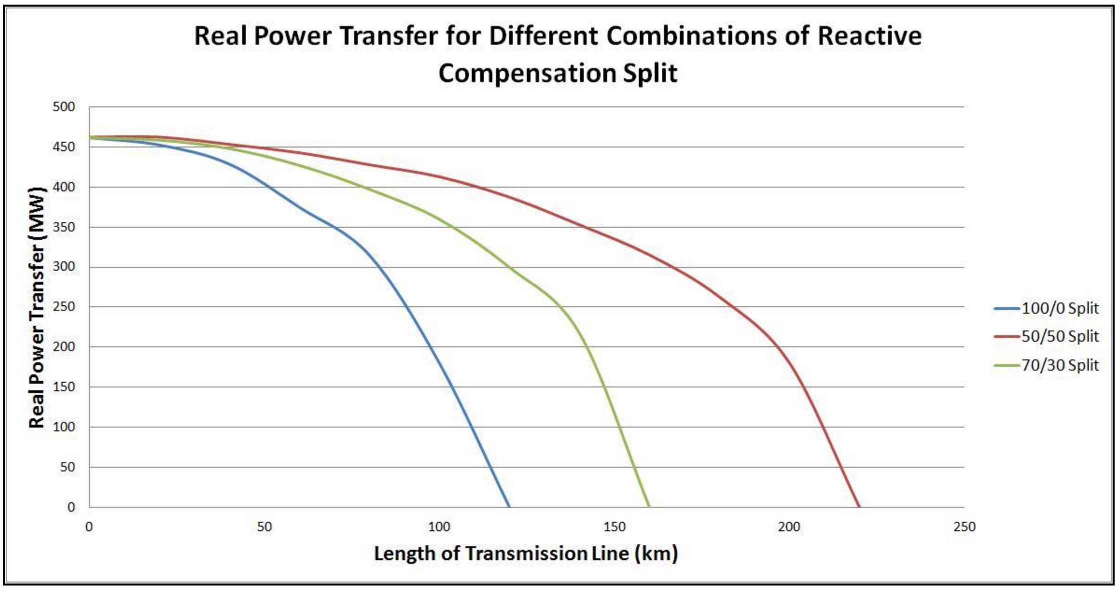


Figure 5-3: Graphical Representation of Results Obtained from the Constructed Model

Figure 5-2 shows results already obtained in a previous study and published in the National Grid Offshore Development Information Statement 2010. Figure 5-3 shows results which have been obtained from the model constructed on the PowerWorld Simulator. The nature of the characteristics obtained in both cases is similar.

Therefore, from this, we conclude that the model constructed is validated and may be used for further investigation of other scenarios.

5.2.6 Investigation of Various Scenarios

On confirming the validity of the constructed model, various scenarios were investigated with it. The scenarios investigated are as under.

- Different generation scenarios when the offshore windfarm is not generating any power to when it is generating its full capacity. That is, the generation of the windfarm was varied from 0 MW to 2000 MW.
- The distance of the offshore windfarm from the onshore grid connection point was varied from 50 km to 200 km for each of these scenarios.
- The reactive compensation to be applied to keep the current within the designed cable ampere rating. BS IEC 60287 (British Standards Institution, 2007) recommends the normal current to be within 80% of the designed maximum current carrying capacity of a cable. The required reactive compensation required in each of the above cases was investigated.

5.2.7 Tabulation, Representation and Conclusions from Results

The results obtained from each of the above scenarios was tabulated and represented in appropriate formats. The maximum information was tried to be extracted out of these results. The results were represented in graphical form and have been discussed in section 6.0.

On obtaining all the results, they were carefully studied and conclusions were drawn from them.

This completed the overall process of the project.

6.0 Results and Discussion

This section presents the results obtained from the model and a discussion with their interpretation.

6.1 Technical Results

On completion of the investigation of various scenarios with the constructed model, the results were tabulated and represented in graphical form.

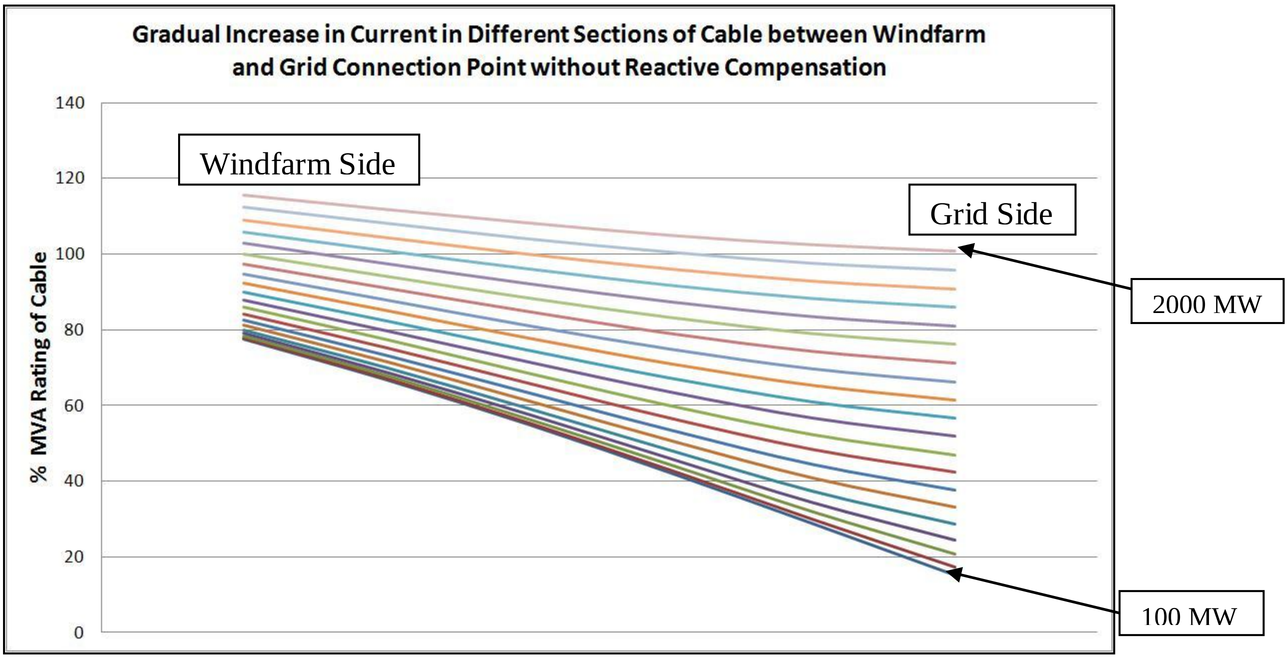


Figure 6-1: Gradual Increase in Current with Increase in Real Power Transfer

Figure 6-1 shows the gradual increase in current in different sections of the cable. The bottom most line represents the characteristics of the cable for a real power transfer of 100 MW and the top most line represents that of 2000 MW. The left hand side of the chart represents the windfarm side and the right had represents the grid side.

For the transfer of 100 MW real power, it is observed that all the sections are well within the recommended power rating of 80% of the cable (British Standards Institution, 2007), whereas for 2000 MW real power transfer, all the sections exceed the designed rating of the cable. The percentage loading of the cable for 100 MW of real power transfer varies from 15.2% to 77.5%, whereas for a 2000 MW real power transfer these values shoot up to between 100.7% and 115.6%. This is due to the build up of reactive power in different sections of the cable. Managing this reactive power becomes more and more difficult with long sections of cable. The amount of reactive power in the cable is observed to be manageable up to a real power transfer of 500 MW, but greater than that, the sections of the cable which are closer to the windfarm and farthest away from the onshore grid connection points are observed to exceed the designed power rating. This reactive power, building up on the grid side is being absorbed by the existing electrical grid and being balanced out. This is not happening on the windfarm side. Reactive power is known to not travel long distances and this is the reason why reactive compensation is required at very localised locations for long transmission lines (Bucea & Kent, 2007).

