Electrical System Design for the Proposed One Gigawatt Beatrice Offshore Wind Farm

A dissertation presented in fulfilment of the
requirements for the degree of Master of Science
Energy Systems and the Environment

Roy Maclean
September 2004

Faculty of Engineering
University of Strathclyde

DECLARATION OF AUTHOR’S RIGHTS

The copyright of this dissertation belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.49. Due acknowledgement must always be made of the use of any material contained in, or derived from, this dissertation.

ABSTRACT

This project looked at the proposed one gigawatt Beatrice offshore wind farm (OWF) in Scotland and considered some of the different ways of optimising electrical power transmission within the farm and to shore. In particular, it focused on identifying the electrical flow of power along the individual cables that inter-connected each wind turbine and transferred electricity to the mainland.

The physical arrangement of the OWF was selected according to criteria later described. Then a suitable electrical collection system was designed. Three different electrical designs for the OWF transmission system were researched and developed: two utilising alternating current (AC) transmission technology; and one direct current (DC) transmission technology. The operational characteristics of each design were determined on results obtain from modelling the designs on computer. The computer models were designed using the power system simulator tool, PSS/E^{TM}. Each model provided the voltages, currents and losses present in the main electrical cables and buses present in each wind farm design.

As part of the project a literary review on OWFs - their importance, usage, their components, and in particular, their electrical characteristics - was carried out. A study on PSS/E^{TM} programming techniques and operations was also completed.

Electrical simulations using fixed speed and variable speed turbine generators were conducted. The results showed that the voltage drop and current flow within the collection system were well within acceptable limits but there was a higher than expected voltage in the turbine and Beatrice buses when AC transmission was employed. The simulations of different transmission techniques showed that DC transmission had smaller overall losses than AC, however DC requires a very large amount of compensate reactive power to operate.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor Dr. Graham Ault for his insight and encouragement throughout the course of this dissertation.

I am grateful to Mr. Colin Foote, PhD student for his assistance with PSS/E$^{\text{TM}}$ and the elusive “dongles”.

I also thank all my lecturers and colleagues from the Energy Systems and the Environment MSc for helping to make this course so enjoyable.

Finally, I give special thanks to my parents and Anna. Without your support, I would not have been able to complete this degree.

TABLE OF CONTENTS

CHAPTER ONE ? INTRODUCTION

CHAPTER TWO ? OFFSHORE WIND FARM ELECTRICAL SYSTEM: BACKGROUND THEORY AND APPLICATIONS

CHAPTER THREE - THE BEATRICE OFFSHORE WIND FARM PROJECT

CHAPTER FOUR - POWER FLOW SIMULATION OF BEATRICE OFFSHORE ELECTRICAL SYSTEM

CHAPTER FIVE - ELECTRICAL PERFORMANCE OF OFFSHORE WIND FARM AND DESIGN RECOMMENDATIONS

CHAPTER SIX - CONCLUDING REMARKS

APPENDIX A

APPENDIX B

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	alternating current
CSA	cross-sectional area
DC	direct current
DFIG	doubly-fed induction generator
DOWNViND	distant offshore wind farms with no visual impact in deepwater
EPR	ethylene propylene rubber
HV	high-voltage
HVDC	high-voltage direct current
IG	induction generator
IGBT	isolated gate bipolar thyristors
IRC	integrated return conductor
OWF	offshore wind farm
ROV	remotely operated vehicle
SCADA	supervisory control and data acquisition
SSE	Scottish and Southern Energy
VSC	voltage sourced converter
XLPE	cross-linked polyethylene

CHAPTER ONE

INTRODUCTION

1.1 Aim

The main goal of this project was to find the optimum electrical arrangement for the proposed 1 GW Beatrice OWF. Specifically, this project focused on the electrical power flow associated with the interconnection of wind turbines and the transportation of electricity to the high voltage (HV) grid onshore. Concepts employing both AC and DC transmission techniques were considered for the sea to shore connection. The project aimed to examine a number of different electrical transmission configurations using the power system simulator PSS/E^{TM} to model each design. Suitable voltage levels, cable properties and transformer configurations could then be deduced and recommendations given regarding the benefits of AC and DC transmission.

1.2 Motivation

In recent times, the business of electrical power generation has changed irrevocably. The main drivers for change have been international agreement to tackle "greenhouse gases" and reduce carbon emissions; and securing future energy supplies. The UK government believes that wind power, particularly offshore wind power, will play a leading role in helping to establish a secure and environmentally sustainable method of meeting our electricity needs. Furthermore, the Scottish Executive consider large OWFs, such as the Beatrice wind farm, key to meeting its target for 18% of electricity generation in Scotland to be sourced from renewables by 2010 [1].

OWFs are attractive because, firstly they do not have the same noise and visual impact that restrict their onshore counterparts; and secondly the wind speeds offshore are higher than those found on land so the turbines are turning and generating electricity for more of the time. However, the more hostile environment means that both the equipment and connection to the grid network is more expensive and so OWFs have thus far only been built in shallow water close to shore. The challenge of siting wind turbines in water up to 50 m deep and 25 km from the shore, as is the case with the Beatrice, is new. Development of dedicated offshore concepts is essential to reduce costs and make OWF proposals like the Beatrice more practicable. In particular, the process of designing the electrical arrangement of very large offshore wind farms (500 MW plus) has still to be clearly defined. As such, designing an effective electrical system for the proposed Beatrice OWF is the principal aim of this research.

1.3 Proposed approach

The nature of this project is to find the optimum electrical arrangement for the Beatrice OWF through computer simulation and examination of recent research.

An in-depth literature review using conference proceedings, papers, journals and websites was carried out to assess the current level of knowledge on the electrical aspects of large OWFs. The particular topics of interest were turbine generators; subsea cable properties; transformers; AC and DC technology; voltage levels within OWFs; the physical layout of turbines and the corresponding effects on cabling; the need for redundancy and offshore substations. Section 2.4 describes the main findings of the review and lists the most important texts.

In order to analyse different OWF electrical configurations the geographic layout of the site was devised. Thereafter, electrical generators, transformers and cables were selected to form the “collection” system of the OWF. Three different transmission opinions were than compared, each using the same collection system. All the models used two hundred 5 MW turbine generators to simulate the 1 GW output of the farm. For each design the electrical cabling, transformers and generator data was based on manufacturers’ specifications. Each option was modelled using PSS/E^{TM} in the “Institute for Energy and Environment” department of the University of Strathclyde. The models were used to calculate the power flow within the wind farm and in the connection to shore of each different design.

1.4 Organisation of this dissertation

The remaining portion of this dissertation is organised as follows:

CHAPTER TWO: OFFSHORE WIND FARM ELECTRICAL SYSTEMS BACKGROUND THEORY AND APPLICATIONS. In chapter two the main electrical systems within OWFs and the technology behind the transmission of power to shore are covered. A section on the review of literature is also presented.

CHAPTER THREE: THE BEATRICE OFFSHORE WIND FARM PROJECT. Chapter three discusses the Beatrice oilfield in the Moray Firth followed by the Beatrice two turbine demonstrator project. The majority of the chapter describes how the proposed full-scale OWF could be laid out and determines a geographic plan for the site.

CHAPTER FOUR: POWER FLOW SIMULATION OF BEATRICE OFFSHORE ELECTRICAL SYSTEM. In chapter four, the selection process for the electrical equipment within the collection and transmission area of the OWF is discussed. Three electrical transmission options are outlined, two AC systems and one DC system.

CHAPTER FIVE: ELECTRICAL PERFORMANCE OF OFFSHORE WIND FARM AND DESIGN RECOMMENDATIONS. In chapter five, the electrical performance of three different transmission configurations is discussed. For the power flow analysis PSS/E^{TM} Raw data files were written, each of which is given in full in Appendix B.

CHAPTER SIX: CONCLUDING REMARKS. Chapter six summarises the dissertation and draws conclusions on the project. It finishes with recommendations for future work.

APPENDIXES. The appendixes are:

A Main PSS/E^{TM} values for Beatrice OWF electrical system
B Raw Data Files

CHAPTER TWO

OFFSHORE WIND FARM ELECTRICAL SYSTEMS: BACKGROUND THEORY AND APPLICATIONS

2.1 Introduction

The function of a wind turbine is to generate electricity. A number of electrical and power systems engineering related topics are thus directly linked with OWFs. These include electrical generators, active and reactive power, transformers, transmission of electrical energy and protection systems.

This chapter will review the electrical components present within OWFs, and discuss the technologies employed when transmitting power to the mainland. The purpose of this chapter is to familiarise the reader with the equipment and terminology described in subsequent chapters. A detailed literature review of current research and development of OWFs was carried out for this dissertation. In the final section of this chapter the reasoning behind the importance of reviewing available literature and some of the most relevant findings are given.

2.2 Electrical systems within offshore wind farms

The electrical power system within a wind farm concerns the electrical components between each wind turbine, and, where present, an offshore hub, and the way these components are interconnected and operated. This region of an OWF is known as the collection system and comprises of amongst other things generators, transformers, power cables, switchgear and offshore substations. Each will be discussed below.

2.2.1 Wind turbine generators

Wind turbine generators fall into two main categories; those that operate at a fixed speed and those that run at variable speed. Fixed speed generators, as the name suggests, essentially run at a constant mechanical speed and are typically high efficiency squirrel-cage induction generators (IG). Speed variations on these units are typically less than 1% [2]. Variable speed wind turbine generators commonly use doubly-fed induction generators (DFIG) but can also employ converter-driven synchronous generators.

Induction (or asynchronous) machines were seldom employed as generators until the advent of distributed generation in the mid 1970s [3]. They are now the most common type of generator found in wind turbines. They are popular because they have a simple, tough construction, are relatively low-priced and may be connected and disconnected from the electrical grid network relatively simply. Fig. 2.1 shows how an IG can be configured for wind turbine use.

IGs require an external source of reactive power. Reactive power is important because it establishes and sustains the AC electric and magnetic fields that allow these machines to operate. They also require an external constant frequency source to control the speed of rotation. For these reasons, they are most commonly connected to large electrical networks where they are supported by synchronous generators that set the frequency and supply the required reactive power. In addition, to compensate for the fact that they absorb reactive power, capacitors are frequently connected to the machine at or near the point of connection to the electrical network.

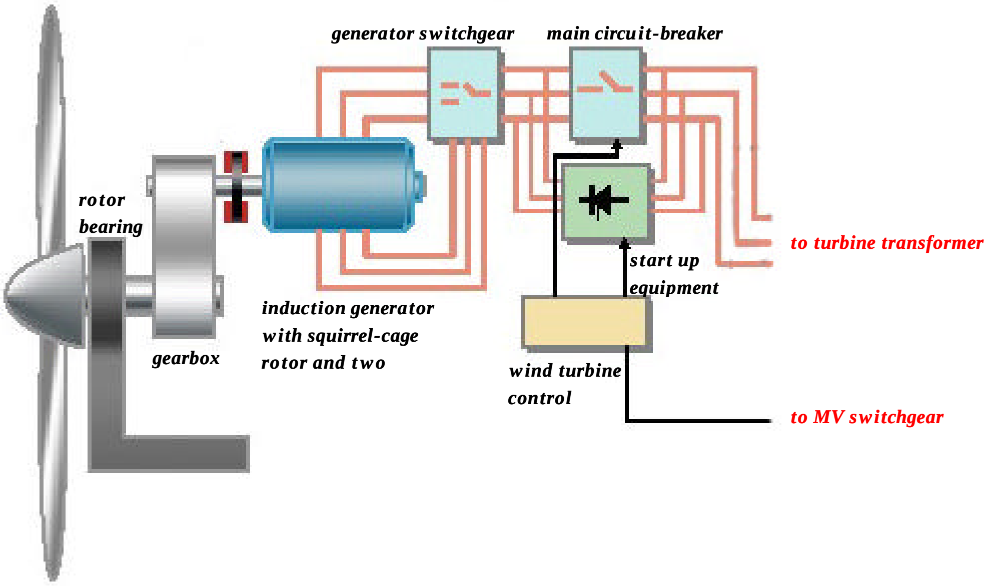


Figure 2.1 Induction generator wind turbine configuration [4]

DFIGs are an enhanced version of the IG achieved by use of a wound rotor and converter based rotor-winding controller. They are referred to as doubly-fed because power may be sent to or taken from the rotor, as well as from the stator (see Fig. 2.2). The design employs a series voltage source converter to feed the wound rotor of the machine. Such converters work by varying the frequency of the AC supply at the terminals of the generators. Operating the rotor circuit at a variable AC frequency controls the mechanical speed of the machine. Compared to their fixed speed counterparts, the variable speed designs such as the DFIG are more efficient and capture more wind energy by varying the speed of the machine with wind speed. These designs also have better power quality; by storing the energy contained within a gust of wind, the power output of the unit is kept relatively constant. In addition, these machines can also produce or absorb reactive power.

DFIGs are more expensive and less rugged than those generators with squirrel-cage rotors. For example, the two DFIGs used at the UK's first OWF, at Blyth in Northumberland both failed due to winding overheating and had to be replaced within 4 years of operation [5]. However, because they supply reactive power and allow increased energy yield at low wind speeds, for turbines rated higher than 1 MW, DFIG are now the most commonly used machine.

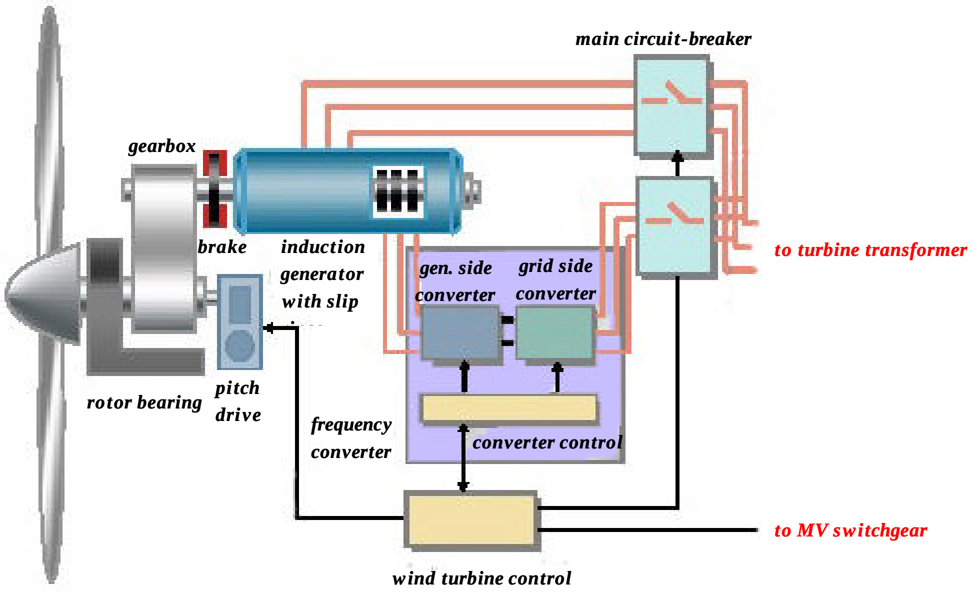


Figure 2.2 Doubly-fed induction generator wind turbine configuration [4]

2.2.2 *Transformers*

Modern wind turbines typically generate power at low-voltage, usually 690 V. To minimise the power losses associated with low-voltage, high-current transmission, this voltage is raised to a higher level. This allows much smaller and less expensive cable conductors to be used. To facilitate this “stepping-up” of voltage, turbine voltage transformers are employed. Depending on the ratio between the generator voltage and transmission voltage to shore, it may be necessary to step-up the voltage at least once. The voltage levels within a wind farm depend on the distances between generators and transformers and between each turbine. Selecting the voltage level is always a trade off between equipment cost and power losses. Choosing a high voltage will minimise cable conductor size, losses and voltage drop. On the other hand, the application of high-voltage equipment is expensive because of the extra costs of space and insulation.

The transformers may be either inherently 3-phase, or may be three single-phase transformers connected together to form a 3-phase transformer bank as illustrated in Fig. 2.3. Transformers are rated in terms of their apparent power (VA). For wind turbine applications, generator transformers are typically rated 105% to 125% of the generator rated active power. For example, the 2 MW turbine generators used at North Hoyle used transformers rated at 2100 kVA [6]. Just like an IG, transformers need reactive power. In a typical transformer, the consumption of reactive power at full load is approximately 6% of the rated power [7].

Figure 2.3 A cast resin transformer designed specifically for wind power applications [4]

Many modern wind turbines come with a transformer installed in the tower base. In others, such as Vestas V80 and V90 models the transformer is located in the turbine nacelle (see Fig. 2.4). The advantage of this arrangement is it means the transformer is physically very near the generator, thus helping to reduce power (I^2R) losses.

One of the major concerns regarding offshore turbine transformers is their reliability. Horns Rev OWF began to experience turbine transformer failures shortly after commercial operation began in the summer 2003. A combination of manufacturing problems and the weather conditions offshore meant that by the winter of 2003 some 20% to 30% of the transformers had failed [5]. It is believed that the components were not insulated correctly, which led to short-circuits. With a fifth of the turbines affected in the first year, the wind farm owners - the Danish utility company Elsam - was forced to change every single transformer in all 80 turbines.

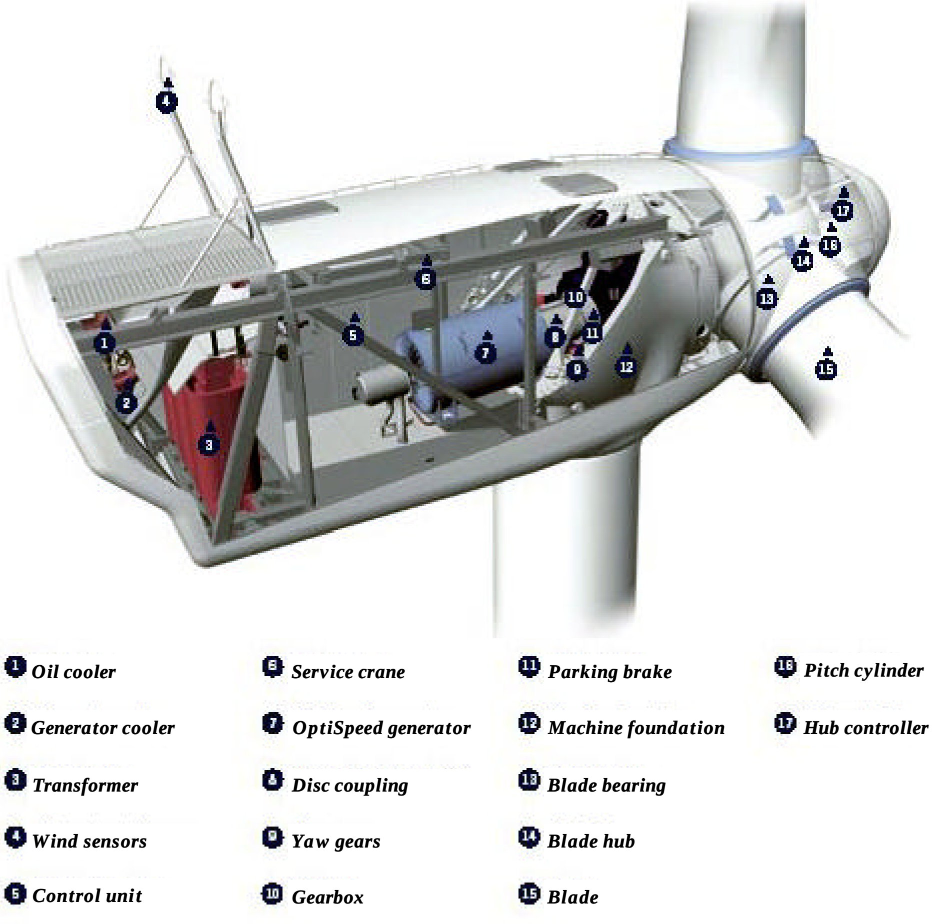


Figure 2.4 Diagram of the Vestas V90 - 3 MW turbine [8]

2.2.3 Power cables

Within a wind farm, the electrical power must be transferred from the turbine generator transformer to switchgear at the tower base. Power must also be transmitted to other turbines in the farm and then, in the case of Beatrice OWF, to an offshore hub. From here, the total power can be transmitted to shore by means of HVAC or HVDC submarine cables (HVAC and HVDC cable technology will be dealt with in detail in Section 2.3). Designing the cable array of an OWF requires careful attention to numerous technical and economic issues including: transmission voltage; power losses; cable electrical characteristics; cable burial technologies; service intervals/repairs and cost.

