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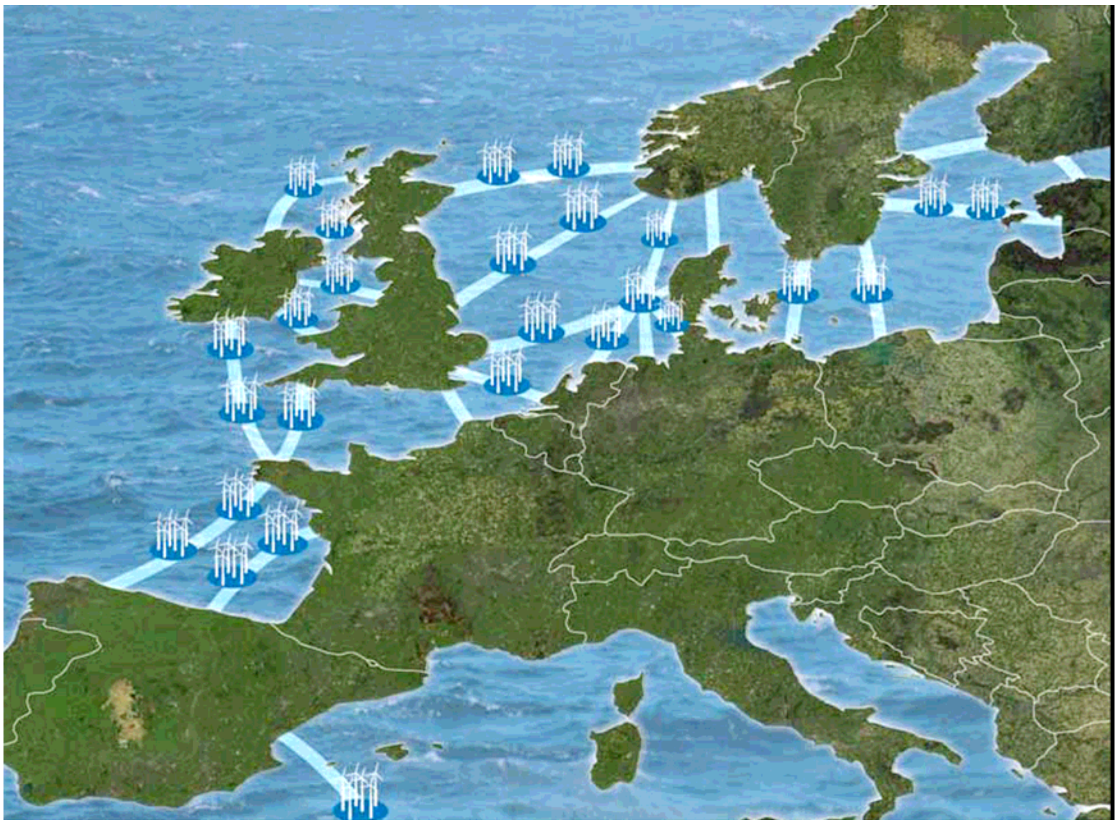

Offshore Wind Energy Integration in the European Power System

Thesis for the Degree of Master of Science

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008

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In Europe there are large plans for offshore wind energy and especially the North Sea region are of interest. This large scale integration of wind power generation in power systems presents several problems that must be confronted for a better development. Some of them are generation scheduling, load-frequency control, reactive power-voltage control and power system stability. In this thesis, the stability of the future North Sea electric grid in the presence of large off-shore wind farms will be studied.

A test system is modeled using the simulation tool PSS/E. The first step is to estimate the configuration and parameters of the offshore wind network connected to land. Results from the static and dynamic simulations of the model are analyzed to discuss how the power balance and system reliability with the increased wind power penetration can be maintained. The new technology based in transistors HVDC Light is taken in consideration for connecting islanded systems to AC grid systems when connection points are far away.

It is found that a scenario with more than 6% of offshore wind power supply does not serve grid connection requirements in UK. This value increases up to 12% in Germany in part because of the offshore platforms network. Therefore some grid reinforcements are needed to carry out the goal for European offshore wind energy in the North Sea, 10 GW of installed power in 2020. A 6% offshore wind integration scenario in the North Sea is analyzed interconnecting both offshore areas with DC cables and simulating some contingencies. It is concluded that the HVDC link does not endanger the system stability but improves it in some cases, i.e., critical fault clearing time.

Keywords: offshore wind power integration, power system stability, HVDC transmission, critical fault clearing time, dynamic models, fault ride-through capability.

Resumen

El tema de este proyecto fin de carrera es el estudio de la futura red eléctrica submarina, llamada Supergrid, que conectará en una primera fase de desarrollo parques eólicos marinos en el mar del Norte y en el Mar Báltico. El proyecto fundacional instalará en el Mar del Norte una potencia de 10GW hasta 2020. Concretamente se analizarán varias simulaciones y se comprobará el cumplimiento de ciertos requisitos de conexión, tanto estáticos como dinámicos, a los sistemas de potencia de Gran Bretaña y Alemania.

La inserción a gran escala de energía eólica presenta ciertos problemas en los sistemas eléctricos de potencia en temas como disponibilidad variable de energía generada, control frecuencia–potencia, control voltaje–reactiva y cuestiones de estabilidad. Un circuito equivalente de parques marinos conectados a red eléctrica terrestre ha sido estimado para simular escenarios estáticos de flujos de carga así como respuestas dinámicas a contingencias con el objetivo de analizar la estabilidad del sistema. La herramienta de simulación empleada en todo el trabajo es PSS/E. La nueva tecnología en cables de corriente continua de alta tensión, HVDC Light, ha sido también considerada ya que formará parte de la futura red submarina en conexiones de larga distancia. HVDC Light emplea transistores, lo que permite transmitir a mayor voltaje un flujo mayor de potencia.

Los resultados de las simulaciones realizadas están intrínsecamente vinculados al circuito equivalente empleado, el cual ha sido enteramente desarrollado por el autor en PSS/E dada la confidencialidad por parte de los operadores nacionales. Su extrapolación a la realidad carece de fiabilidad desde que se han empleado valores estimados para los parámetros. Los resultados concluyen: un escenario en el que más del 6% por ciento de potencia eólica instalada en Reino Unido proviene de energía eólica marina requiere profundas mejoras en la red de transmisión inglesa, esta cifra se eleva al 12% en Alemania; interconexiones entre ambas costas mediante cables de corriente continua no solo no ponen en peligro la seguridad del sistema sino que en algunos casos, como el tiempo crítico de falta a tierra, la mejoran

Acknowledgement

This thesis report has been carried out at the Division of Electric Power Engineering, Department of Energy and Environment at Chalmers University of Technology. I express my sincere gratitude towards my supervisor Professor Ola Carlson for his excellent guidance, kind patience and encouraging comments and suggestions. I would like to thank Licentiate Nayeem Rahmat, Dr. Tuan A. Le and Licentiate Marcia Martins for their valuable technical assistance, especially helping me to understand and estimate the parameters of the dynamic models in PSS/E.

I do appreciate PhD student Javier Tabernero from IIT (ICAI) for his useful and generous help during all my thesis work. Special thanks go to José for his real friendship and his contagious joy. I express sincere appreciation to my colleagues at Comillas University, Raúl, Enrique and Ricardo, for those wonderful years. I also want to remember some of the teachers who aroused my interest on science: Enrique, Lucía, Maidagan, Chacón and Fidel.

My most heartfelt gratitude must go to my family; especially to my parents, Enriqueta and Juan Julián, because of their unconditional love and constant support.

Finally, I would like to thank all the Swedish and Erasmus people I have met in Göteborg for sharing with me an amazing and unique year, I have felt really comfortable and happy here.

Table of Content

1 INTRODUCTION

I will specify the organization and the main targets of the thesis in the present chapter.

1.1 Topic of the thesis

The topic of the thesis is to model a part of the European Offshore Wind Project. Afterwards, simulate some contingencies in order to analyze the power system stability of the future grid with the main international connections.

1.1.1 Offshore Wind Power Generation in Europe

Europe is quite dependant on energy imports. The half of its energy needs is imported and that share is expected to increase to 70% by 2020 unless Europe changes direction. The dependency of Europe on imported fossil fuel has become a threat to economic stability because of the impact of increased fuel prices on the cost base, especially on the price of electricity. As a result the support of renewable energy sources is one of the key issues in European energy policy in order to develop its own internal energy resources.

Nowadays, Europe is the world leader in renewable energy and particularly in the most promising renewable technology, wind power, it has a competitive advantage. As a realization of the Directive 2001/77/EC of the European Parliament the wind power in Europe has increased to nearly 67 GW in 2008, which means some 65% of the world installed wind power capacity. The highest amount of wind power is concentrated in Germany with the 40% of the European installed capacity. This is followed by Spain, Great Britain and Denmark; in Denmark more than 25% of electricity demand is met by wind power.

Wind energy will contribute to securing European energy independence and climate goals in the future; the European Union should decrease the 8% of the carbon dioxide emissions from 2008 to 2012 according with the Kyoto protocol (in comparison with 90´s levels). Besides, the actual technology research could turn in an opportunity for Europe in the forms of commercial benefits, exports and employment. Wind turbines and electrical generators are being improved continuously; the wind turbines have already reached a rated power of 7 MW and the production cost tends to reduce a 50% each five years [1, 2].

Wind provides less than 5% of European power needs, but is capable of delivering much more. The EU Commission fixed a target to reduce a 20% in emissions and reach a 20% of renewable energy share by 2020. The Transport and Energy Directorate of the European Commission (DGTREN) has estimated the 20% will translate to 34% of electricity coming from renewable. There are three main sources of renewable: hydro, biomass and wind. The European Wind Energy Association (EWEA) concluded that 13% of the total electricity supply will come from wind, which means 150GW approximately. This amount is such that given constraints onshore, such as planning and availability of land at least a third will have to come from offshore. EWEA's target for offshore in Europe is 60GW by 2020.

Onshore, huge energy losses occur when electricity is transmitted long distances, for instance, 10% is the loss when transporting el energy from the North to the South of Sweden. Wind farms are dispersed in marginal areas and save on transmission costs, because they reduce the need to move power long distances. Offshore wind, utilizing HVDC technology, makes long distance transmission more economic. HVDC Light, advanced transmission technology based on transistors, is suitable for connecting islanded systems to AC grid systems, supporting them with voltage control and forming the multi-terminal networks necessary for the Supergrid. It has fewer losses than conventional transmission technology. ABB has developed HVDC Light over the last ten years; it has been implemented in several systems and it is already in operation. It can now transmit 1080MW on a pair of subsea cables each of diameter 94mm and it is already commercially available at 300kV.

The future Supergrid allows the economic utilization of the wind resource further out to sea and creates the infrastructure for an internal market in electricity. Its topology will combine the connections from offshore wind farms to shore with interconnections between grid systems so can be used for intra- or inter-system trading when the wind farms are not at full output, and for interconnections within and between grid systems at a lower cost (transmission costs are very likely to 10-20% of the total costs associated with an offshore wind farm). It will be more cost-effective to integrate offshore wind farms more than 70km from the onshore grid using the Supergrid topology than with the conventional radial connections.

The first step of the offshore Supergrid, called Foundation Project, are planned to take place in the North Sea interconnecting Great Britain and Germany. The total wind power capacity installed will be 10GW, which means roughly two thousand 5MW wind turbines distributed in more than twenty wind farms, most of them already approved. The estimated operational date for the entire network is by 2020. This will prove the concept at a regional level and will form the basis for developing the European offshore wind project as a whole.

1.1.2 Power System Stability and wind energy integration

According with the huge increase of renewable sources in Europe there is an urgent need to address inefficiencies and distortions of the overall structure of the broader European power electricity infrastructure. It needs a secure and reliable operation in presence of variable generation.

There are three categories when studying power system stability according with the IEEE (Institute of Electrical and Electronics Engineers) [3]:

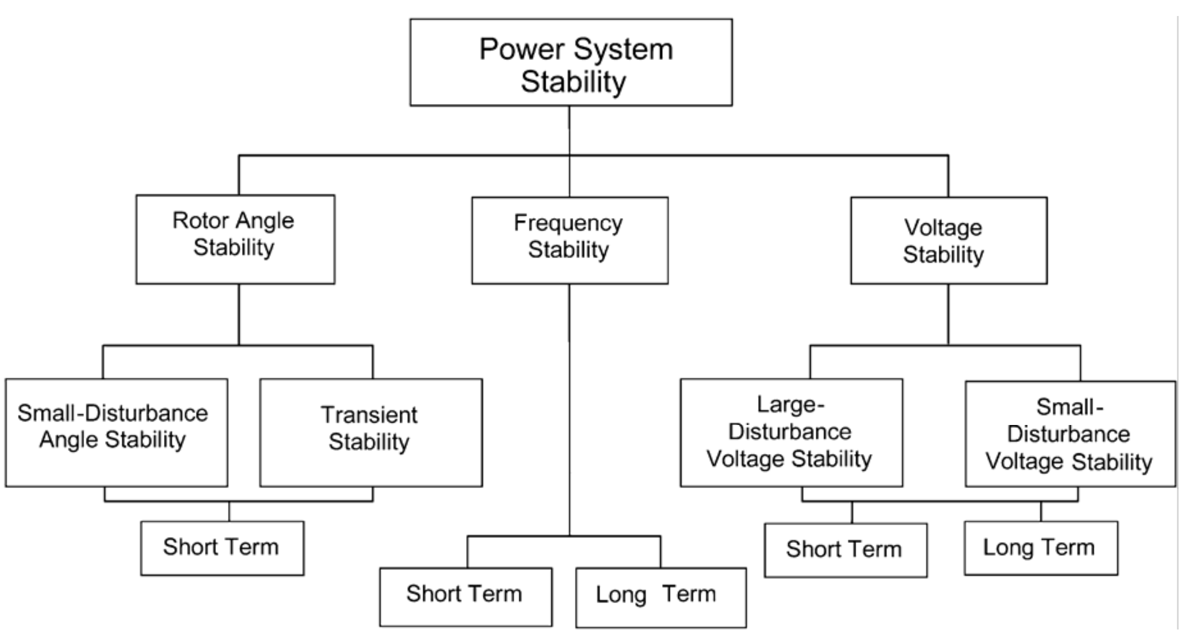

Figure 1.1 Classification of power system stability

Rotor angle stability. This stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. The disturbance can be small, such as changes in system load, or severe, such as a short circuit or loss of generation. The time frame of interest in rotor angle stability studies is on the order of 10 to 20 seconds following a disturbance.

Frequency stability. This term refers to ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. The time frame of interest for a frequency stability study varies from tens of seconds to several minutes.

Voltage stability. This term refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a small or large disturbance from a given initial operating condition. The period of interest for this kind of study varies from a few seconds to tens of minutes.

Wind power cannot be analyzed in isolation from the other parts of the electricity system. The role of a variable power source like wind energy needs to be considered as one aspect of a variable supply and demand electricity system. The major issues of wind power integration are related to: connection requirements for wind power plants to maintain a stable and reliable supply, extension and modification of the grid infrastructure, influence of wind power on system adequacy and the security of supply [4].

It is convenient to highlight several specific characteristics of wind power production:

- High wind power production needs more reactive power because wind installations are built far away from the main load centers, especially offshore wind farms. Long distance transmission of wind energy leads to a higher load factor of the electric lines which thus consume more reactive power (but offshore cables which are able to produce reactive power).

- Conventional power stations do not disconnect from the grid even following serious grid failures, instead they generally trip into auxiliary services supply and "support" the grid. Wind farms, however, have so far disconnected themselves from the grid even in the event of minor, brief voltage dips. Experience in grid operation showed that this can lead to serious power failures. In order to prevent the risk of large outages, manufacturers and operators must technically ensure that in the event of a fault, wind farms also support system stability. The new wind farms remain connected to the grid during grid disturbance
- The need for balancing power increases proportionally with the growing wind power capacity. Furthermore, a considerable amount of reserve capacity is needed for system adequacy and security.
- A regional concentrated high wind power generation which is producing a high surplus of power generation such as in Northern Germany results in temporary large load flows through the neighboring transmission systems. These unscheduled flows could reduce system stability and increasingly affect trading capacities.
- Voltage stability problems may also be experienced at the terminals of HVDC links used for long distance. They are usually associated with HVDC links connected to weak AC systems and may occur at rectifier or inverter stations and are associated with the unfavorable reactive power "load" characteristics of the converters. The new technology HVDC Light solves this problem.

Already today, it is generally considered that wind energy can meet up to 20% of electricity demand on a large electricity network without posing any serious technical or practical problems. This thesis is aimed to find out the technical question as to whether there is an upper limit for offshore wind penetration into the existing European grid.

1.1.3 Wind generators range

The generator model must define the electro-mechanical and control system performance of the wind farm under steady state and disturbance conditions. The dynamic model and the associated model parameter values should [5, 6]:

1) Represent the wind farm for all possible wind speeds where the wind farm would be in operation, and for all possible steady state output levels of the wind farm.
2) Have parameters for an equivalent aggregated generating unit derived from the best information available, including rotor transient effects.
3) Include any other controllers that can adjust the wind farm output or affect its performance in the time domain simulation timeframe.
4) Have a bandwidth of at least 0.05Hz-10Hz and must settle to the correct final value for the applicable system conditions and applied disturbance.

The wind farms consist of hundreds of identical wind turbines, representing the wind farm with individual wind turbines for power system stability studies increases the complexity of the model and requires time-consuming simulation. As a consequence, simplification of wind farms consisting of a large number of wind turbines is essential. I will model all of the turbines in the generating system as a single equivalent turbine. I will enter all data with respect to the base MVA of a single unit, and the value of MBASE entered in the load flow case will be the sum of the ratings of all connected units [7].

1.2 Purposes of the work

A more precise description of the targets of the thesis is following:

- Obtain the necessary information about the Foundation Project. Some support will be requested from companies and organisms to get the available data in order to use the simulation tool PSS/E.
- Establish the appropriate models and an extended aggregated model of each national power system with a realistic feeder configuration.
- Steady-state and dynamic simulations and validation of the grid proposed.
- Analyze and discuss how the power balance and system reliability with the increased wind power penetration can be maintained according with the results from the simulations.

1.3 Resources and tools

The main tool used in this thesis is the Power System Simulator for Engineering, PSS/E. PSS/E is a suite of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. At present two primary simulators, one for steady-state analysis and one for dynamic simulation, facilitate calculations for a variety of analyses, including: Power flow and related network functions, optimal power flow, balanced and unbalanced faults, network equivalent construction and dynamic simulation.

The tool provides an extensive library of power system components, which includes generator, exciter, governor, stabilizer, load and protection models. Many of these have been validated. Additionally, users are allowed to develop user defined models. In respect to wind power generation, PSS/E provides several types of wind turbine models as Vestas V80, GE 3.6 MW and Vestas V47.

1.4 Plan of activities

January and February

Get knowledge about the topic of the thesis and learn how to use PSS/E.

March

Establish the appropriate models and an extended aggregated model of each national power system with a realistic feeder configuration. I will also start to simulate the steady power flow.

April

Dynamic investigation. Several simulations related to the different hypothesis, fault situations and stability categories.

May

Analyze how the power balance and system reliability with the increased wind power penetration can be maintained according with the results from the simulations. Conclusions.

2 OFFSHORE WIND ENERGY INTEGRATION IN UK

2.1 Equivalent circuit of the national transmission grid

In this chapter the increasing offshore wind energy penetration in the United Kingdom will be presented and investigated. The wind farms will be tested on an equivalent model of the transmission grid of England and Wales (see Figure 2.1), the majority of the wind farms are connected to this network and I consider it quite independent of the rest of the British grid as a first step. I will not take in consideration external factors as the interconnections with Scotland or the existing HVDC connections 2000 MW to France or 500 MW to Northern Ireland. The required information in order to get a network with a realistic feeder configuration was confidential. Consequently this equivalent model has been estimated all by me using the available public information from the national operator [8, 9]. It is also studied what kind of generator should be chosen to increase the transient stability of nearby conventional generators.

As part of the project to deliver the new offshore transmission regime, the DTI (Centre for Distributed Generation and Sustainable Electrical Energy) is currently considering the regulatory options for the geographic scope of offshore transmission licenses and the method for allocating them. To assist in considering the options the DTI requires an analysis of the most up to date information to inform them about the developing shape of offshore connections. Following the decision in March 2006 to regulate high voltage offshore connections by a price control approach similar to onshore, the DTI has been taking forward the detailed work programmed to implement the new regime. The next major milestone in the project is a document which will seek views on the regulatory options that DTI believes will deliver the aims of the project set out in the background annex to the Offshore Transmission Experts' Group's.

Figure 2.1 British Transmission System as at December 2006. The big circles represents the three main offshore wind areas. Blue Lines (400kV); Red Lines (275kV). The small circles are generation units.

There are three main offshore areas in UK: North West, Greater Wash (Figure 2.2) and Thames Estuary (Figure 2.3). In this paper, I will study the offshore wind integration by modeling five main wind parks: Westermost Rough, Triton Knoll, Greater Gabbard, London Array and North West. There are many possible connection points at 275kV and 400 kV close to the East coast. The DTI Centre for Distributed Generation and Sustainable Electrical Energy elaborated in 2006 a techno-economical report studying the potential configurations options for the offshore grid in UK [10]. I will use their optimal connections to model my grid as shown in the Figures 2.2 and 2.3.This analysis assumed that offshore transmission voltage levels will include the application of 220 kV.

