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System integration of large scale offshore wind power

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Problem Description

The European Commission proposal for 20% renewable energy by 2020 paves the way for a massive expansion of wind energy and a new energy future for Europe. To reach the goal wind energy is a key technology and large scale integration is required both onshore and offshore. This represents heavy challenges to the power system requiring new ways of designing and operating the system. Especially large scale offshore wind power will require attention to new focus areas. The wind may be more stable offshore, but there will be less geographical smoothing effect, so wind variations will still be a key issue. Power transmission and grid connection represent other main challenges for realisation of large scale wind power, and especially for offshore wind farms.

The scope of the project is defined as how to find an efficient and secure design and operation of the overall system when large scale offshore wind power is integrated.

Assignment given: 05. September 2010
Supervisor: Terje Gjengedal, ELKRAFT

PREFACE

The work of this thesis was performed in the Department of Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU) in collaboration with Statnett, the Norwegian transmission system operator. It ends my two years studies in Norway in order to complete a Master in Energy and Environment.

I would like to thank Terje Gjengedal, who is SVP-R&D director for Statnett and my supervisor, for giving me the opportunity to do this thesis. As a professor in NTNU, his course entitled Wind power in the Norwegian energy system, gave me the motivation to focus my studies on wind power and to do my Master Thesis in this field.

Trond Toftevaag, researcher for SINTEF Energy Research and professor at NTNU, has giving me a very precious help for my work and I am grateful for spending so much time with me even though he is not my supervisor. His help regarded translation of the grid model from different software and transmission problems.

I would like to thank the other researchers in SINTEF who worked with Professor Toftevaag and gave me some advice regarding transmission in HVAC and HVDC as long as help with programming and translating files.

My thanks go to Sachin and Mahesh from India who were my two office workmates. We had a lot of discussion and exchange regarding our master works. Mahesh particularly helped me with the simulation tool.

My Erasmus and Norwegian roommates are to be thanked for making my stay enjoyable. I met a lot of people during those two years and I will never forget this foreign experience.

I would like to thank Helen, my girlfriend, for being supportive regarding my studies abroad since she lives in France. My family helped me getting installed in Norway and supported me all along and I am thankful to them.

Finally, I would like to thank my friend Jennifer who is completing a doctoral thesis in France and who helped me with the page setting of my work.

ABSTRACT

Electricity generation, along with motor vehicles, is one of the biggest sources of pollution for the planet. Renewable energies are not able to replace massively polluting power plants but they can at least alleviate for it. Biomass and hydro power are the main source of renewable energy but wind power is developing to high extent, increasing by 30% its installed capacity every year in the world. Norway is increasing its wind power production since every hydro power areas are already used. The shallow Norwegian waters along with the increase of energy demand leads to offshore wind project.

The aim of this thesis is to study the integration of large scale offshore wind farms into the grid. The biggest offshore wind farm is currently installed in the United Kingdom (Thanet) and its capacity is 300 MW. The wind farm studied here has a capacity of 1000 MW. HVAC and HVDC transmission are investigated in order to connect the wind farm to Norway. Case faults are performed in order to study the system stability. The connection points are located in the most populated areas of Norway, where there is a real need for new power plants: Sørlandet and Vestlandet.

Statnett is the Norwegian transmission system operator and thus the focus was made on the connection with power flow and stability analysis and not on the full description of the wind farm. For simulations, Statnett is mainly using PSS®E (Power System Simulator) from Siemens but as much of the help was providing by SINTEF, the largest independent research organisation in Scandinavia, it was more convenient to use their tool: SIMPOW from STRI AB.

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INTRODUCTION

Wind energy is widely used nowadays in Europe and especially in Denmark where it represents more than 20% of the total production. In Norway, wind power gained a lot of interests in the last decade and now reaches an annual production above 3 TWh. However, suitable onshore sites for large wind parks (over 1000 MW) are already exploited or can't be exploited.

Europe is one of the best areas in the world for the implementation of offshore wind farms since the maritime part is made of relatively shallow waters. Winds are strong and stable in the Baltic and North Sea and thus offshore implementation of wind farms is seen as the development of many future wind farm projects. It is such that offshore wind power could represent 10% of the electric production of European Union in 2020.

Offshore sites can be found in the South and West of Norway but most of the fjord area is protected from industrial infrastructures. Modern wind farms are installed in shallow waters, at depth up to 50 meters but for example, the most promising places in Norway are at water depths from 30 to 150 meters. Thus, the development of large scale offshore wind farm is limited by the development of the necessary foundations.

Three main types of transmission technologies are available on the market for offshore connexion of wind parks: High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). HVAC is the easiest way to make this connexion and it is very well-known. However, the reactive power capability of AC cables has shown its limits and HVDC tends to replace most of offshore connexions. Line-Commutated Converter (LCC) based HVDC equips most of HVDC transmissions but Self commutating converters are also the next step, with Voltage-Source Converters (VSC) already replacing LCC. VSC stations are smaller and thus for high amount of power, it is much easier to install offshore.

This thesis was made in regard of integration of large scale offshore wind farms. Firstly, offshore wind energy is studied in order to show the state of the art in this field. Then, the different types of transmission are compared to each other. The simulation model is thus constructed based on the knowledge acquired previously. Finally, the model is simulated with different configurations and different case faults in order to understand the system stability. SIMPOW from STRI AB is the simulation tool used.

1 OFFSHORE WIND ENERGY

1.1 HISTORY OF OFFSHORE WIND GENERATION

The first use of a wind as a source of power generation was in 1888 in Cleveland, Ohio. The 12 kW produced out of a windmill were the premises to the development of large scale wind power generation in 1991. That year, the German Strom-Einspeise-Gesetz, a law regarding energy demand, required the use of renewable energy sources to feed into their grids. This law led to the development of wind parks in Germany (1).

The history of offshore wind generation begins in 1986 with the world's first wind farm construction in Denmark. Sixteen turbines of 55 kW each produced energy to a city of 4000 inhabitants. Through the late 1990, this development paved the way to new projects in Scandinavia.

1.2 STATE OF OFFSHORE WIND GENERATION

Offshore wind power is a very promising branch of renewable energies. Its potential for development is huge since offshore winds are strong and steady. This potential is not fully exploited because offshore wind farms require high technologies, even though massive research and development are in progress. Offshore wind power could represent 10% of the electric production of European Union in 2020 (2).

Europe is one of the best areas in the world for the implementation of offshore wind farms since the maritime part is made of relatively shallow waters. The North Sea and the Baltic Sea are the most promising places in terms of depth and strong wind potential. Moreover, those areas are located closed to European megalopolis, the most densely populated and energy consuming place of the continent. Even though offshore winds are stronger and steadier than onshore winds, the tariff is higher than with onshore wind farms as linking and investment costs are higher. As an example, according to the decree of November 17, 2008, French tariff is 13 c€/kWh for the ten first years and between 3 and 13 c€/kWh the ten next years. In Germany, it is 15 c€/kWh and Portugal 23 c€/kWh.

The installed capacity of offshore wind turbines by the end of year 2009 is represented on Figure 1. The United Kingdom owns 900 MW and is leading the production of offshore wind power. The amount of installed offshore wind turbines is small compared to onshore wind farms but as Figure 2 shows, over 3 700 MW are under construction in Europe, especially in the United Kingdom, Germany and Belgium. This is due to the fact that the offshore wind energy market is new and many researches are still in progress. Figure 3 illustrates the share of consented offshore wind capacity per country and shows the trend followed by European countries regarding offshore projects. Germany consents over 8 500 MW and a total of 16 GW is consented over Europe (3).

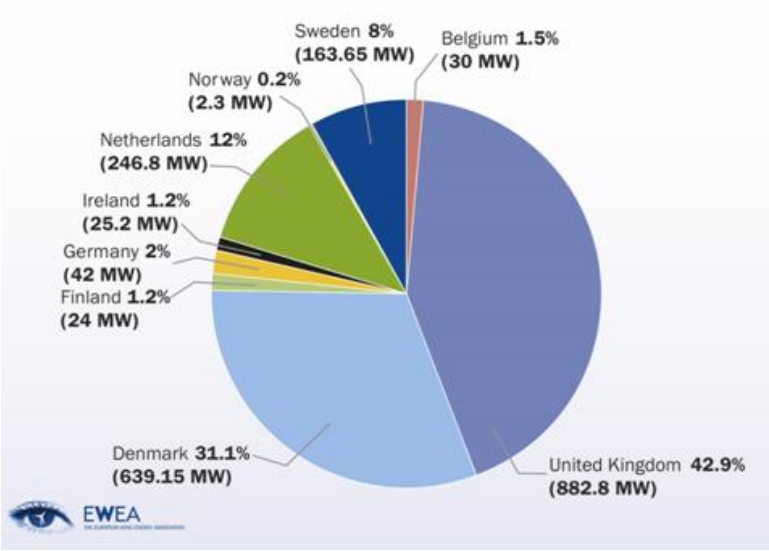


Figure 1 Installed capacity: cumulative share by country (end 2009) in MW (3)

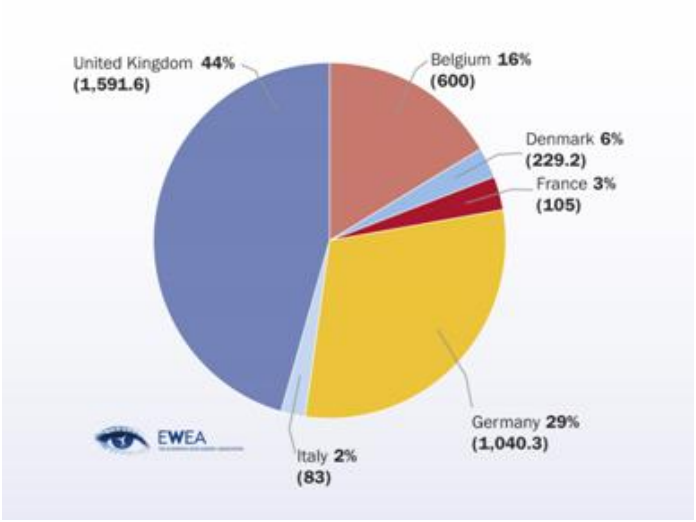


Figure 3 Share of offshore wind capacity under construction (3)

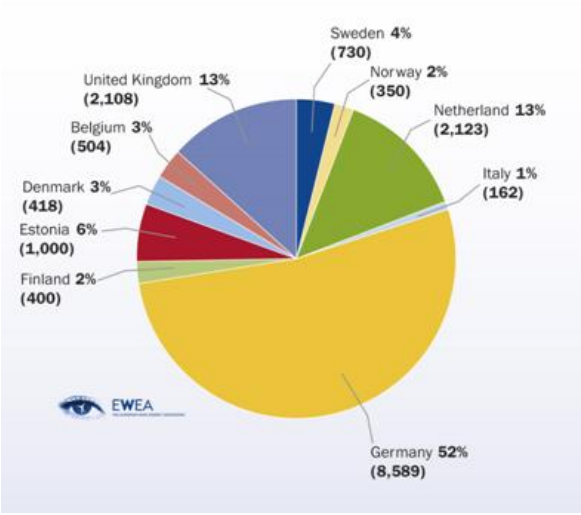


Figure 2 Share of consented offshore wind capacity per country (3)

By the end of 2009, 32 offshore wind farms were operational in ten countries: United Kingdom, Denmark, Netherland, Sweden, Germany, Belgium, Ireland, Finland, Norway and Italy. The total amount of installed power is 1400 MW and the production is 11 TWh. The biggest sites are installed in Denmark and are called Horns Rev 1 and Horns Rev 2. They own respectively 80 and 91 wind turbines, which represents 160 MW and 209 MW.

Even though offshore wind turbines are working on the same principle than onshore ones and are built from almost the same materials, their foundations are different. They can be built out of metal or concrete and it depends on the depth and characteristics of the sea bed. Actual offshore wind turbines can only be installed at a maximum depth of 30 meters. Offshore wind turbines have a higher power rating (5 MW) compared to onshore turbines (3 MW).

Wind turbines are often classified as noisy and ugly by the population. Thus, the offshore implementation is alleviating for those problems. However, the installation of wind turbines must

take into account the environment where it is placed: the marine life and underwater flora but also seabirds. Moreover, it can also impact human activities such as fishing, sand extraction, maritime traffic and tourism.

1.3 INSTALLATION OF OFFSHORE WIND TURBINES

Modern wind farms are installed in shallow waters, at depth up to 50 meters but for example, the most promising places in Norway are at water depths from 30 to 150 meters. There are several research and development projects in progress today, regarding the design of the foundations of wind turbines in order to achieve better depths. Offshore oil platforms use tripod and jack support structures, up to 70 meters deep but these must be scaled in size and costs to fit offshore wind turbines (4).

Figure 4 illustrates the characteristics of the marine environments researchers have to study in order to design floating platforms for offshore wind turbines (5). Those characteristics also have to be taken into account by other offshore wind turbines designs. Wind quality is important and weather conditions have to be taken account for the design of the turbine. The sea bed where the turbine lies has to be studied also regarding earth movement.

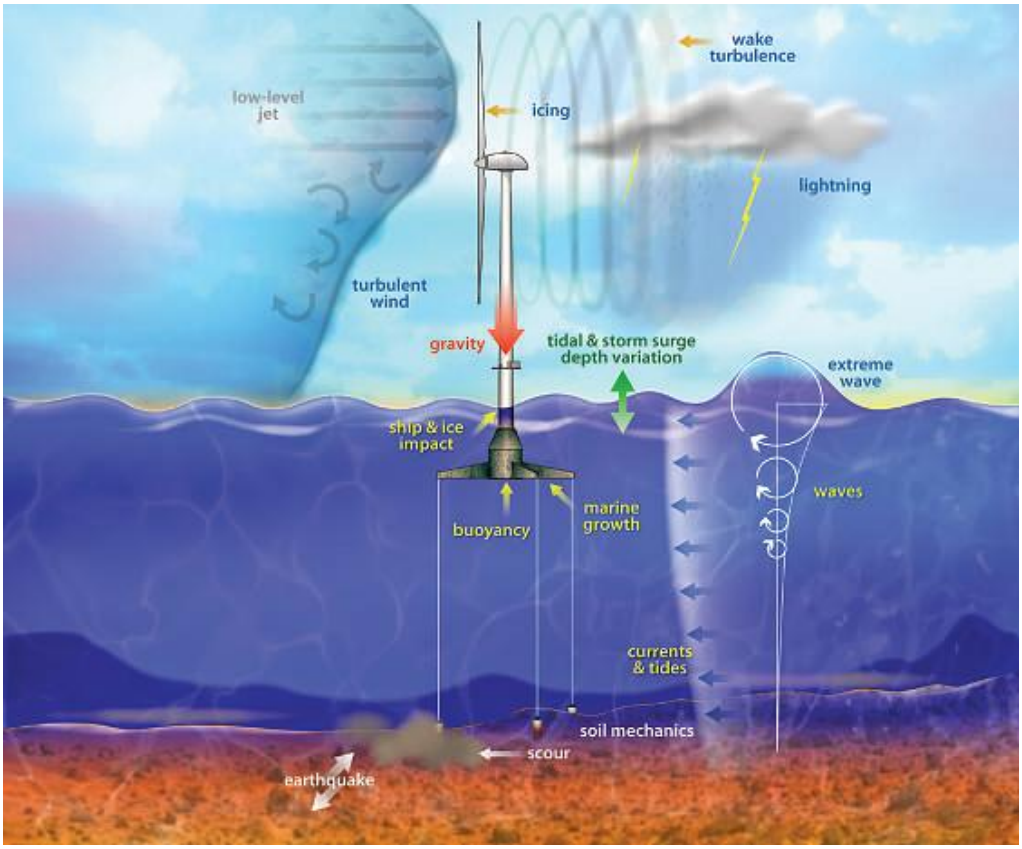


Figure 4 Characteristics of the marine environments

OWEC Tower AS has developed through its projects called Beatrice and Alpha Ventus that the Jacket Quattropod is a proven design. Substructures, along with the tower, account for 25% of the

total cost of an offshore wind turbine. The jack support is suitable for moderate to deep water (6). The Beatrice project is shown on Figure 5. Many projects like this are in progress nowadays and the aim for companies is to be able to install turbines at deeper places.

Figure 5 Beatrice Project

There are various foundations designs available on the market and they depend on the sea bed where the turbine is placed. They are depicted in Figure 6 (7). The monopile foundation is a simple construction consisting of a steel pile with a diameter of about 4 meters that is driven 10 to 20 meters into the seabed. Erosion is normally not a problem with this type of foundation. Such an installation costs between 1.7 M NOK and 2.3 M NOK (215 000€ to 286 000€). The cost is proportional to the size of the foundation, which depends on the place where it is installed. In the North Sea, the wave size determines the dimension whereas in the Baltic Sea, the pack ice pressure is determining it (8). Concrete foundations are more expensive than steel ones because for water depths of more than 10 meters, concrete foundations tend to become prohibitively heavy to install. The tripod foundation relies on light weight and cost efficient three-legged steel jackets. This type of foundation is suitable for deeper installation and is not suitable for water depth above 7 meters. The price is roughly the same than for a monopile foundation. Suction bucket is mostly used on sand sea beds whereas tripod foundations can be used on a rocky sea bed.

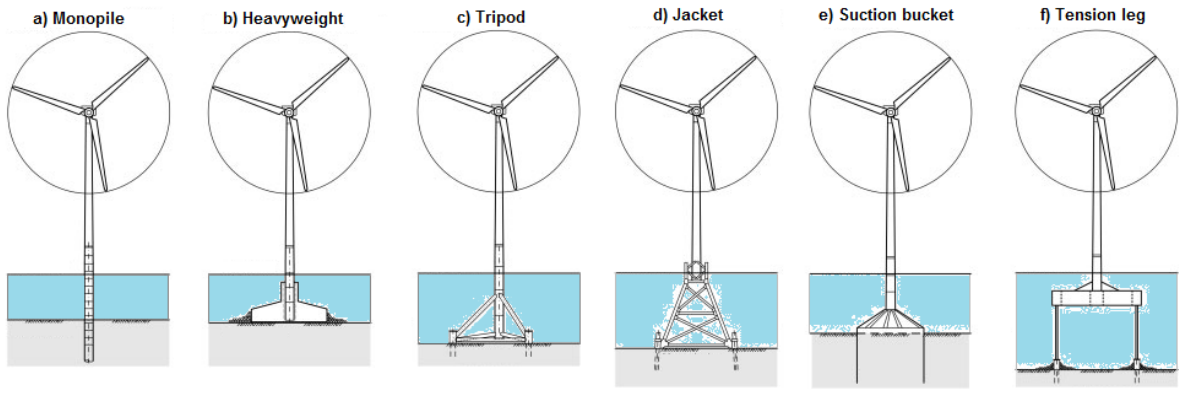


Figure 6 Different foundations designs

1.4 WIND POWER IN THE NORDIC GRID

1.4.1 GENERATION IN THE NORDIC GRID

Over 5 000 MW of cumulated onshore and offshore wind power plants are currently installed in the Nordic Grid. Denmark is the major producer and Sweden is the second but is producing much less out of wind power. Norway and Finland are generating little power from wind power since Norway owns many hydroelectric dam and Finland is using coal and nuclear power plants. Table 1 shows the part of wind power generation in GWh in the Nordic Grid (Denmark, Sweden, Finland and Norway) (9).

Table 1 Part of wind power generation in the Nordic Grid

Country	Total generation (GWh)	Wind power generation (GWh)	Percentage of wind power generation
Denmark	34 648	6 977	20.14%
Sweden	146 021	1 995	1.37%
Finland	74 137	262	0.35%
Norway	142 727	917	0.64%

Table 2 represents the wind generation volumes in the Nordic Grid. The details of registered wind power installed (MW) and the energy delivered (TWh) in 2009 is computed. The table contains also the estimated goals for 2020. A total of 5 300 MW of wind power plants were installed in 2009 for Denmark, Sweden, Finland and Norway and the goal for 2020 is 17 700 MW, which represents an increase of 334%. This increase in wind power generation is the consequence of the European wide climate policy and is achievable thanks to renewable support systems. There are a large number of projects in the Nordic region and the capacity of generation proposed by projects largely exceeds the planned estimations.

Norway's goal for 2010 has been 3 TWh but it was not achieved. The estimate of 12 TWh for 2020 seems is set to be on the same level as the Swedish estimate, due to a green certificate market with Sweden. Though, such a fast development is achievable since it already occurred in Germany and Spain.

Table 2 Wind generation volumes in the Nordic Grid (2009 and 2020) (9)

Country	Installed/delivered in 2009 (MW/TWh)	Estimated in 2020 (MW/TWh)
Denmark	3273/9	5635/14
Sweden	1448/2.52	4550/12.5
Finland	147/0.3	2500/6
Norway	431/1	5000/12
Total	5300/13	17700/44.5

1.4.2 IMPACT OF LARGE SCALE WIND POWER ON POWER SYSTEM OPERATION

The main challenges a Transmission System Operator (TSO) has to face concerning system operation with an important contribution from wind generation are:

- To balance the production and the consumption acknowledging the variability of wind
- To manage the various technical features of wind power generation such as the amount of rotating mass, the voltage support and the short-circuit capacity

To address these challenges, improvements in forecasting and the extensive use of flexible generation units and loads are done. The full Nordic grid is featured by the company Nordel and is shown in Figure 7 (10).

Figure 7 Nordic Grid (10)

An example from the wind production curve for Western Denmark, shown in Figure 8, is relevant to represent the challenge of the variability of wind. Due to its location between the North Sea and the Baltic Sea, and due to its shape, Denmark has one of the highest wind penetrations in the world. Depending on the wind conditions, the output power for Western Denmark can vary from 200 MW to 1 600 MW. Thus a deviation in the wind forecast of +/- 1m/s can result in +/- 320MW.

The production level of wind power largely varies and hence induces uncertainties into the operation for the TSO. Wind power production when the wind production is high would be easy to forecast but for speeds over 25m/s, wind turbines are shut down for safety reasons. As result, within a few hours, the production can change from full to null.

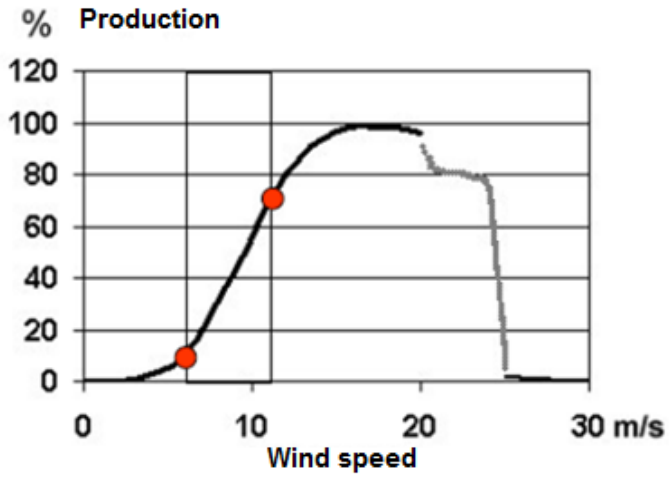


Figure 8 Aggregated wind production curve for Western Denmark (9)

Fluctuations in wind power production due to meteorological variations, such as low and high speed winds, are smoothed out over large areas. This allows higher predictability and thus production for the TSO. It is important to consider the geographical spreading of wind farms in the Nordic area since it contributes to the mitigation of the variations of wind power as it can be seen in Figure 9. The prediction error for a single site is higher than for the aggregated output of four sites with a maximum distance of 380 km between them.

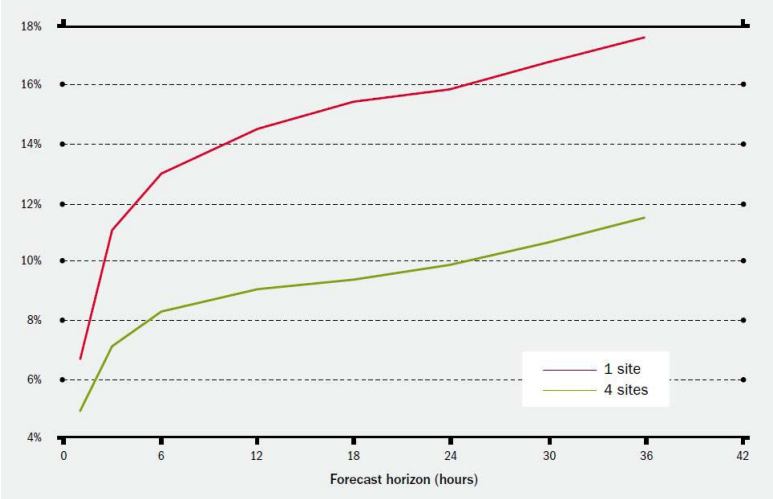


Figure 9 Mean absolute error as % of capacity (Finland, 2004) (9)

1.5 WIND POWER IN NORWAY

1.5.1 POWER EXCHANGE IN NORWAY

The Norwegian electric network is connected to the ones of Sweden, Finland, Russia, Denmark and the Netherlands. The connection between Norway and Denmark is the HVDC transmission system of Cross-Skagerrak. As the main source of energy in Norway is hydropower, energy is supplied to Norway during dry years, and is supplied to Denmark during years with sufficient precipitations. Moreover, this link serves as an energy supply in case of emergency (loss of generation in one country). Cross-Skagerrak went in service in 1977 and was updated to Cross-Skagerrak 3 in 1993, and Cross-Skagerrak 4 is in research. The current state is a 500 MW - 350 kV monopole and the maximum power transfer capability is 1050 MW (11).

The connection between Norway and the Netherlands is NorNed and is a monopolar HVDC link of 700 MW, 450 kV. It is the longest submarine power cable in the world and was in operation in 2008. It benefits to the Netherlands since the importation of energy from Norway is a source of renewable energy, considering hydro power and wind power.

Norway mainly exports electricity, especially during the summer since dams are generally full and there is no need for extensive lighting and heating. Winters are tough in Norway and especially the previous one in 2009-2010. Figure 10 represents the importation and exportations of energy over the last three years in MWh/h and the winter of 2009-2010 shows a lot of importation from Norway.

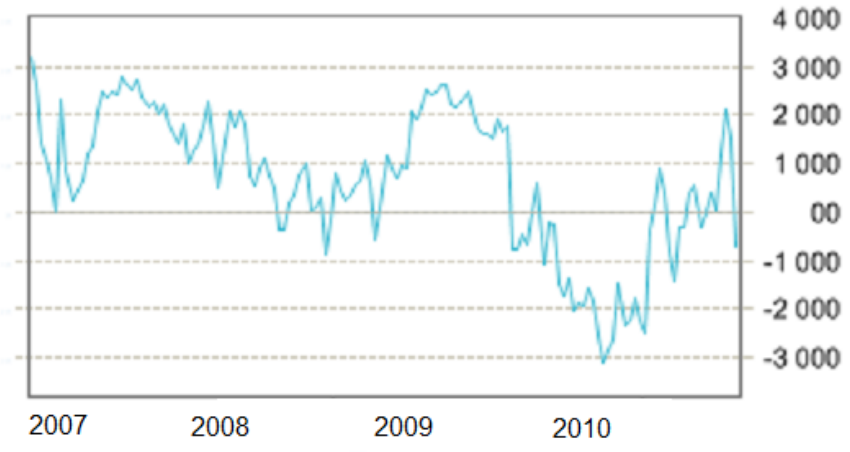


Figure 10 Total power exchange in MWh/h

1.5.2 THE GRID CODE

Norway is part of the Nordic grid and thus has to follow the rules of the Nordic Grid Code. The aim of this code proposed by Nordel is to harmonise the rules that govern the national grid companies of Norway, Sweden, Finland and Denmark. It concerns the transmission system operators (TSO) and it is made of general provisions for cooperation, a planning code, an operational code, a connection code and a data exchange code. Interconnections between Nordic countries date back from 1912 between Sweden and Denmark, and thus there is a long tradition of cooperation in the field of power exchange between the four countries. Those countries depend on each other and

contribute to the improvement of renewable energy. For example Norway is the best area for hydropower and Denmark for wind power. Thus, they can develop in their way since they can count on each other's power resources. More stable sources of energy such as thermal plants exist in Denmark, Sweden and Finland. Figure 11 (12) illustrates the frequency control and regulating reserves used by Nordel to keep the balance in the grid.

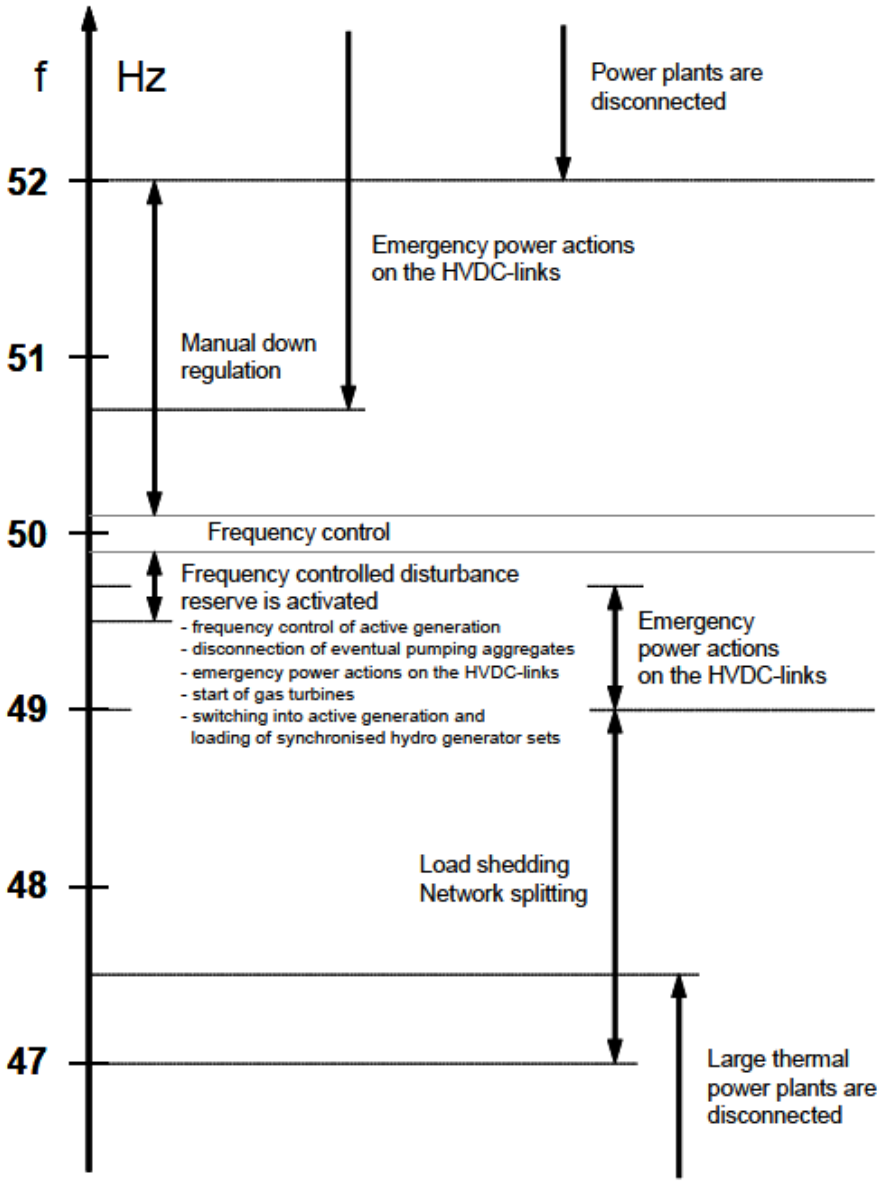


Figure 11 Frequency controlled actions in the Nordel system (12)

The requirements that are given by Nordel regarding wind generation are:

- **Active power control**. An adjustable upper limit to the active power production from the wind farm must be set. This limit should be made possible to control in the range of 20% to 100% of the wind farm's rated power. Ramping control of active power production, fast down regulation and frequency control must be possible. The details of the frequency control depend on the TSO. The grid frequency can't be lower than 47.5 Hz and higher than 53 Hz.

- **Reactive power control**. It must be done continuously and automatically. The wind plants must be able to perform this control by controlling the voltage at the connection point.

- **Operation during grid disturbances**. Wind turbines must be able to stay connected to the system after dimensioning of a fault in the grid. They can also disconnect if the voltage is too low.

If the voltage in the connection point is zero, the fault duration is set to 250 ms. The voltage at the wind turbine generator terminals is higher in case of a fault because of the transformer and the network impedance. Figure 12 (12) shows the voltage dip profile a wind power plan must be able to withstand without disconnecting from the grid.

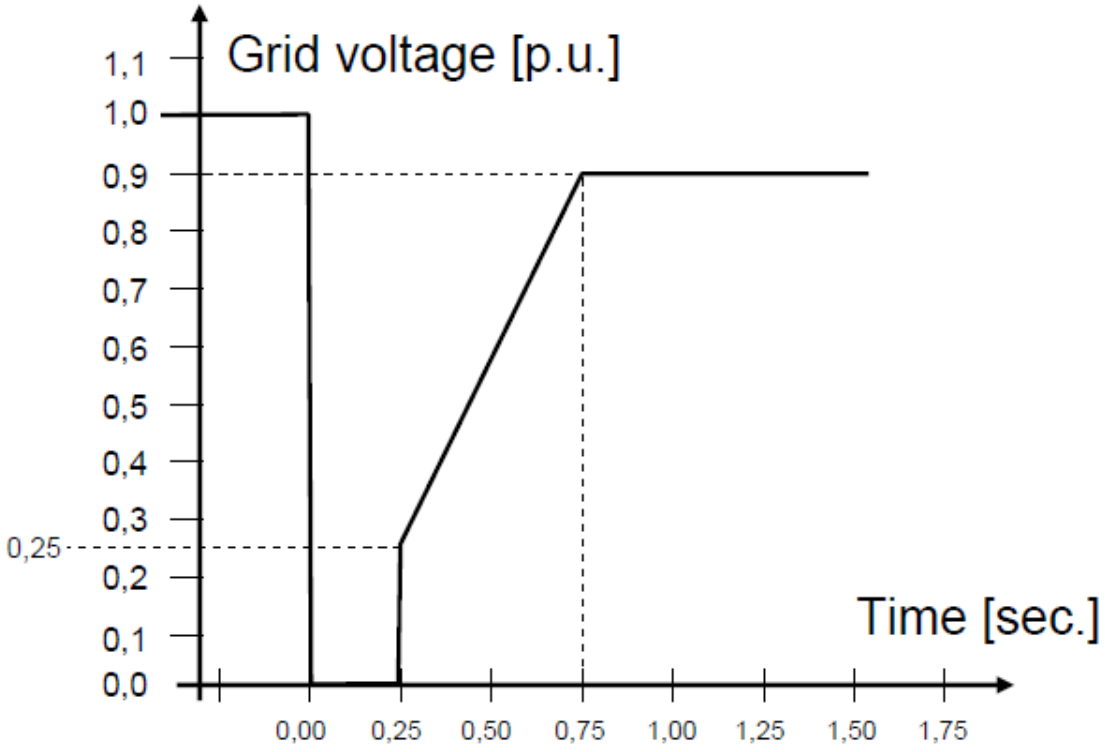


Figure 12 Voltage dip profile due to a fault (12)

1.5.3 ONSHORE WIND POWER

The wind map for Norway is shown in Figure 13 (13). It represents the annual mean wind speed in land and offshore. The highest wind speed areas are located offshore but some regions in the South offer acceptable wind conditions. Moreover, Norway owns many islands where the wind blows almost as high as offshore wind park sites. For example, the island of Smøla, located on the western coast closed to Trondheim, offers a profitable site where Statkraft installed 68 turbines for a total capacity of 150 MW (14).

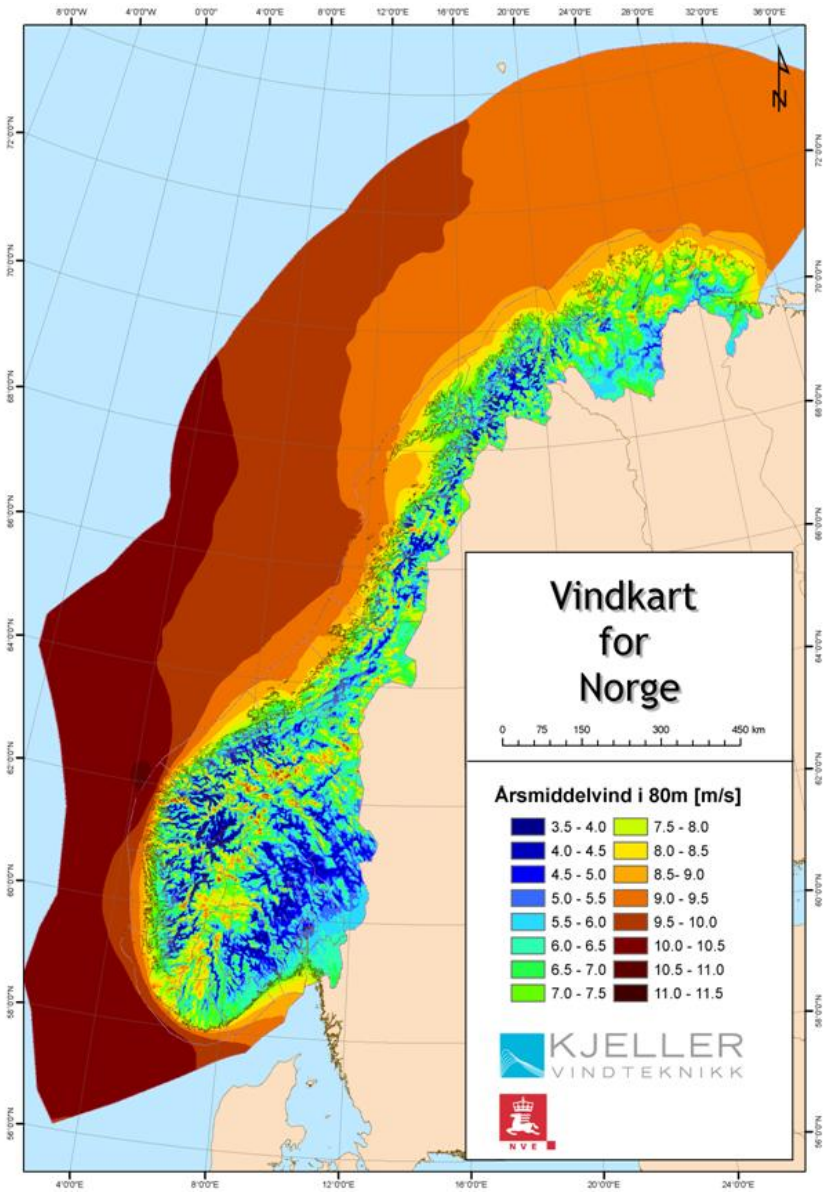


Figure 13 Wind map for Norway (13)

Even though wind power has played a modest role in Norwegian production, some wind studies and small turbines were installed from the late 1980's. In 1997, the interest grew up and as can be seen from Figure 14 (15), the annual production from wind power gained a lot more importance in the Norwegian grid. At the end of 2007, the annual production was closed to 1 TWh, based on power plant owners' estimations. Those numbers will keep increasing, since new licenses are given every year to build additional turbines.

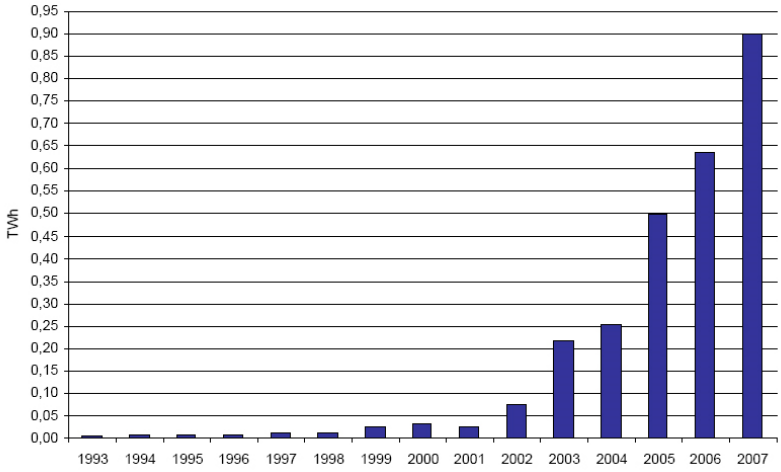


Figure 14 Annual Norwegian production of wind power (15)

Figure 15 (15) shows the size of the Norwegian wind power park that was installed over the years. The Norwegian goal of 3 TWh for 2010 represents approximatively 1 000 MW. This goal is realistic since in 2008, plans were reported from the Norwegian Water Resources and Energy Directorate (NVE) and that involved 1 800 MW (under construction and already existing) for that year. The development of wind power in Norway is largely determined by the budgetary authorities because wind power is not yet profitable and therefore depends on public support.

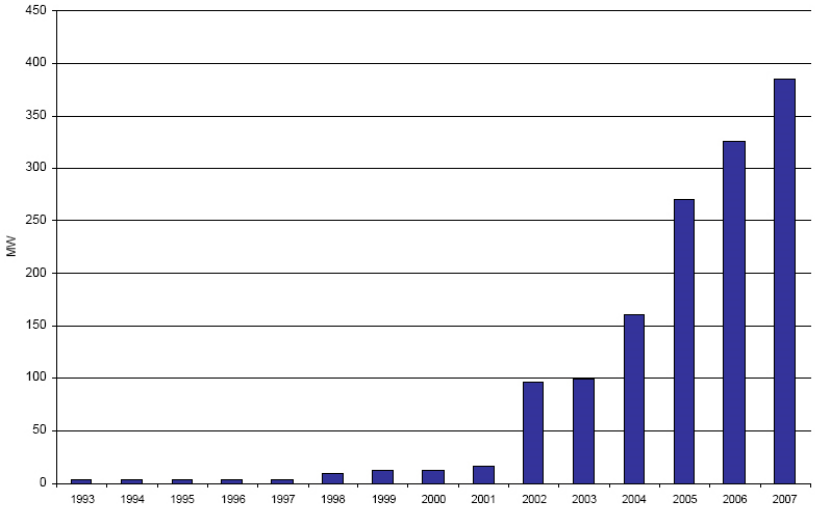


Figure 15 Installed Norwegian wind power (15)

1.5.4 OFFSHORE WIND POWER

In shallow regions, where the depth does not exceed 20 meters, the estimated potential for offshore wind generation is 6 000 to 30 000 MW. This amount depends on the minimal distance from the plant to the land which can be 1 km to 10 km. Moreover, areas protected from substructures installations are also taken into account. In fact, only a portion of the estimation can be made practical, if specific costs for installation and characteristics of the environment are accounted.

During the past years, wind generation industry suffered from an increase in installation costs. It is due to unusual tight market situation where the demand for offshore wind energy is not followed by a corresponding increase in production capacity for wind turbines. Moreover, high steel costs is also making it worst. However, it is estimated that prices will begin to decrease from 2010. Figure 16 (16) shows this trend (1 øre = 0.00125 €).

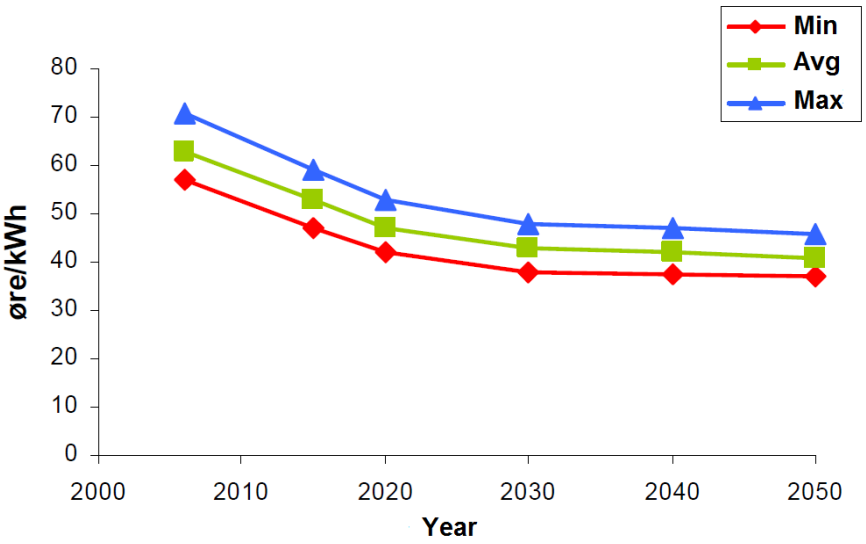


Figure 16 Offshore production costs (16)

Costs of offshore and onshore wind farm installations are different on many points. For an onshore wind farm, 67% to 75% of the farm is the turbine cost, but this is not applicable to an offshore farm. Depending on the sources, the costs of offshore wind farms are different and it can be explained by the fact that each project is different and depends on the site where it is installed. However, Figure 17 (16) tries to show how the costs are split inside the whole farm (1 kr = 0.125 €). Connection to existing networks is not registered. The turbine is cheaper for an offshore park, but the foundations and the installation are much more expansive, since it requires maritime skills.

In Norway, wind conditions off the coast are satisfactory except in the fjord areas (South West). The further from the coast, the better the wind conditions but the depth sometimes becomes a problem as soon as far as 50 km from the shore. For such a distance, the wind blows at an average 11-12 m/s, which is slightly slower than that of the best areas of Norway where the terrain is such that there is acceleration effect. However, the maritime wind is less turbulent and therefore easier to exploit. As a result, the wind is generally not a limiting factor for the installation of offshore wind farms, except in the fjord areas.

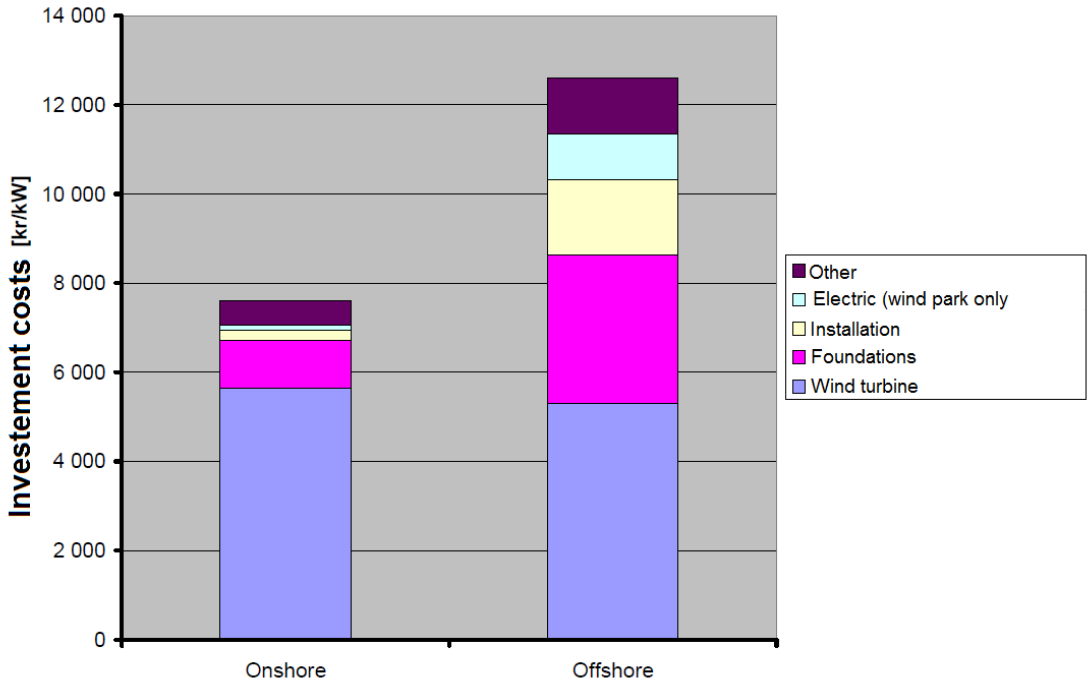


Figure 17 Distribution of costs for an onshore and offshore wind farm (16)

As Figure 13 illustrates, the wind energy resources of Norway are among the best available in Europe but the seas off the Norwegian coast are generally very deep. This is a consequence of the Norwegian Trench. Even though Norway as a long coastline, the possibilities of offshore wind installations are compromised, making it much different from its European neighbours benefiting from the large shallow water areas of the North Sea and the Baltic Sea. Moreover, there are many area restrictions. The coastal traffic and fishing in Norway are important and wind turbines can be spaced by 1 km inside a wind farm (16), which implies sea lanes right through the farm. Moreover, national parks, plants and animal conservation areas and UNESCO's World Heritage places limits further offshore wind power development.

2 TECHNOLOGIES INVOLVED

2.1 WIND TURBINES' DESIGN

Nowadays, the most common design for wind turbines is the Horizontal Axis Wind Turbine (HAWT). Its axis of rotation is parallel to the ground. HAWT are classified according to the orientation of the rotor (upwind or downwind), the design of the hub (rigid or teetering), the control of the rotor (pitch and stall), the number of blades and the alignment of the blades towards the wind (free yaw or active yaw) (17). Figure 18 is a sectional view of the hub of a Siemens wind turbine SWT-2.3-82 VS and shows the typical elements of a wind turbine (18).