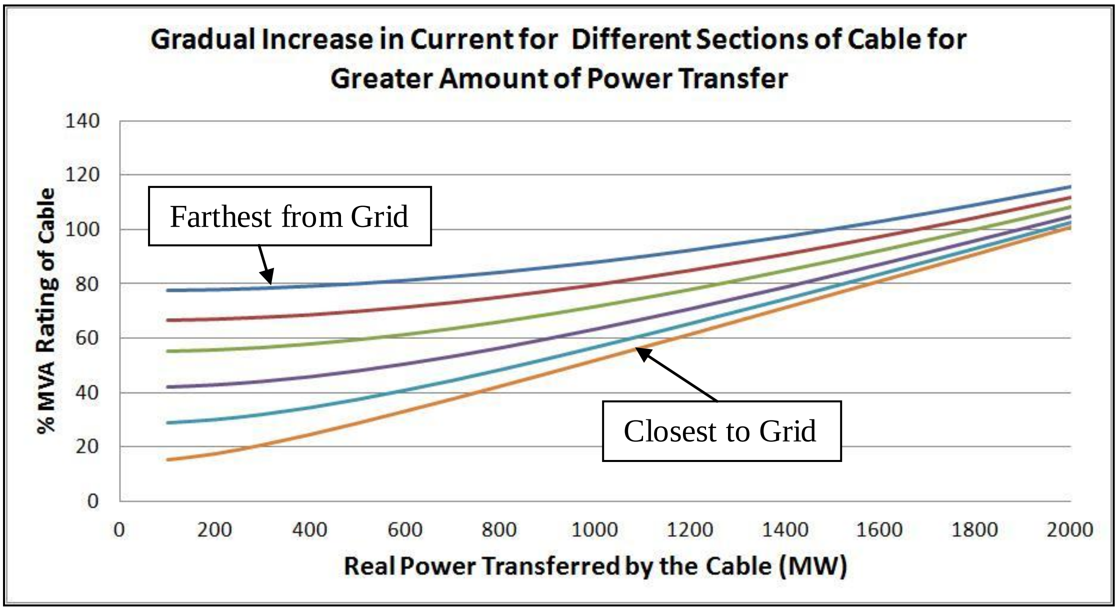


Figure 6-2: Current Characteristics in Different Sections of the Transmission Line

Figure 6-2 shows the percentage of designed power capacity in each section of the cable with the increase in total real power transfer. The entire cable has been divided into six different sections. The bottom most line in the graph represents the section which is closest to the onshore grid connection point, whereas the top most line represents the section which is farthest away from the grid.

The above mentioned phenomenon is more evident from Figure 6-2. The different sections of the submarine cable for power transmission are analysed separately. The section of the cable which is closest to the grid is loaded to only 15.2% of its maximum capacity for a real power transfer of 100 MW, whereas the section which is farthest is loaded to 77.5%, which is very close to the maximum operating limit.

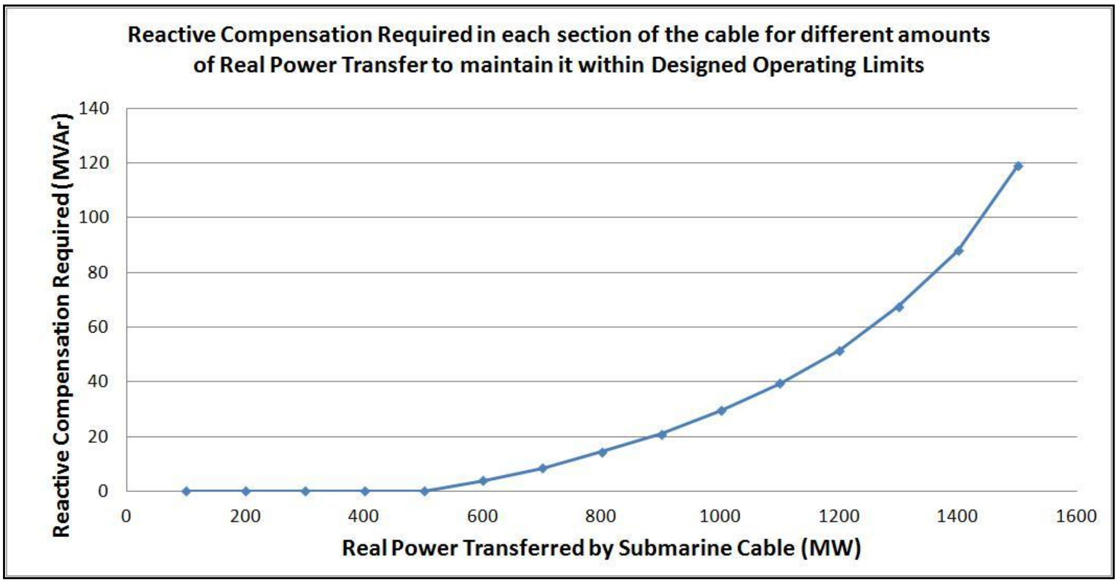


Figure 6-3: Reactive Compensation to be Applied in Each Section of the Submarine Cable

The amount of reactive compensation required to be applied to each section of cable to maintain it within the designed operating limits was examined. The results are shown in Figure 6-3. There is no reactive compensation required up to a real power transfer of 500 MW. The reactive compensation to be applied for real power transfer above 500 MW increases rapidly. The maximum limit was reached at 1500 MW. Above 1500 MW, no amount of reactive power compensation could maintain the cable within its operating limits. Therefore, only up to 75% of the generated power could be transmitted from the offshore windfarm to the electricity grid with the maximum possible reactive compensation applied.

The possibility of transferring the whole 2000 MW of real power generated by the windfarm, when operating at full load was examined. It was observed that the transmission line needed to be oversized to achieve this. The submarine cable for power transmission was required to be designed for around 2800 MVA to be able to transfer 2000 MW of real power through it. This again was with very highly increased amounts of reactive compensation on each section of transmission line and though theoretically possible, would make it practically impossible with the highly increased amount of capital required for this purpose. A more detailed economic analysis is contained in the following section.

6.2 Economical Results

The costs shown in Table 6-1 and Table 6-2, taken from the National Grid Offshore Development Information Statement (ODIS), published in September 2010 have been used in calculations for the detailed economic analysis.

Table 6-1: Cost of Equipment for a HVAC Transmission Line

Component	Specification	Cost (in Million Pounds)
Transformer	240MVA, 132/400 kV	2 each
Gas Insulated Switchgear (GIS)	132 kV	0.75 each
Gas Insulated Switchgear (GIS)	400 kV	2.6 each
Shunt Reactor	200 MVAr, 400 kV	1.5 each
Cable	400 MVA	2.5 / km

Table 6-2: Cost of Equipment for a HVDC Transmission Line

Component	Specification	Cost (in Million Pounds)
Voltage Source Converter (VSC)	2000 MW, 400 kV	130
Cable	2000 MVA, 400 kV	0.62 / km

The cost of the cable for the HVAC transmission system was found to be much higher than that of the HVDC system. This is because of the greater amount of copper conductor required in a HVAC transmission system to transfer the same power in a HVDC transmission system (Anders, 2004). There is no phenomenon like the skin effect observed in the HVDC system, which is a major phenomenon in HVAC cable systems. The skin effect in the HVAC conductor makes the power to flow only towards the outer diameter of the conductor and hence, more conductor material is required in this case, which is not the case in a HVDC cable. However, the other components in the HVAC transmission system viz., transformer, Gas Insulated Switchgear (GIS), shunt reactor were found to be much lower in terms of cost than the Voltage Source Converter (VSC), which is required in HVDC systems. Therefore, though the cost per unit length of cable was much higher in HVAC systems, the VSC was found to be much more expensive for HVDC systems. A techno-economic study was made for both systems for offshore windfarms of distances between 50 km to 200 km from the onshore grid connection point.

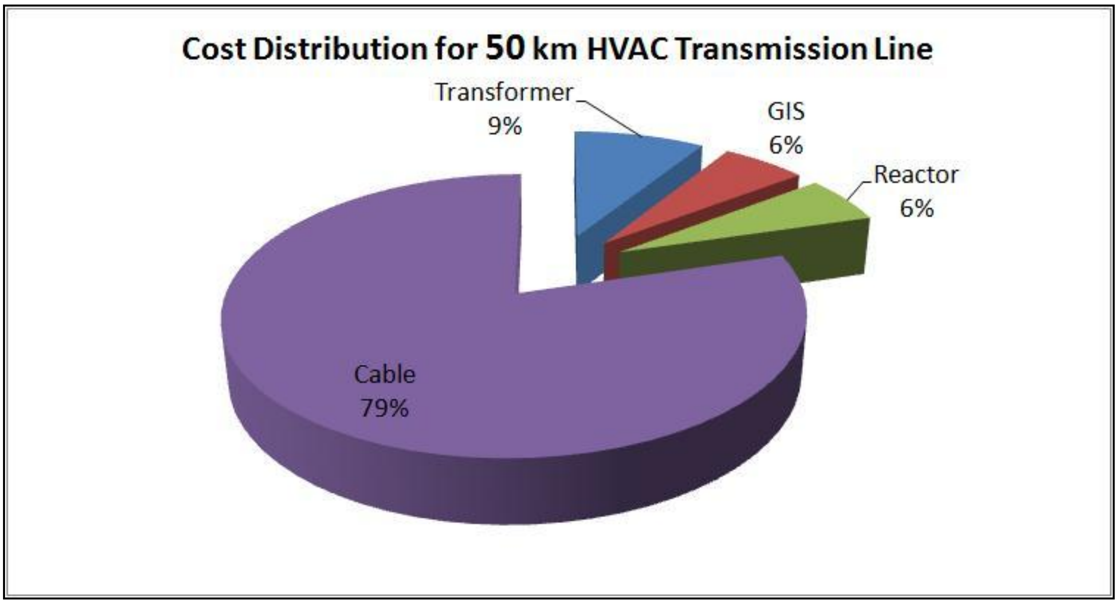


Figure 6-4: Cost Analysis of a 50 km HVAC Transmission Line

Figure 6-4 shows the cost analysis of a 50 km HVAC transmission line. It is observed that in this transmission line, the cable costs are 79% of the total project cost. Other than this, the cost of all other components in total is 21% of the total project cost. Therefore, it is seen that the cost of the cable comprises of a major portion of the project cost.