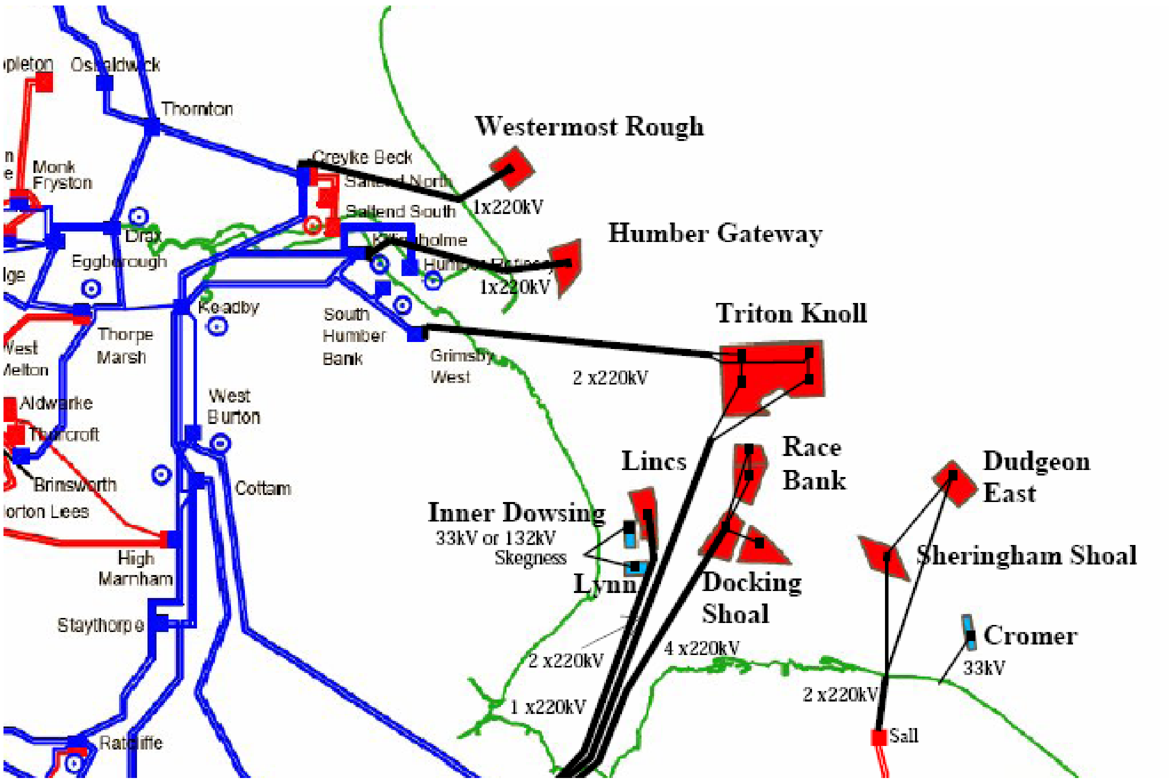

Figure 2.2 Greater Wash region. Color codes: Blue Parks – Round One Projects (generating or under construction); Red Parks – Round Two Projects (predicted to be finished by 2020); Blue Lines (400kV); Red Lines (275kV). The circles are generation units.

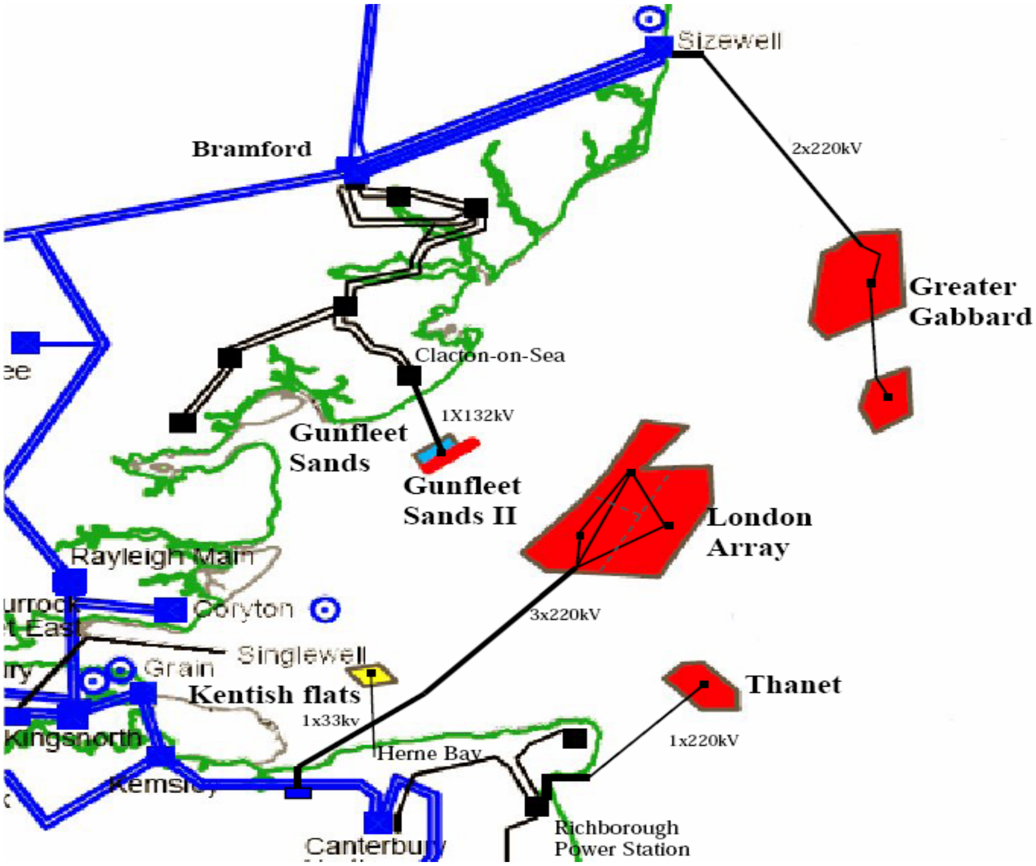

Figure 2.3 Thames Estuary region. The same color codes.

Most projects from now on are likely to use the modern 400kV overhead lines which can carry over than 2000MW over longer distances. The equivalent circuit of the UK grid consists on forty buses (named by its bus code [8]) in order to model the basic high voltage network (most of the main generation units are connected directly at 400kV) and also some 275kV circuits. It is assumed that only 85% of the total stock of generating plant could be predicted to be available at the time of winter peak demands several years ahead, then it would be necessary to plan to meet that peak demand (100%) with only 85% of the generation. The total installed capacity of the equivalent national grid is 12656 MW with 21 generation units; the load is 10240 connected mainly to the medium voltage circuits. The Generation capacity of England and Wales is around 60 GW and the national peak load around 50 GW; accordingly, it is assumed this test system (Figure 2.4) is 20% scaled down version of the English transmission grid.

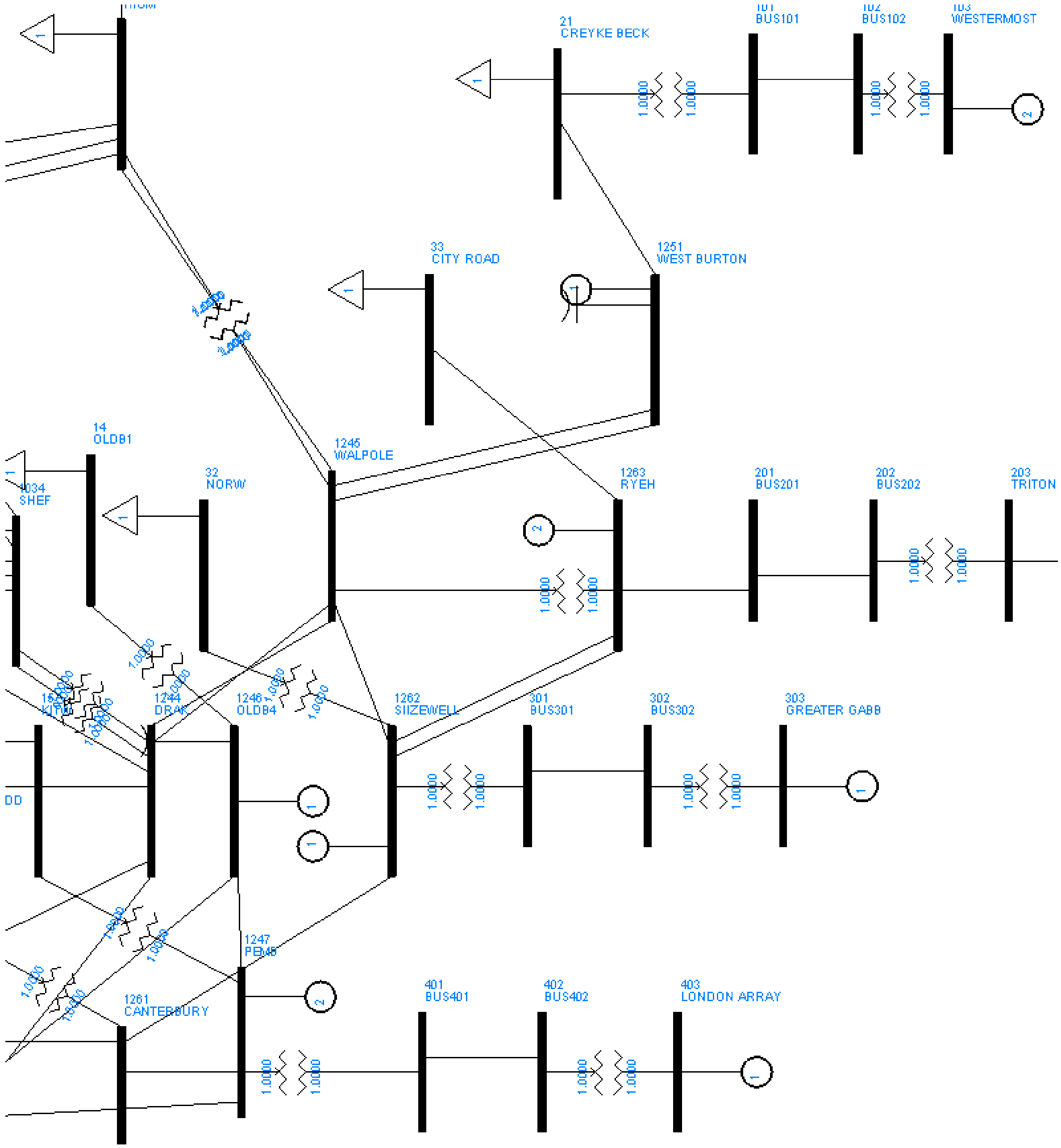

Figure 2.4 Equivalent circuit of the Greater Wash and Thames Estuary offshore wind parks connection with a part of the British Grid.

2.2 Offshore Wind Parks

There are seven different types of generators competing in the Supergrid project. Nowadays, the most widely used generator type for units above 2MW is the doubly-fed induction machine because it has several advantages over a synchronous machine in wind power applications. Firstly, as the rotor voltage is controlled by a power electronics converter, the induction generator is able both to import and export reactive power. This has important consequences for power system stability and allows the machine to remain connected to the system during severe voltage disturbances. Secondly, control of the rotor voltage enables induction machine to remain synchronized with the grid while the wind turbine varies in speed. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. GE, REpower Systems and BARD are some of the companies that already sell that kind of generators, RE has reached a 7MW wind turbine. I will use developed in the PSS/E library adjusting the parameters in order to fit as much as possible with the offshore wind turbines.

2.3 Steady-State and Dynamic Power Flow

Typical dynamic testing will include the same family of contingencies and are augmented by representation of the severity of the initiating disturbance which results in the loss of system elements (three-phase and single-phase faults with normal or delayed clearing times for example). Acceptable system conditions prior to and subsequent to the contingencies depend on the severity of the contingency and include:

- Voltages within defined normal or emergency limits.
- Changes in voltage within defined limits.
- Branch loadings within normal or emergency loading limits.
- Maintenance of transient and dynamic stability.

There are two more contingencies I will not analyze because of the lack of information:

- Maintenance or loss of limited amounts of load.
- Maintenance of system integrity or breakdown into viable sections.

For this thesis, variable speed turbines are considered with fault ride-through capability. This means that the turbine remains online even during the fault without being tripped by under voltage relays. The focus is the protection of the distribution side of the network and hence the generator protection is not considered. In the dynamic analysis, I convert the loads by the worst case possible that is 100% constant current in active power and 100% constant admittance in reactive power.

2.3.1 Actual scenario without Offshore Wind Power Supply

Present energy mix will be compared afterwards against the future one in order to analyze how the wind power integration affects in the stability issues.

Normal Steady-State Power flow

I verify the normal loading and voltage limits in all the buses of the system.

The voltages are between 0.96 pu and 1.04 pu. It means a range of variation of 4% around the nominal which is quite tolerable. The charging of the lines is not over the 80% of its capacity in any case.

Transient Stability

PSS/E facilitates a tool called "ranking" of designated single branch outage contingencies and builds a Contingency Description Data File with contingencies specified in decreasing order of their estimated severities. The ranking can be based on either or both of the following criteria:

1. An overload criteria measuring branch loadings relative to their ratings.
2. A voltage depression criteria which indicates increased reactive power consumption by estimating increases in reactive losses due to increased line loadings.

I simulate so far a three phase to ground fault at the nearest substation (Sizewell) to the wind farms that has a conventional generator connected. I verify acceptable conditions within emergency loading and voltage limits immediately after outage and within normal limits after system adjustments.

Immediately after outage the voltages go down till 0.5 pu in the near buses West Burton and Walpole (see Figure 2.5).After system adjustments, voltages are still within a +-20% around the nominal and the charging of the lines is under the unit.

I will determine the critical fault clearing time which is defined as the maximum duration of a given fault that will not lead to the loss of synchronism of the generators. I apply a three phase to ground fault at bus 1262 (Sizewell) because it is the nearest bus to the wind farms that has a conventional generator connected. The target is checking if the critical fault clearing time of the system will decrease or not because of the wind farms.

In the specific case of the fault in Sizewell, the generators do not loss the synchronism if the fault time is less than 220ms.

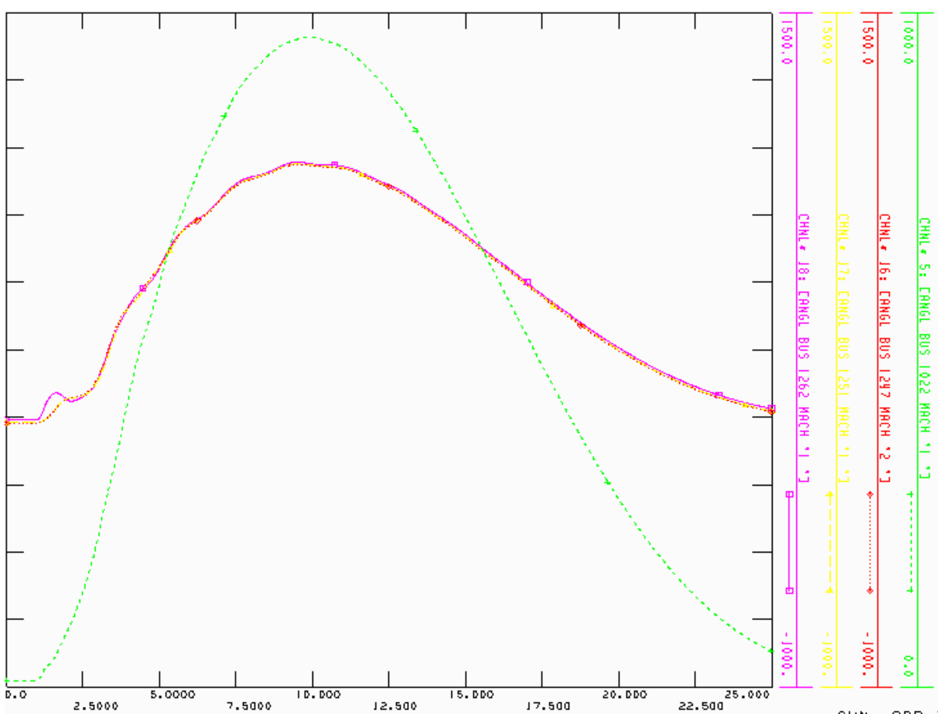

Figure 2.5 Angle variation of the closest buses of Sizewell substation when a 210ms. fault to ground is applied in there.

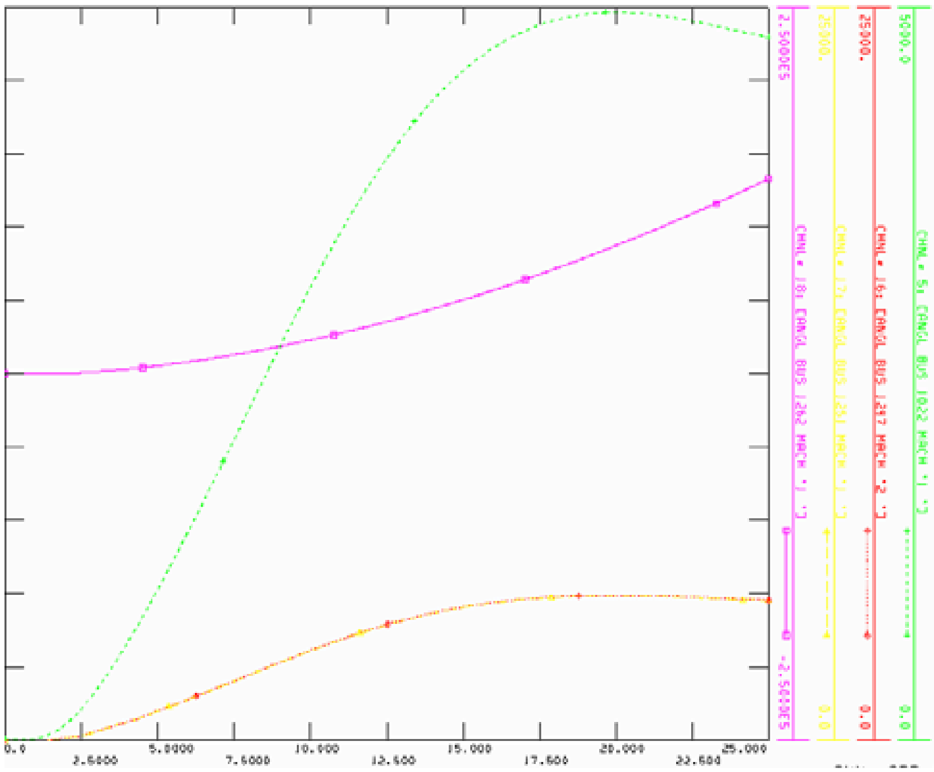

Figure 2.6 Angle variation of the closest buses of Sizewell substation when a 250ms. fault to ground is applied in there.

2.3.2 Offshore Wind penetration scenario 6%

A realistic timing for UK is 3 GW offshore wind power by 2020. The Generation capacity of England and Wales is around 60 GW and the national peak load around 50 GW. Consequently the wind penetration, ratio between the wind power and the total national load, will be 6%. I will connect five 125MW wind farms, it means 625MW offshore wind generation capacity in the test system (20% scale down).

Each wind farm has to be operated at a lagging power factor to assure a zero reactive power exchange with the grid since the wind parks are connected to the grid by a long cable. I consider every park operating at a power factor of 0.98 which corresponds to 25 MVar of reactive power absorption at the wind farm. I consider also that the minimum operating voltage at the wind turbine is 0.9.

Normal Steady-State Power Flow

A normal loading and voltage limits in every bus of the system is verified.

The voltages are between 0.93 pu and 1.03 pu. It means a range of variation of 7% around the nominal, which is quite tolerable. The charging of the lines is not over the 90% of its capacity in any case. See Appendix F.

Transient Stability

I apply a three phase to ground fault at bus 1262 (Sizewell).

Immediately after outage the voltages behavior at near buses (West Burton, Walpole and Canterbury) is pretty similar than the case with no offshore wind power. After system adjustments, voltages are still within a +-20% around the nominal and the charging of the lines is under the unit.

The critical fault clearing time of the system is 180ms., if the fault is longer the equivalent generator at Greater Gabb offshore wind farm will loss the synchronism.

So the new wind farms endanger the system transient stability.

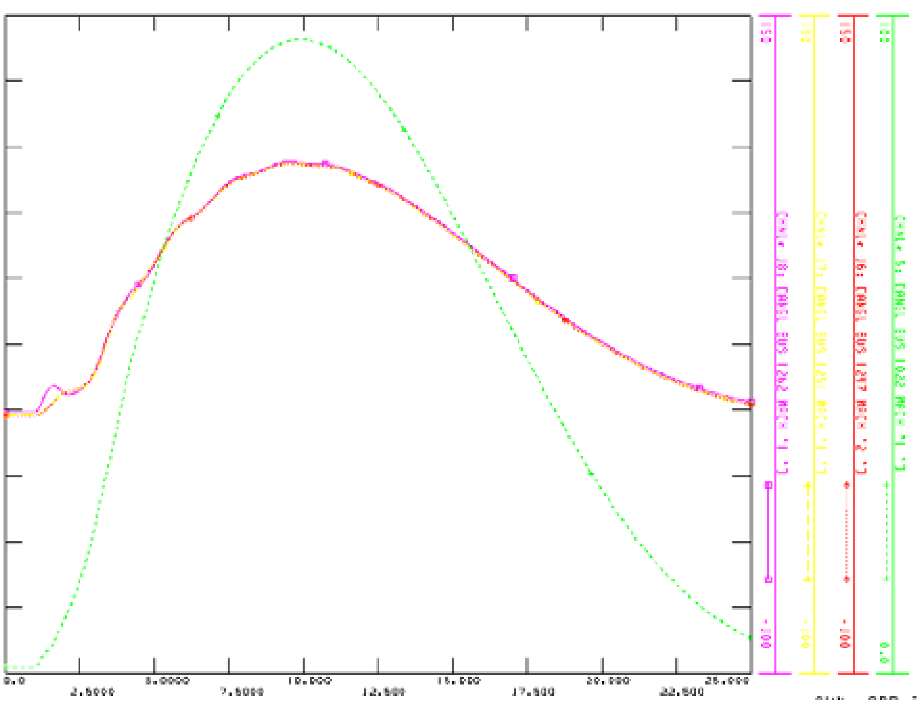

Figure 2.7 Angle variation of the closest buses of Sizewell substation when a 170ms. fault to ground is applied in there.