1. Spinner
2. Spinner bracket
3. Blade
4. Pitch bearing
5. Rotor hub
6. Main bearing
7. Main shaft
8. Gearbox
9. Brake disc
10. Coupling
11. Service crane
12. Generator
13. Meteorological sensors
14. Yaw gear
15. Yaw ring
16. Tower
17. Nacelle bedplate
18. Canopy
19. Oil filter
20. Generator fan
21. Oil cooler

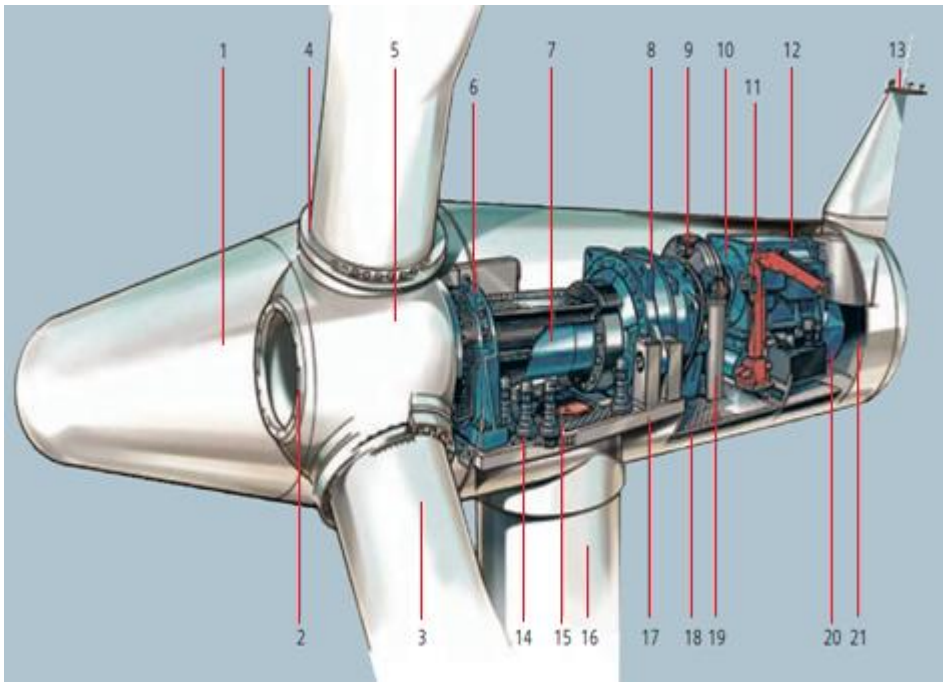


Figure 18 Sectional view of a wind turbine (18)

There are several options for controlling aerodynamically the power output of the wind turbine. They all result in different changes in the design of the turbine.

STALL

The stall is a passive torque regulation, determined by the turbine's aerodynamic properties. Aerodynamic lifts occur at high angle of attack from the blade of the turbine and the aim of the stall is to reduce the high torque induced. The rotor speed of the generator needs to be controlled separately for this power control and connecting an induction generator directly to the grid is the most common solution. The blades of the turbine are simply connected to the hub, without a pitch bearing as shown in Figure 18. The drive train has to be designed to contain the torques encountered during high wind speeds.

PITCH

The pitch is an active torque regulation, made through the pitching of the rotor blades. It is applied for both optimization and power output limitation. Turbines equipped with variable pitch systems have their blades that can rotate around their long axis, which results in changing the pitch angle. Thus, the angle of attack is changed and the torque produced can be controlled. Pitch provides more control than stall but the hub of the turbine needs more elements such as pitch bearings and pitch actuation systems. When only the outer part of blades is pitched, the system is called partial span pitch control.

A power curve is a plot used to understand the relationship between power and wind speed. Cut-in speed (approx. 3-5 m/s) and cut-out speed (approx. 25 m/s) are the operating limits of the turbine.

Figure 19 is the power curve for pitch-controlled and a stall-controlled wind turbine. The curve for pitch-controlled is the ideal power curve since the energy capture is maximized and the power quality is ensured. Operation above the rated speed (approx. 15 m/s) is the power regulation is efficient. On the contrary, the stall-controlled turbine is not able to match the ideal power curve and can only operate at maximum efficiency at one wind speed. Thus, the power regulation is poor.

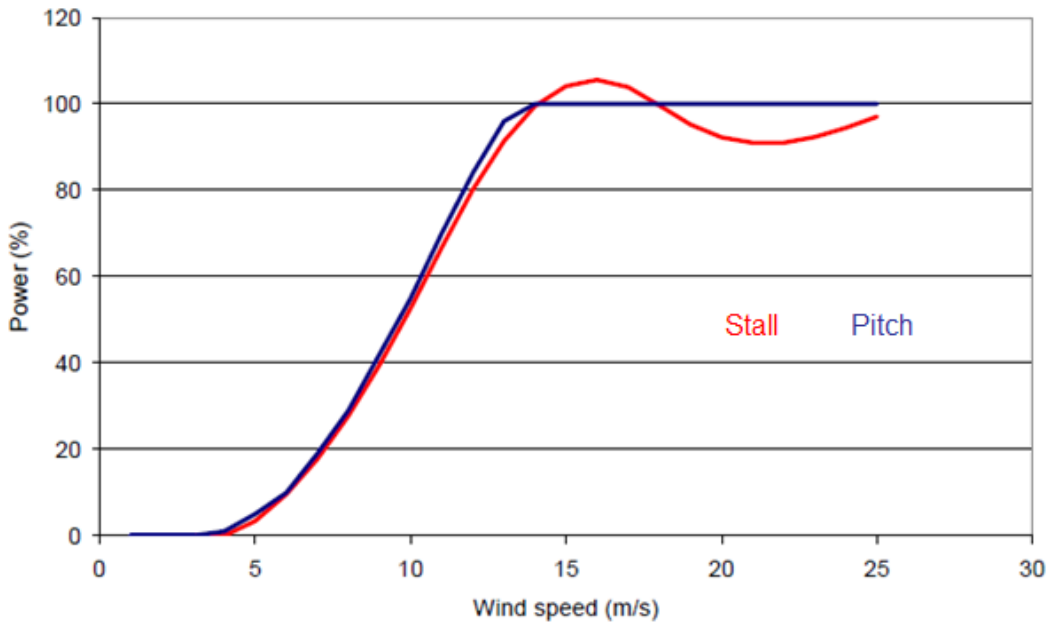


Figure 19 Power curve: pitch versus stall

YAW

During high winds, yaw control allows the rotor to turn away from the wind and results in a reduced power output. The yaw ring is shown in Figure 18 and the system must be resistant to high wind forces.

2.2 OPTIMISATION

2.2.1 BETZ' LAW

Albert Betz, a German physicist developed a theory in 1919 that induced that the maximum possible energy that could be derived by a wind turbine is limited to 59.3% of the kinetic energy in wind. The theoretical calculations imply perfect and thus unreachable assumptions in reality. Thus the Betz coefficient (C_p) appears as a limit and even the best modern turbines can only operate at efficiencies substantially below the Betz limit. Typical values for a 3-bladed turbine is C_p = 0.5 (19).

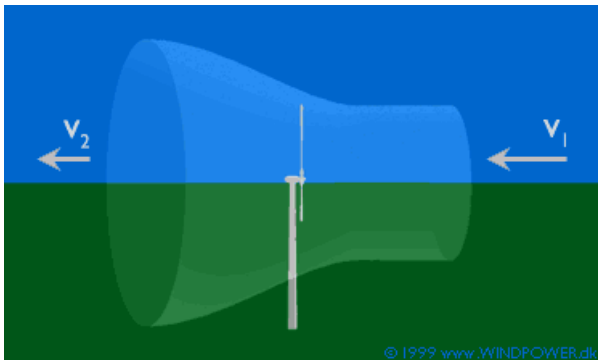


Figure 20 Upstream and downstream wind (19)

The maximum theoretical efficiency is calculated out of a thin rotor imagined to be replaced by a disc that withdraws energy from the fluid passing through it. The application of conservation of mass gives the force exerted on the wind by the rotor:

$$F = \rho.S.v.(v_1 - v_2)$$

Where ρ is the fluid density, S the area of the turbine, v the speed at the fluid power device, and v1 and v2 respectively the speed upstream and downstream.

The turbine power can be expressed by the following equation:

$$P = \frac{dE}{dt} = F.\frac{dx}{dt} = F.v = \rho.S.v^2.(v_1 - v_2)$$

The wind velocity of the rotor may be taken as the average of the upstream and downstream velocities. Thus:

$$v = \frac{1}{2}.(v_1 + v_2)$$

By differentiating the expression for power based on kinetic energy, the maximum is achieved when

$$\frac{v_2}{v_1} = \frac{1}{3}$$

Hence, the power is given by the following equation, where $C_p = \frac{16}{27}$:

$$P_{wind} = \frac{1}{2}.C_p.\rho_{air}.S_{rotor}.v_{wind}^3$$

2.2.2 TIP SPEED RATIO

Figure 21 Tip speed

The tip speed ratio is the ratio between the rotational speed of the tip of the blade, called tip speed, and the velocity of the wind. On one hand, if the rotor of the wind turbine turns too slow, most of the wind will pass undisturbed through the gap between the blades. On the other hand, if the rotor turns too fast, the blades will appear like a solid wall to the wind. Thus, there is a trade-off to extract as much power as possible from the wind (20).

$$Tip\ speed = U = \omega . R$$

$$Tip\ speed\ ratio = \lambda = \frac{\omega . R}{v}$$

The optimum tip speed ratio for the maximum power output is $\lambda_{max} = \frac{4\pi}{n}$, where n is the number of blades.

2.3 WIND TURBINES' GENERATORS

Generators for offshore and onshore wind turbines are similar. There are four types of generation principles: fixed speed, limited variable speed, variable speed with doubly-fed induction generators (DFIG) and variable speed with full-scale frequency converter. These configurations will be discussed and they show that wind turbines have gradually upgraded over the last 25 years from simple constant speed turbines to fully variable speed systems, with active output control.

In constant speed turbines, the speed is given by the electrical grid frequency and the turbine is not operating at its peak efficiency. Though, it is a cost effective and robust configuration. Variable speed systems use power electronic converters. It enables an optimisation of the performance by reducing the mechanical loading and delivering active control. Until the late 1990s, constant speed wind turbines were the most used ones and still represent 30% of the installed turbines (21).

Wind turbine concepts are classified by type of generator, power electronics and methods of power control into four types: A, B, C and D.

2.3.1 TYPE A: FIXED SPEED

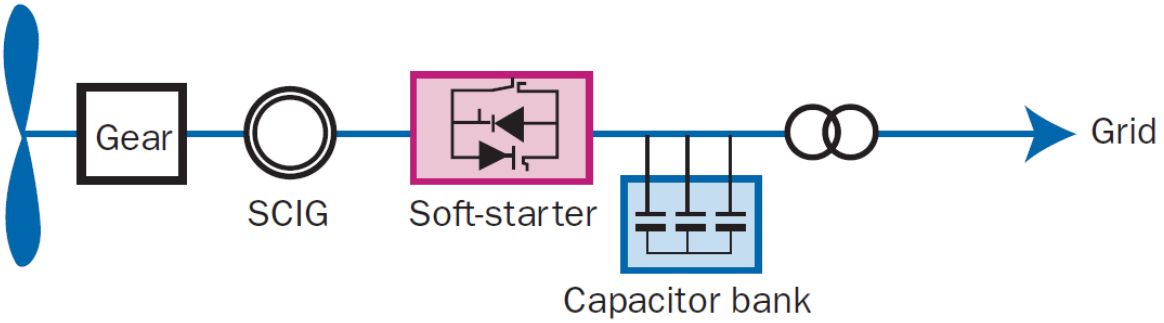


Figure 22 Fixed speed wind turbine

A schematic representation of a fixed speed wind turbine is shown in Figure 22. The generator is a squirrel cage induction generator (SCIG). The turbine drives the rotor of the generator, and the stator is directly connected to the grid. This is the simplest model. As the name suggest, the rotation speed is constant, but it can slightly change between 1% and 2%. There are two versions of the fixed speed turbine: a single speed and a double speed version. The double speed configuration allows improved performance and lower noise disturbance at low speed compared to the single speed configuration.

The aerodynamic control that exists on this type of turbine is passive stall and thus there are few active control options, except connection and disconnection of the turbine. However, a rotor angle control can be installed, and is called *pitch-control* or *active stall* (22).

The main manufacturers of type A wind turbines are Suzlon, Siemens Bonus, Ecotècnia and Nordex. They have been used since the 80s and still represent 30% of the market share.

2.3.2 TYPE B: LIMITED VARIABLE SPEED

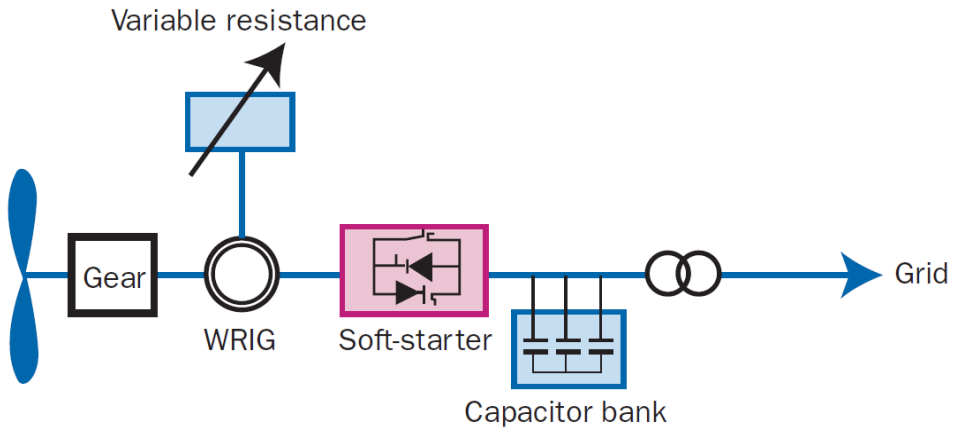


Figure 23 Limited variable speed wind turbine

Limited variable speed wind turbines use wound-rotor induction generators (WRIG). The main difference with the previous type of turbines is the variable resistance that changes the generator's rotor current and thus the speed. Power electronics play an important role since they control the rotor electrical resistance. The variation in speed is not total and is limited to +/- 10% . However, it can maximise the power quality and reduce the mechanical loading of the components of the turbine (21).

There are limitations to pitch control with regard to actuator speed and performance. Additional achievements can be done by variable speed control such as a further optimization of efficiency. Moreover, wind turbines can't store energy but thanks to variable speed control, the energy of the rotor inertia can be exploited as short-term energy storage. Variable speed control enables faster and more precise control. Implementation of variable speed control is achieved with type B, C and D (22).

The main manufacturer is Vestas. They have been mostly used in the 80s and the 90s, and they represent 10% of the market share today.

2.3.3 TYPE C: VARIABLE SPEED WITH DFIG

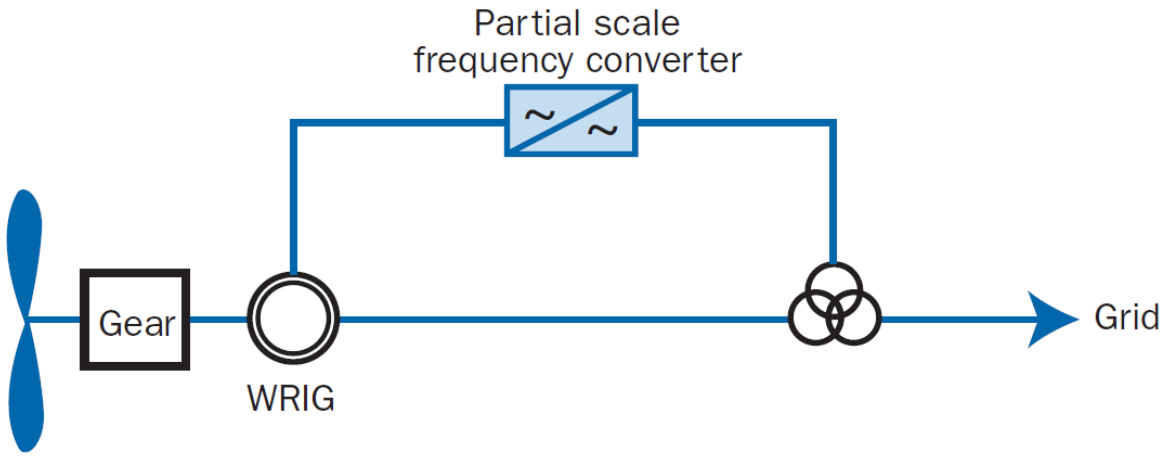


Figure 24 Variable speed wind turbines with DFIG

Induction machines draw high starting currents, up to 8 times the nominal current, but grid codes demand low inrush currents. DFIGs have an inrush current lower than nominal (22).

The variable speed with DFIG is the most popular system and represents 45% of the market share today. Its popularity comes from the fact that this type of wind turbines combines the advantages of type A and B, with improved power electronics. The DFIG that is usually used is the wound-rotor doubly-fed induction generator. The partial scale frequency converter is a back-to-back voltage source converter (VSC) that is connected to the rotor of the WRIG and to the grid. The VSC

controls the excitation of the machine in order to match the frequency of the rotor and the frequency of grid.

The use of power electronics allows a control of the active and the reactive power produced by the turbine. There is thus an active voltage control. Only 40% of the output power of the machine passes through the partial scale frequency converter and the rest goes directly into the grid. As a result, the speed variation that is possible to achieve with type C turbines is +/- 40% of the synchronous speed.

The main manufacturers are General Electric, Repower, Ingetur, Suzlon, Gamesa, Ecotècnia, Vestas and Nordex.

2.3.4 TYPE D: VARIABLE SPEED WITH FULL-SCALE FREQUENCY CONVERTER

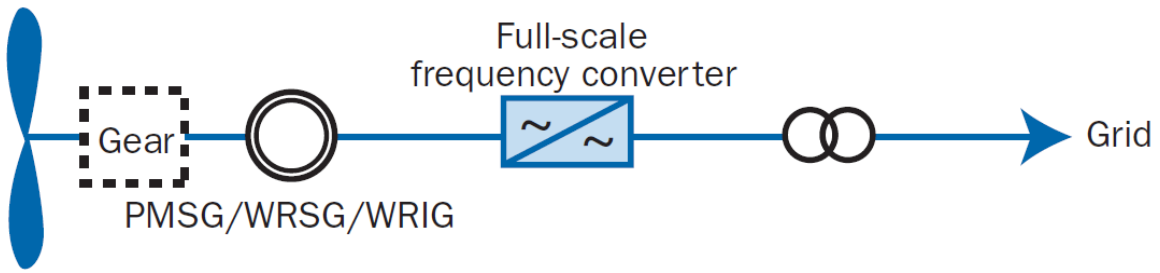


Figure 25 Variable speed wind turbine with full-scale frequency converter

Type D wind turbines are similar to type C, on the exception that the frequency converter is completely decoupling the generator from the grid. Thus, the turbine's generator can run at a wider range of operating speeds than type C turbines. Moreover, the range of reactive power and voltage control capacities is also increased.

Many types of generators can be used: permanent magnet synchronous generators (PMSG), wound-rotor synchronous generators (WRSG), wound-rotor induction generators (WRIG) and also squirrel cage induction generators.

The main manufacturers are Jeumont, Mtorres, Enercon, Multibrid (Areva), General Electric, Leitner, Made, Zephyros, Winwind and Siemens. Type D turbines represent 15% of the market share.

3 STABILITY IN WIND POWER SYSTEMS

The Institute of Electrical and Electronics Engineers (IEEE) and the International Council on Large Electric Systems (CIGRE) have proposed a definition of power system stability (23):

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

Even though power stability is a single problem, there can be various types of instabilities a system can undergo. In order to perform practical analysis of stability problems, it is necessary to classify power system stability. Stability can be classified depending on the physical nature of the mode of instability, on the size of the disturbance, the time taken to reach stability after a fault, etc. Figure 26 shows the classification proposed by IEEE and CIGRE (23).

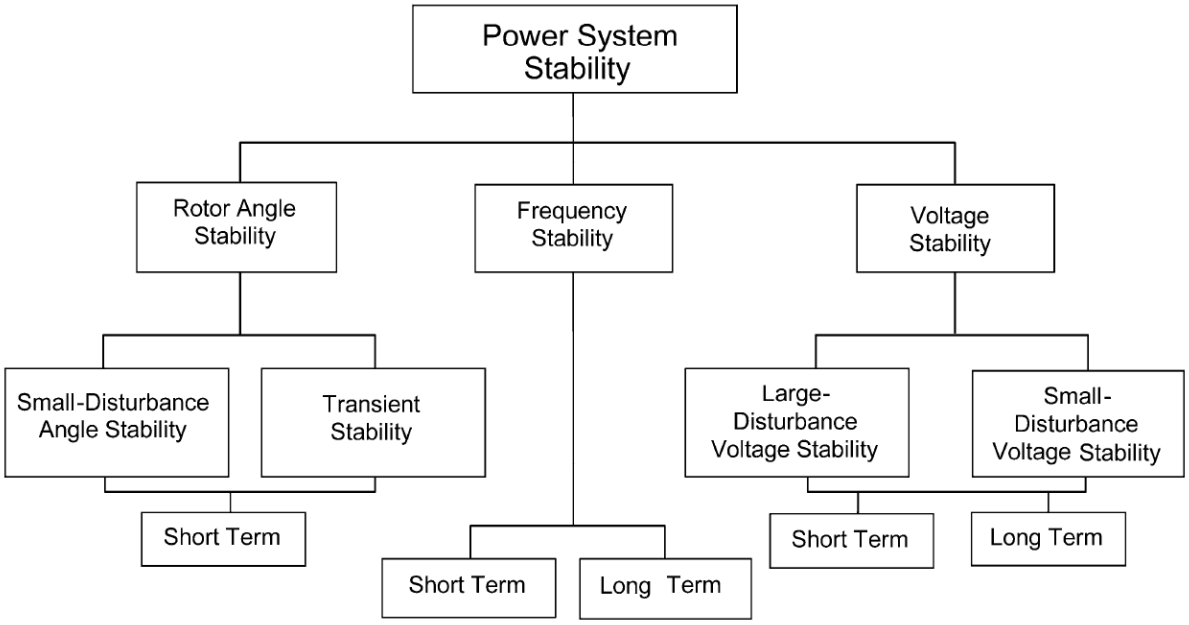


Figure 26 Classification of power system stability (23)

In an interconnected system, rotor angle stability is the ability to remain in synchronism after a fault, for a synchronous machine. Frequency stability refers to the power system being able to maintain a constant frequency when an imbalance between the generation and the load occurs. Voltage stability is the ability to maintain a steady voltage at each bus of the system after a disturbance.

The world's total wind power capacity by the end of 2010 was approximately 200 GW. It represents 19 000 TWh of energy production, and thus 2.2% of the world's production (24). Wind power is becoming more and more competitive and a number of researches are currently in progress regarding large scale integration of wind power into the grid. It involves power system stability and thus concerns network reinforcement and reserve requirements. The main parameters that need to be investigated are the fluctuations of wind power, the location of wind resources, the generator technologies and their control.

Wind power is different from conventional power stations. Firstly, wind resources are located at specific locations, onshore or offshore, and require specific power systems optimized for the transportation of energy. Secondly, wind turbines' generators are not conventional synchronous machines and are more complex, especially in their control due to fluctuation of wind resources. Thirdly, wind farms are generally connected to subtransmission or distribution voltage levels and not to transmission levels as conventional power stations (25).

Transient stability is a phenomenon that has to be investigated. Even though wind speed variations are slow compared to transient stability time frames (from one to ten seconds), those variations have an indirect influence on transient stability. High amount of wind power than can especially be found offshore require high spinning reserve and thus add inertia to the system, which has an influence on transient stability.

It has been shown (25) that the location of wind parks can have a large impact on transient stability. In high wind speed regions, the power flow can be changed to such an extent that the critical fault clearing times can be reduced and that it might be necessary to install new lines. Fixed-speed induction machines have a negative impact on dynamic voltage stability but variable speed induction generators are able to improve transient stability margins, especially when upgraded with low voltage ride-through and reactive current boost. Moreover, the connection of wind farms to subtransmission or distribution voltage levels also has a negative impact on transient stability because high reactive losses can occur.

Voltage stability is another phenomenon that needs to be looked at. Regarding large scale wind farms, the amount of wind power can be increased thanks to Static Var Compensators (SVC) which provides extra reactive power supply. It thus increases the voltage stability limit, proportionally to the active power that can be produced out of the wind farm. Even though voltage control and reactive power compensation helps on the damping of the oscillation modes of the system, it can have both positive and negative impact on the entire system (26).

4 TRANSMISSION TECHNOLOGIES

In order to transmit bulk electrical power, three phase alternating current and high-voltage direct current are used. Since the energy lost in a transmission line is proportional to the square of the current, transmission lines operate at high voltages. For a given power output of a generation system, a higher voltage means a lower current and thus lower losses in the wires used. This power lost can also be reduced by increasing the diameter of the cable, and thus reducing the resistance. However, bigger cables means higher costs.

4.1 HISTORY OF DC TRANSMISSION

Electricity supply dates back from 1883 in the West End of London where the *Grosvenor Gallery Company* started to deliver electricity to the neighbour houses, linking the entire system with overhead lines across the roofs of houses (27). In the late 1880s, the War of the Currents happened between the defenders of Tom Edison's Direct Current (DC) and Nicolas Tesla and George Westinghouse's Alternating Current (AC). In 1887, Tesla filed for polyphase AC motors and power transmission (transformers, transmission lines, etc.) patents which Westinghouse found to be the solution to long-distance power transmission. The War ended at the Columbian Exposition on May 1, 1893 where a hundred thousand incandescent lamps were lighted the surrounding buildings thanks to AC generation (28). From that point, more than 80% of the US electrical devices ordered were AC systems. However, DC transmission was not forgotten and engineers understood that higher voltage levels were necessary. DC installations up to 1500 V in Chelsea in 1889 and Lambeth in 1896 were performed.

Figure 27 English Electric mercury arc valves at the Manitoba Hydro Radisson Converter Station

HVDC was firstly made possible in 1889 by the *Society Acquedotto de Ferrari-Gallieri*, under the direction of Pr. Thury, in Italy. The installation was 121 km long and was able to transmit 630 kW at 14 kV (29). Other installations based on Thury's continuous current system were performed later, up to 100 kV in the 1930s but the required machinery was not efficient and required high maintenance.

The introduction of mercury arc valves to convert high-voltage or high-current alternating current into direct current became of interest for power transmission at that time. The fully static mercury arc valve was used industrially from 1954 and started the modern HVDC era. That year, on the Swedish east coast, the HVDC Gotland link was the first fully static commercial HVDC transmission. It could transfer 20 MW at 100 kV over a submarine distance of 98 km. From 1975, Line-Commutated Converters (LCC) replaced mercury arc valves with thyristor valves. At the beginning of the 21th Century, force commutated converters are believed to replace LCC systems, such as Capacitor Commutative Converters (CCC). Self commutating converters are also the next step, with Voltage-Source Converters (VSC) already replacing LCC.

4.2 HVAC CONFIGURATION

High voltage alternating current is mostly used in transmission systems, with three phase lines. The current produced out of the generator is directly transmitted to the grid via a transformer unit if there is the need for a stepping up or down. The power transmission and operation is achievable in both directions. However, AC lines produce large amount of reactive power and thus require reactive compensation units.

For HVAC transmission, the use of 3-cores cables is preferred to single-core cables since 3-cores cables require the installation of only two cables compared to four cables for single-core ones. In case of external damage of one cable, it is necessary to achieve a reasonable security of supply by adding an additional cable. Though, 3-cores cables are not able to meet with major cable installations ratings and then one-core cables are necessary. AC submarine cable systems can be constructed with three-core cables where all three insulated conductors are stranded into a single cable. For larger transmission power, the AC systems comprise three single-core cables, each containing only one insulated conductor. A fourth spare cable is often added.

In order to connect a large offshore wind farm to a grid with HVAC, the system shown in Figure 28 is the most common (30). This configuration presents a local wind park grid at lower voltage level (20-30 kV) than the transmission line. This local grid is connected to a transformer before the transmission system. This HVAC configuration requires and the installation of an offshore platform for the transformer and the switch gear.

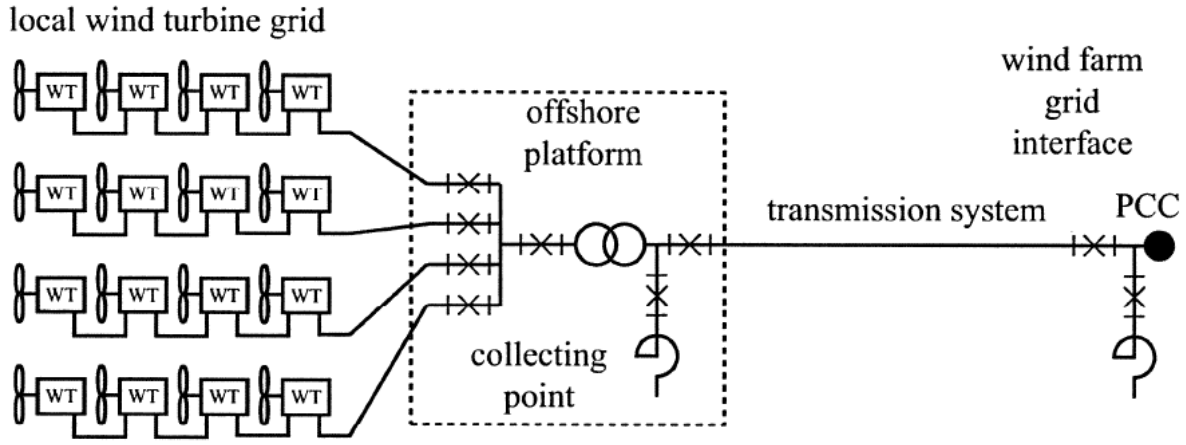


Figure 28 Electrical system for a large AC wind park

The voltage control is ensured by Automatic Voltage Regulators (AVR) in case of wind turbine equipped with synchronous generators. Otherwise, switched capacitor banks, mechanically or thyristor based, are more common than AVRs. The use of converter based power electronics can be made internally as a part of wind turbines' power conversion system. It can also be used externally, as separate solutions within the wind farm transformer station, at the point of common connection, such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) (31).

4.3 HVDC CONFIGURATION

Submarines transmission cables have a high capacitance that results in a high charging current in AC transmission. Capacitance is proportional to length and thus there is a maximum acceptable length from which the charging current is equal to the thermal current rating of the cable, resulting in no capability for active power. Moreover, the voltage also has an influence on the charging current which results in reducing the maximum length when increasing the rated voltage. Expansive shunt reactors placed at intervals along the cable can overcome this effect but this is not practicable for submarine use. DC cables also encounter a charging current but only during switching on or off and thus, this current has no effect on the continuous current rating of the system (32).

As a result, there is no length limitation to be applied to DC transmission and as a result, this type of transmission is preferred over AC transmission in our study. Moreover, a minimum of two cables is necessary for DC transmission whereas three cables are necessary for AC transmission which is a reduction in cost on cables for DC transmission. This transmission can consist of one polarity cable carrying full circuit power or two cables, one with a positive polarity and the other negative, each carrying half circuit power.

Figure 29 shows an AC/DC wind park. In this system the AC transmission has been replaced with a DC transmission compared to the HVAC solution proposed in Figure 28. This configuration is not present in many existing offshore farms but is proposed in many modern farm projects when the transmission distance is long or when the AC grid to which the farm is connected is weak (30). The local AC system is independent where both the frequency and the voltage are completely controllable thanks to the offshore converter station. Such a configuration can be used for a collective variable speed system of all wind turbines that are in the wind farm. The main benefit is that the aerodynamic and electrical efficiency can be increased.

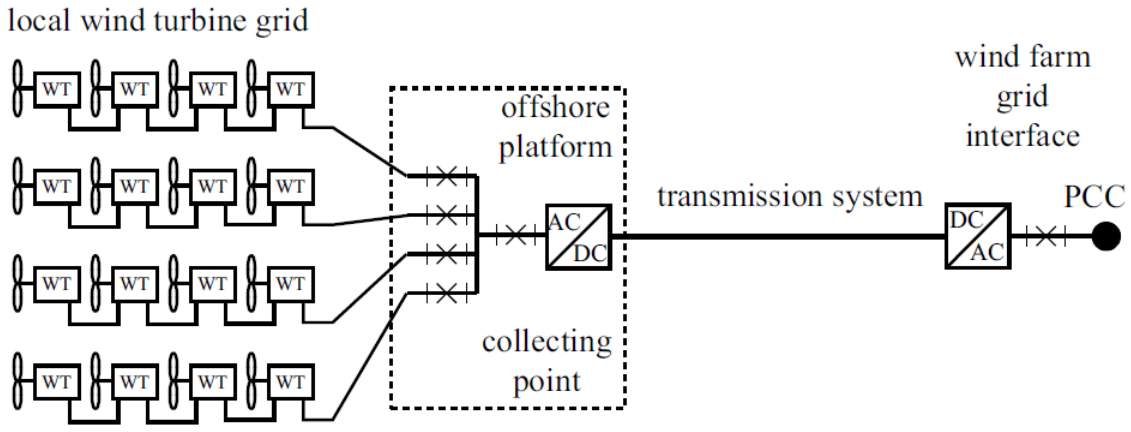


Figure 29 The electrical system for an AC/DC wind park

In Figure 29 appear only one cable for the transmission system but there is in fact a bipolar configuration installed, one for the positive pole and one for the negative pole, referred to as one cable. In case of a large DC wind park, the configuration differs from the large AC park because it requires one or two transformation steps in order to increase the voltage output of the wind turbines to a suitable transmission voltage level. Generally, if the DC output voltage of the wind turbines is over 20 kV, only one transformation step is necessary, but in case of a typical lower voltage, such as 5

kV, two steps are needed. Figure 30 shows a large wind farm that includes two DC transformer steps. As voltage levels are low, the entire wind farm is divided into several smaller clusters connected one by one to the first transformation step. The high voltage side of the first transformer is connected to the second transformation step.

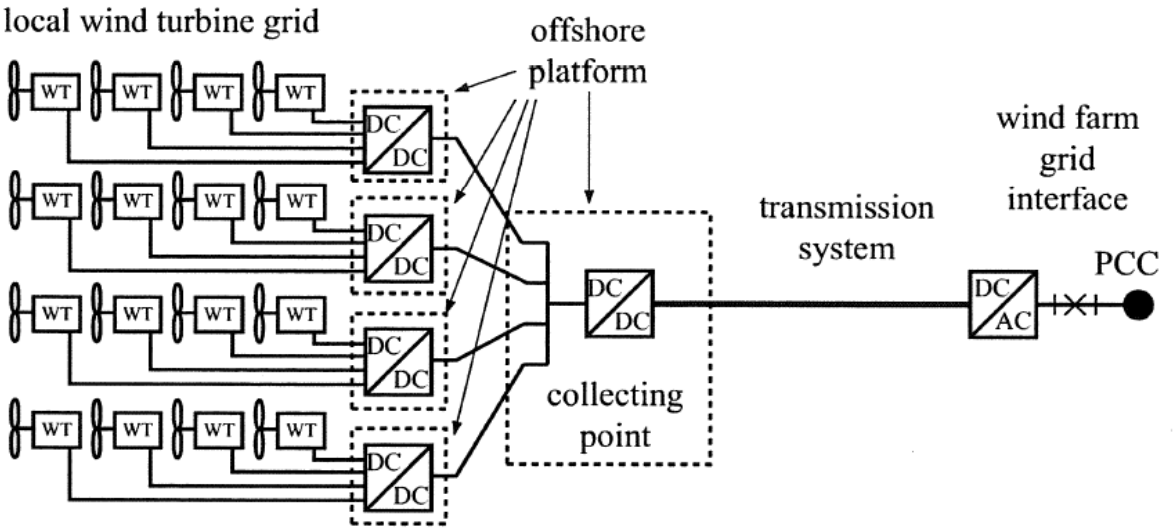


Figure 30 Electrical system for a large DC wind park with two DC transformer steps

A DC electrical system with series connected wind turbines is presented in Figure 31. The size of such a wind farm can be large but it does not necessarily imply large DC transformers and offshore platforms. There is however an electrical insulation provided by the local DC/DC transformer for safety reasons. Despite the huge benefit of not having a large transformer, the DC/DC converters need to have the capability to operate towards HVDC at their terminals. If a single wind turbine does not feed out energy and thus fails to hold its output voltage, the other turbines must compensate for this lack and thus increase their output voltage.

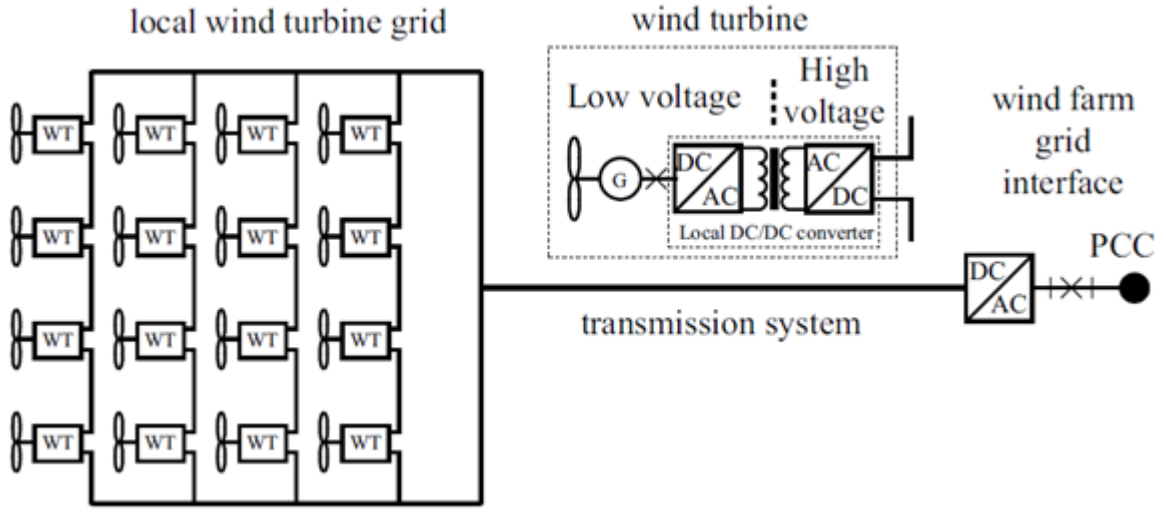


Figure 31 DC electrical system with series connected wind turbines

4.4 COMPARISON BETWEEN AC AND DC LINES

4.4.1 ECONOMIC COMPARISON OF AC AND DC LINES

A simple economic comparison can be carried out with these considerations (33):

- The same power is transmitted by a three-phase AC line and a bipolar DC line
- The DC voltage is equal to the AC peak voltage (Udc = sqrt(2)*Uac)
- The DC current in every pole is equal to the RMS AC current in each three-phase conductor

$$Pac = 3 * Uac * Iac * \cos(\varphi)$$
$$Pdc = 2 * Udc * Idc$$

The ratio between the DC and AC power is then:

$$\frac{Pdc}{Pac} = \frac{2 * Udc * Idc}{3 * Uac * Iac * \cos(\varphi)} = \frac{2 * \sqrt{2} * Uac * Iac}{3 * Uac * Iac * \cos(\varphi)} = \frac{2 * \sqrt{2}}{3 * \cos(\varphi)}$$

This ratio is equal to 1 when cos(phi) is equal to 0.945. A bipolar DC line that has the same voltage as the peak phase-to-ground voltage of a three-phase AC line is able to transport the same power, with the same current. However, the DC line requires only two conductors of the same size as the AC line which requires three conductors. Moreover, a DC line leads to a reduction from 25 to 35% of ohmic losses compared to an AC line over the same distance for the same power. This comparison does not include shunts, transformers and substations costs.

4.4.2 TECHNICAL COMPARISON OF AC AND DC LINES

The advantages of DC lines towards AC lines when operating isolated are (33):

- lower power losses
- lower switching overvoltages
- no problem of stability as the interconnected systems do not operate in synchronism
- great ability to interconnect systems of different frequencies thanks to back-to-back converter stations
- reduced levels of short-circuit powers

The disadvantages of DC lines towards AC lines are caused by the lack of simple voltage transformation into DC voltages and its contrary:

- DC lines can't supply loads directly. Converter stations are needed and are usually expansive
- DC transmission can't compete economically with AC transmission regarding intermediate substations to supply consumers
- Converter stations for DC transmission require a high reactive power reaching 60% of the active power in order to supply the commutation equipment.

4.5 SUBMARINE POWER CABLES

4.5.1 REQUIREMENTS

AC and DC submarines cables used for power transmission have to fulfil the requirements listed below. Those requirements are more or less relevant depending on the water depth and the length of the cable route (32):

1) The cable must have a high electrical factor of safety since maintenance underwater is complicated and expensive.

2) The cable should be designed to reduce transmission losses.

3) The cable should preferably be laid into the sea while the entire length is joined together with flexible joints during the manufacture or prior to the underwater fitting. There should not be any need to insert joints while at sea.

4) The cable must withstand the high bending under tension, the twisting and the coiling that can occur during the manufacture and the installation.

5) The cable must withstand the external water pressure at any part of its route.

6) The cable's armour must be sufficiently robust to resist impact damage and severance of the cable if fouled by a ship's anchor or fishing gear.

7) The cable must be reasonably torque balanced to avoid uncontrolled twisting during the underwater installation.

8) The cable's weight must be sufficient to allow as few movements as possible due to tidal currents since this would cause abrasion and fatigue damage to the cable.

9) The cable must be adequately protected from all corrosion hazards.

10) All cable components must have adequate flexural fatigue life.

11) All paper insulated and some polymeric insulated cables are required to be watertight along their complete lengths.

4.5.2 CONSTRUCTION OF DC CABLES

The conductor

DC lines do not suffer from skin and proximity effects (32). As a result, thinner conductors can be used. The use of DC results in lower conductor losses. Copper conductors are suitable for medium voltage and high voltage. They offer a better conduction and better thermal properties compared to other materials but they are also more expensive. Aluminium is more convenient for

low voltage applications. It is lighter and cheaper but the losses are higher. Moreover, it requires a larger cross-section area compared to copper, and it corrodes more easily. The conductor of DC cables can be up to $2000\ mm^2$.

The semiconductor screen

Its aim is to protect the cable. There are two screens, one placed directly on the cable's core, which is the inner screen, and the other placed on the cable's outer shell, which is the outer screen. It is generally made of polyethylene materials which have a high percent of black carbon. Partial discharges are due to space charges accumulations and thus damage the insulation. Semiconductor screens have a large resistivity because of their poor dielectric properties and thus the electric field is not able to penetrate the insulation part.

The insulation

The insulation part of the cable insulates it electrically from the environment where it lies. DC cables can be operated at higher electrical stresses than AC cables. The stress in a DC cable is governed by the insulation's resistivity and by its geometry. The resistivity is expressed by the equation: $\rho = \rho_0 e^{-\alpha\theta} e^{-\beta E}$ where ρ_0 is the resistivity at reference temperature, θ is the difference in temperature between the actual and reference temperatures, α is the temperature coefficient of electrical resistivity, β is the stress coefficient of electrical resistivity and E is the electrical stress in the insulation.

The optimal configuration for a DC cable would imply a constant insulation resistivity, as less sensitive as possible to electrical field and temperature changes. It would also require minimal thermal resistivity, small capacity of storing space charges and high DC breakdown strength insensitive to temperature rise.

4.5.3 MASS-IMPREGNATED CABLES

These cables can transmit up to 1000 MW per cable in a 600 kV DC system and thus 2000 MW at bipolar operation (34). Mass-impregnated cables have been used since 1895 in medium voltage AC transmission applications. Nowadays, it is mainly used in HVDC for large power transfer and for such high DC voltages as 600 kV, there is no alternative than those cables (35). The current longest distance achieved is the NorNed submarine power cable between Norway and the Netherlands which is 580 km.

Mass-impregnated paper insulation cables do not need oil-feeding system. The insulation part is made of oil impregnated paper, with high density (1 kg/dm^3) in order to obtain the best dielectric strength. Different types of papers are used such as semi-conducting carbon-black paper for the conductor screen and carbon-black paper combined with metal-laminated paper for the insulation screen. With high-viscosity compounds in the cable, the length can be infinite, since external pressurization stations aren't needed.

This type of cable is not suitable for HVAC transmission since under repeated partial discharges due to AC current, paper disintegration and breakdown can happen. Regarding environmental aspects, mass-impregnated cables do not leak oil when they are damaged, which thus preserves the area where it is placed in case of injuries.

The construction of the cable is shown in Figure 32 (36):

1 - Conductor (key-stone type)
2 - Conductor shielding
3 - Insulation (oil impregnated paper)
4 - Insulation shielding
5 - Lead sheath
6 - Plastic jacket
7 - Tape armour
8 - Optical fiber (option)
9 - Steel wire armour
10 - Serving

Figure 32 Mass-impregnated cable construction

4.5.4 LOW-, MEDIUM-, AND HIGH-PRESSURE GAS FILLED CABLES

The first gas filled cable installation was made in 1938. Low-pressure gas filled cable systems are in the range of 10 kV to 40 kV and operating with a gas pressure between 10 to 15 pounds per square inch. Medium pressure systems are in the range of 40 kV to 69 kV with pressures between 24 and 40 pounds per square inch. High pressure systems are in the range of 69 kV to 138 kV with pressures between 150 and 200 pounds per square inch (37).

The construction is similar to solid type paper-insulated cables but longitudinal gas feed channels are created in order to perform a uniform gas-pressure maintenance and control. During operation of the cable, the heat dilates the oil and the surplus of oil is forced to go out of the cable. Thus, oil tanks are used to maintain a satisfying amount of oil the cable.

The main advantages of this type of cable is that it is simple, economical and of small size. However, as the cable is under oil pressure, it has to be reinforced, which induces an additional weight compared to Mass Impregnated cables. Moreover, as the oil is flowing inside the cable, the length of the cable is limited to short distances, which does not make it practical for offshore wind installations. Even though the cable is of a small size, oil tanks that permit the constant oil pressure are bulky and not easy to install.

4.5.5 CROSS-LINKED POLYETHYLENE CABLES

Cross-Linked Polyethylene (XLPE) cables have been used since 1973 for submarine transmission. The cross-linking of polyethylene allows much more stability of the material at higher temperature. It does not melt, but it is however destroyed by pyrolysis above 300°C. The temperature it usually stands is 90°C and the short-circuit temperatures can go above 200°C (35).

XLPE cables are lighter than paper insulating cable since they require less insulation material. XLPE cables also have interesting mechanical properties. They have a higher mechanical resistance and bending capabilities which is the reason why they don't require maintenance. Moreover, as there is no oil circulation as in gas-filled cables, there is no need for oil tanks or many joints along the cable.

XLPE cables suffer from moisture ingress into the insulation and an impermeable moisture barrier must be provided to the cable. Applying a lead alloy sheath to the cable prevents moisture and also helps the cable's stabilization when placed underwater. This water sensitivity was a real problem to the expansion of XLPE cables because water-trees could be initiated and cause electric breakdown. Triple-extrusion and dry curing tubes are now provided to the cables by manufacturers to avoid any water-treeing problem.

The most important parameter of the cable is the dielectric strength but the value depends on the manufacturers, the material used, the temperature, the sample preparation and more. Thus it is not possible to obtain a fixed value. Among others benefits, XLPE submarine cables are maintenance free, have low electrical losses and are environmentally friendly.

Joints are a limiting factor for the use of XLPE cables in submarine applications. This is the only option for linking pieces of cables together along the cable route. Joints have been made possible up to 345 kV but generally, manufacturers try to deliver the cable as a simple piece, which restricts the available cable length. However, submarine cable for lower AC ratings such as 170 kV can be produced for distances over 50 km. For example, ABB produced XLPE-insulated AC cables for system requirements of 420 kV and 1000 MVA (34). Figure 33 shows a single-core XLPE cable. Its design is similar to the one of mass-impregnated cables.

Figure 33 Cross-linked polyethylene cable

Three-core cables are available for very long length of more than 50 km and single-core cables are rated up to 500 kV but for limited lengths.

4.5.6 PAPER-INSULATED OIL-FILLED CABLES

This type of cables are filled with low viscosity oil and are known under various abbreviations such as Low-Pressure Oil-Filled cables (LPOF), Self-Contained Fluid-Filled cables (SCFF) and Self-Contained Oil-Filled cables (SCOF). High pressure cables are not used for submarine power transmission. The paper used in this type of cables has a lower density (0.7 kg/dm^3) than Mass-Impregnated cables (1 kg/dm^3).

The insulation is achieved with thin paper since it has a higher dielectric strength than thicker one (35). However, this strength relies on the pressure applied to oil inside the cable by external stations. As the pressure is not the same at the centre of the cable route and at both ends of the cable, it is necessary to provide the cable with large enough oil channels. For single core cables, the oil channel is located in the conductor centre and the voltage rating can be over 150 kV. As external pressurization stations are required, the cable length is small (30-60 km).

This type of cable tends to disappear to Mass-Impregnated cables which are more conventional. Yet, the paper insulation of oil-filled cables can be improved with reinforced polymeric films and voltage ratings have been achieved up to 800 kV in AC transmission.

4.6 TRANSMISSION SYSTEMS

In order to connect an offshore wind farm to the shore, three different transmission technologies are mostly used. HVAC transmission is the most common nowadays since the majority of offshore wind farms are of a relatively small size compared to onshore ones and because distances are not far from the shore. However, the offshore wind market is leading towards bigger power and implementations further away from the coast. HVDC is thus a necessity and LLC-HVDC and VSC-HVDC are also presented.

4.6.1 HVAC TRANSMISSION

As investigated previously, a typical HVAC transmission consists of:

- An offshore AC collector system that includes, in the case of a large offshore wind project, a transformer unit with reactive power compensators
- Single- or Three-core cross-linked polyethylene cables (XLPE)
- An onshore substation including a static VAR compensator (SVC)

Some parameters have to be taken into account before deciding to investigate HVAC for a project. High inductance means more voltage drop and thus it is important to choose the cross-section area of the cable wisely (38). The larger the cross-section, the lower the inductance but the bigger the cable and thus the cost.