Figure 6-5 shows the cost analysis of a similar HVAC system with a transmission line of a length of 200 km.

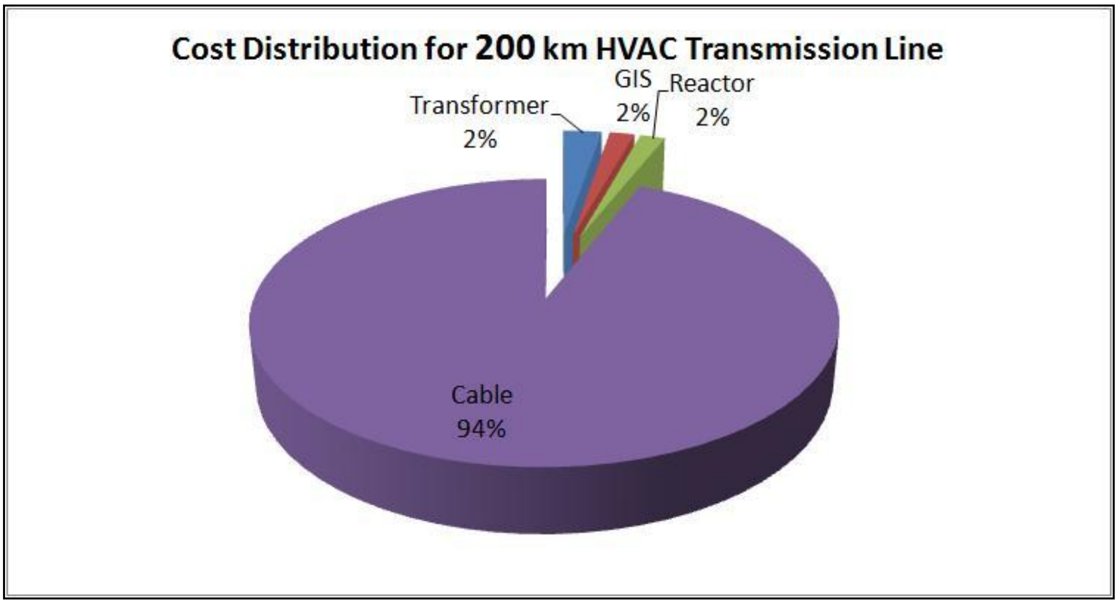


Figure 6-5: Cost Analysis of a 200 km HVAC Transmission Line

In this case, the proportional cost of the cable increases to 94% of the total project cost. The other equipment of the project cost only 6% of the total cost. Therefore, it is observed that in HVAC transmission systems, the cost of the cable is the greatest proportion of costs. The cable is that component which dictates the total value of the project. The other components are a fixed cost and remain the same, irrespective of the distance of the offshore windfarm from the onshore grid connection point. Therefore, the farther the offshore windfarm is from the shore, the greater is the total cost of connecting it to the grid. It can further be said that if a HVAC transmission system is selected for an offshore windfarm, it should be tried to be constructed as close to the onshore grid connection point as possible, to be able to complete it at the minimum possible cost.

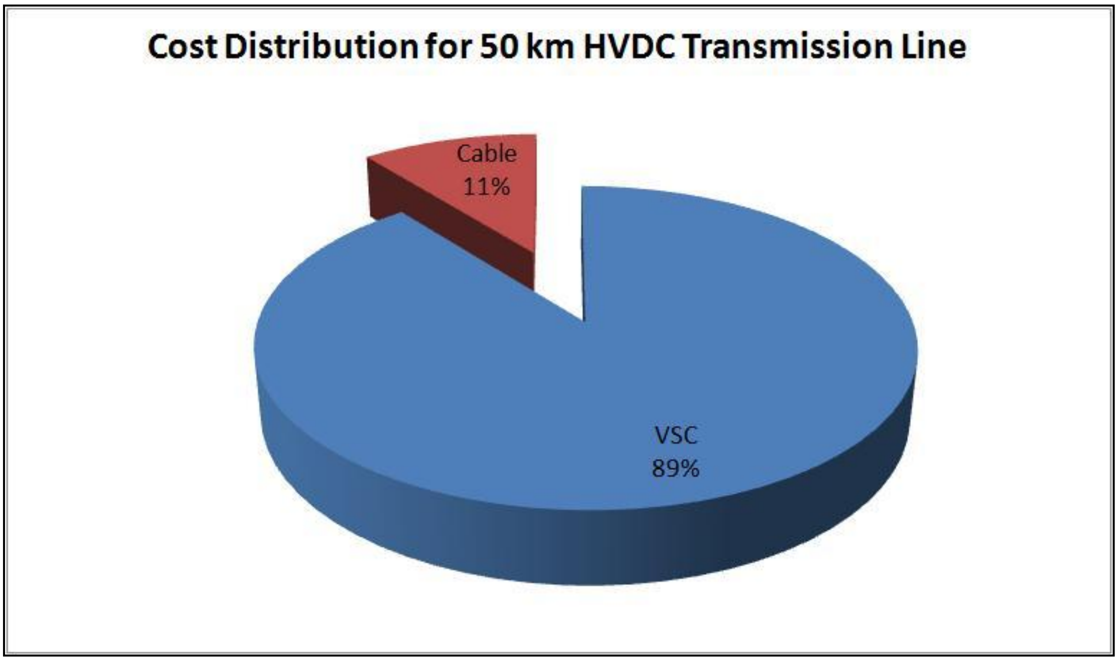


Figure 6-6: Cost Analysis of a 50 km HVDC Transmission Line

A similar analysis was done for a HVDC system. Figure 6-6 shows the cost analysis of a HVDC system with a 50 km transmission line. In this case, it is observed that the cable cost is 11% of the total value of the project. The major proportion of the project is for the cost of the Voltage Source Convertor (VSC). This is a fixed cost in HVDC systems and is irrespective of the length of the transmission line.

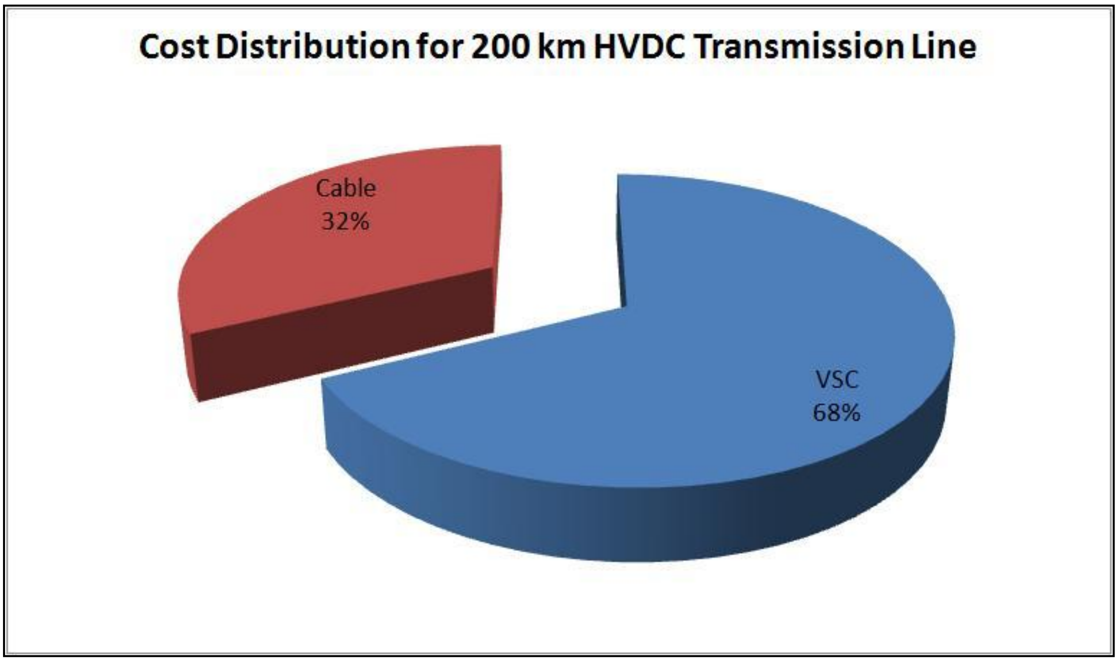


Figure 6-7: Cost Analysis of a 200 km HVDC Transmission Line

Figure 6-7 shows a similar cost analysis of a HVDC transmission system with a 200 km transmission line. Here it is observed that only a third of the cost is for the cable and the remaining two thirds is for the VSC. Even though the length of the cable has increased significantly, the major proportion of the cost of the project is for the VSC, which is a fixed cost. Therefore, it is inferred that in a HVDC transmission system, the length of the cable, that is, the distance of the offshore windfarm from the onshore grid connection point does not have a large impact on the project cost. The fixed cost is due to the convertor station, which remains constant, irrespective of the distance from the grid connection point.