For the relatively short distance between turbines, medium-voltage (typically 2.4 kV to 69 kV) AC cables are employed. The voltage levels employed so far have been limited to 33 kV, because both switchgear and transformer size and cost increase rapidly above this value [9]. The cable conductors are normally of copper or less commonly aluminium, which has a lower current-carrying capacity and so requires a larger diameter. The two most common subsea cable insulation technologies are cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) and are shown in Fig. 2.5. Both have now all but replaced the older oil-filled paper insulated submarine cables because of their far superior electrical and mechanical characteristics.

Figure 2.5 MV submarine cables [10]

XLPE is in widespread use on land (and is therefore cheaper) but needs a moisture barrier under water. EPR insulation has the advantage that no metal sheath is required and the cables can be of "wet" construction [11]. EPR has similar properties to XLPE at lower voltages, but at 69 kV and above, has higher capacitance [12]. The thickness of cable insulation increases with the voltage rating, while the conductor cross-section increases with the current rating. Submarine cable can also come complete with integrated fibre optics to provide communications links for any control systems.

The greatest hazards to subsea cables come from anchors and fishing [3]. The most cost-effective solution to these problems is to find a cable route that avoids fishing and anchoring areas. Cable burial is another possible solution, for example the original Mull-Coll submarine cable suffered repeated damage due to clam dredgers and so SSE chose to bury its replacement [13]. Cables may also need to be buried to avoid wave action, and where abrasion on rock is a problem, armoured cable may be needed. There are many types of burial machines including towed, free-swimming and tracked remotely operated vehicles (ROV). Fig. 2.6 shows the cable laying vessel used at Horns Rev OWF. The choice of cable laying and burial method depends upon the length of the run, water depth, seabed characteristics and equipment available. A good cable layout will require an assessment and survey of the route and consider how any damaged section of cable can be easily located and economically repaired.

Figure 2.6 Photo of one of the ships used to bury the subsea cables at Horns Rev OWF [14]

2.2.4 Switchgear and protection equipment

Switchgear, as defined by the IEE wiring regulations, are *"an assembly of main and auxiliary switching apparatus for the operation, regulation, protection or other control of an electrical installation"* [15]. Major electrical components include circuit-breakers, protection relays, meters, control switches, fuses, motor control centres and both current and voltage transformers.

Switchgear can be present in each individual turbine as in Fig. 2.7, on offshore substations to control clusters of turbines or onshore to control the entire farm. Switchgear within each turbine must be small to fit into the limited space in the tower but still have sufficient capacity to accommodate a chosen cable size. Furthermore, the special circumstances that apply offshore, such as tight limits on weight, fewer opportunities for maintenance and a more corrosive atmosphere mean that switchgear is different to conventional gear on land and must be designed specifically for OWF applications.

Figure 2.7 Photo of cables terminated to switchgear within a turbine tower [14]

A turbine switchgear arrangement based on the North Hoyle OWF is shown in Fig. 2.8. In this case, the offshore switchgear for each wind turbine consisted of a ring main unit arrangement installed in each tower base [6]. The cables running between each turbine are terminated at the switchgear on switch disconnectors, whilst flexible cable connecting the turbine transformer to the switchgear is terminated onto a circuit-breaker. The turbine transformers and cables were protected by over-current and earth-fault relays installed in the circuit-breaker in the tower ring main unit. A fault in any of the wind farm submarine cable network would be detected by directional overcurrent/earth fault protection installed on the onshore circuit-breakers. All cable disconnectors were fitted with motor mechanisms and capable of being remotely operated from shore via a Supervisory Control And Data Acquisition (SCADA) system.

The role of protection equipment is to detect an electrical fault and isolate the equipment in which the fault occurs, leaving as much of the healthy equipment connected as possible. It is therefore very important that the rating and operation of protection equipment should always be co-ordinated with that of other local equipment to ensure that equipment is properly protected and only isolated when necessary.

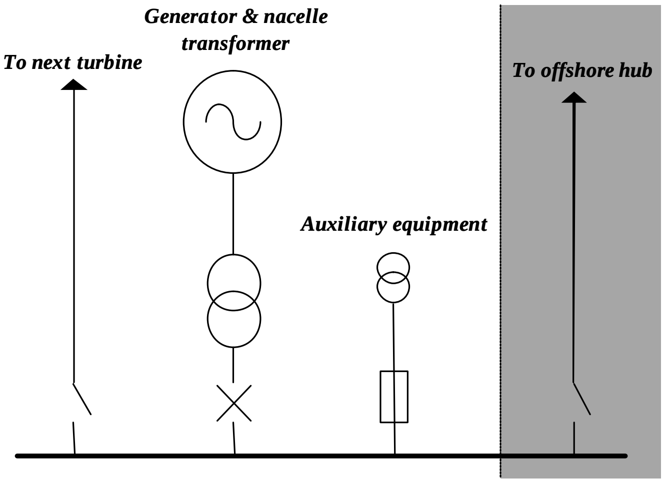


Figure 2.8 A simplified diagram of the turbine switchgear arrangement at North Hoyle wind farm

2.2.5 Offshore substations

For large OWFs long distances offshore, there is a need to use higher transmission voltages to reduce cable costs and power losses. This means that a method of housing transformers, switchgear and support structure near a farm is necessary. These structures are termed offshore substations or offshore hubs. The Beatrice OWF is unique in that the infrastructure to house the electrical equipment already exists in the form of the Beatrice Alpha oil platform and therefore in this case, there is no need to construct a new substation.

For the Horns Rev OWF a purpose-built offshore platform was constructed near the wind turbines and is shown in Fig. 2.9. The substation module contains the main 34/165 kV transformer; the 150 kV, 34 kV and communication systems and the low voltage distribution system [16]. It also possesses a helicopter deck. All systems are containerised and there are also containers for service personnel. A diesel generator is installed on the platform to provide a back-up supply to essential equipment if, for example, there is no wind.

Other offshore substation options include having several small hubs, each one having a number of turbines connected to it and a separate connection to shore.

Figure 2.9 A photo of the transformer substation module at Horns Rev OWF [14]

Alternatively, locating substations on the seabed is another option. Similar technology has been successfully applied to the oil and gas industry for some years. However, the power and voltage levels would be much higher for an OWF than an oil and gas application. Also, as with any subsea structure the risk of damage from shipping, maintenance access and costs could cause problems and require careful consideration.

If HVDC transmission were employed, the substations would also need to hold AC to DC converter equipment (see Fig. 2.10). This option has yet to be tried in practice and may only be financially viable for large wind farms situated several tens of kilometres offshore.

Due to the limited space offshore, all equipment should be as compact as possible, thus reducing the overall unit size. Furthermore, the extremely harsh and variable environment with constant exposure to high winds, salt air and water requires equipment to be either located indoors or in sealed enclosures. This means equipment should be as durable as possible with long maintenance intervals or preferably no maintenance at all. The demand for high reliability means that redundancy should be included in critical areas. There may need to be extensive use of automation, with remote control and monitoring of as much of the offshore plant as possible, using remote diagnostics.

Figure 2.10 An artist's impression of an offshore HVDC converter module [17]

2.3 Transmission of power to shore

The electrical power generated by an OWF must be carried to shore in such a way as to minimise cable costs and power losses. The most efficient means of power transfer is at high voltage. The two options for HV transmission are HVAC and HVDC. These will be explained below.

2.3.1 HVAC transmission

At the present time, all OWF have transmitted their power to shore via AC connections. AC cable systems are well understood, established technology and are currently the most cost-effective transmission method for voltages below 175 kV [12]. The highest voltage level for a three-core XLPE submarine cable in existence is 170 kV in the 21 km long 630 mm^2 cable linking the Horns Rev OWF to the Danish mainland (see Fig. 2.11).

This level could potentially go up as high as 245 kV by employing a slightly larger insulation thickness [18]. At present, this represents the maximum realistic voltage limit because beyond this level the cable size would be so great that the production, handling and transportation would be impractical.

- ***copper conductors with water blocking compound***
- ***XLPE insulation***
- ***insulation screen***
- ***lead sheath on each core***
- ***fibre optic element***
- ***filler elements***
- ***galvanised steel wire armour***
- ***outer corrosion protection***

Figure 2.11 The 3-core 150 kV a.c. submarine cable used at Horns Rev OWF [10]

AC systems have higher losses than DC. This is due to reactive elements' losses, skin effects, harmonic losses and other losses typical to AC. The main losses in AC cables are ohmic losses in the current-carrying conductors. The time varying magnetic field in the conductor causes an uneven distribution of the current in the conductor, and the magnetic fields from the nearby conductors reinforce this. The magnetic fields also induce currents in all metallic layers in the cable. As protective armour wire is present within most HV submarine cables this gives rise to considerable losses. The severity of the losses varies depending on the number of cable conductor cores. In single core cables, the current in the conductor will induce a return current in the armour creating power losses. If copper wire armour is used the losses will be lower than with steel wire armour due to better conductivity, but the cable cost will increase. In a 3-core cable with balanced load no circulating currents are induced in the armour, so steel wire armour is the most cost effective choice [19].

HVAC transmission also involves high dielectric losses, i.e. the insulation materials act as a capacitor. For long AC cables, a large part of their current-carrying capacity is used for capacitive-charging current, so less active power can be transferred to the grid onshore. The capacitance of a cable limits AC power transmission to a few tens of kilometres. Beyond this limit, the capacitive-charging current exceeds the current rating of the cable itself. The transmission length can be extended by compensation of the capacitive current at both ends of the cable. This is mostly achieved by the use of compensation shunts.

The losses in the grid terminals of an AC system are typically between 0.5 and 1.25% for each station. If step-up/step-down transformers are used the additional loss amounts to 0.2 to 0.3% of the nominal transformer rating [18].

When the charging current and losses of an AC cable cannot be tolerated due to excessive length or power level, the only other option is high voltage direct current (HVDC).

2.3.2 HVDC transmission

An elementary DC transmission system consists of a rectifier at one end of the transmission line to convert AC to DC while an inverter at the other end of the line reconverts the DC into AC. OWF compatible HVDC is still under development and currently costs considerably more than AC transmission. With the development of high-power, high voltage electronic converters, however, HVDC is becoming more feasible. Two types of HVDC systems are available, conventional thyristor-based current-source converters, and the newer voltage-source converters (VSC) systems.

Conventional HVDC transmission has been widely used for many years for delivering electrical power over long distances and/or for interconnecting between two unsynchronised AC networks. The 500 MW Moyle interconnector (see Fig 2.12) between Scotland and Northern Ireland demonstrates its application for high-powered submarine cable transmission.

As well as conventional HVDC transmission recent advances in improving the performance of self-commuted semiconductor devices have led to VSC HVDC. These converters use isolated gate bipolar thyristors (IGBT's) and allow independent control of both active and reactive current.

Figure 2.12 The 1-core 250 kV d.c. submarine cable used for the Moyle interconnector [10]

VSC HVDC has several advantages over conventional HVDC when it comes to OWF applications. It is more compact and more flexible due to the reactive power capabilities, as they do not require an independent AC source for commutation on the wind farm end. VSC HVDC is not yet in commercial operation at the highest power levels and, although it offers great promise a number of important aspects need further work, including electrical losses, device ratings and cost. The losses in conventional HVDC including the converter transformer losses are between 0.7 and 0.8 % per converter station [18]. The corresponding converter losses for a 150 kV VSC converter and transformer are 3% per converter station [18].

A DC transmission system can consist of one cable (monopolar) or two cables (bipolar). In monopolar mode, the single cable constitutes the HV carrying component while the return current flows through the ground or sea. While reducing the cable and laying costs, single pole transmission can create stray currents that may lead to corrosion on nearby metallic structures and sea electrodes generate large amounts of harmful chlorinated compounds [17].

Bipolar is the more common design, but often includes back-up sea electrodes for temporary use in the case of damage of one of the cables. Recent developments in cable technology mean that it has become possible to operate in bipolar mode using only one cable. A bipolar coaxial cable has recently been developed with the return conductor surrounding the main conductor, outside the lead sheath (see Fig. 2.12) thus obtaining the advantages of the monopolar system without the drawbacks.

The DC cables themselves are less expensive than AC cables, because for a given amount of insulation they can be operated safely at higher currents, therefore they allow more power per cable. HVDC cable capacity is 290% AC capacity and has 35% of AC resistive losses [20]. However, the costs of the power converters (inverters and rectifiers) at either end of the transmission line are considerable.

Although HVDC converters lead to electrical losses on either end, the DC system has lower overall losses compared with AC. Furthermore, the losses in a DC cable are significantly lower because of the lack of both the charging currents in the main conductor, and the induced current in the shielding. The nominal losses in DC cables are the ohmic losses caused by the DC current in the conductor. However, depending on the network on the DC-side some harmonic currents may enter the cable and contribute to the loss particularly at the ends.

In DC cables the voltage distribution is dependent on the geometry of the cable and highly dependent on the temperature drop across the insulation, as the conductivity of the insulation material increases exponentially with temperature [18]. Therefore, there is a direct correlation between the conductor losses and maximal electrical stress in the insulation in a load carrying cable. Usually it is the design stress and not the maximal allowable conductor temperature that limits the transmission capacity of a DC cable.

The unavoidable capacitive electrical losses count against AC installations, while DC equipment is hampered by the expense of converters. A decision between the two schemes can only be made by evaluating the total cost (including cable laying costs) of each.

2.4 Literature Review

The first step in this project was an extensive study of up-to-date relevant literature and background material. This was necessary in order to deepen my understanding of the topic and highlight any new interesting or useful facts.

For the purposes of this project mainly material on the electrical interconnection of offshore wind turbines and transmission techniques were read and consulted. However, other material on a variety of topics including: environmental impacts of OWFs, the history of the Beatrice oilfield and government renewable policy, were also examined.
One of the most important texts studied regarding the electrical systems of OWFs was the collection of papers contained within the "International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms" booklet. Many of the papers referred to in this text where obtained from this collection.

A considerable amount of papers were consulted on the 160 MW Horns Rev OWF, the worlds largest OWF in operation. Knutsen B. E. and Mikkelsen S. D. [19] discussed the development, manufacture and installation of the 3-core HV transmission cable. Christiansen P., Jorgensen K. and Sorensen A. [21] focused on the grid connection issues and wind turbines at Horns Rev. In addition, another paper co-written by Christiansen [16] described the wind farm monitoring and control system and the challenges of locating a farm more than 15 km off the coast. Another important OWF is the North Hoyle, the UK's largest OWF in operation. Pechey J. [6] paper on the electrical systems of North Hoyle gave a useful insight into the electrical infrastructure of the farm.

The electrical aspects of wind power have been previously studied by many authors. Gardner P., Craig L. M. and Smith G. J., [9] produced a paper that provided a good starting point and general classification of the electrical systems for OWFs.

Jonasson K., Carlson M. and Goteborg E. [22] paper on the "Integration of a 300 MW Wind Park at Fladen, Kategatt, into the Swedish 130 kV grid" supplied informative background information, that led to a deeper understanding of the effort and ideas behind planning a large OWF. Ohrstrom M. and Soder L. [23], Rasmussen C., Jorgensen P. and Havsager J. [24] and Bolik S. M. [25] present some of the challenges of integrating wind power into the grid network. In these works, reactive power support, fault current levels and frequency deviations were investigated as well as new grid codes that OWFs have to meet.

Brakeelmann [26] discusses the some of the possibilities of optimising cabling inside an OWF. He concludes that the impacting factors for the total cost include the choice of voltage level, the geographic arrangement of the wind turbines and especially the position of the central platform as it determines the length of the connections.

Power transmission options for OWF have been extensively investigated with most authors focusing on AC transmission vs. DC transmission. Eriksson and Wensky, [27] pointed out DC has the advantage of lower cost of cables and lower cable losses above a certain distance and these offset the high converter costs. Wright et al. [12] concur and add that the losses in a DC cable are significantly lower because of the lack of both charging currents in the main conductor, and the induced current in the shielding.

Weatherill's review paper [28] was more cautious, stating that the economical advantage of HVDC transmission is uncertain due to high investment costs. It does add that some types of cables can be converted to use both AC and DC for example; the same cable used for transmission of 150 MW a.c. and can be used for transmission 600 MW d.c., as the installation can withstand higher DC voltages than AC.

A more recent report by Sobrink K, Woodford D. and Belhomme R, [29] looked at AC vs. DC transmission at Laeso Syd in Denmark. It concluded that in this case both an AC and DC transmission cable was technically feasible. However, the capital cost of transmission with DC cables was high compared with the AC cable option. The DC cable option does however have varying frequency control and a higher probability that it will ride through most contingencies in the transmission grid.

On the subject of turbine generators, several papers proved useful. Lahtinen M and Katancevic A. [30] discussed whether a synchronous or an asynchronous generator would best meet the Finnish transmission system operator's performance requirements. It concluded that asynchronous machines where unlikely to fulfil the requirements. Ekanayake J, Holdsworth L. and Jenkins N. in [31] and Fortmann J. [32] both described DFIG wind turbines, presenting an overview of control techniques. The modelling of wind turbine generators is discusses in [33] by Poller M. and Achilles S. and by Morren J. et al [34].

Finally, Manwell J. F., McGowan J. G. and Rogers A. L. book "Wind Energy Explained" was important in gaining an understanding of many non-electrical wind power topics. It was used as a reference throughout the course of this project.

Throughout this dissertation, every effort was made to thoroughly document all points of reference. An extensive referencing section to guide the reader to further sources of information on a variety of topics is found on pages 63 to 67. Papers that are not expressly cited in the body of the text of this dissertation but were useful are given in the Bibliography on page 68.

CHAPTER THREE

THE BEATRICE OFFSHORE WIND FARM PROJECT

3.1 Introduction

Scotland is a particularly “wind-rich” nation, with 40% of Europe’s wind resource blowing off its coast. In 2003, plans were unveiled to investigate the construction in Scotland of the world’s biggest OWF in an attempt to harness some of this massive resource. A partnership between Talisman Energy and Scottish and Southern Energy (SSE) plan to install 200 wind turbines in the Beatrice oilfield acreage in the Moray Firth (see Fig. 3.1). The idea is to re-use the existing Beatrice infrastructure as a hub for a 1 GW OWF.

This chapter provides background information on the Beatrice oilfield and the progress of the Beatrice OWF project to date. In order to investigate the electrical aspects of the farm the geographic layout of the wind turbines and their position around the Beatrice had to be deduced. The majority of the chapter therefore describes the layout options for the farm and following this, suggests a possible formation.