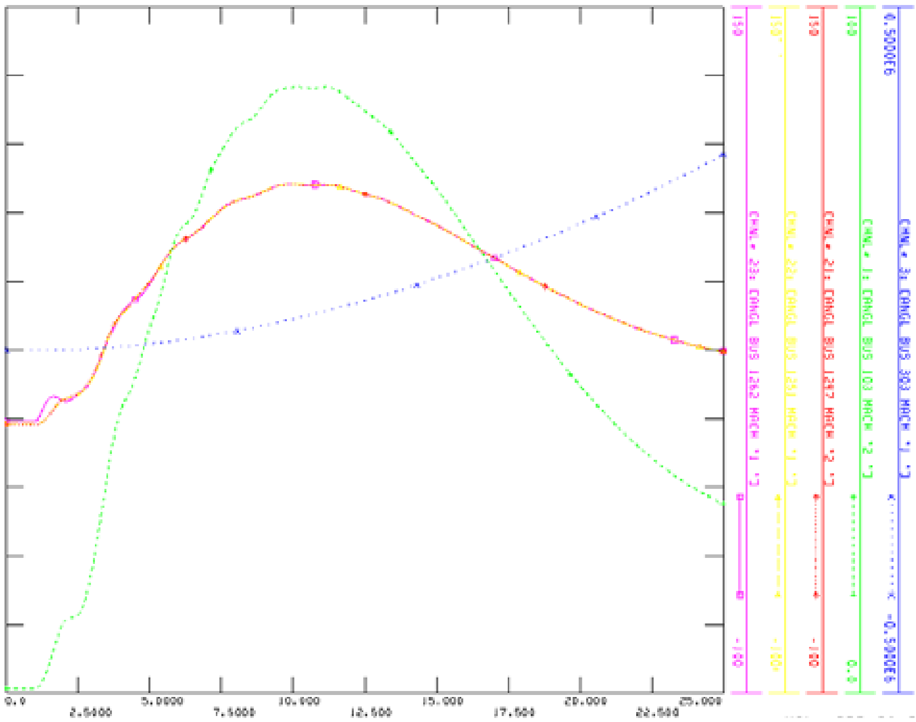

Figure 2.8 Angle variation of the closest buses of Sizewell substation when a 200ms. fault to ground is applied in there.

2.3.3 Offshore Wind penetration scenario 12%

Another UK energy goal is 6 GW offshore wind power by 2030 that means a 12% offshore wind penetration scenario. I will connect five 250MW wind farms, it means 1250MW offshore wind generation capacity in the test system (20% scale down).

Normal Steady-State Power flow

I verify the normal loading and voltage limits in all the buses of the system.

The voltages are between 0.89pu and 1.01pu. It means a range of variation of 11% around the nominal, which is not tolerable. The charging of the lines is not over the 100% of its capacity in any case.

Transient Stability

I apply a three phase to ground fault at bus 1262 (Sizewell).

Immediately after outage the voltages go straight down in the near buses: West Burton, Walpole, Canterbury (see Figure 2.9) and at the four wind parks nearby (Westermost Rough and Greater Gabbard are represented in the curve).After system adjustments, voltages are fluctuating in a range of almost 0.8 pu that is totally not acceptable.

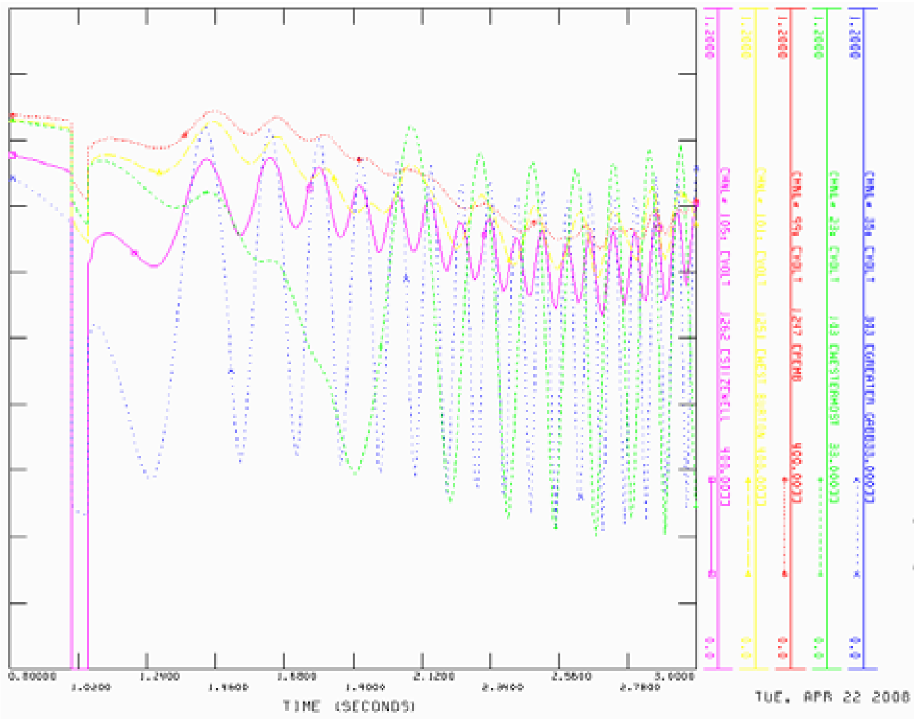

Figure 2.9 Voltage oscillations of the closest buses of Sizewell substation when a 50ms fault to ground is applied in there

The critical fault clearing time of the system is less than 50ms. The Figure 2.10 shows us how all the nearby generators loss synchronism when a 50ms fault is applied.

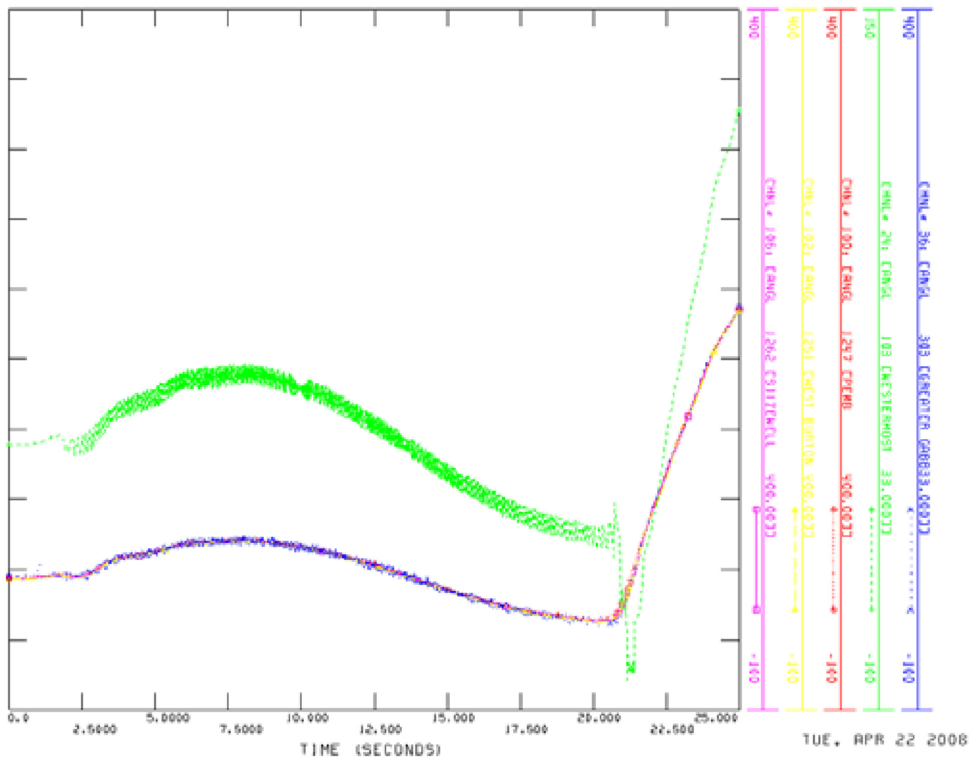

Figure 2.10 Angle variation of the closest buses of Sizewell substation and two wind parks (purple and yellow) when a 50ms. fault to ground is applied in there

2.4 Power Oscillations Comparative

1%, 6% and 12% offshore wind scenarios have been simulated in order to compare the oscillations when a fault is applied in different parts of the network.

One of the transmission lines between Sizewell and RYEH is disconnected which results in power oscillations in different parts of the network. The voltage at the terminal of one substation (Creyke Beck) is shown also in figures. Note the huge oscillations in the 12% scenario (see Figure 2.11), in which the generators lose the synchronism. Consequently, it makes not sense keep analyzing this last scenario because some grid reinforcements are needed to make it possible and this is out of my thesis objective.

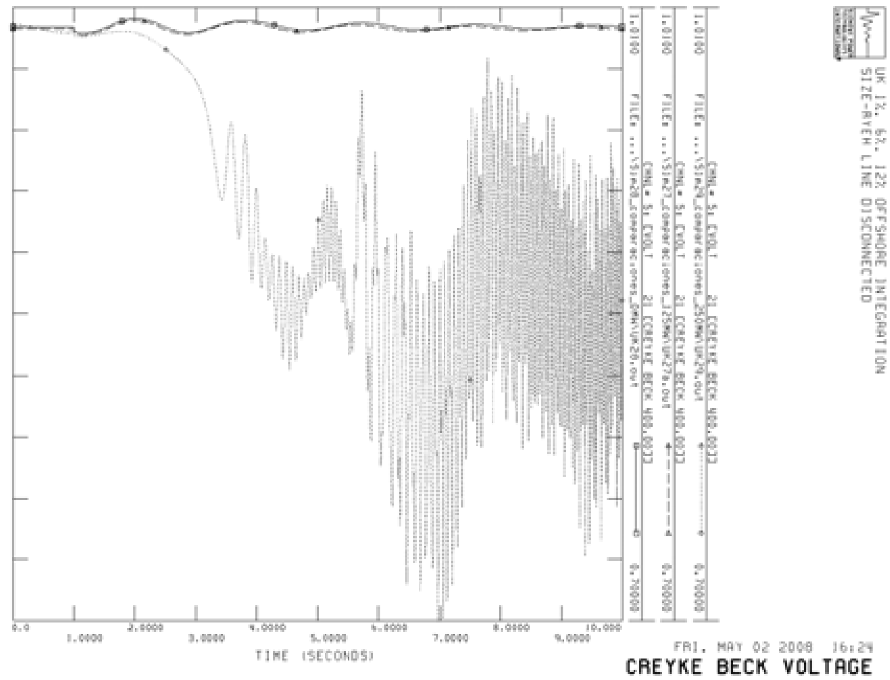

Figure 2.11 Voltage oscillations in 0%, 6% and 12% offshore integration scenarios

A zoom in (see Figure 2.12) shows us the oscillations in 0% and 6% scenarios are very similar, just in the second one the voltage is a bit up. I have used a synchronous dynamic model in the wind generator which is similar than the conventional models so the oscillations in both scenarios are also very similar. I will use an induction generator model in the next chapters 3. and 4. in order to get more interesting dynamic behaviors.

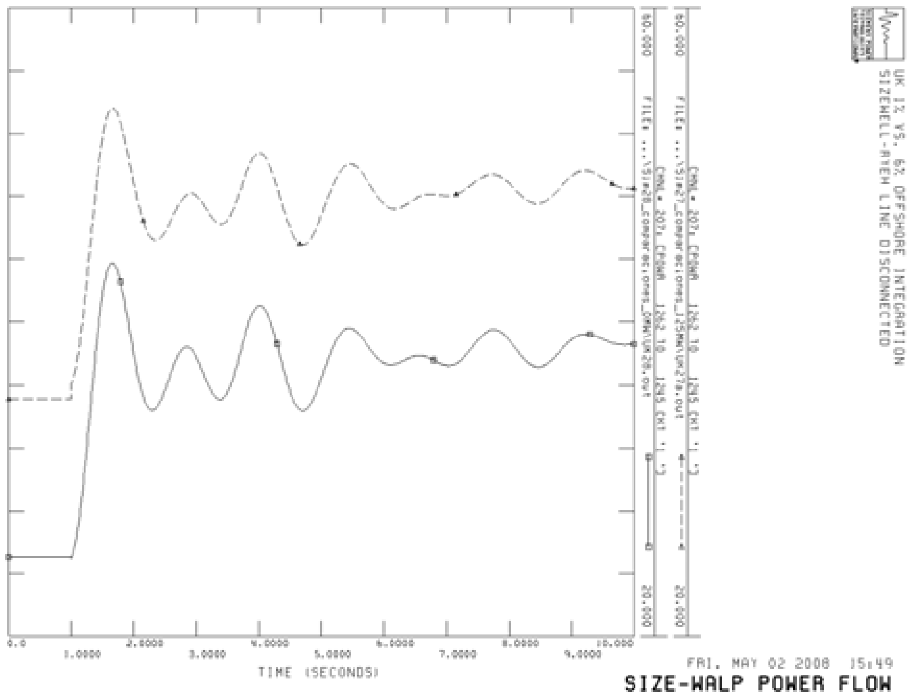

Figure 2.12 Power oscillations in 0% and 6% offshore integration scenarios

The generating unit at Sizewell is disconnected. The resulting power oscillations in different transmission lines of the East region are monitored in figures 2.13, and 2.14. A similar damping in power oscillations is shown in both scenarios.

I appreciate no significant power oscillations in the lines electrically far away from Sizewell as noted in Figure 2.13, it represents the power flow between two buses of the North West Region. We can also appreciate more damping in oscillation (see Figure 2.14) in the 6% scenario because the generator which models the North West offshore wind park is quite close so it has a positive contribution into grid stability.

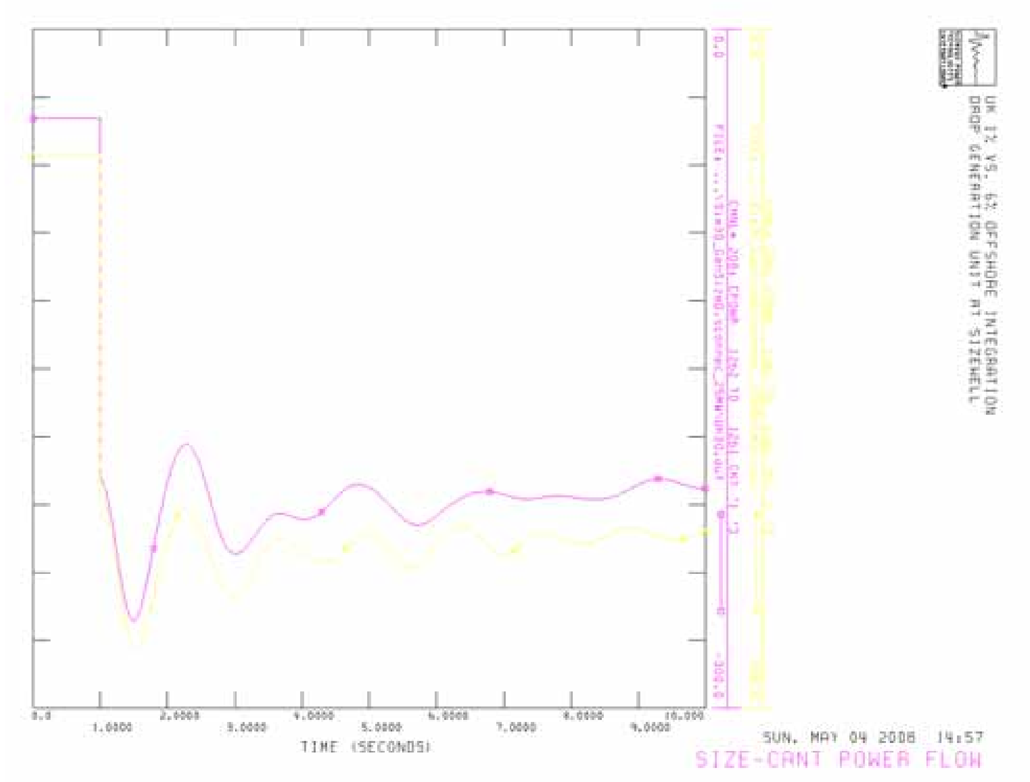

Figure 2.13 Power oscillations in 0% and 6% offshore integration scenarios

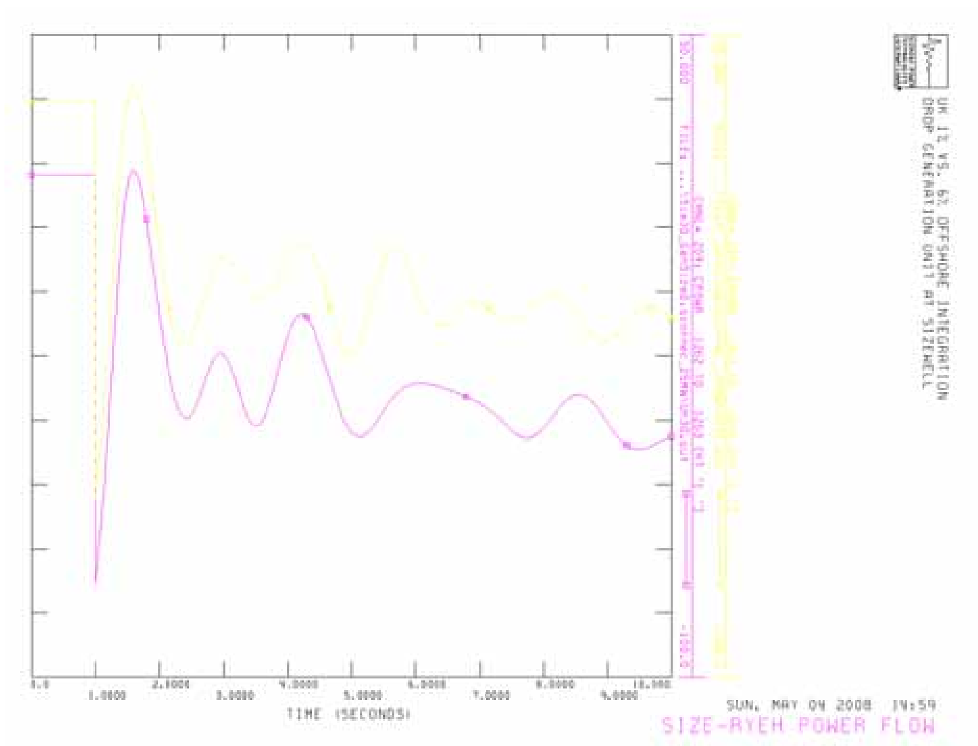

Figure 2.14 Power oscillations in 0% and 6% offshore integration scenarios

Voltage oscillations at the substations, in which the wind parks are connected, are monitored (see Figure 2.15 and 2.16). We appreciate the curves are within the UK grid connection requirements range: after 3 seconds the values are stabilized above 0.9 pu; the oscillations are in a permissible range but in the 6% offshore integration case the fault ride–through capability of the wind parks is endanger.

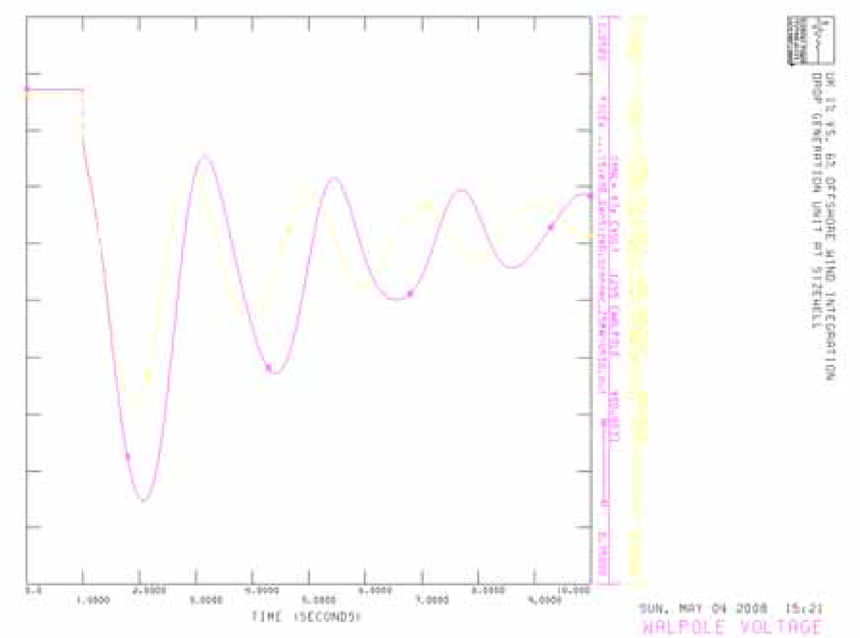

Figure 2.15 Voltage at the offshore wind farms connection points

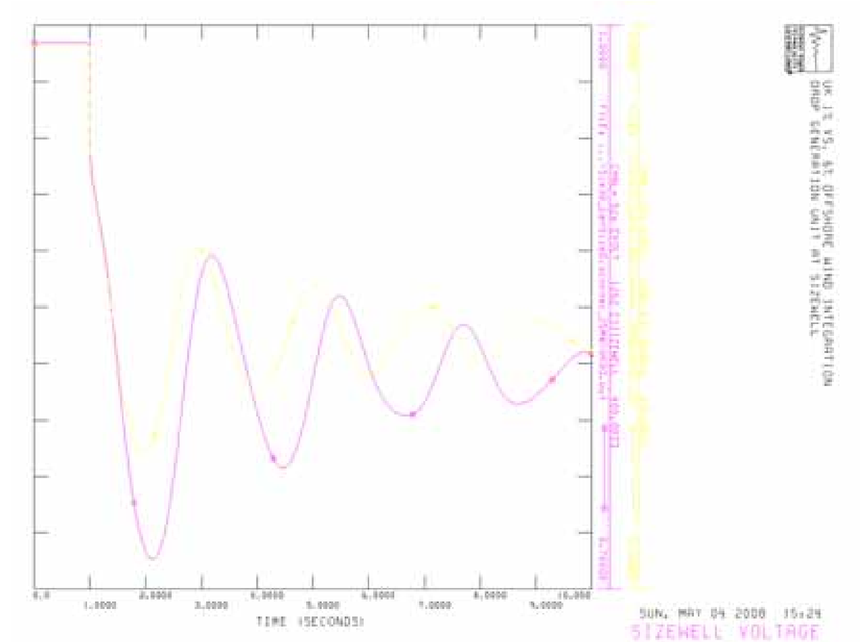

Figure 2.16 Voltage at the offshore wind farms connection points

We see the peak value of the voltage is lower in the scenario with more offshore integration. The final value of the voltage is the same in both scenarios.

So it is concluded from this very simple park wind dynamic model that by incorporating new offshore wind parks, transient stability of the conventional generators operating in the East region can be increased.