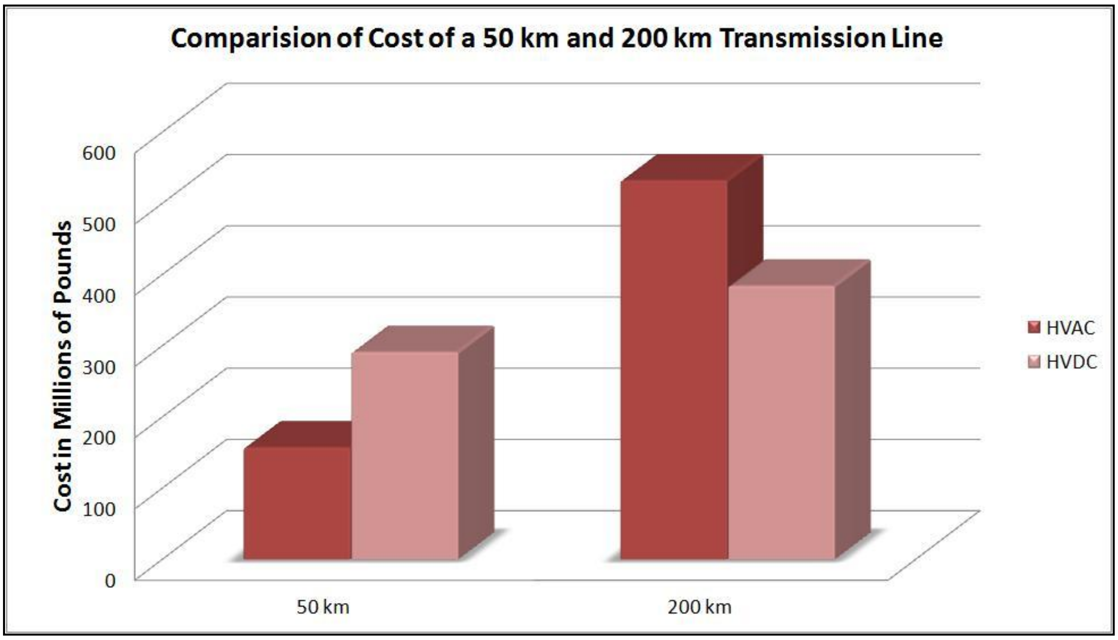


Figure 6-8: Cost comparison of HVAC and HVDC Transmission Line

Figure 6-8 shows a cost comparison for a HVAC and HVDC system for 50 km and 200 km lengths. It is observed that the total project cost for a 50 km transmission line is £ 157 million for a HVAC system and £ 291 million for a HVDC system. For a 50 km transmission line, having a HVAC system will be more economical than a HVDC one.

The cost for a 200 km HVAC system is found to be greater than a HVDC system of the same length. A HVAC system would cost £ 532 million in comparison to £ 384 million of a HVDC system of a similar length. Since the offshore windfarm is much farther away from the onshore grid connection point in this case, it increases the total project cost. However, a HVDC transmission system is found to be a much more economical option in this case.

Table 6-3 shows the individual costs of the offshore power transmission systems for the proposed offshore windfarms in Scotland. It is evident that the total cost for a HVDC system for all the windfarms taken together would be about 2.5 times that for an alternate HVAC system. Therefore, there is a large impact of the type of transmission system chosen on the total cost of the projects taken together.

Table 6-3: Individual Costs of Power Transmission Systems of Proposed Windfarms

Name of Proposed Windfarm	**Distance from Grid Connection Point (km)**	**Cost (in Millions of Pounds)**	
		HVAC	HVDC
Moray Firth	126	347	338.12
Firth of Forth	32	112	279.84
Islay	13	64.5	268.06
Argyll Array	5	44.5	263.1
Beatrice	14	67	268.68
Inch Cape	22	87	273.64
Neart na Gaoithe	15	69.5	269.3
Forth Array	19	79.5	271.78
Total		871	2232.52

A further investigation was made to find a break-even point for the costs of a HVAC and HVDC transmission system.

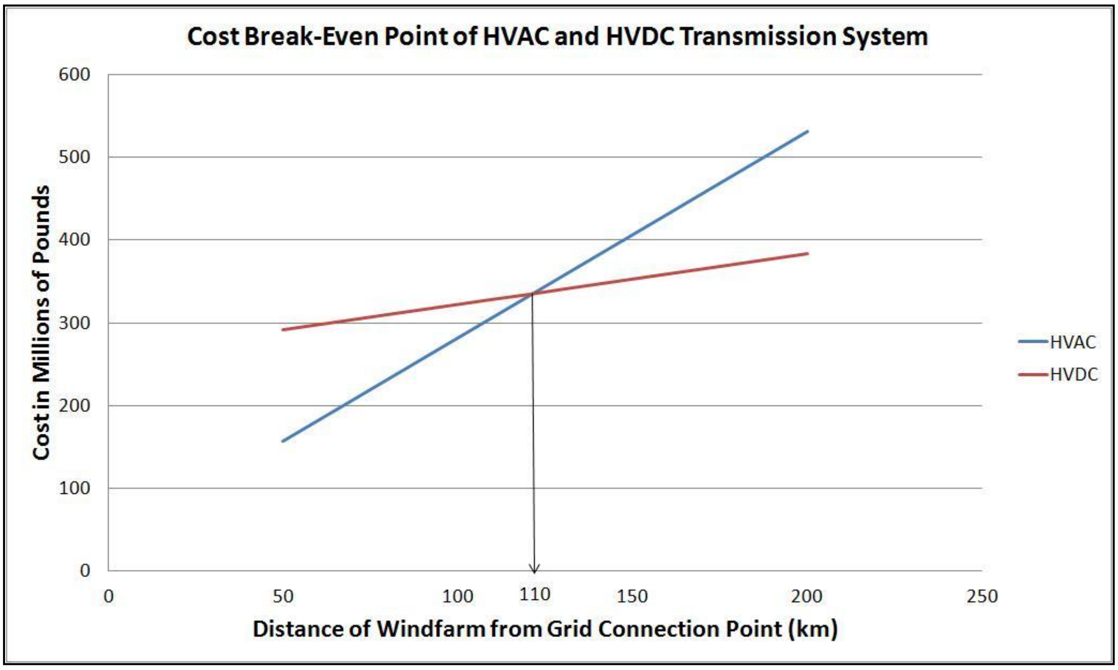


Figure 6-9: Cost Break-Even Point of a HVAC and HVDC Transmission System

Figure 6-9 shows the cost of HVAC and HVDC systems of different lengths in absolute numbers. The cost is found to be the same for a HVAC and HVDC system for a transmission line length of 110 km. That is, if the offshore windfarm is at a distance of 110 km from the onshore grid connection point, it will have a similar cost to connect it to the onshore grid connection point. Therefore, it may be inferred from this finding that a HVAC transmission system will be more economically viable for those offshore windfarms which are located lesser than 110 km away from the grid connection point and a HVDC system for those which are located farther than that.

7.0 Conclusions and Further Work

This section gives details of the conclusions that are drawn from this project and of the scope of further work in continuation of this.

7.1 Conclusions

The main conclusions of the project are listed as under.

- Offshore windfarms have a significant environmental impact on marine life and a comprehensive environmental impact assessment and mitigation plan should be made during the planning stages of an offshore windfarm project.
- Reactive power management has been known to be a major issue for long HVAC transmission lines. This is even more severe for submarine power transmission networks. Therefore, for better reactive power management, efforts should be made to plan and execute the development of offshore windfarms at locations closest to the shore.
- Reactive power significantly decreases the real power transfer capacity of the cable and the transmission cable has to be well oversized to accommodate and transfer the total real power generated by an offshore windfarm.
- The fixed costs for a HVAC transmission system are proportionally small and the variable cost is that of the length of the transmission line, which dictates the total cost of the project.
- The fixed costs for a HVDC transmission system are proportionally large and this dictates the total cost of the project.
- HVAC transmission lines are more economically viable for windfarms which are closer to the shore and HVDC transmission lines for those which are farther away from the shore.
- There is no single answer to which is the best option for power transmission networks and each offshore windfarm should be independently studied and the best option for that should be decided.