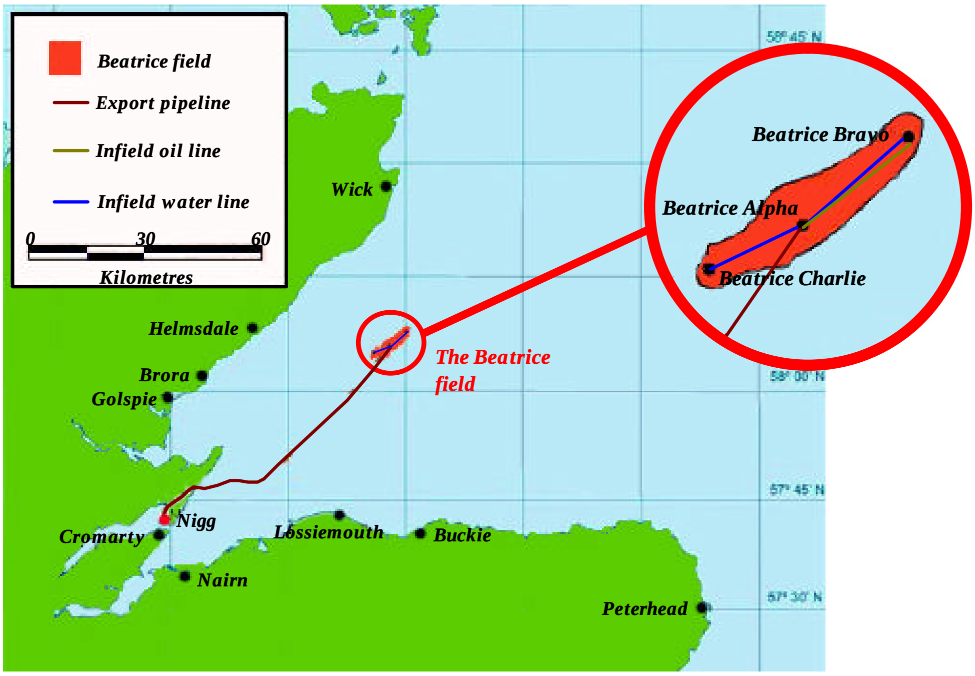


Figure 3.1 The Beatrice oilfield

3.2 The Beatrice oilfield

Situated in the Moray Firth, the Beatrice oilfield lies 24 km off the Caithness coast and covers an area of around 23 km^2. The oil installations in the region tap-into oil deposits some 2,100 m below the seabed [35]. Since oil production began in 1981, the Beatrice field has yielded more than 150 million barrels of oil and at its peak in the mid 1980s; it had a production of 300,000 barrels per month. The current production is around 25,000 barrels of oil per month [36] and the number of staff on the platform has shrunk from 240 to just 20 employees [37]. In an interesting and unique development the rig, which is still producing oil but was to be decommissioned some time between 2005 and 2010, is to be the site of the world's first deepwater wind farm.

The Talisman owned Beatrice Alpha (see Fig. 3.2) is the main rig in the Beatrice field. The production platform half of Alpha that feeds oil into the Nigg terminal in the Cromarty Firth is powered by electricity from SSE. The supply of electricity is via a 25 km buried submarine cable from the metering substation on the mainland at Dunbeath. The cable is a medium-voltage EPR insulated design with a copper conductor cross-sectional area (CSA) of 120 mm^2.

Figure 3.2 The Beatrice Alpha production and drilling rigs [38]

3.3 The Beatrice wind farm demonstrator

Prior to development of the full-scale 1 GW wind farm Talisman are installing two prototype turbines adjacent to the Beatrice Alpha platform, as part of a demonstrator programme. During a five year trial, the demonstrator turbines will be used to collect performance data, investigate ways to reduce costs and develop operating procedures. The success or failure of the demonstrator will ultimately determine if large-scale developments of this kind are a practical source of renewable energy.

The demonstrator project is a key element of DOWNViND (Distant Offshore Windfarms with No Visual Impact in Deepwater). DOWNViND, a pan-European initiative led by Talisman, was established as a catalyst for commercialising deepwater wind farm technology. It is now Europe’s largest renewable energy research and technology development programme, comprising of 14 different participants from six countries.

To date, SSE and Talisman have spent more than £2 million to reach this point in the project and anticipate contributing a further £7 million each in the coming years [39]. The project has also attracted funding from the Scottish Executive, the Department of Trade and Industry and the European Commission.

Figure 3.3 The two turbine Beatrice demonstrator (photo-simulation) [39]

The demonstrator project is technically very challenging. No developer has ever designed and built a structure to support 300 ton wind turbines in 40 - 50 m of water.

The project will involve the design, construction, installation and operation of two 4.5 MW turbines, tie back to Talisman Energy's Beatrice Alpha platform and eventual connection to the UK grid as illustrated in Fig. 3.4. Both demonstrator turbines will be located south-east of Beatrice Alpha's production platform. The two turbines (A and B) will be fixed to the seabed 45 m below the surface. They will be spaced 750 m apart and be linked by a 910 m long submarine cable.

Turbine A is connected to the 33 kV switchgear on the Beatrice via a 1.9 km length of submarine cable [40]. Both cables will be laid in a trench on the seabed and buried. The length of the power cables for the demonstrator scheme is shown in Fig. 3.5. The combined output from the two turbines will initially be used by the Beatrice platforms and should be generating power by autumn 2006 [41]. If the demonstrator trial proves a success, Talisman and SSE plan to construct a full-scale OWF.

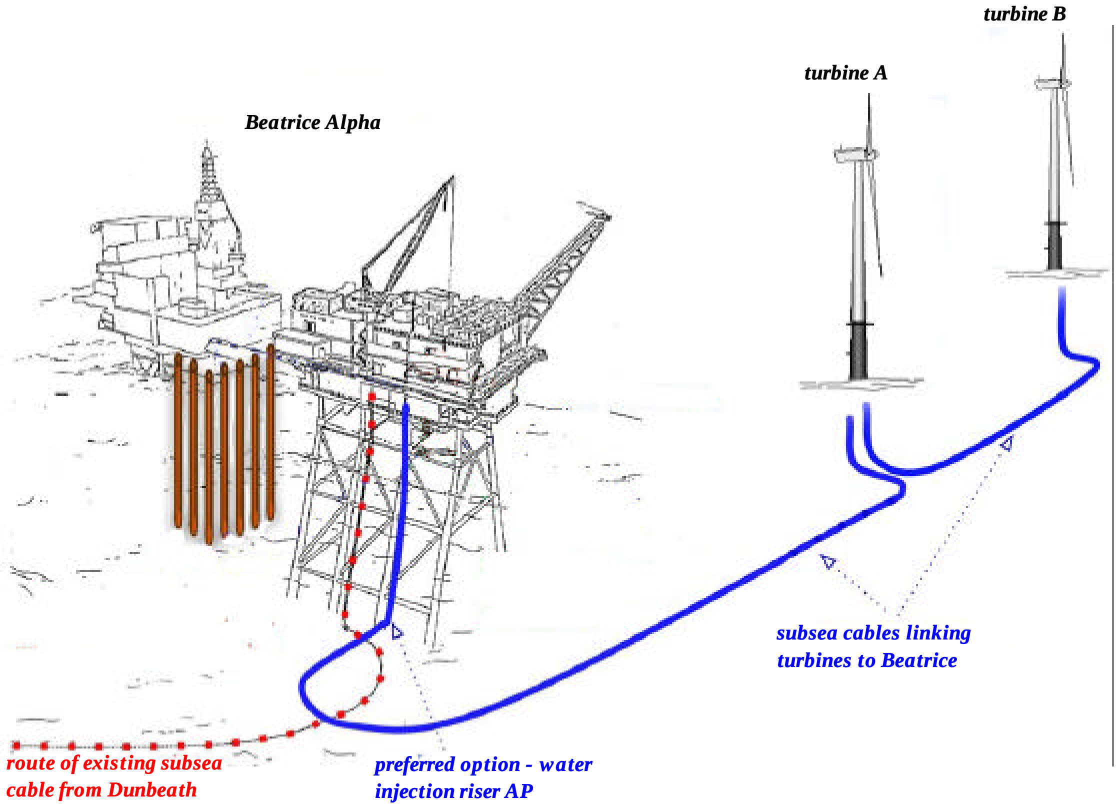


Figure 3.4 A sketch showing the Beatrice demonstrator proposal

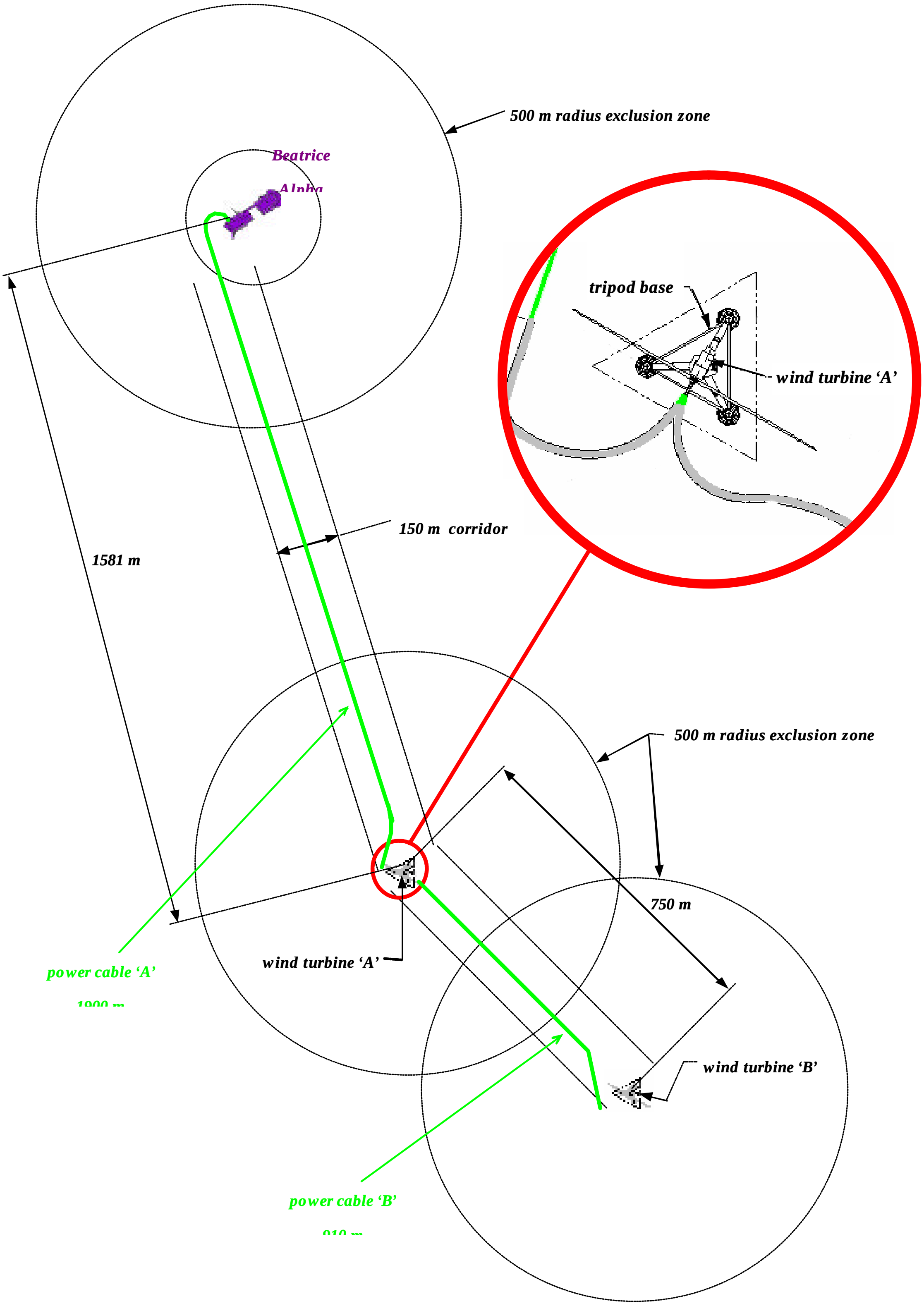


Figure 3.5 The Beatrice demonstrator cable lengths

3.4 The Beatrice 1 GW wind farm development

The Beatrice facility consumes a lot of power and is one of the largest single-facility users of electricity in Scotland [42]. The wind power idea was originally envisioned as a way of extending the life of the Beatrice facility by providing it with the means to generate its own electricity and so reduce its operating cost. The concept has since developed into the biggest, onshore or offshore, wind farm project in the world. This innovative idea will see the existing Beatrice infrastructure "recycled" into an operations and maintenance base for transmission and protection equipment for the OWF. Once the wind farm is fully operational it will be able to generate up to 1 GW of "green" electricity, providing nearly half of the Scottish Executive's aim to generate 40% of Scotland's electricity from renewable sources by 2020 [43].

The remainder of this chapter examines how the proposed 1 GW farm could be laid out in the Moray Firth. Although this project was concerned with the electrical aspects of the Beatrice OWF, before selecting a suitable electrical design for the farm, it was necessary to know the distances between turbines and their position relative to the Beatrice because as discusses in section 2.2.3, cable properties vary with length. Therefore, it is necessary to establish a geographic plan of the site.

Figure 3.6 The full-scale 1 GW Beatrice OWF (photo-simulation)

3.4.1 Wind turbines employed within the farm

The 200 turbines that will form the wind farm will each have a rated power of 5 MW. At the moment this size of turbine is not available "off-the-shelf" but both REPower and Nordex turbine manufactures have 5 MW test units and it is expected that in the next three to five years, commercially available 5 MW units will emerge. As this rating of unit is still under design the tower height and rotor diameter have been based on the most current representative sizes and are illustrated in Fig. 3.7.

The turbines will be erected in 45 m of water and be fixed to the seabed using the same tri-support foundation employed for the demonstrator prototypes. Each turbine will be fitted with tubular cable guides ("J" tubes) to allow the undersea power cables to enter and leave the turbine tower. It is assumed that the generator transformer is fitted in the turbine nacelle and the switchgear is located at the bottom of the tower.

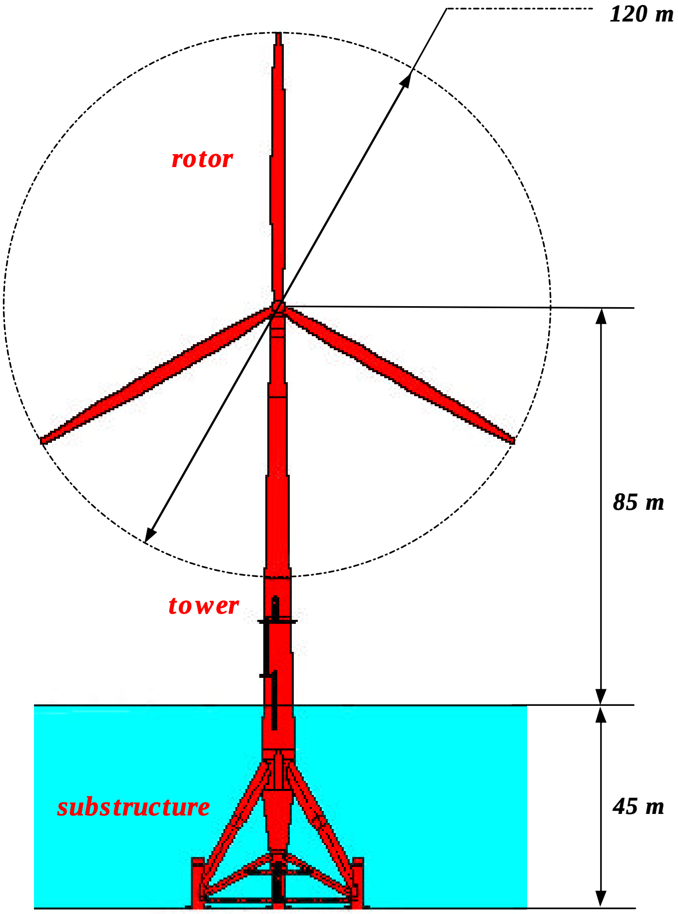


Figure 3.7 Wind turbine dimensions

3.4.2 Spacing of wind turbines

The extraction of energy from the wind by a wind turbine results in an energy and velocity deficit, compared with the prevailing wind, in the wake of the turbine. This results in lower wind speeds behind a wind turbine and therefore less energy capture by the downwind turbines in the OWF. The extent of the wake in terms of its length depends primarily on the turbine rotor size. In an onshore wind farm, turbines generally have to be spaced centre-to-centre between three and nine rotor diameters apart in order to avoid turbulent wakes. In OWFs the spacing between individual turbines should typically be larger. This is because the wake of a turbine dissipates more slowly offshore than onshore and because space constraints are less significant offshore.

The most commonly used spacing offshore is between five and seven rotor diameters [44]. In the case of the Beatrice OWF, the turbines will have a spacing equivalent to six rotor diameters or 720 m. This spacing is in line with the demonstrator dimensions and should be large enough to minimise turbulent wakes. Figure 3.8 shows the spacing arrangement of four turbines and the 500 m exclusion zone that surrounds each turbine designed to prohibit unauthorised entry.

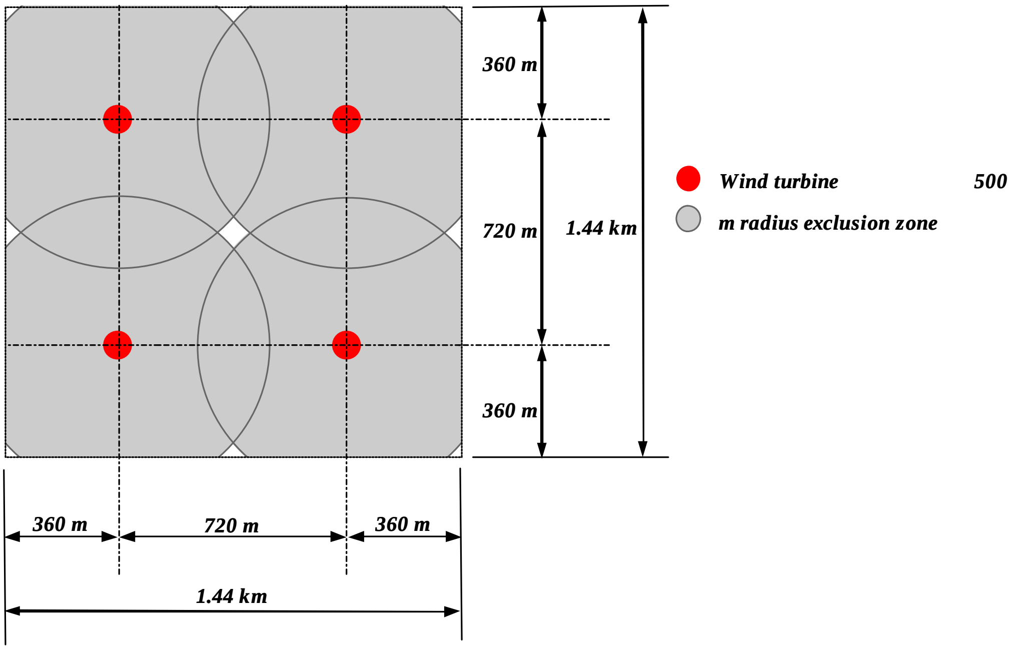


Figure 3.8 Wind turbine spacing arrangement and exclusion zones

3.4.3 Geographic layout of the wind farm

The design of a wind farm needs to consider the effect of different geographic arrangements in order to maximise energy capture. The layout of the turbines in an OWF typically varies between a line, a rectangle or a square. The layout of the wind turbines depends on amongst other things water depth, seabed condition, wind direction and wind intensity and the number and size of turbines. One of the most important parameters when selecting the farm geography is its effect on cable lengths.

The geographic layout of the Beatrice OWF had to give significant space between each of the 200 turbines and the existing oil infrastructure and yet minimise the length of cables. If the turbines were spread over too wide an area to increase the efficiency of the farm, the cost of cabling would be very large. Therefore, only a fairly concentrated group of turbines was considered. Ideally, all the wind turbines should be as close to the Beatrice as possible in order to reduce the length of cables. This could be achieved simply by encircling the platform with a ring of turbines. However, as the Beatrice is dependent on supply vessels it would be impractical to completely surround the rig and increase the risk of a ship colliding into a turbine. It was therefore decided to arrange the on only three sides of the Beatrice (see Fig. 3.9).