The capacitance plays also an important role in the determination of having an HVAC transmission system since it sets the technical and economical limit of the cable length (39). Capacitance is responsible for charging current flowing in the cable route. This current is not desirable but the cable has to carry it along with the useful current. It results in a lower load capability for the cable. A longer cable means a higher capacitance and thus higher charging current. The capacitance itself can also create overvoltages, high harmonic currents and resonance effects. As a result, special circuit breakers can be necessary for the system.

The real power losses also limit the HVAC line length. Four losses of this kind occur in the cable: the dielectric losses (small), the Joule's law losses in the conductor (large), the Joule's law losses in the metallic shield (one third of the conductor losses) and the Joule's law losses in the steel wire armour (one half of the conductor losses) (39).

AC connections undergo a major matter that is the reactive power control. The reactive power transfer into the transmission cables needs to be compensated depending on the load. The compensation is maximal at no load, and is then approximately halved during rated operation (40). Figure 34 illustrates a basic configuration of a 600 MW wind farm with a HVAC solution. The compensation is shown as separated in two. The fixed compensation is the smaller and can be placed on offshore substations. The controlled compensation is placed onshore, to maintain the voltage within a range of rated values. Moreover, the wind generators also provide some reactive power and

voltage control. At the onshore grid connection point, SVCs are used to balance the reactive power and to control the voltage. Moreover, centrally placed SVC can improve the behaviour of any wind turbine generator model during and after faults. Thus SCV at the offshore substation is necessary in most cases.

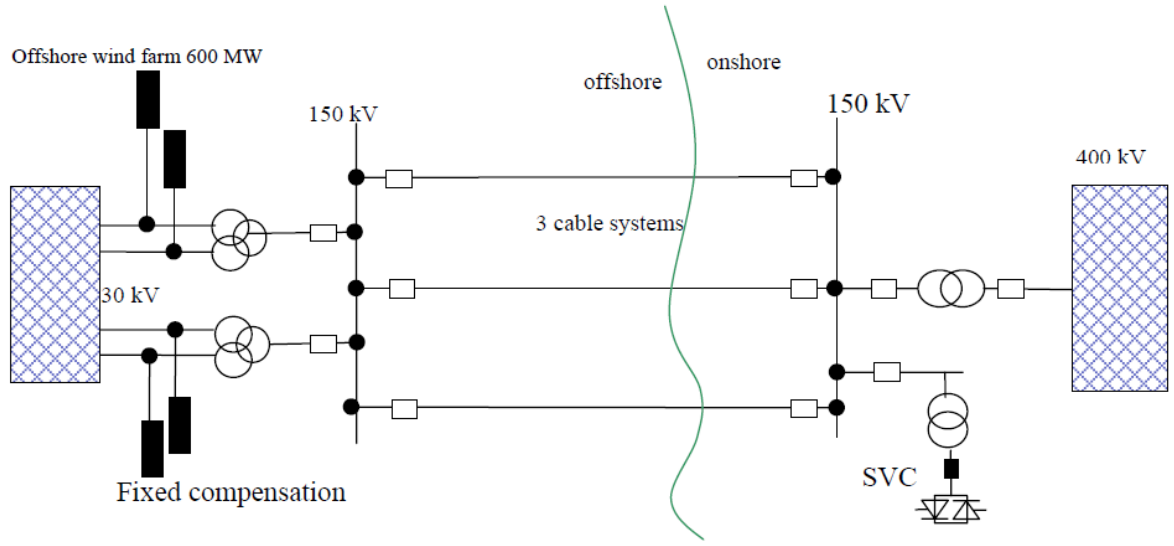


Figure 34 Basic configuration of a 600 MW wind farm with a HVAC solution

Nowadays, the maximum rating of HVAC submarine cables is approximately 200 MW per three-phase cable at a voltage rating of 150 to 170 kV, accounting for compensation at both ends of the cable and a maximum cable length of 200 km (41). Thus, in order to study a large wind farm of 1000 MW with HVAC, five cables would be required to connect the farm to the grid. Rated voltage up to 275 kV are possible (34) but for shorter distances, with powers of 400 MW. Under same conditions, a 230 kV cable can transmit 350 MW over 100 km with 4.3% of losses, and 300 MW over 200 km with 7.3% of losses. However, researches are on the way for higher ratings, such as 400 kV cable transmitting 1200 MVA over 100 km.

4.6.2 LINE-COMMUTATED CONVERTER BASED HVDC TRANSMISSION

LCC based HVDC has been used since 1954 as a transmission technology for bulk power over long distances and for system interconnection. However, it has never been used for offshore wind power applications. The reason is that it can only transfer power between two active grids, and thus an auxiliary start-up system is required in order to connect an offshore wind farm to the grid (42).

A typical LCC based HVDC system comprises transformers, thyristor-based power converters, AC and DC filters, a DC current filtering reactance and capacitors (or STATCOM) for reactive power compensation at each end of the DC cable. Thyristor valves are used and it requires a synchronous voltage source in order to operate. The building block that is most commonly used is a three-phase full-wave bridge. This bridge is a 6-pulse bridge and thus has 6 controlled switching elements which are thyristor valves. Each valve comprises a number of series-connected thyristors, depending on the voltage rating.

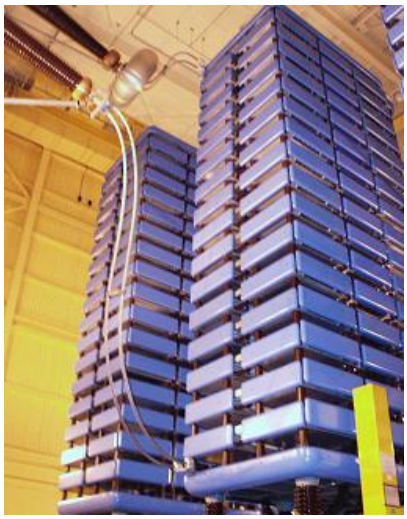


Figure 35 Thyristors valves stacks at the Manitoba Hydro Radisson Converter Station

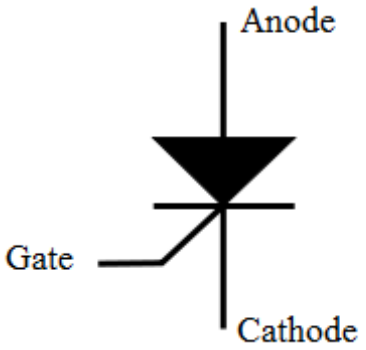


Figure 36 Thyristor circuit model

12-pulse operation can be used when two 6-pulse bridges are connected in series when phase-displaced by 30 degrees. This operation mode is convenient to increase the DC voltage and suppress some of the AC current and DC voltage harmonics. This phase-displacement is achieved by using a transformer with a wye-connected secondary for one bridge and a delta-connected secondary for the other bridge. Figure 37 shows this configuration. 12-pulse conversion gives two independent DC circuits that are capable to transmit half of the capacity.

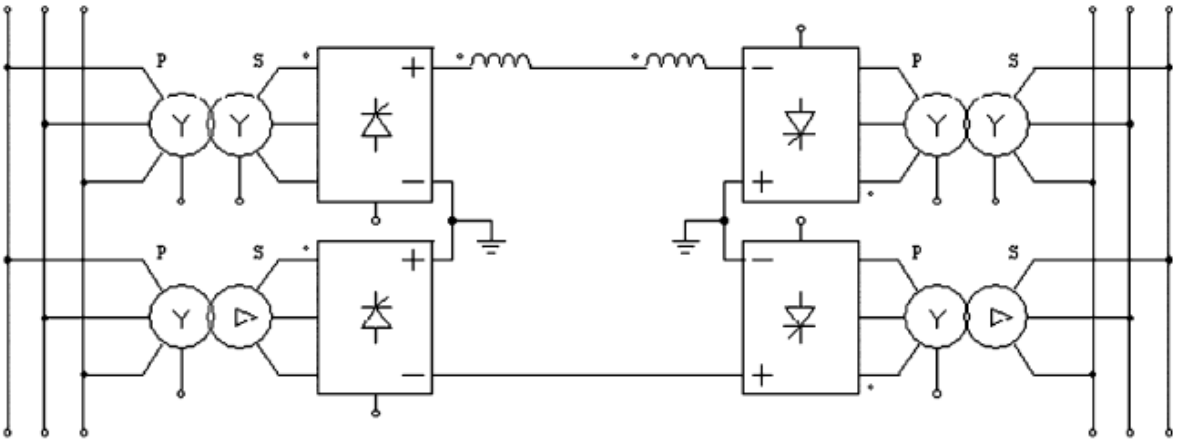


Figure 37 12-pulse HVDC LCC transmission line

The transformers are placed at substations at each end of the cables, in order to raise the voltage to the transmission line requirements. It provides also electric isolation for the AC and the DC circuit and it must include tapping for the system control.

The thyristors are the core of the inverters and rectifiers used in the LCC based HVDC transmission system. They are made with silicon wafers of 125 mm with voltage ratings of 8kV and DC currents of 4 kA (42). Thyristors operate at switching frequencies of 50-60 Hz with power losses of 1 or 2 % (42) depending on the transmission system. As a result, the total conversion efficiency using the two converters at each end of the cable (AC - DC - AC) is between 97 and 98% (41). The higher the efficiency, the higher the cost of the installation. Line-Commutated Current Source Converters can only operate with the AC current lagging the voltage. As a result, reactive power is needed for the conversion process (43) by the thyristors. Moreover, the control characteristics of the system are affected by the reactance of the cable and by the reactance of the transformers. Thus, constant extinction angle control is also required.

The AC and DC filters are needed in order to alleviate for the low-order harmonics in the line currents, generated by the thyristors. They also provide reactive power that is required by the thyristors. The DC current filtering reactance also helps reducing the undesirable harmonics and it allows uninterruptible operation during minimum load.

Different arrangements of the converters are possible depending on the system that needs to be connected to the grid. The most common is the monopolar configuration shown in Figure 38. The monopole with ground return is the easiest and thus most feasible configuration for long distances. As there is only one cable, the costs are reduced as low as possible. Electrodes are used in order to return the current into the ground or the sea. This causes troubles if metallic objects are on the cable route, such as underwater oil or gas pipes. The monopole with metallic return is based on the same principle but the earth is guaranteed by a low voltage DC cable. It suppresses the undesirable behaviour of the ground return, but increases the total cost.

If the capacity of the system becomes too high, a bipolar configuration can be used. This is the combination of two monopolar systems, one with a positive polarity and the other one with a negative polarity. Figure 39 shows two bipolar configurations and the series connection of bipolar converters.

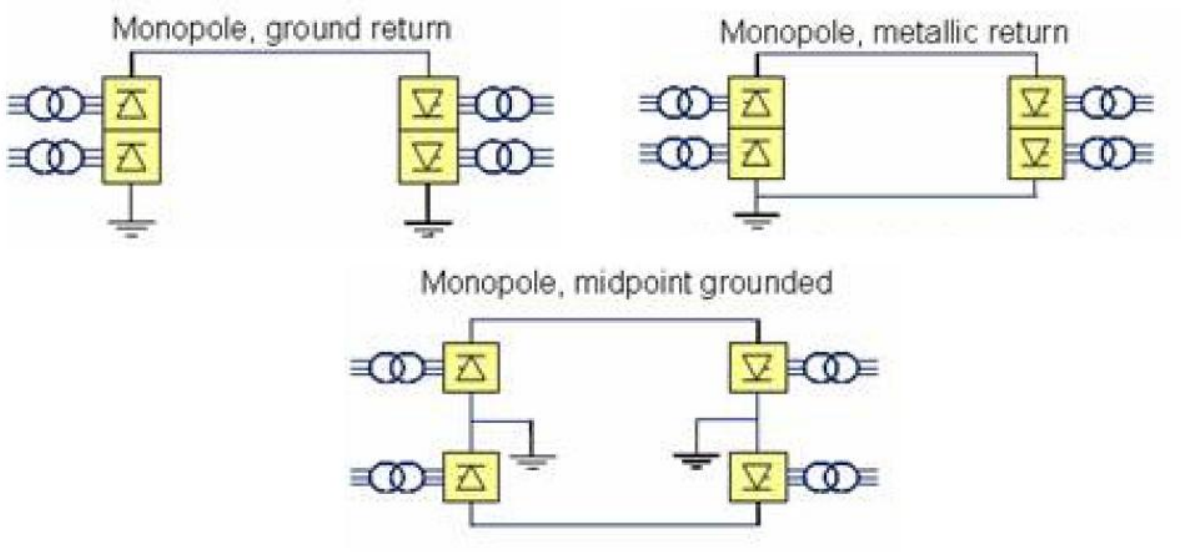


Figure 38 Monopolar LCC based HVDC (43)

The bipole with ground return offers safety to the system in case of fault. If a fault occurs on one line, the current of the second line will return by the ground. In case of such a fault with a bipole with metallic return, the current of the second line will return by the metallic return patch. Half of the power can still be transmitted by the operating line during the clearing of the fault. The configuration with ground return is achieved with electrodes based on the same principle than the monopolar configuration. In case electrodes shall not be used, the metallic return is a suitable option but it is more expansive, due to the additional cables allocated for the return.

Bipolar configuration with series-connected converters is used for high power transmission in HVDC, for voltages between 500 kV and 800 kV (43). The series connection is made to increase the availability of power in case of a defective converter or of a default of insulation.

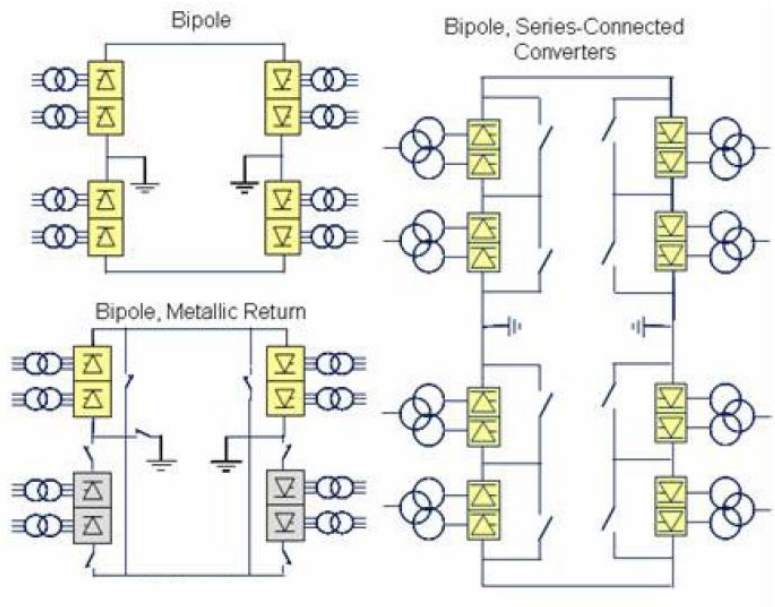


Figure 39 Bipolar LCC based HVDC (43)

Figure 40 shows a multiterminal configuration. It is used when the connection of three or more AC systems is necessary.

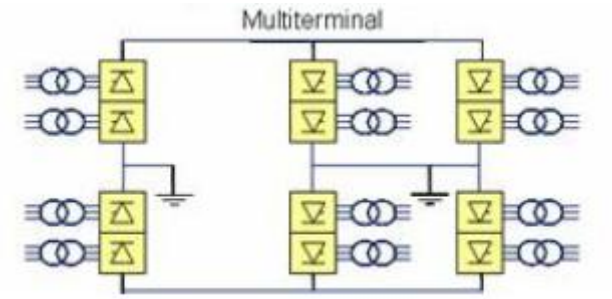


Figure 40 Multiterminal LCC based HVDC (43)

A conventional HVDC converter station with Current Source Converters (CSC), which is the same than LCC based HVDC, is drawn in Figure 41. Such stations can be large. The one shown in Figure 41 is a 600 MW station and the size is 200 x 120 x 22 meters. Offshore substations are smaller but yet it requires a lot of space and real infrastructures.

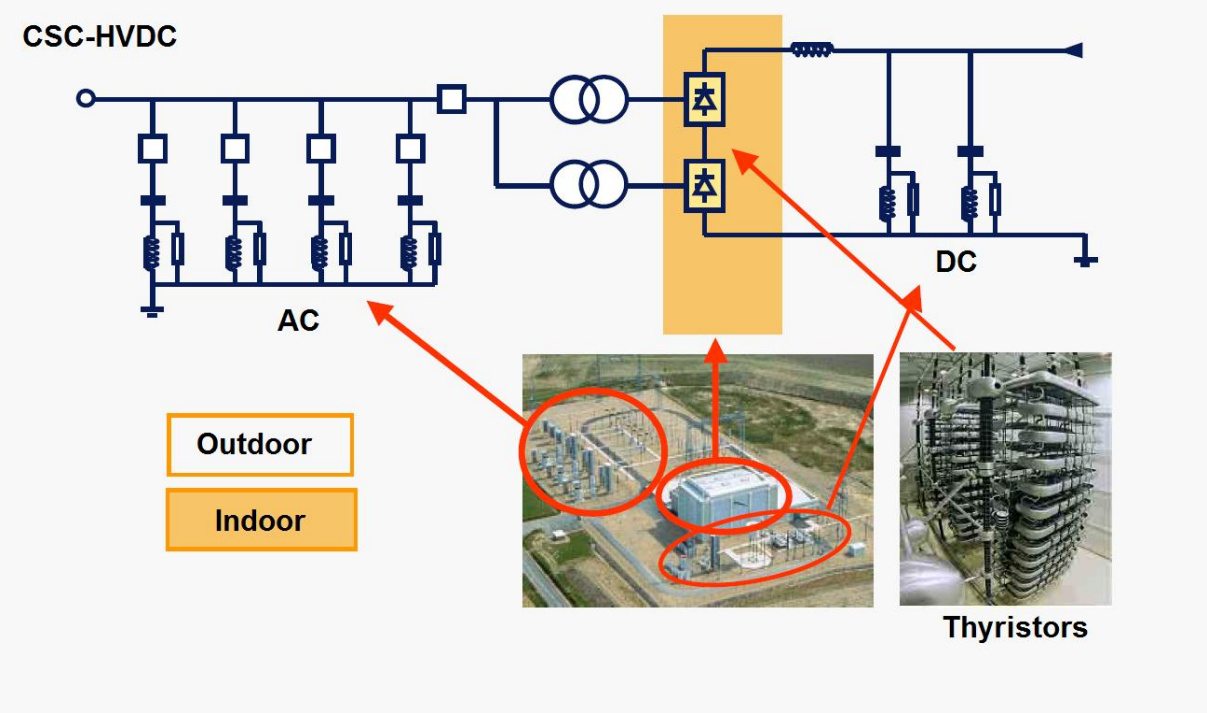


Figure 41 LCC converter station

4.6.3 VOLTAGE SOURCE CONVERTER BASED HVDC TRANSMISSION

VSC based HVDC is a brand new technology that results from major improvements in power electronics. It relies on the use of Insulated-Gate Bipolar Transistors (IGBTs). VSC based HVDC is called HVDC Light by the power technology company ABB, and HVDC Plus by Siemens. As Table 3 shows (41) (40), by the end of 2005, few operational offshore implementations were using VSC transmission technology but it is gaining a large interest in future projects.

Table 3 VSC based HVDC existing systems (2005)

Project	Country	Distance (km)	Rating (MVA)	Start operation	Main motive
Gotland Light	Sweden	70	60	1999	Infeed wind power
Direct Link	Australia	65	3x60	2000	Power trading
Tjæreborg	Denmark	4	8	2000	Infeed wind power
Eagle Pass	USA	Btb	36	2000	AC voltage control
Cross Sound	USA	40	330	2002	Power trading
Murray link	Australia	180	200	2002	Power trading
Troll A	Norway	67	2x41	2005	Power to platform

A VSC transmission system consists of an AC based collector system inside the offshore wind farm, an offshore and an onshore substation with VSCs, AC and DC filters and a DC current filtering reactance. It does not differ compared to LCC based HVDC except on the VSC converters. Figure 42 shows a high power IGBT module. Figure 43 shows its circuit model.

Figure 43 1200 A, 3300 V IGBT module (IGBTs and free- wheeling diodes)

Figure 42
IGBT circuit model

IGBTs are electronic switches that combine and take benefits of the command simplicity of Field-Effect Transistors (FET) and low conduction losses of Bipolar Junction Transistors (BJT). IGBTs in VSC based HVDC operate at high frequency in the range of 1 to 2 kHz. As a result, losses are higher, in the range of 4 to 5 %. As the frequency is higher, there is lower harmonic distortion compared to LCC based HVDC. Thus, the use of filters is reduced. The topology of VSCs is based on the use of two cables since it is generally not connected to the ground. Figure 44 shows a VSC based HVDC transmission system that is connected to the ground.

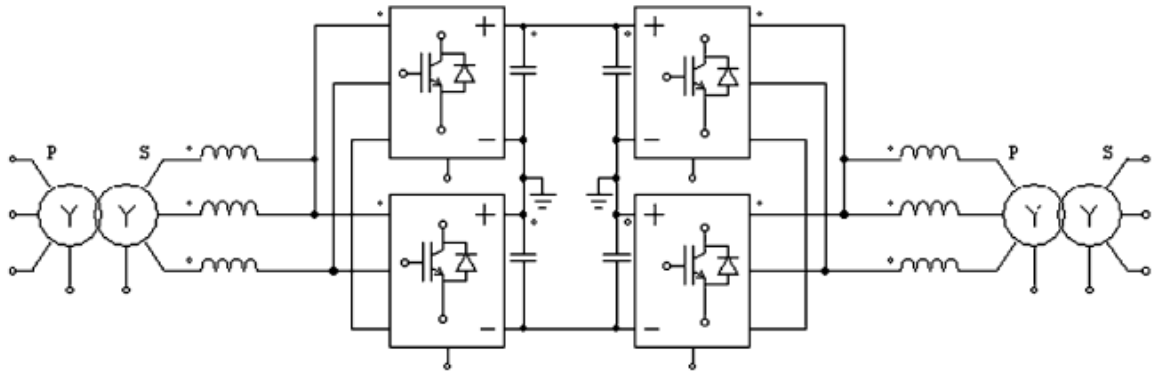


Figure 44 VSC based HVDC transmission system

The transformers onshore and offshore adapt their voltage level to the transmission line requirements while VSCs make the AC/DC conversion.

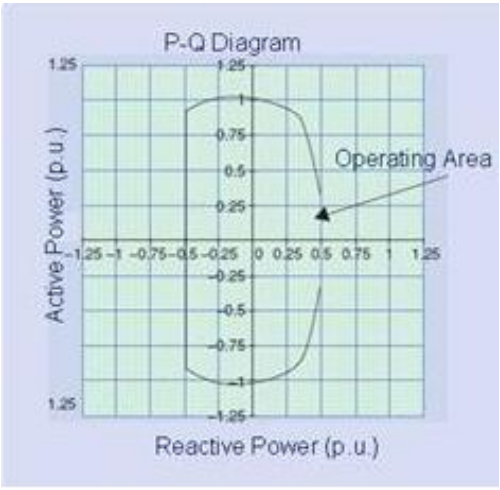


Figure 45 Active and reactive power operating range for VSCs

VSC based HVDC systems allow the active and reactive power supply to be controlled independently of each other at each end of the line (42). Thus, power transmission can be controlled with high flexibility. On the one hand, reactive power can be supplied at the offshore station for the Wind Turbine Generators, and it can also be supplied at the onshore stations to regulate the voltage. On the other hand, active power can be used to control the grid frequency, in case it is weak. Figure 45 shows the active and reactive power operating range of a VSC based HVDC system.

VSCs can start up against a nonloaded network because the current inside the converters can be switched off and thus active commutation voltage is not required. When the onshore grid has collapsed, the system can start by itself. The VSCs synthesize a balanced set of three phase voltages like a virtual synchronous generator (43).

A HVDC converter station with Voltage Source Converters is shown in Figure 46. This station has almost the same power rating than the one shown for the LCC based HVDC system, 550 MW instead of 600 MW, but the size is reduced by half. It only does 120 x 50 x11 meters. Thus, offshore stations are more compact and take less space, and thus are less expensive. However, from now (41), the rating per converter is only 300 to 350 MW with cable ratings of 150 kV, 500 MW. Thus, for higher power transfers than 300 MW, several converter stations have to be connected. Figure 47 shows a 600 MW wind farm using two VSC.

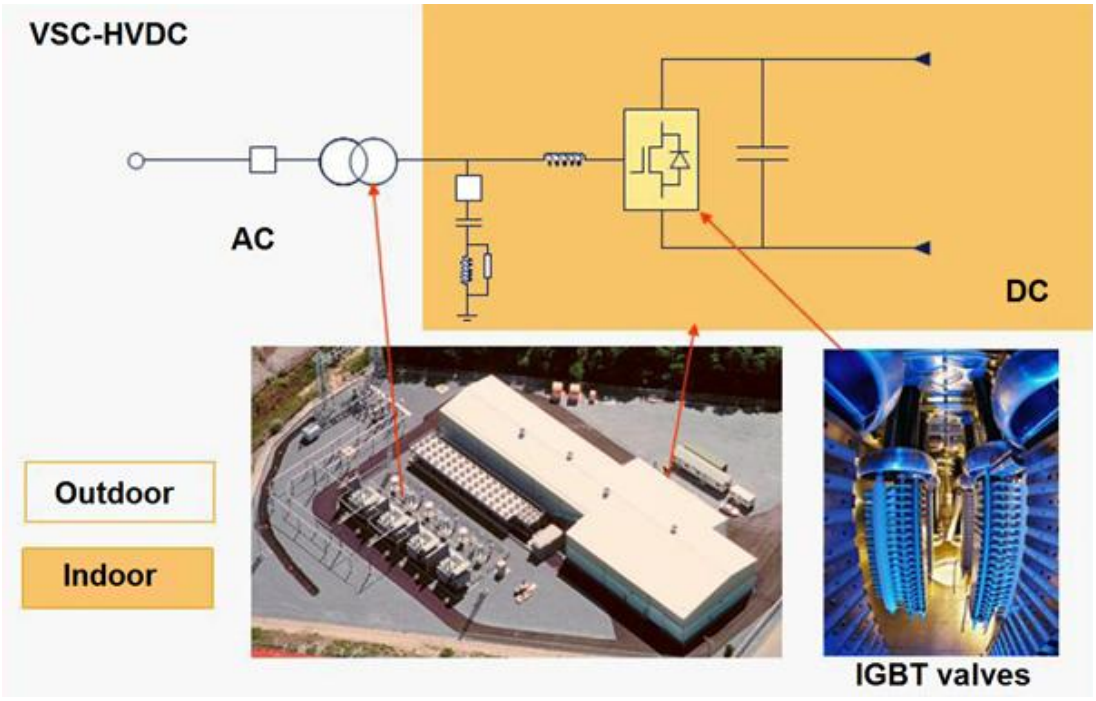


Figure 46 VSC based HVDC converter station

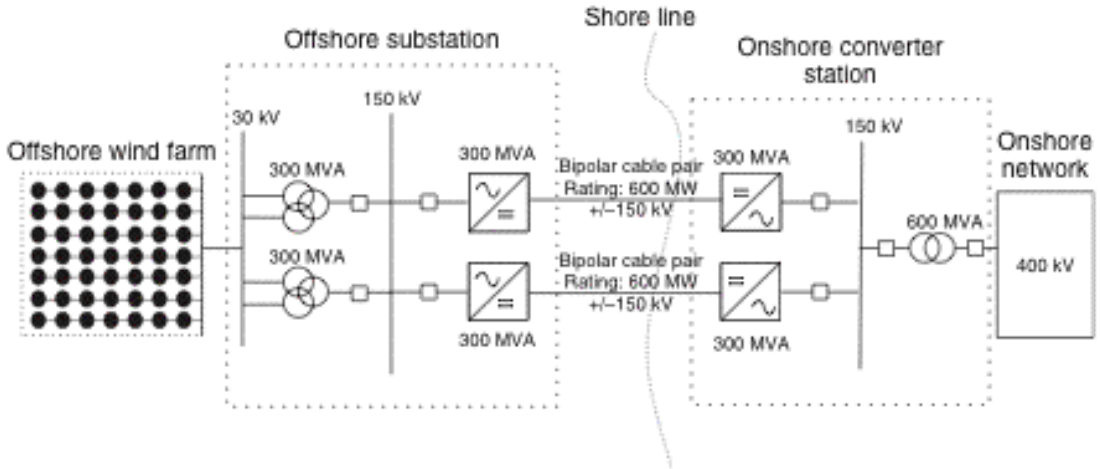


Figure 47 600 MW wind farm connected with VSC based HVDC

4.7 TRANSMISSION SYSTEMS COMPARISON

4.7.1 TECHNICAL COMPARISON

As presented before, the maximum rating of three-phase AC cables is 200 MW for a maximum distance of 200 km with a voltage level of 150-170 kV. For distances of less than 100 km, this rating can be improved to 350 MW at 245 kV. For VSC based HVDC, the rating of bipolar cables is 600 MW for any distance at a voltage level of 150 kV. However, converter stations are not able to transfer that amount of power, and their maximum rating is 350 MW. Thus, in order to use the full 600 MW cable, two converter stations are needed. Research is on the way for 500 MW converter stations (41). LCC based HVDC cables are limited to 1000 MW even though cable and converter ratings are not limiting factors. Table 4 (41) shows the number of cables required for different configurations. A higher number of cables imply higher costs but also better reliability. For VSC based HVDC, the power rating of the converter station is specified.

Table 4 Number of cables required for different configurations

Capacity (MW)	HVAC	LCC based HVDC		VSC based HVDC	
100 km	150 kV	150 kV, bipolar	450 kV, monopolar	150 kV, 300 MW	150 kV, 500 MW
300	2	1+1	1	1+1	1+1
500	3	2+2	1	2+2	1+1
900	5	4+4	2	3+3	2+2
1200	6	5+5	2	4+4	3+3

The power loss is often used as the main parameter to tell when switch to DC transmission. Figure 48 shows the power loss against the cable length, for HVAC, LCC based HVDC and VSC based HVDC.

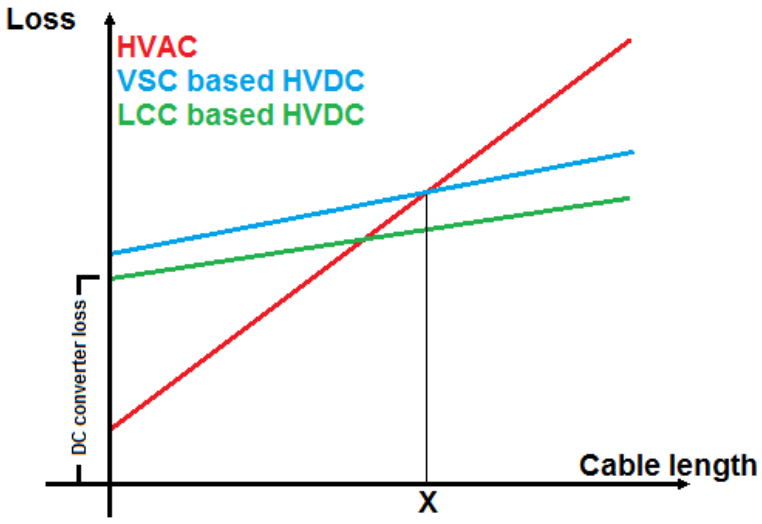


Figure 48 Loss against cable length comparison

For AC configurations, power losses increase significantly with distance, and thus depend on the length and on the cable characteristics. In HVDC transmission, there is a small correlation between the length of the cable and the loss. The main power loss is due to the efficiency of the converter station. As stated previously, VSC based HVDC converter stations are less efficient than LCC based HVDC ones. There is a distance called X on Figure 48 from which HVAC losses become higher than HVDC losses for the same transmission length. The value of X is not fixed and depends on the voltage levels and cable types. For the example of a 200 MW wind farm, X is approximately 100 km. Thus, for a distance over 100 km, the power loss is lower in the case of a VSC based HVDC transmission system than in the case of a HVAC one.

Offshore converter stations are expensive and require expertise to fit as much as possible in the transmission system. Generally, HVAC offshore stations are one third of the size of HVDC offshore stations. Even though LCC based HVDC converter stations have lower power loss then VSC based HVDC stations, their size is a lot larger has explained in Chapter 4.6. However, for power ratings above 300 MW, VSC based HVDC converter stations need to duplicate since 300 MW is their maximum rating. Thus, for 1000 MW wind farms, LCC based HVDC converter stations might take less space compared to multiple VSC converter stations.

The grid impact of the three transmission technologies presented is important regarding the expansion of offshore wind farms in the network. Large offshore wind farms represent a significant amount of energy for a region and it has to be operational at all time. New regulations are proposed, especially in Denmark and Germany where a lot of wind power is installed. The requirements for the onshore network to remain stable during faults is that wind farms will have to be able to reduced their output power to 20% of their rated capacity in 2 seconds in case of a fault. After the fault, the wind farm has to return to the prefault capacity in less than 30 seconds (41). HVDC transmission systems benefit more to the grid than HVAC transmission since they reduce the fault contribution to the onshore network. Upgrades of onshore transformers and switchgears are expensive but may not be necessary when using HVDC transmission. Moreover, VSC based HVDC can provide active and reactive power supply as well as voltage control which benefit to the grid. HVAC and LCC based HVDC can also do so, with the addition of SVC or STATCOM.

Table 5 is the summary of the technical comparison. The total system power losses is higher for LCC based HVDC if offshore ancillary services is required to meet the capability for network support of VSC based HVDC. The HVAC maximum capacity and voltage level for the latest XLPE cables can be up to 1000 MW for 420 kV according to ABB. This could increase the maximum ratings of the cables.

Table 5 Summary of the technical comparison

	HVAC	LCC based HVDC	VSC based HVDC
Maximum capacity	350 MW	1200 MW	500 MW
Maximum voltage level	245 kV	500 kV	150 kV
Transmission capacity depends on distance	Yes	No	No
Total system power losses	Depends on distance	2-3%	4-6%
Black-start capacity	Yes	No	Yes
Capability for network support	Limited	Limited	Wide
Offshore substations in operation	Yes	No	Planned
Space requirement of offshore substations	Small	Large	Medium

4.7.2 ECONOMICAL COMPARISON

This comparison relies on the technological developments at one time and further research in power electronics can change the results. Figure 49 (41) shows the most economical choice for a configuration depending on the transmission distance and the capacity of a wind farm.

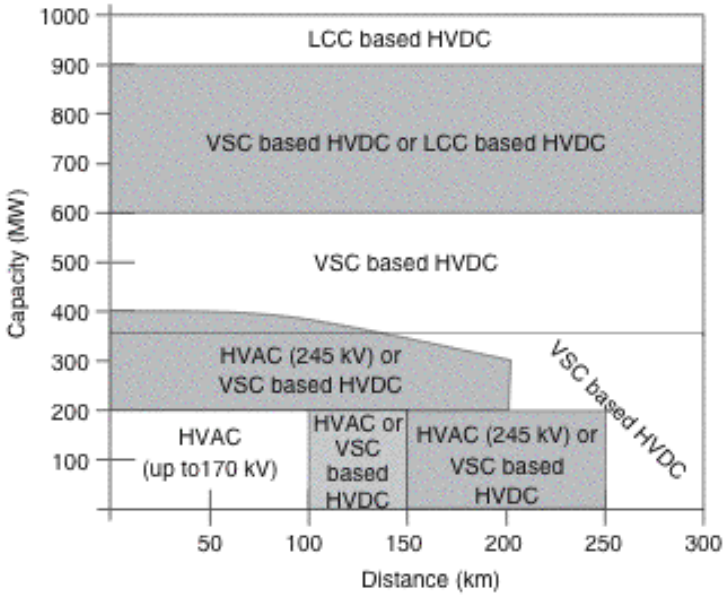


Figure 49 Choice of transmission technology depending on distance and capacity

For wind farms of a capacity less than 200 MW, the cost of three-core XLPE AC cable and the cost of a bipolar DC cable is the same, under 200 km. Though, the converter station for a VSC based HVDC transmission is 10 times higher compared to HVAC. For larger distances, the loss in the cable becomes too high for AC cables and it becomes economically less interesting compared to VSC based HVDC. However, HVAC is still feasible with compensation stations placed on the cable route on offshore platforms.

For wind farms of a capacity between 200 and 350 MW, HVAC transmission is ensured by two 150 kV three-core XLPE cables or one 250 kV three-core XLPE cable. With increasing distance up to 200 km, the use of HVAC is still possible, with a reduced maximum capacity of 300 MW. With such a capacity, it is possible to use VSC based HVDC instead of two AC cables.

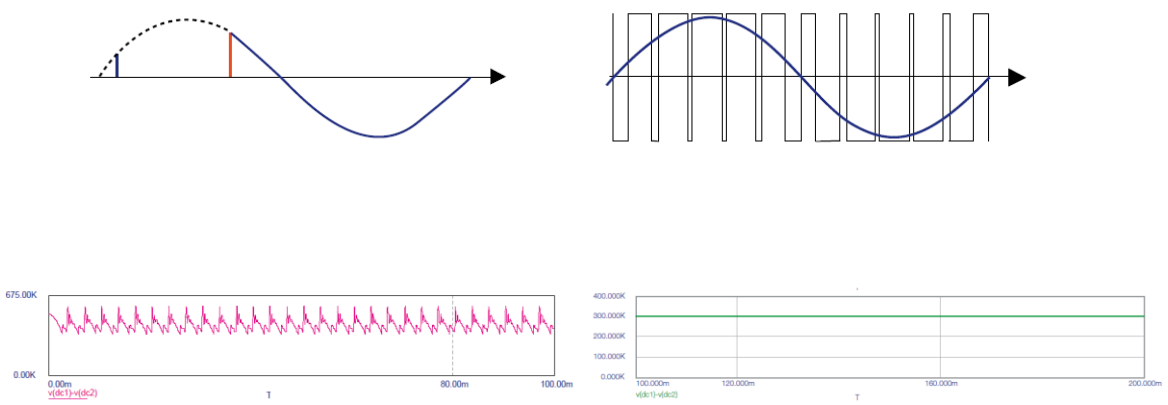
LCC based HVDC becomes interesting above 600 MW compared to VSC based HVDC. At this capacity, LCC based HVDC requires only one cable and one offshore converter station whereas VSC based HVDC needs two cables and at least three converter stations. However, even though is economically preferred, the benefit of having two cables is predominant, since if a fault occurs on the single DC cable of the LCC based HVDC system, then the whole offshore wind farm is disconnected, leading to a huge loss of power for the grid. It is still the case above 900 MW.

4.7.3 COMPARISON BETWEEN VSC AND LCC BASED HVDC

Table 6 shows the differences in the converters between LCC and VSC based HVDC technologies. For VSC based HVDC, the Pulse Width Modulation (PWM) controls both active and reactive power (44).

Table 6 Comparison between VSC and LCC based HVDC

LCC based HVDC	VSC based HVDC
Thyristors	IGBTs
Single silicon wafer	Multi-chip
Forward and reverse blocking capability	Forward blocking capability
Very high surge current capability	Current limiting characteristics
No gate turn-off	Gate turn-off fully controllable
Operate at 50-60 Hz	Operate at 2000 Hz
Power up to 6400 MW	Power up to 1100 MW



DC VOLTAGES

5 SIMULATION MODELS

5.1 SIMULATION TOOL

Several simulation tools are being used by the electrical engineering industry and research institutes. The most notables are PSS®E (Power System Simulator) from Siemens, PowerFactory from DIgSILENT GmbH and SIMPOW from STRI AB. Those three simulation tools are more or less equivalent and provide the user with advanced and proven methods regarding power flow, fault analysis, dynamic simulations and planning of electrical power networks.

SINTEF, the largest independent research organisation in Scandinavia, has a large research centre in NTNU and thus can provide help to master students. The first choice for the simulations was to use PSS®E since SINTEF, Statnett (The Norwegian transmission system operator) and Statkraft (The main Norwegian energy producer) are using it. However, it was complicated to get help from the SINTEF department in relation with this subject and thus SIMPOW was chosen.

5.2 GRID MODEL

In order to study large scale integration of offshore wind farms, it is necessary to have a model of the grid to which the wind farms can be connected. As the study is made with Statnett, SINTEF and NTNU, the Scandinavian grid is considered. The Nordic grid model from NORDEL was presented in Chapter 1.4.2 in Figure 7. This model is complex since it is made of more than 2200 busses and it is not necessary for the simulations of this thesis to obtain such a degree of complexity. A simplified grid model was given by SINTEF in PSS®E and has been partly translated to SIMPOW thanks to the program PSSE2SIMPOW from STRI AB.

The Nordic grid model used in for the simulations is composed of 35 busses representing Norway and Sweden for the most, but also Finland and Denmark. Thus the entire Scandinavian system is taken into account. 13 geographical regions are considered such as Southern or West regions. There are 22 busses with a voltage level of 420 kV, 12 at 300 kV and one at 135 kV. This last one is the HVDC connection between Sweden and Denmark. Cross-Skagerrak, the connection between Norway and Denmark, and NorNed, the connection between Norway and the Netherlands, were presented in Chapter 1.5.1 but are not computed in the grid model.

Generators and loads that are part of the simple grid model can generate and absorb up to 5000 MW of active power and up to 1500 MVar of reactive power. This is due to aggregation of regions and it should not be considered as real power plants but as an equivalent system. However, the voltage at each bus is within the limits of the grid code. This code states that the voltage should be +/- 10% of the nominal value.

The grid model computed in SIMPOW is fully shown in Figure 50. Each country is represented schematically.

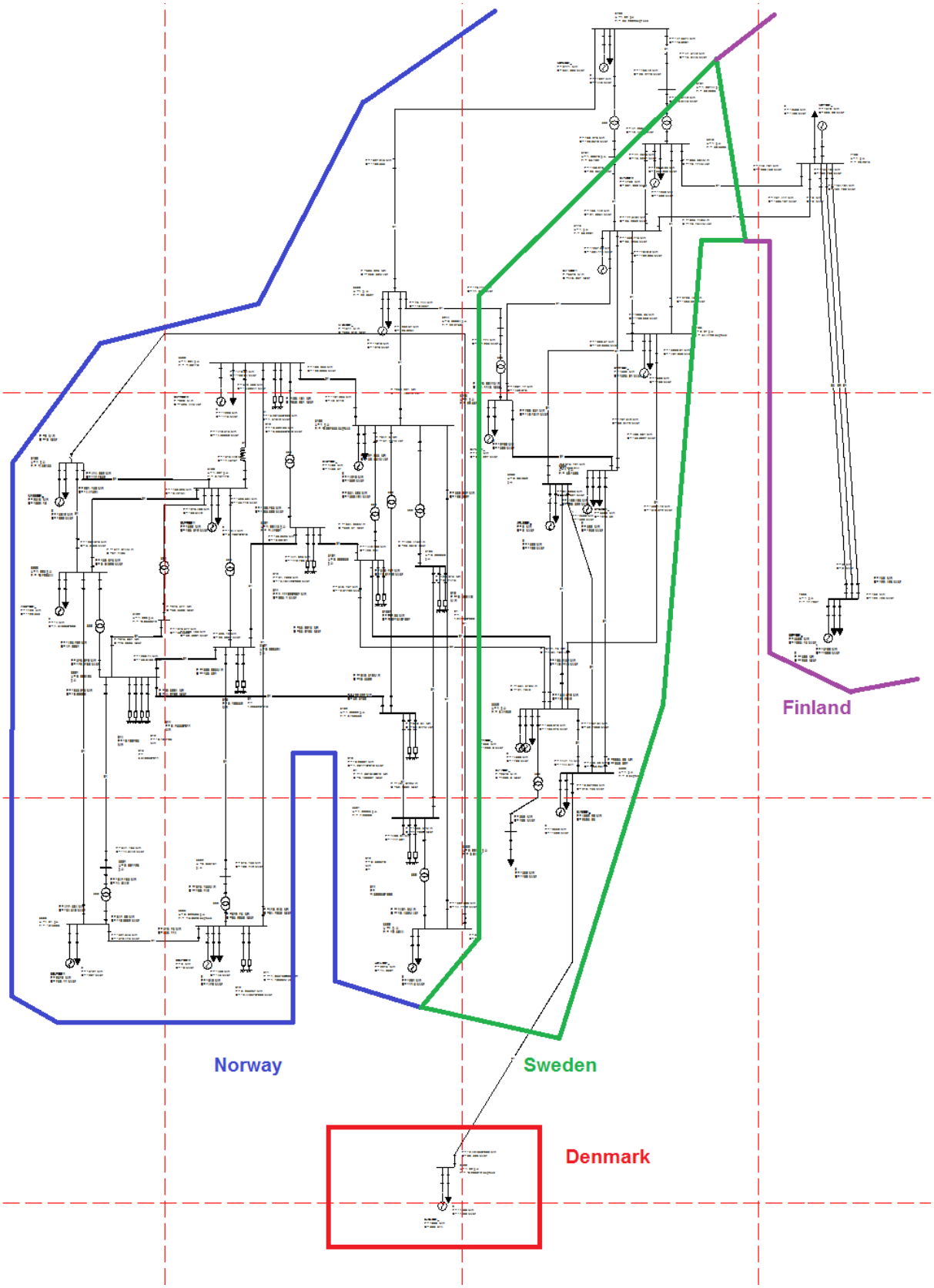


Figure 50 Grid model

The values of exportation and importation in MW and MVar of active and reactive power in the entire grid model are given in Table 7. In this case, Sweden completely exports active power to Denmark and Finland. On the overall, Sweden exports active power to Norway but on the north connection between the two countries, Norway provides active power to the Sweden grid. Denmark creates as much power as it needs but imports little reactive power.

Table 7 Grid model power exchange

	Productions and Network generation		Load absorbed and network losses	
Country	P (MW)	Q (Mvar)	P (MW)	Q (Mvar)
Norway	16306	4897,6	17159,7	4613,7
Sweden	24302,3	11117,4	21699,9	11186,6
Finland	6610	1671,2	8100	1650
Denmark	1000	909,6	1000	1000
Total	**48218,3**	**18595,8**	**47959,6**	**18450,3**

The total generated and consumed powers are not equal even though the entire system is stationary, because shunts and transmission losses are not accounted in Table 7. Shunt capacitors, shunt reactors and line reactors exchange rates are shown in Table 8.

Table 8 Grid model power exchange

	P (MW)	Q (Mvar)
Productions	48218,3	16411
Shunt capacitors	0	997,7
Network generation	-	3485,4
Total production	**48218,3**	**20894,1**
Load absorbed	47407,4	10115,3
Shunt reactors	0	969,1
Line reactors	0,6	0
Network losses	810,3	9809,7
Total load	**48218,3**	**20894,1**

The power flow between countries is depicted in Figure 51.

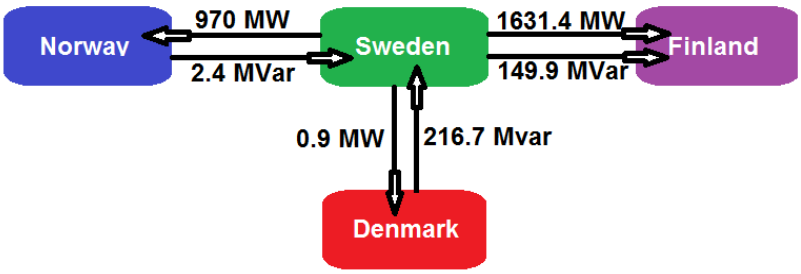


Figure 51 Grid model power flow

The grid model was already constructed in PSS®E but had to be translated into SIMPOW. Table 9 shows the parameters of the generators that are in the original case file. Each generator comprises a generator model, a turbine model, an excitation model and eventually a stabilizer model. The generators are different because they represent different type of generation for each region. Some regions are using thermal power plants and some other, mainly in Norway, incorporate hydro power plants. GENROU generators represent thermal plants and GENSAL hydro turbines.

Table 9 PSS®E generator models

Generator bus	Generator model	Turbine model	Excitation model	Stabilizer model
3300	GENROU	IEESGO	SCRX	STAB2A
3000	GENROU	IEESGO	IEEET2	STAB2A
3100	GENSAL	HYGOV	SCRX	
3115	GENSAL	HYGOV	SCRX	STAB2A
3200	Disconnected			
3245	GENSAL	HYGOV	SCRX	
3249	GENSAL	HYGOV	SCRX	
3359-1	GENSAL	HYGOV	SCRX	
3359-2	GENROU	IEESGO	SCRX	STAB2A
5100	GENSAL	HYGOV	SEXS	
5300	GENSAL	HYGOV	SCRX	STAB2A
5400	GENSAL	HYGOV	SEXS	
5500	GENSAL	HYGOV	SEXS	
5600	GENSAL	HYGOV	SCRX	
5603	Disconnected			
6000	GENSAL	HYGOV	SEXS	
6100	GENSAL	HYGOV	SCRX	STAB2A
6500	GENSAL	HYGOV	SEXS	
6700	GENSAL	HYGOV	SCRX	STAB2A
7000	GENROU	IEESGO	IEEET2	STAB2A
7100	GENSAL	HYGOV	SCRX	STAB2A
8500	GENROU	IEESGO	SCRX	STAB2A

Each of those models has equivalence in SIMPOW which is shown below.

5.2.1 GENROU GENERATOR MODEL

The model for thermal plants used in PSS®E is GENROU, which corresponds to a round-rotor generator model with quadratic saturation. The turbine and governor model is the IEEE Standard Model, called IEESGO in PSS®E. The equivalent in SIMPOW is the general steam turbine model ST2 along with the approximate speed-governing model SG3. Figure 52 (45) shows the turbine model in SIMPOW, Figure 53 (45) shows the governor model in SIMPOW and Figure 54 (46) shows the PSS®E model.