New transmission capacity should be provided when the 12% offshore wind penetration scenario is taken in consideration. The provision of this infrastructure could decide the rate at which new offshore wind farms will be connected. Some grid requirements must be checked in future works: Power quality, power control, power interruptions, frequency control, voltage control (reactive power), voltage and frequency ride through. Nowadays, there are already some bottlenecks for north-south transmission affecting onshore wind power in Scotland and offshore wind power in the North West area and Greater Wash. Consequently some grid reinforcements are necessary especially at Greater Wash above 3000 MW of offshore wind may require reinforcements.

3 OFFSHORE WIND ENERGY INTEGRATION IN GERMANY

3.1 Equivalent circuit of the national transmission grid

In this chapter the increasing offshore wind energy penetration in Germany will be presented and investigated. The wind farms will be tested on an equivalent model of the German transmission grid. This grid has been also estimated all by myself using the available public information from the national operators.

The public information about the German and Holland transmission system was much fewer than about the UK grid. Only the North-West region (electrically close to the offshore wind parks) high voltage network is modeled by thirty buses. The total installed capacity of my equivalent circuit is 10 GW with 18 generation units, the load is 8 GW. The Generation capacity of this North-West European region is around 50 GW and the national peak load around 40 GW [10], accordingly, it is assumed this test system (Figure 3.1) is 20% scaled down version of the real transmission grid.

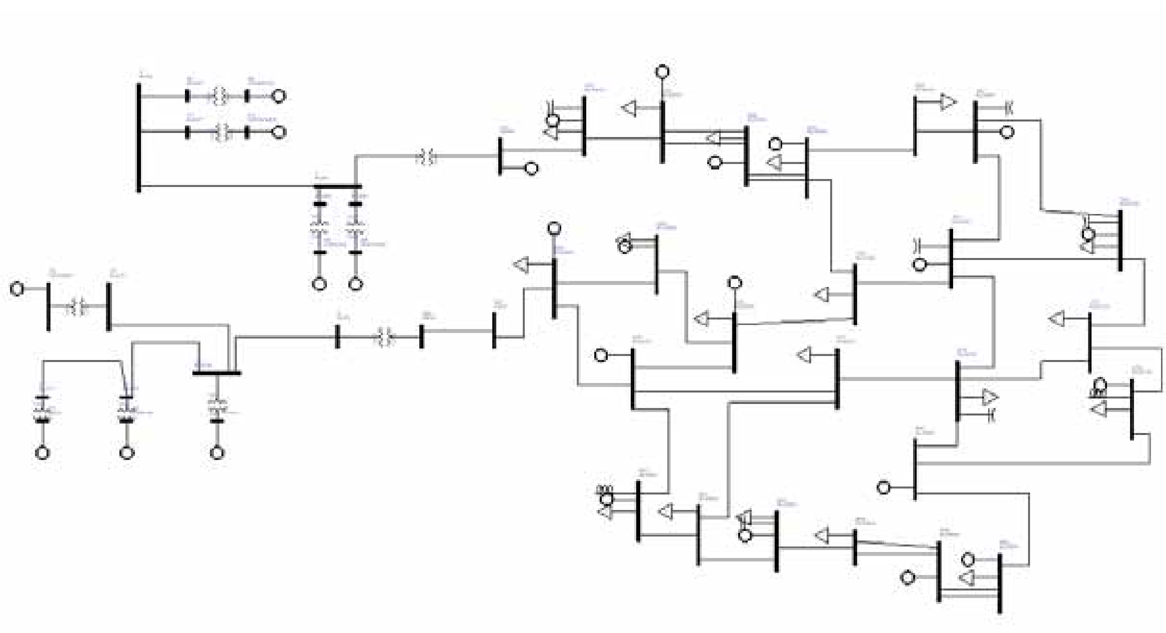

Figure 3.1 Equivalent circuit of the offshore wind farms at the German cost connected with German and Dutch national grid (main high voltages buses).

3.2 Offshore platforms and wind farms

For the period beyond 2012 a system model has been developed for the further expansion of wind farms in the North Sea which avoids a large number of parallel submarine cables. This system model should be implemented as soon as possible. It consists of four offshore collection stations, to which several wind farms could be hooked. Wind power could then be transmitted to shore from these collection stations by use of only one common submarine cable (see Figure 3.3).

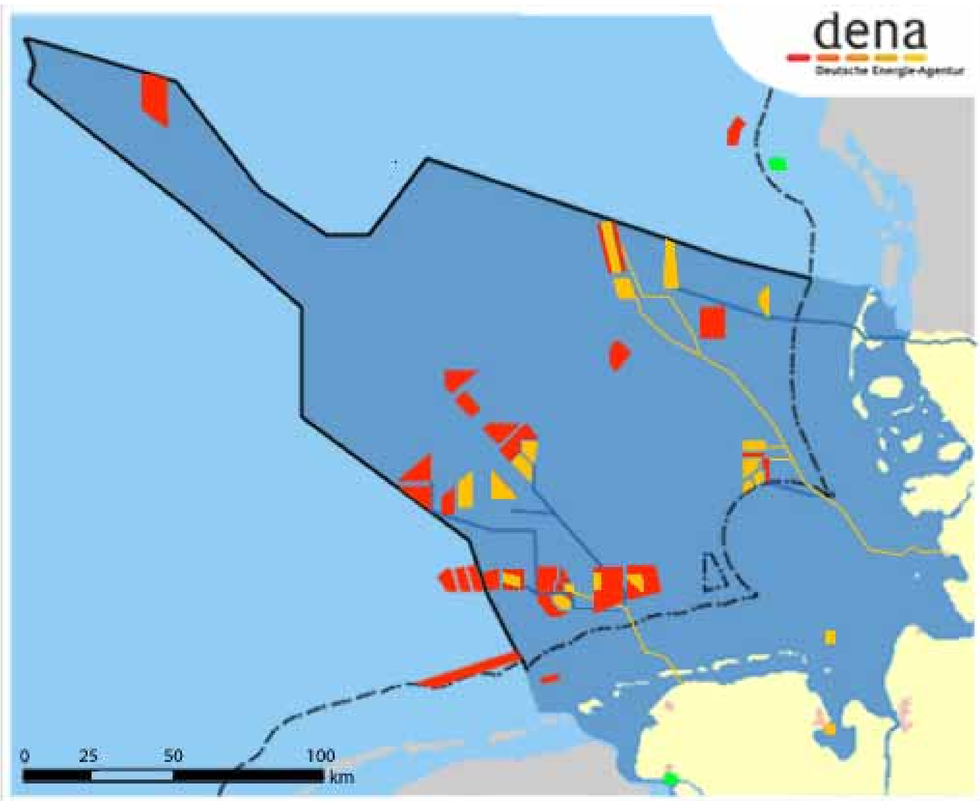

Figure 3.3 Future offshore park network at the German coast [11].

I will model the future complex grid through eight main wind parks in the North Sea: Borkum (1040MW), NorthSea (1250MW), BARD (1600MW), Hochsee (2286MW), Meerwind (1350MW), Nordsee Ost (1250MW), Nördlicher (2010MW) and Sandbank (4720MW).

There are four high voltage suited substations at coast of the North Sea: Diele, Conneforde, Moorriem and Brunebüttel. According with previous German reports after installation of phase shifters at substations Moorriem and Diele, extensions of several existing lines inland, extension of substations (inland), provision of capacitors (inland): 6 GW offshore (2020 scenario) could be connected as scheduled but need to be curtailed at high wind/low load.

Assumption: 400 kV gas insulated cables (GIL) Parks should be clustered in groups of several MW at an offshore substation, substations will be connected to shore via as little as possible GIL routes (2010 to 2020): environmental issue of passing the Wadden Sea (North Sea) and the Bodden Seas (Baltic).

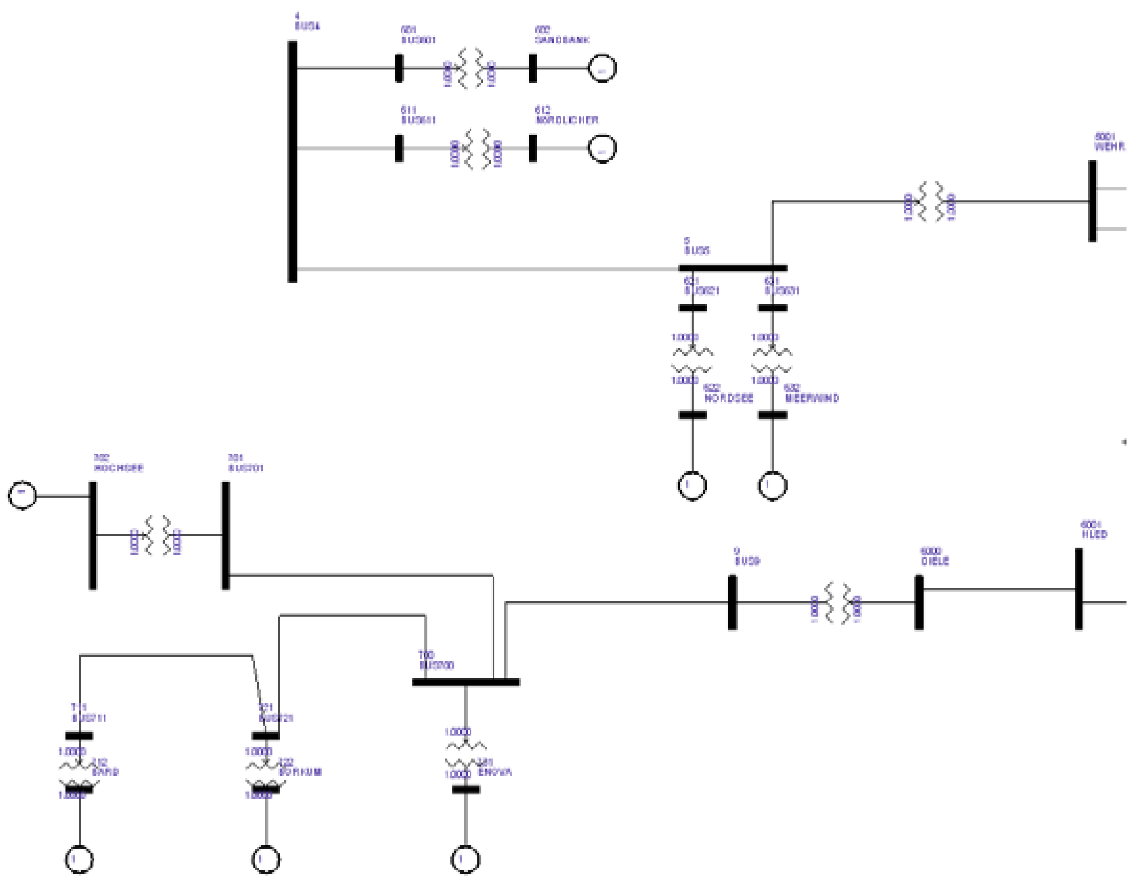

Figure 3.4 Equivalent circuit of the offshore park network at the German coast.

3.3 Steady-State and Dynamic Power Flow

3.3.1 Wind penetration scenario 6%

A realistic timing for Germany is 6 GW offshore windpower by 2020. The Generation capacity is around 125 GW and the peak national load around 100 GW. Consequently the wind penetration, ratio between the wind power and the total national load, will be 6%. In our North-West 40 GW peak load and 20% scaled down, this means 2.4 GW offshore wind power distributed in eight wind parks, 300 MW per each.

Each wind farm has to be operated at a lagging power factor to assure a zero reactive power exchange with the grid since the wind parks are connected to the grid by a long cable. I consider every park operating at a power factor of 0.98 which corresponds to 25 MVar of reactive power absorption at the wind farm.

Normal Steady-State Power flow

If the wind farms would be installed solely to maximize energy output they would have major limitations in terms of:

(a) Power Control and Frequency Range.
(b) Power Factor and Voltage Control.
(c) Transient Fault Behavior, Voltage Operating Range.

The association of German transmission grid operators, VDN, summarized special requirements concerning renewable energy sources operating on the high voltage network in a document as an appendix to the existing general grid codes [12].

The transient fault behavior is divided mainly two categories:

(a) Generators with big fault current contribution at the GCR i.e. fault current is at least two times nominal current for at least 150 ms
(b) Generators where the fault current contribution is less than that.

The voltages are between 0.97pu and 1.07pu. It means a range of variation of 7% around the nominal, which is tolerable. The power flow is not over the 80% of the permissible capacity at any line.

Transient Stability

I will determine the critical fault clearing time which is defined as the maximum duration of a given fault that will not lead to the loss of synchronism of the generators. I apply a three phase to ground fault at bus Diele because it is the worst fault case possible. The target is checking if the critical fault clearing time of the system will decrease or not because of the wind farms.

In the specific case of the fault in Diele, the generators do not lose the synchronism if the fault time is less than 300ms.

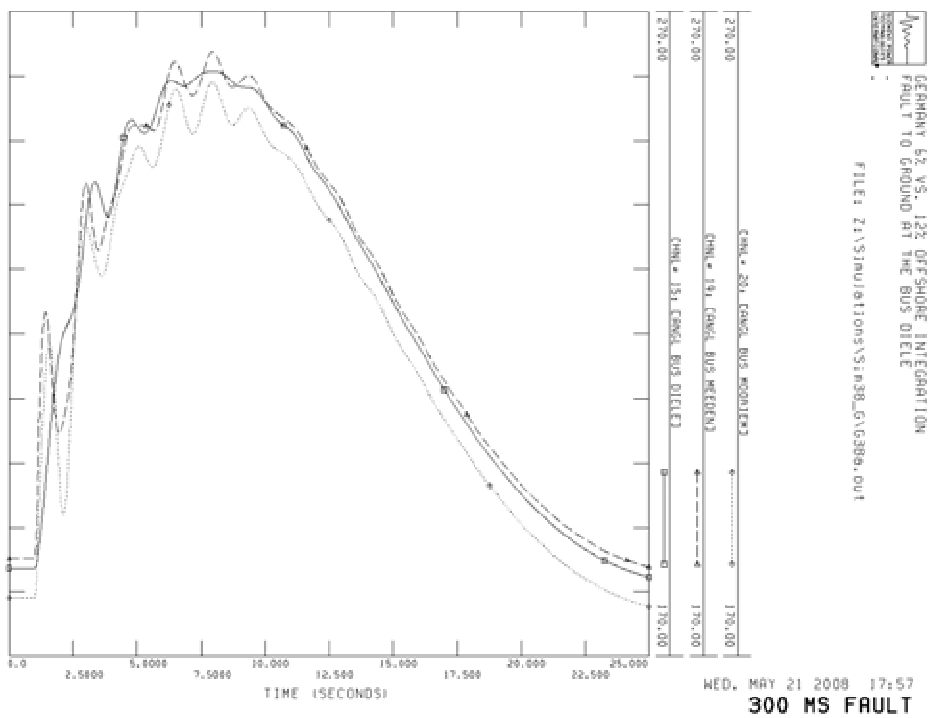

Figure 3.6 Angle variations of the generators electrically close to Diele when a 300 ms. fault to ground is applied

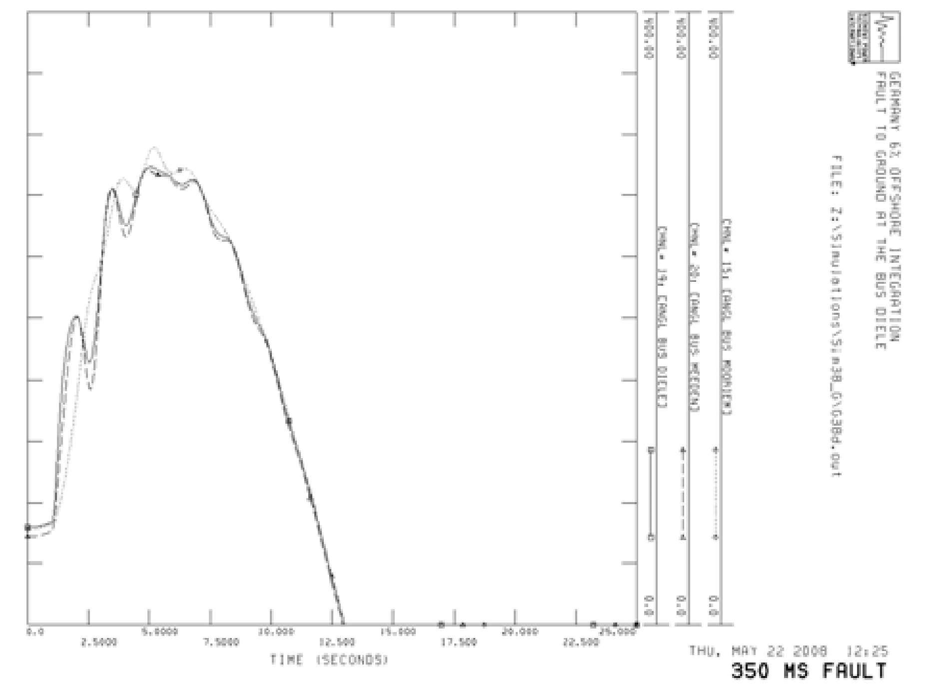

Figure 3.7 Angle oscillations of the closest buses of the Bus Diele when a 350ms. fault to ground is applied.

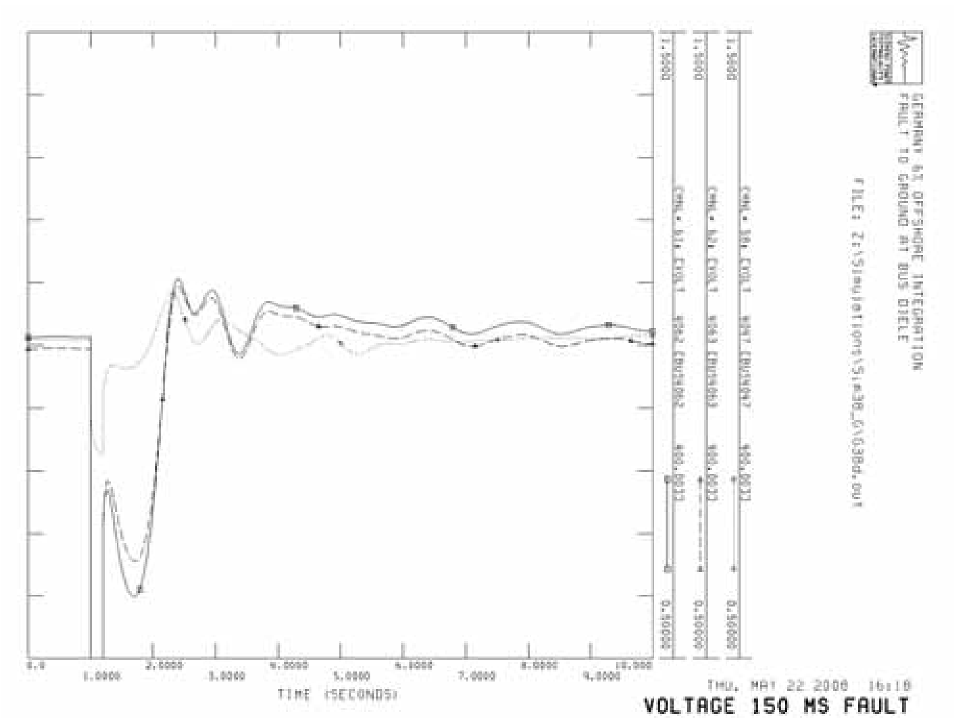

Figure 3.8 Voltage variations of the closest buses of the bus Diele when a 150ms fault to ground is applied.

3.3.2. Wind penetration scenario 12%

I will add in the network the rest of the wind farms to get a goal of 12 GW.

Normal Steady-State Power flow

I verify the normal loading and voltage limits in all the buses of the system.

The voltages are between 0.93pu and 1.05pu. It means a range of variation of 7% around the nominal, which is tolerable. The charging of the lines is not over the 90% of its capacity in any case.

Transient Stability

I apply a three phase to ground fault at bus Diele again.

The critical fault clearing time of the system is around 150 ms in this case. This is probably not assumable by the German normative. After outage the voltages at near buses go straight down and after system adjustments the voltages are fluctuating in a range of around 0.9 pu that is not acceptable.

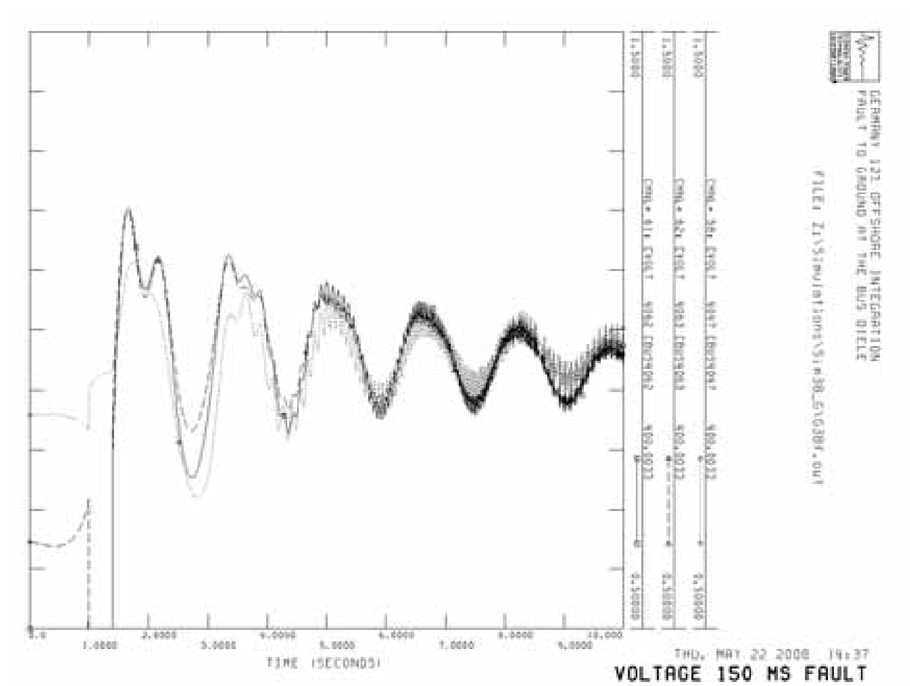

Figure 3.9 Voltage variation of the closest buses of Diele substation when a 150ms fault to ground is applied

3.4 Power Oscillations

I simulate 6% offshore wind scenario in order to compare the oscillations when a fault is applied in different parts of the network.