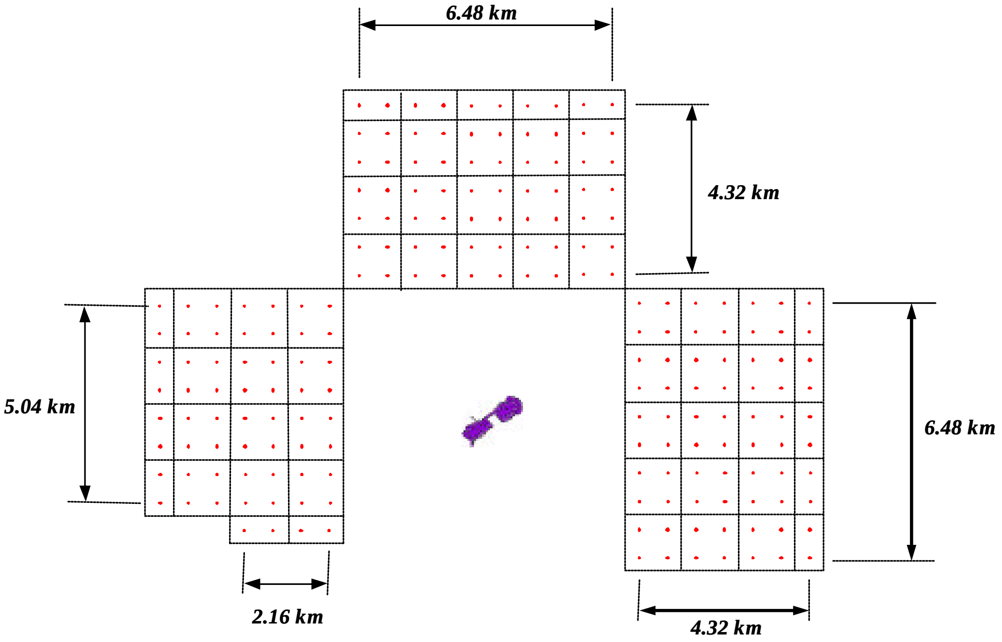


Figure 3.9 The proposed layout of the Beatrice OWF

This formation allows supply vessels to approach the platform from the south in safety, even in rough seas. Furthermore, by not siting the turbines to the south of Beatrice Alpha, they do not interfere with the main export oil pipeline. The three turbine clusters are laid out in a grid as this formation lends itself best to an efficient, concentrated shape. The turbines in the north cluster are placed in 10 north-south oriented columns separated by a distance of 720 m. Each of these columns contains 7 turbines. The reason why the turbines are arranged in lines of 7 is due to the maximum power rating of the inter-linking cables and is discussed in detail in section 4.2.3. The turbines in the east and west clusters are placed in 10 and 9 rows respectively. Of these rows, 18 contain 7 turbines and 1 row contains 4 turbines again separated by 720m, adding up to 200 turbines in total.

The distance between the first row of turbines in the north and east clusters and the Beatrice Alpha ranges between 3.24 and 4.58 km^2 (see Fig. 3.10). The north and east clusters cover an area of 25 km^2 and the west cluster covers an area of 23 km^2. A summary of the OWF layout proposed in this paper is given in Table 3.1.

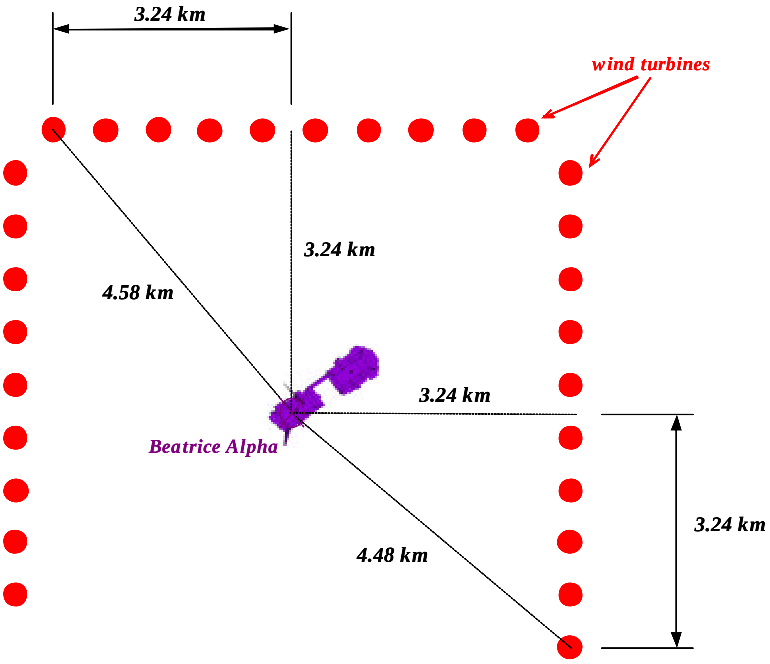


Figure 3.10 The distance between the turbines and the Beatrice Alpha

Parameter	**Value**
Total power output	1 GW
Wind turbine type	Generic design - 5 MW

Rotor diameter	120 m
Tower height	85 m
Depth of water	45 m
Distance to shore connection	Beatrice to Dunbeath - 25 km
Distance between turbines	six rotor diameters - 720 m
Area of wind farm site	79 km^2

Table 3.1 Summary of proposed Beatrice wind farm

3.5 Chapter Summary

This chapter began by providing some historical information on the Beatrice oilfield in the Moray Firth. It described how over the next five years Talisman Energy and SSE plan to construct and test two 4.5 MW demonstration turbines adjacent to the Beatrice Alpha as precursors for a full-scale deepwater OWF. The planned full-scale 1 GW farm will use the existing Beatrice oilfield infrastructure as a hub and will utilise 200 turbines, each capable of generating 5 MW of electricity.

The focus of this chapter was identifying a suitable layout for the 1 GW development. Various different formations and shapes were considered for the wind farm layout before a semicircular formation was selected. The distances between turbines, Beatrice and shore for this layout were discussed. The chosen arrangement will minimise negative turbulent wake effects and the length of power cables. It will also allow supply vessels safe access to the Beatrice Alpha platform.

CHAPTER FOUR

POWER FLOW SIMULATION OF BEATRICE OFFSHORE ELECTRICAL SYSTEM

4.1 Introduction

Chapter three outlined a potential geographic layout for the Beatrice OWF. Using this layout, this chapter will investigate the options for the electrical system and suggest a number of workable electrical configurations. The first part of this chapter deals with the collection system of the proposed farm (see Fig. 4.1). It recommends the types of turbine generators, transformers and the cabling arrangement within this region of the farm. The second half of the chapter deals with the transmission system. For this region of the OWF three designs were investigated, two employing AC transmission technology and one employing DC transmission technology. All three configurations looked at the effect of using variable and fixed speed generators.

4.2 The Beatrice OWF collection system

The collection system includes all the electrical equipment within each turbine and the way this equipment is connected to the Beatrice Alpha. It is called the collection system because it deals with how power from each turbine is gathered together *before* transmission to shore.

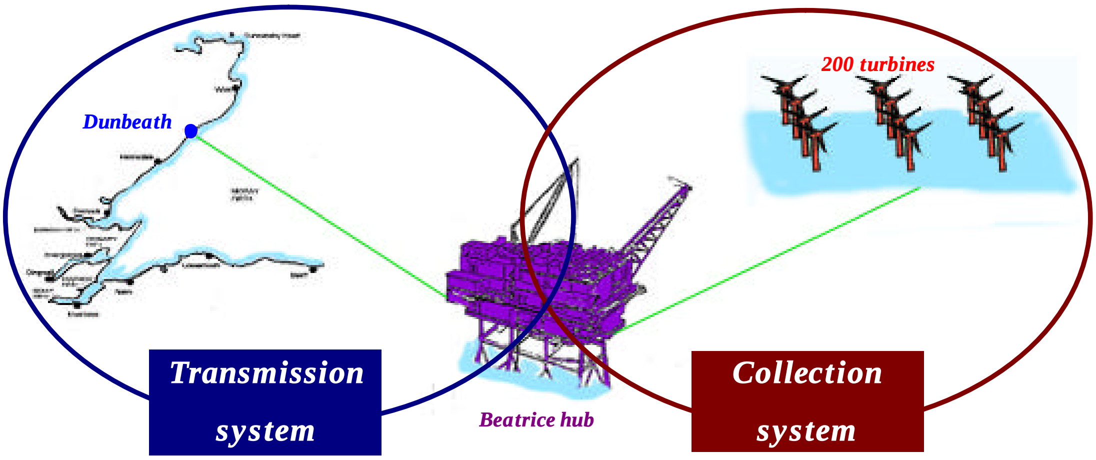


Figure 4.1 The collection and transmission areas of the wind farm

4.2.1 Turbine generator selection

As discussed in section 2.2.1, there are two main categories of wind turbine generators; fixed speed and variable speed machines. Fixed speed machines are cheaper and more robust then variable speed units but have the disadvantage of absorbing reactive power. For this project, both fixed and variable speed machine performance was assessed for each different transmission configuration presented in section 4.3. Both types of generators had a rated output power of 5 MW at 690 V. This voltage level was selected as it is currently the most common wind turbine generator voltage and has been used at many OWFs.

The fixed speed generators were taken to be squirrel-cage IG machines and it was assumed they had no form of reactive power compensation. Squirrel-cage IGs rated above 1 MW have a power factor range of 0.87 to 0.9 leading [45]. It is therefore assumed that the 5 MW IG under consideration here could absorb up to a maximum of 2.83 Mvars of reactive power.

The variable speed generators were DFIG machines with a power factor range of between 0.9 lagging to 0.9 leading [46]. This means for the 5 MW generators employed here, each can produce or absorb up to 2.42 Mvars of reactive power. Table 4.1 summarises the specifications of the two types of turbine generator.

Parameter	**Fixed speed generator**	**Variable speed generator**
Type	Squirrel-cage IG with no load compensation	Doubly-fed induction generator
Rated power	5.0 MW	5.0 MW
Rated voltage	690 V a.c.	690 V a.c.
Rated frequency	50 Hz	50 Hz
Power factor range	0.87 - 0.9 leading	0.9 leading - 0.9 lagging

Table 4.1 Turbine generator specification

4.2.2 Turbine transformer selection

The turbine transformers selected were dry-type cast resin insulated units. These have the advantage that they are compact, can be taken apart for ease of installation and no forced cooling is necessary. Each turbine transformer stepped-up the generator output of 0.69 V to a nominal 33 kV collection voltage. This voltage level was chosen as it is the highest available in a dry-type transformer design [46]. Each unit had a vector group of delta, star neutral and HV tapping range of ? 2.5% based on the dry-type transformers at North Hoyle OWF. This means each transformer had a turns ratio upper limit of 1.025 pu and lower limit of 0.975 pu.

Each 0.69/33 kV turbine transformer had a rated capacity of 6.25 MVA; this corresponds to 125% of the generator's active power rating. This transformer rating is higher then any currently available dry-type transformer but it is assumed transformers with this rating will be available in the near future. The rated impedance voltage for this size of transformer was assumed to be 7% based on similar machines. Each of the 200 turbine transformers was fitted in the nacelle of every turbine to reduce transmission losses. It is assumed that the transformers were linked to their generator via an isolated phase bus with zero impedance. A summary of each turbine transformer's specifications is given in Table 4.2.

Parameter	**Value**
Type	Cast resin
Rated power	6250 kVA
Rated primary voltage	33 kV (36 kV (U_m) equipment voltage)
Rated frequency	50 Hz
Vector group	Dyn
HV tapping range	? 2.5%
Secondary voltage	690 V
Rated impedance voltage	7%

Table 4.2 Turbine transformer specification

4.2.3 Collector cable selection

This section deals with the cable section process within the collection system. It describes how turbines within the OWF are linked to one another and how in turn individual turbines are connected to the Beatrice. In order to simplify the collector cable selection process, a system was devised where each cable was categorised into one of six groups, depending on what equipment it linked. The various cable categories are illustrated in Fig. 4.2. Note that category 5 and 6 are part of the transmission system and are discussed in section 4.3. It was assumed all submarine cables had copper conductors and were XLPE insulated as the quality and life span of this insulation is firmly established and the very low power factor of the XLPE gives only minor dielectric losses even at high voltage.

When sizing cables it is often preferred to size the largest cable first i.e. the one carrying the most power and work "backwards", sizing the intermediate and small cables last. In the collection system, the cables that must support the largest flow of power are those that connect each turbine "string" to the Beatrice hub, here designated category 4. A turbine string is simply a number of turbines connected in series to form a chain. In order to accurately size the category 4 cables, a decision had to be made regarding the number of turbines per string. This was achieved by considering the maximum power rating of different cables (as a certain cable conductor CSA. can only carry a certain amount of power).

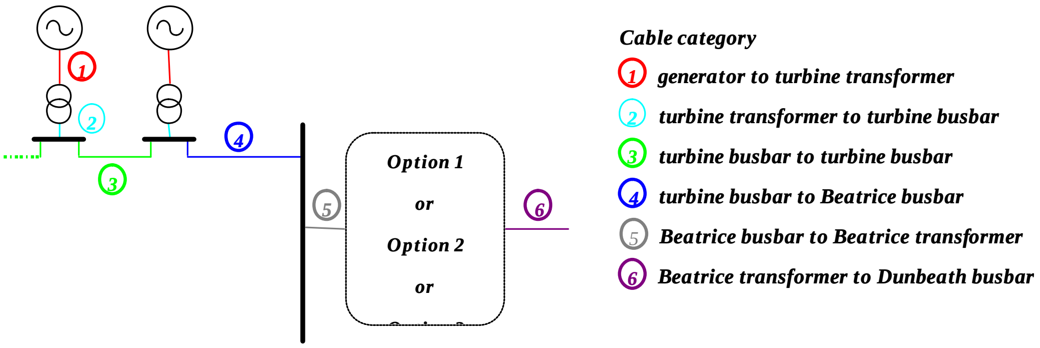


Figure 4.2 The cable categories for the OWF

A large number of turbines per string would require very large cable conductor CSA. because for each additional cable segment (category 3) there is a section-by-section increase in load current. A small number of turbines per string would mean smaller cables could be employed but many turbines would have to be directly linked to the Beatrice Alpha. As the distance between the turbines and the Beatrice is greater than between individual turbines, this would mean there were many more long cable runs.

Based on the above, strings of between 4 and 8 turbines were considered initially. After investigating the effect on geographic layout of the site, the total length of cabling and turbine entry limitations, a 500 mm^2 cable conductor CSA. was selected for all category 4 cables. In Table 4.3, an overview is given of the maximum cable power rating as a function of conductor CSA. for 33 kV XLPE submarine cables. Table 4.3 states that the maximum power a cable CSA of 500 mm^2 at 33 kV can support is 39.7 MVA. Assuming each turbine generates 5 MW, a cable with this CSA and voltage can safely support 7 turbines linked together (see Fig. 4.3).

Conductor CSA (mm^2)	**Conductor resistance AC 90 ^{o}C (? /km)**	**Inductance (mH/km)**	**Current rating (A)**	**Power rating (MVA)**
120	0.20	0.41	325	18.6
150	0.16	0.40	365	20.9
185	0.13	0.38	449	25.7
240	0.10	0.37	513	29.3
300	0.08	0.36	572	32.7
400	0.06	0.35	637	36.4
500	0.05	0.33	695	39.7
630	0.04	0.32	776	44.4
800	0.03	0.31	838	47.9

Rated values based on solid Cu conductor. Ratings are calculated for a 1.0 m burial depth with 1.0 K?m/W and sea temperature no higher than 20 ^{O}C.

Table 4.3 33 kV submarine cable data [47]

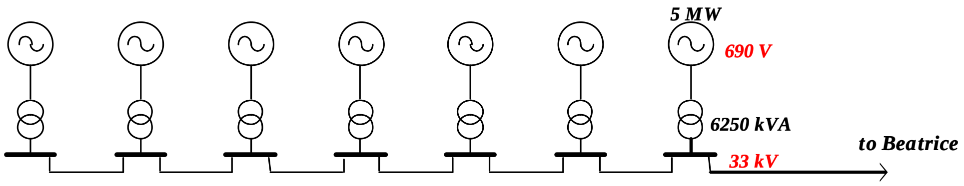


Figure 4.3 One string of 7 turbines

With category 4 cables sized, attention could move to the inter-turbine cables (category 3). In order to size the category 3 cables, a decision had to be made concerning whether the turbines were linked in a radial or ring arrangement. A ring (or closed-loop) arrangement composed of an additional 0.9 km length of cable connecting each string at the far Beatrice end would provide redundancy in the event of a failure at some point in the string (see Figure 4.4). A faulty cable segment could be isolated and operation could continue without any loss of generation. However, a closed-loop arrangement would not lend itself to the graduation of cable sizes and because the probability of a fault in a buried submarine cable is low, 0.1 faults per year per 100 km [9], it was decided the slight improvement in reliability did not warrant the added cable costs.

Therefore, the wind turbines were connected in a radial arrangement. This means their power outputs were superimposed from cable to cable. So, cable segments within each string that are farther from the Beatrice would carry less current than those closer to the Beatrice. This permits the use of a smaller size conductor for the more lightly loaded segments at a considerable cost saving.

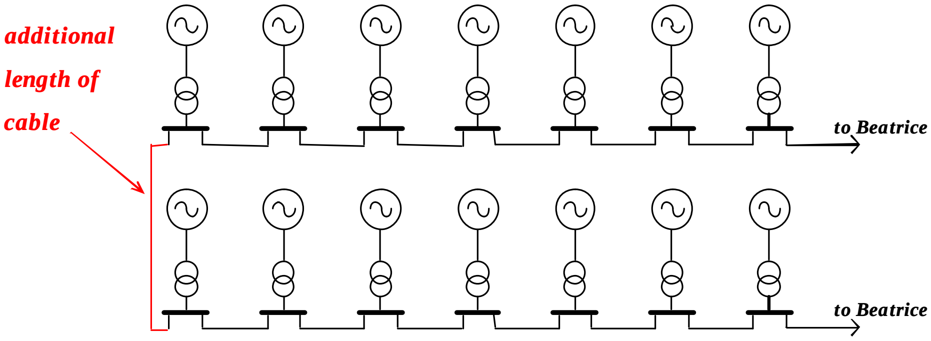


Figure 4.4 Two strings connected in a ring arrangement

It is worth noting that a constant conductor cross-section in each string section would be advantageous with respect to cable storage as well as accessories. However, the dimension of the conductor cross-section for the last string segment would be greatly over sized for the first sections. This would mean unnecessarily high cable costs.

Category 3 cables were divided into 3 sub classes, A, B and C, dependant on the load they had to carry (see Figure 4.5). Using the power rating values given in Table 4.3 each category 3 cable sub class was sized. Class 3A cables had a conductor CSA of 120 mm^2, class 3B cables had a conductor CSA of 185 mm^2 and class 3C cables had a conductor CSA of 300 mm^2.

Using the wind farm dimensions calculated in chapter 3, the length of each cable could be estimated. It was assumed that the category 3 cables were 900 m long. This length included 180 m of slack to take into account detours, the bending radius of the cable and burial. Likewise, each category 4 cable was estimated to be 5 km long allowing 400 m of slack. The cables linking the turbine transformer to the turbine switchgear, category 2, were estimated at 90 m in length based on the tower height and allowing 5 m of slack.

Using these lengths and the data in Table 4.3 the cable impedance for each category could be calculated as follows:

Example calculation

ii. Class 2 - 33 kV 3c x 120 mm^2

R (?) = length ? resistance

= 0.09 km ? 0.2 ? /km

= 0.0180 ?

X (?) = length ? (2?f ? inductance/1000)

= 0.09 km ? 0.1288 ? /km

= 0.0116 ?

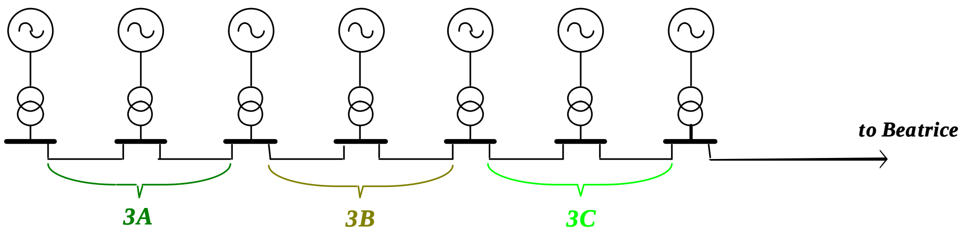


Figure 4.5 The three sub-classes of cable category 3

In this way Table 4.3 that summarises the cable properties of the OWF collection system was compiled.