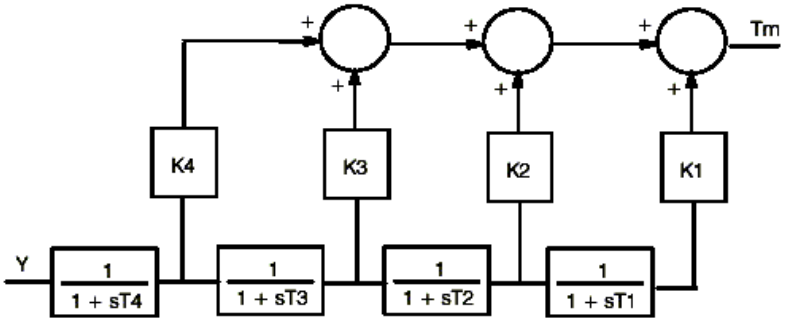


Figure 52 SIMPOW turbine model ST2

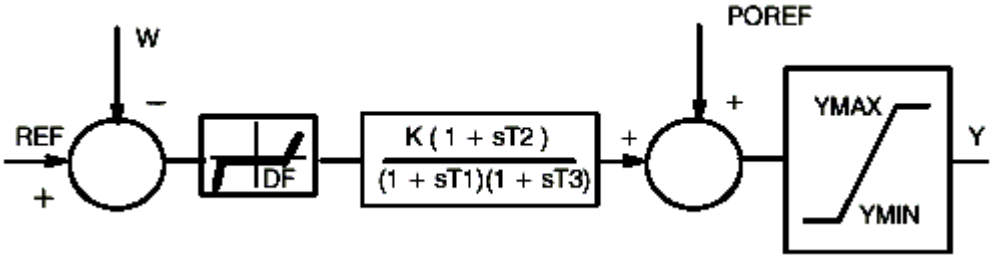


Figure 53 SIMPOW governor model SG3

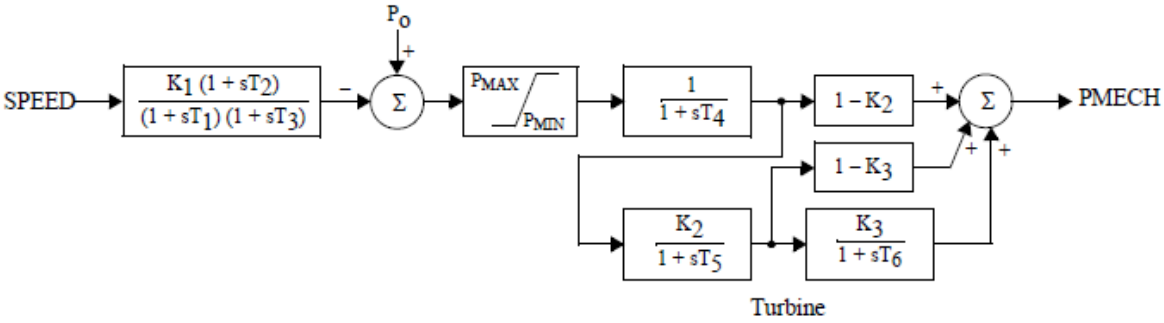


Figure 54 PSS®E turbine and generator model IEESGO

Table 10 describes the parameters identification between the SIMPOW turbine model and the PSS®E one.

Table 10 Generator parameters identification

SIMPOW ST2	K1	T1	K2	T2	K3	T3	K4	T4
PSS®E IEESGO	K3*K2	T6	K2*(1-K3)	T5	1-K2	T4	0	0

5.2.2 GENSAL GENERATOR MODEL

The model for hydropower plants used in PSS®E is GENSAL, which corresponds to a salient-pole generator model with quadratic saturation on d-axis. The turbine and governor model is the hydro turbine-governor model, called HYGOV in PSS®E. The equivalent in SIMPOW is the hydro turbine model HYTUR along with the hydro governor model HYGOV. Figure 55 (45) shows the turbine model in SIMPOW, Figure 56 (45) shows the governor model in SIMPOW and Figure 57 (46) shows the PSS®E model.

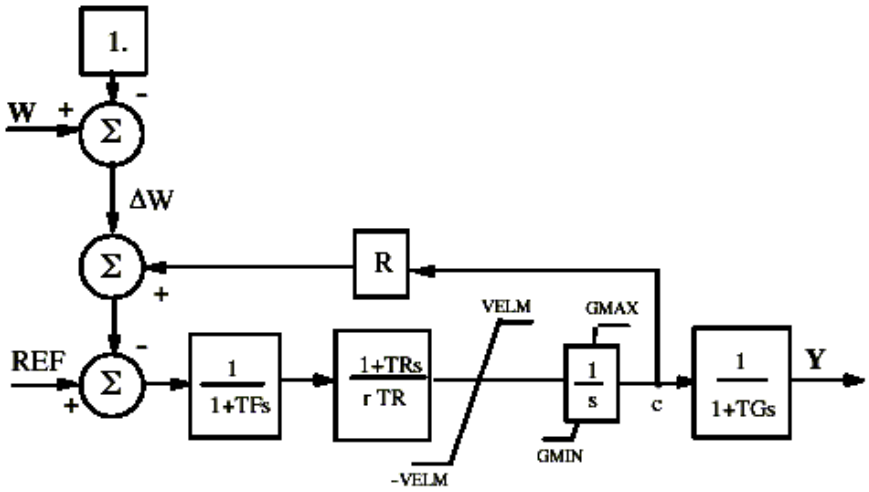


Figure 55 SIMPOW turbine model HYTUR

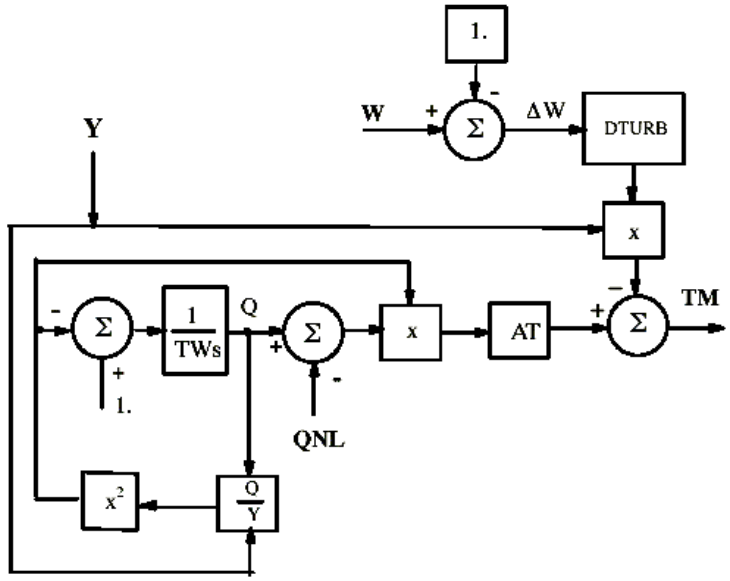


Figure 56 SIMPOW governor model HYGOV

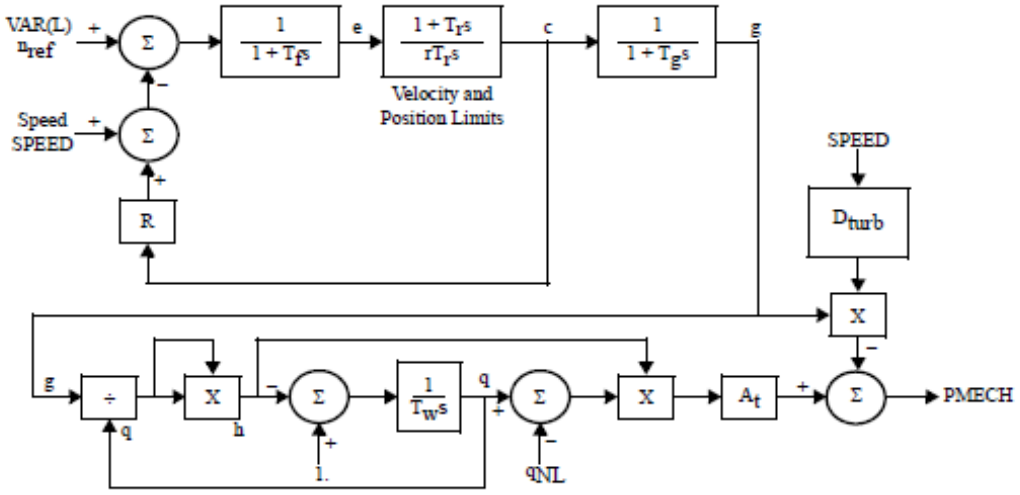


Figure 57 PSS®E turbine and generator model HYGOV

5.2.3 EXCITERS AND STABILIZERS

Three models of exciters are used in PSS®E for the grid model: SCRX, SEXS and IEEET2. Each of them is described below. SCRX is a bus fed static exciter and corresponds to an excitation system with DC commutator exciter referred as type ST3 in SIMPOW. The SIMPOW model is shown in Figure 58 (45) and the PSS®E model is shown in Figure 59 (46).

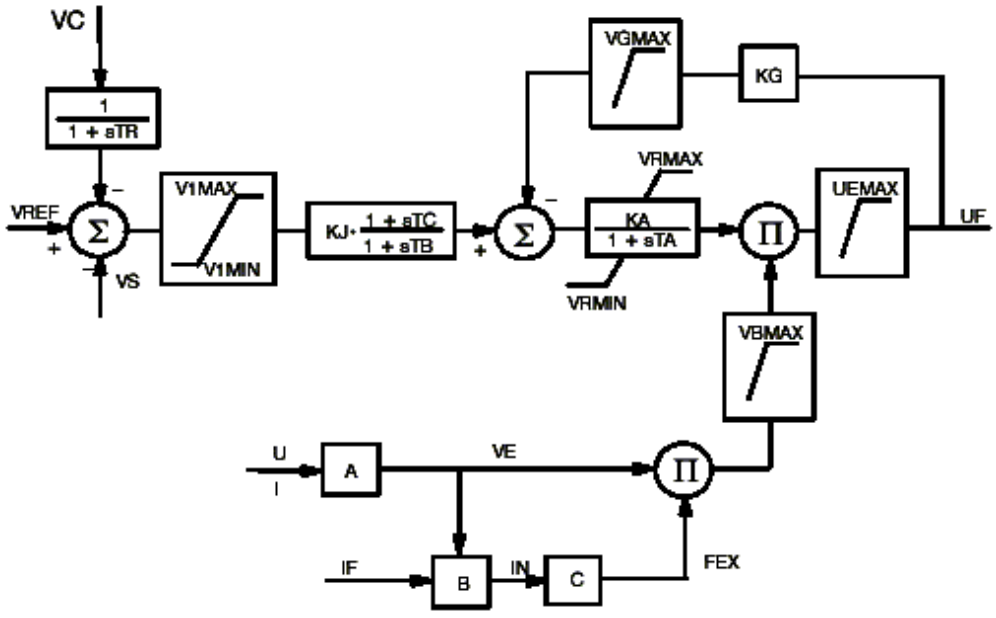


Figure 58 SIMPOW exciter model ST3

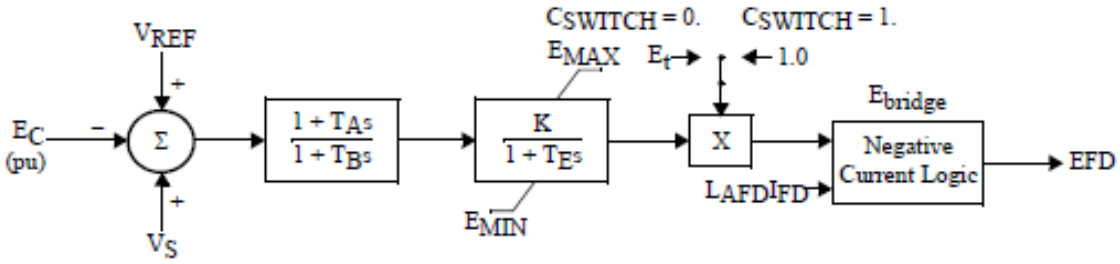


Figure 59 PSS®E exciter model SCRX

SEXS is a simplified excitation system and corresponds to an excitation system with potential source controlled rectifier exciter referred as type BBC1 in SIMPOW. The SIMPOW model is shown in Figure 60 (45) and the PSS®E model is shown in Figure 61 (46).

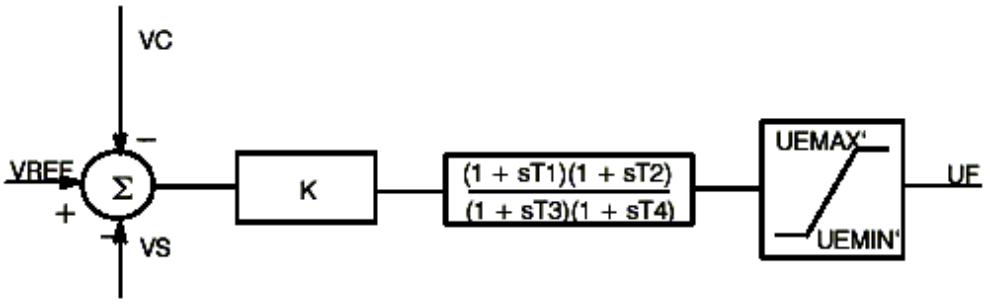


Figure 60 SIMPOW exciter model BBC1

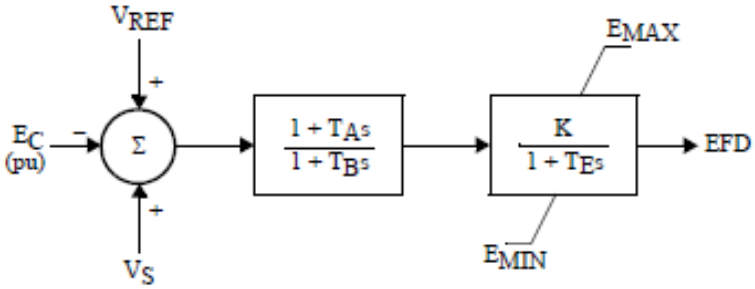


Figure 61 PSS®E exciter model SCRX

IEEET2 is IEEE type 2 excitation system and corresponds to the exact same termination in SIMPOW, as the name IEEEX2 suggests. The SIMPOW model is shown in Figure 62 (45) and the PSS®E model is shown in Figure 63 (46).

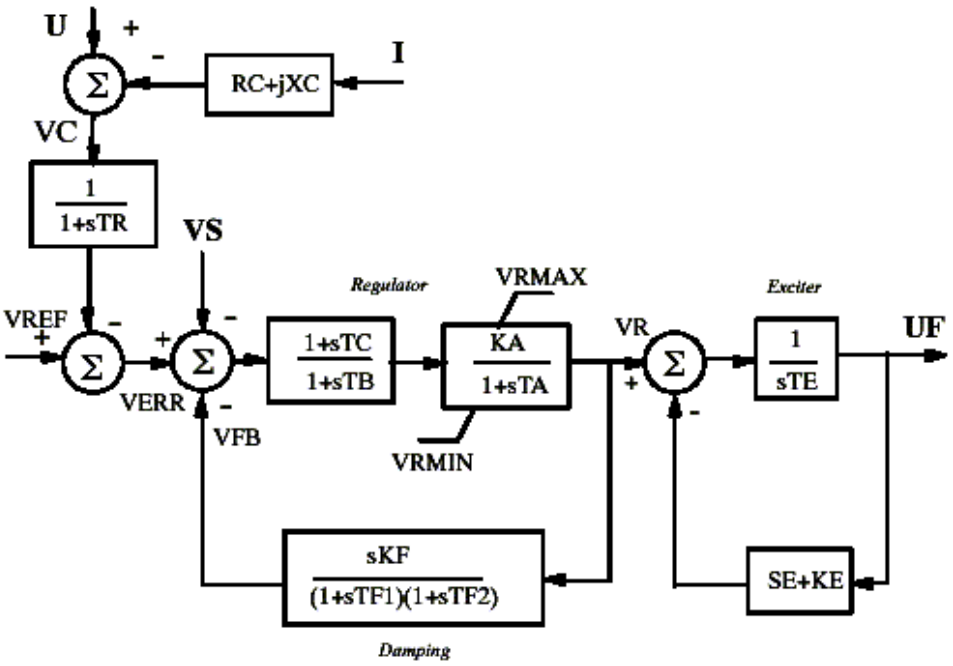


Figure 62 SIMPOW exciter model IEEEX2

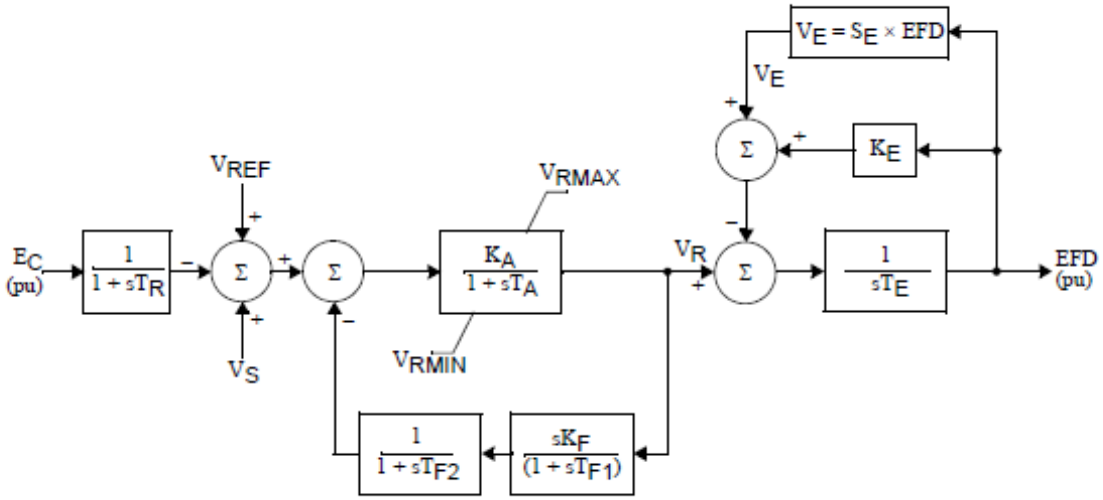


Figure 63 PSS®E exciter model IEEET2

The model used for the stabilizers in PSS®E is STAB2A, which corresponds to a power sensitive stabilizing unit (ASEA). The SIMPOW model has the same name. The SIMPOW model is shown in Figure 64 (45) and the PSS®E model is shown in Figure 65 (46).

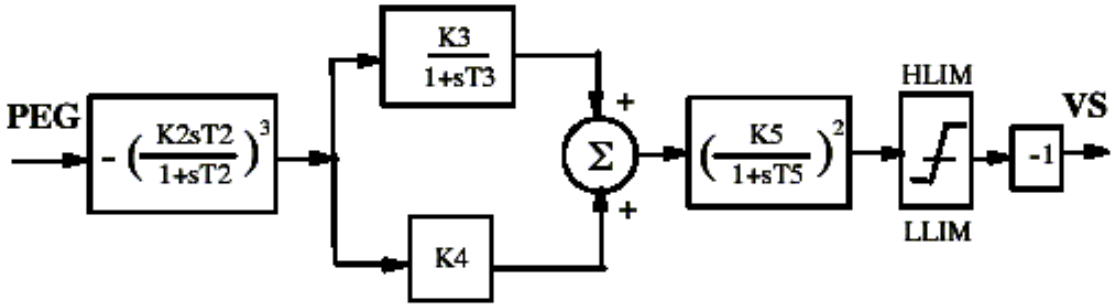


Figure 64 SIMPOW stabilizer model STAB2A

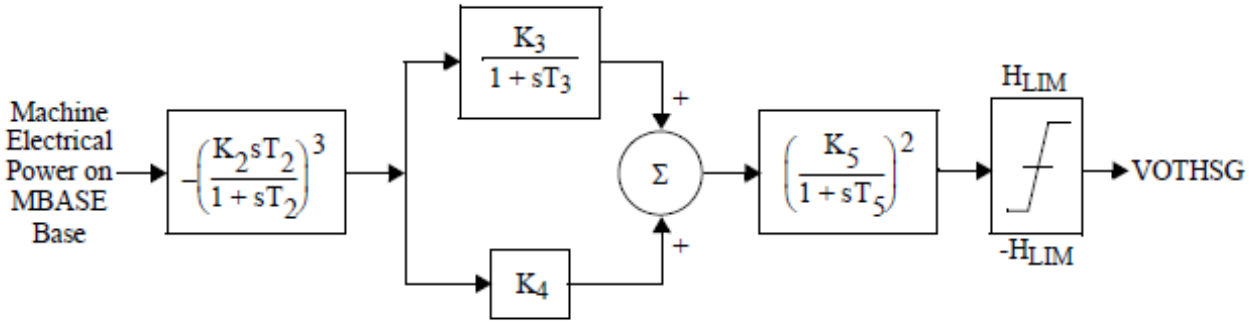


Figure 65 PSS®E stabilizer model STAB2A

5.2.4 POWER LINES

Lines in PSS®E are not always translated as a single line model in SIMPOW. Line type 13,14 and 15 are translated as lines type 12 in SIMPOW. The schematic representation of these types of lines is shown in Figure 66. As a result, the corresponding G1, B1, G2 and B2 are translated as two shunts impedances at each end of the line. Each shunt is either a pure reactance or a pure resistance. They are thus linked to the busses. Table 11 shows the shunt impedances that were added in order to match the lines in the PSS®E file.

At both ends of the line, the reactance value of the shunt capacitor, which symbolizes the susceptance of the line, is equal but the sign is different. Moreover, the resistance value of the shunt capacitor, which symbolizes the conductance of the line, is almost equal at each end of the line, but the sign is also different. Thus, half of shunt impedances have negative value, as if there was production of power. However, SIMPOW only translated what the PSS®E contained, and these negative impedances come from the PSS®E file. This is due to the PSS®E file being an aggregated and reduced model of a very complex one. Thus, in order to meet the production for every region, some lines had to fulfil the power flow and angle direction.

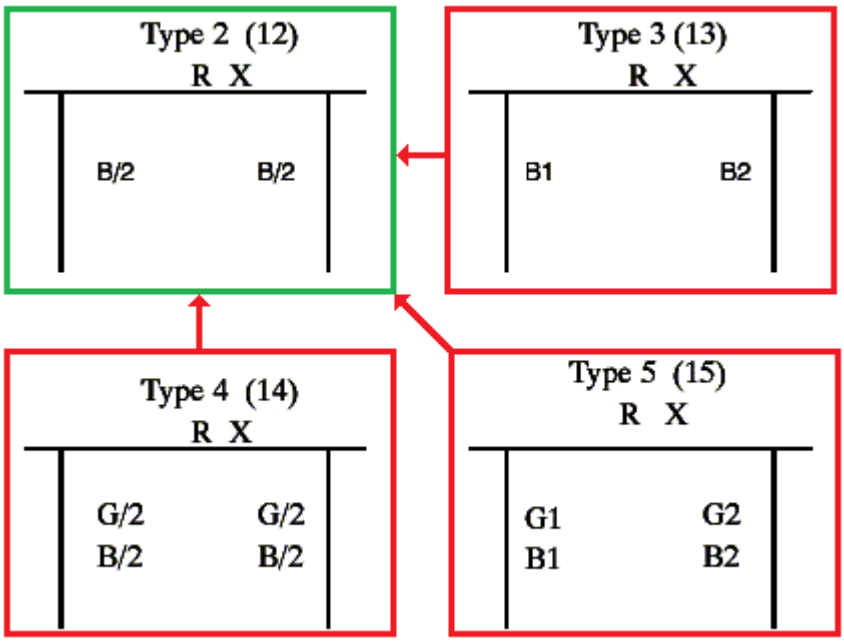


Figure 66 SIMPOW line types

TYPE=12 line is described with R, X and B. TYPE=13 line is described with R, X, B1 and B2. TYPE=14 line is described with R, X, G and B. TYPE=15 line is described with R, X, G1, G2, B1 and B2. R is the resistance, X is the reactance, G is the conductance and B is the susceptance. All values are given in per-unit of the line base power and the node base voltage (45).

Table 11 Shunt impedances

Bus A	R (Ω/phase)	X (Ω/phase)	Bus B	R (Ω/phase)	X (Ω/phase)
5101	0	181.034	**5501**	0	-181.034
	7910.31	0		-8166.67	0
5102	0	-0.176397E+07	**6001**	0	0.176397E+07
	882000	0		-882000	0
5103	0	13889.8	**5301**	0	-13889.8
	441000	0		-588000	0
5401	0	352800	**6001**	0	-352800
	-882000	0		882000	0
5500	0	-69230.8	**5603**	0	69230.8
	300000	0		-300000	0

5.3 WIND FARM MODEL

Large scale wind farm of a rated power of 1000 MW require more than 340 turbines for the latest models used on the market (47) and can be up to 500 turbines for regular models. To study such a big farm in an easier but still accurate way, an aggregated model is proposed. Representing each wind generator in the model increases to a high extend the calculation time of dynamic simulations. Thus, the entire offshore wind park is modelled by a single equivalent wind generator.

Among the four classes of wind turbines generators described in Chapter 2.3, the two most widely used nowadays are class C and D. Both models of Doubly-Fed Induction Generators (DFIG) and Full Power Converter Wind Turbines (FPCWT) are available in SIMPOW. In this type of variable-speed generators, the active power is controlled by fast power electronics converters, in order to reduce the impact of wind-fluctuations to the grid. The frequency converters with two PWM-converters of DFIGs and FPCWTs are similar.

In this study, the simulations are considered over a short period of time as it is transient stability analysis. As a result, wind speeds and mechanical speeds are assumed to be almost equal and aggregation of the generators and the mechanical model of variable-speed wind generators are possible (48). Even if full aggregation is easier, a good compromise between accuracy and calculation speed is to aggregate only the electrical system and then to model the mechanical system of each turbine. As the wind farm studied is of 1000 MW, a full aggregation is made and gives sufficient results for the studied cases (48).

Vestas Wind Systems A/S is the largest wind turbine manufacturer in the world and its latest research technology is the V112 (47). Its rated power is 3 MW and it uses a full-scale converter with a permanent magnet generator. In order to study large scale integration of possible future wind farms, such a modern wind turbine is taken into account. Thus, the Full Power Converter Wind Turbine model from SIMPOW is used. The main difference with a DFIG is that the generator is a synchronous machine. The generator terminals are connected to the grid through a frequency converter which consists of a PWM rectifier, an intermediate DC system and a PWM inverter. Figure 67 shows the SIMPOW model.

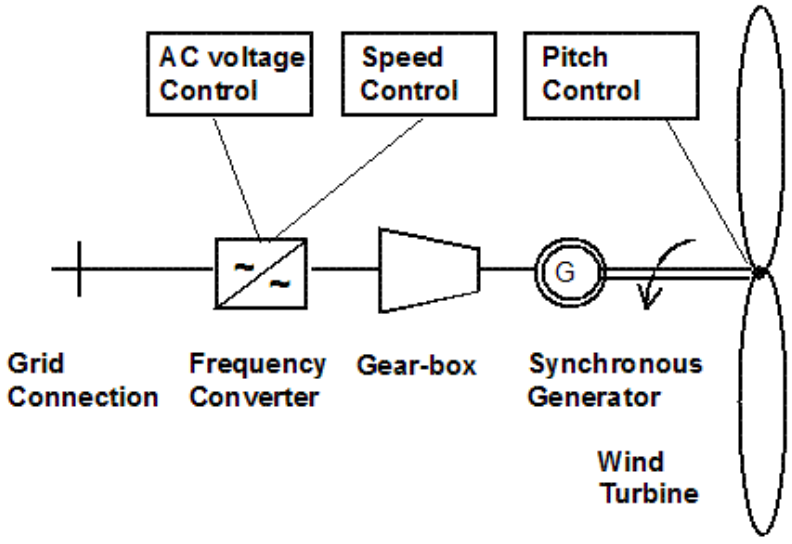


Figure 67 Full Power Converter Wind Turbine model

The values of the parameters used in the 1000 MW (1060 MVA) wind farm aggregated model are computed in Table 12. The aggregation consists of 518 wind turbines.

Table 12 FPCWT data

Wind turbine	
FPCWT rated power (MVA)	2,05
Air density (kg/m^3)	1,2
FPCWT blade length (m)	36
Nominal wind turbine speed (rpm)	23,4
Generator type	One field winding, one damper winding in d-axis, one damper winding in q-axis, saturation excluded
Inertia constant (MVA)	5,5
Stator resistance (p.u.)	0,0025
Stator leakage reactance (p.u.)	0,14
Direct-axis synchronous reactance (p.u.)	1,9
Quadrature-axis synchronous reactance (p.u.)	1,6
Direct-axis transient reactance (p.u.)	0,32
Direct-axis subtransient reactance (p.u.)	0,2
Quadrature-axis subtransient reactance (p.u.)	0,21
Direct-axis transient open-circuit time constant (s)	5
Direct-axis subtransient open-circuit time constant (s)	0,03
Quadrature-axis subtransient open-circuit time constant (s)	0,07
Pitch control	
Gain factor	60
Gain factor in integration	3
Gain factor for speed deviation	20
Gain factor in integration of speed deviation	20
Filter time constant	0,3
Maximum blade angle (deg)	27
Minimum blade angle (deg)	0
Maximum derivative of the blade angle	4
Minimum derivative of the blade angle	-4
Transformer	
Short circuit resistance between winding 1 and 2 (p.u.)	0,0032
Short circuit reactance between winding 1 and 2 (p.u.)	0,0599
DC capacitor	
Time constant (ms)	14,6
Rectifier and inverter	
Series reactance in p.u. of converter base	0,3
No-load losses in p.u. of converter base	0,02
Rectifier Active power (MW)	1000
Inverter DC voltage (kV)	5

In order to perform an aggregation in SIMPOW with the FPCWT model, the parameters listed below are the most relevant and must be taken care of. Most of the data of the wind turbine model is in per-unit and thus, they are taken care automatically by the simulation tool when increasing the rated base power. However, as stated in the help manual (45) under "Modelling of the wind turbine", in *Full Power Converter Wind Turbine* chapter, the sweep area and the turbine nominal speed have to be correct in order to use the default Cp/λ curves.

OPTPOW parameters (Power flow)

SN: base power in MVA

ORDER, in the FPCWT_REC (rectifier): set value for the active power in MW

DYNPOW parameters (Dynamic simulations)

NOM_TURBSPEED: nominal angular speed of the wind turbine in rpm

BLADELENGTH: length of the blades in m

The sweep area is related to the blade length and thus, in order to use the default Cp/λ curves, it is possible to specify that the blade length and the nominal turbine speed are null. As a result, SIMPOW will automatically consider the aggregation, taking the base power and the active power as the only input parameters.

Scaling up the wind farm also implies with the FPCWT available from SIMPOW that the initial wind speed increases. Table 13 shows how the initial speed grows up with an increased value of power.

Table 13 Initial speed

ORDER	SN	NOM_TURBSPEED	Initial speed	BLADELENGTH
0.91	2.05	18	9.044724	36
3	3.2	12.5	10.1955	54.65
5	5.3	14.1	11.396485	59.7
50	53	0	11.56960	0
250	265	0	11.569607	0

This initial speed should not be mixed up with the speed given to the wind curve. It is possible to enter any value of the wind speed but for the 1 ms, the speed is constant and is given a specific value by SIMPOW which can't be changed from now, even by redesigning the parameters.

This phenomenon is depicted in Figure 68. The wind speed is set to be constant during the entire simulation (100 s), to the value of 10 m/s. During the first millisecond, the speed is equal to a value above 11.5 and then drops all of a sudden to 10 m/s. This sudden drop induces a real perturbation on the wind turbine simulation since all the parameters (torque, power, etc.) are calculated in pre-simulation, and thus before the first millisecond. The consequence on the torque is shown in Figure 69. It can be seen that the torque also drops at the beginning and then stabilizes after 40 seconds.

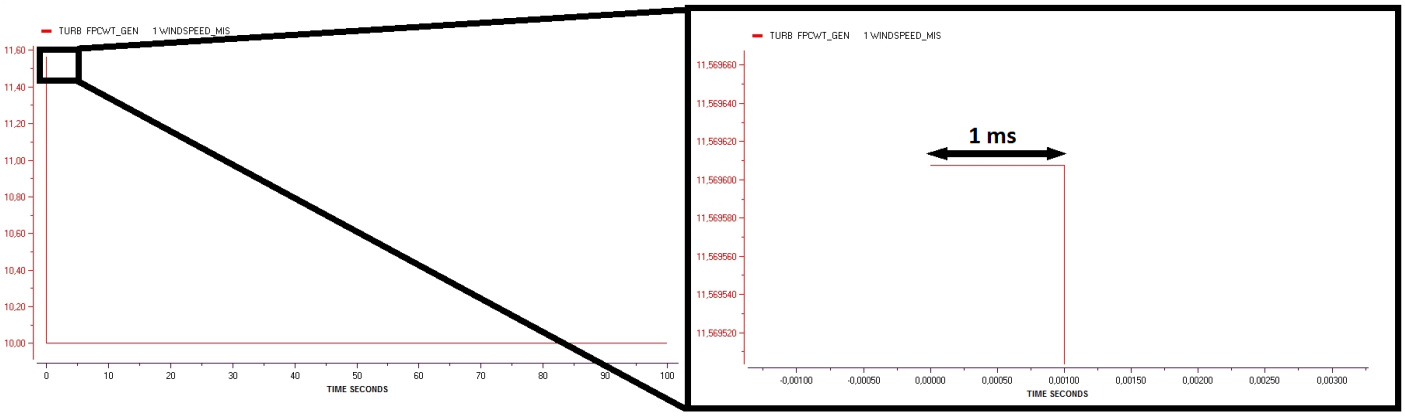


Figure 68 Inital speed drop

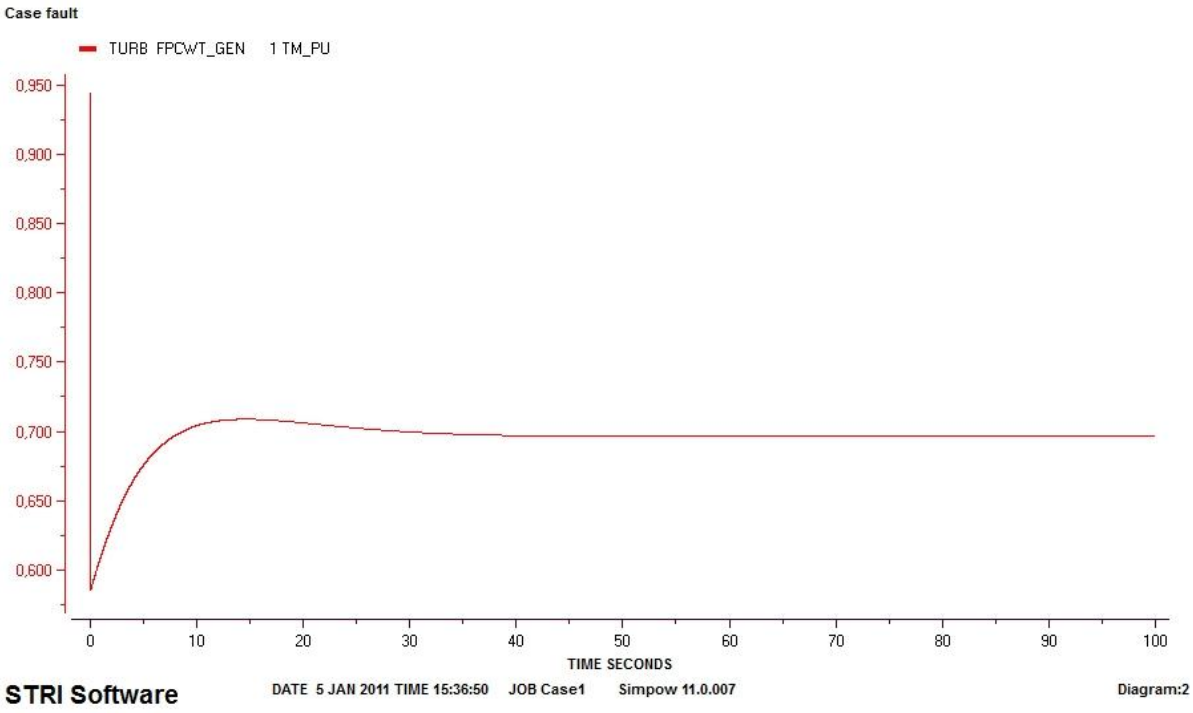


Figure 69 Initial torque drop

The torque is given in per-unit and starts at approximately 0.95 p.u. and drops to 0.7 p.u. This is a huge change that is not desirable for the wind farm simulations. To avoid this phenomenon, the wind curve initial value can be set to the initial value we observe. The maximum precision obtainable with the SIMPOW plotting tool is 1.10^{-15}. As a result the value is 11.569607734680176 m/s.

The torque is again plotted in Figure 70 with the speed given above. There is still a change but it will be neglected compared to the perturbations made in the simulations. The change here is 0.00014 p.u.

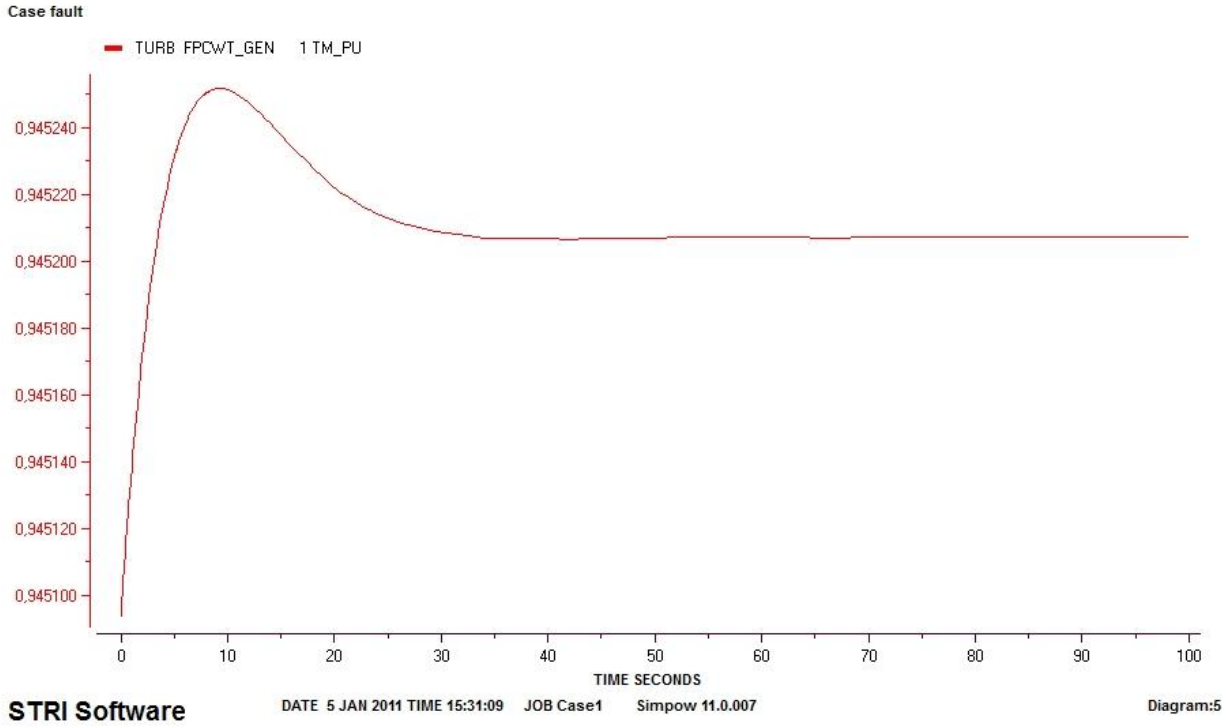


Figure 70 Initial torque change

5.4 HVAC CONFIGURATION

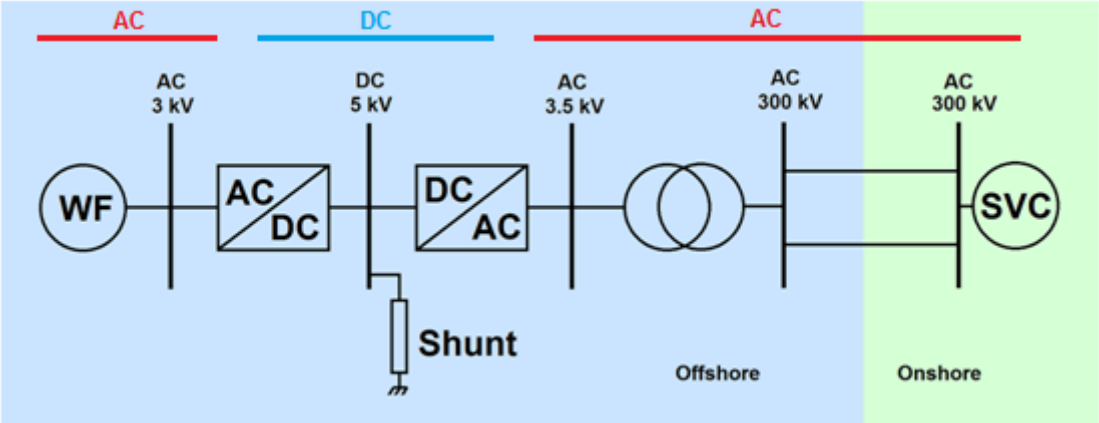


Figure 71 HVAC configuration

HVAC is the simplest and most reliable configuration for short distances. The distance of the wind farm from the shore is considered here to be 50 km which is often the case for offshore wind farms. The wind farm capacity is 1060 MVA, with a production of 1000 MW. The configuration with rectifier, shunt capacitor and inverter is shown in Figure 71.

Exactly one production source acting as a swing bus must be given in each AC network, as the voltage and the phase angle are used as calculation start values (45). As there are two separated AC network, two swing busses are implemented: the wind farm equivalent generator and bus 3300, located far from the onshore connection point. It ensures that there is sufficient influence of the wind farm on the network.

The model used for the cable is a PI-link which corresponds to the connection of two AC nodes with a resistance and a reactance in series and a susceptance at each end of the line. It is the TYPE 2 SIMPOW model and it is shown in Figure 72. Data are given in Ohms and Siemens per kilometre.

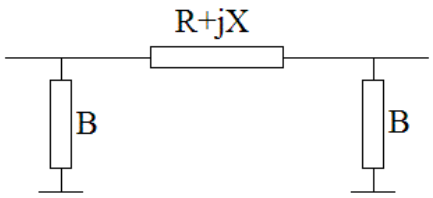


Figure 72 PI-link model

The parameters are chosen according to the manufacturer ABB (49). The cable chosen are three-core XLPE submarine cables with lead sheath. The conductor is made in copper. For a rated power of 1000 MW with 300 kV, the rated current is equal to 1170 A. Copper conductor cross-sections for submarine XLPE cables are limited to 1000 mm² which corresponds to a maximum current of 825 A. Thus, two cables with cross-sections of 500 mm² are able to transmit 655 A each, which is sufficient. For a maximum voltage of 300 kV, the parameters of the chosen cable are shown in Table 14.

Table 14 Chosen XLPE cable data

Cross-section of con-ductor	Diameter of con-ductor	Insulation thickness	Diameter over insulation	Lead sheath thickness	Outer diameter of cable	Cable weight (Aluminium)	Cable weight (Copper)	Capaci-tance	Charging current per phase at 50 Hz	Inductance
mm^2	mm	mm	mm	mm	mm	kg/m	kg/m	µF/km	A/km	mH/km
500	26.2	26.0	81.6	2.9	229.0	75.3	84.7	0.14	6.8	0.44

The resistance R of the cable is calculated with the formula $R = \frac{\rho.L}{S}$ where ρ is copper resistivity, L the cable length and S the cross-section area. The susceptance is calculated using the formula $B = \omega.C$ where ω is the angular frequency at 50 Hz and C is the capacitance. With requested units, the cable data used in SIMPOW are:

R= 0.034 [Ω/km] X=0.1382 [Ω/km] B=0.0000438 [S/km] L=50 [km]

As stated previously, it is important for voltage stability and reactive power correction to implement a Static Var Compensator. The inverter of the FPCWT is trying to keep the voltage of the AC node it is connected to as closed to its rated value as possible. By doing so, it sets the required reactive power needed by the wind farm. Moreover, the 50 km HVAC cables also increase the demand for reactive power.

The SVC is connected on the grid bus, as closed as possible to where the reactive power is needed. The equations below are solved in order to calculate the rating of the SVC. The Nordic Grid Code imposes the power factor to be higher than 0.95. The power output of the wind farm is 954.5 MW, after the step-up transformer. Thus, the value of the maximum reactive power compensation Q_{SVC} is calculated.

$$P = UIcos(\varphi)$$
$$Q = UIsin(\varphi)$$
$$Q_{SVC\,max} = P.\tan(\text{acos}(\varphi)) = 954.5 * \tan(\text{acos}(0.95)) = 313.7\ MVar$$

The maximum value of the SVC is set to 320 MVar but the actual value can be lower if reactive power is already taken into account by the bus generator. The model used in SIMPOW is a Symmetrical SVC with proportional-integral regulator. Its block diagram is shown in Figure 73. The values of the parameters of the SVC are shown in Table 15.

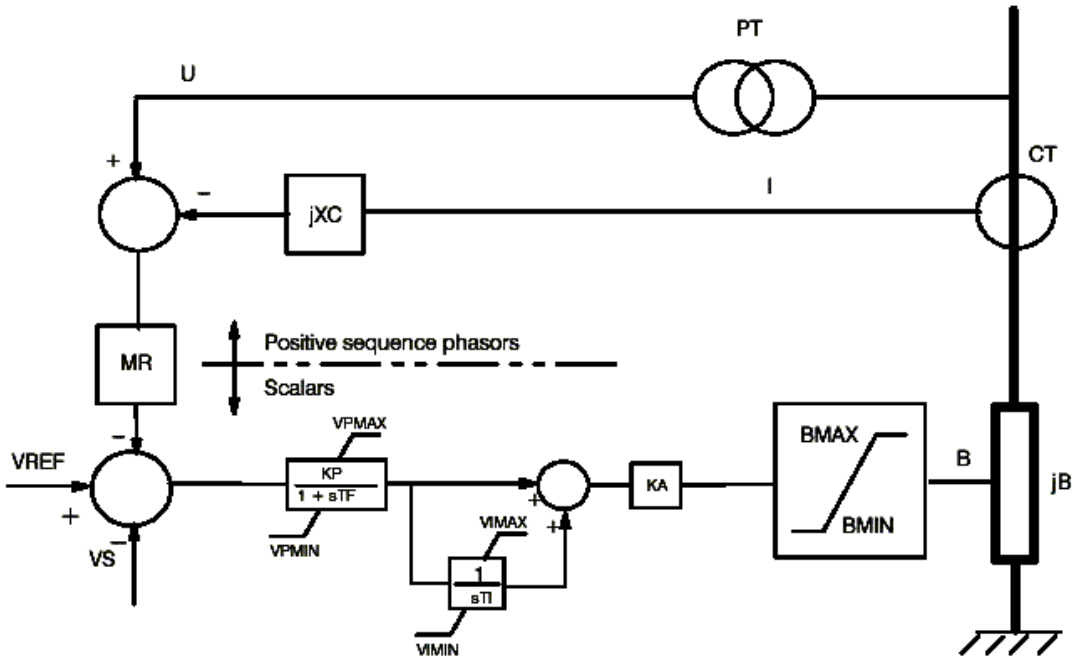


Figure 73 Symmetrical SVC with proportional-integral regulator

Table 15 SVC parameters

Parameter	Value
Proportional gain (p.u.)	15
Filter time constant (s)	0,02
Maximum value of VP	2
Minimum value of VP	-2
Adaptation gain (p.u.)	30
Maximum value of VI	0,1
Minimum value of VI	0
Maximum reactive power absorbed (Mvar)	320
Minimum reactive power absorbed (Mvar)	-320

5.5 HVDC CONFIGURATION

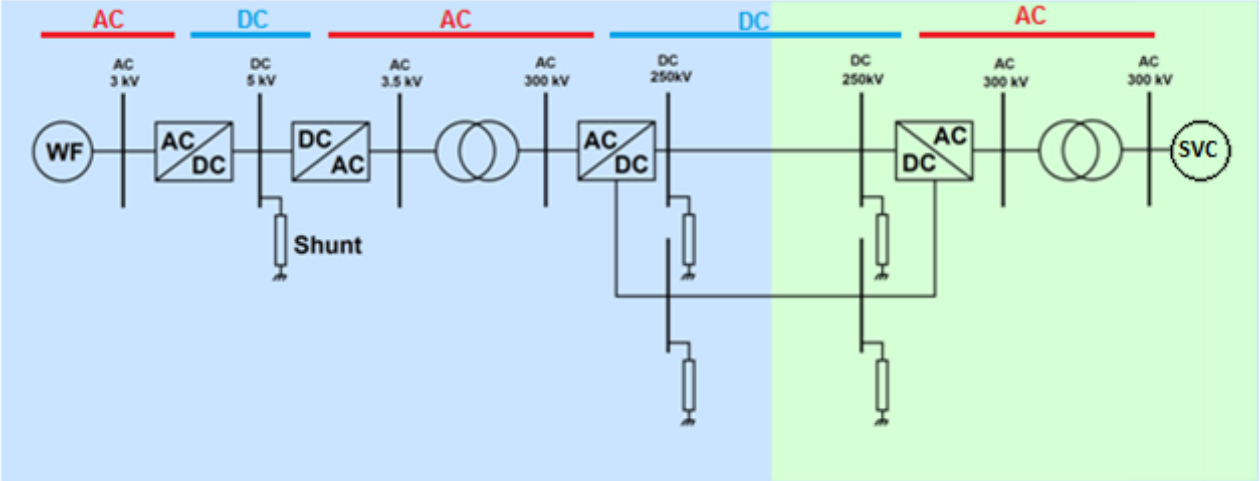


Figure 74 HVDC configuration

HVDC is used for relatively long transmission distances compared to HVAC since losses and total cost become more interesting past a certain distance, based on total capacity. Since VSC-HVDC is a growing field, it may be used for such high power applications for future projects. The choice has been made to use HVDC Light from ABB. The distance of the wind farm from the shore is considered here to be 100 km which is twice the distance considered for the HVAC case. The wind farm capacity is 1060 MVA, with a production of 1000 MW. The configuration with FPCWT and HVDC Light is shown in Figure 74.