The generating unit at Wehrendorf is disconnected. The resulting power oscillations from the main offshore platform, when the generation unit at Wehrendorf drops, are monitored in figure 3.10.

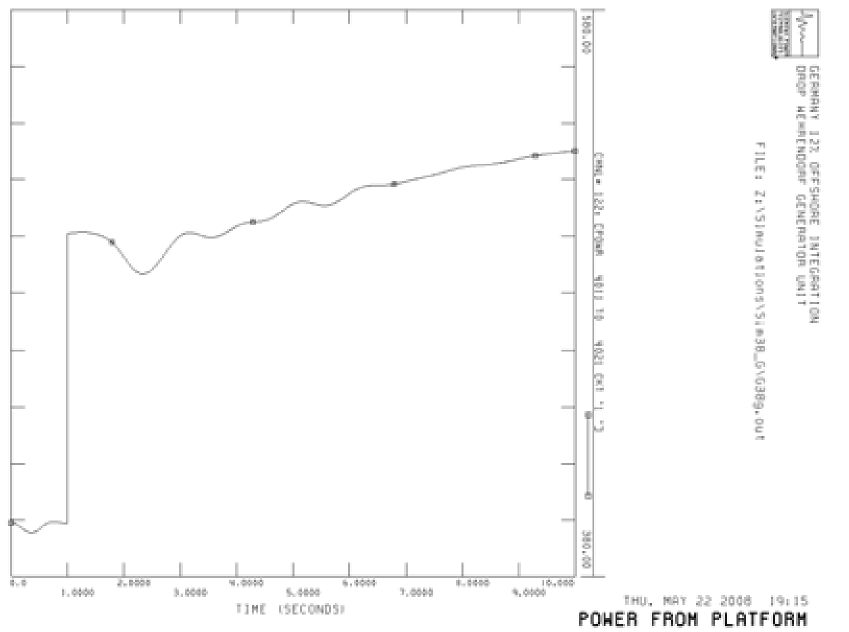

Figure 3.10 Power flow: Offshore platform (Bus 5) → Onshore connection point (Bus 6)

I appreciate no significant power oscillations in the lines that are not electrically close from Wehrendorf (see Figure 3.11).

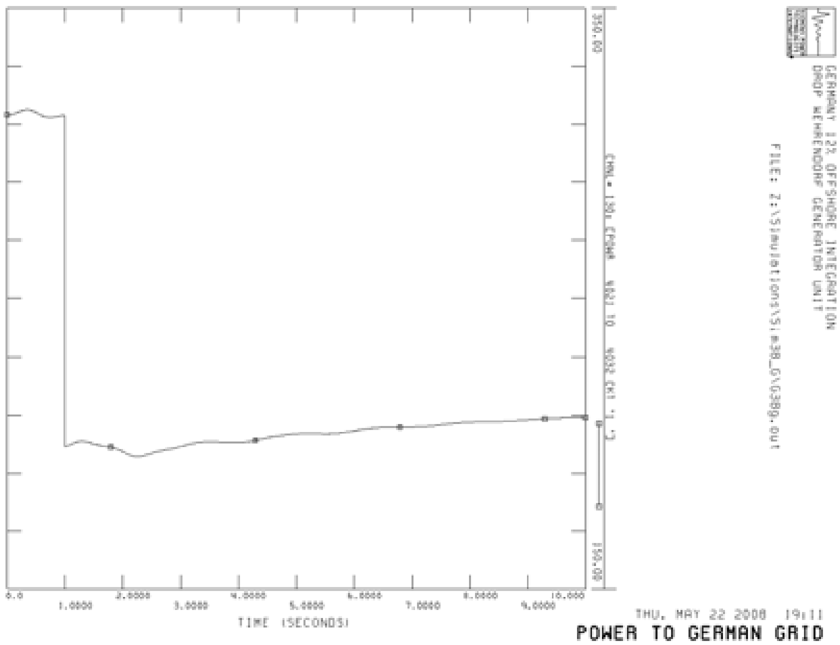

Figure 3.11 Offshore platform (Bus 5) – Bus 5002 (connection with the rest of the German grid)

I also verify every voltage oscillations are in the permissible margins:

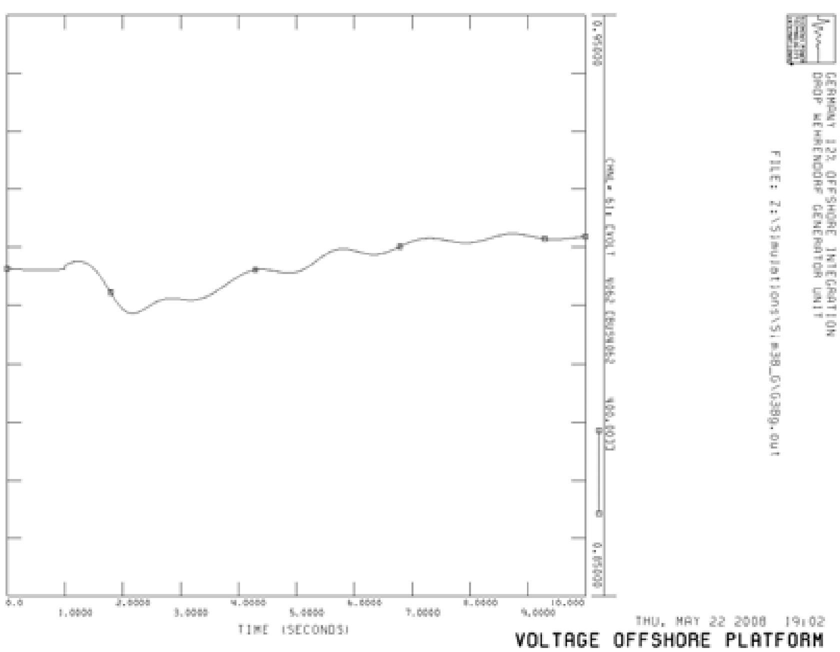

Figure 3.12 Voltage oscillations at the offshore platform

4 OFFSHORE WIND ENERGY INTEGRATION IN THE NORTH SEA

4.1 Foundation Project

At the EWEC 2003 in Madrid, the European Wind Energy Association announced that the goal for European offshore wind energy will be 10 GW of installed power in 2010 and 70 GW in 2020 [11].

A major expansion of offshore wind farms have been carried out the last years, especially in United Kingdom and Germany, see figure 4.1. It is expected, in 2012, offshore wind farms will account for approximately 20% of European wind turbine capacity.

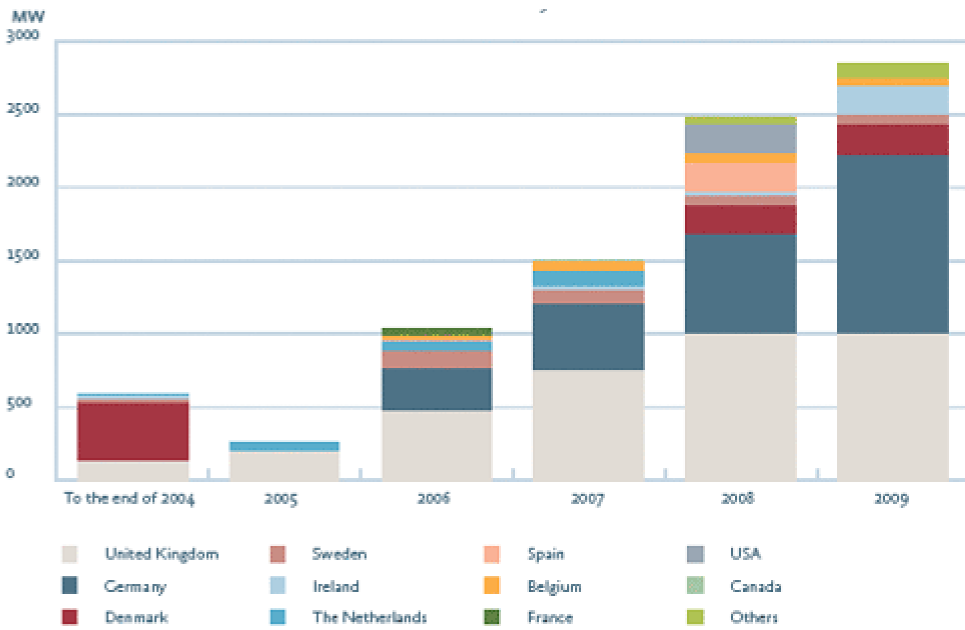

Figure 4.1 Global offshore wind power expansions to 2009

Large-scale renewable energy resources will be integrated to the North-Sea countries power system. I will study how it affects to the existing national grids since they have not been designed to carry as much energy from remote ends. There could be overloading and stability problems. The grids at these points are often of low voltage and relatively weak. They may be not ready to take on large-scale renewable power injection without some reinforcements.

The main benefits of the Supergrid come from combining the connections from offshore wind farms to shore with interconnectors between grid systems. The topology that results is that of interconnectors between countries being formed by linking up one or two offshore wind farms with each other and with the grid systems of two or more countries.

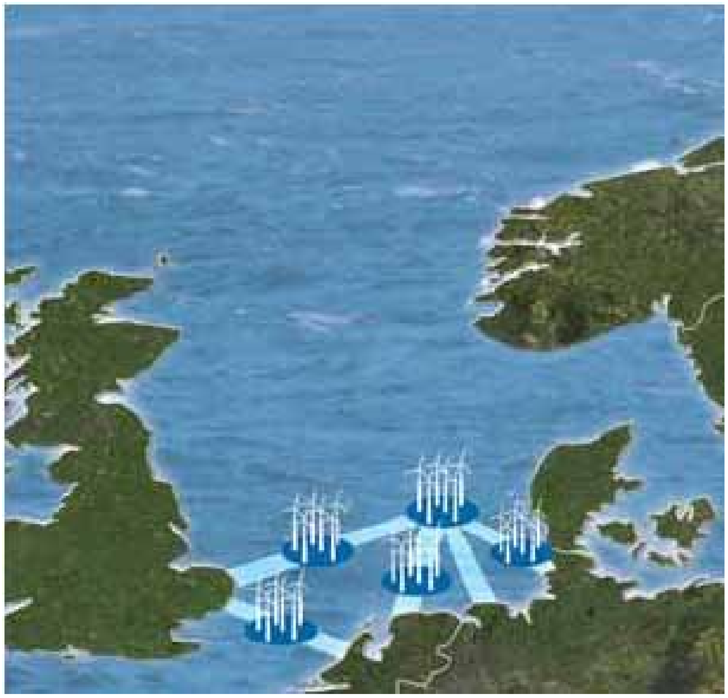

Figure 4.2 Foundation Project gross network

The major issues of wind power integration are related to: changed approaches in operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply [13], extension and modification of the grid infrastructure, and influence of wind power on system adequacy and the security of supply. The need for infrastructure investments is not based on wind energy only; consequently, grid extensions, grid reinforcement and increased backup capacity benefit all system users. An integrated approach to future decisions is needed. A large contribution from wind energy to European power generation is feasible in the same order of magnitude as the individual contributions from the conventional technologies. The capacity of European power systems to absorb significant amount of wind power is determined more by economics and regulatory rules than by technical or practical constraints. Already today a penetration of 20% of power from wind is feasible without posing any serious technical or practical problems.

4.2 Offshore wind farms and substations

With more and larger wind parks set to be built offshore, major investments are needed to find ways to feed the power into the grid. The alternating current technology used in the first, smaller offshore wind parks is increasingly reaching its limits on account of the high reactive power production of the cables. For wind farms distant to the coast, HVDC Light is the ideal means to bring the power to shore, to interconnect far away grids and to assure a good power quality.

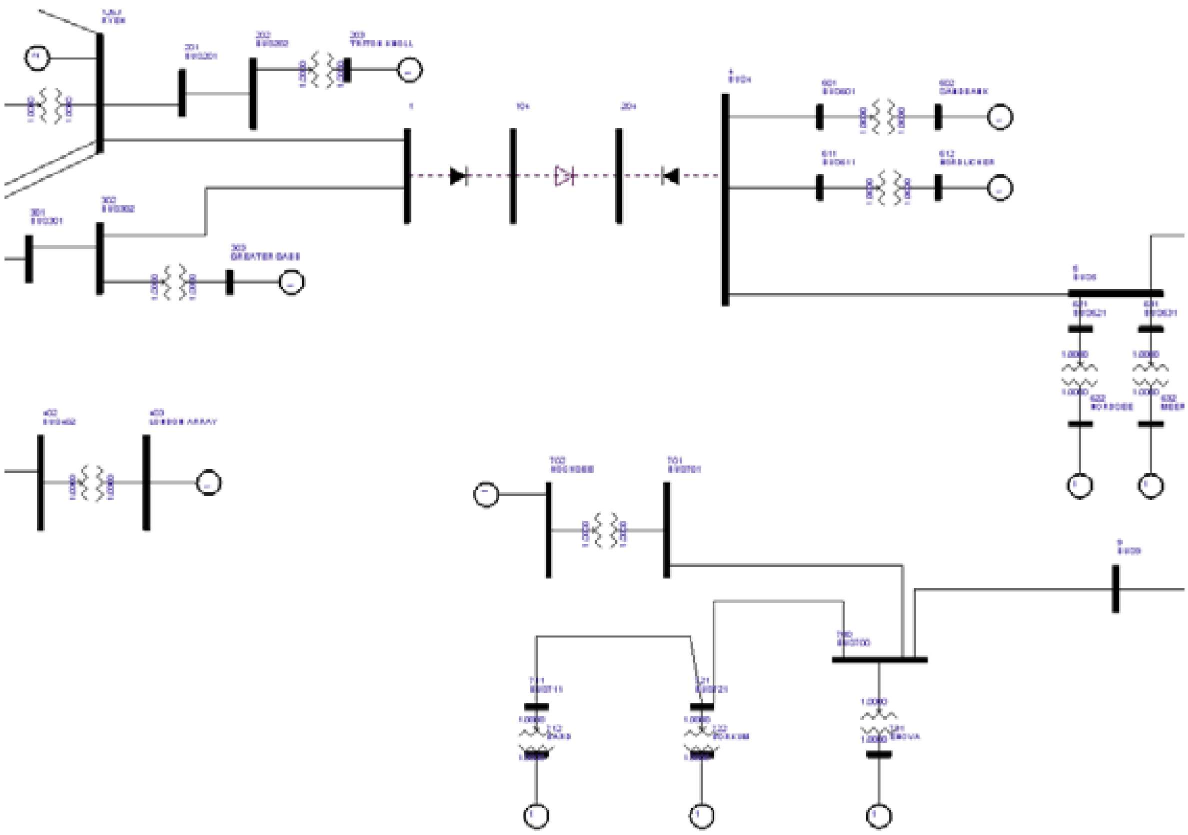

Figure 4.3 HVDC connection between offshore Northsea wind farms

The on-shore (receiving) converter station can be located close to the shore or further inland. The grid is sometimes rather weak (radial structure) along the coastline, but this may not neccesarily be a problem, since HVDC Light can be connected to weak points. But it is also easy to bring the connection point to a major substation at some distance from the shore by means of the HVDC Light cables. Offshore substations will require a step-up transformer if voltages are greater than 33 kV for the links to shore. There is no precedent for a small substation at sea. Probably, offshore transformer stations would be a three-legged steel structure with all the equipment necessary. Packaged substations are available, but these are usually used as emergency replacements or for quick installation in remote areas.

It is not an easy task to decide the number and size of offshore substations. A single large substation is likely to be cheaper due to the structure costs, but a failure results in the loss of the output from the entire wind farm group. The same argument applies to the cable link to shore. It is likely that offshore wind farm design will include formal assessment of these risks, in order to select the optimum configuration.

The main item in the offshore substation will be the transformer, but there will also be medium-voltage switchgear and possibly high-voltage switchgear. Due to the rough weather conditions and difficulties with access, electricity supply cuts for prolonged periods are possible. It may be justified to equip the station with a diesel generator in order to keep all essential equipment and also supply the auxiliary loads in the wind turbines.

4.3 HVDC model

Nowadays, fast progress in the field of power electronics devices with turn off capabilities such as IGBT and GTO, makes Voltage Source Converters (VSC) more attractive for HVDC applications. There are mainly two manufacturers that have developed the state-of-the-art HVDC technology suitable for offshore wind farms: ABB and Siemens. As an example case, Siemens Power Transmission and Distribution Division has outlined a preliminary version of a possible 675 MW offshore DC/AC-Converter station. ABB has developed HVDC Light over the last ten years; it has been implemented in several systems and it is already in operation. It can now transmit 1080MW on a pair of subsea cables each of diameter 94mm and it is already commercially available at 300kV.

AC links are inversely proportional to the distance but the power carrying capability of a DC link is unaffected by the transmission distance. The transmission distance with AC cables is limited due to the high steady-state charging currents [14]. This restriction does not exist for DC cables, thus making the breakeven distance up to 100 km. Final benefits are that DC links can be used to connect two AC systems with different frequencies or different control philosophies. When two AC networks are interconnected by a DC link, the fault level of the system does not increase significantly, which is not the case with AC connections.

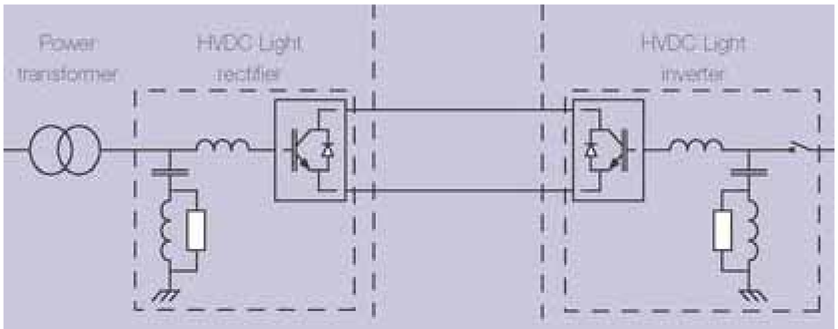

Figure 4.4 HVDC Light transmission system

Some disadvantages of DC transmission are [15]:

a) Transformers cannot be used to vary voltage levels,

b) High cost of converter stations,

c) Converter stations generate harmonics that need to be filtered out,

d) Complex controls of DC transmission.

Each converter bridge is controlled by a local feedback loop of bandwidth consistent with the firing delay accuracy requirements of the rectification/inversion process. These local loops work independently to maintain bridge current or voltage at desired values. The desired values are provided by an outer control loop which works in a supervisory role and coordinates the action of the several converter bridges and the ac power system (see Figure 4.5).

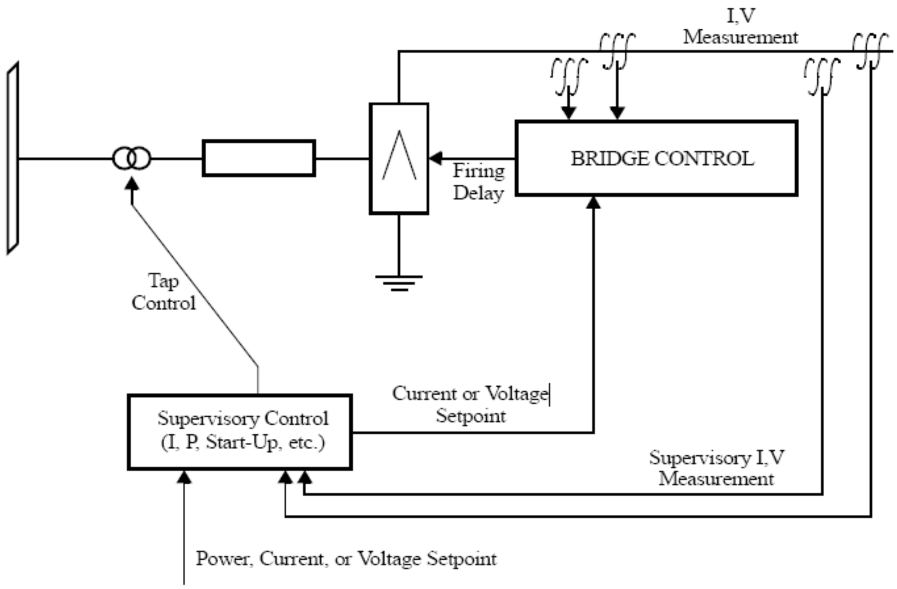

Figure 4.5 PSS/E HVDC transmission control model

The PSS/E DC model [7] used in this work , CDC4, treat dc converter pairs as if they move instantaneously to their new operating point when any of their input signals or ac feed voltages are changed. These pseudo steady-state, HVDC dynamic models calculate the active and reactive power loading of the HVDC converters using steady-state converter relationships similar to those used for load flow except that transformer taps remain fixed and the direct current and dc voltage or margin angle may be varied to model the effects of higher level controls. These PSS/E dc transmission models, then, are not concerned with the internal dynamic behavior of dc converters and lines, just as the ac network model is not concerned with the internal transient behavior of transformers and three-phase transmission lines.

The scheduled DC voltage and scheduled DC power (or current) are as specified in the load flow working case by the parameters VSCHED, SETVAL and MDC (see appendix D). The instantaneous current setpoint, Iset, is adjusted continuously if the line is in constant power mode (MDC = 1). The inverter current setpoint is assumed to follow the rectifier current setpoint to always provide the current margin, DELTI, as specified in the load flow working case. Changing of the dc operating setpoints VSCHED, SETVAL, and MDC, must be handled by changing the load flow data values via the network changes section of activity ALTR or via activity LOFL and CHNG.

CDC4 maintains the desired constant power as long as the inverter-end DC voltage stays above the value VCMODE, but switches to the nominal current setting Pset/Vsched, if the DC voltage falls below this level. If the control switches out of constant power mode for this reason, it is blocked from returning for a time delay, TCMODE, and may return to power control if the inverter dc voltage rises above VCMODE. Transformer taps are not adjusted automatically during dynamic simulation runs but may be changed manually via load flow data change dialog.