There is a main HVDC network planned for the UK power transmission system for connecting offshore windfarms which will be developed until 2030 (National Grid, 2011). For Scotland, the recommended options, in conclusion to this project are listed as under.

Table 7-1: Recommended Power Transmission Technologies for Offshore Windfarms in Scotland

Proposed Offshore Windfarm	Distance from Coast (km)	Recommended Option
Moray Firth	126	HVDC
Firth of Forth	32	HVAC
Islay	13	HVAC
Argyll Array	5	HVAC
Beatrice	14	HVAC
Inch Cape	22	HVAC
Neart na Gaoithe	15	HVAC
Forth Array	19	HVAC

It is evident from Table 7-1 that HVDC transmission lines are not a good option for the proposed offshore windfarms in Scotland. Having HVDC transmission lines will largely increase the construction and development costs of these offshore windfarms.

7.2 Further Work

The recommended scope of further work for this project is listed as under.

- This study has made only steady state analysis of the power transmission system. A further transient study could be done to get more detailed results.
- The techno-economic analysis has been limited to only equipment costs and not considered other material and construction costs. This could be taken account of in a further study.

The feasibility for the better power transmission technology for the offshore windfarms have been made on a one to one basis, without considering the further implications of other issues which may arise by connecting these to the onshore high voltage power transmission network. This could be analysed in a further study. The implications of connecting these windfarms to the UK power transmission network and making an economic analysis of the complete project in a larger picture could be done.

8.0 References

ABB Cable Systems, 2010. *HVDC Light® Cables - Submarine and Land Power Cables*.

ABB High Voltage Cable, 2010. *HVDC Cable Transmissions*. ABB Power Systems.

ABB, 2012. *ABB XLPE Submarine Cable Systems*. [Online] Available at: http://www05.abb.com/global/scot/scot245.nsf/veritydisplay/2fb0094306e48975c125777c00334767/$file/XLPE%20Submarine%20Cable%20Systems%202GM5007%20rev%205.pdf [Accessed 26 July 2012].

Alldritt, D. & Hopwood, D., 2010. Renewable Energy in Scotland. *Renewable Energy Focus*, May/June. pp.28-33.

Amberg, A., Rangel, A. & Smelich, G., 2012. *Validating Transmission Line Impedances Using Known Event Data*. Schweitzer Engineering Laboratories, Inc.

American Bureau of Shipping, 2010. *Guide for Building and Classing Offshore Wind Turbine Installations*. American Bureau of Shipping.

Anders, G.J., 2004. Review of Power Cable Standard Rating Methods. In *Rating of Electric Power Cables in Unfavorable Thermal Environment*. Institute of Electrical and Electronics Engineers. pp.1-75.

Anon., 2006. *Wind Energy Potential on the U.S. Outer Continental Shelf*. Minerals Management Service, Renewable Energy and Alternate Use Program, U.S. Department of the Interior.

Arrillaga, J., Liu, Y.H. & Watson, N.R., 2007. *Flexible power Transmission - The HVDC Options*. Chichester, England: John Wiley & Sons Ltd.

AWS Truewind, LLC, 2009. *Offshore Wind Technology Overview: Long Island - New York City Offshore Wind Collaborative*. New York: AWS Truewind.

Benato, R. & Paolucci, A., 2005. Operating Capability of Long AC EHV Transmission Cables. *Electric Power Systems Research*, 75, pp.17-27.

Bergen, A.R. & Vittal, V., 2000. *Power System Analysis*. 2nd ed. New Jersey: Upper Saddle River, NJ : Prentice Hall.

Berglund, A., 2009. *Control System for Reactive Power of an Offshore Wind Farm*. Uppsala: Teknisk- naturvetenskaplig fakultet UTH-enheten.

Bilfinger Berger, 2007. *Offshore Windfarm Alpha Ventus Transformer Station*.

Brakelmann, H., 2003. Efficiency of HVAC Power Transmission from Offshore-Windmills to the Grid. In *IEEE Bologna PowerTech Conference*. Bologna, Italy, 2003.

British Standards Institution, 2007. *BS 60287-1-1:2006*. [Online] BSOL Available at: https://bsol.bsigroup.com/BsolHomePage/?al=Home [Accessed 14 June 2012].

Bruns, E., Andersson, A. & Thor, S.-E., 2002. Environmental Issues of Offshore Windfarms. In *Summary of IEA R&D Wind - Tropical Expert Meeting #40*. Husum, Germany, 2002.

Bucea, G. & Kent, H., 2007. *Reactive power compensation - Critical Length of Cable Circuit*.

Bucea, G. & Kent, H., 2007. *Submarine Cable Review*.

Camm, E.H. et al., 2009. *Reactive Power Compensation for Wind Power Plants*. IEEE PES Wind Plant Collector System Design Working Group.

Cecchi, V., St. Leger, A., Miu, K. & Chika, N., 2004. *Experimental Validation of Power System Transmission Line Models in the Presence of Non-Fundamental Frequencies*. Drexel University.

Chakrabarti, A., Soni, M.L., Gupta, P.V. & Bhatnagar, U.S., 2006. *A Text Book on Power System Engineering*. 9th ed. New Delhi: Dhanpat Rai & Co. (P) Ltd.

Chaneliere, J.L., Dumas, S., Giard, A. & Martin, F., 2007. *Reactive Power Compensation - Installation of New Reactive Power Compensation Equipment on RTE's Grid in France*. ABB, France.

Chokhwala, R., 2008. *Connecting Platforms - Connecting Oil and Gas Platform to Mainland Power Grids*. ABB.

COLLA, L., 2010. Technical (Electrical) Issues Regarding the Integration of a Long Distance Underground or Submarine Cable in the Network. In *CIGRE 2010 General Session*. Paris, 2010.

Colla, L. et al., 2009. Steady-state Operation of Very Long EHV AC Cable Lines. In *Power Tech Conference*. Bucharest, 2009. IEEE.

Colla, L., Gatta, F.M., Iliceto, F. & Lauria, F., 2010. *Design and Operation of EHV Transmission Lines including Long Insulated Cable and Overhead Sections*. IEEE.

Cowdroy, S., Hill, J. & Halliday, M., 2005. *Study on Development of the Offshore Grid for Connection of the Round Two Wind Farms*. London: Econnect.

Crown Copyright, 2009. *The UK Renewable Energy Strategy*. HM Government.

Dai, Y. et al., 2003. A Cost Allocation Method for Reactive Power Service based on Power Flow Tracing. *Electric Power Systems Research*, 64, pp.59-65.

Danish Energy Authority, 2006. *Danish Offshore Wind - Key Environmental Issues*. DONG Energy, Vattenfall, the Danish Energy Authority and the Danish Forest and Nature Agency.

Daoyu, J., Qiang, G. & Cheng, Z., 2010. *Research on Modeling for Submarine Cable Monitoring System Based on Timed Colored Petri Nets*. Guangzhou, Guangdong: China Southern Power Grid EHV Power Transmission Company Guangzhou Branch.

de Alegria, I.M. et al., 2009. Transmission Alternatives for Offshore Electrical Power. *Renewable and Sustainable Energy Reviews*, 13, pp.1027-38.

Department of Energy & Climate Change, 2011. *UK Renewable Energy Roadmap*. London: UK Government.

Department of Energy and Climate Change, 2011. *Energy Act*. Department of Energy and Climate Change.

Djapic, P. & Strbac, G., 2008. *Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems*. Department for Business Enterprise & Regulatory Reform.

EirGrid, 2011. *Offshore Grid Study - Analysis of the Appropriate Architecture of an Irish Offshore Network*. EirGrid.

Engström, J., 2007. *Underground Cables in Transmission Networks*. Lund University.

ESS Inc. Consultants, 2004. *Transmission Issues with Offshore Windfarms with Specific Application to sitting of the proposed Cape Wind Project*. ESS Inc. Consultants.

Finn, J., 2008. Designing Substations for Offshore Windfarm Connections. In *CIGRE NGN NAREC*., 2008. Siemens Transmission and Distribution Ltd.

Gardner, P., 2009. *European Experience in Wind Power Grid Integration*. Beijing: Garrad Hassan & Partners Ltd.

Gardner, P., Craig, L.M. & Smith, G.J., 2008. *Electrical Systems for Offshore Wind Farms*. Glasgow, UK: Garrad Hassan & Partners.

Gatta, F.M., Geri, A., Lauria, S. & Maccioni, M., 2011. Steady-state Operating Conditions of very long EHVAC Cable Lines. *Electric Power Systems Research*, 81, pp.1525-33.

Gerdes, G., Tiedemann, A. & Zeelenberg, S., 2010. *Case Study: European Offshore Wind Farms - A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms*. Power (Pushing Offshore Wind Energy Regions).

Glover, J., Sarma, M.S. & Overbye, T.J., 2012. *Power System Analysis and Design*. 5th ed. Stamford, CT : Cengage Learning.