Exactly one production source acting as a swing bus must be given in each AC network, as the voltage and the phase angle are used as calculation start values (45). In the HVDC configuration, three AC networks are connected through two DC systems. Thus, it requires three swing busses: the wind farm generator, bus 3300 which is located onshore and a new swing bus.

This new swing bus has to be created in the intermediate AC network where the first transformer operates. Even if in reality such a swing bus does not exist, it has to be created to perform the simulations. It was thus added to the 3.5 kV node via an AC line. It has to be noted that a particular specification needs to be entered for the line linking this swing bus in order to have the system working. The connection specification in the datagroup “LINES” is the parameter NCON. The default value (connected) is NCON=0. Default parameters don’t need to be written and are taken care automatically by the software. However, the parameter NCON=0 has to be explicitly written in the code or there won’t be any convergence. Another solution is to call the parameter ICPV in datagroup “CONTROL DATA”, and to set it to 4.

Figure 75 presents the HVDC Light module from ABB, available in SIMPOW. It consists of four modules: a converter transformer model, a PWM converter model, shunt DC capacitors and DC cables. Each PWM converter consists of an AC filter, a series reactor and a converter. The first PWM converter is the one on the wind farm side and it control strategy is: active power control and reactive power control. The second PWM converter located on the grid side has the following control strategy: DC voltage control and AC voltage control. Converter data is found in Table 17.

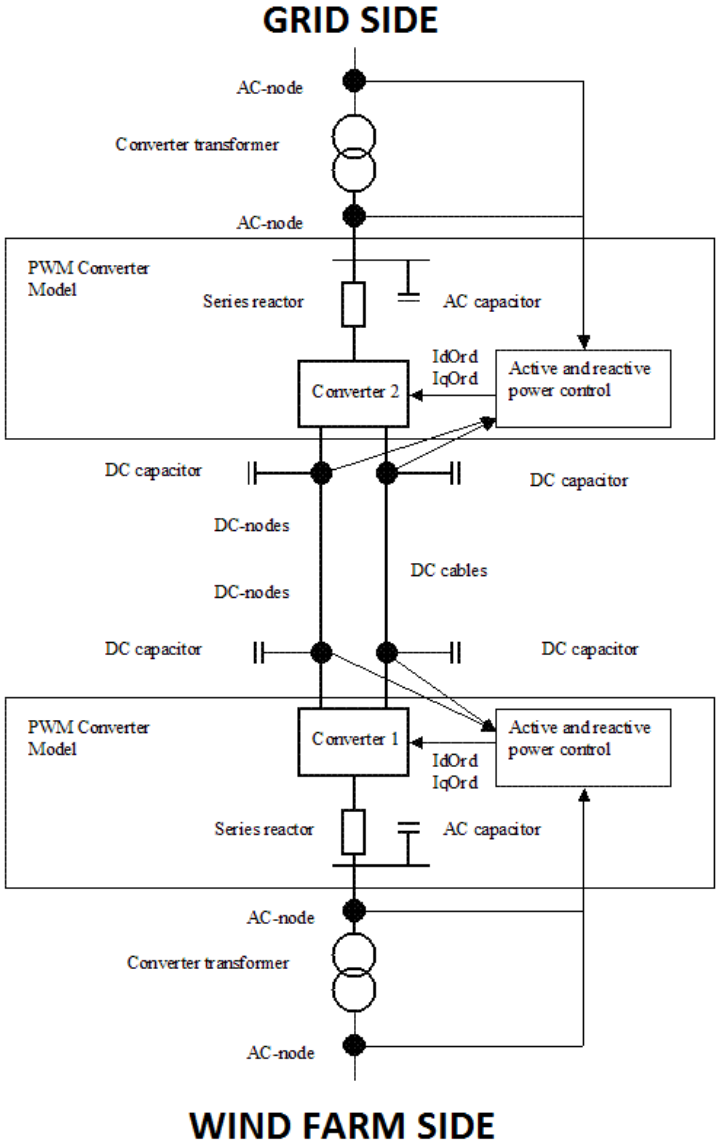


Figure 75 ABB HVDC Light Open Model Version 1.1.6

The line is modelled by a simple DC cable with resistance and inductance. ABB offers three modules depending on the base voltage: 80 kV, 150 kV and 300 kV. Thus, the 300 kV cable bipole in moderate climate is used. The climate influences the amount of power that can be transferred since the soil temperature and thermal resistivity decrease the efficiency. Table 16 shows the cable ratings from ABB (50).

The resistance R of the cable is calculated with the formula $R = \frac{\rho.L}{S}$ where ρ is copper resistivity, L the cable length and S the cross-section area. A 1600 mm² conductor area is chosen.

R= 0.0105 [Ω/km] X=0 [Ω/km] L=100 [km]

The DC cable capacitance is merged with the DC capacitors (45). The size of the DC capacitors is obtained with the sum of all the DC capacitances divided by four for symmetrical reasons. It can also be chosen according to the DC time constant.

A reasonable value for the time constant is 15 ms (45). The formula below links the time constant T with the DC capacitance C, the nominal DC voltage U_{DC} and the nominal DC power P_{DC}.

$$T = 4 * \frac{1}{2} * \frac{C * U_{DC}^2}{P_{DC}} \qquad \text{and thus} \qquad C = \frac{2 * T * P_{DC}}{4 * U_{DC}^2} = 1.2 \times 10^{-4}\ F$$

The active power reference P_{REF} has to be chosen for the first PWM converter. The no-load losses of the converters of the FPCWT are given by the coefficient 0.02 (Table 12 – FPCWT Data). Thus, for a 1060 MVA aggregated wind turbine, the losses are:

$$P_L = 0.02 * 1060 * 2 \text{ (two converters)} \qquad \text{and thus} \qquad P_L = 42.4\ MW$$

As a result, the output power of the FPCWT is:

$$P = 1000 - 42.4 = 957.6\ MW$$

This sets the active power reference in p.u. of the converter base to:

$$P_{REF} = \frac{957.6}{1060} = 0.903396$$

Table 16 HVDC Light cable ratings

Area	Ampacity		150 kV cable bipole				300 kV cable bipole			
Con-ductor	Close laying	Spaced laying	Close laying	Spaced laying	Weight per cable	Outer cable diam.	Close laying	Spaced laying	Weight per cable	Outer cable diam.
mm²	A	A	MW	MW	kg/m	mm	MW	MW	kg/m	mm
1200	1458	1791	437	537	29	100	875	1 075	40	126
1400	1594	1962	478	589	32	103	956	1 177	43	130
1600	1720	2123	516	637	35	107	1 032	1 274	47	133
1800	1830	2265	549	680	38	110	1 098	1 359	50	137
2000	1953	2407	586	722	41	113	1 172	1 444	53	140
2200	2062	2540	619	762	45	118	1 237	1 524	58	145

Table 17 PWM converters data

Parameters	PWM 1	PWM 2
Rated power (MVA)	1060	1060
Rated voltage (kV)	300	300
AC filter (S)	1,50E-03	1,50E-03
Series reactance (p.u.)	0,15	0,15
Nominal total losses (p.u.)	0,0165	0,0165
Part of the losses that are no-load (p.u.)	0,3	0,3
First control	Active power control	DC voltage control
Second control	Reactive power control	AC voltage control
AC voltage reference (p.u.)	1	1
Reactive power reference (p.u.)	0	0
Active power reference (p.u.)	0,903396	-

6 LOAD FLOW

6.1 INITIAL POWER FLOW

Table 18 Initial power flow

BUS	U (p.u.)	U (kV)	FI(u) (°)	Pgen (MW)	Qgen (MVar)
3000	1	420	30,1386	5300	1276,32
3100	0,97	407,4	34,4729	1500	1323,91
3115	1	420	60,2281	3570	446,937
3200	0,964952	405,28	4,28289	-500	-100
3244	0,99984	299,952	22,2758		
3245	1	420	22,367	780	987,927
3249	1	420	59,3385	4750	901,069
3300	1	420	0	4902,28	2593,95
3359	1	420	6,41252	3500	2419,6
3360	0,99455	134,264	6,04957		
3701	1,00747	302,242	60,6685		
5100	1	300	-0,897533	1480	1408,97
5101	0,989859	415,741	0,255727		
5102	1,00002	420,01	0,760339		
5103	0,998059	419,185	1,56563		
5300	1	300	12,5044	2275	14,9587
5301	1,00063	420,265	7,28899		
5400	1,007	302,1	0,167178	1588	106,812
5401	0,996324	418,456	-2,0789		
5402	1,006	422,519	-0,0659512		
5500	1,004	301,2	-1,80119	828	-523,44
5501	1,00445	421,87	-1,47001		
5600	1,01	303	-9,15986	2378	750,11
5601	0,991126	416,273	-8,8728		
5602	0,956161	401,588	-11,7764		
5603	0,922383	276,715	-13,0629		
6000	1,005	301,5	-0,729344	1129	-129,353
6001	0,999483	419,783	-1,22774		
6100	1	300	-4,58435	2346	1002,18
6500	1	300	22,0527	1511	565,949
6700	1,02	306	63,2992	2771	634,885
6701	1,00678	422,847	63,102		
7000	1	420	17,7937	5300	1005,15
7100	1	420	26,2615	1310	666,08
8500	1,02	428,4	-0,296812	1000	909,614

Table 18 shows the values of voltage in both per-unit and kV, the phase angle and active and reactive powers production at each node. This is the power flow of the initial file before any addition of a wind farm and case faults.

6.2 CONNECTING THE WIND FARM

As the wind farm model has been described in the previous section, it is important to know where to place it. As Norway is the most described area of the grid model, the wind farm will be connected on the shore of this country. The possible connection busses are 5600, 5603, 6000, 6100, 5500, 6500 and 6700. However, connecting 1000 MW to the grid implies the neighbour busses and connections to be able to withstand this amount of power. Moreover, the bus where it is connected must be strong enough to resist faults that could occur.

Every bus is able to integrate the wind farm in this grid model since it is a simplified one. Thus, two places are chosen according to their degree of relevance and their place in the grid. Busses 5600 and 6000 are located respectively in Sørlandet and Vestlandet, the most populated areas in Norway. This is where the power will be needed, and it is also the places in the grid model where most of the connections and details are. Busses 5600 and 6000 are shown in Figure 76.

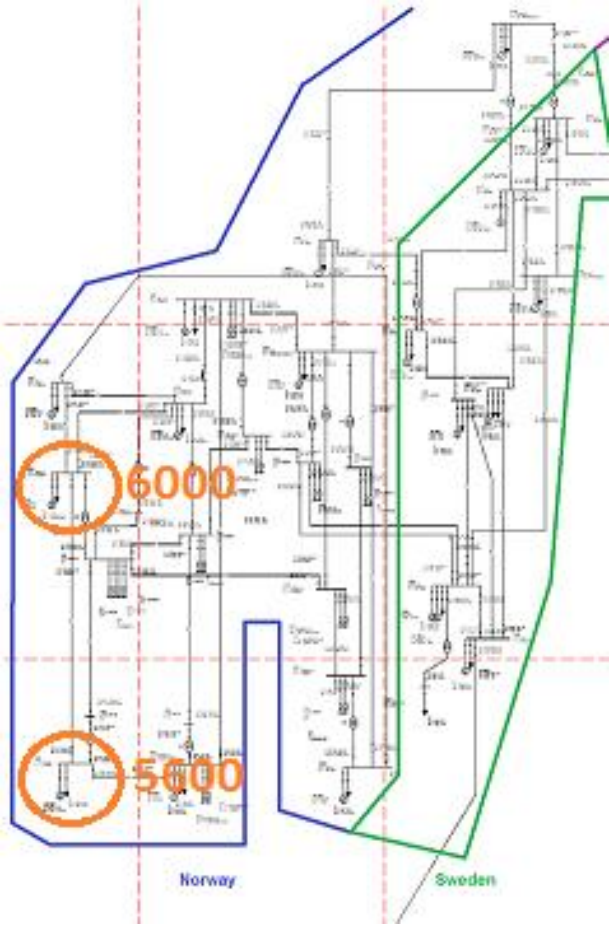


Figure 76 Location of busses 5600 and 6000

6.3 POWER FLOW ON BUS 5600

Figure 77 shows the power flow without a wind farm being connected to Bus 5600. Busses of a 300 kV rated voltage are drawn in green and busses of a 420 kV rated voltage are drawn in blue. The name of the bus is given in the first row, followed by the per-unit value of the voltage and the phase angle in degrees. Closed to the lines, the active and reactive powers are given respectively in MW and MVar. A positive sign stands for production and a negative sign for exportation. Thus, on one line two power pair values appear and are opposite to each other, regardless of the transmission losses, depending on which side they are taken into account.

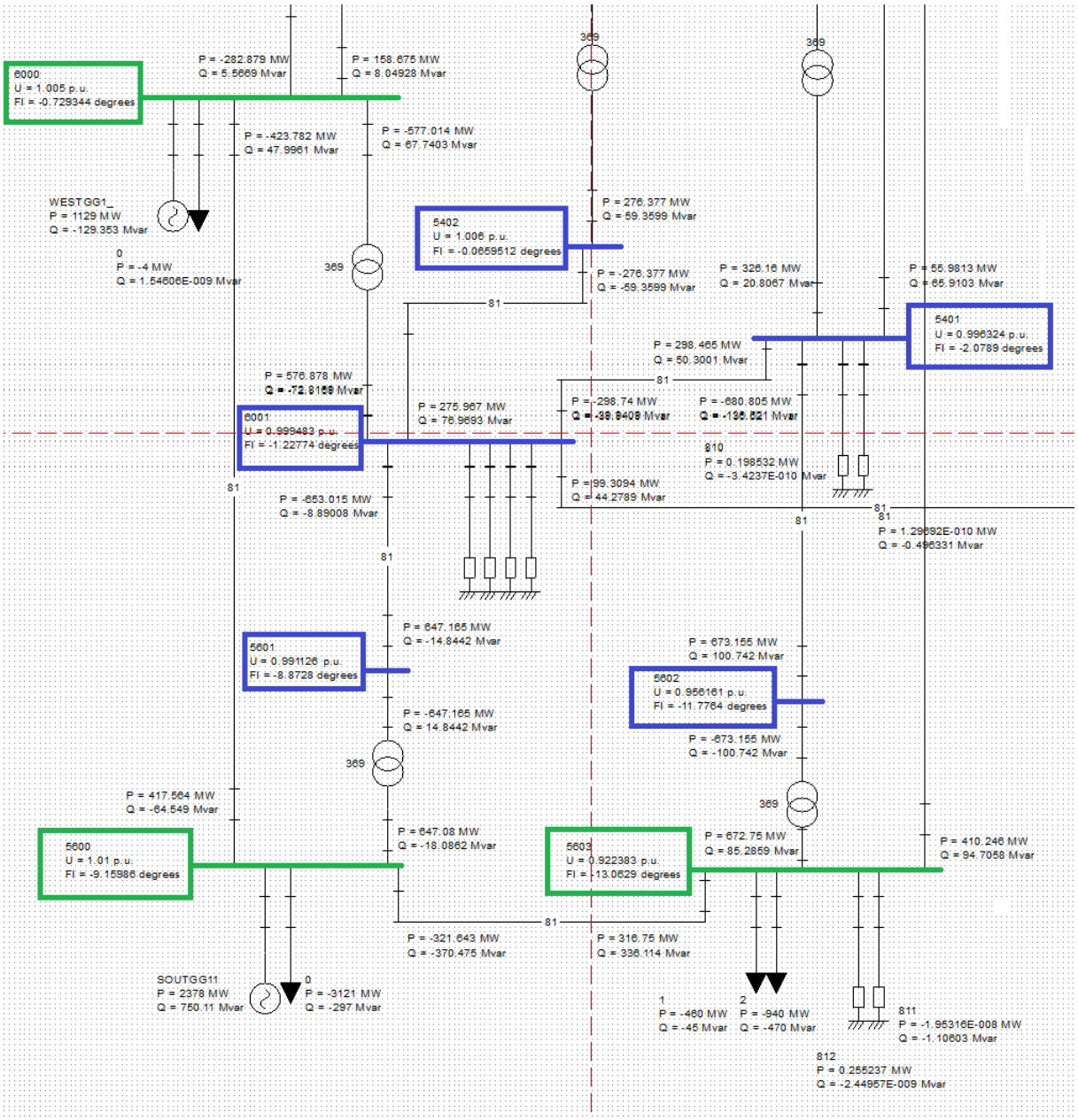


Figure 77 Power flow around bus 5600 without a wind farm connected

The 1000 MW wind farm is now connected to bus 5600. The HVAC configuration is depicted on Figure 78 with two AC lines leaving bus 5600 for bus 1003.

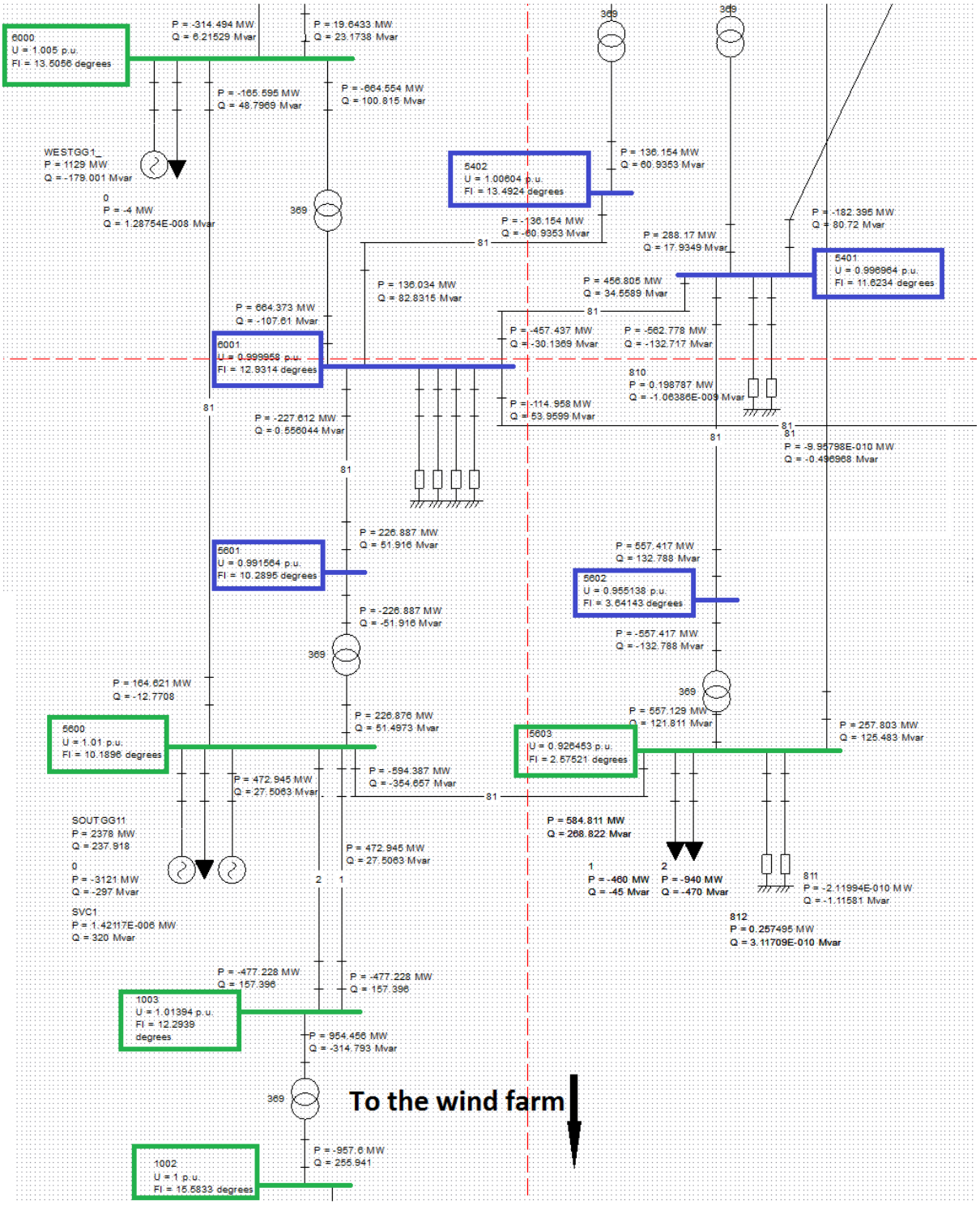


Figure 78 Power flow around bus 5600 with a wind farm connected in HVAC

The wind farm is exporting 954 MW and importing 322 MVar. However, seen from the grid side, bus 5600 is importing 946 MW and 47 MVar from the wind farm. Thus, the rating of the SVC is correct. There is thus roughly 8.58 MW lost in the HVAC connection (0.9% loss) and as the wind farm generator produces 1000 MW, 45 MW are lost in total in the converters, the transformer and the lines. It represents 4.54% loss in active power. According to previous chapters, losses correspond to what we should obtain.

Figure 79 shows the connection of the 1000 MW on bus 5600 with HVDC Light. The wind farm is exporting 941 MW, which is lower than the HVAC case since the first PWM converter consumes energy. Bus 5600 receives 920 MW from the wind farm and exports 357 Mvar to the wind farm. The total active power losses represent 7.97% of the generation. According to Table 5, losses should be in the range of 4-6% but the power exchange in the case of a large wind farm is high, and converter stations suffer from too many losses.

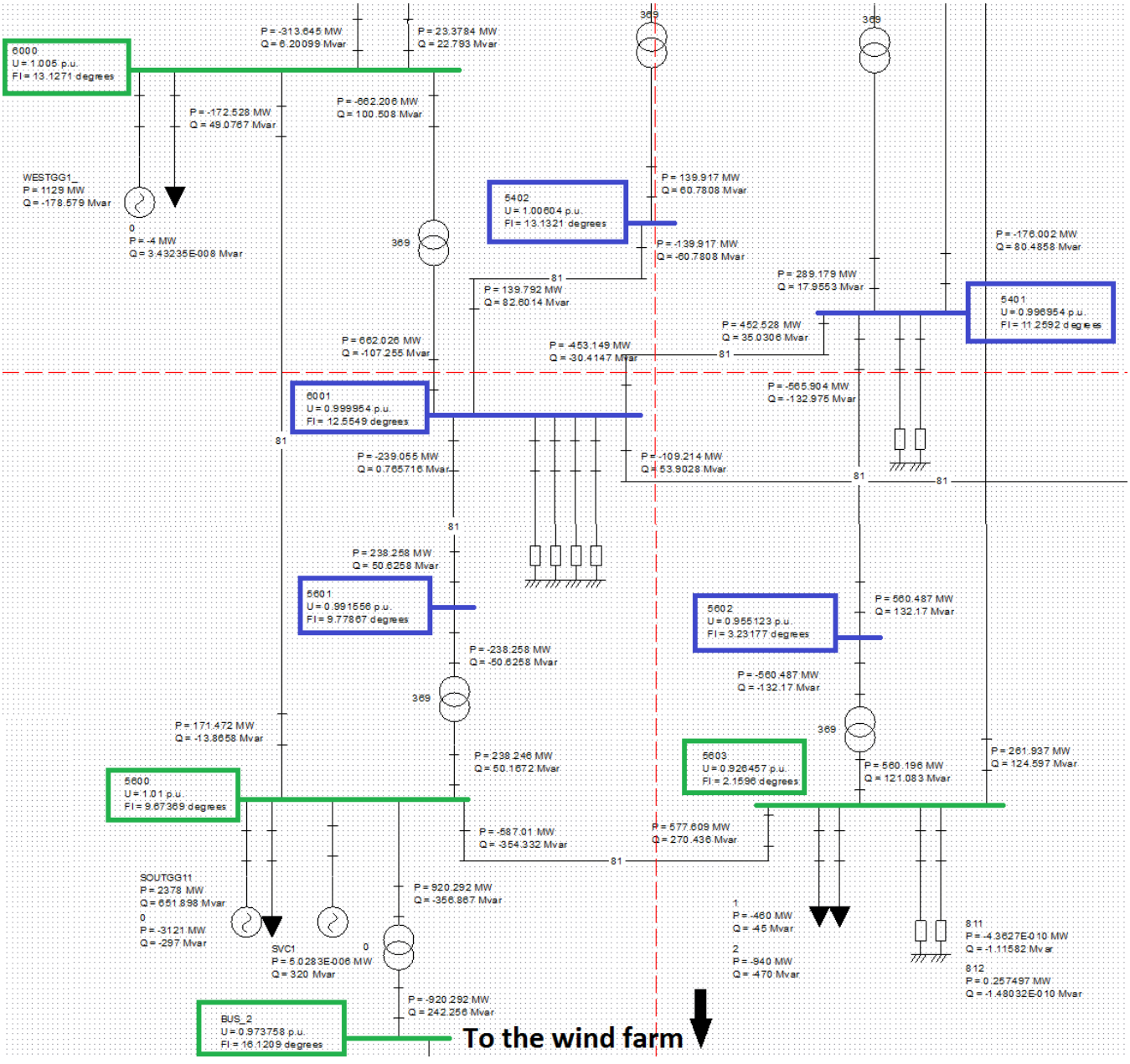


Figure 79 Power flow around bus 5600 with a wind farm connected in HVDC

Table 19 is the summary of the power flow around the connection point (bus 5600) between the wind farm and the grid. A negative sign symbolizes exportation and a positive sign symbolizes importation. The areas are shown on Figure 80. First of all, the addition of a 1000 MW to the grid has almost no effect on the total importation and exportation for each area. The values are roughly equal when no wind farm is connected or when it is connected in HVAC or HVDC. However, the exchange between the areas is completely changed since the power has to flow onto the entire grid to reach the swing bus that will perform the balance of active power. Other generators attached to grid busses are generating the same amount of active power.

Area 56, where the wind farm is connected, imports power from areas 60, 54 and 55. Since the wind farm produces approximately 1000 MW, the amount of power it has to import by has been reduced by the same amount. Most of the reduction was done by a lower exchange with area 60 with HVAC and HVDC connexions. Thus, as area 60 was exporting most of its power to area 56 and as it has to balance, area 60 now exports to all of its neighbour areas. The HVAC- and HVDC-connected cases show the same tendency. Values are poorly changed since the production from the HVDC-connected wind farm is lower by 26 MW compared to the HVAC-connected wind farm.

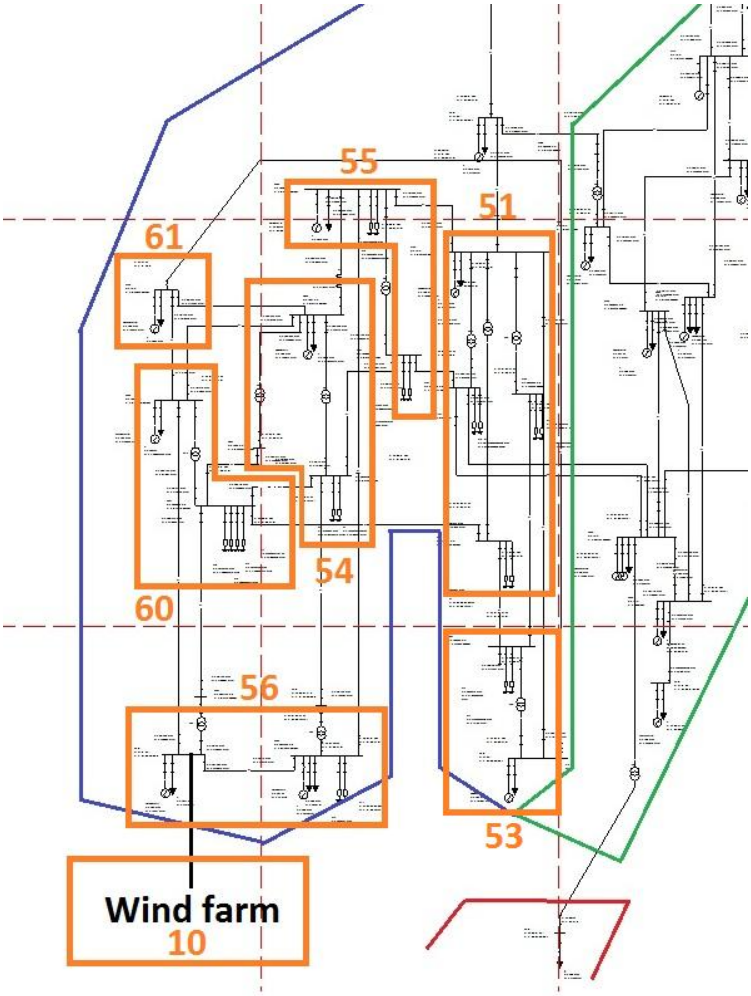


Figure 80 Areas in the Norwegian grid model

Table 19 Inter-area power exchange, connection on bus 5600

Connection on bus 5600 - No Wind Farm			
AREA	FROM AREA	P (MW)	Q (Mvar)
54	60	-136.837	-9.48111
	61	-418.313	-4.66958
	55	-257.468	58.4529
	56	-680.805	-136.521
	TOTAL	-1493.42	-92.2185
56	54	673.155	100.742
	55	410.246	94.7058
	60	1064.73	-79.3932
	TOTAL	2148.13	116.054
60	51	99.3094	44.2789
	54	135.902	45.0777
	56	-1076.80	39.1061
	61	-282.879	5.56690
	TOTAL	-1124.46	134.030

Connection on bus 5600 - HVAC Connection				Connection on bus 5600 - HVDC Connection			
AREA	FROM AREA	P (MW)	Q (Mvar)	AREA	FROM AREA	P (MW)	Q (Mvar)
54	60	301.000	-39.4997	54	60	289.224	-38.5073
	61	-386.607	-5.29944		61	-387.457	-5.27993
	55	-845.137	82.4899		55	-829.382	82.1838
	56	-562.778	-132.717		56	-565.904	-132.975
	TOTAL	-1493.52	-95.0262		TOTAL	-1493.52	-94.5782
56	10	945.891	55.0126	56	10	920.292	-356.867
	54	557.417	132.788		54	560.487	132.170
	55	257.803	125.483		55	261.937	124.597
	60	391.508	39.1452		60	409.730	36.7600
	TOTAL	2152.62	352.429		TOTAL	2152.45	-63.3403
60	51	-114.958	53.9599	60	51	-109.214	53.9028
	54	-301.759	75.8684		54	-289.979	74.9798
	56	-393.207	49.3530		56	-411.583	49.8424
	61	-314.494	6.21529		61	-313.645	6.20099
	TOTAL	-1124.42	185.397		TOTAL	-1124.42	184.926

6.4 POWER FLOW ON BUS 6000

Figure 81 shows the power flow without a wind farm being connected to Bus 6000. The colour code is unchanged.

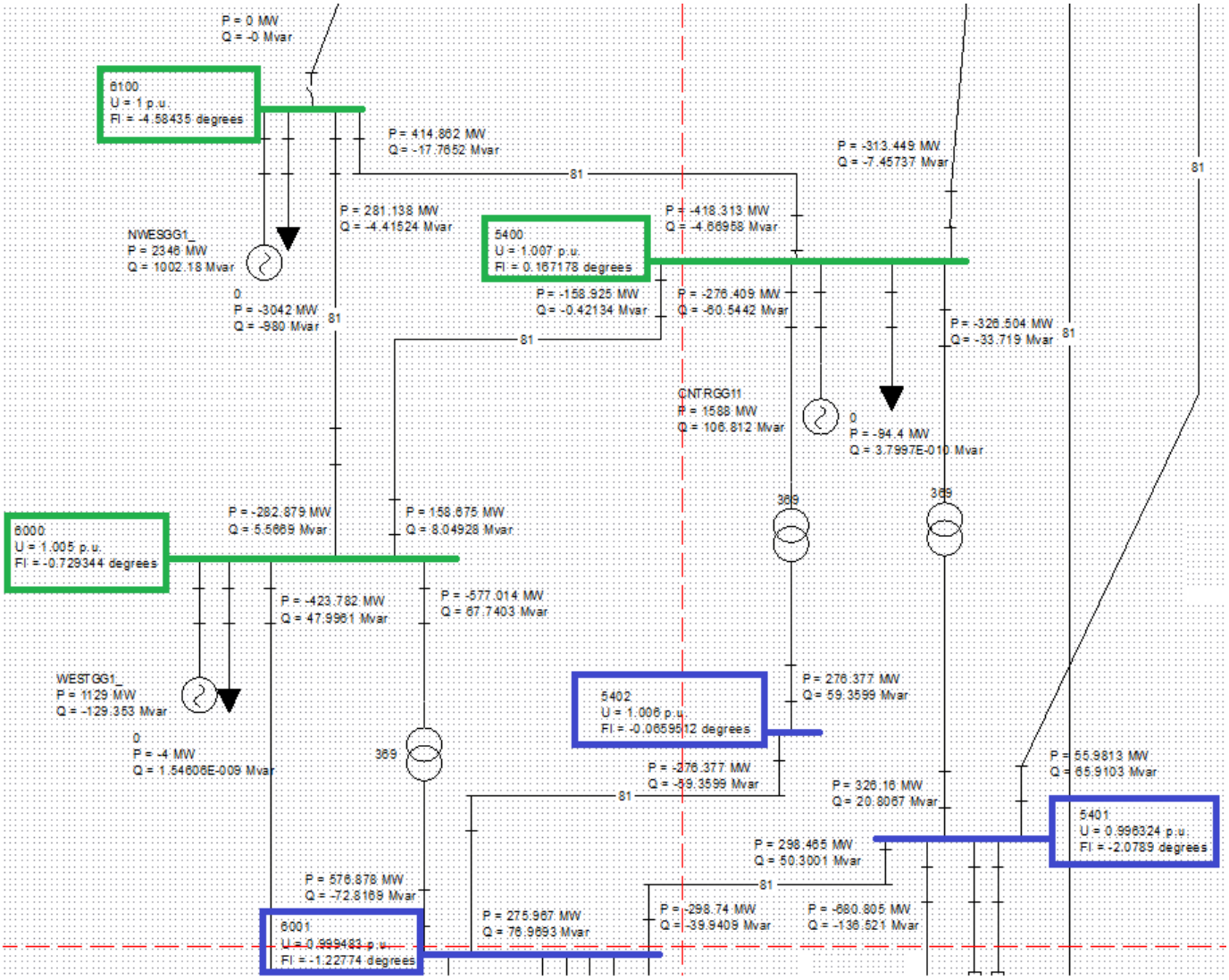


Figure 81 Power flow around bus 6000 without a wind farm connected

The 1000 MW wind farm is now connected to bus 5600. The HVAC configuration is depicted on Figure 82 with two AC lines leaving bus 6000 for bus 1003. Figure 83 shows the connection of the 1000 MW on bus 6000 with HVDC Light. The power output of each wind farm is the same compared to the connection on bus 5600. Voltages are almost unchanged by the addition of a wind farm.

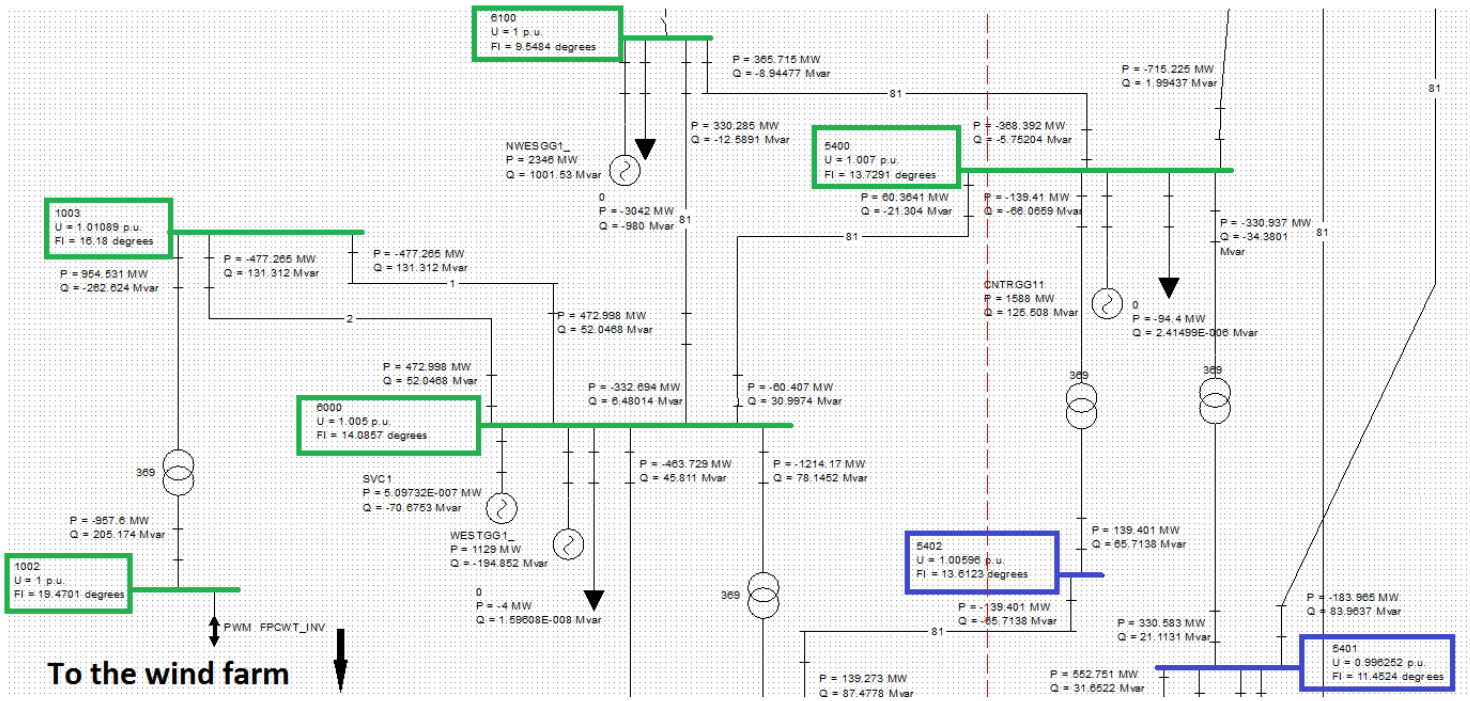


Figure 82 Power flow around bus 6000 with a wind farm connected in HVAC

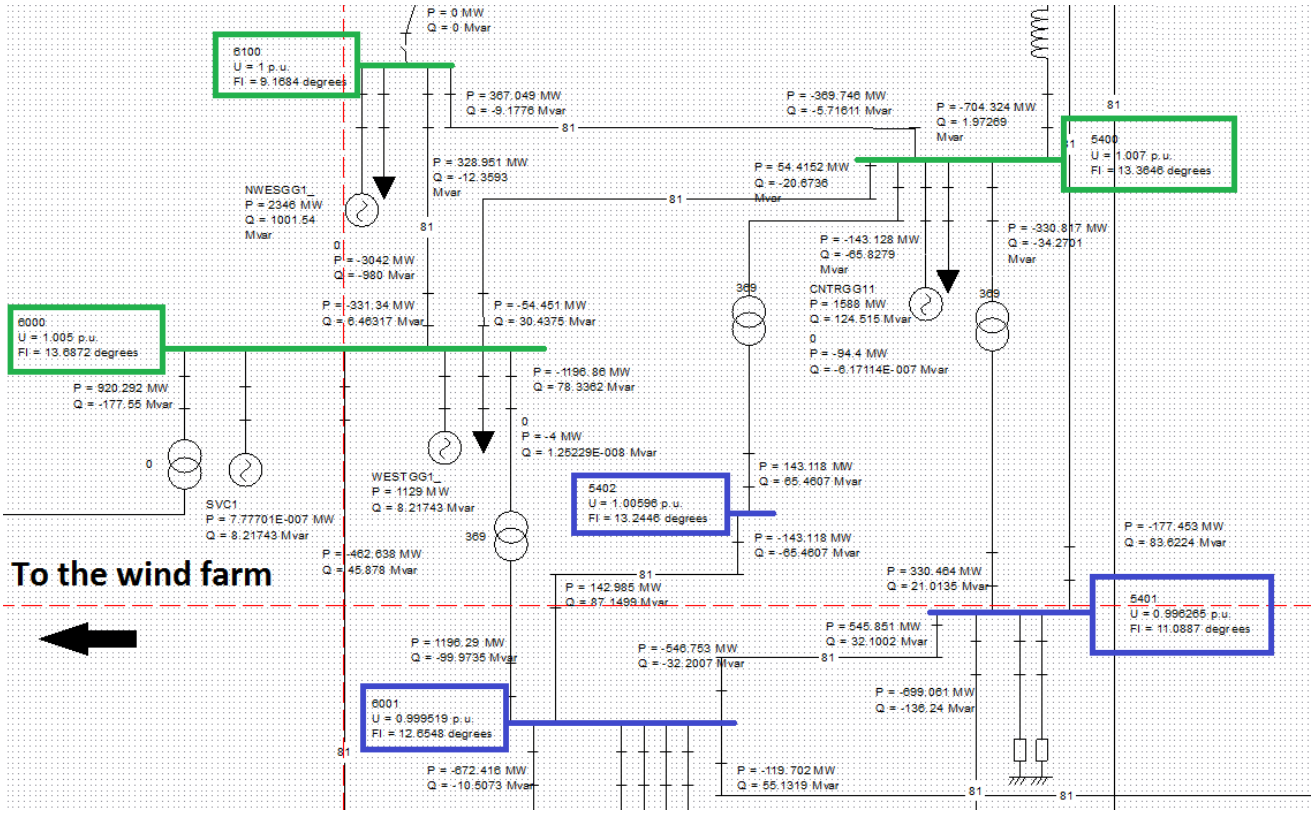


Figure 83 Power flow around bus 6000 with a wind farm connected in HVDC

Table 20 Inter-area power exchange, connection on bus 6000

Connection on bus 6000 - No Wind Farm			
AREA	FROM AREA	P (MW)	Q (Mvar)
54	60	-136.837	-9.48111
	61	-418.313	-4.66958
	55	-257.468	58.4529
	56	-680.805	-136.521
	TOTAL	-1493.42	-92.2185
56	54	673.155	100.742
	55	410.246	94.7058
	60	1064.73	-79.3932
	TOTAL	2148.13	116.054
60	51	99.3094	44.2789
	54	135.902	45.0777
	56	-1076.80	39.1061
	61	-282.879	5.56690
	TOTAL	-1124.46	134.030
61	54	414.862	-17.7652
	60	281.138	-4.41524
	TOTAL	696.000	-22.1804

Connection on bus 6000 - HVAC Connection				Connection on bus 6000 - HVDC Connection			
AREA	FROM AREA	P (MW)	Q (Mvar)	AREA	FROM AREA	P (MW)	Q (Mvar)
54	60	473.811	-55.3734	54	60	457.148	-54.0342
	61	-368.384	-5.75226		61	-369.746	-5.71611
	55	-899.291	85.9601		55	-881.776	85.5951
	56	-699.571	-136.233		56	-699.061	-136.240
	TOTAL	-1493.44	-111.398		TOTAL	-1493.44	-110.395
56	54	691.523	94.2386	56	54	691.023	94.4217
	55	334.328	114.141		55	336.404	113.632
	60	1123.05	-93.1792		60	1121.45	-92.7635
	TOTAL	2148.90	115.201		TOTAL	2148.88	115.290
60	10	946.145	98.3516	60	10	920.292	-177.550
	51	-125.842	55.1923		51	-119.702	55.1319
	54	-474.908	86.3466		54	-458.220	85.3867
	56	-1136.70	35.2847		56	-1135.05	35.3707
	61	-332.701	6.48024		61	-331.340	6.46318
	TOTAL	-1124.01	281.655		TOTAL	-1124.02	4.80279
61	54	365.707	-8.94341	61	54	367.049	-9.17760
	60	330.293	-12.5905		60	328.951	-12.3593
	TOTAL	696.000	-21.5339		TOTAL	696.000	-21.5368

Table 20 describes the inter-area power exchange on the surrounding busses of bus 6000. When the wind farm is not connected to the grid, area 60 imports active power from area 51 and 54 but exports five times more to area 56. However, when a wind farm is connected in HVAC or HVDC to bus 6000, area 60 only exports power since the wind farm provides 946 MW to this area. As a result, area 51 and 54 are not giving power to area 60 and thus import power from it. As a result, area 54 increases it exportation to area 55 by 650 MW. The power flow is reversed as in the wind farm connexion to bus 5600, since it tends to reach the swing bus, located in Sweden.

7 DYNAMIC SIMULATIONS

Simulations were made with DYNPOW, which is the tool available in SIMPOW for dynamic simulations of electric power systems. New files have to be done in order to complete initial conditions given by the load flow achieved with OPTPOW.

The aim of these dynamic simulations is to determine the behaviour of the grid and the wind farm when a fault occurs. HVAC and HVDC transmissions have different configurations and thus may have different performance when a problem occurs on the grid. On the contrary, as the wind farm produces a high amount of power, a brutal disconnection of the wind farm from the grid will have a bad influence on the grid.

7.1 THREE-PHASE FAULT AND CRITICAL CLEARING TIME

The three-phase fault is used to explore transient stability in the system. This fault is applied either on a node or on a line. Figure 84 (51) is the schematic representation of a synchronous generator. It is the classical model where E' is the transient e.m.f., X_d' the transient reactance, X_T the transformer reactance, X_L the line reactance, X_S the equivalent reactance of the system and V_S the voltage of the system.

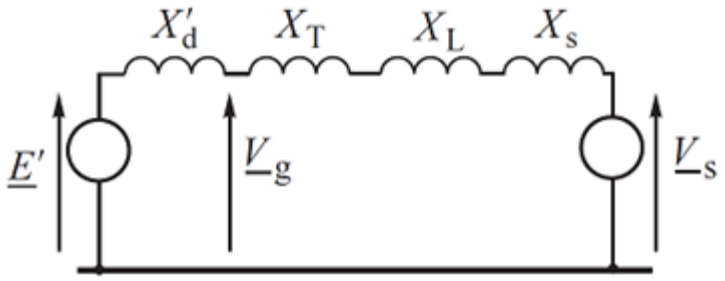


Figure 84 Classical model of a synchronous generator

During a fault, the system can be represented with a fault shunt Δx_F which value is zero in case of a three-phase fault. Figure 85 (51) shows this shunt reactance.

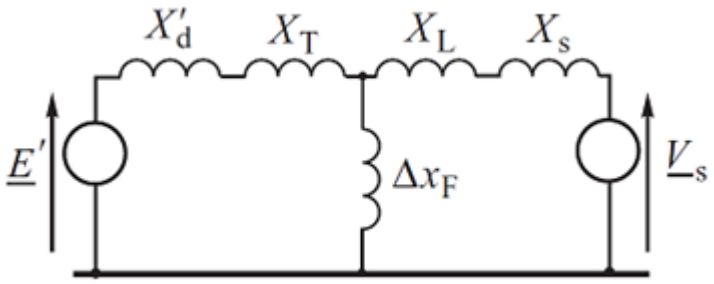


Figure 85 Equivalent circuit during the fault

With a shunt reactance equal to zero, the power transfer from the generator to the rest of the system is impossible. Thus, during the fault, the power drops from the prefault value to zero. It then remains to zero until the fault is cleared when the circuit-breakers are opened. This phenomenon is illustrated in Figure 86, which is the power-angle characteristic. P is the power and δ' is the transient power angle between E' and V_S. Figure 86-a is for a short clearing time and Figure 86-b for a long clearing time. The blue are is the acceleration area and the red area is the deceleration area.

Line 1-2 is when the fault occurs since the power goes down to zero. Before the fault is cleared, the rotor moves which is line 2-3. Then, when the fault is cleared, the rotor of the generator follows the power-angle curve on line 3-4-5. This jump being consequent, the rotor experiences a deceleration but the angle keeps increasing until both areas are equal. If the damping is not sufficient, the cycle starts again on point 1: this is the rotor swing. If the clearing time is too long, as in Figure 86-b, the areas can't be equal and it results in a loss of synchronism from the generator. This method is called the equal-area criterion. It is possible to find a limit from which the generator steps out of phase, and this limit is called the critical clearing time.