Cable Category	**Conductor CSA (mm^2)**	**Voltage rating (kV)**	**Length of cable (km)**	**Cable resistance**		**Cable reactance**	
				(?)	**(pu)**	**(?)**	**(pu)**
1	N/A	0.69	N/A	0.0000	0.0000	0.0000	0.0000
2	120	33	0.09	0.0180	0.0017	0.0116	0.0011
3A	120	33	0.9	0.1800	0.0165	0.1159	0.0106
3B	185	33	0.9	0.1170	0.0107	0.1074	0.0099
3C	300	33	0.9	0.0720	0.0066	0.1018	0.0093
4	500	33	5.0	0.2500	0.0230	0.5184	0.0476
5	*Option 1,2 or 3 specific*						
6	*Option 1,2 or 3 specific*						

Table 4.4 Collector system cable information

4.3 The Beatrice OWF transmission system

The transmission system deals with the electrical equipment used to transmit the total power output of the 200 turbines to shore (see Fig. 4.1). Talisman and SSE have provisionally identified three sites in the north of Scotland as suitable points for connecting the offshore operation to the National Grid (see Fig. 4.6) but no final decision has been made as yet. For this project it was assumed that the sea to shore power cables were connected to the 132 kV grid network at Dunbeath. A link between Beatrice Alpha and Dunbeath already exists in the form of the 25 km Beatrice supply cable; therefore the length of cable could be accurately estimated. It was assumed that the grid network in this region had been strengthened to cope with the increased power flow.

In this section, three different schemes for transmission of power between the Beatrice OWF and Dunbeath are presented. Option 1 considered a HVAC transmission connection using two-winding transmission transformers. Option 2 also considered a HVAC transmission connection but this time using three-winding transmission transformers. Finally, option 3 considered a conventional HVDC transmission connection using converter transformers.

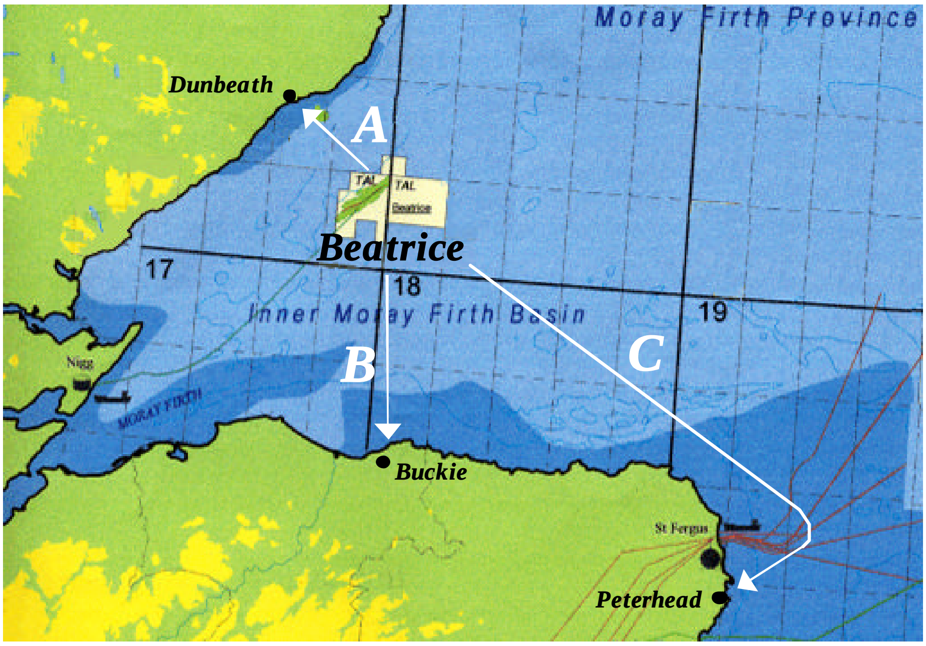


Figure 4.6 The possible transmission locations for the Beatrice OWF

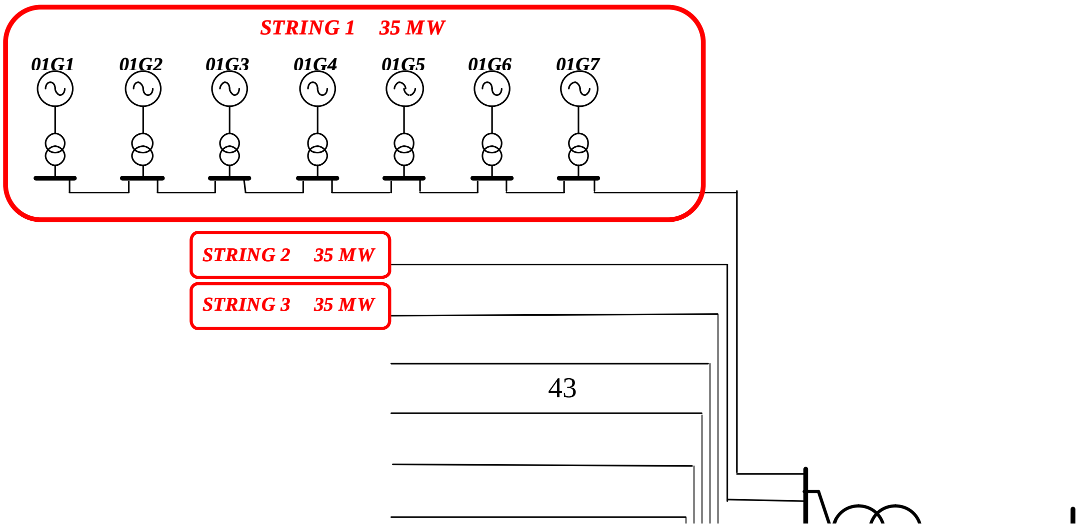
4.3.1 Option one - HVAC transmission using two-winding transformers

This transmission design used six 200 MVA 33/132 kV two-winding transformers, each situated onboard the Beatrice Alpha platform. The configuration was based on the Horns Rev wind farm transmission arrangement. Horns Rev OWF used a single 160 MVA transformer to transmit its 160 MW output to the Danish mainland. In this scheme, six transformers were used to transmit the 1,000 MW output to the mainland at Dunbeath.

Of the six 200 MVA transformers, five were linked on their low-voltage side to five strings of seven turbines and one transformer was linked to four strings (see Fig. 4.7). It was assumed the main transformers on the Beatrice had a HV tapping range of ? 10%, which therefore meant that each transformer had a turns upper limit of 1.1 pu and lower limit of 0.9 pu. Each three-phase transformer was of the forced-oil cooled type because of the high power rating. The rated impedance voltage for this size of transformer was assumed to be 16% based on similar machines. Table 4.5 summarises the chosen specification of the option 1 transmission transformers.

Parameter	**Value**
Type	Forced-oil cooled
Rated power	200 MVA
Rated primary voltage	132 kV
Rated frequency	50 Hz
Vector group	Dy
HV tapping range	? 10%
Secondary voltage	33 kV
Rated impedance voltage	16%

Table 4.5 Option 1 transmission transformer specification



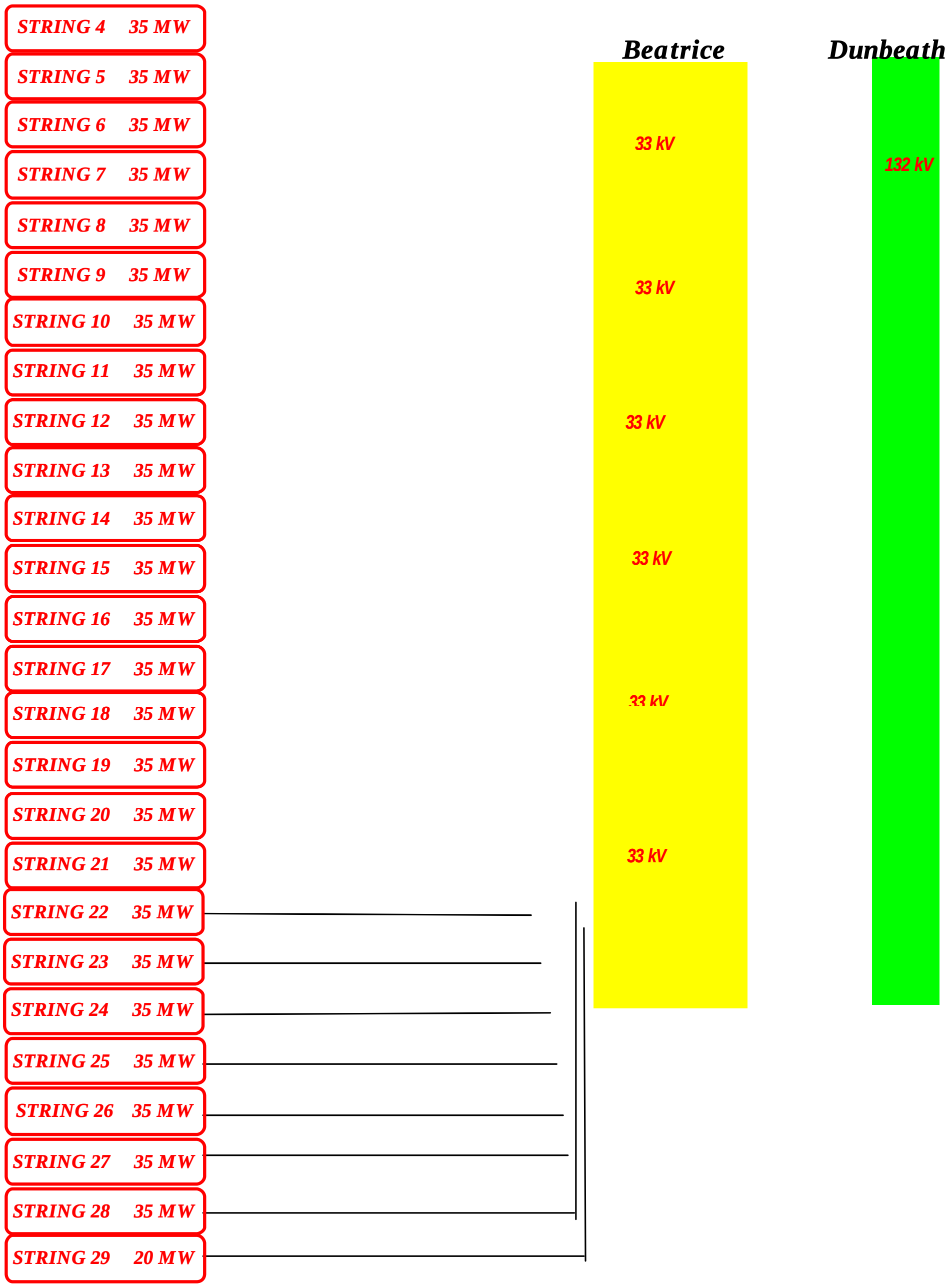


Figure 4.7 Simplified diagram showing the overall arrangement for transmission option 1

Six 3-core cables were used because they are cheaper to install then the equivalent number of single-core cables. XLPE was selected as the insulation type as XLPE insulated cables for 132 and 150 kV have been in use for many years with a good service record [19]. At present, the highest voltage level for a three-core XLPE submarine cable is the 21 km long 170 kV 630 mm^2 transmission cable at Horns Rev OWF. The rated line voltage for this cable is 150 kV and the transmission capacity is 160 MW. This design assumes that six cables similar to the one described, each carrying 167 MW, are employed. Each transmission cable had its own transformer. Table 4.6 summarises the properties of option 1 transmission cables.

Cable Category	**Conductor CSA (mm^2)**	**Voltage rating (kV)**	**Length of cable (km)**	**Cable resistance**		**Cable reactance**	
				(?)	**(pu)**	**(?)**	**(pu)**
5	N/A	33	N/A	0.0000	0.0000	0.0000	0.0000
6	630	132	25	10.000*	0.0574	6.2832*	0.0361

* These values have been estimated based on Horns Rev 160 MW cable

Table 4.6 Option 1 transmission cable information

4.3.2 Option two - HVAC transmission using three-winding transformers

Option 2 also considered HVAC transmission but using three instead of two-winding transformers. This transmission design employed four 132/33/33 kV three-winding transformers rated 400/200/200 MVA to step-up the voltage before transmission to shore. No OWFs have yet used three-winding transformers however, the proposed 500 MW OWF “NL7” off the Dutch coast will use 3 three-winding transformers and a number of large OWFs planned in Germany will use three-winding offshore transformers.

In this scheme three transformers were linked on their low-voltage side to four strings of seven turbines per winding and one transformer was linked to five strings (see Fig. 4.8). It was assumed each transformer had the same turns ratio and rated impedance voltage as option 1 and the transformer was forced-oil cooled. Table 4.7 summarises the chosen specifications of the option 2 transmission transformers.

Parameter	**Value**
Type	Forced-oil cooled
Rated power	200 MVA
Rated primary voltage	132 kV
Rated frequency	50 Hz

HV tapping range	? 10
Secondary voltage	33 kV
Rated impedance voltage	16%

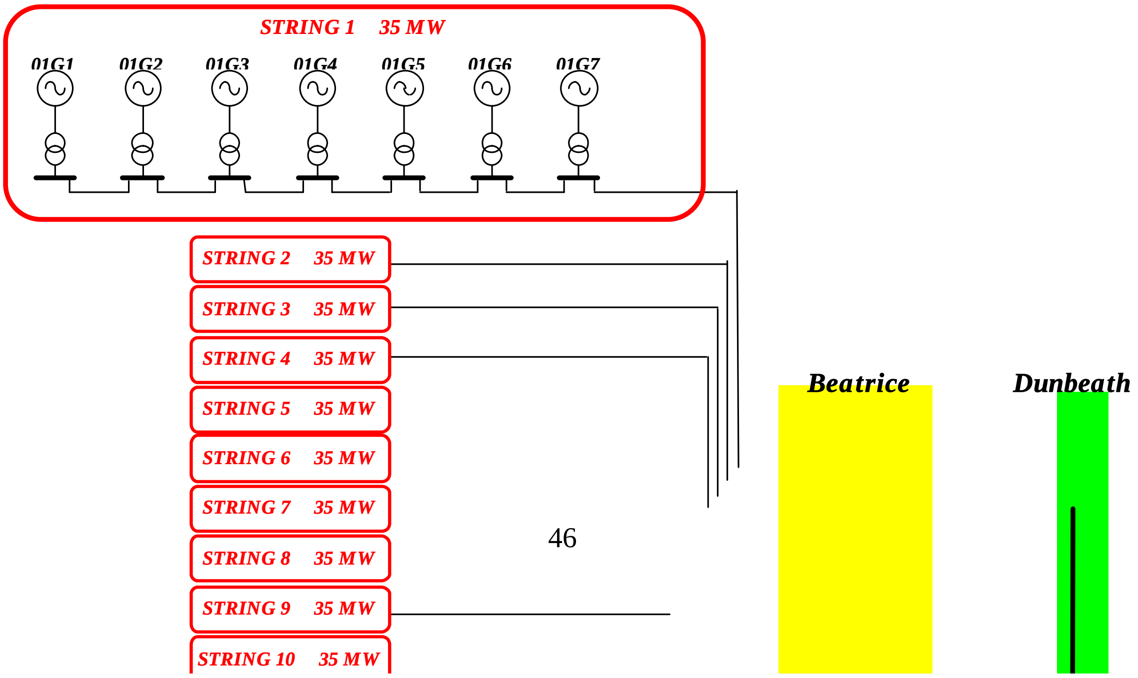
Table 4.7 Option 2 transmission transformer specification

The four transmission submarine cables connecting each transformer to Dunbeath had a conductor CSA of 800 mm^2 and were rated at 200 MVA. This size and rating of cable is not available at present so the resistance and reactance values were estimated based on the Horns Rev cable - the largest submarine cable currently available. Table 4.8 summaries the transmission cable information used for option 2.

Cable Category	Conductor CSA (mm^2)	Voltage rating (kV)	Length of cable (km)	Cable resistance		Cable reactance	
				(?)	(pu)	(?)	(pu)
5	N/A	33	N/A	0.0000	0.0000	0.0000	0.0000
6	800	132	25	10.5*	0.0603	7.0686*	0.0406

* These values have been estimated based on Homs Rev 160 MW cable

Table 4.8 Option 2 transmission cable information



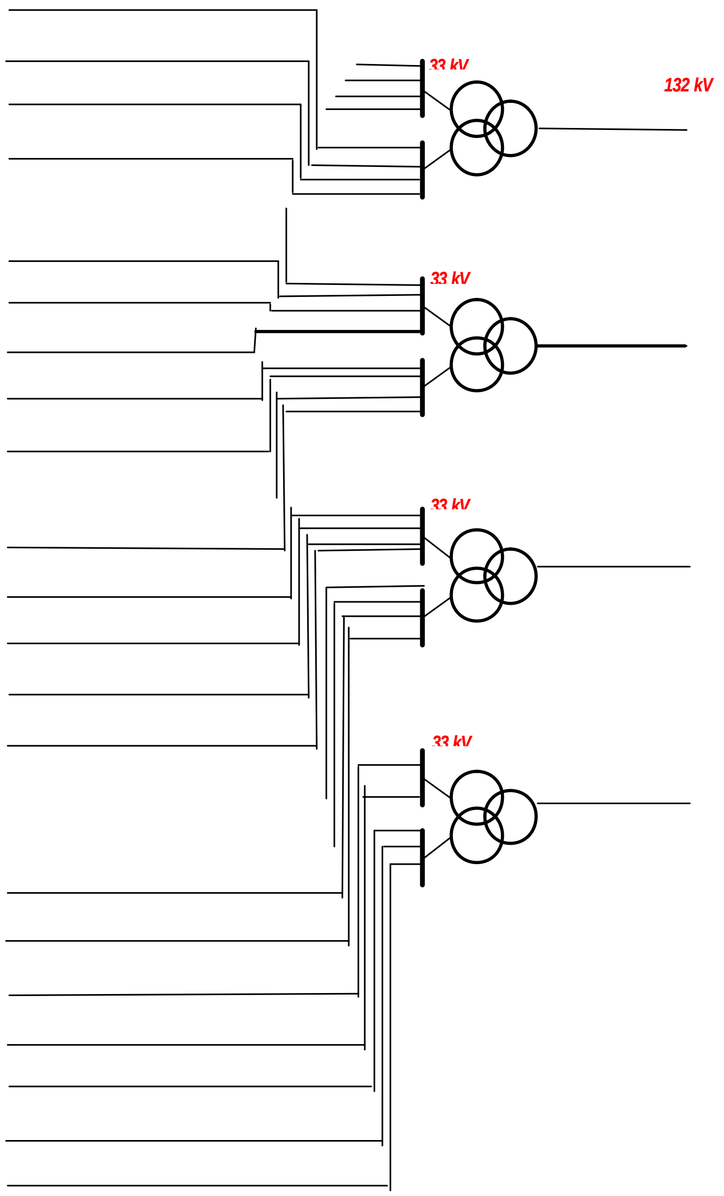


Figure 4.8 Simplified diagram showing the overall arrangement for transmission option 2

4.3.3 Option 3 - HVDC transmission

Due to the high power transfer between the Beatrice OWF and the grid network, it was decided to consider a DC transmission option as an alternative to the previous AC options. The DC transmission system used conventional HVDC technology and was based on the Moyle interconnector that runs between Northern Ireland and Scotland. This system consisted of two submarine HVDC cable links. The converters had a power rating of 2 x 500 MW. The DC operating voltage of each pole was 400 kV and the nominal direct current was 1250 A per pole. The 25 km subsea cable was of the integrated return conductor (IRC) type, where the return cable was integrated into the

HVDC cable. The converter transformers were of the single-phase three-winding type. This option would involve the construction of a HVDC converter station on the mainland as well as converter equipment on the Beatrice Alpha.

Each DC cable had a conductor CSA of 1200 mm^2 and a maximum d.c. resistance of 20 ^{o}C for a copper core of 0.0151 ? /km. The total DC cable resistance was therefore 25 x 0.0515 = 0.3775 ? . The desired dc flow was 1000 MW, or 500 MW per pole. Table 4.9 summarises the properties of option 3 transmission cables.

For the power circuit model created (see Fig. 4.9) a 1000 Mvar synchronous compensator on the Beatrice was required. The synchronous compensator controls the AC voltage on the common bus by providing or absorbing reactive power. The very large synchronous compensator was used because there was no reactive power control by the HVDC converter in this study and no switched capacitor banks.