During faults in the AC side, the parallel connection of HVDC with the AC grid makes the response time very important. A standard voltage controller cannot be used to manage these situations. The parameters settings are fixed in order to consider that the system must not be too fast in normal operation and it has to act rapidly when something happens.

4.4 Steady-State and Dynamic Power Flow

HVDC Light converters include Insulated Gate Bipolar Transistors (IGBT) and operate with high frequency Pulse Width Modulation in order to get high speed control of both active and reactive power. HVDC Light is a transmission system that does not require any additional compensation, as this is inherent in the control of the converters.

Normal Steady-State Power flow

I simulate the 6% offshore integration scenario of both UK and Germany grids connected by DC transmission lines. I verify the normal loading and voltage limits in all the buses of the system. The voltages are between 0.94pu and 1.06pu. It means a range of variation of 6% around the nominal, which is quite tolerable. The charging of the lines is not over the 80% of its capacity in any case.

Nominal voltages of the system are 380 kV. Before failure planning voltage limits are between 380kV and 440kV for 400kV transmission system. In the locations not having 380kV system, the limit is assumed to be between 270kV and 300kV for 275kV.
After system adjustments the charging of the lines is under the unit. The load flow in the DC line is 700MW.

Transient Stability

HVDC Light utilizes state of the art semiconductors, control and cable insulation and can offer many new transmission opportunities Wind power, even large parks, can easily be connected to the grid. In many cases, HVDC Light can give new opportunities as feeding islands or far away located communities and multiterminal applications. In this mode of operation, a wind farm operates at a certain power factor to maintain a zero reactive power exchange with the grid. This is the classical way to control a wind farm today. In the case where a wind farm is connected to the grid by a long cable, the wind farm has to absorb some reactive power generated by the cable to keep the reactive power exchange to zero at the grid connection point.

DC line short circuit is different from AC short circuit, because once DC fault starts it will not be extinguished by itself until the current is reduced to zero and the arc is deionised. Some control function is needed to bring the current down to zero when a fault occurs on a DC line. The amplitude of the DC line fault current is smaller than the AC one; usually limited to two or three per unit by the smoothing reactor and by control action.

After the fault detection, the rectifier is forced to full inversion operation and does not supply any current to the fault. The inverter voltage already has the correct polarity, thus the two converters are temporarily inverting at the same time and transferring the energy stored in the DC circuit electric and magnetic fields into the two AC systems. HVDC Light has the advantage of being able to almost instantly change its working point within its capability curve.

For the short-term balancing of electrical power in the North Sea grid (i.e. on a seconds to minutes scale) it is expected that no further adjustments are needed at the 6% offshore integration scenario. The long-term balancing of power (time periods of a quarter of an hour to several days) seems more difficult but again adjustments can be avoided, provided that [4]:

· The operating method of offshore wind farms shifts more to that of a conventional power plant rather than simply maximising the power output,

· Application of power prediction methodologies that will be widely implemented.

For the long-term balancing of power, adequate distribution of wind power in the Dutch North Sea, i.e. taking advantage of regional variations in wind speed, may be helpful.

At a connection point, the installed power of wind turbine generating system which is at most %5 of short circuit power of national grid is allowed to connect to it.By considering the feature that wind turbine generating systems are automatically disabled when wind speed exceeds any given limit, wind turbine generating system is allowed to connect to national grid at the installed power which does not exceed alternative auxiliary power capacity in order to avoid instantaneous voltage variations and frequency fluctuations. System nominal frequency is controlled at about 50 Hertz (Hz), in the range of 49.8 – 50.2 Hz [9].

For the purpose of limiting the disturbances conveyed to the system by production foundations based on wind energy, power factor of production foundation having asynchronous wind turbine based on wind energy, can not be below 0,99. The power factor can be increased by the suitable compensation foundations [9]. If, i.e., nominal voltages of the system are 380 kV. Before failure planning voltage limits are between 390kV and 440kV for 400kV transmission system. In the locations not having 400kV system, the limit is assumed to be between 140kV and 170kV for 154kV.

It is stated however that the requirement do not apply to radial connected wind farms, where a fault would isolate the wind farm, i.e. wind farms do not need to ride through faults, whose clearance would open-circuit the wind farms' terminals. Under such circumstances the wind farms may disconnect. Wind farms have to stay connected and stable under permanent 3-phase faults, on any arbitrary line or transformer and under transient 2-phase fault (unsuccessful auto-reclosure), on any arbitrary line. **In the wake of**

a fault the voltage can be down to 70% of the initial voltage for a duration of up to 10 seconds, which must not lead to instability of the wind farm. The controllability of the wind farm must be sustained for up to 3 faults within 2 minutes, or for up to 6 faults if the delay between the faults is 5 minutes; each fault happening during steady state operation. This requirement makes sure that the turbines are fitted with sufficient auxiliary power supplies. When the voltage directly after a fault falls below 60- 80% for longer than 2-10 seconds, it is likely that the turbines have accelerated so much, that the grid cannot get them back to normal speed. In such a case a fast reduction of the active power and a fast increase of reactive power have to be conducted. If this does not successfully re-establish the grid voltage the wind farm has to be disconnected [16].

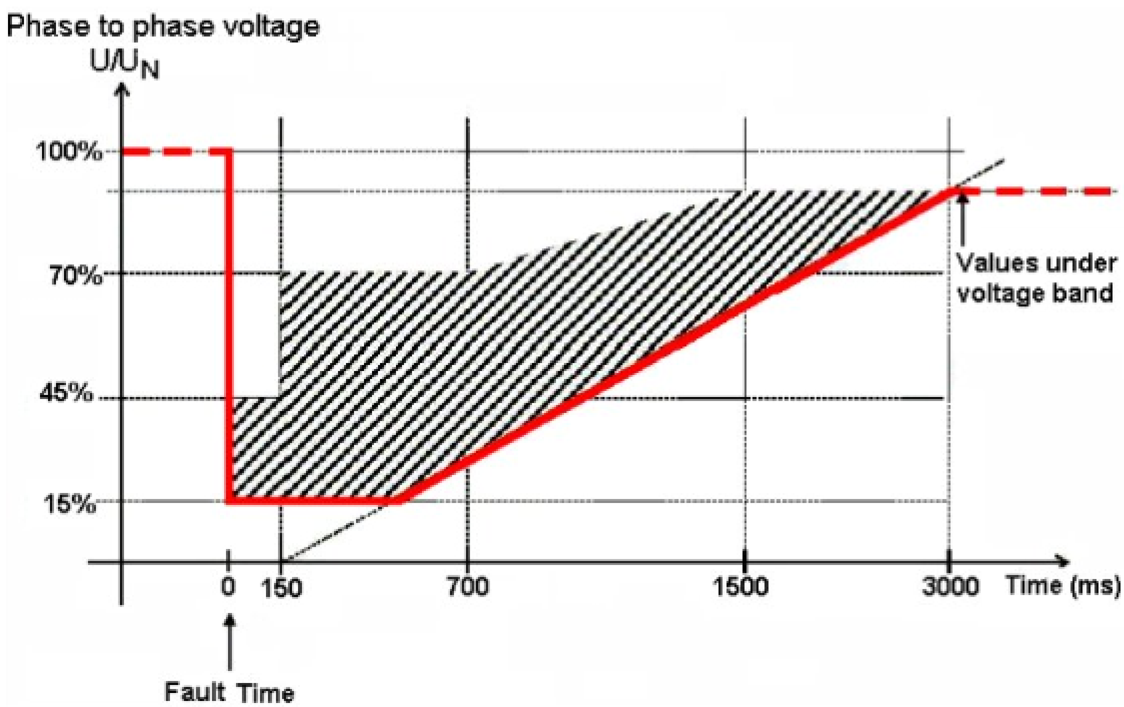

Figure 4.7 Failure and after failure performance of the production foundations based on wind energy

I apply a three phase to ground fault at bus 1262 (Sizewell).

The critical fault clearing time of the system is 250ms. because if the fault is longer the equivalent generator at Greater Gabbard offshore wind farm will loss the synchronism. So the DC link between offshore wind areas not only is available but improves the system transient stability of the East coast UK grid.

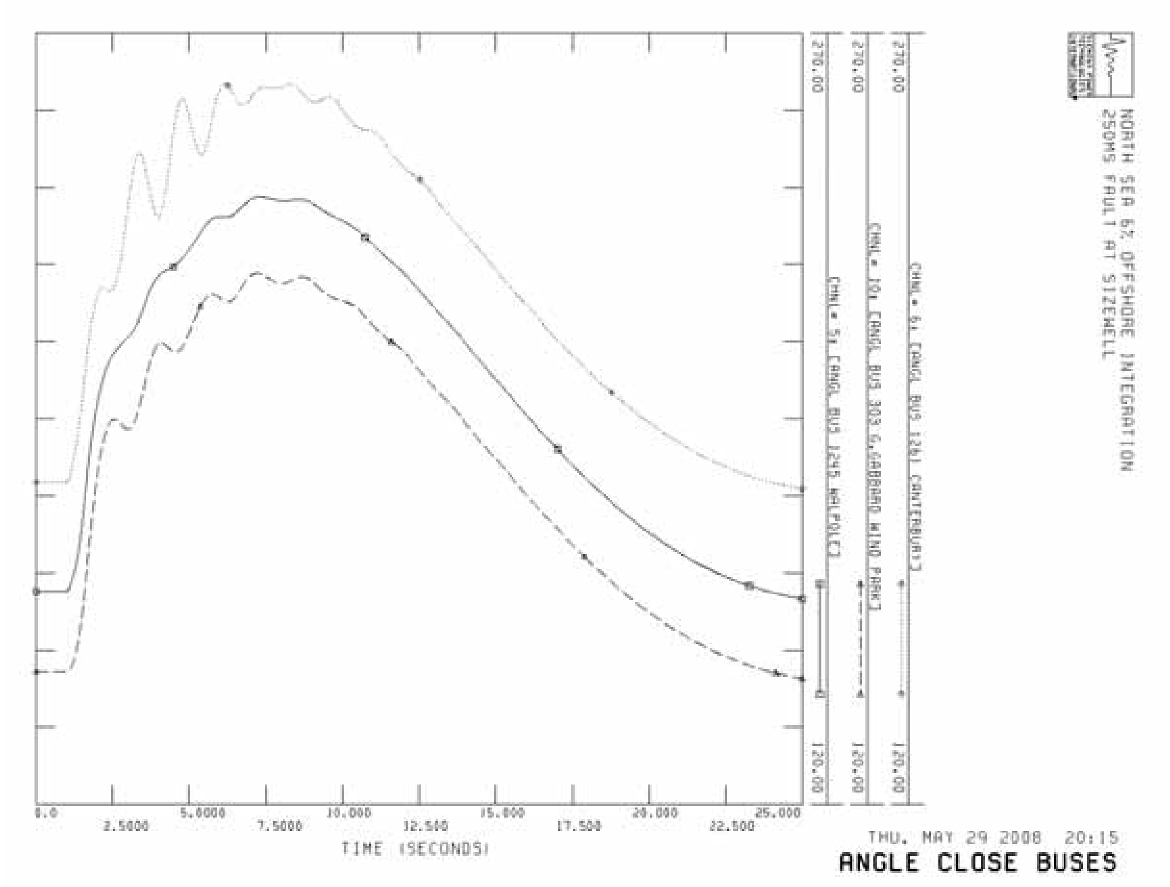

Figure 4.8 Angle variation of the closest buses of Sizewell substation when a 250ms. fault to ground is applied in there.

I check also the voltage at the closest substations oscillate in a bandwidth of 0.2 pu (Walpole and Canterbury buses) and 0.3 at the closest wind farm in which the voltage drops till almost 0.7 pu. This probably will not lead to the disconnection of the Greater Gabbard wind farm because after the clearing of the fault the voltage is almost inmediatelly back to the nominal. The bandwidth of the oscillations afterwards is in the permissible range, the curve is totally flat after seven seconds.

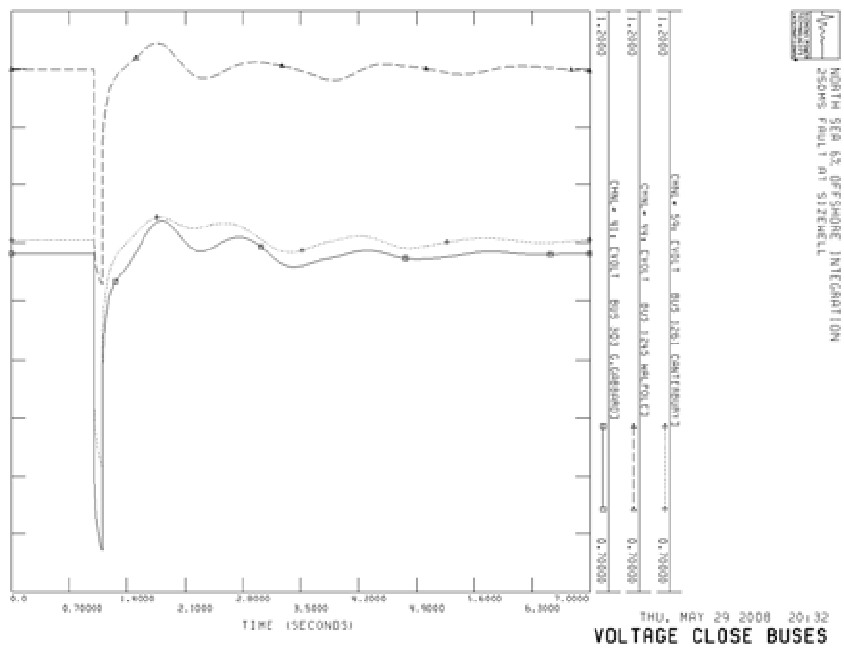

Figure 4.9 Voltage variation of the closest buses of Sizewell substation when a 250ms. fault to ground is applied.

The three-phase fault is initiated at Diele, close to the biggest offshore platform in the network and also close to the HVDC link to see if the DC link endanger the system transient stability of the other side (German offshore network).

The critical fault clearing time of the system is 280ms. because if the fault is longer every wind farm connected to the offshore platform (BUS 700) loses the synchronism. So the DC link between offshore wind areas improves also the system transient stability of the other side, at least in terms of fault clearing time.

The Figure 4.10 shows the voltage oscillations at the biggest offshore platform. The curve rise to the nominal value in less than one second, the protections will not act and the farms will keep connected because in comparison with the Figure 4.7 the values of the closest buses of Sizewell are over the voltage band.

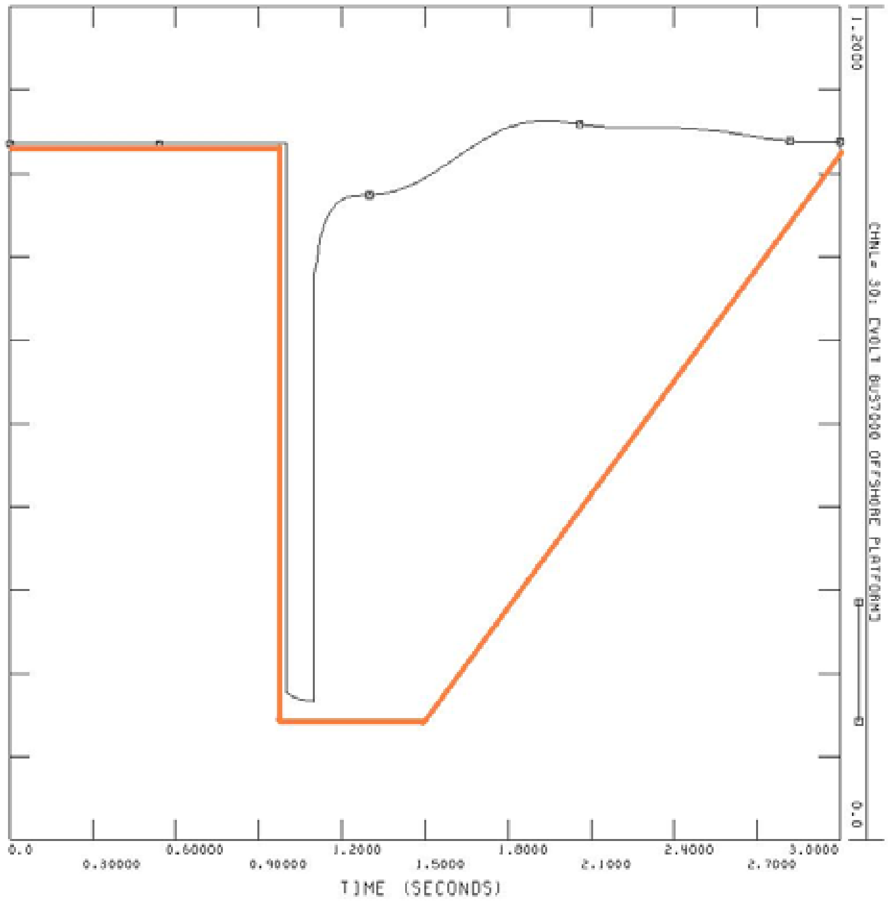

Figure 4.10 Voltage at the offshore platform in the permissible range when a 250ms. fault to ground is applied at Diele

The power flow in the HVDC line is 700 MW, this is relatively small in comparison with the rest of the German and European grid so the consequences of the lost of the line are not serious for the German grid or the UK grid either. I do not take in consideration the control of the wind farms that determines the stability limits of the wind farm. Such control could be much lower than the time setting of the typical time-graded protection devices, which are normally installed on the distribution feeders.

An optimal power flow is met by PSS/E by a series of criteria in order to minimize the losses and to avoid overload on the AC lines. Transformers tap changers are automatically moved. To avoid overload on the AC grid because of any disturbances on a HVDC, the control automatically disconnects, within 100 ms, the amount of wind power production that was being transmitted on HVDC Light, plus a margin.

This demonstrates that the DC connection has the potential to improve wind farm performance during faults in the AC grid. The wind farm can be quickly isolated from the AC grid and rapidly recovers to full wind power production when the AC grid fault has been restored.

The voltage recovery following fault conditions may become impossible, and consequently the wind farm experiences voltage collapse at its terminals. I simulate voltage variation of the offshore platform (BUS 700) when the HVDC line is disconnected.

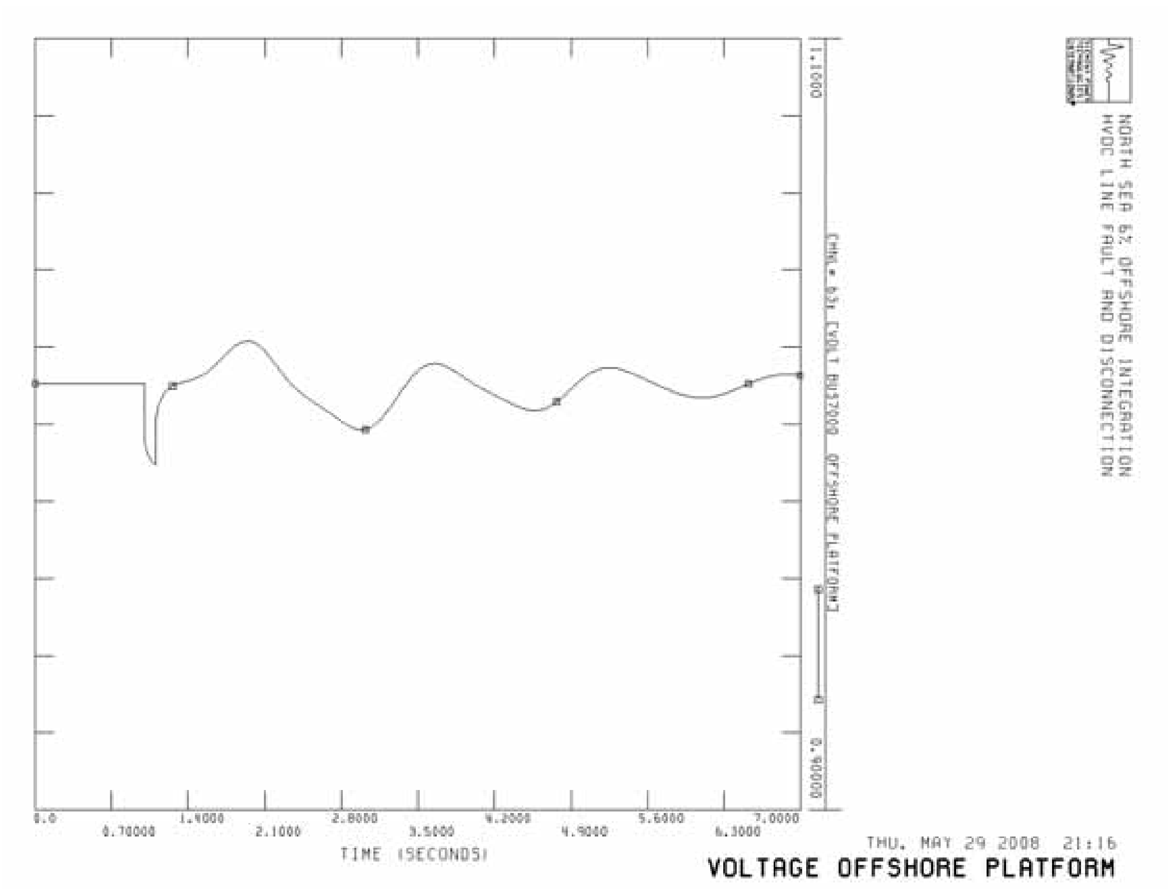

Figure 4.11 Voltage variation of the offshore platform (BUS 700) when the HVDC line is disconnected.