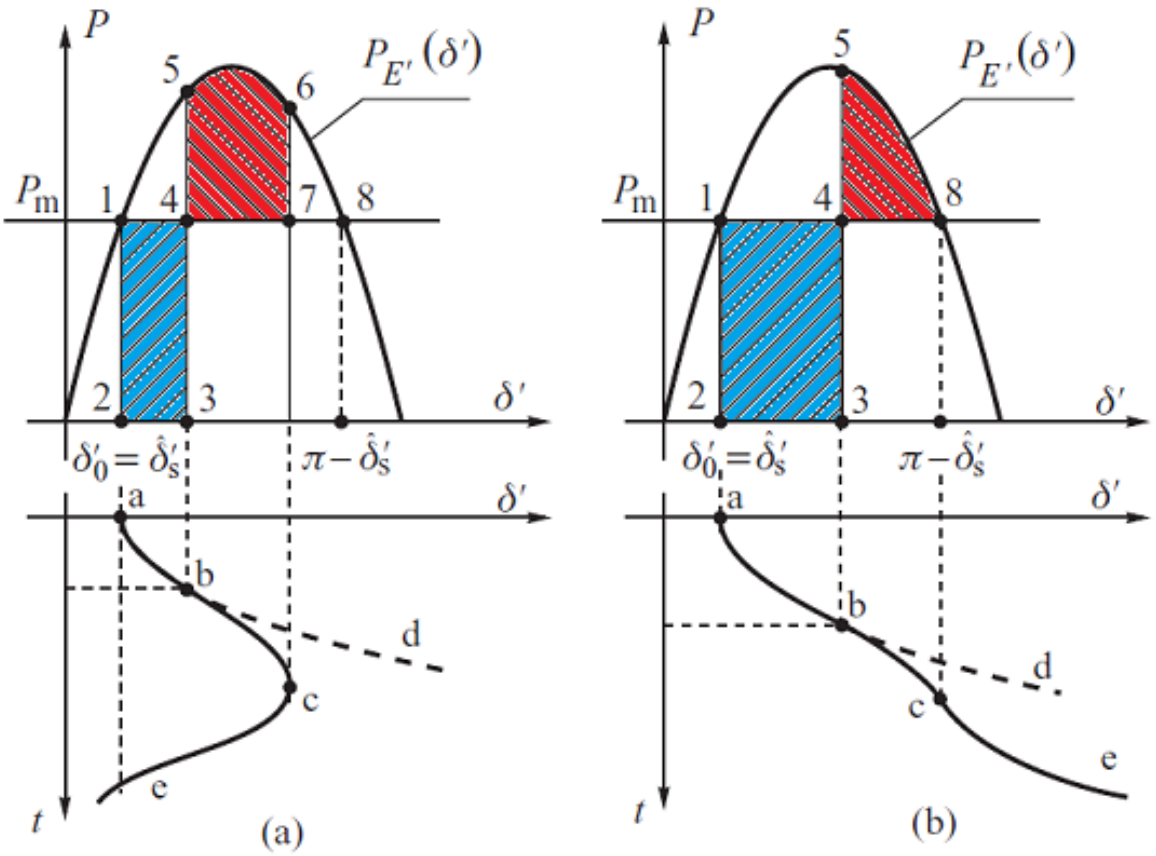


Figure 86 Power-angle characteristics

In order to find the critical clearing time of the system, a three-phase fault to ground is thus applied to the SIMPOW model. The name of the fault is 3PSG and it is applied at exactly t = 1 s. The critical clearing time is found to be 185 ms, which means that beyond that point, one of the generators will step out of phase and will not be able to recover from the fault.

7.2 CASE FAULTS

Six HVAC cases and two HVDC cases are studied. The aim of these simulations is to understand the dynamic behaviour of the constructed models. Cases are shown in Table 21. The duration of the simulations is 20 s.

Table 21 Case faults

Case number	Connexion type	Connexion point	Fault type	Fault duration (ms)
1	HVAC	5600	3PSG on connexion point	185
2	HVAC	5600	3PSG on connexion point	50
3	HVAC	5600	3PSG on connexion point	5
4	HVAC	6000	3PSG on connexion point	50
5	HVAC	5600	Stop production on 6100	∞
6	HVAC	5600	Line disconnection	50-∞
7	HVDC	5600	3PSG on connexion point	185
8	HVDC	5600	Stop production on 6100	∞

3PSG refers to the three-phase fault to ground which is applied directly on one bus. The fault that corresponds to the “stop production” is the disconnection of a generating unit that is between the connexion point and the swing bus. The “line disconnection” means that one of the two lines linking the wind farm to the grid is disconnected after a 50 ms fault is applied on the connection point. Thus, the disconnection is permanent. As the output of making a fault on bus 5600 and 6000 have the same behaviour, this is not looked at for the HVDC connexion.

Faults are coded with the two following data groups. The fault is written in “FAULTS” and then the instruction is run at specific times. The bolded sequences correspond to the parameters that are changed in the nine cases.

```
FAULTS
        F1 TYPE=3PSG NODE 5600
END

RUN INSTRUCTION
        AT 1.000  INST      CONNECT  FAULT  F1
        AT 1.050  INST  DISCONNECT  FAULT  F1
        AT 1.050  INST  DISCONNECT   LINE   1003   5600   NO=2
END
```

The following figures are the output of the nine cases.

7.3 CASE 1: HVAC - 3PSG ON 5600 FOR 185 ms

This case is a three-phase fault to ground made for a time corresponding to the critical clearing time of our system. Figure 87 is the voltage in p.u. on bus 1000, which is where the synchronous generator of the FPCWT is connected. During the fault, the voltage decreases almost linearly to 0.92 p.u. (-8%) and stops decreasing until the fault is cleared. When the fault is cleared, the voltage increases to 1.08 p.u. (+8%) to try to compensate for the loss that occurred. At t=1.4s, the voltage finally decreases to reach the initial value since the compensation is done. The voltage is stabilized quickly since the value of 1 p.u. is reached in a time of 1 second after the fault is cleared. There is no oscillation on the voltage.

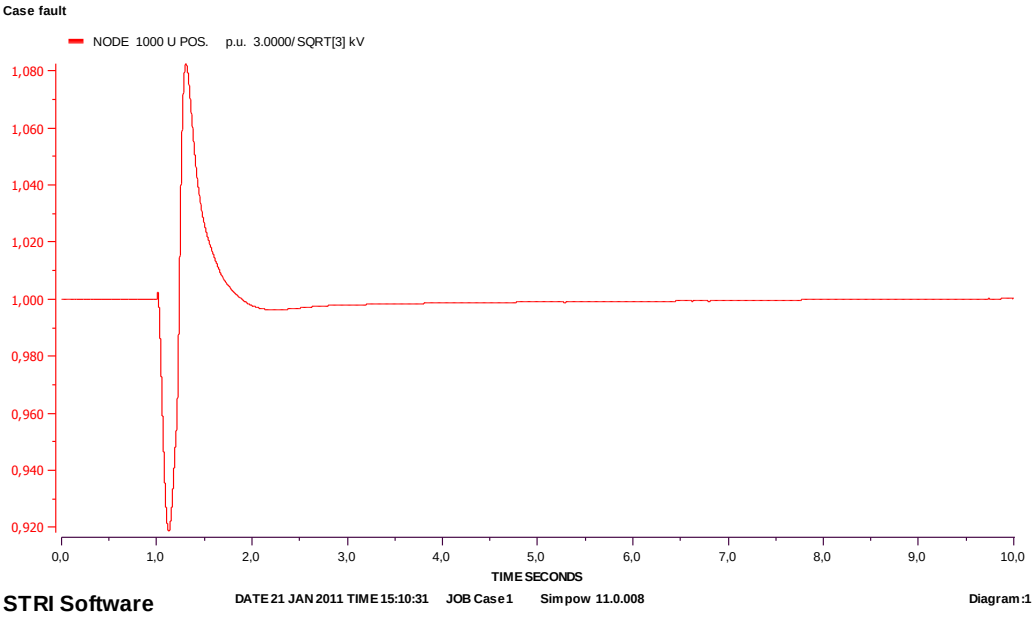


Figure 87 Case1: Voltage on bus 1000

Figure 88 is the voltage onshore (bus 5600) and offshore (bus 1003) in p.u. As the fault occurs on bus 5600, the bus voltage drops immediately to zero until the fault is cleared. The offshore voltage falls to 0.04 p.u. because of the contribution of the FPCWT and because of the losses in the lines. If the lines were perfect, the voltages would have been equal. However, the same behaviour for both voltages is observed after the fault is cleared. The voltage values jump to over 0.8 p.u. and then there is a stabilization that takes 2 s. At t=5s, there is small perturbation because the entire system is not yet stable.

This is shown in Figure 89 with the SVC reactive power. The production of reactive power drops to zero during the fault since the voltage is null. When the fault is cleared, the aim of the SVC is to stabilize the voltage to its previous value. The first oscillations until t=1.5s are the same than those of the voltage. As the time chosen for the fault is the critical clearing time, the system struggles to balance and the SVC has to make too many changes to try to match the reactive power absorption and production.

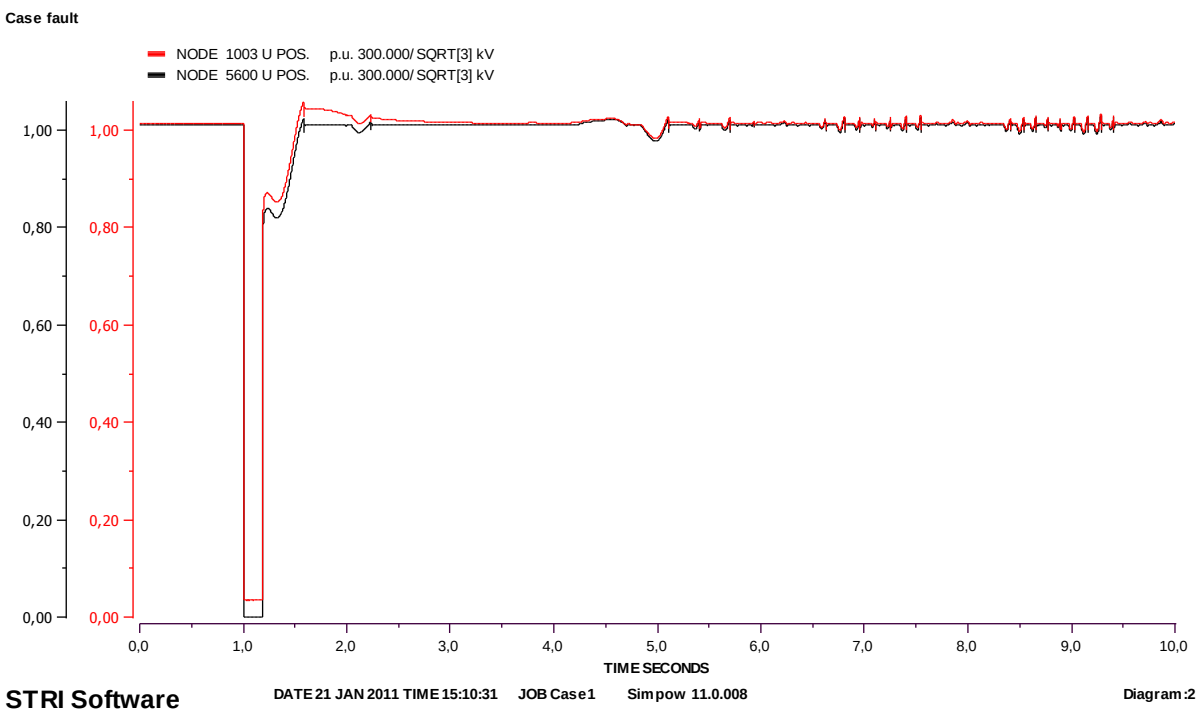


Figure 88 Case 1: Voltages on busses 1003 and 5600

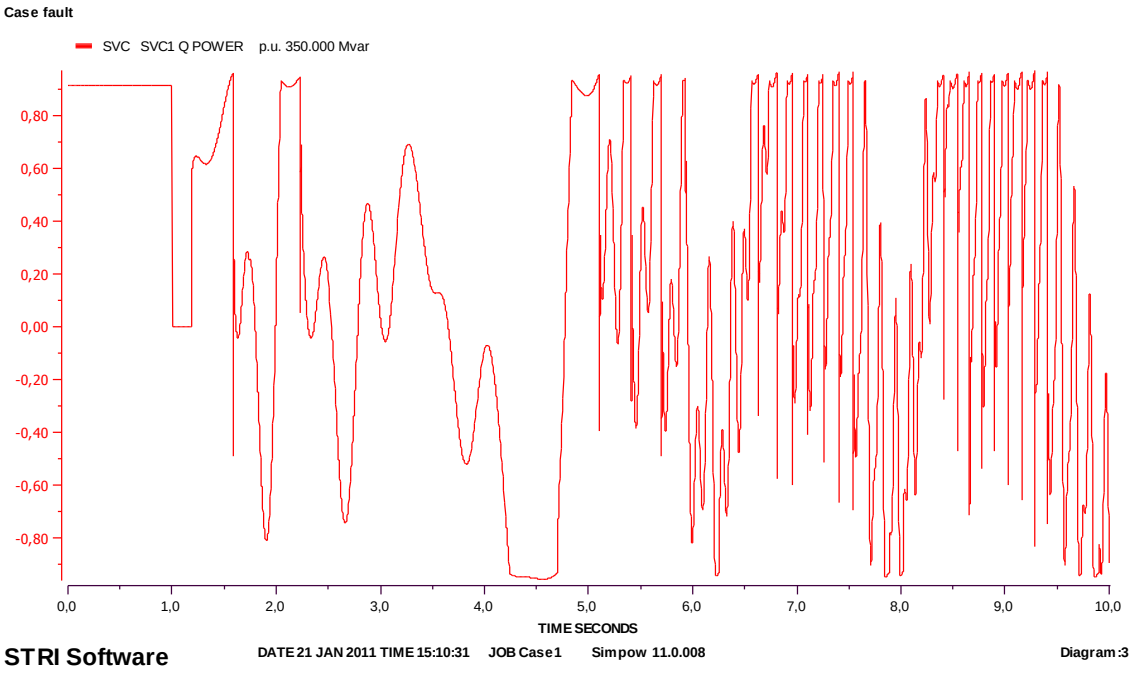


Figure 89 Case 1: Reactive power of the SVC

Figure 90 is the wind turbine mechanical power in p.u. The power is decreasing like the voltage on bus 1000 during the fault. After the fault is cleared, it keeps on decreasing until the voltage is stabilizing. In the FPCWT, there is a frequency converter at the generator terminal that reduces the output power to the grid until this frequency converter is safe from too high currents generated by the fault. The increase in voltage helps the decrease in current and thus, when the voltage is high enough and then decreases, the power can start increasing again.

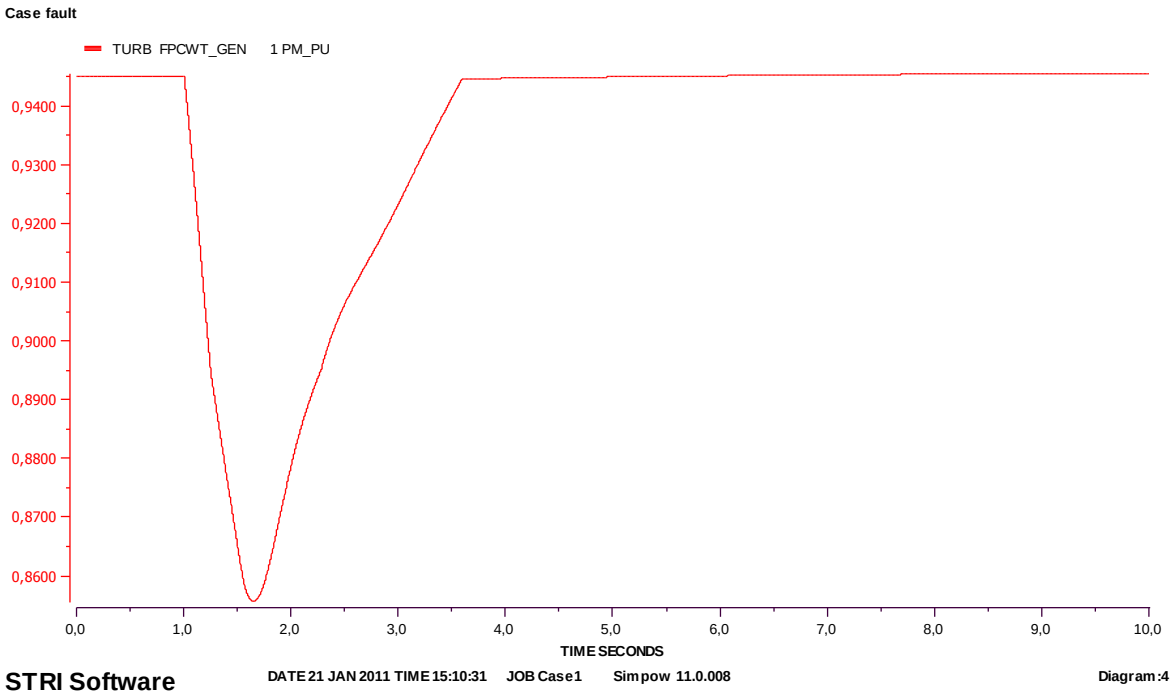


Figure 90 Case 1: Mechanical power of the FPCWT

Figure 91 is the speed of the wind turbine generator. The speed barely changes during the fault, because even if the power is lowered, it is due to the converters and not because the speed is changed. However, the increase of power passed t=1.60s is made by the increase of the speed. When the speed reaches the maximum value of 1.02 p.u., the power has reached its pre-fault value. Thus, the speed can start decreasing to match its own pre-fault value. The stability is long to operate because the speed control is not fast enough.

Figure 92 shows the power transfer from offshore to onshore by the two HVAC transmission lines. During the fault, the transfer is null since the fault is made on the bus to which it is connected. Then, the power transfer stabilizes after 1.5s like the voltage. The post-fault value of the power is 2% higher than the pre-fault one. The pre-fault value is only reached after 10 s.

The reactive power transfer is shown in Figure 93. The reactive power drops to zero during the fault and then increases to a value ten times higher than the pre-fault one. The maximum is reached at t=1.8s at a value of 450 MVar per cable which is huge. In Figure 89 where the SVC reactive power is shown, there is absorption of 290 Mvar at t=1.8s. Thus, the SVC tries to balance for the reactive power contribution from the FPCWT along with the contribution from the rest of the grid.

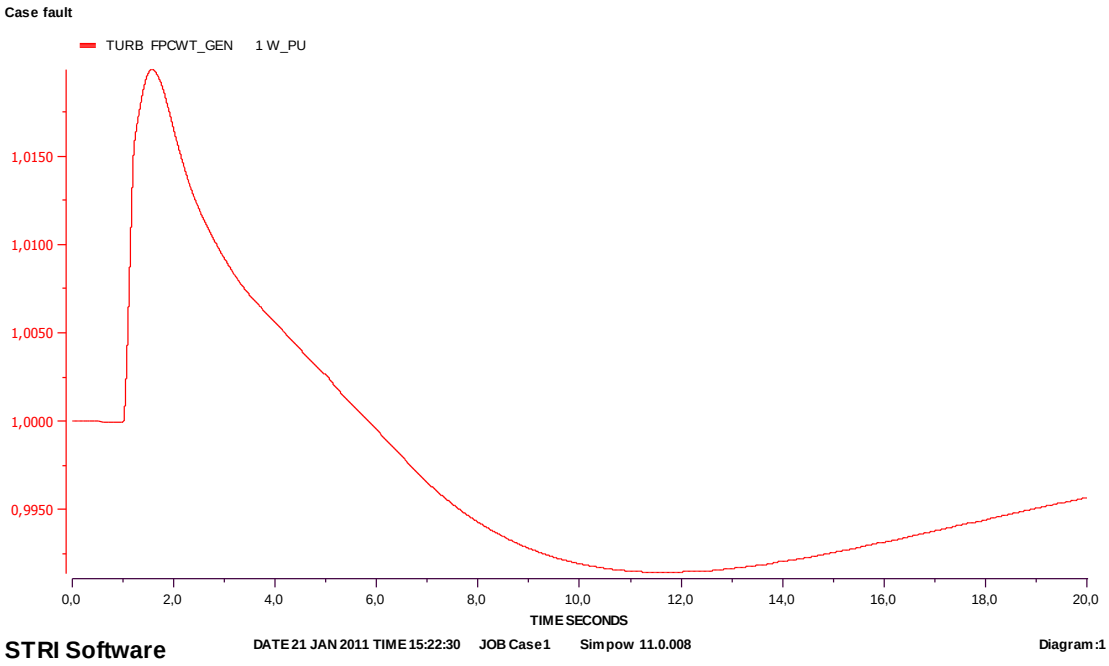


Figure 91 Case 1: Speed of the FPCWT

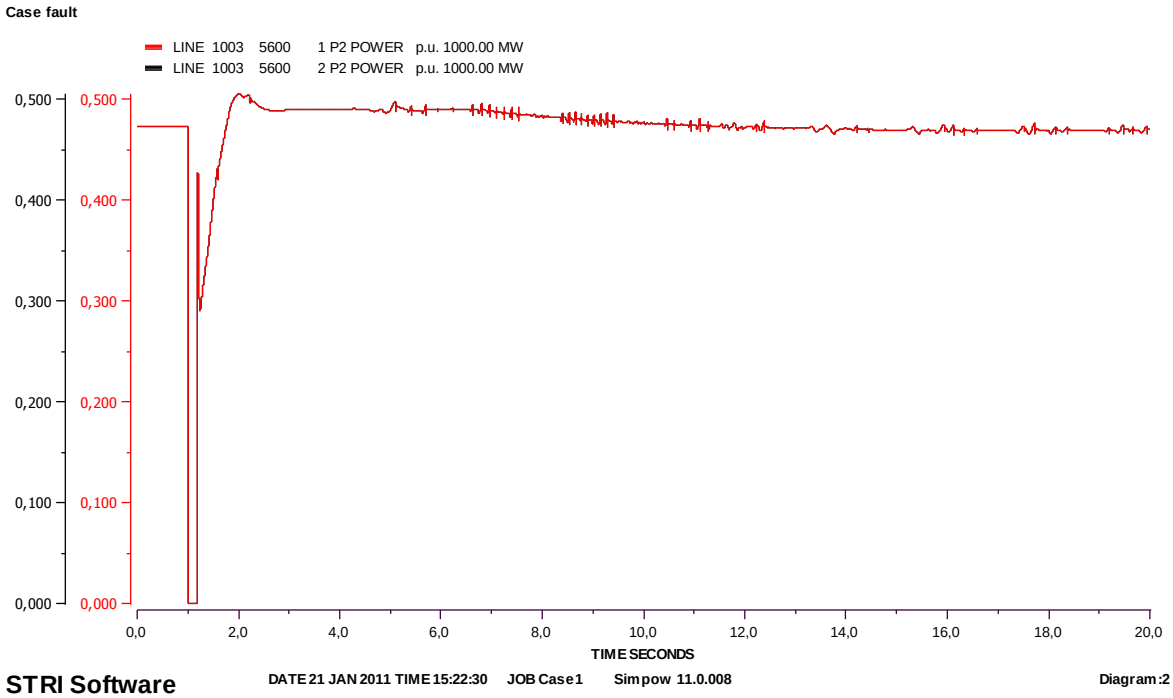


Figure 92 Case 1: Active power transfer from offshore to onshore

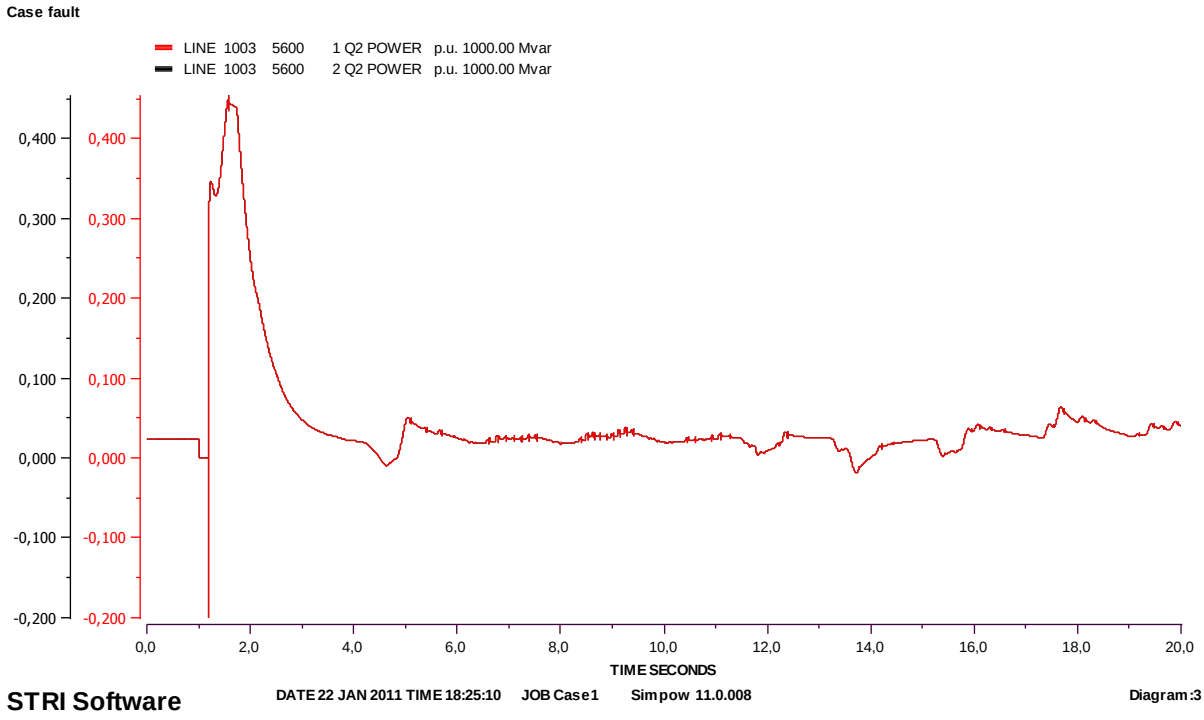


Figure 93 Case 1: Reactive power transfer from offshore to onshore

7.4 CASE 2: HVAC - 3PSG ON 5600 FOR 50 ms

A fault that lasts shorter than the previous one is applied on the same bus. Figure 94 is the voltage on the FPCWT bus. As the fault is shorter, the voltage drop is lower, and equal to -4% instead of -8%. The behaviour is unchanged but the voltage reaches its pre-fault value in 0.5 s instead of 2 s. Figure 95 shows the voltages of the onshore and offshore busses. The onshore bus voltage stabilizes very fast, in 0.1 s. The offshore bus reaches the 5% response time in 0.5 s and then reaches its pre-fault value in 2.7 s. The system is much more stable since the fault duration is far from the critical clearing time.

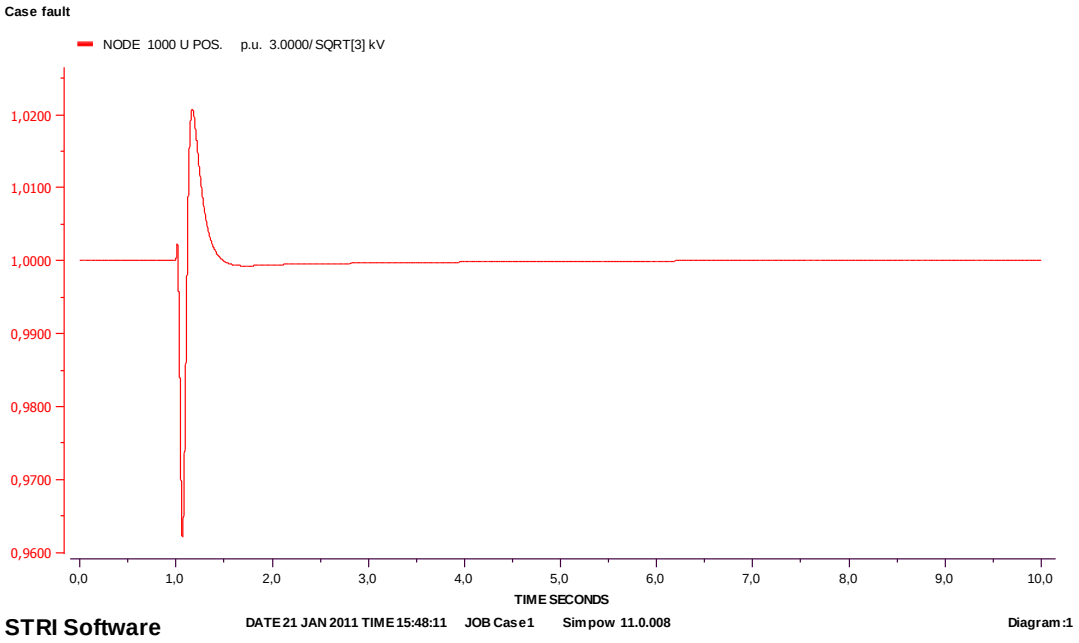


Figure 94 Case 2: Voltage on bus 1000

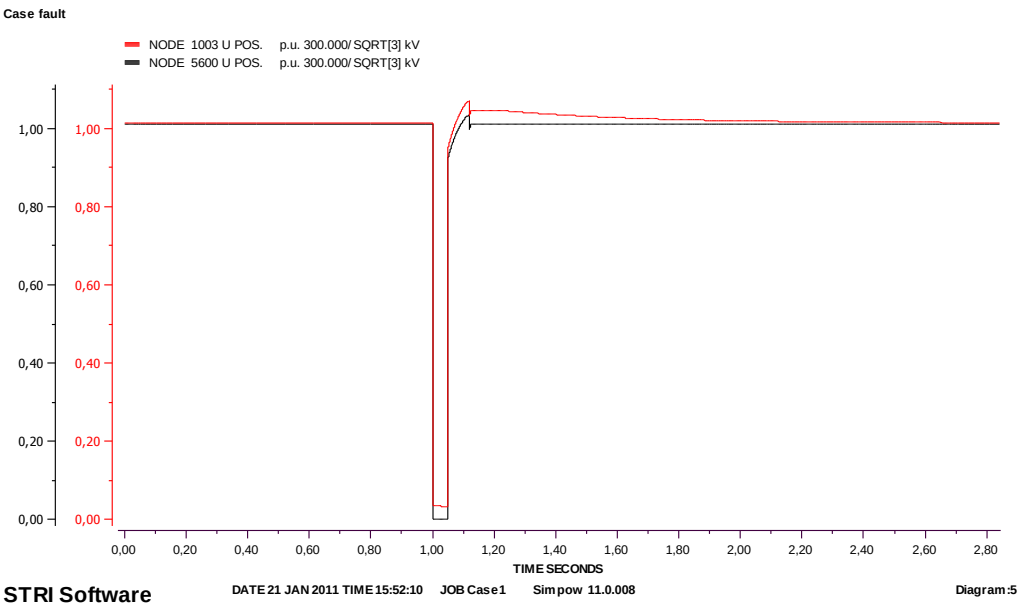


Figure 95 Case 2: Voltages on busses 1003 and 5600

Figure 96 shows the reactive power of the SVC. As the fault is relatively short, the main changes of the SVC reactive power are due to the wind farm and not to the neighbour onshore busses. Thus, the drop of -0.9 p.u. (-315 Mvar) is due to the reactive power exchange with the wind farm. The wind farm is only connected to bus 5600 whereas the neighbour busses of 5600 are connected to other areas which can then provide enough reactive power for this short time. The reactive power of the SVC fluctuates less than in the previous case but it does not stabilize to the pre-fault value. As the other busses had to compensate for the reactive power change, a change of 200 Mvar is observable at the SVC.

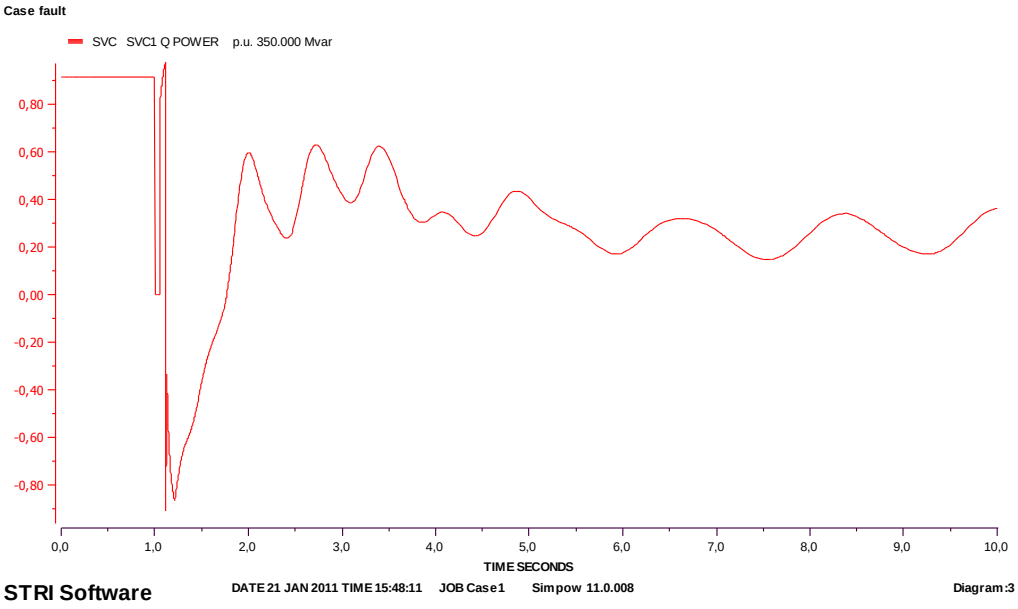


Figure 96 Case 2: Reactive power at the SVC

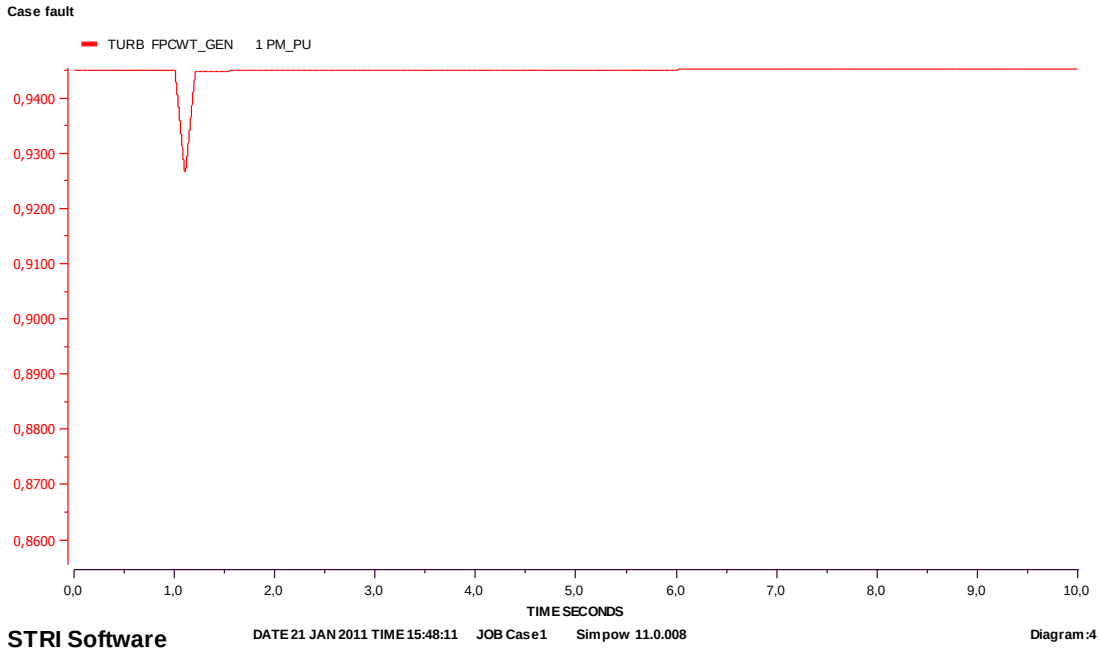


Figure 97 Case 2: Mechanical power of the FPCWT

Figure 97 is the mechanical power of the FPCWT. There is a 1.5% drop in the power for twice the duration of the fault. As the currents at the frequency converter are not high for a long time, the power does not need to be reduced for too long.

The power transfer between the offshore and onshore busses is shown in Figure 98. The power is still zero during the fault but the stabilization is done much faster than in the previous case. After 0.5 s, the post-fault value of the power equals to pre-fault one. The overshoot that appears after the clearing of the fault is a bit higher than in case 1.

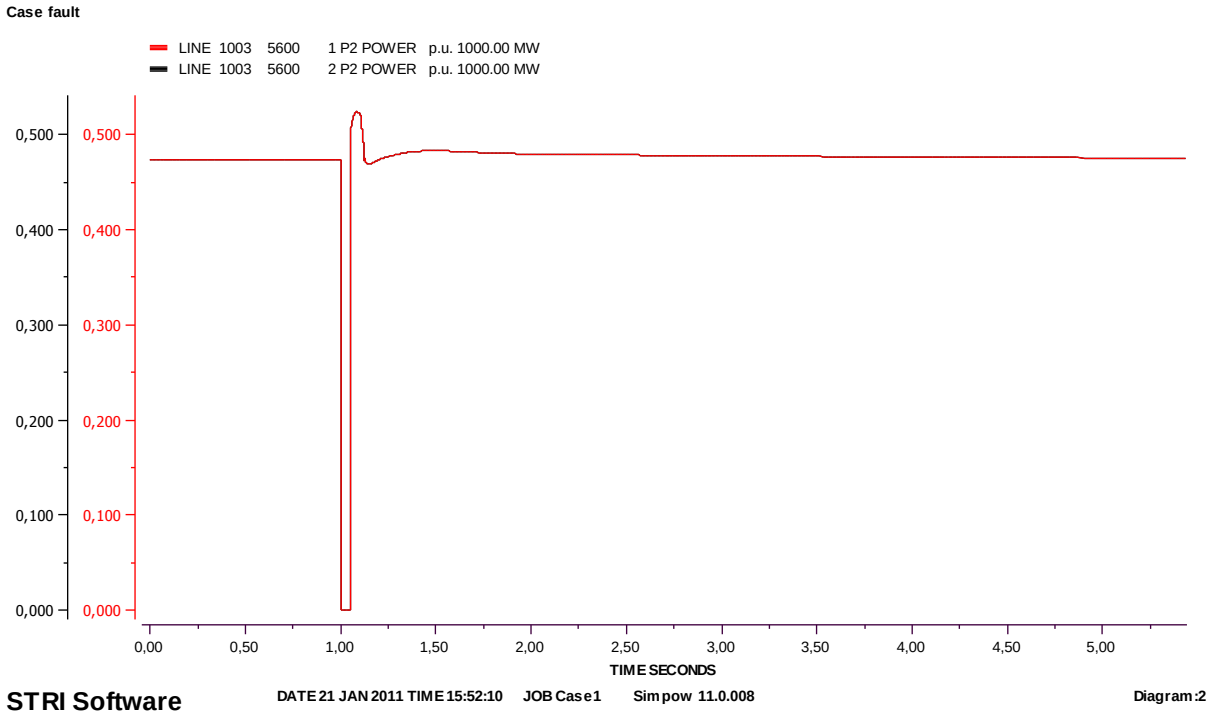


Figure 98 Case 2: Active power transfer from offshore to onshore

Figure 99 shows the reactive power exchange from the offshore bus to the onshore bus. The curve is similar to the one obtained in case 1 since the maximum of reactive power is the same and there is the same decreasing transfer after the maximum. However, as the overall system stabilizes much faster, the curve is a lot smoother and the pre-fault value is obtained after 2.5 s and there are no oscillations.

Figure 100 is the speed of the FPCWT. In case one, the maximum was 1.02 p.u. and it is now 1.003. Moreover, the speed stabilizes much faster, in 8 s instead of more than 20 s in the previous case. Thus, the change in speed of the FPCWT is almost negligible for the system.

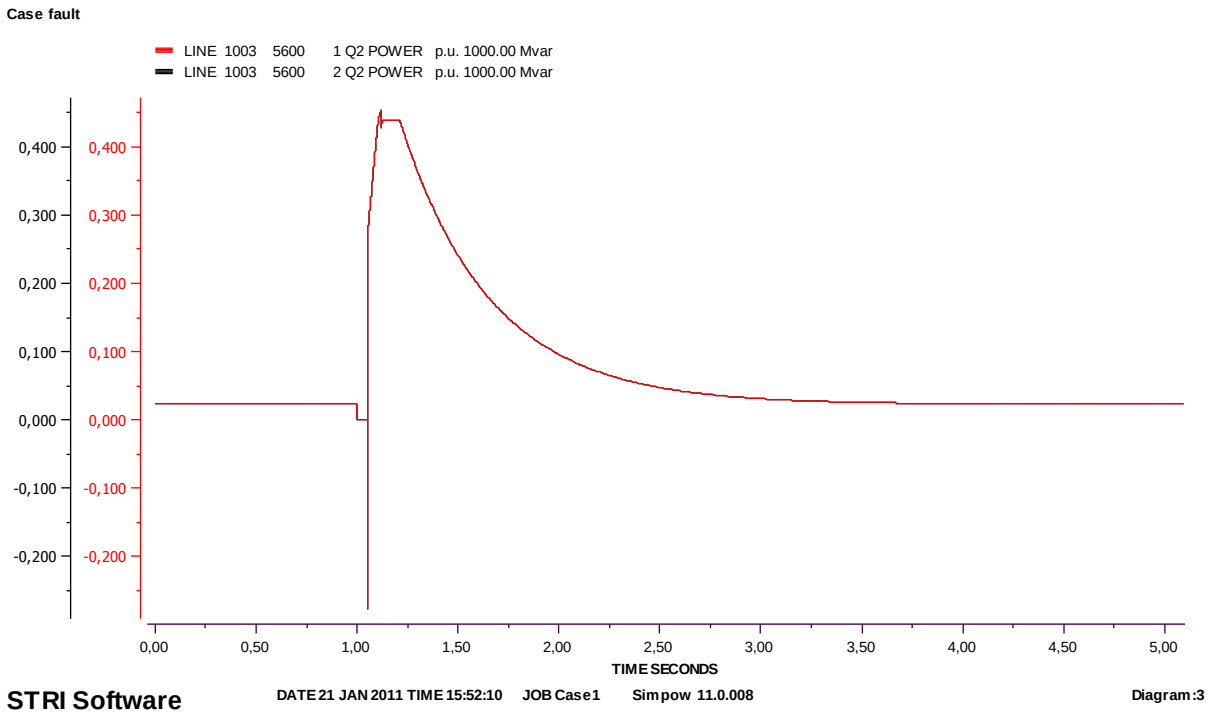


Figure 99 Case 2: Reactive power transfer from offshore to onshore

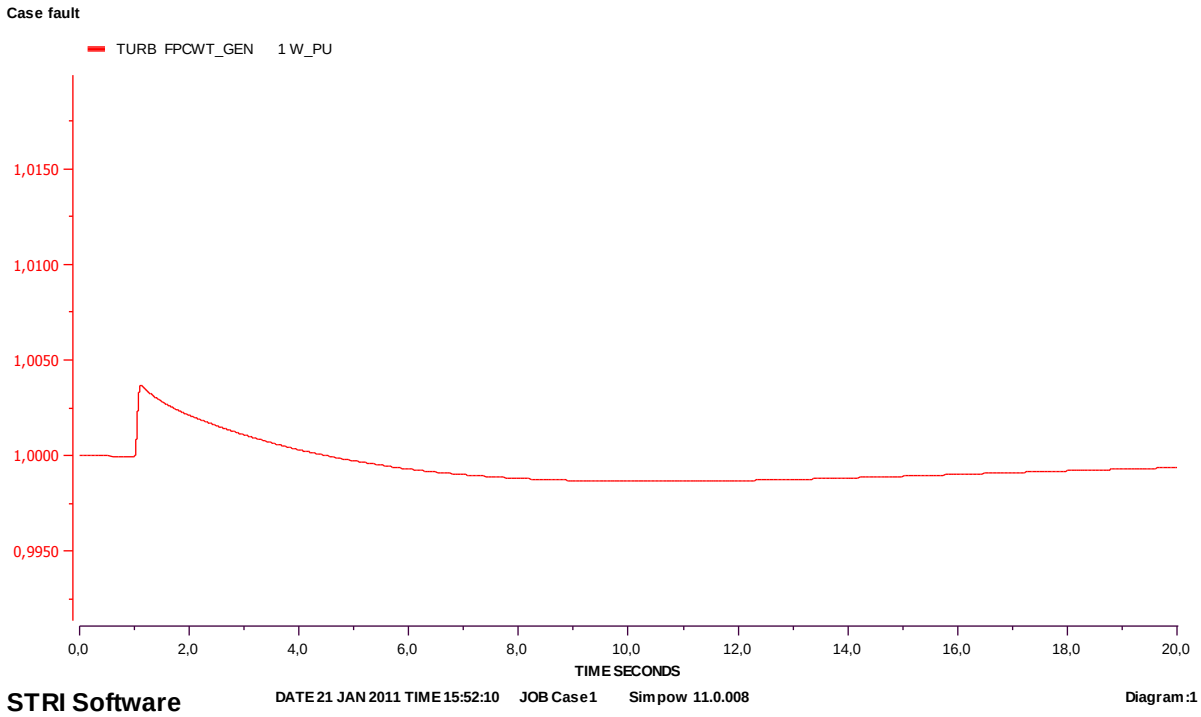


Figure 100 Case 2: Speed of the FPCWT

7.5 CASE 3: HVAC - 3PSG ON 5600 FOR 5 ms

The aim of this case is to study a small fault that could occur at any time from a generating unit. The voltage at the FPCWT is shown in Figure 101. The maximum and minimum due to the fault are up to +/- 0.15%. The voltage now stabilizes in 0.4 s. The mechanical power is not changing during and after the fault since the change in voltage is insignificant. The same behaviour occurs to the speed of the FPCWT.

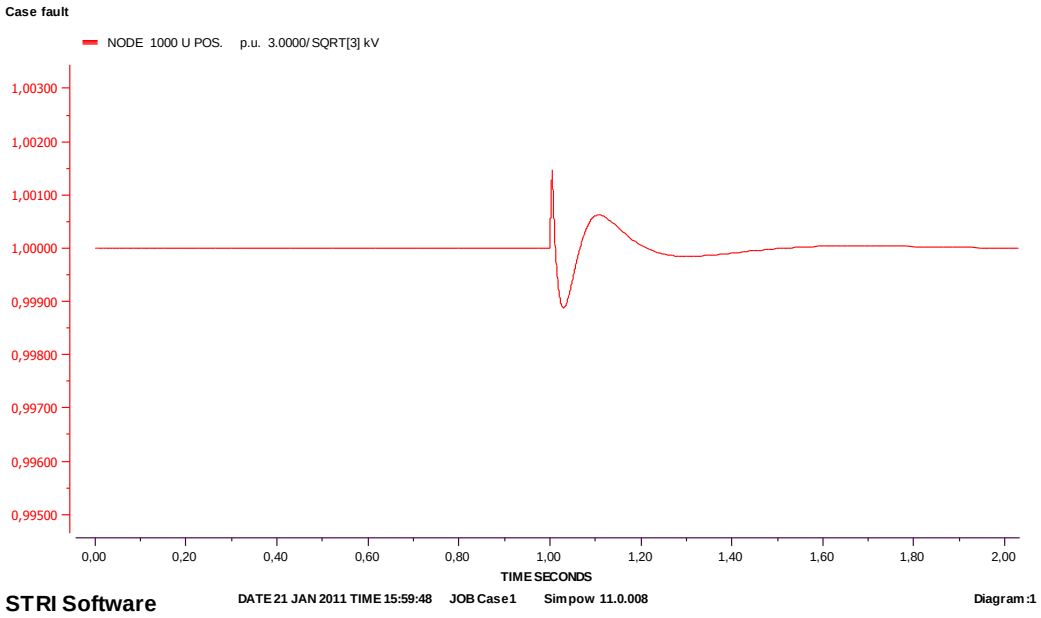


Figure 101 Case 3: Voltage on bus 1000

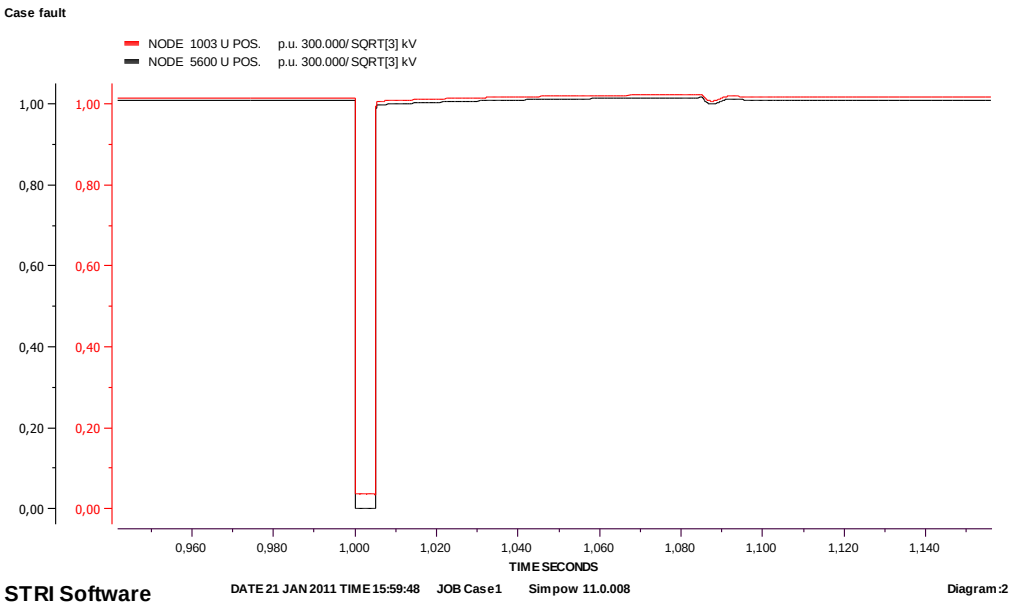


Figure 102 Case 3: Voltages on busses 1003 and 5600

The voltages on busses 1003 and 5600 are shown in Figure 102. They are equal almost to the pre-fault state values after the fault is cleared. Thus the voltage is stable for such a small fault.