Cable Category	**Conductor CSA (mm^2)**	**Voltage rating (kV)**	**Length of cable (km)**	**Cable resistance**		**Cable reactance**	
				(?)	**(pu)**	**(?)**	**(pu)**
5	N/A	33	N/A	0.0000	0.0000	0.0000	0.0000
6	1200	400	25	0.3775*	0.0002	N/A	N/A

*These values have been estimated based on Moyle interconnector cable

Table 4.9 Option 3 transmission cable information

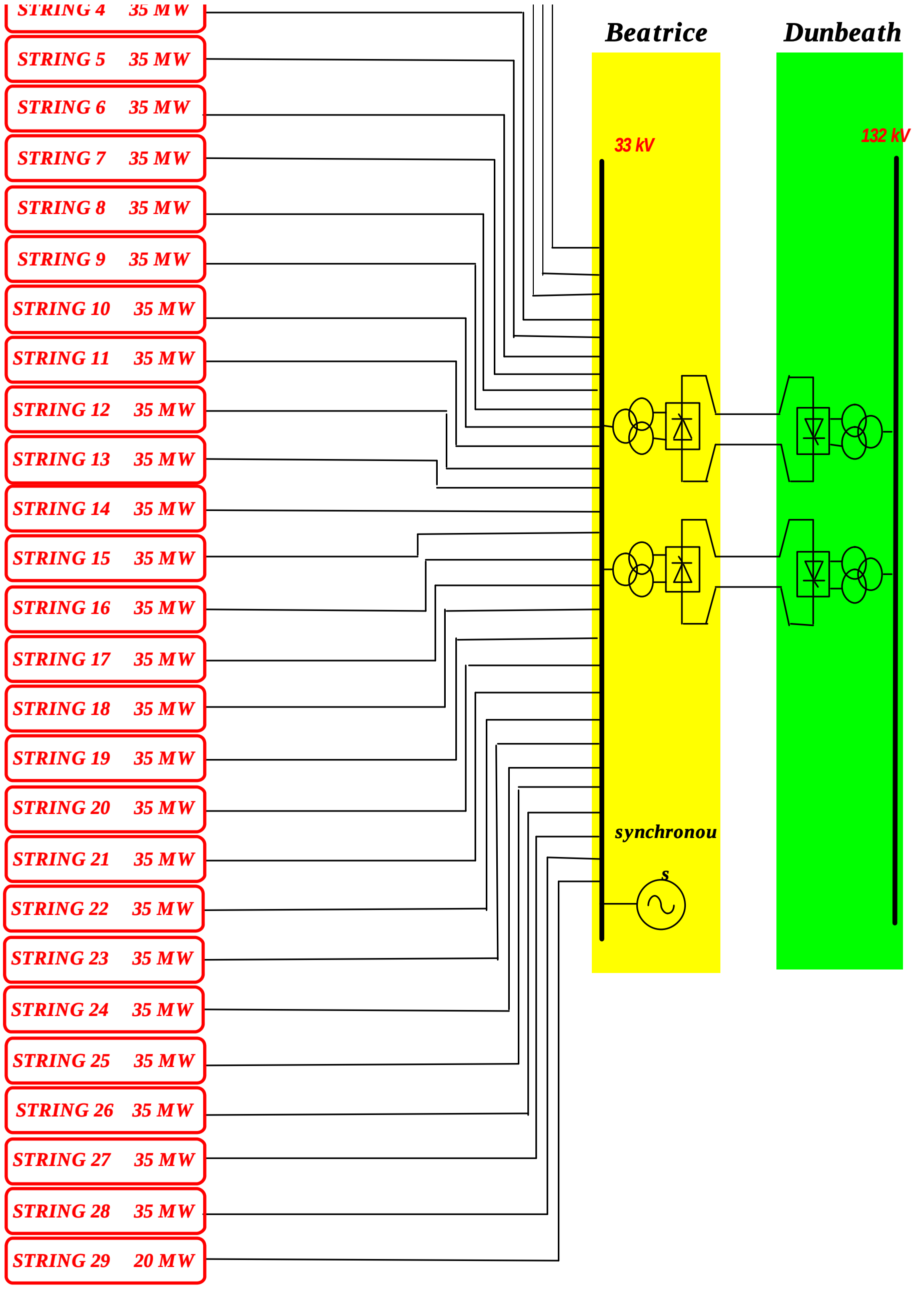


Figure 4.9 Simplified diagram showing the overall arrangement for transmission option 3

4.4 Chapter Summary

This chapter has examined the collection and transmission options for the proposed full-scale Beatrice OWF. It gave the specifications of the turbine transformers and the two types of turbine generators that were to be tested. It described the cabling arrangement within the farm collection system and how, in order to simplify the cable selection process, a system was devised where each cable was categorised into one of six groups.

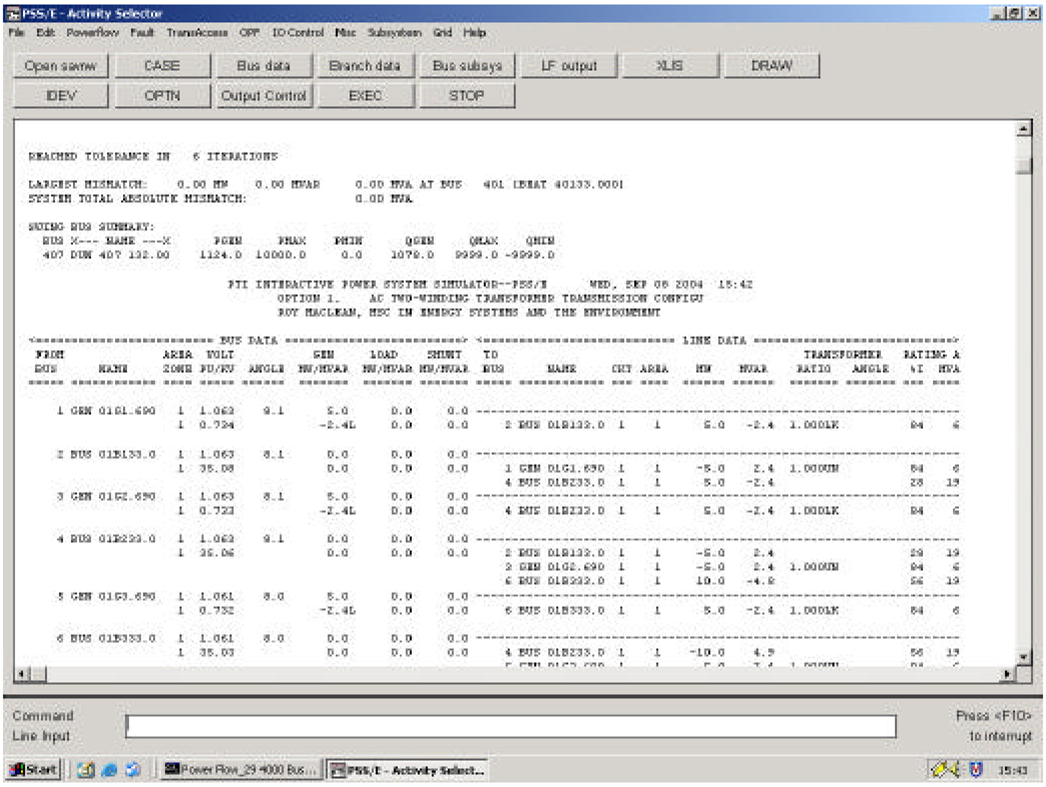
It also outlined three electrical designs chosen as a possible means of transmitting the generated electrical power to the grid network, two employing AC transmission technology and one employing DC transmission technology. The performance of the various electrical configurations and comparison between AC and DC transmission is discussed in chapter 5.

CHAPTER FIVE

ELECTRICAL PERFORMANCE OF OFFSHORE WIND FARM AND DESIGN RECOMMENDATIONS

5.1 Introduction

In the previous chapter, an electrical collection system and three distinct transmission configurations for the Beatrice OWF were outlined. The purpose of this chapter is to examine the electrical performance of each option. The analysis was undertaken within the PSS/E^{TM} power flow simulator program. PSS/E^{TM} is an interactive program for simulating, analysing and optimising power system performance. In this case, the analysis considered a steady-state network solution and used the "Full Newton-Raphson" algorithms to calculate the power flows; bus voltages and angles and losses in the electrical components between the wind turbine generators and the shore connection. The program code written to assess each option is given in condensed form in Appendix A and in full in Appendix B.



```
REACHED TOLERANCE IN    6 ITERATIONS

LARGEST MISMATCH:     0.00 MW     0.00 MVAR      0.00 MVA AT BUS    401 [BEAT 40133.000]
SYSTEM TOTAL ABSOLUTE MISMATCH:                  0.00 MVA

SWING BUS SUMMARY:
  BUS X--- NAME ---X      PGEN     PMAX    PMIN      QGEN     QMAX    QMIN
  407 DUN 407 132.00    1124.0  10000.0     0.0    1079.0   9999.0 -9999.0

                         PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      WED, SEP 08 2004  15:42
                              OPTION 1.    AC TWO-WINDING TRANSFORMER TRANSMISSION CONFIGU
                              ROY MACLEAN, MSC IN ENERGY SYSTEMS AND THE ENVIRONMENT

<======================== BUS DATA ========================> <========================= LINE DATA ==========================>
 FROM                  AREA  VOLT           GEN     LOAD   SHUNT   TO                                       TRANSFORMER    RATING A
 BUS      NAME         ZONE PU/KV  ANGLE  MW/MVAR MW/MVAR MW/MVAR BUS      NAME      CKT AREA    MW    MVAR    RATIO   ANGLE  %I  MVA
===== ============ ==== ===== ====== ======= ======= ======= ===== ============ === ====  ====== ======  ======= ======= === ====

    1 GEN 01G1.690   1  1.063    8.1     5.0     0.0     0.0 -----------------------------------------------------------------
                     1  0.724          -2.4L     0.0     0.0     2 BUS 01B133.0  1    1      5.0   -2.4  1.000LK           84    6

    2 BUS 01B133.0   1  1.063    8.1     0.0     0.0     0.0 -----------------------------------------------------------------
                     1  35.08            0.0     0.0     0.0     1 GEN 01G1.690  1    1     -5.0    2.4  1.000UN           84    6
                                                                 4 BUS 01B233.0  1    1      5.0   -2.4                    28   19
    3 GEN 01G2.690   1  1.063    8.1     5.0     0.0     0.0 -----------------------------------------------------------------
                     1  0.723          -2.4L     0.0     0.0     4 BUS 01B233.0  1    1      5.0   -2.4  1.000LK           84    6

    4 BUS 01B233.0   1  1.063    8.1     0.0     0.0     0.0 -----------------------------------------------------------------
                     1  35.06            0.0     0.0     0.0     2 BUS 01B133.0  1    1     -5.0    2.4                    28   19
                                                                 3 GEN 01G2.690  1    1     -5.0    2.4  1.000UN           84    6
                                                                 6 BUS 01B333.0  1    1     10.0   -4.8                    56   19
    5 GEN 01G3.690   1  1.061    8.0     5.0     0.0     0.0 -----------------------------------------------------------------
                     1  0.732          -2.4L     0.0     0.0     6 BUS 01B333.0  1    1      5.0   -2.4  1.000LK           84    6

    6 BUS 01B333.0   1  1.061    8.0     0.0     0.0     0.0 -----------------------------------------------------------------
                     1  35.03            0.0     0.0     0.0     4 BUS 01B233.0  1    1    -10.0    4.9                    56   19
```

Figure 5.1 Screen shot of the PSS/E^{TM} power system simulator tool

5.2 Simulation results

5.2.1 Magnitude and phase of the voltage at OWF buses

For the three transmission options the voltage and phase angle of each bus was calculated for both IGs and DFIGs. The results are shown in Tables 5.1, 5.2 and 5.3.

Bus	Voltage (kV)		Voltage (pu)		Angle (degrees)	
	IG	DFIG	IG	DFIG	IG	DFIG
Turbine 1 - 33 kV	34.77	35.03	1.054	1.062	8.6	8.0
Turbine 2 - 33 kV	34.76	35.01	1.053	1.061	8.5	8.0
Turbine 3 - 33 kV	34.73	34.98	1.052	1.060	8.4	7.9
Turbine 4 - 33 kV	34.70	34.95	1.052	1.059	8.3	7.8
Turbine 5 - 33 kV	34.67	34.92	1.051	1.058	8.1	7.6
Turbine 6 - 33 kV	34.65	34.90	1.050	1.058	7.9	7.4
Turbine 7 - 33 kV	34.65	34.88	1.050	1.057	7.7	7.2
Beatrice - 33 kV	34.70	34.89	1.052	1.057	6.6	6.2
Dunbeath - 132 kV	132	132	1.0	1.0	0.0	0.0

Table 5.1 Summary of bus voltages for option 1

Bus	Voltage (kV)		Voltage (pu)		Angle (degrees)	
	IG	DFIG	IG	DFIG	IG	DFIG
Turbine 1 - 33 kV	35.00	35.33	1.061	1.071	10.6	9.8
Turbine 2 - 33 kV	34.98	35.31	1.060	1.070	10.5	9.8
Turbine 3 - 33 kV	34.95	35.28	1.059	1.069	10.4	9.7
Turbine 4 - 33 kV	34.93	35.25	1.058	1.068	10.3	9.6
Turbine 5 - 33 kV	34.90	35.22	1.057	1.067	10.1	9.4
Turbine 6 - 33 kV	34.89	35.20	1.057	1.067	10.0	9.3
Turbine 7 - 33 kV	34.88	35.18	1.057	1.066	9.8	9.1
Beatrice - 33 kV	34.93	35.19	1.059	1.066	8.6	8.0
Dunbeath - 132 kV	132	132	1.0	1.0	0.0	0.0

Table 5.2 Summary of bus voltages for option 2

Bus	Voltage (kV)		Voltage (pu)		Angle (degrees)	
	IG	DFIG	IG	DFIG	IG	DFIG
Turbine 1 - 33 kV	33.1	33.02	1.000	1.001	3.7	3.7
Turbine 2 - 33 kV	33.0	33.0	1.000	1.000	3.7	3.7
Turbine 3 - 33 kV	32.95	32.97	0.999	0.999	3.6	3.6
Turbine 4 - 33 kV	33.00	33.00	1.000	1.000	2.7	2.7
Turbine 5 - 33 kV	33.08	33.10	1.003	1.003	1.6	1.6
Turbine 6 - 33 kV	33.05	33.07	1.002	1.002	1.4	1.4
Turbine 7 - 33 kV	33.02	33.02	1.001	1.001	1.2	1.2
Beatrice - 33 kV	32.98	32.98	0.999	0.999	0.0	0.0
Dunbeath - 132 kV	132	132	1.0	1.0	0.0	0.0

Table 5.3 Summary of bus voltages for option 3

The simulation results showed that all the turbine and Beatrice buses had a higher than anticipated voltage level in the AC options 1 and 2. In both cases many of the voltages were around 35 kV, 2000 volts over the chosen bus voltage. Therefore, in practice all the switchgear and other affected electrical equipment must have adequate voltage control and compensation capabilities to tolerate the voltage rise without sustaining damage. In contrast, the DC transmission option had a far smaller voltage deviation, ranging from 32.95 kV to 33.1 kV and so would not require the same level of voltage control. One reason why the DC bus voltage is closer to the selected voltage rating than either of the two AC options is because the DC converters form a buffer between the collection system and the grid network.

The voltage drop in the cables linking each turbine and between each string of turbines and the Beatrice was calculated to ensure that the voltage level remained within acceptable limits. A voltage drop that does not exceed 4% of the nominal voltage of the supply is normally deemed to be acceptable [15]. Voltage drop is always a critical issue because of the corresponding rise in current, which can cause damage to the system.

The voltage drop calculations showed that the drop between each turbine was relatively, very small for all three transmission options. Both AC options had a 0.4% drop in voltage between turbines 1 and 7 when IGs were employed and a 0.45% drop when DFIGs were used. The DC option had an even smaller voltage drop, 0.15% when IGs were employed and no mean voltage drop when DFIGs were used. The voltage drop in the category 4 cables were also well within acceptable limits. This very small voltage drop in all 3 options may be because each cable conductor was sized based on its power rating rather than on the maximum allowable voltage drop. These results suggest that smaller cables than those chosen in chapter 4 could be used provided the current ratings remained adequate.

5.2.2 Power flow for each cable category

For the three transmission options the power flow, of each of the cable categories described in chapter 4, was calculated. As before, each transmission option was simulated using IGs and DFIGs in order to compare the two. A summary of the power and current flow and the losses for each category is shown in Tables 5.4 to 5.9.

Cable category	**Real power (MW)**	**Reactive power (Mvar)**	**Current flow as a % of current rating (%)**	**Power losses (MW & Mvar)**
3A segment 1	5.0	-2.8	29	0.0 MW 0.0 Mvar
3B segment 3	15.0	-8.5	64	0.1 MW 0.0 Mvar
3C segment 5	24.9	-14.2	83	0.1 MW 0.1 Mvar
4	34.8	-20.1	96	0.4 MW 0.7 Mvar
6	172.1	-103.9	96	21 MW 13.2 Mvar

Table 5.4 Summary of cables power flow for option 1 IG

Cable category	Real power (MW)	Reactive power (Mvar)	Current flow as a % of current rating (%)	Power losses (MW & Mvar)
3A segment 1	5.0	2.4	28	0.0 MW 0.0 Mvar
3B segment 3	15.0	-7.3	61	0.1 MW 0.0 Mvar
3C segment 5	24.9	-12.2	80	0.1 MW 0.0 Mvar
4	34.8	-17.2	92	0.3 MW 0.6 Mvar
6	172.4	-89.2	92	19.4 MW 12.1 Mvar

Table 5.5 Summary of cables power flow for option 1 DFIG

Cable category	Real power (MW)	Reactive power (Mvar)	Current flow as a % of current rating (%)	Power losses (MW & Mvar)
3A segment 1	5.0	-2.8	29	0.0 MW 0.0 Mvar
3B segment 3	15.0	-8.5	63	0.1 MW 0.0 Mvar
3C segment 5	24.9	-14.2	83	0.1 MW 0.1 Mvar
4	34.8	-20.1	96	0.4 MW 0.7 Mvar
6	233.7	-194.3	76	41.7 MW 28.3 Mvar

Table 5.6 Summary of cables power flow for option 2 IG

Cable category	**Real power (MW)**	**Reactive power (Mvar)**	**Current flow as a % of current rating (%)**	**Power losses (MW & Mvar)**
3A segment 1	5.0	-2.4	28	0.0 MW 0.0 Mvar
3B segment 3	15.0	-7.3	61	0.0 MW 0.0 Mvar
3C segment 5	24.9	-12.2	79	0.0 MW 0.0 Mvar
4	34.8	-17.2	92	0.3 MW 0.6 Mvar
6	237.5	-168.5	73	38.3 MW 25.9 Mvar

Table 5.7 Summary of cables power flow for option 2 DFIG

Cable category	**Real power (MW)**	**Reactive power (Mvar)**	**Current flow as a % of current rating (%)**	**Power losses (MW & Mvar)**
3A segment 1	5.0	-2.8	31	0.0 MW 0.0 Mvar
3B segment 3	15.0	-2.9	59	0.0 MW 0.2 Mvar
3C segment 5	24.9	-7.8	80	0.0 MW 0.1 Mvar
4	34.8	-13.6	94	0.3 MW 0.7 Mvar
6	500	146.9	-	0.6 MW 36.7 Mvar

Table 5.8 Summary of cables power flow for option 3 IG

Cable category	Real power (MW)	Reactive power (Mvar)	Current flow as a % of current rating (%)	Power losses (MW & Mvar)
3A segment 1	5.0	-2.4	30	0.0 MW 0.0 Mvar
3B segment 3	15.0	-2.4	59	0.1 MW 0.3 Mvar
3C segment 5	24.9	-7.8	80	0.0 MW 0.1 Mvar
4	34.8	-12.8	93	0.3 MW 0.7 Mvar
6	500	146.9	-	0.6 MW 36.7 Mvar

Table 5.9 Summary of cables power flow for option 3 DFIG

To ensure that the current in the various branches of the OWF did not exceed a safe working limit they must all be operating below 100% of their maximum current rating. The power flow calculations showed that every cable in each design was operating within this level. Interestingly, the simulation results showed that for the DFIG machine scenarios, the cables had slightly less current flowing through them compared with the IG scenarios. This could therefore potentially permit the use of a smaller cable conductor for certain cable categories if DFIG were employed.