The frequency range wind turbines have to tolerate is about 47.5-51.5 Hz. According to the wishes of German transmission grid operators large wind farms have to be treated in the future like conventional power plants. The frequency range at two wind farms at the UK coast when the generation unit at Sizewell drops is about 49.7 – 50.5 Hz (see Figure 4.12)

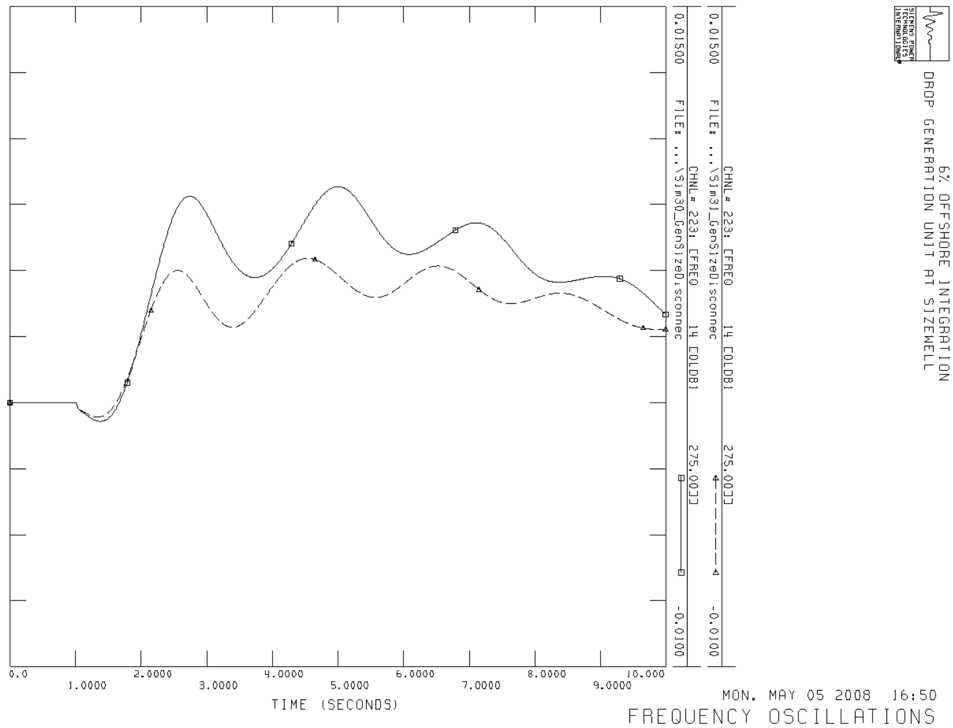

Figure 4.12 Frequency oscillations in p.u.

The simulations so far have been done only for the peak hour operations, when the system is heavy loaded. The heavy load can normally last 3-4 hours each day, while during the rest of the time load is decreased and therefore the system is becoming able to transfer the needed power without overloading the system components. Accordingly the losses are becoming lower. In such a case, when the loads are lowered, the reactive power sources, which we applied to the system during the peak hour operations, become excessive and their injected reactive power can cause even more losses and destructive overvoltage. Therefore it’s very important the reactive power sources to be properly operated and switched to the system only in case when they will be needed, i.e. during the heavy loads of the system.

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

It is found that a scenario with more than 6% of offshore wind power supply does not serve grid connection requirements in UK. New transmission capacity should be provided when more offshore wind energy need to be integrated. The provision of this infrastructure could decide the rate at which new offshore wind farms will be connected. Nowadays, there are already some bottlenecks for north-south transmission affecting onshore wind power in Scotland and offshore wind power in the North West area and Greater Wash. Consequently some grid reinforcements are necessary especially at Greater Wash above 3000 MW of offshore wind may require reinforcements. Scenarios up to 12% in Germany are within connection requirements. The value is increased in the German test system in part because by using offshore platforms provides more flexibility in the way to connect the wind farms to land, a more distributed grid is got so the security of the system is improved.

In the North Sea, a 6% offshore wind integration scenario is analyzed interconnecting both offshore areas with DC cables and simulating some contingencies. When two AC networks are interconnected by a DC link, the fault level of the system does not increase significantly, which is not the case with AC connections. . Large offshore wind farms can be operated as conventional power plants. Offshore wind power integration using HVDC Light technology makes possible that power variations do not stress the AC grid as much as in conventional networks. Voltage quality is better since a important problem in conventional networks is that the current may be very high during voltage recovery from a fault, especially if the voltage dip was deep and there are asynchronous generators electrically close. HVDC Light's voltage control function can considerably mitigate this problem. It is concluded that the HVDC link does not endanger the system stability but improves it, i.e., critical fault clearing time in UK.

The incorporation of wind farm gives rise to severe voltage recovery problem following fault condition on the associated network. The voltage recovery following fault conditions may become impossible, and consequently the wind farm experiences voltage collapse at its terminals. Therefore, the main requirements concern the fault ride through capability of wind turbines. Accordingly, disconnection of wind turbines and wind farms above 15% nominal voltage at the grid connection nodes is not allowed. Besides, following network faults wind turbines have to supply a definite reactive current depending on the instantaneous voltage. Furthermore, they must return quickly to normal operation. The conclusions of this project work are valid for the fictitious grid created in this work and no further conclusions may be done

5.2 Future Work

Much more simulations and analyzes of contingencies on the test system with and without HVDC cables are needed in order to insure that the future Supergrid will not endanger the system stability. It should be clear that the test system improved in this paper is very simple because of the lack of data about the future offshore network, futures works will require more detailed information about the Supergrid, for example, FACTS and reactive power sources to be properly operated and switched to the system. The variances of the simulations taking in consideration all the elements of the future electrical grid are expected to be quite different than in the present thesis.

Equivalent circuits of the prospective European national grids with a more realistic feeder configuration, more detailed models to define the dynamic behavior of the specific wind turbines and specific HVDC Light dynamic models are also possible future directions; also to study the optimal places to insert FACTS to a better reactive performance of the grid. The control of a wind farm due to a fault on the associated network determines the stability limits of the wind farm, such control has not been studied here and it will be necessarily included in future works.

Some grid requirements must be checked in future works: Power quality, power control, power interruptions, frequency control, voltage control (reactive power), voltage and frequency ride through. Beside, interconnecting the rest of the futures offshore wind farms (in the Baltic sea, Mediterranean,…) to the European power system is another challenge for future researchers.

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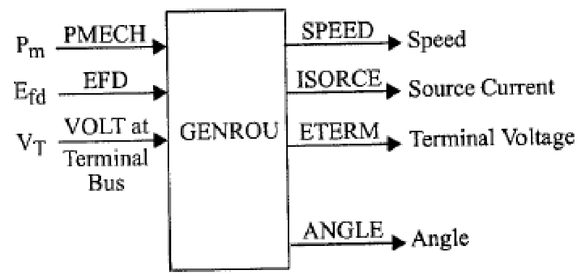
7. APPENDICES

Appendix A

GENROU: Dynamic data sheet example of one of the round rotor generator model

This model is located at system bus # 1263 IBUS,
machine # 1 I.
This model uses CONs starting with # ______ J,
and STATEs starting with # ______ K,
The machine MVA is 2 for each of 1 units = 2 MBASE.
ZSORCE for this machine is 0 + j 0.2 on the above MBASE



CONs	#	Value	Description
J		7	T'_{do} (>0) (sec)
J+1		.05	T''_{do} (>0) (sec)
J+2		1.5	T'_{qo} (>0) (sec)
J+3		.05	T''_{qo} (>0) (sec)
J+4		6	Inertia, H
J+5		0	Speed damping, D
J+6		2.2	X_d
J+7		2	X_q
J+8		.3	X'_d
J+9		.4	X'_q
J+10		.2	$X''_d = X''_q$
J+11		.15	X_l
J+12		.1	S(1.0)
J+13		.3	S(1.2)

STATEs	#	Description
K		E'_q
K+1		E'_d
K+2		ψkd
K+3		ψkq
K+4		Δ speed (pu)
K+5		Angle (radians)

Note: X_d, X_q, X'_d, X'_q, X''_d, X''_q, X_l, H, and D are in pu, machine MVA base.

X''_q must be equal to X''_d.

IBUS, 'GENROU', I, T'_{do}, T''_{do}, T'_{qo}, T''_{qo}, H, D, X_d, X_q, X'_d, X'_q, X''_d, X_l, S(1.0), S(1.2)/

Appendix B

GENSAL: Dynamic data sheet example of one of the salient pole generator model

This model is located at system bus # 1012 IBUS,

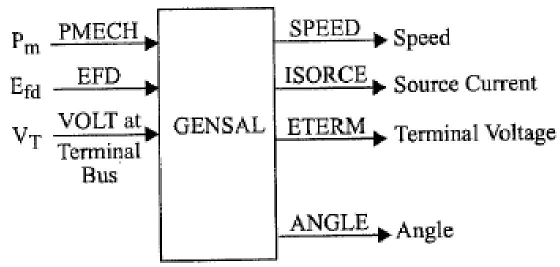
machine # 1 I.

This model uses CONs starting with # ______ J,

and STATEs starting with # ______ K.

The machine MVA is 1 for each of units = 1 MBASE.

ZSORCE for this machine is 0 + j 0.25 on the above MBASE.



CONs	#	Value	Description
J		5	T'_{do} (>0) (sec)
J+1		.05	T''_{do} (>0) (sec)
J+2		.1	T''_{qo} (>0) (sec)
J+3		3	Inertia, H
J+4		0	Speed damping, D
J+5		1.1	X_d
J+6		.7	X_q
J+7		.25	X'_d
J+8		.2	$X''_d = X''_q$
J+9		.15	X_l
J+10		.1	S(1.0)
J+11		.3	S(1.2)

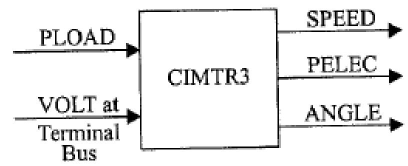
STATEs	#	Description
K		E'_q
K+1		ψkd
K+2		ψ''_q
K+3		Δ speed (pu)
K+4		Angle (radians)

Note: X_d, X_q, X'_d, X''_d, X''_q, X_l, H, and D are in pu, machine MVA base.

Appendix C

CIMTR3: Dynamic data sheet of one of the induction generator model

This model is located at system bus #_7000_ IBUS,
machine #_1_ I.
This model uses CONs starting with #____ J,
and STATEs starting with #____ K,
and VARs starting with #____ L,
and ICON #____ M.
The machine MVA is _300_ for each of _4_ units = _1200_ MBASE.



CONs	#	Value	Description
J		2	T' (sec) (>0)
J+1		0	T" (sec) (≥0)*
J+2		2	Inertia, H
J+3		3.5	X
J+4		0.2	X'
J+5		0	X"*
J+6		0.1	X_l
J+7			E_1 (≥0.)
J+8			$S(E_1)$
J+9			E_2
J+10			$S(E_2)$
J+11		0.	Switch
J+12		/	SYN-POW, mechanical power at synchronous speed (>0). Used only to start machine, otherwise ignored.

*If T" = 0. or X" = 0., machine is assumed to be single cage and ZSORCE should be set equal to X'.

Note: X, X', X", X_l, and H are in pu, machine MVA base.

IBUS, 'CIMTR3', I, T', T", H, X, X', X", X_l, E_1, $S(E_1)$, E_2, $S(E_2)$, 0., SYN-POW/

STATEs	#	Description
K		E'_q
K+1		E'_d
K+2		E''_q
K+3		E''_d
K+4		Δ speed (pu)
K+5		Angle deviation

VARs	#	Description
L		Admittance of initial condition Mvar difference
L+1		Motor, Q
L+2		T_{elec}

ICON	#	Description
M		Memory

Appendix D

VSCDCT: Dynamic data of the VSC DC model (applied in HVDC Light)

VSCDCT

VSC DC Model with Two VSC Converters

VSC DC Line Name	'VSC DC Name', as defined in load flow data
using ICONs starting with	#_______ I,
and CONs starting with	#_______ J,
and STATEs starting with	#_______ K,
and VARs starting with	#_______ L,

ICONs	#	Values	Description
M		0	Block_Flag_1, 1= Blocked Converter (For VSC # 1)
M+1		0	XFBus_Ctrl_Side_1, System bus number for voltage or reactive power control. When 0, controlled bus number is assigned from corresponding load flow input data (For VSC # 1).
M+2		0	Block_Flag_2, 1= Blocked Converter (For VSC # 2)
M+3		0	XFBus_Ctrl_Side_2, System bus number for voltage or reactive power control. When 0, controlled bus number is assigned from corresponding load flow input data (For VSC # 2).

CONs	#	Values	Description
J		0.05	Tpo_1, Time constant of active power order controller, sec (For VSC # 1).
J+1		0.0	AC_VC_Limits_1, Reactive power limit for ac voltage control, pu on converter MVA rating. When 0, it is not used and Qmax/Qmin pair is used instead (For VSC # 1).
J+2		2.4	AC_Vctrl_kp_1, AC Voltage control proportional gain, converter MVA rating/BASEKV (For VSC # 1).
J+3		0.01	Tac_1 > 0.0, Time constant for AC voltage PI integral, sec (For VSC # 1). When 0, VSC#1 is ignored.
J+4		0.01	Tacm_1, Time constant of the ac voltage transducer, sec (For VSC # 1).
J+5		1.0	Iacmax_1, Current Limit, pu on converter MVA rating (For VSC # 1).
J+6		0.00	Droop_1, AC Voltage control droop, converter MVA rating/BASEKV (For VSC # 1).
J+7		1.07	VCMX_1, Maximum VSC Bridge Internal Voltage (For VSC # 1).
J+8		0.17	XREACT_1 > 0.0, Pu reactance of the ac series reactor on converter MVA rating (For VSC # 1). When 0.0, default value 0.17 is used.
J+9		60	QMAX_1, Maximum system reactive limits in Mvars (For VSC # 1). When AC-VC_Limits_1 >0, QMAX_1 is not used.
J+10		-60	QMIN_1, Minimum system reactive limits in MVARs (For VSC # 1). When AC-VC_Limits_1 >0, QMIN_1 is not used.
J+11		1.2	AC_VC_KT_1, Adjustment Parameter for the feedback from reactive power limiter to ac voltage controller (For VSC #1).
J+12		1.0	AC_VC_KTP_1, Adjustment Parameter for the feedback from current order limiter to ac voltage controller (For VSC #1).
J+13		0.05	Tpo_2, Time constant of active power order controller, sec (For VSC # 2).
J+14		0.0	AC_VC_Limits_2, Reactive power limit for ac voltage control, pu on converter MVA rating. When 0, it is not used and Qmax/Qmin pair is used instead (For VSC # 2).

CONs	#	Values	Description
J+15		2.4	AC_Vctrl_kp_2, AC Voltage control proportional gain, converter MVA rating/BASEKV (For VSC # 2).
J+16		0.01	Tac_2 > 0.0, Time constant for AC voltage PI integral, sec (For VSC # 2). When 0, VSC#2 is ignored.
J+17		0.01	Tacm_2, Time constant of the ac voltage transducer, sec (For VSC # 2).
J+18		1.0	Iacmax_2, Current Limit, pu on converter MVA rating (For VSC # 2).
J+19		0.00	Droop_2, AC Voltage control droop, converter MVA rating/BASEKV (For VSC # 2).
J+20		1.07	VCMX_2, Maximum VSC Bridge Internal Voltage (For VSC # 2).
J+21		0.17	XREACT_2 > 0.0, Pu reactance of the ac series reactor on converter MVA rating (For VSC # 2). When 0.0, default value 0.17 is used.
J+22		60	QMAX_2, Maximum system reactive limits in MVARs (For VSC # 2). When AC-VC_Limits_2 >0, QMAX_2 is not used.
J+23		-60	QMIN_2, Minimum system reactive limits in MVARs (For VSC # 2). When AC-VC_Limits_2 >0, QMIN_2 is not used.
J+24		1.2	AC_VC_KT_2, Adjustment Parameter for the feedback from reactive power limiter to ac voltage controller (For VSC #2).
J+25		1.0	AC_VC_KTP_2, Adjustment Parameter for the feedback from current order limiter to ac voltage controller (For VSC #2).
J+26		0.050	Tpo_DCL, Time constant of the power order controller, sec (For DC Line).
J+27		0.050	Tpo_lim, Time constant of the power order limit controller, sec (For DC Line).

STATEs	#	Description
K		P_ref_pu, Active power reference auxiliary input, PU on CONVERTER MVA RATING (For VSC # 1).

STATEs	#	Description
K+1		Uac_int, AC Voltage controller integral output, pu on converter MVA rating (For VSC # 1.
K+2		Uac_p_filt, AC voltage measured, PU (For VSC # 1).
K+3		P_ref_pu, Active power reference auxiliary input, pu on converter MVA rating (For VSC # 2).
K+4		Uac_int, AC Voltage controller integral output, PU on converter MVA rating (For VSC # 2).
K+5		Uac_p_filt, AC voltage measured, pu (For VSC # 2).
K+6		P_ret_pu, Power Order, pu on SBASE (For DC Line).
K+7		Plimit, Power Order Limit, pu on SBASE (For DC Line).

VARs	#	Description
L		P_aux, Active power reference auxiliary order, MW (For VSC # 1).
L+6		Q_ref, Reactive power order, pu on converter MVA rating (For VSC # 1).
L+7		P_ref, Interface Active power, pu on SBASE (For VSC # 1).
L+10		PELE, Active power, pu on SBASE (For VSC # 1).
L+11		QELE, Reactive power, pu on SBASE (For VSC # 1).
L+12		P_aux, Active power reference auxiliary order, MW (For VSC # 2).
L+18		Q_ref, Reactive power order, pu on converter MVA rating (For VSC # 2).
L+19		P_ref, Interface Active power, pu on SBASE (For VSC # 2).
L+22		PELE, Active power, pu on SBASE (For VSC # 2).
L+23		QELE, Reactive power, pu on SBASE (For VSC # 2).
L+24		P_ref_main, Active power main order, pu on SBASE (For DC Line).
L+32		Pzero_loss, DC system losses at zero current, MW (For DC Line).
L+33		Pdc_loss, DC losses, MW (For DC Line).
L+34 • • • L+45		Isormod History, PSSE Variables for internal usage as well as: L+1 through L+5, L+8, L+9, L+13 through L+17, L+20, L+21, L+25 through L+31.

'VSC Name' , 'VSCDCT', Block_Flag_1, XFBus_Ctrl_Side_1, Block_Flag_2, XFBus_Ctrl_Side_2, Tpo_1, AC_VC_Limits_1, AC_Vctrl_kp_1, Tac_1, Tacm_1, Iacmax_1, Droop_1, VCMX_1, XREACT_1, QMAX_1, QMIN_1, AC_VC_KT_1, AC_VC_KTP_1, Tpo_2, AC_VC_Limits_2, AC_Vctrl_kp_2, Tac_2, Tacm_2, Iacmax_2, Droop_2, VCMX_2, XREACT_2, QMAX_2, QMIN_2, AC_VC_KT_2, AC_VC_KTP_2, Tpo_DCL, Tpo_lim /

Appendix E

CIMTR3: Dynamic data file (.dyr) of the total North Sea grid

“induction generator”

```
103 'CIMTR3' 2 0 2 3.5 .2 0 .1/
203 'CIMTR3' 2 0 2 3.5 .2 0 .1/
303 'CIMTR3' 2 0 2 3.5 .2 0 .1/
403 'CIMTR3' 2 0 2 3.5 .2 0 .1/
503 'CIMTR3' 2 0 2 3.5 .2 0 .1/
602 'CIMTR3' 2 0 2 3.5 .2 0 .1/
612 'CIMTR3' 2 0 2 3.5 .2 0 .1/
622 'CIMTR3' 2 0 2 3.5 .2 0 .1/
632 'CIMTR3' 2 0 2 3.5 .2 0 .1/
702 'CIMTR3' 2 0 2 3.5 .2 0 .1/
712 'CIMTR3' 2 0 2 3.5 .2 0 .1/
722 'CIMTR3' 2 0 2 3.5 .2 0 .1/
731 'CIMTR3' 2 0 2 3.5 .2 0 .1/
```

“solid rotor generator”

```
1242 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1246 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1247 'GENROU' 2 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1251 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1262 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1263 'GENROU' 2 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1032 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
1033 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5001 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5002 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5003 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5004 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5005 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
5007 'GENROU' 1 7 .05 1.5 .05 6 0 2.2 2 .3 .4 .2 .15 .1 .3/
```