Figure 103 is the SVC reactive power. It succeeds to stabilize after 3.5 s to a value lower by 0.1 p.u. compared to the pre-fault one.

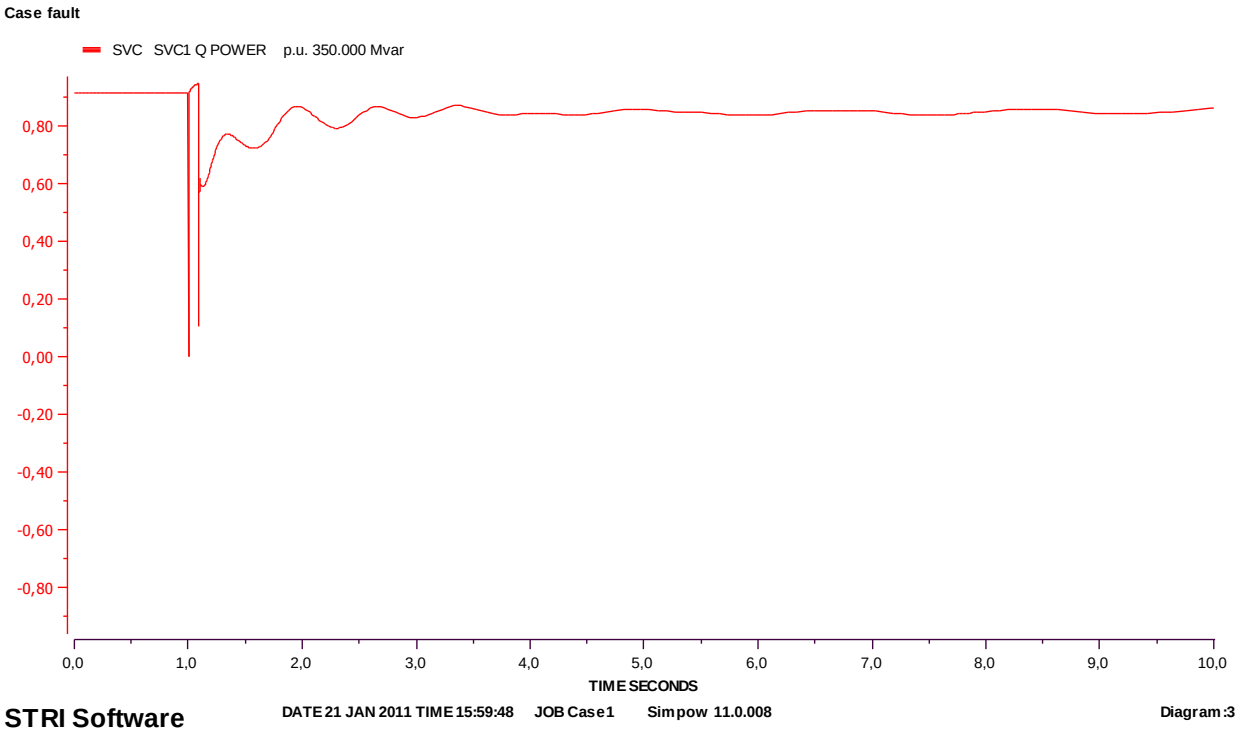


Figure 103 Case 3: Reactive power at the SVC

The active power transfer between the offshore and onshore busses is shown in Figure 104. The same overshoot is observed after the fault is disconnected but the system becomes stable after only 0.1 s.

The reactive power transfer is shown in Figure 105. In cases 1 and 2, the overshoot was equal but in case 3, as the fault is short, the overshoot is ten times smaller. Moreover, the system stabilizes faster, in 1.5 s.

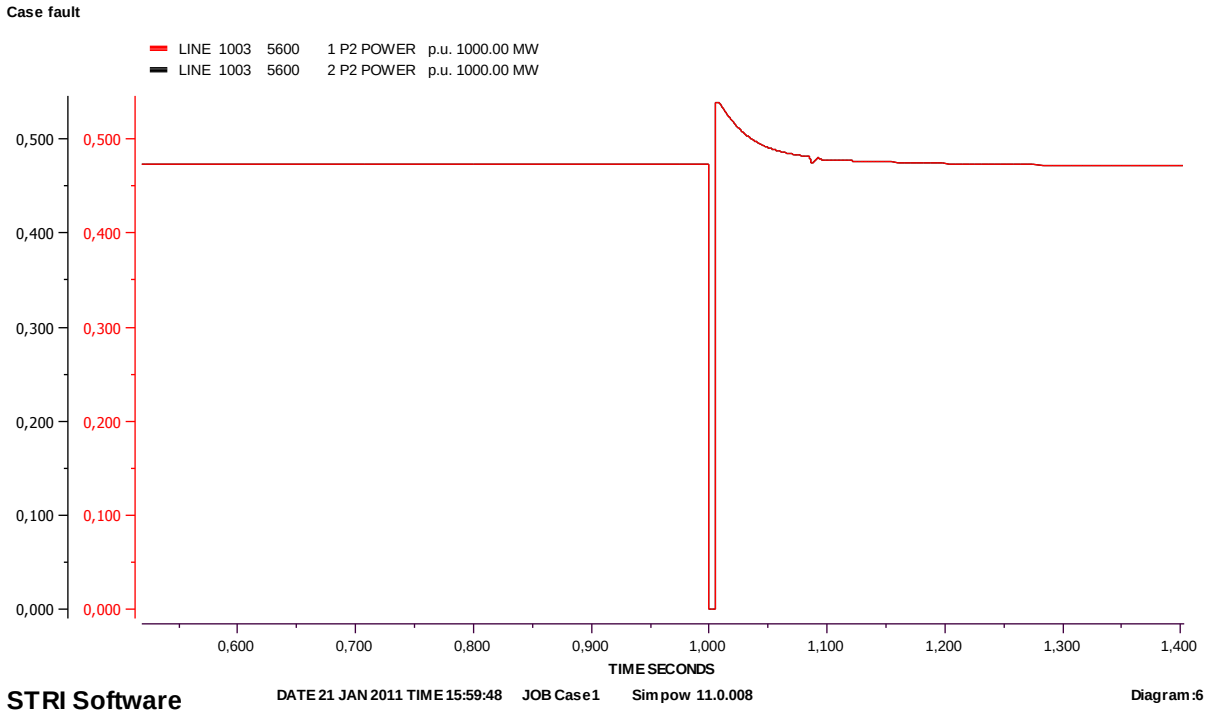


Figure 104 Case 3: Active power transfer between the offshore and onshore busses

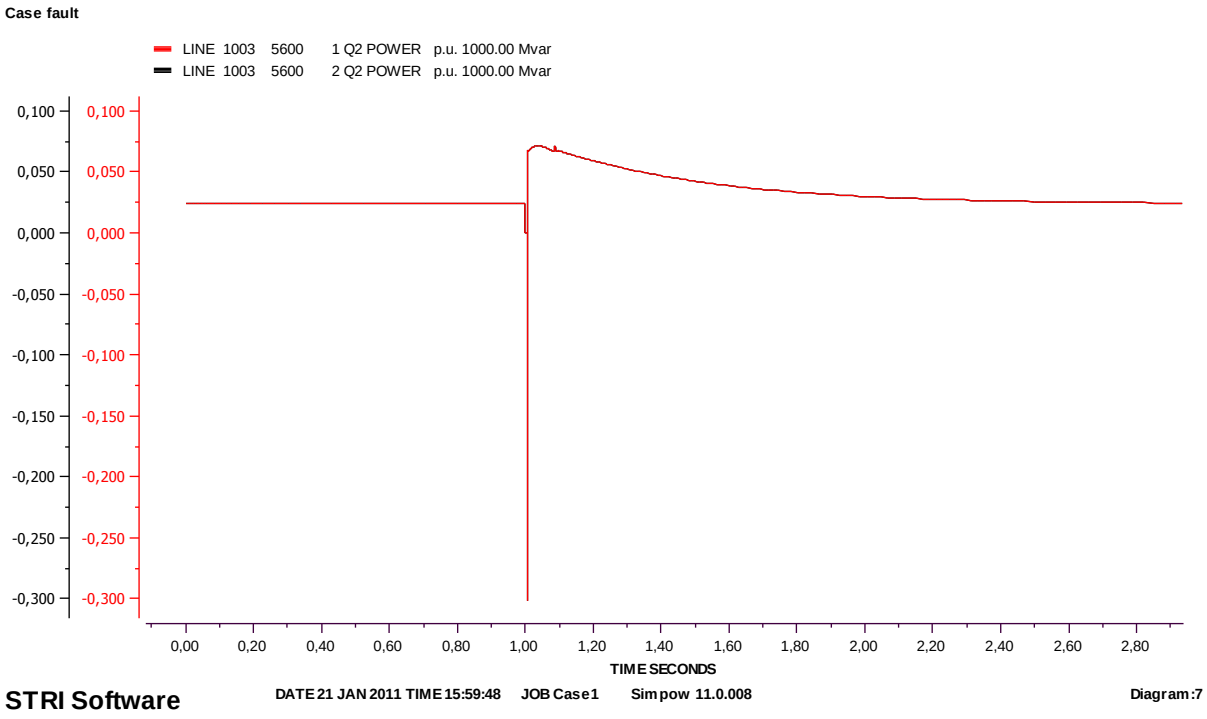


Figure 105 Case 3: Reactive power transfer between the offshore and onshore busses

7.6 CASE 4: HVAC - 3PSG ON 6000 FOR 50 ms

In this case, the wind farm is connected in HVAC to bus 6000 located in the West of Norway instead of the South. The fault applied on bus 6000 is the same than the one applied on bus 5600 in case 2. Thus, it is possible to compare cases 2 and 4.

Figure 106 is the voltage on the FPCWT bus. The minimum and maximum values of the voltage are the same for both cases since this is the same fault and this is the same wind farm. The time taken to reach the pre-fault value after the fault is also unchanged.

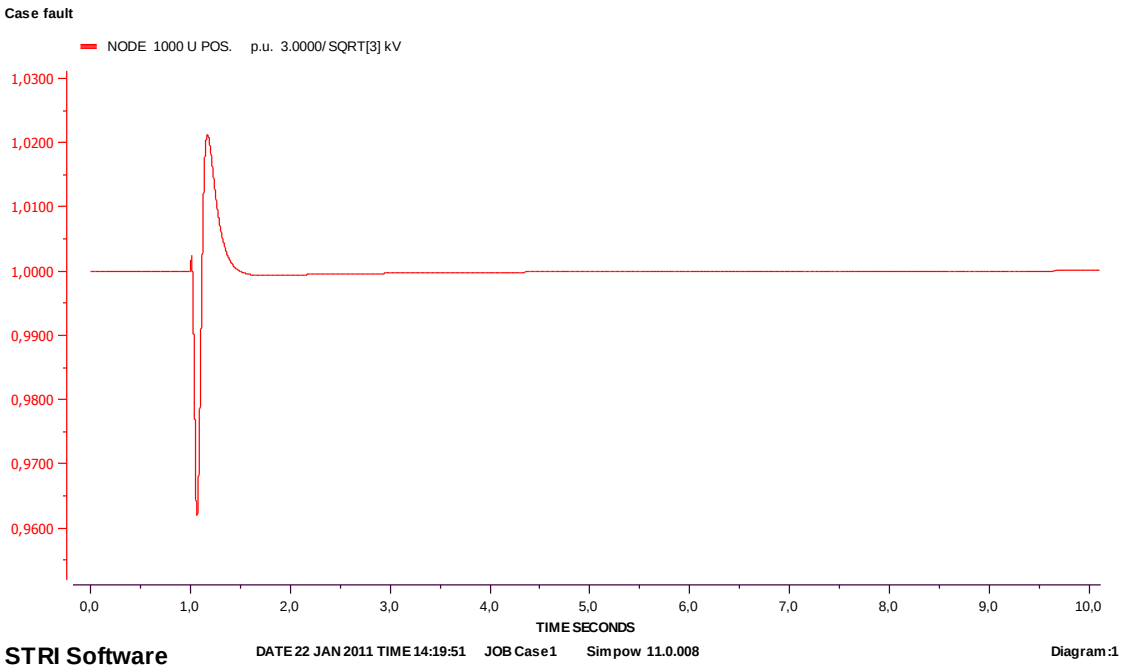


Figure 106 Case 4: Voltage on bus 1000

Figure 107 is the voltage on the offshore bus and the onshore bus. The maxima are the same than in case 2. However, the onshore voltage is less stable, there are some oscillations. Though, the 5% time response is the same since oscillations are small.

In case 2, the reactive power from the SVC was oscillating around a 30 p.u. after the fault but in case 4, reactive power is needed during the first five seconds after the fault is cleared. This is shown in Figure 108. Before the fault, the SVC was absorbing reactive power and during the fault it is delivering reactive power to the system. In case 2, the SVC was delivering reactive power before the fault and it is then equal to zero during the fault.

The mechanical power is exactly the same than in case 2 and so is the speed of the FPCWT.

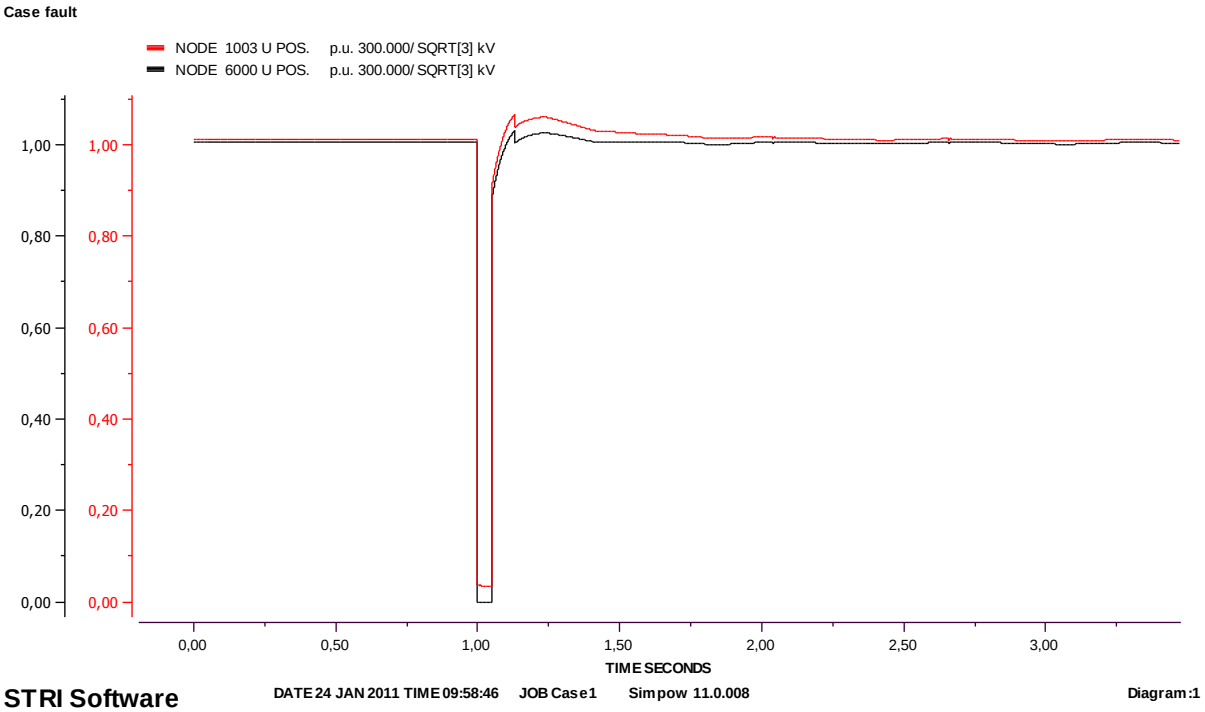


Figure 107 Case 4: Voltages on busses 1003 and 6000

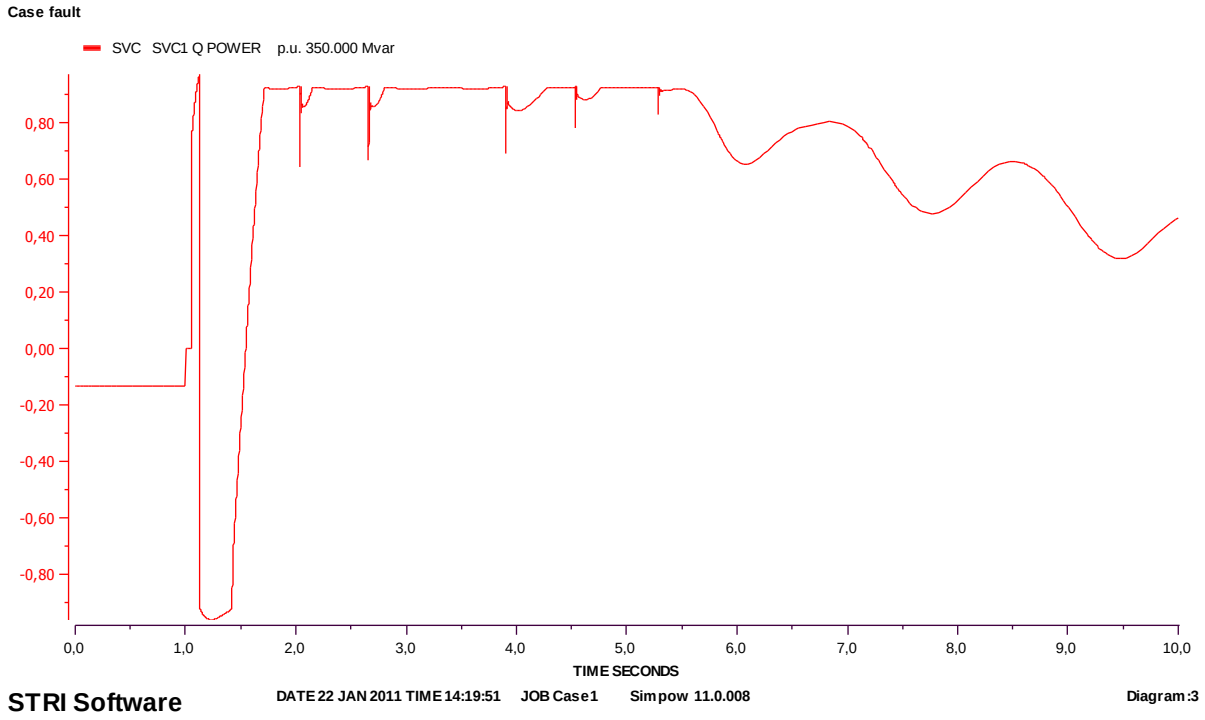


Figure 108 Case 4: Reactive power at the SVC

Figure 109 is the active power exchange between the offshore and onshore busses. The overshoot is similar to case 2 but the system is a bit less stable, even though the 5% time response is the same.

The reactive power exchange is shown in Figure 110. The plot is exactly the same than the one found in case 2. Thus, the change in the two plots of the reactive power in the SVC is mainly due to the neighbour onshore busses.

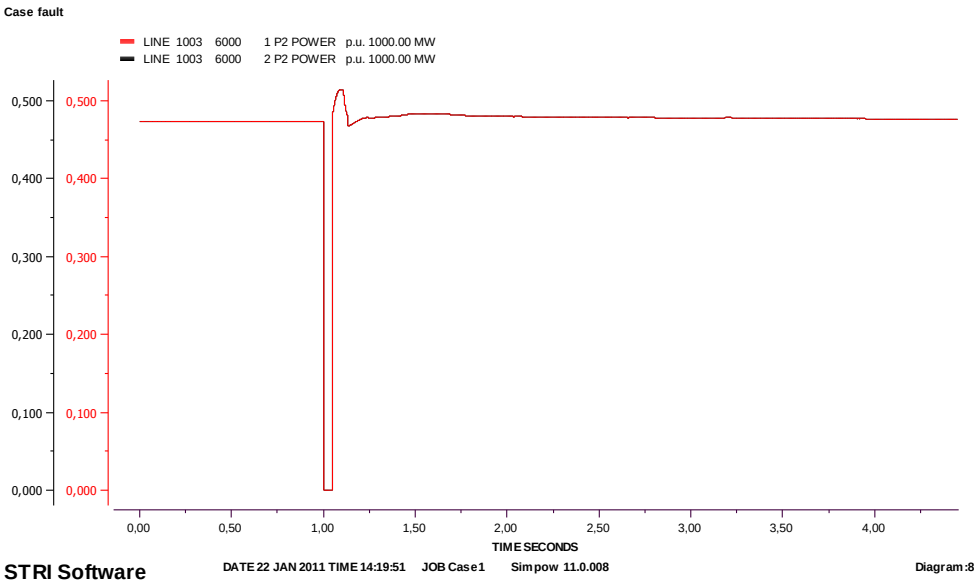


Figure 109 Case 4: Active power transfer between offshore and onshore

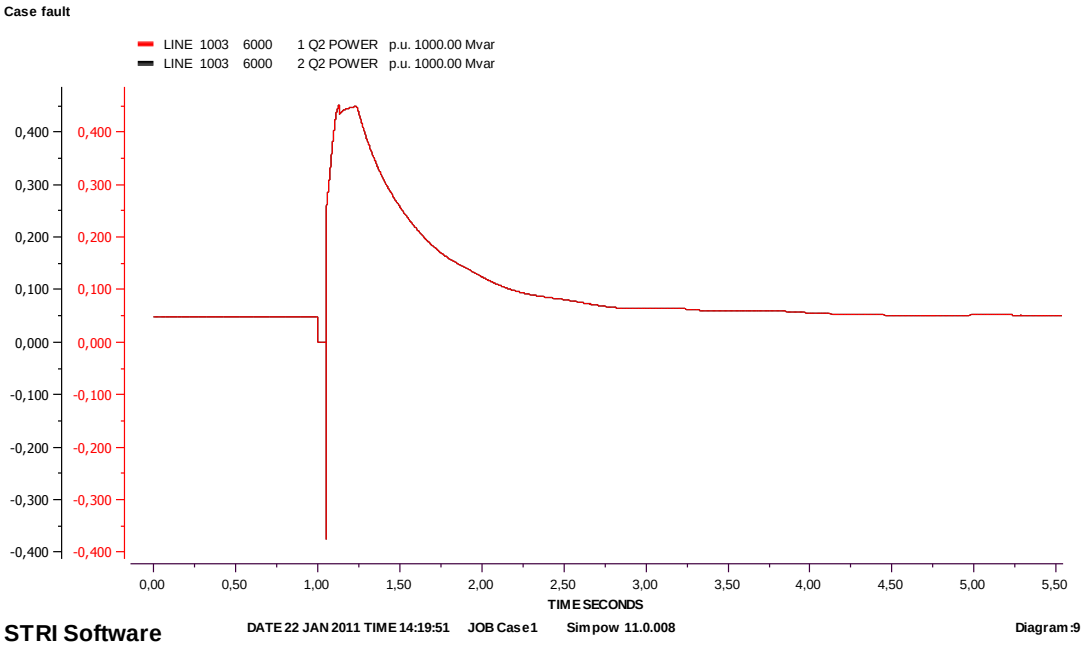


Figure 110 Case 4: Reactive power transfer between offshore and onshore

7.6 CASE 5: HVAC – STOP OF PRODUCTION OF 6100

In this case, the production of bus 6100 is stopped. Bus 6100 is located in Vestlandet and connected to bus 6000. Thus, the main link between bus 5600, where the wind farm is connected, and bus 6100 is bus 6000. The generator on bus 6100 was producing 2346 MW which is approximately the same amount than bus 5600 but twice the production on bus 6000.

The voltage at the FPCWT bus is shown in Figure 111. As soon as the generator is disconnect, the FPCWT experiences oscillations up to 0.00065 p.u. which is less than 2 Volts. Then, the system tends to stabilize after five seconds but oscillates again since the overall system fails to stabilize.

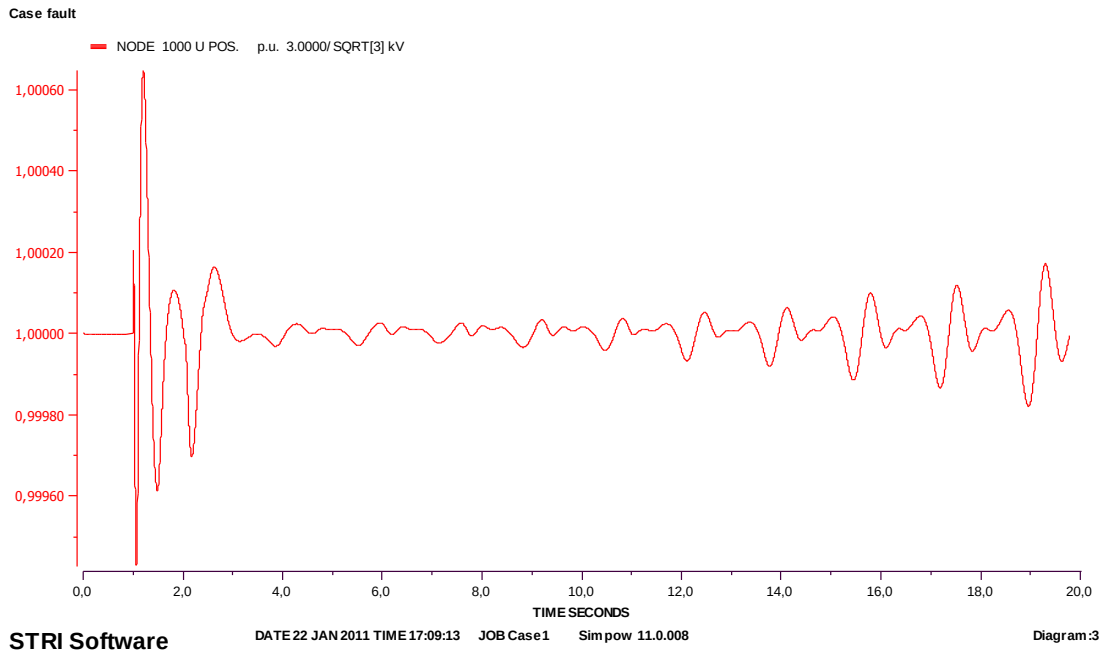


Figure 111 Case 5: Voltage on bus 1000

Figure 112 is the voltage on busses 1003 and 5600. Right after the fault, the voltages drop to 0.88 p.u. before the voltage control starts to act. The difference in voltage between both voltages is enlightened after the fault is applied due to oscillations. The voltages fail to stabilize.

Figure 113 is the voltage on the swing bus of the grid. The oscillations that increase constantly on magnitude prove that the system is totally unstable.

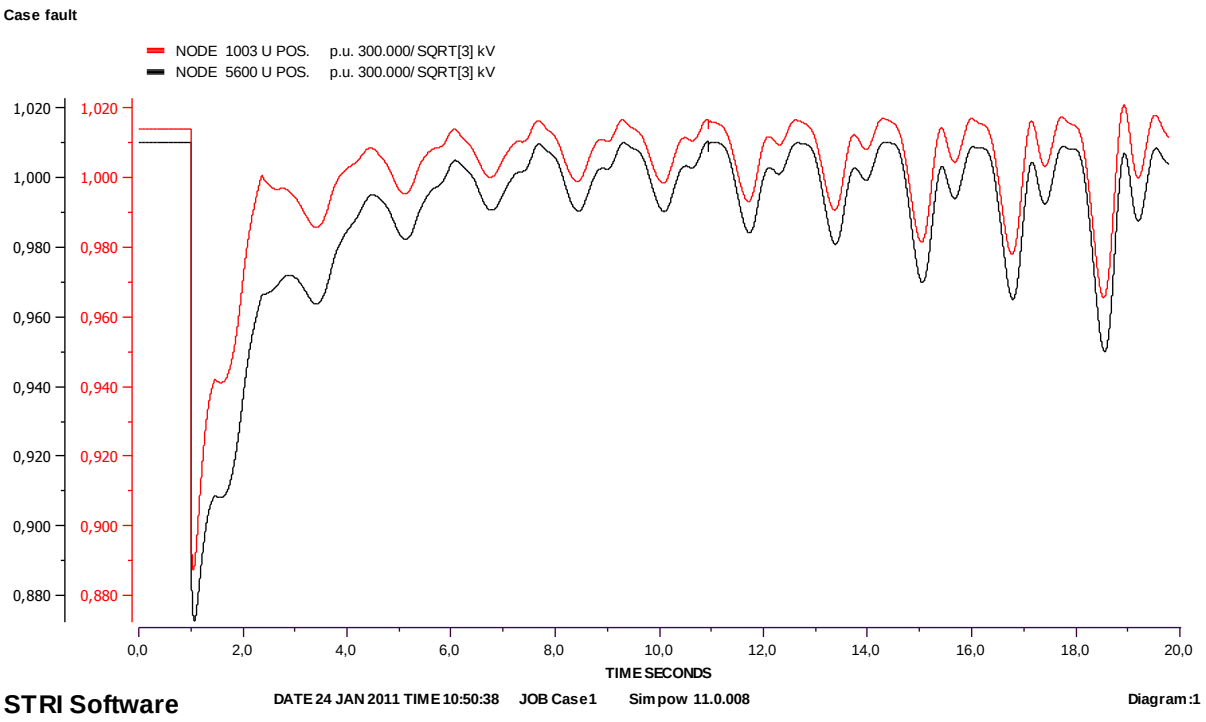


Figure 113 Case 5: Voltage on busses 1003 and 5600

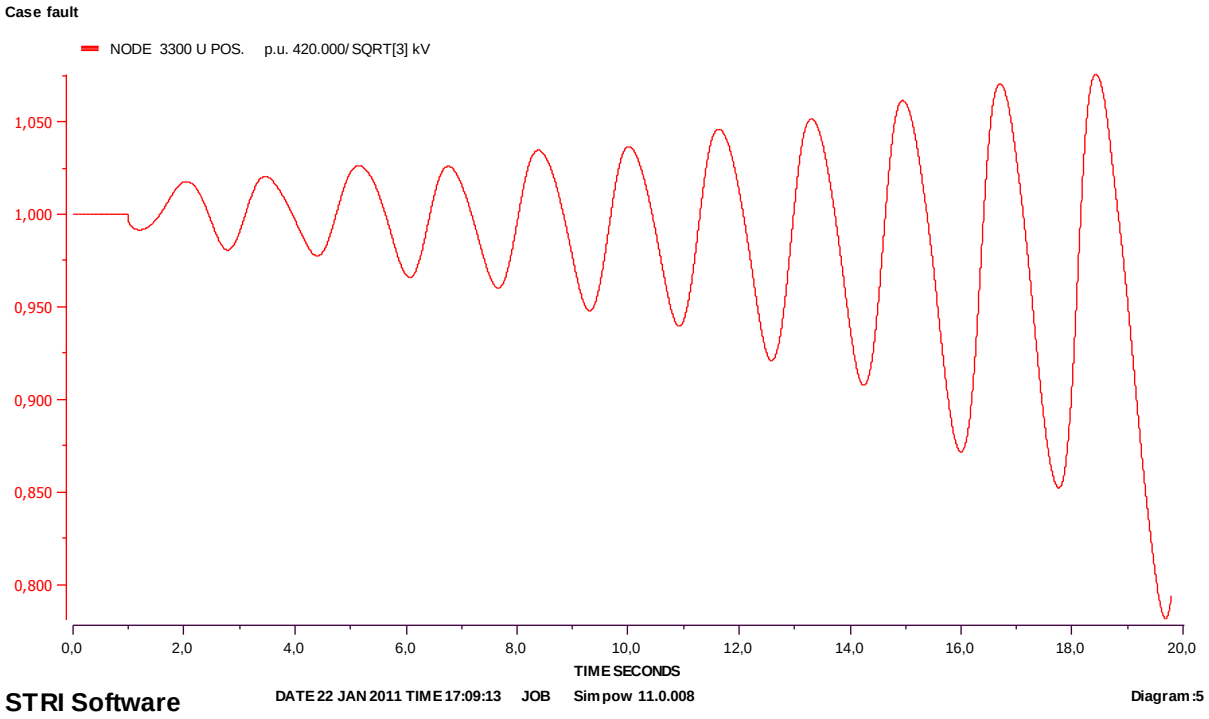


Figure 112 Case 5: Voltage on bus 3300

Figure 114 is the mechanical power of the FPCWT. It doesn't stabilize after the fault is connected but the changes during the first twenty seconds of the simulation are small, up to 0.00005 p.u.

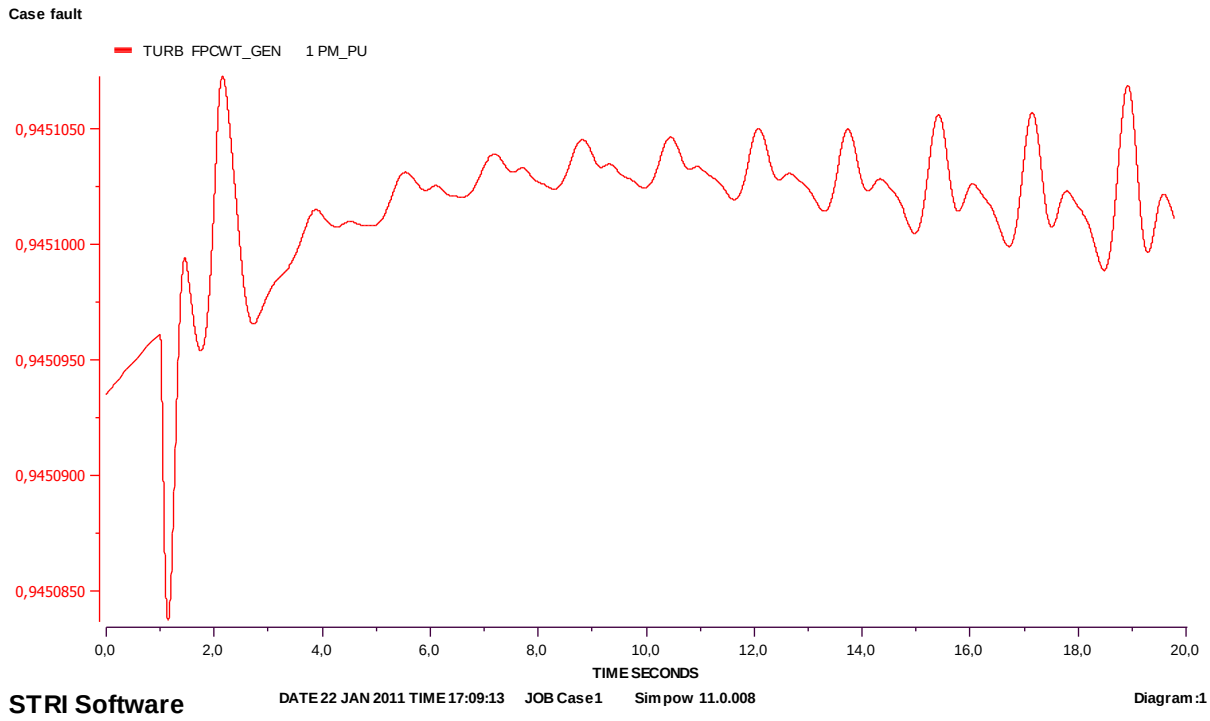


Figure 114 Case 5: Mechanical power of the FPCWT

Figure 115 shows the active power exchange between the offshore and onshore busses. There is drop of 0.05 p.u. after the fault is connected. The overshoot is not as high as in previous examples but the active power does not succeed to stabilize even if after two seconds, the 5% time response was achieved.

The reactive power transfer is shown in Figure 116. Maximum values obtained right after the fault, when the system tries to react as fast as possible, are equal to the one found in previous cases. However, instead of being able to stabilize right after the first overshoot, the reactive power exchange oscillates and fails to remain stable.

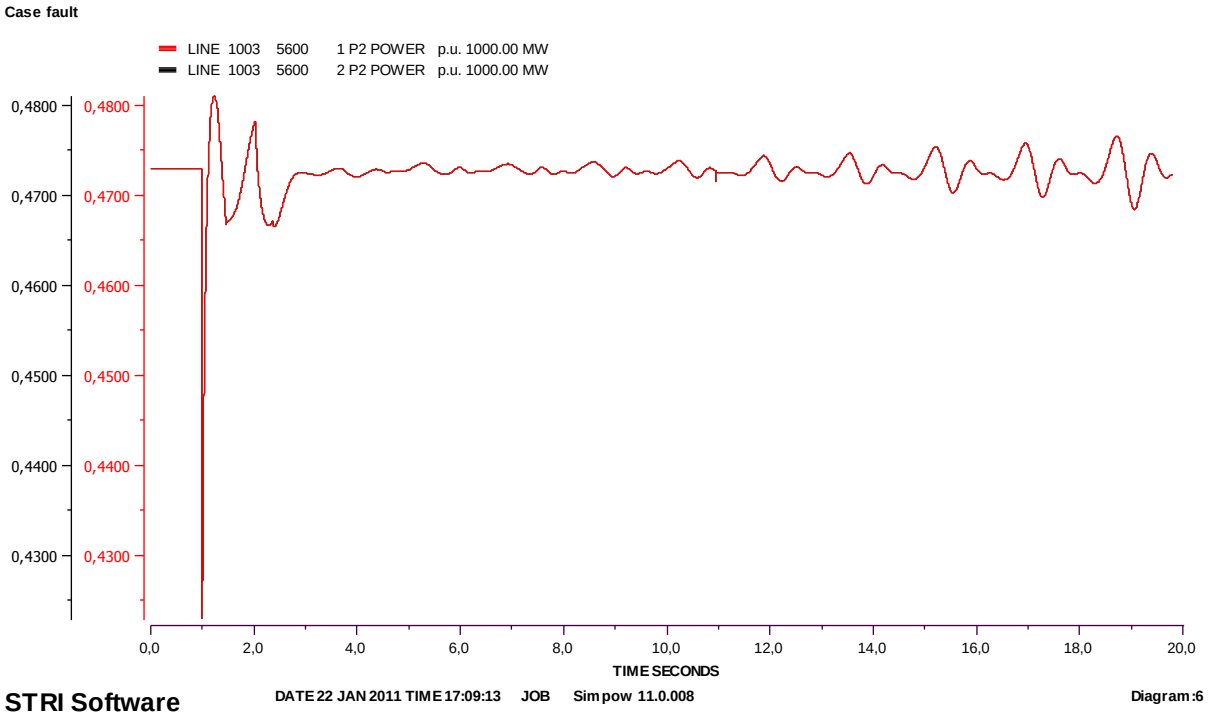


Figure 115 Case 5: Active power transfer between the offshore and onshore busses

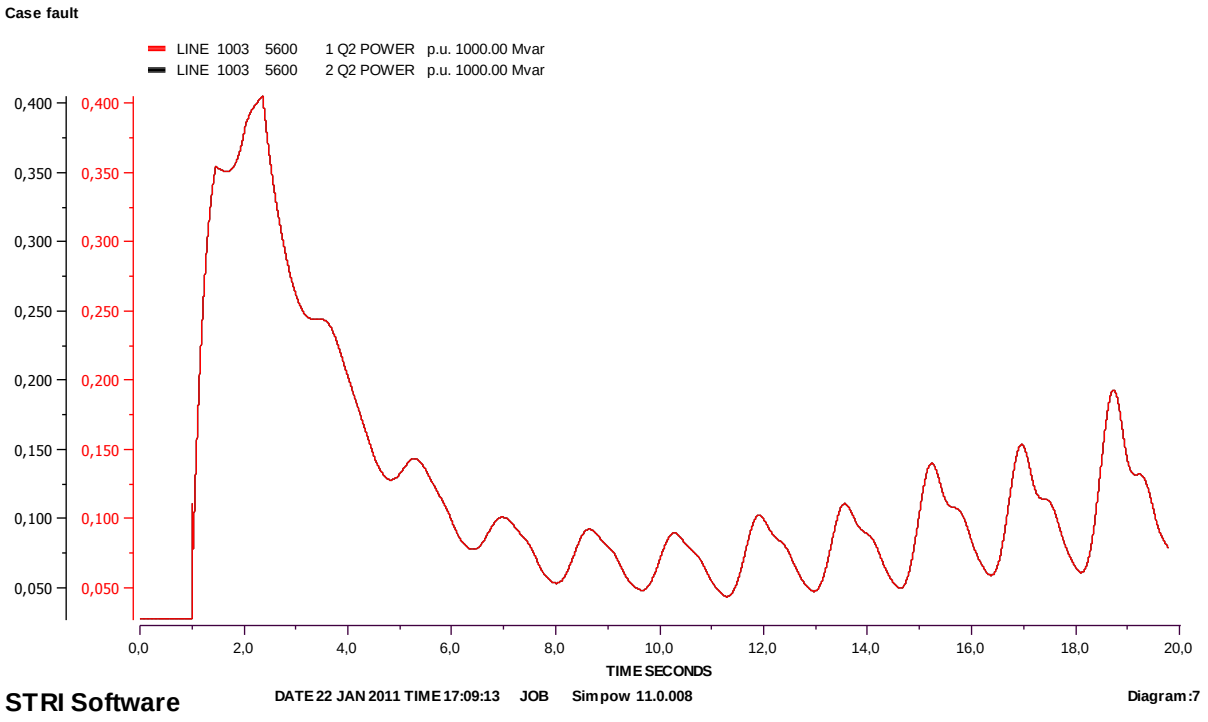


Figure 116 Case 5: Reactive power transfer between the offshore and onshore busses

7.7 CASE 6: HVAC – DISCONNECTION OF A LINE

In this case, the wind farm is connected to bus 5600. A 50 ms 3PSG is performed as in case 2 but line 2 between busses 1003 and 5600 is disconnected after the fault is cleared. The FPCWT voltage, mechanical power and speed are similar to the ones found in case 2.

The voltages of the offshore and onshore busses are shown in Figure 117. They are similar to the one found in case 2 but there is a small oscillation at t=1.95 s but it is negligible and disappears after.

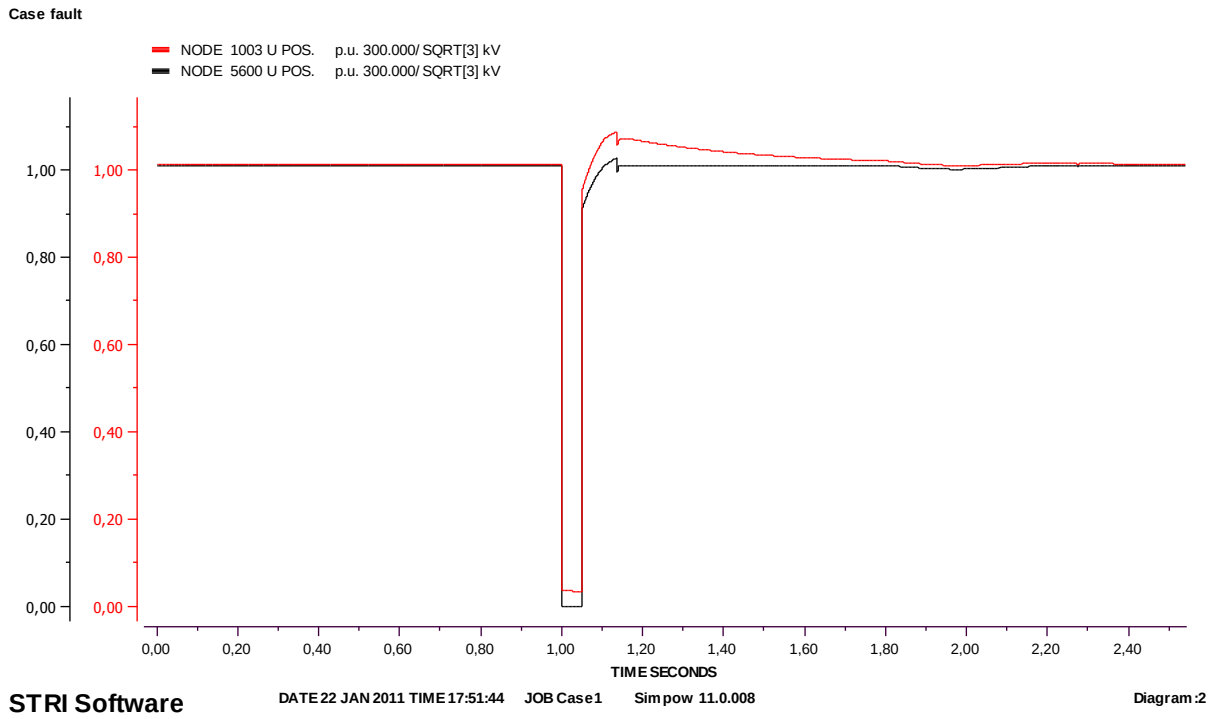


Figure 117 Case 6: Voltages on busses 1003 and 5600

Figure 118 shows the reactive power of the SVC. As one line is disconnected, the amount of reactive power the SVC has to absorb is lower than in case 2. It is here -0.1 p.u. but it is -0.8 p.u. in case 2 just after the fault. However, the amount of reactive power injected to the grid by the SVC oscillates around 0.8 p.u. instead of 0.3 p.u. in case 2. Thus, more reactive power is injected into the grid and to the wind farm as it will be seen on the line that is connected.

Figure 119 is the active power exchange between the offshore and onshore busses. As line 2 is disconnected after the fault is cleared, it can't transfer any power. The amount of power line 1 has to transmit is thus doubled and has exactly the same behaviour than in case 2.

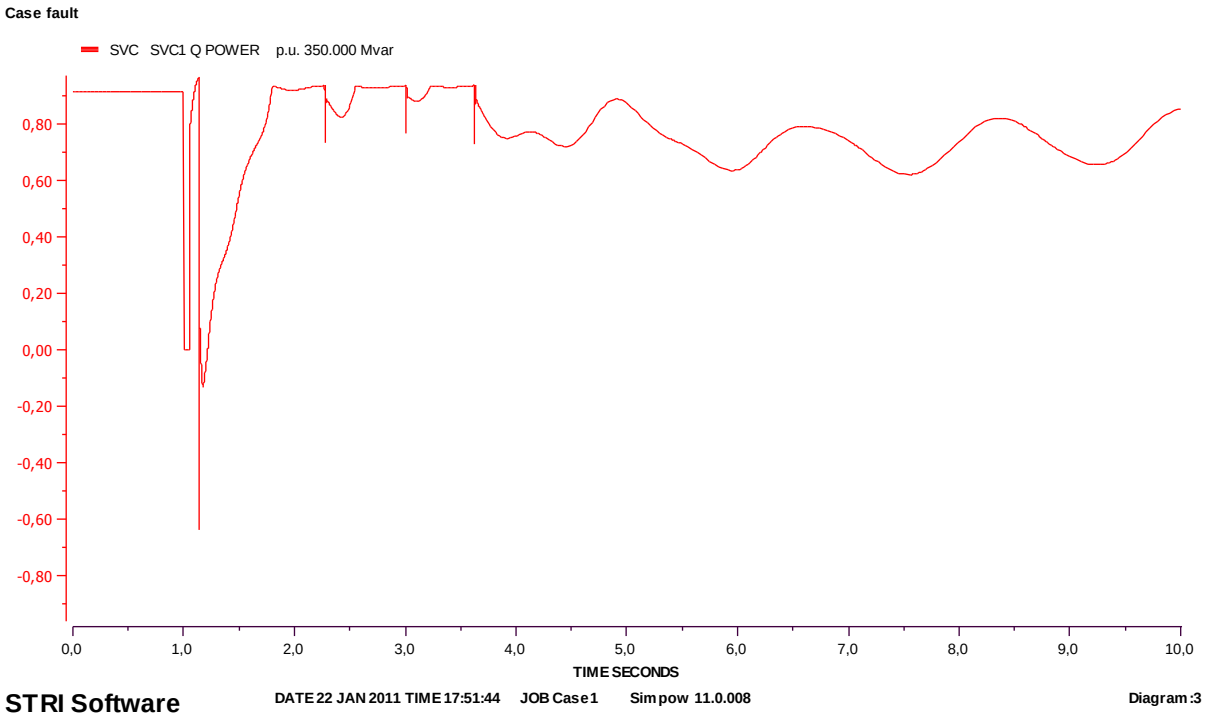


Figure 118 Case 6: Reactive power at the SVC

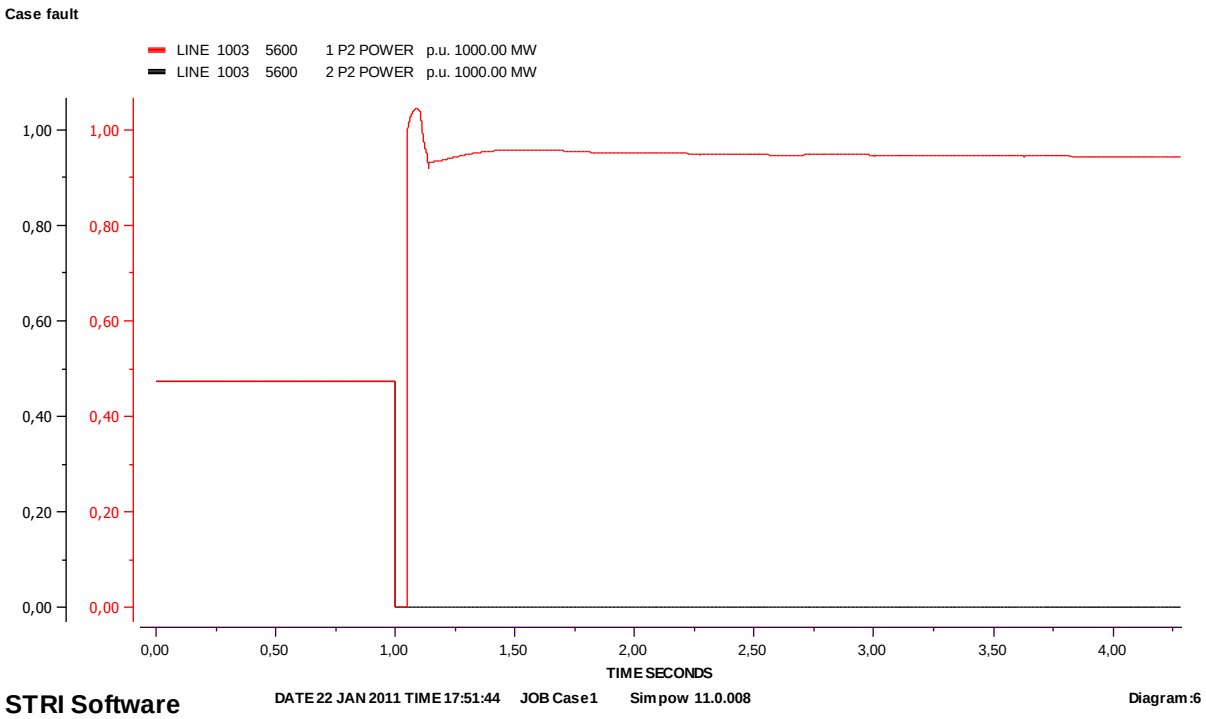


Figure 119 Case 6: Active power exchange between the offshore and onshore busses

The reactive power exchange between the offshore and onshore busses is shown in Figure 120. The maximum of reactive power after the fault is cleared is obtained at the same time than in case 2 but it is higher by 0.2 p.u. since line 2 is disconnected. However, after the stabilization at time t=3.5 s, the reactive power flow is reversed and the wind farm consumes reactive power instead of producing. This is because line 1 takes all the power.