The power losses within each sting were small - around 0.1 MW and 0.1 Mvar, for all three options. As expected, by far the largest losses for each option occurred in the 25 km long sea to shore cables. For option 1, the six sea to shore transmission cables each had real and reactive power losses of ~20 MW and ~12.5 MW and for option 2; the four transmission cables each had real and reactive power losses of ~40 MW and ~27 MW respectfully. These figures show that the transmission losses for option 2 were significantly higher than option 1. The DC option had very small real power transmission losses, 0.6 MW, but, significantly, higher reactive power losses, 36.7

Mvar than either of the AC configurations. This higher reactive power loss may be due to the HVDC converters on either end of the transmission line.

5.2.3 Effect on the grid network

This wind farm is made up of 200 generators and transformers, all of which require reactive power to function. The power factor of these machines is, therefore, less than unity and so, too, is the power factor of the OWF where they are installed. A low power factor increases the cost of electricity because utilities must generate the reactive power elsewhere and then supply it to the farm. Most electrical utilities require that the power factor of generation plant is between 90% - 95%. Tables 5.10 gives a summary of the total real power output from the farm and the demand for reactive power for each design.

Transmission option		**Total real power output (MW)**	**Total reactive power required (Mvar)**
Option 1	*IG*	868.2	665.8
	DFIG	878.4	576.2
Option 2	*IG*	844.8	686.5
	DFIG	857.4	595.0
Option 3	*IG*	998.8	$367.7_{grid} + 702.6_{SC} = 1069.7$
	DFIG	998.8	$367.7_{grid} + 679.7_{SC} = 1047.4$

Table 5.10 Summary of the total power output and input for each option

Two things are immediately obvious from the load flow calculations. Firstly, option 3 is far more efficient at transferring useful work to the grid than either of the two AC options. Secondly, all the options require a considerable amount of reactive power compensation. It should be noted that the amount of reactive power compensation required from the grid by all three options is reduced when DFIG were employed.

The total amount of reactive power needed for option 1 with IGs was 665.8 Mvar, giving a power factor ? 0.83. Option 2 with IGs had a slightly smaller power factor ˜ 0.82. In both cases the power factor increased by 4% when DFIGs were used. In order to increase the power factor for options 1 and 2 with IGs to ? 0.95 (required by utility) approximately 337 Mvar and 357.8 Mvar respectfully must be installed. If DFIGs were used approximately 247.5 Mvar must be installed for option 1 and 266.3 Mvar for option 2. To improve the power factor a capacitor bank could be installed at the 132 kV bus offshore. This could supply part, or all, of the reactive power required by the plant.

The total amount of reactive power required for option 3 with IGs was 1069.7 Mvar, 367.7 supplied form the grid and 702.6 supplied for the synchronous compensator. In a contrast to both AC options, using DFIGs had less impact on reducing the demand for reactive power. The results showed that a very large synchronous compensator was needed for the DC design. This could be because there was no reactive power control by the HVDC converter in this study and no switched capacitor banks. In reality, with switched capacitor banks and the reactive power control capability of the HVDC converter, a much smaller compensator could be used. The overall losses for option 1 are less than option 2.

CHAPTER SIX

CONCLUDING REMARKS

6.1 Summary of Research

In this project, the design and comparison of various electrical arrangements for the proposed 1 GW Beatrice OWF in the Moray Firth were investigated. A thorough study of up-to-date and relevant literature and background material on the electrical aspects of OWFs was completed as well as a study of the history of the Beatrice oilfield and how the OWF idea came about. The upcoming plan to test two demonstrator turbines adjacent to the Beatrice Alpha was also examined.

The geographic layout of the proposed full-scale wind farm, the arrangement of turbines and the cable lengths, rating and type were chosen. Suitable types of generator and transformers were also selected. Three different electrical configurations to perform the function of power transmission to shore were investigated, two utilising alternating current (AC) transmission technology; and one direct current (DC) transmission technology. Using the power system simulator program, PSS/E^{TM}, the flow of power in the main electrical components present in each configuration was identified and conclusions drawn.

6.2 Conclusions

Offshore wind power in Scotland can make a major contribution to climate change objectives, to secure electricity supplies and to the economic well-being of the nation through job creation and exports. However, offshore wind generation poses many new challenges. The proposed 1 GW Beatrice OWF development has some particularly formidable problems not only due to its size but because uniquely, it will combine offshore oilfield capability and infrastructure with wind farm technology.

This dissertation sought to design an effective electrical system for the proposed Beatrice OWF. It has provided specifications for the main electrical equipment sited within the wind farm as well as details of three possible transmission options.

The electrical collection system proposed in this paper led to a higher than expected voltage level in the turbine and Beatrice buses when AC transmission was employed. In contrast, the DC transmission option had a far smaller turbine bus voltage rise. The voltage drop and current flow within the collection system was shown to be well within acceptable limits.

With transmission costing as much as 20% of the total farm costs, the choice of transmission voltage and accompanying technology is an important one. Both AC and DC transmission need a considerable amount of reactive power compensation to be supplied from the grid. The simulations of different transmission techniques showed that DC transmission had higher reactive power losses but smaller overall losses than AC transmission; however DC required a very large amount of compensatory reactive power on the wind farm end to operate. Consequently a large synchronous machine or power electronics would be required on the Beatrice and because the conventional DC converters themselves are typically quite large, the limited space on the Beatrice platform may be a problem.

Especially at sea, the total cost of a cable is mainly determined by the cost of laying it, so it is best to minimise the number of individual cables. In this respect, DC had the advantage of only two sea-to-shore transmission cables, while the AC options require a minimum of four transmission cables to transmit the farm output.

Major technical, regulatory and environmental challenges will have to be conquered to construct the OWF Talisman and SSE envisage. It will require a great deal of effort and ingenuity to deliver a sustainable development, which is commercially viable, environmentally sound and provides jobs and economic opportunities for Scotland. This project has provided useful data on the Beatrice offshore wind farm project and it is hoped that its findings have contributed to the knowledge and understanding of some of the issues facing this ground-breaking venture.

6.3 Recommendations for Future Work

This work can be used as a stepping-stone for the development of more detailed models. For example, the designs presented in this paper have been modelled in steady-state not dynamically but wind turbines are dynamic entities. They produce power that varies in a broad range of frequencies and amplitudes. These continuous variations of active and reactive power from the wind farm cause dynamic voltage variations. The next step to make the electrical designs in this paper more realistic would be to model them dynamically.

This study has not considered the physical impact of a large-scale wind farm on the immediate environment. The Moray Firth is a haven for wildlife. The open sea supports a wealth of marine life as well as a resident population of dolphins, seals, porpoises and whales, all of which play a vital role in the marine ecosystem. The possible effects of electromagnetic fields created by underwater power cables on undersea fauna is not very well understood [48]. Any future electrical study should consider the possible negative effects of the electromagnetic fields from the cable as they could have a negative influence on marine life and preserve the outstanding environment of the Moray Firth.

For this project it was assumed the transmission to shore was made at Dunbeath's 132 kV network. It would be interesting to investigate the effect of connecting these same electrical collection system designs to a 275 kV network. This would lower the electrical losses and, for AC transmission, perhaps allow fewer sea to shore cables. A future project must however balance the benefits against the substantially higher need for investment in the grid network.

REFERENCES

1. Scottish Executive. (2004) Renewable energy policy. Retrieved 2nd August from the Scottish Executive website (www.scotland.gov.uk).
2. Richardson B. and Jones P. (2004) Bringing wind power ashore. *The IEE Power Engineer, Vol. 18 No. 1* (pp. 35). IEE.
3. Manwell J. F., McGowan J. G. and Rogers A. L. (2003) Induction machines. *Wind Energy Explained* (pp.223). Wiley.
4. ABB (2004) Wind turbine generators and transformers. Retrieved 2nd August from the ABB website (www.abb.co.uk).
5. Wood J. (2004) Up and Running?. *The IEE Power Engineer, Vol. 18 No. 4* (pp. 26). IEE.
6. Pechey J. (2004) North Hoyle: the UK's first major offshore wind farm. *IEE Seminar: Electrical Aspects of Offshore Renewable Energy Systems* 24-25 February 2004. IEE.
7. Design & Construction Engineers data sheet (2004) ANSI standard dry-type transformer specification. Retrieved 17th August from D&C Engineer's website (www.dcengineers.com).
8. Vestas V90 - 3 MW An effective way to move power. Retrieved July 29th from Vestas website (www.vestas.com).
9. Gardner P., Craig L. and Smith G. (1997) Electrical Systems for Offshore Wind Farms. Garrad Hassan & Partners.
10. Nexans cable brochures on Horns Rev OWF and HVDC Scotland to Northern Ireland link. Retrieved 19th August from the Nexans website (www.nexans.no).
11. Grainger W. and Jenkins N. (1998) Offshore Wind Farm Electrical Connection Options. *Paper by Border Wind Ltd and Dept. of Electrical Engineering and Electronics, UMIST*. Retrieved 14th July from the OWEN website (www.owen.eru.rl.ac.uk).
12. Wright S., Rogers A., Manwell J. and Ellis A. (2002) Transmission Options for Offshore Wind Farms in the United States. *Renewable Energy Research Lab, University of Massachusetts*. Retrieved 14th July from the University of

Massachusetts website (www.ecs.umass.edu).

13. Smith M. (2004) email correspondence with Scottish and Southern Energy. 26th July 2004
14. Nexans (2004) presentation on Horns Rev offshore windfarm
15. British Standard (2001) Requirements for Electrical Installations BS 7671:2001 *IEE Wiring Regualtions 16TH Edition*
16. Christiansen P. and Kristoffersen J. R. (2003) The Wind Farm Main Controller and the Remote Control System of the Horns Rev Offshore Wind Farm. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
17. Kirby N. M., Xu L., Luckett M. and Siepmann W. (2002) HVDC transmission for large offshore wind farms. *Power Engineering Journal, Vol. 16 No. 3* (pp.135). IEE.
18. Balog G E., Christl N., Evenset G. and Rudolfsen F. (2003) Power Transmission over long distances with cables. *Nexans & Siemens paper 134-04*
19. Knutsen B. E. and Mikkelsen S. D. (2003) Development, manufacture, and installation of the world's most powerful 3-core HV submarine cable for the Horns Rev Wind Farm. *Nexans Norway paper*
20. Bathurst G. (2004) Line Commutated Convertor HVDC Transmission Schemes (for wind energy). *IPSA Power*. Retrieved 3rd of August from the IEE website (www.iee.org).
21. Christiansen P., Jorgensen K. and Sorensen A. (2002) Grid Connection and Remote Control for the Horns Rev 150 MW Offshore Wind Farm in Denmark. *Tech-wise paper*. Retrieved 3rd of August form horns rev website (www.hornsrev.dk)
22. Jonasson K., Carlson M. and Goteborg E. (2003) Integration of a 300 MW Wind Park at Fladen, Kategatt, into the Swedish 130 kV grid *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
23. Ohrstrom M. and Soder L. (2003) The use of fault current limiters as an alternative to substation upgrade when there is a need to increase the available

short-circuit power. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.

24. Rasmussen C., Jorgensen P. and Havsager J. (2003) Integration of wind power in the grid in Eastern Denmark. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
25. Bolik S. M. (2003) Grid Requirements challenges for Wind Turbines. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
26. Brakeelmann H. (2003) Aspects of cabling in great offshore wind farms. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
27. Eriksson K. and Wensky D. (2003) Systems approach on designing an offshore windpower grid connection. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
28. Weatherill J. (2000) Feasibility of HVDC Transmission Networks for Offshore Wind Farms. *Review of First International Workshop on Feasibility of HVDC Transmission Networks for Offshore Wind Farms Stockholm March 2000*. Retrieved 14th July from the OWEN website (www.owen.eru.rl.ac.uk).
29. Sobrink K, Woodford D. and Belhomme R. (2003) AC Cable versus DC Cable Transmission for Offshore Wind Farms, a Study Case. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
30. Lahtinen M. J. and Katancevic A. R. (2003) Considerations of Requirements of TSO for Wind Farm Connection. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
31. Ekanayake J, Holdsworth L. and Jenkins N. (2003) Control of DFIG wind turbines. Power Engineer Vol. 17 issue 1 p28. (IEE).
32. Fortmann J. (2003) Validation of DFIG model using 1.5 MW turbine for the analysis of its behaviour during voltage drops in the 100 kV grid. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.

33. Poller M. and Achilles S. (2003) Aggregated Wind Park Models for Analysing Power System Dynamics. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
34. Morren J., Pierik J., de Haan S. and Bozelie J. (2003) Fast Dynamic Models of Offshore Wind Farms for Power System Studies. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
35. Lyne J. (2003) Talisman Outlines Record-Setting Offshore Wind Farm. Retrieved 24th June from the Site Selection Online insider website. (www.conway.com/ssinsider).
36. DTI (2004) UK Monthly Oil Production - Beatrice. Retrieved 16th August from DTI website (www.og.dti.gov.uk).
37. Symon K. (2003) World's first deepwater offshore wind farm. *Sunday Herald August 31, 2003*.
38. Talisman Energy and Scottish and Southern Energy Presentation (2004) Cost Effective Offshore Windfarms in Deepwater "DOWNViND". Retrieved 16th August 2004 from europa website (www.europa.eu.int/comm/energy/res/events/doc)
39. MacAskill A. (2004) Beatrice windfarm comes step nearer. *The Press and Journal, ENERGY September 2004.*
40. Talisman slide Presentation. (2004) Beatrice Windfarm Demonstrator, Castleton House Hotel 5th May 2004. *FEED Study Results Technical & Commercial Review*
41. Watson J. (2004) Talisman sinks £350m in oil, wind projects. *The Press and Journal, Friday August 27th 2004 page 1.*
42. Blakeley P. (2004) Windfarm a barmy idea that got a head of steam. *The Press and Journal, ENERGY September 2004.*
43. Macdonald A. (2004) Wind farm plan for oil field moves step closer. Retrieved 20th July from this is north Scotland website. (www.thisisnorthscotland.co.uk).
44. DWEA (2004) Frequently Asked Questions About Wind Energy. Retrieved 13th August from Danish wind industry association website

(www.windpower.org/en/faqs.htm)

45. Wildi T. (2000) *Electrical Machines, Drives, and Power Systems*. Fourth ed. Prentice Hall.
46. Bryan C., Smith J. W., Taylor J. and Zavadil B. (2003) Engineering Design and Integration Experience from Cape Wind 420 MW Offshore Wind Farm. *International workshop on large-scale integration of wind power and transmission networks for offshore wind farms*.
47. ABB (2004) Submarine cables for inter-turbine connections. Retrieved August 10th from ABB website (www.abb.com/cables).
48. Energi report (2002) Nysted Offshore Wind Farm Environmental Monitoring Program 2002.

BIBLIOGRAPHY

1. J. Pierik, M Damen, P. Bauer and S de Hann. (2001) Electrical and control aspects of offshore wind farms. Vol. 1
2. Rademakers L. and Braam H. (2002) O & M Aspects of the 500 MW Offshore Wind Farm at NL7 - 80 x 6 MW Baseline Configuration. *Document DOWEC 10080 rev 2*.
3. Pavlovsky M. and Bauer P. (2002) Cable Selection and Shunt Compensation for Offshore Windparks. *Delft University of Technology*
4. Atkinson I., Harvey C., Smith M., Damgaard P., Haeusler M., Kuhn M., Lips P., Wohlmuth M., Balog G. and Stenseth K. (2002) The Moyle interconnector. *Power Engineering Journal, Vol. 16 No. 3* (pp. 117). IEE.
5. Halliburton. (2004) KBR appointed as consultant for the Beatrice offshore wind farm front-end engineering. Retrieved 24th June 2004 from Halliburton website. (www.halliburton.com)
6. Milborrow D., 2002, “Assimilating wind”, *IEE Review*, Vol. 48 No. 1, 11, (IEE)

APPENDIX A

A.1 Main PSS/E^{TM} values for the Beatrice OWF collection system

This section highlights the most important values in the OWF models. For an explanation of how these values were derived refer to chapters three and four. Appendix B gives the Raw. Data files used in PSS/E^{TM}.

Bus Data

	Generator bus	*Turbine bus*	*Beatrice bus*	*National Grid bus*
BASKV	0.69 kV	33 kV	33 kV	132 kV
IDE	2	1	1	3

Load Data

PL	2000 MW
QL	500 Mvar

Generator Data

	Fixed speed	*Variable speed*
P	5 MW	5 MW
Q	0 Mvar	2.42 Mvar
Qmax	0 Mvar	2.42 Mvar
Qmin	-2.83 Mvar	-2.42 Mvar
Pmax	5 MW	5 MW
Pmin	0 MW	0 MW

Non-transformer Branch data

	Class 1	*Class 2*	*Class 3A*	*Class 3B*	*Class 3C*	*Class 4*
Length (km)	-	0.09	0.9	0.9	0.9	5.0
R (pu)	0	0.0017	0.0165	0.0132	0.0066	0.0230
X (pu)	0	0.0011	0.0106	0.0104	0.0093	0.0476
Rating (MVA)	6.25	18.6	18.6	25.7	32.7	39.7

Transformer Data

	Turbine transformer
R1-2	0.0017 pu
X1-2	0.0011 pu
Rating	6.25 MVA
RMA	1.025 pu
RMI	0.975 pu

A.2 Main PSS/E^{TM} values for the Beatrice OWF transmission system

A.2.1 Option 1 - Two-winding AC transformer

Branch data

	Class 5	*Class 6*
Length (km)	-	25
R (pu)	0	0.0574
X (pu)	0	0.0361
Rating (MVA)	85	170

Transformer Data

	Beatrice Transformer
R1-2	0.0574 pu
X1-2	0.0361 pu
Rating	170 MVA
RMA	1.1 pu
RMI	0.9 pu

A.2.2 Option 2 - Three-winding AC transformer

Branch data

	Class 5	*Class 6*
Length (km)	-	25
R (pu)	0	0.0603
X (pu)	0	0.0406
Rating (MVA)	125	250

Transformer Data

	Beatrice Transformer
R1-2	0.0603
X1-2	0.0406
R2-3	0.0603
X2-3	0.0406
R3-1	0.0603
X3-1	0.0406
RMA	1.1
RMI	0.9

	Winding 1	*Winding 2*	*Winding 3*
Rating	400 MVA	200 MVA	200 MVA

A.2.3 Option 3 - HVDC transformer

Branch data

	Class 5	*Class 6*
Length (km)	-	25
R (pu)		0.0002
Rating (MVA)	500 MVA	500 MVA

Two-Terminal DC Line Data

RDC	0.3775 ?
SETVL	500 MW
VSCHD	400 kV
VCMOD	100 kV
DELTI	0.1 pu

	Rectifier	*Inverter*
NB	2	2
MX	15^o	19^o
MN	10^0	16^0
XC	4 ?	4 ?
EBASE	33 kV	132 kV
TR	4.545	1.1364

APPENDIX B

B.1 Raw Data Files

This appendix provides the power flow source data records that were used to simulate the various electrical designs developed for this project. Note for the sake of brevity, only the IG models are shown here. The DFIG generator data is given in appendix A.