Grainger, J.J. & Stevenson, W.D., 1994. *Power System Analysis*. New York: McGraw-Hill.

Greedy, L., 2011. *The Application of FACTS Devices in Offshore Wind Farm Systems*. Garrad Hassan & Partners Limited.

Gudmundsdottir, U.S., Bak, C.L. & Wiechowski, W.T., 2008. *Modeling of Long High Voltage AC Underground Cables*.

Gudmundsdottir, U.S. et al., 2006. *Measurements for Validation of High Voltage Underground Cable Modelling*. IEEE.

Guo, H., Rudion, K., Heyde, C. & Styczynski, Z.A., 2011. *Stability Studies of Offshore Wind Farms*. IEEE.

Gustavsen, B., 2005. Validation of Frequency-Dependent Transmission Line Models. *IEEE Transactions on Power Delivery*, 20(2), pp.925-33.

Hanson, J. & Hunger, T., 2009. *Network Studies for Offshore Wind Farm Grid Connections - Technical Need and Commercial Optimization*. University of Applied Science Ansbach.

Johansson, S.G. et al., 2010. *AC Cable solutions for Offshore Wind Energy*. ABB Power Systems Research.

Kanitkar, R., 1988. Fundamental Concepts Of Transmssion Lines Derived From AC Theory. In *Power Transmission Technologies*.

Koller, J., Koppel, J. & Peters, W., 2006. *Offshore Wind Energy - Research on Impact Assessment*. Berlin: Springer.

Meah, K. & Ula, S., 2008. Comparative Evaluation of HVDC and HVAC Transmission Systems.

National Grid, 2006. *Voltage Limits for Planning and Operation of Offshore Transmission Networks*. Offshore Transmission Expert Group - Great Britain Security and Quality of Supply Sub-group.

National Grid, 2010. Integrated Offshore Grid Solutions. In *Renewable UK*. London, 2010. National Grid.

National Grid, 2010. *Offshore Development Information Statement*. National Grid Electricity Transmission plc.

National Grid, 2011. *National Electricity Transmission System Seven Year Statement*. National Grid plc.

National Grid, 2011. *Offshore Transmission Network Feasibility Study*. The Crown Estate.

National Grid, 2011. *UK Future Energy Scenarios*.

Negra, N.B., Todorovic, J. & Ackermann, T., 2006. Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Windfarms. *Electric Power Systems Research*, 76, pp.916-27.

Normark, B. & Nielsen, E.K., 2011. *Advanced Power Electronics for Cable Connection of Offshore Wind*. ABB Power Technologies AB, Sweden.

Offshore Standard, 2009. *Offshore Substations for Windfarms*. DNV-OS-J201.
Offshore Wind Industry Group (OWIG), 2011. *Scotland's Offshore Wind Routemap - Developing Scotland's Offshore Wind Industry to 2020*. E.ON.

Pappala, V.S., Wilch, M., Singh, S.N. & Erlich, I., 2007. Reactive Power Management in Offshore Windfarms by Adaptive PSO. In *The 14th International Conference on Intelligent System Applications to Power Systems*. Kaohsiung, Taiwan, 2007.

Piwko, R. et al., 2005. Integrating Large Wind Farms into Weak Power Grids with Long Transmission Lines. In *IEEE/PES Transmission and Distribution Conference & Exhibition: Asia & Pacific*. Dalian, China, 2005.

Ragheb, M., 2012. *High Voltage Direct Current Transmission*.

Renewable UK, 2012. *RenewableUK - How does an Offshore Windfarm work?* [Online] Available at: http://www.bwea.com/offshore/how.html [Accessed 26 July 2012].

Santjer, F., 2008. *Influence of Transmission Lines on Grid Connection*. Wilhelmshaven, Germany: DEWI GmbH Deutsches Windenergie-Institut.

Scottish Power Renewable Energy, 2012. *Windfarms - A Guide to Our Sites*. Scottish Power.

ScottishPower Renewable Energy Group, 2009. *Windfarms*. Glasgow.

Shaaban, M. et al., 2003. Calculation of Total Transfer Capability Incorporating the effect of Reactive Power. *Electric Power Systems Research*, 64, pp.181-88.

Siemens Energy, 2007. Transformers. In *Siemens Power Engineering Guide · Transmission and Distribution*. 4th ed. Siemens Energy.

Siemens Energy, 2011. *High Voltage Direct Current Transmission – Proven Technology for Power Exchange*. Siemens Energy.

Siemens Wind Power, 2012. *SWT-3.6-107 - Siemens*. [Online] Available at: http://www.energy.siemens.com/hq/en/power-generation/renewables/wind-power/wind-turbines/swt-3-6-107.htm#content=Design [Accessed 27 July 2012].

SVOMA, R., DICKINSON, M. & BROWN, C., 2007. Subsea Connections to High Capacity Offshore Windfarms: Issues to Consider. In *19th International Conference on Electricity Distribution*. Vienna, 2007. CIRED.

Tenti, P., Mattavelli, P. & Tedeschi, E., 2007. Compensation Techniques Based on Reactive Power Conservation. *Electrical power Quality and Utilisation*, XIII(1), pp.17-24.

The Crown Estate, 2011. *A Guide to an Offshore Windfarm*. London: The Crown Estate.

The Crown Estate, 2011. *Round 3 Offshore Wind Farm Connection Study*. The Crown Estate.

The Crown Estate, 2012. *Submarine Cables and Offshore Renewable Energy Installations*. London: The Crown Estate.

The Crown Estate, 2012. *UK Offshore Wind Report 2012*. The Crown Estate.

The Scottish Government, 2010. *Scottish Planning Policy*. Edinburgh: Crown Copyright.

The Scottish Government, 2011. *2020 Routemap for Renewable Energy in Scotland*. Edinburgh.

The Scottish Government, 2011. *Marine Scotland*. Edinburgh: BLUE SEAS - GREEN ENERGY.

Trakadas, P.T. & Capsalis, C.N., 2001. Validation of a Modified FDTD Method on Non-Uniform Transmission Lines. *Progress In Electromagnetics Research*, 31, pp.311-29.

Tricas, T. & Gill, A., 2011. *Effects of EMFs from Undersea Power Cables on Elasmobranchs and other Marine Species*. U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement, Pacific OCS Region.

Valov, B., 2009. Transformers for Offshore Wind Platforms: Expected Problems and Possible Approaches. In *8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms*. Bremen, Germany, 2009.

Vargas, J., Guzmán, A. & Robles, J., 2010. *Underground/Submarine Cable Protection using a Negative Sequence Directional Comparison Scheme*.

Vella, G., 2010. The Environmental Implications of Offshore Wind Generation. *White Paper*.

Wiechowski, W. & Eriksen, P.B., 2008. *Selected Studies on Offshore Wind Farm Cable Connections - Challenges and Experience of the Danish TSO*. IEEE.

Wilch, M., Pappala, V.S., Singh, S.N. & Erlich, I., 2009. Reactive Power Generation by DFIG Based Wind Farms with AC Grid Connection., 2009.

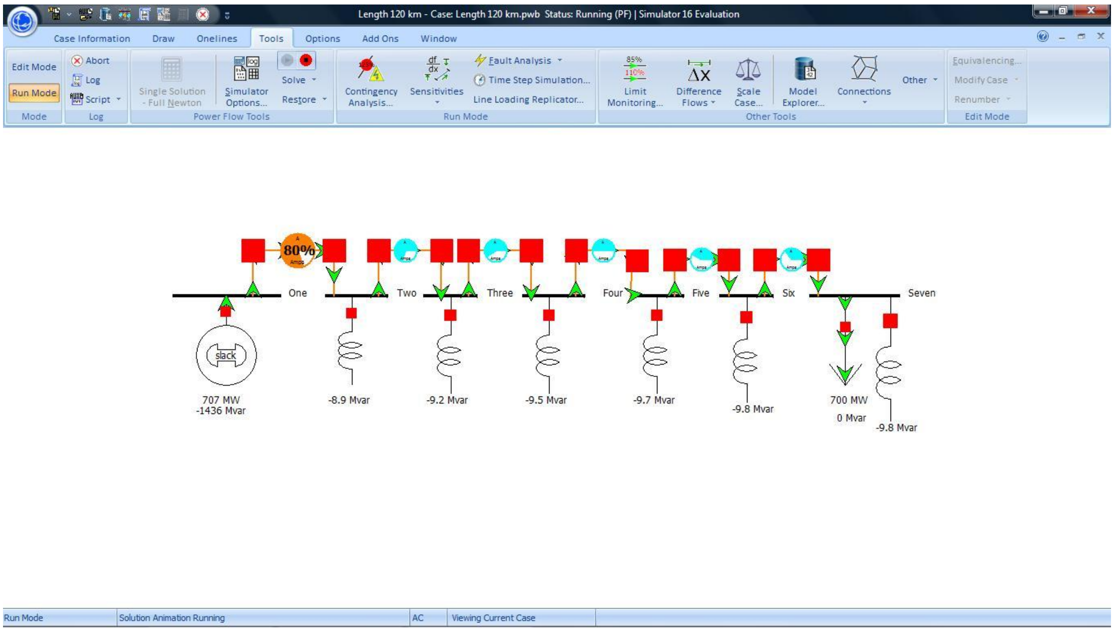
Worzyk, T., 2009. *Submarine Power Cables - Design, Installation, Repair, Environmental Aspects*. Rodeby: Springer.