“*salient pole machine*”

```
1211 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1212 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1221 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1231 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1241 'GENSAL' 1 7 .05    .1  2 0 1.55 1 .3  .2 .15 .1 .3/
1271 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1272 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1012 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1013 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1014 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1021 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1022 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1112 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
1112 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
6000 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
6002 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
6004 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
6005 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
6100 'GENSAL' 1 7 .05    .1  2 0 1.55 1 .3  .2 .15 .1 .3/
6104 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
7001 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
7002 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8001 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8003 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8004 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8005 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8006 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
8007 'GENSAL' 1 5 .05    .1  3 0 1.1 .7 .25  .2 .15 .1 .3/
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“Excitation system”

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1011 'SEXS'   1 .2 20 50 .1 0 4/
1012 'SEXS'   1 .2 20 50 .1 0 4/
1021 'SEXS'   1 .2 20 50 .1 0 4/
1031 'SEXS'   1 .2 20 50 .1 0 4/
1041 'SEXS'   1 .2 20 50 .1 0 4/
1271 'SEXS'   1 .2 20 50 .1 0 4/
1272 'SEXS'   1 .2 20 50 .1 0 4/
1012 'SEXS'   1 .2 20 50 .1 0 4/
1013 'SEXS'   1 .2 20 50 .1 0 4/
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1014 'SEXS'   1 .2 20 50 .1 0 4/
1021 'SEXS'   1 .2 20 50 .1 0 4/
1022 'SEXS'   1 .2 20 50 .1 0 4/
1112 'SEXS'   1 .2 20 50 .1 0 4/
1032 'SEXS'   1 .1 50 120 .1 0 5/
1033 'SEXS'   1 .1 50 120 .1 0 5/
1242 'SEXS'   1 .1 50 120 .1 0 5/
1246 'SEXS'   1 .1 50 120 .1 0 5/
1247 'SEXS'   1 .1 50 120 .1 0 5/
1251 'SEXS'   1 .1 50 120 .1 0 5/
1262 'SEXS'   1 .1 50 120 .1 0 5/
1263 'SEXS'   1 .1 50 120 .1 0 5/
602 'SEXS'   1 .1 50 120 .1 0 5/
612 'SEXS'   1 .1 50 120 .1 0 5/
622 'SEXS'   1 .1 50 120 .1 0 5/
632 'SEXS'   1 .1 50 120 .1 0 5/
702 'SEXS'   1 .1 50 120 .1 0 5/
712 'SEXS'   1 .1 50 120 .1 0 5/
722 'SEXS'   1 .1 50 120 .1 0 5/
731 'SEXS'   1 .1 50 120 .1 0 5/
6000'SEXS'   1 .2 20 50 .1 0 4/
6002 'SEXS'   1 .2 20 50 .1 0 4/
6004 'SEXS'   1 .2 20 50 .1 0 4/
6005 'SEXS'   1 .2 20 50 .1 0 4/
6100 'SEXS'   1 .2 20 50 .1 0 4/
6104 'SEXS'   1 .2 20 50 .1 0 4/
7001 'SEXS'   1 .2 20 50 .1 0 4/
7002 'SEXS'   1 .2 20 50 .1 0 4/
8001 'SEXS'   1 .2 20 50 .1 0 4/
8003 'SEXS'   1 .2 20 50 .1 0 4/
8004 'SEXS'   1 .2 20 50 .1 0 4/
8006 'SEXS'   1 .2 20 50 .1 0 4/
8007 'SEXS'   1 .2 20 50 .1 0 4/
5001 'SEXS'   1 .1 50 120 .1 0 5/
5002 'SEXS'   1 .1 50 120 .1 0 5/
5003 'SEXS'   1 .1 50 120 .1 0 5/
5004 'SEXS'   1 .1 50 120 .1 0 5/
5007 'SEXS'   1 .1 50 120 .1 0 5/
1211 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/            "Hydro turbines"
1212 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1221 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1231 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1271 'HYGOV'  1 .08 1.6 5 .05 .2 .1 .95 0 1 1 0 0/
1272 'HYGOV'  1 .08 1.6 5 .05 .2 .1 .95 0 1 1 0 0/
1012 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1013 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1014 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1021 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1022 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1112 'HYGOV'  1 .04 .8 5 .05 .2 .1 .95 0 1 1 0 0/
1211 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/                        "stabilizing units"
1212 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1221 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1231 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1241 'STAB2A' 1 1 4 0 2 0 1 .05 .05/
1271 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1272 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1012 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1013 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1014 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1021 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1022 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1112 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1262 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1263 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1263 'STAB2A' 2 1 4 1 2 .3 1 .05 .05/
1251 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1251 'STAB2A' 2 1 4 1 2 .3 1 .05 .05/
1247 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1247 'STAB2A' 2 1 4 1 2 .3 1 .05 .05/
1242 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
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1032 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
1033 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
6000 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
6002 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
6004 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
6005 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
6100 'STAB2A' 1 1 4 0 2 0 1 .05 .05/
6104 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
7001 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
7002 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
8001 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
8003 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
8004 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
8006 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
8007 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
5001 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
5002 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
5003 'STAB2A' 2 1 4 1 2 .3 1 .05 .05/
5004 'STAB2A' 1 1 4 1 2 .3 1 .05 .05/
5007 'STAB2A' 2 1 4 1 2 .3 1 .05 .05/
0 'OLTC1'  1034 1244 1 40 0 7.0/            "on line tap changing"
0 'OLTC1'  1034 1244 2 40 0 7.0/
0 'OLTC1'  1035 1245 1 40 0 8.0/
0 'OLTC1'  1035 1245 2 40 0 8.0/
0 'OLTC1'  11 1241 1 40 0 8.0/
0 'OLTC1'  12 1242 1 40 0 7.9/
0 'OLTC1'  13 1243 1 40 0 6.5/
0 'OLTC1'  14 1246 1 40 0 7.5/
0 'OLTC1'  14 1247 1 40 0 6.1/
0 'OLTC1'  21 1251 1 40 0 7.4/
0 'OLTC1'  31 1261 1 40 0 6.6/
0 'OLTC1'  32 1262 1 40 0 7.1/
0 'OLTC1'  33 1263 1 40 0 6.2/
0 'OLTC1'  6 7 1 40 0 7.0/
0 'OLTC1'  8 9 1 40 0 8.0/
0 'OLTC1'  601 602 1 40 0 8.0/
0 'OLTC1'  611 612 1 40 0 7.9/
0 'OLTC1'  621 622 1 40 0 6.5/
0 'OLTC1'  631 632 1 40 0 7.5/
0 'OLTC1'  700 731 1 40 0 6.1/
0 'OLTC1'  701 702 1 40 0 7.4/
0 'OLTC1'  711 712 1 40 0 6.6/
0 'OLTC1'  721 722 1 40 0 7.1/
0 'LDFRAL' * 0.75 0 0.75 0/                 "Constant current and MVA in loads"
0 'NETFRQ'/                                 "elements are frequency dependent"
1031 'RELANG' 1/                            "bus reference"
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Appendix F

Steady-state results from the 6% offshore wind energy integration in UK.
Bus names correspond with the real bus code from the UK national operator.

Bus Number	Bus Name	Base (kV)	B-Shunt (MVAR)	Voltage (pu)	Angle (deg)	Pload (MW)	Pgen (MW)
11	CARD	275.0	0.00	0.9855	-60.90	540	0
12	KITW	275.0	0.00	0.9820	-62.14	400	0
13	CILF	275.0	0.00	0.9746	-69.70	900	0
14	OLDB1	275.0	0.00	0.9776	-69.76	700	0
15	KITW	275.0	0.00	1.0012	-66.01	100	0
21	CREYKE BECK	400.0	0.00	0.9938	-76.75	800	0
31	BEDD	275.0	0.00	0.9554	-73.32	500	0
32	NORW	275.0	0.00	0.9602	-77.29	600	0
33	CITY ROAD	400.0	0.00	**0.9343**	-74.07	590	0
101	BUS101	220.0	0.00	0.9981	-76.04	0	0
102	BUS102	220.0	0.00	1.0221	-69.11	0	0
103	WESTERMOST	33.0	0.00	1.0200	-68.43	0	125
201	BUS201	220.0	0.00	1.0040	-71.29	0	0
202	BUS202	220.0	0.00	1.0044	-64.15	0	0
203	TRITON KNOLL	33.0	0.00	1.0000	-63.44	0	125
301	BUS301	220.0	0.00	0.9899	-69.27	0	0
302	BUS302	220.0	0.00	1.0214	-62.32	0	0
303	GREATER GABB	33.0	0.00	1.0200	-61.64	0	125
401	BUS401	220.0	0.00	0.9773	-68.57	0	0
402	BUS402	220.0	0.00	1.0019	-61.35	0	0
403	LONDON ARRAY	33.0	0.00	1.0000	-60.64	0	125
501	BUS501	220.0	0.00	1.0194	2.01	0	0
502	BUS502	220.0	0.00	1.0219	8.26	0	0
503	NORTH WEST	33.0	0.00	1.0124	8.89	0	125
1011	LIST	275.0	0.00	1.0215	1.45	200	0
1012	WASH	275.0	0.00	1.0300	3.07	300	400
1013	FIDD	275.0	0.00	**1.0350**	7.65	100	300
1014	RALN	275.0	0.00	1.0100	9.77	0	550
1021	BARK	275.0	0.00	1.1000	5.42	0	400
1022	TOTT	275.0	50.00	1.0364	-14.50	280	200
1031	CHTE	275.0	200.00	0.9653	-84.92	600	0
1032	PITS	275.0	0.00	1.0000	-68.37	300	360
1033	ALDW	275.0	150.00	0.9932	-79.28	230	180
1034	SHEF	275.0	200.00	0.9852	-70.21	800	0
1035	HIGM	275.0	200.00	0.9962	-74.73	700	0
1111	UPPB	275.0	0.00	1.0301	-36.09	100	0
1112	ABER	275.0	0.00	1.1000	-23.98	200	750
1211	CAPE	400.0	0.00	1.0100	0.00	0	899
1212	PENW	400.0	-100.00	1.0100	1.08	0	500
1221	SHRE	400.0	0.00	1.0000	-34.19	0	250
1222	FLEE	400.0	0.00	0.9658	-16.70	0	0
1231	DIDC	400.0	0.00	0.9904	-39.14	0	310
1232	ECLA	400.0	0.00	0.9983	-44.60	0	0
1241	FAWL	400.0	200.00	1.0000	-57.76	0	0
1242	FECK	400.0	0.00	1.0000	-59.10	0	630
1243	RASS	400.0	200.00	0.9939	-65.97	0	0
1244	DRAK	400.0	0.00	0.9898	-66.81	0	0
1245	WALPOLE	400.0	0.00	1.0020	-72.00	0	0
1246	OLDB4	400.0	100.00	1.0000	-65.65	0	530
1247	PEMB	400.0	0.00	1.0200	-63.76	0	540
1251	WEST BURTON	400.0	100.00	1.0200	-73.02	0	600
1261	CANTERBURY	400.0	0.00	0.9731	-69.31	0	0
1262	SIIZEWELL	400.0	0.00	0.9848	-70.00	0	530
1263	RYEH	400.0	0.00	0.9710	-70.50	0	530
1271	DINO	400.0	-400.00	1.0100	5.84	300	300
1272	WILF	400.0	0.00	1.0100	9.24	1000	1400

Appendix G

Steady-state results from the 6% offshore wind energy integration in Germany

Bus Number	Bus Name	Base kV	GShunt (MW)	BShunt (MVAR)	Voltage (pu)	Angle (deg)	Pload (MW)	Pgen (MW)
4	BUS4	220.0	0.00	-400.00	0.9746	77.67	0	0
5	BUS5	220.0	0.00	-400.00	0.9784	99.37	0	0
6	BUS6	220.0	0.00	0.00	0.9779	114.89	0	0
7	BUS7	400.0	0.00	0.00	0.9823	124.06	0	0
8	BUS8	400.0	0.00	-200.00	0.9834	26.48	0	0
9	BUS9	220.0	0.00	0.00	0.9972	33.27	0	0
601	BUS601	220.0	0.00	0.00	0.9875	79.05	0	0
602	SANDBANK	33.0	0.00	0.00	1.0000	81.05	0	300.0000
611	BUS611	220.0	0.00	0.00	0.9921	79.05	0	0
612	NöRDLICHER	33.0	0.00	0.00	1.0000	81.05	0	300.0000
621	BUS621	220.0	0.00	0.00	0.9811	102.92	0	0
622	NORDSEE	33.0	0.00	0.00	1.0000	104.79	0	300.0000
631	BUS631	220.0	0.00	0.00	0.9754	102.92	0	0
632	MEERWIND	33.0	0.00	0.00	1.0000	104.79	0	300.0000
700	BUS700	220.0	0.00	0.00	**0.9712**	62.83	0	0
701	BUS701	220.0	0.00	0.00	1.0487	70.76	0	0
702	HOCHSEE	33.0	0.00	-200.00	1.0438	72.33	0	300.0000
711	BUS711	220.0	0.00	0.00	1.0009	81.02	0	0
712	BARD	33.0	0.00	-2000.0	1.0000	82.74	0	300.0000
721	BUS721	220.0	0.00	0.00	0.9969	73.21	0	0
722	BORKUM	33.0	0.00	-200.00	1.0000	74.94	0	300.0000
731	ENOVA	33.0	0.00	-200.00	1.0000	64.57	0	300.0000
5000	MOORRIEM	400.0	0.00	-400.00	0.9743	163.29	0	0
5001	WEHR	400.0	0.00	0.00	0.9843	-174.39	0	700.0000
5002	BUS5002	400.0	0.00	150.00	0.9952	-28.74	310	480.0000
5003	BUS5003	400.0	0.00	0.00	1.0613	18.61	280	400.0000
5004	BUS5004	400.0	0.00	0.00	**1.0724**	86.27	500	550.0000
5005	BUS5005	400.0	0.00	0.00	1.0618	142.45	290	600.0000
5006	BUS5006	400.0	0.00	0.00	0.9730	162.05	500	0
5007	BUS5007	400.0	0.00	100.00	1.0000	-100.06	0	530.0000
6000	DIELE	400.0	0.00	0.00	0.9748	-1.22	0	0
6001	HLED	400.0	0.00	0.00	0.9702	-13.71	0	0
6002	BUS6002	400.0	0.00	0.00	1.0502	-16.93	280	750.0000
6004	BUS6004	400.0	0.00	-200.00	1.0000	-18.88	280	360.0000
6005	BUS6005	400.0	0.00	0.00	1.0070	-24.70	980	1400.0000
6100	BUS6100	400.0	0.00	0.00	1.0000	-21.95	0	250.0000
6101	BUS6101	400.0	0.00	0.00	0.9618	-31.63	580	0
6102	BUS6102	400.0	0.00	200.00	0.9886	-33.00	500	0
6103	BUS6103	400.0	0.00	0.00	1.0155	-31.06	240	0
6104	BUS6104	400.0	0.00	-400.00	1.0070	-18.24	280	300.0000
7000	BUS7000	400.0	0.00	-2000.0	0.9654	-52.04	520	0
7001	BUS7001	400.0	0.00	200.00	1.0000	-39.39	0	900.0000
7002	BUS7002	400.0	0.00	150.00	0.9952	-39.48	310	480.0000
8001	BUS8001	400.0	0.00	-400.00	1.0070	-26.21	280	300.0000
8002	BUS8002	400.0	0.00	0.00	0.9776	-27.97	380	0
8003	BUS8003	400.0	0.00	150.00	0.9952	-17.56	310	480.0000
8004	BUS8004	400.0	0.00	0.00	1.0535	-3.66	280	0
8005	BUS8005	400.0	0.00	0.00	1.0424	-2.84	0	550.0000
8006	BUS8006	400.0	0.00	0.00	1.0412	-5.31	260	600.0000
8007	BUS8007	400.0	0.00	0.00	0.9893	-13.39	0	530.0000

Appendix H

Steady-state results from the 6% offshore wind energy integration in the North Sea

Bus Number	Bus Name	Base (kV)	GShunt (MW)	BShunt (MVAR)	Voltage (pu)	Angle (deg)	Pload (MW)	Pgen (MW)
1		220.0	0.00	0.00	1.0000	0.00	0	0
4	BUS4	220.0	0.00	0.00	0.9512	156.54	0	0
5	BUS5	220.0	0.00	0.00	0.9640	161.55	0	0
9	BUS9	220.0	0.00	0.00	0.9934	-102.66	0	0
11	CARD	275.0	0.00	0.00	0.9858	37.37	540	0
12	KITW	275.0	0.00	0.00	0.9823	36.76	400	0
13	CILF	275.0	0.00	0.00	0.9625	35.87	900	0
14	OLDB1	275.0	0.00	0.00	0.9782	36.03	700	0
21	CREYKE BECK	400.0	0.00	0.00	0.9753	46.69	800	0
31	BEDD	275.0	0.00	0.00	0.9376	56.25	500	0
32	NORW	275.0	0.00	0.00	0.9479	66.59	600	0
33	CITY ROAD	400.0	0.00	0.00	0.9537	66.11	590	0
101	BUS101	220.0	0.00	0.00	0.9856	47.42	0	0
102	BUS102	220.0	0.00	0.00	1.0171	50.12	0	0
103	WESTERMOST	33.0	0.00	0.00	1.0200	50.81	0	125
104		220.0	0.00	0.00	1.0000	0.00	0	0
201	BUS201	220.0	0.00	0.00	**0.9365**	76.67	0	0
202	BUS202	220.0	0.00	0.00	0.8878	147.16	0	0
203	TRITON KNOLL	33.0	0.00	0.00	1.0000	147.91	0	125
204		220.0	0.00	0.00	1.0000	0.00	0	0
301	BUS301	220.0	0.00	0.00	0.9861	84.08	0	0
302	BUS302	220.0	0.00	0.00	0.9523	153.54	0	0
303	GREATER GABB	33.0	0.00	0.00	1.0200	154.25	0	125
401	BUS401	220.0	0.00	0.00	0.9518	61.12	0	0
402	BUS402	220.0	0.00	0.00	0.9997	67.52	0	0
403	LONDON ARRAY	33.0	0.00	0.00	1.0000	68.24	0	125
501	BUS501	220.0	0.00	0.00	1.0553	3.56	0	0
502	BUS502	220.0	0.00	0.00	1.0132	10.20	0	0
503	NORTH WEST	33.0	0.00	0.00	1.0000	10.91	0	125
601	BUS601	220.0	0.00	0.00	0.9559	156.69	0	0
602	SANDBANK	33.0	0.00	0.00	1.0000	158.44	0	300
611	BUS611	220.0	0.00	0.00	0.9559	156.69	0	0
612	NöRDLICHER	33.0	0.00	0.00	1.0000	158.44	0	300
621	BUS621	220.0	0.00	0.00	0.9704	161.87	0	0
622	NORDSEE	33.0	0.00	0.00	1.0000	163.61	0	300
631	BUS631	220.0	0.00	0.00	0.9704	161.87	0	0
632	MEERWIND	33.0	0.00	0.00	1.0000	163.61	0	300
700	BUS700	220.0	0.00	0.00	0.9958	-99.89	0	0
701	BUS701	220.0	0.00	0.00	0.9982	-99.03	0	0
702	HOCHSEE	33.0	0.00	0.00	1.0000	-97.31	0	300
711	BUS711	220.0	0.00	0.00	0.9996	-98.09	0	0
712	BARD	33.0	0.00	0.00	1.0000	-96.37	0	300
721	BUS721	220.0	0.00	0.00	0.9979	-98.86	0	0
722	BORKUM	33.0	0.00	0.00	1.0000	-97.14	0	300
731	ENOVA	33.0	0.00	0.00	1.0000	-98.17	0	300
1011	LIST	275.0	0.00	0.00	1.0614	2.96	200	0
1012	WASH	275.0	0.00	0.00	1.0632	25.00	300	400
1013	FIDD	275.0	0.00	0.00	1.0580	18.57	100	300
1014	RALN	275.0	0.00	0.00	**1.0642**	24.72	0	550
1021	BARK	275.0	0.00	0.00	1.0507	48.76	0	400
1022	TOTT	275.0	0.00	50.00	1.0420	28.76	280	200
1031	CHTE	275.0	0.00	200.00	0.9730	33.00	600	0
1032	PITS	275.0	0.00	0.00	1.0000	46.57	300	360
1033	ALDW	275.0	0.00	150.00	1.0000	34.64	230	180
1034	SHEF	275.0	0.00	200.00	0.9452	40.11	800	0
1035	HIGM	275.0	0.00	200.00	0.9516	52.29	700	0

1111	UPPB	275.0	0.00	0.00	1.0542	40.65	100	0
1112	ABER	275.0	0.00	0.00	1.0514	52.95	200	750
1211	CAPE	400.0	0.00	0.00	1.0100	0.00	0	583.9
1212	PENW	400.0	0.00	-100.00	1.0100	24.56	0	500
1221	SHRE	400.0	0.00	0.00	1.0000	29.61	0	250
1222	FLEE	400.0	0.00	0.00	1.0008	26.66	0	310
1231	DIDC	400.0	0.00	0.00	1.0100	37.66	0	0
1232	ECLA	400.0	0.00	0.00	1.0180	36.67	0	0
1241	FAWL	400.0	0.00	200.00	1.0000	40.50	0	0.0000
1242	FECK	400.0	0.00	0.00	1.0000	39.78	0	630
1243	RASS	400.0	0.00	200.00	0.9813	39.60	0	0
1244	DRAK	400.0	0.00	0.00	0.9434	42.82	0	0
1245	WALPOLE	400.0	0.00	0.00	0.9511	56.21	0	0
1246	OLDB4	400.0	0.00	100.00	1.0000	40.12	0	530
1247	PEMB	400.0	0.00	0.00	1.0200	42.39	0	540
1251	WEST BURTON	400.0	0.00	100.00	1.0200	54.34	0	600
1261	CANTERBURY	400.0	0.00	0.00	0.9450	60.36	0	0
1262	SIIZEWELL	400.0	0.00	0.00	0.9710	73.95	0	530
1263	RYEH	400.0	0.00	0.00	0.9710	73.33	0	530
1271	DINO	400.0	0.00	-400.00	1.0100	16.95	300	300
1272	WILF	400.0	0.00	0.00	1.0100	20.35	1000	1400
5001	WEHR	400.0	0.00	0.00	1.0000	-176.92	0	700
5002	BUS5002	400.0	0.00	150.00	1.0000	-160.97	310	480
5003	BUS5003	400.0	0.00	0.00	1.0000	-152.47	280	400
5004	BUS5004	400.0	0.00	0.00	1.0000	-145.85	500	550
5005	BUS5005	400.0	0.00	0.00	1.0000	-138.16	290	600
5006	BUS5006	400.0	0.00	0.00	0.9952	-135.73	500	0
5007	BUS5007	400.0	0.00	100.00	1.0000	-127.45	0	530
6000	DIELE	400.0	0.00	0.00	0.9988	-109.56	0	0
6001	HLED	400.0	0.00	0.00	0.9995	-112.33	0	0
6002	BUS6002	400.0	0.00	0.00	1.0000	-113.02	280	750
6004	BUS6004	400.0	0.00	0.00	1.0000	-113.20	280	360
6005	BUS6005	400.0	0.00	0.00	1.0000	-113.65	980	1400
6100	BUS6100	400.0	0.00	0.00	1.0000	-114.58	0	250
6101	BUS6101	400.0	0.00	0.00	0.9969	-118.77	580	0
6102	BUS6102	400.0	0.00	200.00	0.9995	-120.18	500	0
6103	BUS6103	400.0	0.00	0.00	0.9991	-120.29	240	0
6104	BUS6104	400.0	0.00	-400.00	1.0000	-119.11	280	300
7000	BUS7000	400.0	0.00	0.00	0.9925	-124.92	520	0
7001	BUS7001	400.0	0.00	200.00	1.0000	-122.14	0	900
7002	BUS7002	400.0	0.00	150.00	1.0000	-121.86	310	480
8001	BUS8001	400.0	0.00	-400.00	1.0000	-117.30	280	300
8002	BUS8002	400.0	0.00	0.00	0.9972	-118.33	380	0
8003	BUS8003	400.0	0.00	150.00	1.0000	-118.05	310	480
8004	BUS8004	400.0	0.00	0.00	0.9985	-118.05	280	0
8005	BUS8005	400.0	0.00	0.00	1.0000	-117.78	0	550
8006	BUS8006	400.0	0.00	0.00	1.0000	-117.98	260	600
8007	BUS8007	400.0	0.00	0.00	1.0000	-118.68	0	530