B.1.1 Option 1 - HVAC transmission using two-winding transformers

```
@! RAW data file for PSS/E v.29
0    100.00
Option 1.     AC two-winding transformer transmission configuration with IG
Roy Maclean, MSc in Energy Systems and the Environment
@!
@! Bus data
@!     Bus    Name          kV     Type   Y_re   Y_im   Area   Zone   V      Ang    Owner
       1      'GEN 01G1'    0.69   2      0      0      1      1      1      0      1
       2      'BUS 01B1'    33     1      0      0      1      1      1      0      1
       3      'GEN 01G2'    0.69   2      0      0      1      1      1      0      1
       4      'BUS 01B2'    33     1      0      0      1      1      1      0      1
       5      'GEN 01G3'    0.69   2      0      0      1      1      1      0      1
       6      'BUS 01B3'    33     1      0      0      1      1      1      0      1
       7      'GEN 01G4'    0.69   2      0      0      1      1      1      0      1
       8      'BUS 01B4'    33     1      0      0      1      1      1      0      1
       9      'GEN 01G5'    0.69   2      0      0      1      1      1      0      1
       10     'BUS 01B5'    33     1      0      0      1      1      1      0      1
       .
       .
       .
       .
       .
       390    'BUS 28B6'    33     1      0      0      1      1      1      0      1
       391    'GEN 28G7'    0.69   2      0      0      1      1      1      0      1
       392    'BUS 28B7'    33     1      0      0      1      1      1      0      1
       393    'GEN 29G1'    0.69   2      0      0      1      1      1      0      1
       394    'BUS 29B1'    33     1      0      0      1      1      1      0      1
       395    'GEN 29G2'    0.69   2      0      0      1      1      1      0      1
       396    'BUS 29B2'    33     1      0      0      1      1      1      0      1
       397    'GEN 29G3'    0.69   2      0      0      1      1      1      0      1
       398    'BUS 29B3'    33     1      0      0      1      1      1      0      1
       399    'GEN 29G4'    0.69   2      0      0      1      1      1      0      1
       400    'BUS 29B4'    33     1      0      0      1      1      1      0      1
       401    'BEAT 401'    33     1      0      0      1      1      1      0      1
       402    'BEAT 402'    33     1      0      0      1      1      1      0      1
       403    'BEAT 403'    33     1      0      0      1      1      1      0      1
       404    'BEAT 404'    33     1      0      0      1      1      1      0      1
       405    'BEAT 405'    33     1      0      0      1      1      1      0      1
       406    'BEAT 406'    33     1      0      0      1      1      1      0      1
       407    'DUN 407'     132    3      0      0      1      1      1      0      1
0
@! Load data
@!     Bus    I      Stat   Area   Zone   PL     QL     IP     IQ     YP     YQ     Owner
       407    1      1      1      1      2000   500    0      0      0      0      1
0
@! Generator data
@!     Bus    ID     P      Q      Qmax   Qmin   VS     RegBs  MVAbase       ZR     ZX     RTr    XTr    Gtap   Stat   %      Pmax   Pmin   Oi     Fi
       1      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       3      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       5      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       7      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       9      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       11     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       13     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       15     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       17     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       19     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       .
       .
       .
       .
       .
       389    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       391    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       393    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       395    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       397    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       399    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       407    '1'    10000  5000   9999   -9999  1      0      100           0      1      0      0      1      1      100    10000  0      1      1
0
@! Non-transformer branch data
@!     From   To     Ckt    R             X      B      RateA  RateB  RateC  GI     BI     GJ     BJ     Stat   Leng   Oi     Fi
       2      4      1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       4      6      1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
```

```
        6      8      1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        8      10     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        10     12     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        12     14     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        14     401    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        16     18     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        18     20     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        20     22     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        22     24     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        24     26     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        26     28     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        28     401    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        30     32     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        32     34     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        34     36     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        36     38     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        38     40     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        40     42     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        42     401    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        44     46     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        46     48     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        48     50     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        50     52     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        52     54     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        54     56     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        56     401    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        58     60     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        60     62     1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        62     64     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        64     66     1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        66     68     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        68     70     1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        70     401    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        .
        .
        .
        .
        .
        364    406    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        366    368    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        368    370    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        370    372    1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        372    374    1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        374    376    1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        376    378    1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        378    406    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        380    382    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        382    384    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        384    386    1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        386    388    1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        388    390    1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        390    392    1      0.0066        0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
        392    406    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
        394    396    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        396    398    1      0.0165        0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
        398    400    1      0.0107        0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
        400    406    1      0.023         0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
0
@! Transformer data
@!      From   To     K      ID     CW     CZ     CM     MAG1   MAG2   NMETR  'NAME'Stat   Oi     Fi
@!      R1-2   X1-2   SBASE1-2
@!      WINDV1NOMV1   ANG1   RATA1  RATB1  RATC1  COD    CONT   RMA    RMI    VMA    VMI    NTP    TAB    CR     CX
@!      WINDV2NOMV2
        1      2      0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      2      1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        3      4      0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      4      1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        5      6      0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      6      1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        7      8      0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      8      1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        9      10     0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      10     1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        .
        .
        .
        .
        .
        391    392    0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      394    1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        393    394    0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      394    1.025  0.975  1.1    0.9    33     0      0      0
        1      0
        395    396    0      '1'    1      1      1      0      0      2      ''     1      1      1
        0.0017 0.0011
        1      0      0      6.25   6.25   6.25   0      396    1.025  0.975  1.1    0.9    33     0      0      0
        1      0
```

```
       397    398    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      398    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       399    400    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      400    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       401    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
       402    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
       403    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
       404    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
       405    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
       406    407    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0574 0.0361
       1      0      0      200    200    200    0      407    1.1    0.9    1.1    0.9    33     0      0      0
       1      0
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
0 / END OF TWO-TERMINAL DC DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN IMPEDANCE CORRECTION DATA
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
0 / END OF OWNER DATA, BEGIN FACTS CONTROL DEVICE DATA
0 / END OF FACTS CONTROL DEVICE DATA
```

B.1.2 Option 2 - HVAC transmission using three-winding transformers

```
@! RAW data file for PSS/E v.29
0    100.00
Option 2.    AC three-winding transformer transmission configuration with IG
Roy Maclean, MSc in Energy Systems and the Environment
@!
@! Bus data
@!     Bus    Name          kV     Type   Y_re   Y_im   Area   Zone   V      Ang    Owner
       1      'GEN 01G1'    0.69   2      0      0      1      1      1      0      1
       2      'BUS 01B1'    33     1      0      0      1      1      1      0      1
       3      'GEN 01G2'    0.69   2      0      0      1      1      1      0      1
       4      'BUS 01B2'    33     1      0      0      1      1      1      0      1
       5      'GEN 01G3'    0.69   2      0      0      1      1      1      0      1
       6      'BUS 01B3'    33     1      0      0      1      1      1      0      1
       7      'GEN 01G4'    0.69   2      0      0      1      1      1      0      1
       8      'BUS 01B4'    33     1      0      0      1      1      1      0      1
       9      'GEN 01G5'    0.69   2      0      0      1      1      1      0      1
       10     'BUS 01B5'    33     1      0      0      1      1      1      0      1
       .
       .
       .
       .
       .
       390    'BUS 28B6'    33     1      0      0      1      1      1      0      1
       391    'GEN 28G7'    0.69   2      0      0      1      1      1      0      1
       392    'BUS 28B7'    33     1      0      0      1      1      1      0      1
       393    'GEN 29G1'    0.69   2      0      0      1      1      1      0      1
       394    'BUS 29B1'    33     1      0      0      1      1      1      0      1
       395    'GEN 29G2'    0.69   2      0      0      1      1      1      0      1
       396    'BUS 29B2'    33     1      0      0      1      1      1      0      1
       397    'GEN 29G3'    0.69   2      0      0      1      1      1      0      1
       398    'BUS 29B3'    33     1      0      0      1      1      1      0      1
       399    'GEN 29G4'    0.69   2      0      0      1      1      1      0      1
       400    'BUS 29B4'    33     1      0      0      1      1      1      0      1
       401    'BEAT 401'    33     1      0      0      1      1      1      0      1
       402    'BEAT 402'    33     1      0      0      1      1      1      0      1
       403    'BEAT 403'    33     1      0      0      1      1      1      0      1
       404    'BEAT 404'    33     1      0      0      1      1      1      0      1
       405    'BEAT 405'    33     1      0      0      1      1      1      0      1
       406    'BEAT 406'    33     1      0      0      1      1      1      0      1
       407    'BEAT 407'    33     1      0      0      1      1      1      0      1
       408    'BEAT 408'    33     1      0      0      1      1      1      0      1
       409    'DUN 409'     132    3      0      0      1      1      1      0      1
0
@! Load data
@!     Bus    I      Stat   Area   Zone   PL     QL     IP     IQ     YP     YQ     Owner
       409    1      1      1      1      2000   500    0      0      0      0      1
0
@! Generator data
@!     Bus    ID     P      Q      Qmax   Qmin   VS     RegBs  MVAbase       ZR     ZX     RTr    XTr    Gtap   Stat   %      Pmax   Pmin   Oi     Fi
       1      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
```

```
       3      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       5      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       7      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       9      '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       11     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       13     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       15     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       17     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       19     '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       .
       .
       .
       .
       .
       389    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       391    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       393    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       395    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       397    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       399    '1'    5      0      0      -2.83  1      0      100           0      1      0      0      1      1      100    5      0      1      1
       409    '1'    10000  5000   9999   -9999  1      0      100           0      1      0      0      1      1      100    10000  0      1      1
0
@! Non-transformer branch data
@!     From   To     Ckt    R      X      B      RateA  RateB  RateC  GI     BI     GJ     BJ     Stat   Leng   Oi     Fi
       2      4      1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       4      6      1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       6      8      1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       8      10     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       10     12     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       12     14     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       14     401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       16     18     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       18     20     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       20     22     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       22     24     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       24     26     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       26     28     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       28     401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       30     32     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       32     34     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       34     36     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       36     38     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       38     40     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       40     42     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       42     401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       44     46     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       46     48     1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       48     50     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       50     52     1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       52     54     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       54     56     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       56     401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       .
       .
       .
       .
       .
       338    340    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       340    342    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       342    344    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       344    346    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       346    348    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       348    350    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       350    407    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       352    354    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       354    356    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       356    358    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       358    360    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       360    362    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       362    364    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       364    407    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       366    368    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       368    370    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       370    372    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       372    374    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       374    376    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       376    378    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       378    408    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       380    382    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       382    384    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       384    386    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       386    388    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       388    390    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       390    392    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       392    408    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       394    396    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       396    398    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       398    400    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       400    408    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
0
@! Transformer data
@!     From   To     K      ID     CW     CZ     CM     MAG1   MAG2   NMETR  'NAME' Stat   Oi     Fi
@!     R1-2   X1-2   SBASE1-2      R2-3   X2-3   SBASE2-3      R3-1   X3-1   SBASE3-1      VMSTAR ANSTAR
@!     WINDV1NOMV1   ANG1   RATA1  RATB1  RATC1  COD    CONT   RMA    RMI    VMA    VMI    NTP    TAB    CR     CX
@!     WINDV2NOMV2   ANG2   RATA2  RATB2  RATC2
@!     WINDV3NOMV3   ANG3   RATA3  RATB3  RATC3
       1      2      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      2      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
```

```
       3      4      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      4      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       5      6      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      6      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       7      8      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      8      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       9      10     0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      10     1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       .
       .
       .
       .
       .
       381    382    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      382    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       383    384    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      384    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       385    386    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      386    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       387    388    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      388    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       389    390    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      390    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       391    392    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      392    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       393    394    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      394    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       395    396    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      396    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       397    398    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      398    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       399    400    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      400    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       409    401    402    '1'    1      1      1      0      0      2      ''     1      1      1
       0.0603 0.0406 100    0.0603 0.0406 100    0.0603 0.0406 100    1      0
       1      0      0      400    400    400    0      409    1.1    0.9    1.05   0.95   33     0      0      0
       1      0      0      200    200    200
       1      0      0      200    200    200
       409    403    404    '1'    1      1      1      0      0      2      ''     1      1      1
       0.0603 0.0406 100    0.0603 0.0406 100    0.0603 0.0406 100    1      0
       1      0      0      400    400    400    0      409    1.1    0.9    1.05   0.95   33     0      0      0
       1      0      0      200    200    200
       1      0      0      200    200    200
       409    405    406    '1'    1      1      1      0      0      2      ''     1      1      1
       0.0603 0.0406 100    0.0603 0.0406 100    0.0603 0.0406 100    1      0
       1      0      0      400    400    400    0      409    1.1    0.9    1.05   0.95   33     0      0      0
       1      0      0      200    200    200
       1      0      0      200    200    200
       409    407    408    '1'    1      1      1      0      0      2      ''     1      1      1
       0.0603 0.0406 100    0.0603 0.0406 100    0.0603 0.0406 100    1      0
       1      0      0      400    400    400    0      409    1.1    0.9    1.05   0.95   33     0      0      0
       1      0      0      200    200    200
       1      0      0      200    200    200
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
0 / END OF TWO-TERMINAL DC DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN IMPEDANCE CORRECTION DATA
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
0 / END OF OWNER DATA, BEGIN FACTS CONTROL DEVICE DATA
0 / END OF FACTS CONTROL DEVICE DATA
```

B.1.3 Option 3 - HVDC transmission

```
@! RAW data file for PSS/E v.29
0    100.00
```

```
Option 3.    HVDC transmission configuration with IG
Roy Maclean, MSc in Energy Systems and the Environment
@!
@! Bus data
@!      Bus     Name            kV      Type    Y_re    Y_im    Area    Zone    V       Ang     Owner
        1       'GEN 01G1'      0.69    2       0       0       1       1       1       0       1
        2       'BUS 01B1'      33      1       0       0       1       1       1       0       1
        3       'GEN 01G2'      0.69    2       0       0       1       1       1       0       1
        4       'BUS 01B2'      33      1       0       0       1       1       1       0       1
        5       'GEN 01G3'      0.69    2       0       0       1       1       1       0       1
        6       'BUS 01B3'      33      1       0       0       1       1       1       0       1
        7       'GEN 01G4'      0.69    2       0       0       1       1       1       0       1
        8       'BUS 01B4'      33      1       0       0       1       1       1       0       1
        9       'GEN 01G5'      0.69    2       0       0       1       1       1       0       1
        10      'BUS 01B5'      33      1       0       0       1       1       1       0       1
        .
        .
        .
        .
        .
        390     'BUS 28B6'      33      1       0       0       1       1       1       0       1
        391     'GEN 28G7'      0.69    2       0       0       1       1       1       0       1
        392     'BUS 28B7'      33      1       0       0       1       1       1       0       1
        393     'GEN 29G1'      0.69    2       0       0       1       1       1       0       1
        394     'BUS 29B1'      33      1       0       0       1       1       1       0       1
        395     'GEN 29G2'      0.69    2       0       0       1       1       1       0       1
        396     'BUS 29B2'      33      1       0       0       1       1       1       0       1
        397     'GEN 29G3'      0.69    2       0       0       1       1       1       0       1
        398     'BUS 29B3'      33      1       0       0       1       1       1       0       1
        399     'GEN 29G4'      0.69    2       0       0       1       1       1       0       1
        400     'BUS 29B4'      33      1       0       0       1       1       1       0       1
        401     'BEAT 401'      33      1       0       0       1       1       1       0       1
        402     'SC 403'        33      3       0       0       1       1       1       0       1
        403     'DUN 402'       132     3       0       0       1       1       1       0       1
0
@! Load data
@!      Bus     I       Stat    Area    Zone    PL      QL      IP      IQ      YP      YQ      Owner
        403     1       1       1       1       2000    500     0       0       0       0       1
0
@! Generator data
@!      Bus     ID      P       Q       Qmax    Qmin    VS      RegBs   MVAbase         ZR      ZX      RTr     XTr     Gtap    Stat    %       Pmax    Pmin    Oi      Fi
        1       '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        3       '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        5       '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        7       '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        9       '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        11      '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        13      '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        15      '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        17      '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        19      '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        .
        .
        .
        .
        .
        389     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        391     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        393     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        395     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        397     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        399     '1'     5       0       0       -2.83   1       0       100             0       1       0       0       1       1       100     5       0       1       1
        402     '1'     20      1000    1000    -1000   1       0       100             0       1       0       0       1       1       100     1000    0       1       1
        403     '1'     10000   5000    9999    -9999   1       0       100             0       1       0       0       1       1       100     10000   0       1       1
0
@! Non-transformer branch data
@!      From    To      Ckt     R       X       B       RateA   RateB   RateC   GI      BI      GJ      BJ      Stat    Length  Oi      Fi
        2       4       1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        4       6       1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        6       8       1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        8       10      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        10      12      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        12      14      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        14      401     1       0.023   0.0476  0       39.7    39.7    39.7    0       0       0       0       1       5       1       1
        16      18      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        18      20      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        20      22      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        22      24      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        24      26      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        26      28      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        28      401     1       0.023   0.0476  0       39.7    39.7    39.7    0       0       0       0       1       5       1       1
        30      32      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        32      34      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        34      36      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        36      38      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        38      40      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        40      42      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        42      401     1       0.023   0.0476  0       39.7    39.7    39.7    0       0       0       0       1       5       1       1
        44      46      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        46      48      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        48      50      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        50      52      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        52      54      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        54      56      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
        56      401     1       0.023   0.0476  0       39.7    39.7    39.7    0       0       0       0       1       5       1       1
        58      60      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        60      62      1       0.0165  0.0106  0       18.6    18.6    18.6    0       0       0       0       1       0.9     1       1
        62      64      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        64      66      1       0.0107  0.099   0       25.7    25.7    25.7    0       0       0       0       1       0.9     1       1
        66      68      1       0.0066  0.0093  0       32.7    32.7    32.7    0       0       0       0       1       0.9     1       1
```

```
       68     70     1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       70     401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       .
       .
       .
       .
       .
       364    401    1      0.0239 0.0495 0      39.7   39.7   39.7   0      0      0      0      1      5.5    1      1
       366    368    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       368    370    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       370    372    1      0.0107 0.099  0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       372    374    1      0.0107 0.099  0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       374    376    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       376    378    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       378    401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       380    382    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       382    384    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       384    386    1      0.0107 0.099  0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       386    388    1      0.0107 0.099  0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       388    390    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       390    392    1      0.0066 0.0093 0      32.7   32.7   32.7   0      0      0      0      1      0.9    1      1
       392    401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       394    396    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       396    398    1      0.0165 0.0106 0      18.6   18.6   18.6   0      0      0      0      1      0.9    1      1
       398    400    1      0.0107 0.0099 0      25.7   25.7   25.7   0      0      0      0      1      0.9    1      1
       400    401    1      0.023  0.0476 0      39.7   39.7   39.7   0      0      0      0      1      5      1      1
       401    402    1      0.0001 0.0001 0      750    750    750    0      0      0      0      1      0      1      1
0
@! Transformer data
@!     From   To     K      ID     CW     CZ     CM     MAG1   MAG2   NMETR  'NAME' Stat   Oi     Fi
@!     R1-2   X1-2   SBASE1-2
@!     WINDV1 NOMV1  ANG1   RATA1  RATB1  RATC1  COD    CONT   RMA    RMI    VMA    VMI    NTP    TAB    CR     CX
@!     WINDV2 NOMV2
       1      2      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      2      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       3      4      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      4      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       5      6      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      6      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       7      8      0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      8      1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       9      10     0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      10     1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       .
       .
       .
       .
       .
       389    390    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      390    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       391    392    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      392    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       393    394    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      394    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       395    396    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      396    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       397    398    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      398    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
       399    400    0      '1'    1      1      1      0      0      2      ''     1      1      1
       0.0017 0.0011
       1      0      0      6.25   6.25   6.25   0      400    1.025  0.975  1.1    0.9    33     0      0      0
       1      0
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
@! Two-terminal DC data
@!     Bus    MDC    RDC    SETVL  VSCHD  VCMOD  RCOMP  DELTI  METER  DCVMIN CCCITMX       CCCACC
@!     IPR    NBR    ALFMX  ALFMN  RCR    XCR    EBASR  TRR    TAPR   TMXR   TMNR   STPR          ICR    IFR    ITR    IDR    XCAPR
@!     IPI    NBI    GAMMX  GAMMN  RCI    XCI    EBASI  TRI    TAPI   TMXI   TMNI   STPI          ICI    IFI    ITI    IDI    XCAPI
       1      1      0.3775 500    400    100    0      0.1    'I'    0      20            1.0
       401    2      15     10     0      4.0    33     4.545  1      1.5    0.51   0.00625       0      0      0      '1'    0
       403    2      19     16     0      4.0    132    1.1364 1      1.5    0.51   0.00625       0      0      0      '1'    0
       2      1      0.3775 500    400    100    0      0.1    'I'    0      20            1.0
       401    2      15     10     0      4.0    33     4.545  1      1.5    0.51   0.00625       0      0      0      '1'    0
       403    2      19     16     0      4.0    132    1.1364 1      1.5    0.51   0.00625       0      0      0      '1'    0
0 / END OF TWO-TERMINAL DC DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN IMPEDANCE CORRECTION DATA
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
```

```
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
0 / END OF OWNER DATA, BEGIN FACTS CONTROL DEVICE DATA
0 / END OF FACTS CONTROL DEVICE DATA
```