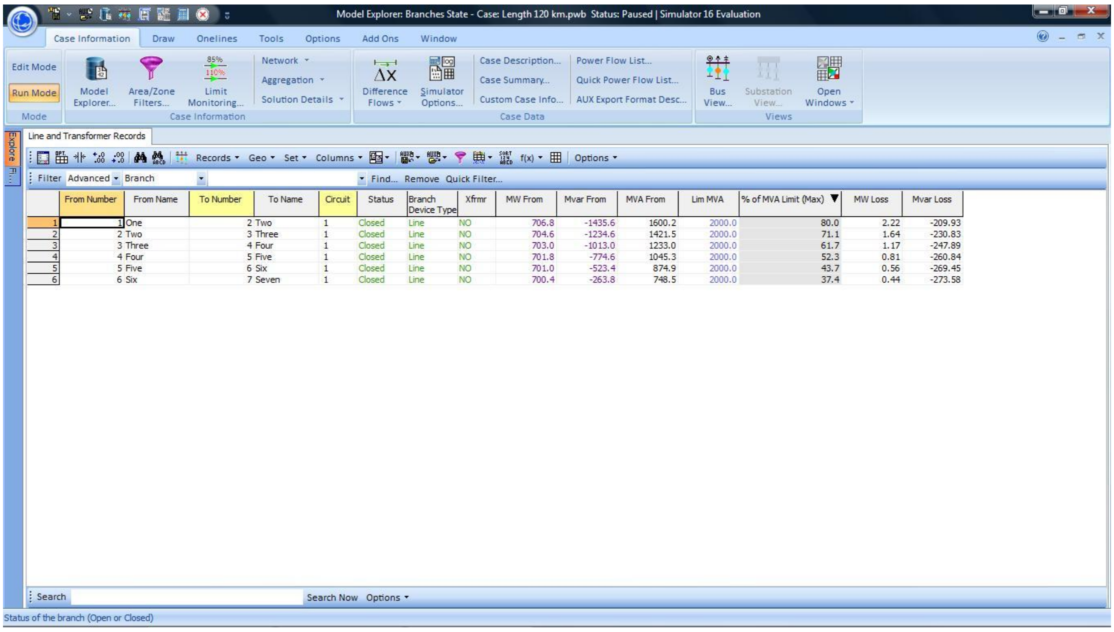
Wright, S.D., Rogers, A.L., Manwell, J.F. & Ellis, A., 2002. *Transmission Options For Offshore Wind Farms in the United States*. Amherst, USA: AWEA University of Massachusetts.

Yuang, H., 2005. *Electromagnetic Simulations of 135 kV Three-Phase Submarine Power Cables*. The University of Liverpool.

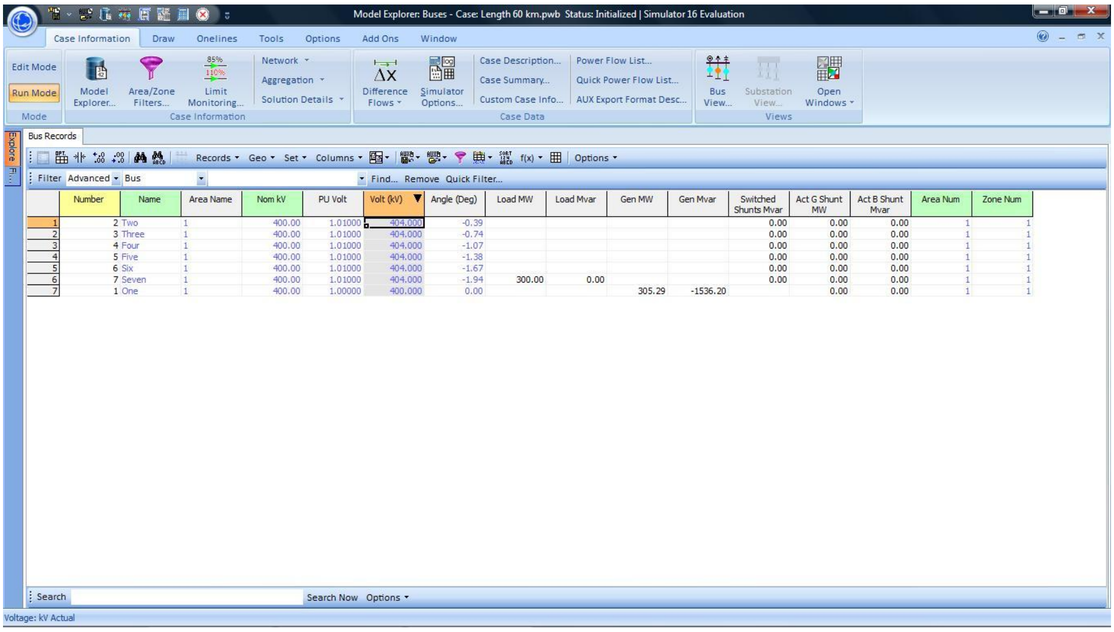
9.0 Appendices

9.1 Appendix I: PowerWorld Simulator Model





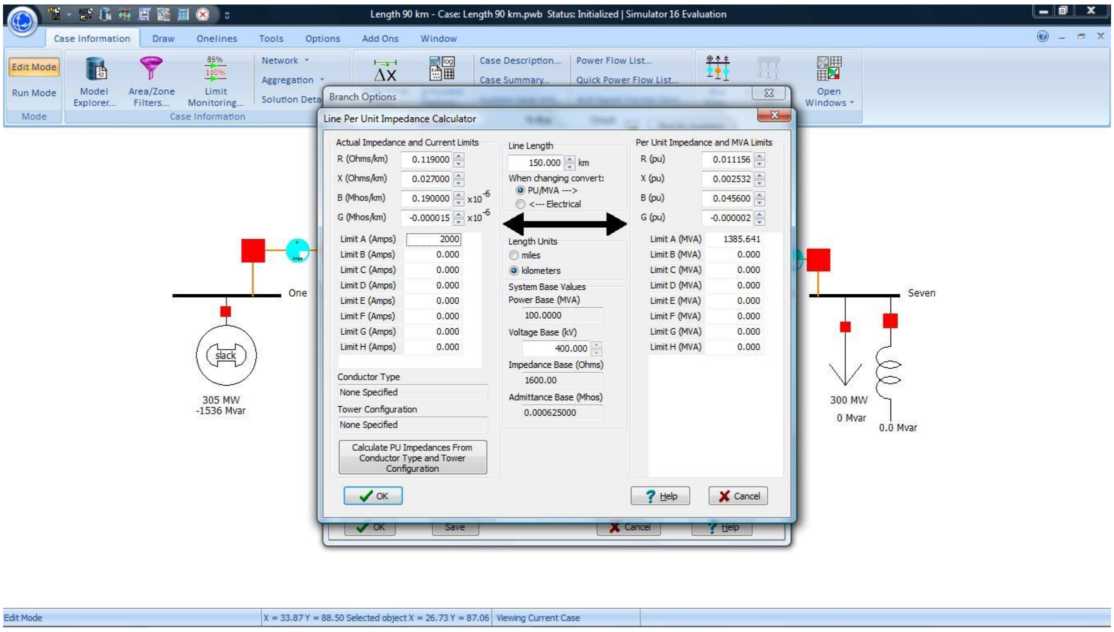
	From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	1	One	2	Two	1	Closed	Line	NO	706.8	-1435.6	1600.2	2000.0	80.0	2.22	-209.93
2	2	Two	3	Three	1	Closed	Line	NO	704.6	-1234.6	1421.5	2000.0	71.1	1.64	-230.83
3	3	Three	4	Four	1	Closed	Line	NO	703.0	-1013.0	1233.0	2000.0	61.7	1.17	-247.89
4	4	Four	5	Five	1	Closed	Line	NO	701.8	-774.6	1045.3	2000.0	52.3	0.81	-260.84
5	5	Five	6	Six	1	Closed	Line	NO	701.0	-523.4	874.9	2000.0	43.7	0.56	-269.45
6	6	Six	7	Seven	1	Closed	Line	NO	700.4	-263.8	748.5	2000.0	37.4	0.44	-273.58



Model Explorer: Buses - Case: Length 60 km.pwb Status: Initialized | Simulator 16 Evaluation

	Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num	Zone Num
1	2	Two	1	400.00	1.01000	404.000	-0.39					0.00	0.00	0.00	1	1
2	3	Three	1	400.00	1.01000	404.000	-0.74					0.00	0.00	0.00	1	1
3	4	Four	1	400.00	1.01000	404.000	-1.07					0.00	0.00	0.00	1	1
4	5	Five	1	400.00	1.01000	404.000	-1.38					0.00	0.00	0.00	1	1
5	6	Six	1	400.00	1.01000	404.000	-1.67					0.00	0.00	0.00	1	1
6	7	Seven	1	400.00	1.01000	404.000	-1.94	300.00	0.00			0.00	0.00	0.00	1	1
7	1	One	1	400.00	1.00000	400.000	0.00			305.29	-1536.20		0.00	0.00	1	1

Voltage: kV Actual



Length 90 km - Case: Length 90 km.pwb Status: Initialized | Simulator 16 Evaluation

Line Per Unit Impedance Calculator

Actual Impedance and Current Limits

R (Ohms/km) 0.119000
X (Ohms/km) 0.027000
B (Mhos/km) 0.190000 $\times 10^{-6}$
G (Mhos/km) -0.000015 $\times 10^{-6}$
Limit A (Amps) 2000
Limit B (Amps) 0.000
Limit C (Amps) 0.000
Limit D (Amps) 0.000
Limit E (Amps) 0.000
Limit F (Amps) 0.000
Limit G (Amps) 0.000
Limit H (Amps) 0.000

Conductor Type
None Specified
Tower Configuration
None Specified

Calculate PU Impedances From Conductor Type and Tower Configuration

Line Length
150.000 km
When changing convert:
● PU/MVA --->
○ <--- Electrical

Length Units
○ miles
● kilometers

System Base Values
Power Base (MVA) 100.0000
Voltage Base (kV) 400.000
Impedance Base (Ohms) 1600.00
Admittance Base (Mhos) 0.000625000

Per Unit Impedance and MVA Limits

R (pu) 0.011156
X (pu) 0.002532
B (pu) 0.045600
G (pu) -0.000002
Limit A (MVA) 1385.641
Limit B (MVA) 0.000
Limit C (MVA) 0.000
Limit D (MVA) 0.000
Limit E (MVA) 0.000
Limit F (MVA) 0.000
Limit G (MVA) 0.000
Limit H (MVA) 0.000

OK Help Cancel

Edit Mode | X = 33.87 Y = 88.50 Selected object X = 26.73 Y = 87.06 | Viewing Current Case

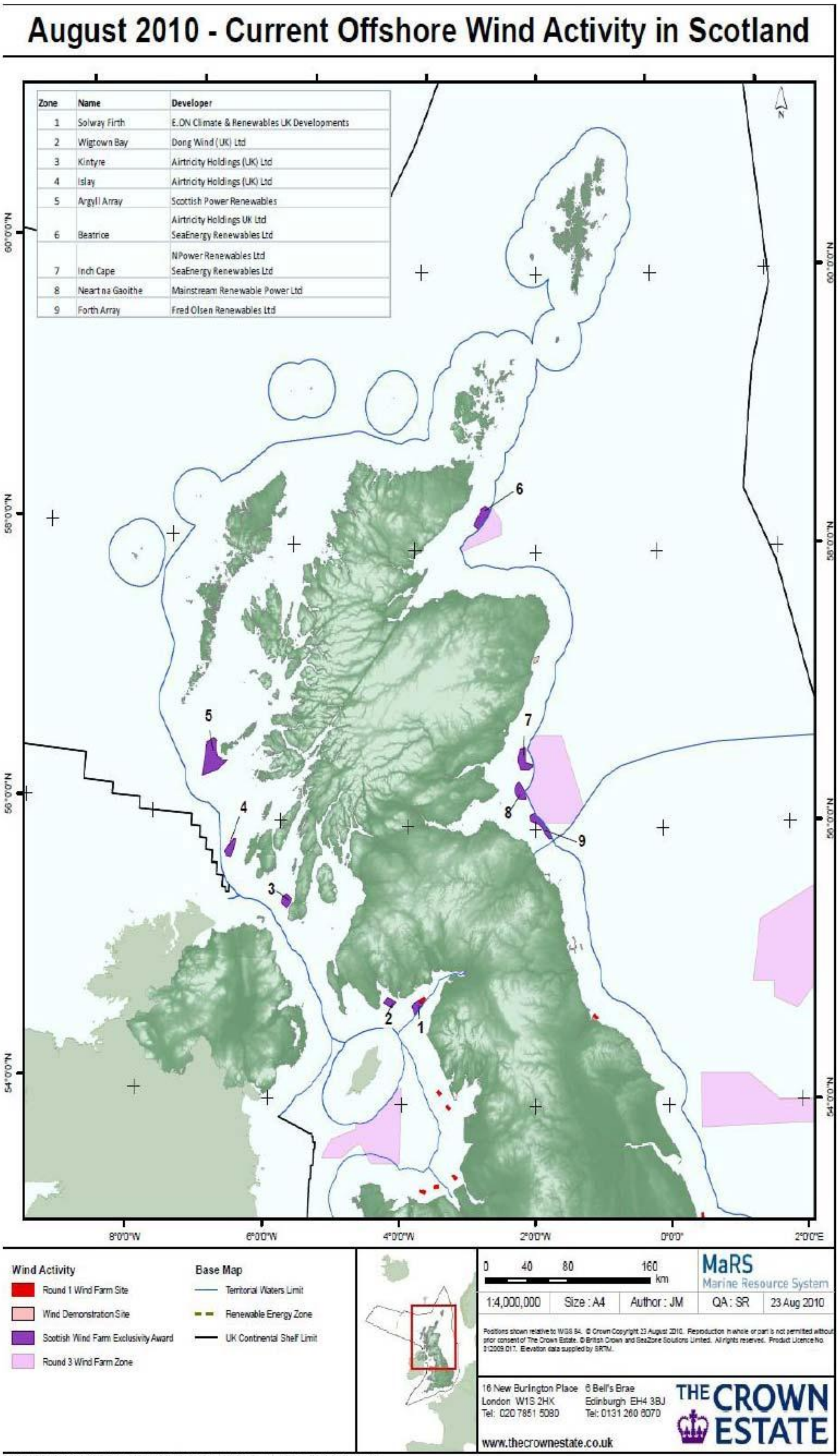
b

9.2 Appendix II: List of Available Documents

A list of publicly available documents on offshore wind power in the UK is as under.

Title of Document	Published by
2020 Routemap for Renewable Energy in Scotland	The Scottish Government
Energy Act 2011	Department of Energy & Climate Change
Marine Scotland – A Sectorial Marine Plan for Offshore Wind Energy in Scottish Territorial Waters	The Scottish Government
National Electricity Transmission System – Seven Year Statement	National Grid
Offshore Transmission Network Feasibility Study	The Crown Estate
Round 3 Offshore Windfarm Connection Study	National Grid
Scotland's Offshore Wind Routemap – Developing Scotlan's Offshore Wind Industry to 2020	The Scottish Government
Scottish Planning Policy	The Scottish Government
The UK Renewable Energy Strategy	HM Government
UK Future Energy Scenarios	National Grid
UK Offshore Wind Report 2012	The Crown Estate
UK Renewable Energy Roadmap	Department of Energy & Climate Change

9.3 Appendix III: Map of Offshore Windfarm Sites in Scotland



August 2010 - Current Offshore Wind Activity in Scotland

Zone	Name	Developer
1	Solway Firth	E.ON Climate & Renewables UK Developments
2	Wigtown Bay	Dong Wind (UK) Ltd
3	Kintyre	Airtricity Holdings (UK) Ltd
4	Islay	Airtricity Holdings (UK) Ltd
5	Argyll Array	Scottish Power Renewables
6	Beatrice	Airtricity Holdings UK Ltd SeaEnergy Renewables Ltd
7	Inch Cape	NPower Renewables Ltd SeaEnergy Renewables Ltd
8	Neart na Gaoithe	Mainstream Renewable Power Ltd
9	Forth Array	Fred Olsen Renewables Ltd

1:4,000,000	Size : A4	Author : JM	QA : SR	23 Aug 2010

Positions shown relative to WGS 84. © Crown Copyright 23 August 2010. Reproduction in whole or part is not permitted without prior consent of The Crown Estate. © British Crown and SeaZone Solutions Limited. All rights reserved. Product Licence No. 012009.017. Elevation data supplied by SRTM.

16 New Burlington Place
London W1S 2HK
Tel: 020 7851 5080

6 Bell's Brae
Edinburgh EH4 3BJ
Tel: 0131 260 6070

www.thecrownestate.co.uk

S:\MARINE\Restricted\MaRS\GIS\Admin\Presentation\Map Library\MXD\2 Current Offshore Wind Scotland.mxd