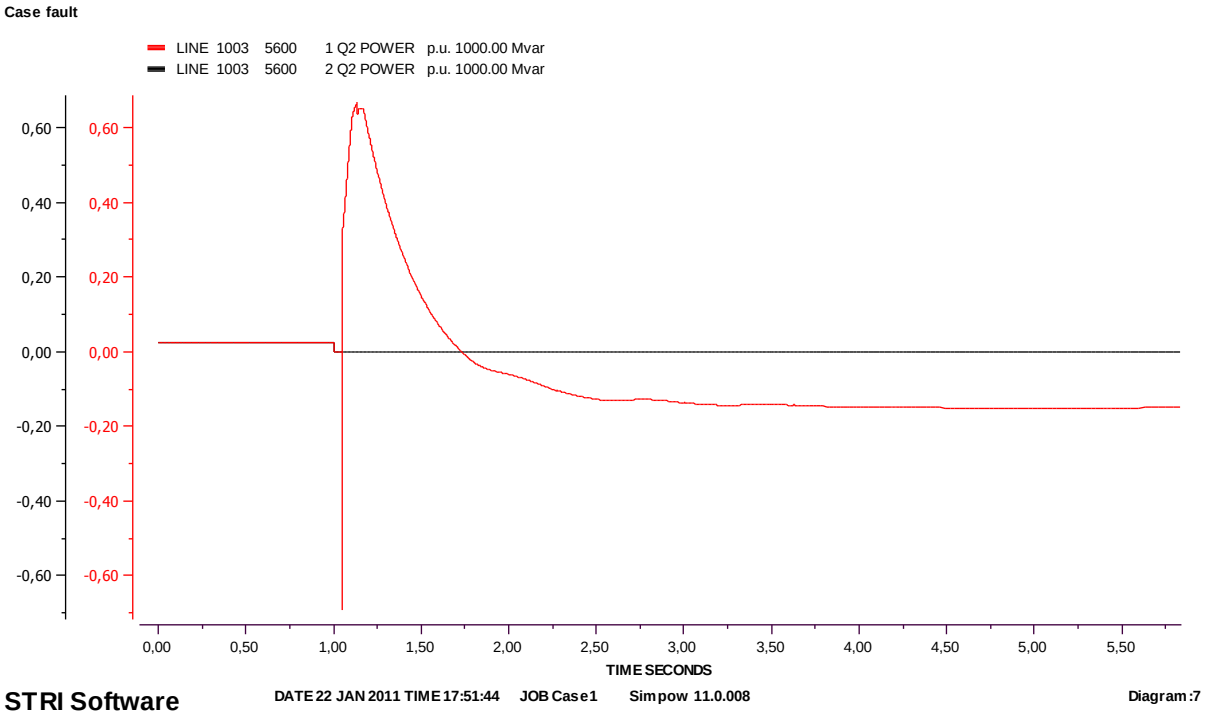


Figure 120 Case 6: Reactive power exchange between the offshore and onshore busses

7.8 CASE 7: HVDC – 3PSG ON 5600 FOR 185 ms

This case is the same than case 1 but the connexion of the wind farm is achieved with HVDC Light, over a longer distance, instead of HVAC.

Figure 121 shows the voltage on the FPCWT. It is not changed during the time of the simulation and so is the mechanical power and the speed. Figure 122 is the AC voltages on the onshore and offshore side. The onshore voltage is the same than in case 1, it is not influenced by the fact that the FPCWT is connected in HVAC or HVDC. However, the offshore voltage is dropping by 0.05 p.u. for a very limited time during the fault and then remains stable. This phenomenon along with the constant voltage on Figure 121 tends to prove that the PWM converters of the HVDC Light module are interfering considerably on voltage regulation.

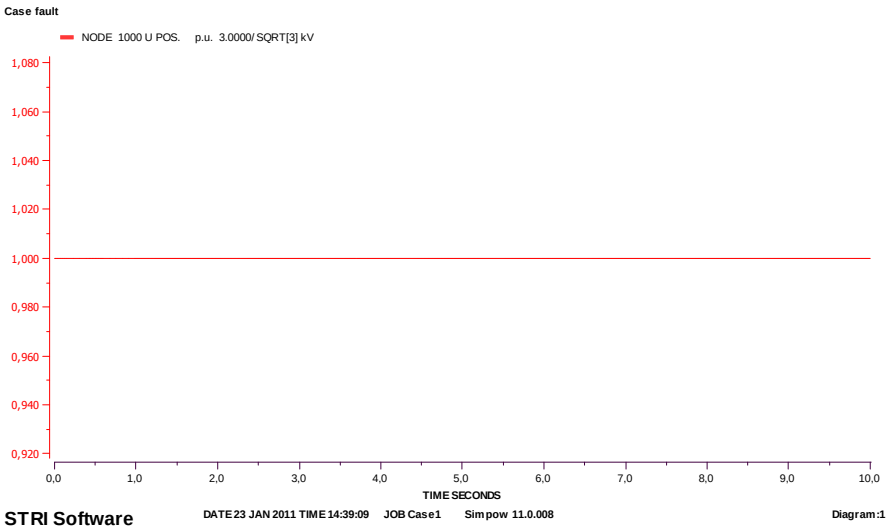


Figure 121 Case 7: Voltage on the FPCWT bus

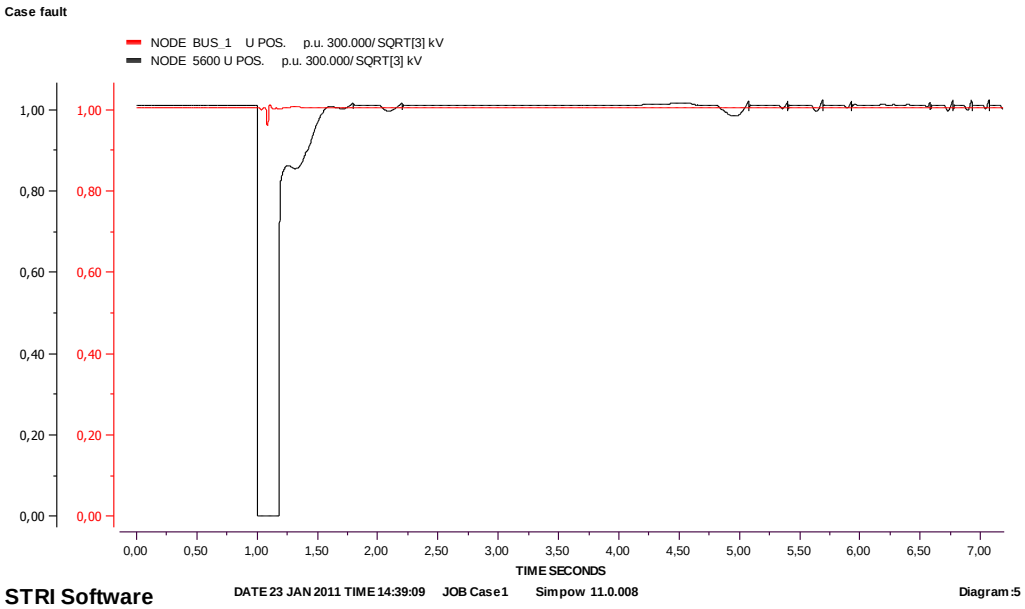


Figure 122 Case 7: Voltage on busses 1003 and 5600

Figure 123 is the SVC reactive power. It shows the same behaviour than in case 1. The same oscillations are observed. In case 1 and 7, the wind farm is exporting between 250 and 300 Mvar of reactive power. Thus, the reactive power seen from bus 5600 and from the SVC is not different.

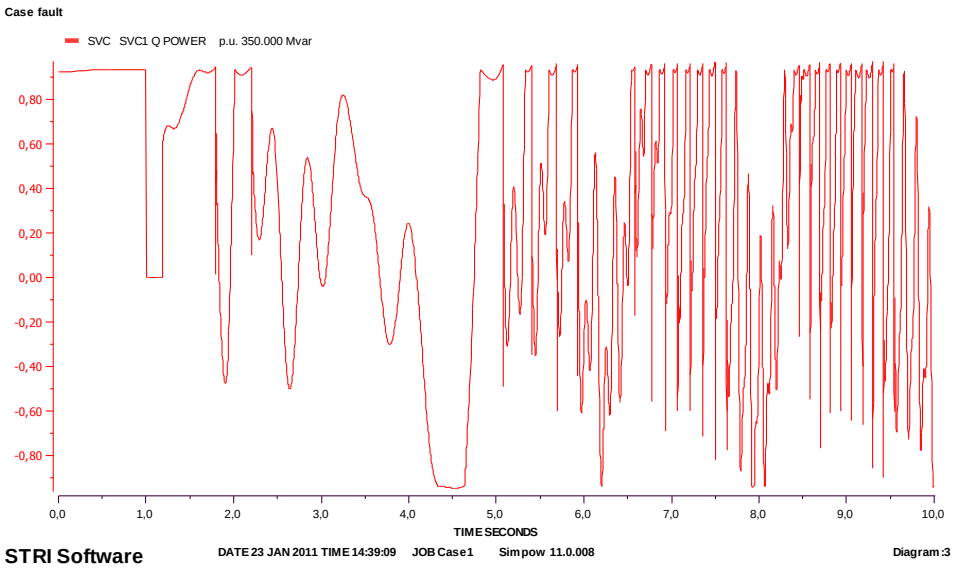


Figure 123 Case 7: Reactive power at the SVC

Figure 124 is the active power exchange in the DC lines. A strange behaviour occurs since during the fault, the power flow reverses to -0.1 p.u. The converter in DC voltage control mode is the one located on the grid side. It is controlling the active power into or out of the AC grid in such a way that the DC system voltage is kept to a constant level. Thus the voltage seen in Figure 122 is kept constant by shortly reversing the power flow. Then the power stabilizes in 0.3 s. However, there is a small increase in power passed 10 s that is explained in case 8. There is no reactive power in the cables; it is taken care by the PWM converter who tried to maintain the AC voltage level.

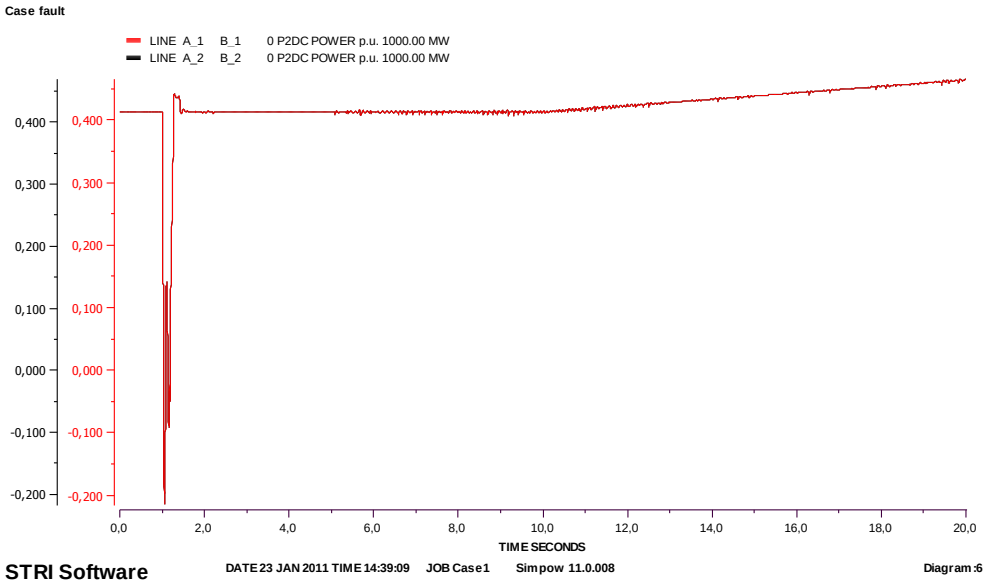


Figure 124 Case 7: Active power transfer in the DC lines

7.9 CASE 8: HVDC – STOP OF PRODUCTION OF 6100

This case is similar to case 5, except that the connexion of the wind farm to the grid is performed in HVDC. As in case 7, the voltage, speed and power of the FPCWT are constant.

Figure 125 is the DC power of the HVDC Light PWM converter on the grid side. When the production is stopped on bus 6100, oscillations are noticeable until t=1.6 s. Then, the DC power seems to be stabilized and the disconnection seems to have no effect on the load flow between the wind farm and bus 5600. However, at t=10s, a magnitude increase of the power can be noticed. In the PWM converter on the wind farm side, a reference number of the set-values of the active power control curve are given in the dynamic file. At t=20s, the reference value of the power is slightly changed to 0.9 instead of the previous 0.8 registered at t=10s. Thus, there is a 0.1 p.u. change from t=10s to t=20s that can be seen in Figure 126. As a result, the other converter observed in Figure 125 registers the same change.

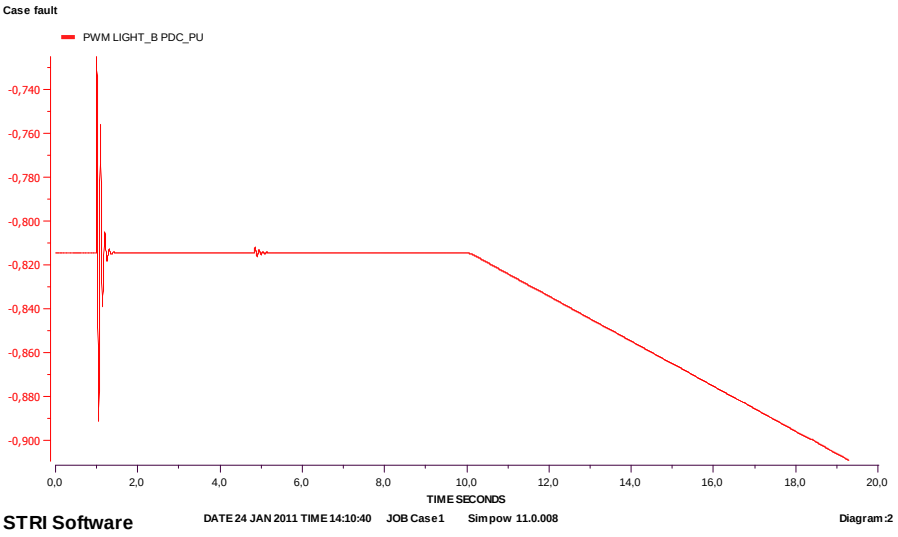


Figure 125 Case 8: DC power on grid-side PWM converter

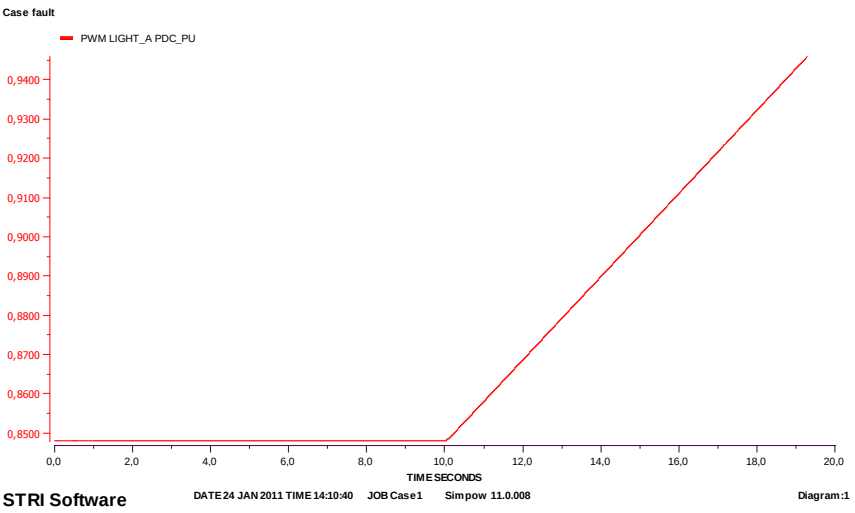


Figure 126 Case 8: DC power on FPCWT-side PWM converter

Figure 127 is the AC voltages on offshore and onshore busses. The onshore bus has the same behaviour than in case 5 except that the oscillations passed t=4s are of a lesser magnitude. The voltage on the AC offshore bus is not perturbed by the disconnection. It is the consequence of the power observed in Figure 126, there is no perturbation observed in the PWM converter to which the AC bus is connected.

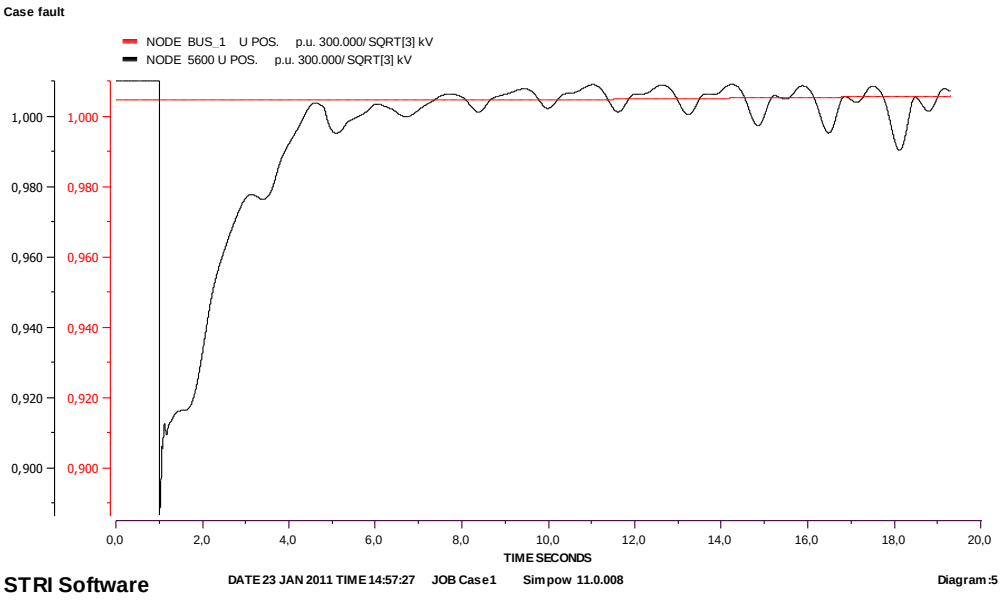


Figure 127 Case 8: Voltages on the offshore and onshore busses

Figure 128 is the reactive power at the SVC. After the disconnection, there is a drop of 0.1 p.u. The 5% time response is equal to 2.3 s and the SVC stabilizes totally to the pre-fault value.

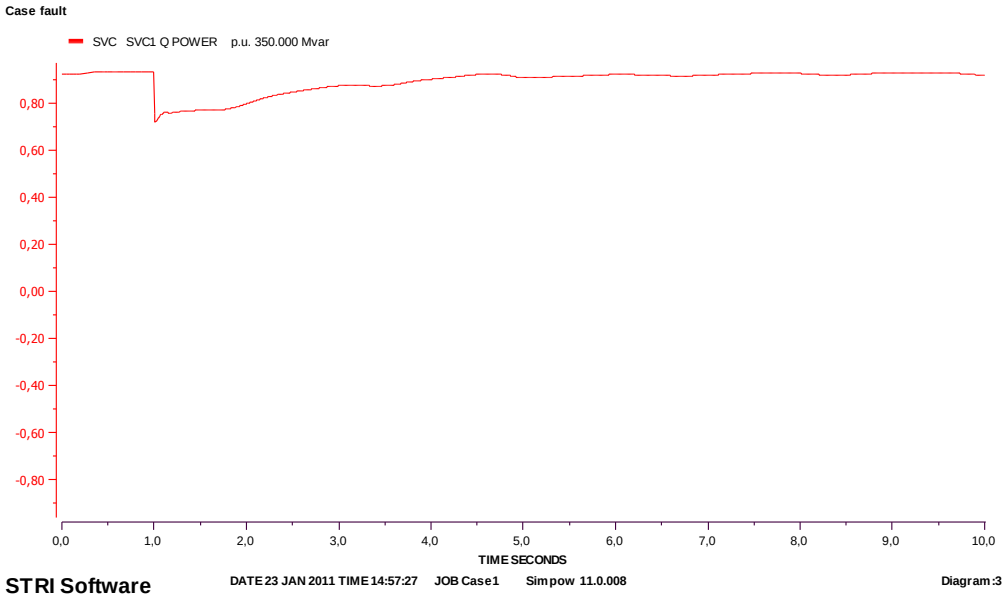


Figure 128 Case 8: Reactive power at the SVC

8 DISCUSSION

HVAC and Voltage Sourced Converters based HVDC transmissions have been implemented on a simplified grid model to connect a large offshore wind farm. The grid should be represented in reality by thousands of nodes. Moreover, the wind farm should not be an aggregated model but about 300 to 500 wind turbines interconnected with different offshore platforms with detailed converters and transformers. This lack of precision is mainly due to a lack of time for the duration of this thesis but also due to ease the work of simulations. However, the model and the simulations can serve has a basis for future works regarding integration of a large scale offshore wind farm to the Norwegian grid.

The HVAC connection in Sørlandet (bus 5600) served as a basis to compare to the other cases. In case 2, for a 50 ms three-phase fault to ground, the low voltage ride through requirements of Statnett's grid code were respected. The wind turbine is not disconnected and supports the grid with reactive power instead.

The 185 ms fault corresponds to the critical clearing time. Thus, beyond this point, a generator of the grid will automatically step out of phase become it will not have enough time to recover from the fault. The results on the SVC are relevant and show that the system is unstable by the end of the twenty seconds simulation. The voltage is regulated but not cleaned and the speed of the wind turbine has not reached a stable state. The results were awaited by implementing such a long fault.

The 5 ms fault shows that system is stable and does not suffer at all from small faults. The post-fault values are reached in a very short time compared to the 50 ms or the 185 ms fault. Moreover, the post-fault values are equal to the pre-fault values, as if nothing had happened.

The HVAC connection in Vestlandet (bus 6000) shows a similar behaviour to faults compared to the connection in Sørlandet since the wind farm and the connexion are the same. However, it can be observed that the results are smoother in the case in Sørlandet. As the generation is two times bigger on bus 5600 than on bus 6000, it seems that the system is more stable when connected to bus 5600. Bus 5600 is less dependent on the wind farm.

The VSC-HVDC connection shows similar results from the grid side than the HVAC connection. On the offshore wind farm bus, some differences can be noticed: the wind farm voltage is much more stable and seems to be totally protected from variations on the grid thanks to the PWM converters. A disconnection of a line on the HVDC link is not possible since both lines are required to operate the PWM converters. Thus, this case has not been studied. Moreover, the connexion in HVDC to Vestlandet has not been computed in this thesis since it gave similar results to the HVAC connexion.

9 CONCLUSION AND FUTURE WORK

Norway mainly exports electricity, especially during the summer because most of it comes from hydro power and dams are often full in this season. During the winter a high increase in power demand is registered, which is due to its location in Northern Europe. Last winter, in 2009-2010, was rough and thus Norway had to import up to 3000 MWh/h peak at certain time. Thus, new generation units are necessary for the growth of Norway.

Onshore wind power sites are fully exploited nowadays and it leads to implementations of wind farm off the shores, in shallow regions. Where the depth does not exceed 20 meters, the estimated potential for offshore wind generation is 6 000 to 30 000 MW with distances from 1 to 10 km. If large scale offshore wind power farms have to be made, they should be implemented further away from the coast, where the wind is even more stable and where the areas are larger. However, it requires foundations for depth of more than 50 km and further developments are needed in this field.

Improvements have been made regarding generators and converters in the wind turbine and as large wind turbines could be very efficient if placed offshore. Improvements have also been made regarding HVDC connexion because converter stations are not easily installed offshore, they are expansive and bulky. Improvements are made to increase their rating and thus reduce the number of cables and platforms needed. The capacity of HVAC and VSC based HVDC transmission technologies are low compared to LCC based HVDC but research is on the way to improve the ratings. For now, LCC based HVDC is the most economical way to connect a wind farm of 1000 MW to the grid but VSC based HVDC is being constantly improved and should replace LCC based HVDC.

The integration of a 1000 MW offshore wind farm to the grid has been studied. Four configurations were simulated: a 50 km HVAC connexion in Sørlandet and Vestlandet and a 100 km VSC based HVDC connexion in Sørlandet and Vestlandet. First the grid model had to be made in order to fit the simulation software. Then, the aggregated wind farm model had to be created. Finally, the connexions with converters, cables and transformers had to be made according to the ratings of the system and the grid code requirements.

The HVAC configuration showed 4.54% losses between the aggregated wind turbine and the connection bus on the grid. The HVDC configuration showed 7.97% losses. However, line losses are accounted and the HVDC configuration has two more PWM converters compared to the HVAC configuration.

Dynamic simulations have proven that the models were acting correctly regarding the grid code requirements. Voltages are automatically regulated and reactive power is taken care. The HVAC cases have shown that reactive power is important and even more compensating equipments should be installed on the model. The wind farm connected with VSC based HVDC cases have shown the independence created by the HVDC link so that if a problem occurs on the grid side, the wind farm is poorly impacted. The converters are very important in this configuration since the onshore converter is contributing to the stabilization of the grid after the fault.

The results of the simulation show that it is possible to install a large offshore wind farm in Norway in the two areas that were tested. The grid code can be respected but reactive power compensation has to be taken care of.

A more detailed wind farm should be implemented instead of such a big aggregation. Five platforms of 200 MW each at different distances would be more realistic. Moreover, the VSC based HVDC model is too basic and suffers from imprecision. A LCC based HVDC model is available in SIMPOW and could be tested instead. Thus, a comparison between both HVDC models could be developed. The grid model could be made more precise also, especially in Norway, in order to see the influence of the wind farm on more specific regions. Implementing a wind farm on a strong bus as in the cases of this thesis is not the same than on smaller busses.

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APPENDIX

APPENDIX A: DEFAULT CP CURVES OF THE FPCWT

β=0 deg.

λ [p.u.]	Cp[p.u.]
0.	0.00
1.	0.01
2.	0.05
3.	0.08
4.	0.28
5.	0.42
6.	0.48
6.5	0.49
7.	0.50
7.5	0.504
8.	0.50
8.5	0. 9
9.	0.48
10.	0.47
11.	0.45
12.	0.42
13.	0.39
14.	0.35
15.	0.30
16.	0.25
17.	0.19
18.	0.11
19.	0.06
20.	0 00

Table 1. Default values of the Cp/λ-curve at β=0 deg.

β=1 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.01
2.	0.03

3.	0.08
4.	0.26
5.	0. 0
6.	0.44
6.5	0.46
7.	0.47
7.5	0.48
8.	0.47
8.5	0.46
9.	0.45
10.	0.44
11.	0.43
12.	0.40
13.	0.37
14.	0 33
15.	0.28
16.	0.23
17.	0.18
18.	0.11
19.	0.05
19.5.	0.00

Table 2. Default values of the Cp/λ-curve at β=1 deg.

β=3 deg.

λ[p.u.	Cp[p.u.]
0.	0.00
1.	0.01
2.	0.04
3.	0.10
4.	0.25
5.	0.37
6.	0.42
6.5	0.43
7.	0.44
7.5	0.45
8.	0.44
8.	0.43

9.	0.42
10.	0.41
11.	0.40
12.	0.39
13.	0.36
14.	0.32
15.	0.27
16.	0.22
17.	0.15
18.	0.08
19.	0.00

Table 3. Default values of the Cp/λ-curve at β=3 deg.

β=5 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.02
2.	0.05
3.	0.15
4.	0.26
5.	0.34
.	0.37
6.5	0.38
7.	0.38
7.5	0.38
8.	0.37
8.5	0.36
9.	0.35
10.	0.32
11.	0.29
12.	0.25
13.	0.18
14.	0.11
15.	0.03
15.5	0.00

Table 4. Default values of the Cp/λ-curve at β=5 deg.

β=7 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.02
2.	0.05
3.	0.
4.	0.26
5.	0.30
6.	0.31
6.5	0.31
7.	0.30
7.5	0.28
8.	0.26
8.5	0.24
9.	0.22
10.	0.16
11.	0.08
12.	0.00

Table 5. Default values of the Cp/λ-curve at β=7 deg.

β=9 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.02
2.	0.05
3.	0.16
4.	0.23
5.	0.25
6.	0.24
6.5	0.22
7.	0.20
7.5	0.17
8.	0.14

8.5	0.10
9.	0.05
9.5	0.00

Table 6. Default values of the Cp/λ-curve at β=9 deg.

β=11 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.03
2.	0.06
3.	0.17
4.	0.21
5.	0.20
6.	0.15
6.5	0.12
7.	0.10
7.5	0.05
.	0.00

Table 7. Default values of the Cp/λ-curve at β=11 deg.

β=13 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.03
2.	0.06
3.	0.17
3.5	0.1
4.	0.18
5	0.13
6.	0.08
7.	0.00

Table 8. Default values of the Cp/λ-curve at β=13 deg.

β=19 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.03
2.	0.07
3.	0.11
3.5	0.08
4.	0.01
4.5	0.00

Table 9. Default values of the Cp/λ-curve at β=19 deg.

β=27 deg.

λ[p.u.]	Cp[p.u.]
0.	0.00
1.	0.03
2.	0.07
2.5	0.07
3.	0.05
3.5	0.00

Table 10. Default values of the Cp/λ-curve at β=27 deg.

APPENDIX B: HVAC OPTPOW FILE

```
SYSTEM BASE = 1000.000 MVA.
Reduced NORDEL power system model
V 3.2, 12.08.97
**
CONTROL DATA
 UBCHECK=NO
 NSEP=NO
END
GENERAL
 SN=1000.000
END
NODES
!                                    PSS NAME
!
! Nodes within the wind farm area    10
!
1000       UB= 3.000      TYPE=AC    AREA= 10
1001       UB= 5.000      TYPE=DC    AREA= 10
1002       UB= 3.500      TYPE=AC    AREA= 10
1003       UB= 300.000    TYPE=AC    AREA= 10
!
! Nodes within area     40
!
3000       UB= 420.000    TYPE=AC    AREA= 40 ! STCKH    !
3100       UB= 420.000    TYPE=AC    AREA= 40 ! STRFN    !
3115       UB= 420.000    TYPE=AC    AREA= 40 ! SV-N1    !
3200       UB= 420.000    TYPE=AC    AREA= 40 ! KRLSK    !
3244       UB= 300.000    TYPE=AC    AREA= 40 ! SV-M2    !
3245       UB= 420.000    TYPE=AC    AREA= 40 ! SV-M1    !
3249       UB= 420.000    TYPE=AC    AREA= 40 ! SV-N2    !
3300       UB= 420.000    TYPE=AC    AREA= 40 ! SV-SW    !
3359       UB= 420.000    TYPE=AC    AREA= 40 ! SV-W     !
3360       UB= 135.000    TYPE=AC    AREA= 40 ! KONT_135 !
3701       UB= 300.000    TYPE=AC    AREA= 40 ! SV-N2B   !
!
! Nodes within area     51
!
5100       UB= 300.000    TYPE=AC    AREA= 51 ! EAST3    !
5101       UB= 420.000    TYPE=AC    AREA= 51 ! EAST4-A  !
5102       UB= 420.000    TYPE=AC    AREA= 51 ! EAST4-B  !
5103       UB= 420.000    TYPE=AC    AREA= 51 ! EAST4-C  !
!
! Nodes within area     53
!
5300       UB= 300.000    TYPE=AC    AREA= 53 ! HDAL3    !
5301       UB= 420.000    TYPE=AC    AREA= 53 ! HDAL4    !
!
! Nodes within area     54
!
```

```
5400       UB= 300.000    TYPE=AC    AREA= 54 ! CNTR3-A  !
5401       UB= 420.000    TYPE=AC    AREA= 54 ! CNTR4-A  !
5402       UB= 420.000    TYPE=AC    AREA= 54 ! CNTR4-B  !
!
! Nodes within area    55
!
5500       UB= 300.000    TYPE=AC    AREA= 55 ! CNTR3-B  !
5501       UB= 420.000    TYPE=AC    AREA= 55 ! CNTR4-C  !
!
! Nodes within area    56
!
5600       UB= 300.000    TYPE=AC    AREA= 56 ! SOUTH3A  !
5601       UB= 420.000    TYPE=AC    AREA= 56 ! SOUTH4A  !
5602       UB= 420.000    TYPE=AC    AREA= 56 ! SOUTH4B  !
5603       UB= 300.000    TYPE=AC    AREA= 56 ! SOUTH3B  !
!
! Nodes within area    60
!
6000       UB= 300.000    TYPE=AC    AREA= 60 ! WEST300  !
6001       UB= 420.000    TYPE=AC    AREA= 60 ! WEST400  !
!
! Nodes within area    61
!
6100       UB= 300.000    TYPE=AC    AREA= 61 ! NWEST3   !
!
! Nodes within area    65
!
6500       UB= 300.000    TYPE=AC    AREA= 65 ! MID300   !
!
! Nodes within area    67
!
6700       UB= 300.000    TYPE=AC    AREA= 67 ! NOR300   !
6701       UB= 420.000    TYPE=AC    AREA= 67 ! NOR400   !
!
! Nodes within area    70
!
7000       UB= 420.000    TYPE=AC    AREA= 70 ! SO-FIN   !
!
! Nodes within area    71
!
7100       UB= 420.000    TYPE=AC    AREA= 71 ! NO-FIN   !
!
! Nodes within area    90
!
8500       UB= 420.000    TYPE=AC    AREA= 90 ! SJOLLAND !
END

SREACTORS
5400    5500     NO= 81 TYPE=11  R= 0.890000E-02 X= 0.111000
END
```

```
PWM CONVERTERS
 FPCWT_REC    1000   1001   AC2=1000
            TYPE=DSLS/FPCWT_PWM_OPT/      SN=1060.0
                 UN=3.0     X=0.3      PL=0.02       MODE=1     ORDER=1000.0

 FPCWT_INV    1002   1001   AC2=1002
            TYPE=DSLS/FPCWT_PWM_OPT/      SN=1060.0
                 UN=3.5     X=0.3      PL=0.02       MODE=2     ORDER=5
END


SHUNT IMPEDANCES ! Line type 13,14 and 15 are translated as lines type 12.
!              Corresponding GI,BI,GJ,BJ are translated as shunts !
1001    NO= 81 R=  1E6        C=  1.2381  !2.4E-3
5101    NO= 81 R=  0.00000    X=  181.034
5101    NO=810 R=  7910.31    X=  0.00000
5501    NO=811 R=  0.00000    X= -181.034
5501    NO=812 R= -8166.67    X=  0.00000
5102    NO= 81 R=  0.00000    X=-0.176397E+07
5102    NO=810 R=  882000.    X=  0.00000
6001    NO=811 R=  0.00000    X= 0.176397E+07
6001    NO=812 R=  882000.    X=  0.00000
5103    NO= 81 R=  0.00000    X=  13889.8
5103    NO=810 R=  441000.    X=  0.00000
5301    NO=811 R=  0.00000    X= -13889.8
5301    NO=812 R= -588000.    X=  0.00000
5401    NO= 81 R=  0.00000    X=  352800.
5401    NO=810 R= -882000.    X=  0.00000
6001    NO=813 R=  0.00000    X= -352800.
6001    NO=814 R=  882000.    X=  0.00000
5500    NO= 81 R=  0.00000    X= -69230.8
5500    NO=810 R=  300000.    X=  0.00000
5603    NO=811 R=  0.00000    X=  69230.8
5603    NO=812 R= -300000.    X=  0.00000
END
LINES
! See also the second LINES-chapter further below,
! containing all lines of TYPE=11.


1003     5600     NO=  1   TYPE=2    R= 0.034  X=0.1382
                       B=0.0000438     L=  50

1003     5600     NO=  2   TYPE=2    R= 0.034  X=0.1382
                       B=0.0000438     L=  50

3000     3115     NO=  81  TYPE=12    R= 0.140000E-01  X= 0.100000
                        B= 0.300000E-01 L=  10.00

3000     3245     NO=  81  TYPE=12    R= 0.125000E-02  X= 0.170100E-01
                        B= 0.127460E-01 L=  10.00
```

3000 3300 NO= 81 TYPE=12 R= 0.113000E-02 X= 0.170100E-01
B= 0.116380E-01 L= 10.00

3100 3115 NO= 81 TYPE=12 R= 0.301000E-02 X= 0.413800E-01
B= 0.775800E-02 L= 10.00

3100 3200 NO= 81 TYPE=12 R= 0.686000E-02 X= 0.561200E-01
B= 0.171790E-01 L= 10.00

3100 3249 NO= 81 TYPE=12 R= 0.108000E-02 X= 0.147400E-01
B= 0.105290E-01 L= 10.00

3100 3359 NO= 81 TYPE=12 R= 0.910000E-03 X= 0.119000E-01
B= 0.221700E-02 L= 10.00

3115 3245 NO= 81 TYPE=12 R= 0.300000E-02 X= 0.500000E-01
B= 0.900000E-02 L= 10.00

3115 3249 NO= 81 TYPE=12 R= 0.150000E-02 X= 0.200000E-01
B= 0.400000E-02 L= 10.00

3115 6701 NO= 81 TYPE=12 R= 0.400000E-02 X= 0.300000E-01
B= 0.500000E-02 L= 10.00

3115 7100 NO= 81 TYPE=12 R= 0.100000E-01 X= 0.700000E-01
B= 0.100000E-01 L= 10.00

3200 3300 NO= 81 TYPE=12 R= 0.125000E-02 X= 0.170100E-01
B= 0.332500E-02 L= 10.00

3200 3359 NO= 81 TYPE=12 R= 0.357000E-02 X= 0.408200E-01
B= 0.775800E-02 L= 10.00

3244 6500 NO= 81 TYPE=12 R= 0.500000E-03 X= 0.500000E-02
B= 0.100000E-03 L= 10.00

3249 7100 NO= 81 TYPE=12 R= 0.100000E-01 X= 0.700000E-01
B= 0.100000E-01 L= 10.00

3300 3359 NO= 81 TYPE=12 R= 0.740000E-03 X= 0.964000E-02
B= 0.166300E-02 L= 10.00

3300 8500 NO= 81 TYPE=12 R= 0.800000E-02 X= 0.310000E-01
B= 0.300000E-01 L= 10.00

3359 5101 NO= 81 TYPE=12 R= 0.148000E-02 X= 0.192800E-01
B= 0.360200E-02 L= 10.00

3701 6700 NO= 81 TYPE=12 R= 0.100000E-02 X= 0.100000
B= 0.500000E-03 L= 10.00

```
5100    5300    NO=  81  TYPE=12   R= 0.400000E-02  X= 0.400000E-01
                     B= 0.500000E-02 L=  10.00

5100    5500    NO=  81  TYPE=12   R= 0.180000E-02  X= 0.150000E-01
                     B= 0.212800E-02 L=  10.00

5100    6500    NO=  81  TYPE=12   R= 0.150000E-01  X= 0.150000
                     B= 0.100000E-03 L=  10.00

5101    5501    NO=  81  TYPE=12   R= 0.610000E-03  X= 0.643000E-02
                B= 0.325920E-01 L=  10.00
           RNO1=  810  RNO2=  812

5102    5301    NO=  81  TYPE=12   R= 0.750000E-03  X= 0.107900E-01
                     B= 0.128600E-01 L=  10.00

5102    6001    NO=  81  TYPE=12   R= 0.200000E-02  X= 0.350000E-01
                B= 0.100000E-01 L=  10.00
           RNO1=  810  RNO2=  812

5103    5301    NO=  81  TYPE=12   R= 0.170000E-02  X= 0.231200E-01
                B= 0.675500E-02 L=  10.00
           RNO1=  810  RNO2=  812

5400    6000    NO=  81  TYPE=12   R= 0.100000E-02  X= 0.100000E-01
                     B= 0.100000E-02 L=  10.00

5400    6100    NO=  81  TYPE=12   R= 0.200000E-02  X= 0.200000E-01
                     B= 0.120000E-02 L=  10.00

5401    5501    NO=  81  TYPE=12   R= 0.150000E-02  X= 0.200000E-01
                     B= 0.600000E-02 L=  10.00

5401    5602    NO=  81  TYPE=12   R= 0.154000E-02  X= 0.240600E-01
                     B= 0.879600E-02 L=  10.00

5401    6001    NO=  81  TYPE=12   R= 0.300000E-03  X= 0.500000E-02
                B= 0.150000E-02 L=  10.00
           RNO1=  810  RNO2=  814

5402    6001    NO=  81  TYPE=12   R= 0.510000E-03  X= 0.751000E-02
                     B= 0.235200E-02 L=  10.00

5500    5603    NO=  81  TYPE=12   R= 0.400000E-02  X= 0.450000E-01
                B= 0.800000E-03 L=  10.00
           RNO1=  810  RNO2=  812

5600    5603    NO=  81  TYPE=12   R= 0.201000E-02  X= 0.221100E-01
                     B= 0.208400E-02 L=  10.00

5600    6000    NO=  81  TYPE=12   R= 0.350000E-02  X= 0.350000E-01
                     B= 0.450000E-02 L=  10.00
```

```
5601    6001    NO=  81  TYPE=12   R= 0.137000E-02  X= 0.203100E-01
                     B= 0.636400E-02 L=  10.00

6000    6100    NO=  81  TYPE=12   R= 0.220000E-02  X= 0.239400E-01
                     B= 0.200000E-02 L=  10.00

6500    6700    NO=  81  TYPE=12   R= 0.800000E-02  X= 0.110000
                     B= 0.100000E-02 L=  10.00

7000    7100    NO=  81  TYPE=12   R= 0.140000E-01  X= 0.100000
                     B= 0.300000E-01 L=  10.00

7000    7100    NO=  82  TYPE=12   R= 0.140000E-01  X= 0.100000
                     B= 0.300000E-01 L=  10.00

3359    5101    NO=  82  TYPE=12   R= 0.148000E-02  X= 0.192800E-01
                     B= 0.360200E-02 L=  10.00

5300    6100    NO=  81  TYPE=12   R= 0.359000E-02  X= 0.382500E-01
                     B= 0.115200E-02 L=  10.00
  NCON=1
7000    7100    NO=  83  TYPE=12   R= 0.140000E-01  X= 0.100000
                     B= 0.300000E-01 L=  10.00
  NCON=1
END
TRANSFORMERS
! Transformers with TCR, i.e. with STEP, -NSTEP!
1002    1003     NO=369   SN=1060.0  UN1=3.5     UN2=300.0
     ER12=0.0032   EX12=0.0599
     STEP=0.025  +NSTEP=2  -NSTEP=2
3244    3245     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
     ER12=   0.00500  EX12=   0.02000 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
3701    3249     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
     ER12=   0.02000  EX12=   0.50000 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
3359    3360     NO=369   SN=1000.000  UN1= 420.000  UN2= 135.000
     ER12=   0.00500  EX12=   0.02000 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5101    5100     NO=369   SN=1000.000  UN1= 420.000  UN2= 300.000
     ER12=   0.00080  EX12=   0.03050 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5102    5100     NO=369   SN=1000.000  UN1= 420.000  UN2= 300.000
     ER12=   0.00080  EX12=   0.03050 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5103    5100     NO=369   SN=1000.000  UN1= 420.000  UN2= 300.000
     ER12=   0.00250  EX12=   0.10000 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5300    5301     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
     ER12=   0.00160  EX12=   0.06100 FI=   0.00       TAPSIDE=1
     STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
```

```
5400    5401     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00320  EX12=  0.12000 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5400    5402     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00040  EX12=  0.01500 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5500    5501     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00040  EX12=  0.01500 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5600    5601     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00020  EX12=  0.00760 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5603    5602     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00080  EX12=  0.03050 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
6000    6001     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00040  EX12=  0.01500 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
6700    6701     NO=369   SN=1000.000  UN1= 300.000  UN2= 420.000
      ER12=  0.00500  EX12=  0.02000 FI=  0.00       TAPSIDE=1
      STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
END
TRANSFORMERS
! 3-WINDING TRANSFORMERS
END
LOADS
! PSS/E load data is translated as follows:
! Constant loads   PSS/E PL,QL defined with exponents MP=0 MQ=0 !
! Constant current PSS/E IP, IQ defined with exponents MP=1, MQ=1 !
! Constant addmittance PSS/E YP,YQ defined withexponents MP=2, MQ=2 !
3000    NO=  1  P=  2500.000  Q=   500.000  MP=0  MQ=0
3000    NO=  2  P=  -500.000  Q=   250.000  MP=0  MQ=0
3100         P=   500.000  Q=   100.000  MP=0  MQ=0
3200         P=   500.000  Q=   100.000  MP=0  MQ=0
3245         P=  2700.000  Q=   500.000  MP=0  MQ=0
3249         P=  1250.000  Q=   300.000  MP=0  MQ=0
3300         P=  9350.000  Q=  1500.000  MP=0  MQ=0
3359         P=  4500.000  Q=   700.000  MP=0  MQ=0
3360         P=   360.000  Q=   180.000  MP=0  MQ=0
5100         P=  4210.000  Q=   692.000  MP=0  MQ=0
5300         P=   201.000  Q=    11.300  MP=0  MQ=0
5400         P=    94.400  Q=     0.000  MP=0  MQ=0
5500         P=  1229.000  Q=   115.000  MP=0  MQ=0
5600         P=  3121.000  Q=   297.000  MP=0  MQ=0
5603    NO=  1  P=   460.000  Q=    45.000  MP=0  MQ=0
5603    NO=  2  P=   940.000  Q=   470.000  MP=0  MQ=0
6000         P=     4.000  Q=     0.000  MP=0  MQ=0
6100         P=  3042.000  Q=   980.000  MP=0  MQ=0
6500         P=  1919.000  Q=   279.000  MP=0  MQ=0
6700         P=  1927.000  Q=   446.000  MP=0  MQ=0
7000    NO=  1  P=  5100.000  Q=  1000.000  MP=0  MQ=0
7000    NO=  2  P=   500.000  Q=   250.000  MP=0  MQ=0
```

```
7100          P=  2500.000  Q=   400.000  MP=0  MQ=0
8500          P=  1000.000  Q=  1000.000  MP=0  MQ=0
END
POWER CONTROL
1000    TYPE=NODE  NAME=FPCWT_GEN   RTYP=SW  U= 3.0         FI=0.0
      QMIN= -49995.00     QMAX=  49995.00
5600    TYPE=NODE  NAME=SVC1       RTYP=UP U=303 P=0
      QMIN=-320  QMAX=320
3300    TYPE=NODE  NAME=SV-SGG1_   RTYP=SW  U= 420.000000    FI=   0.0000     !
      QMIN= -49995.00     QMAX=  49995.00
3000    TYPE=NODE  NAME=STCKGG1_   RTYP=UP  U=  420.0000     P= 5300.000
      QMIN= -49995.00     QMAX=  49995.00
3100    TYPE=NODE  NAME=STRFGG1_   RTYP=UP  U=  407.4000     P= 1500.000
      QMIN= -49995.00     QMAX=  49995.00
3115    TYPE=NODE  NAME=SV-NGG11   RTYP=UP  U=  420.0000     P= 3570.000
      QMIN= -49995.00     QMAX=  49995.00
!3200    TYPE=NODE  NAME=KRLSGG1_   RTYP=UP  U=  420.0000     P=    0.000
!       QMIN= -49995.00     QMAX=  49995.00     NCON=1
3245    TYPE=NODE  NAME=SV-MGG1_   RTYP=UP  U=  420.0000     P=  780.000
      QMIN= -49995.00     QMAX=  49995.00
3249    TYPE=NODE  NAME=SV-NGG12   RTYP=UP  U=  420.0000     P= 4750.000
      QMIN= -49995.00     QMAX=  49995.00
3359    TYPE=NODE  NAME=SV-WGG1_   RTYP=UP  U=  420.0000     P= 2670.000
      QMIN= -49995.00     QMAX=  49995.00
3359    TYPE=NODE  NAME=SV-WGG2_   RTYP=UP  U=  420.0000     P=  830.000
      QMIN= -9999.000     QMAX=  9999.000
5100    TYPE=NODE  NAME=EASTGG1_   RTYP=UP  U=  300.0000     P= 1480.000
      QMIN= -49995.00     QMAX=  49995.00
5300    TYPE=NODE  NAME=HDALGG1_   RTYP=UP  U=  300.0000     P= 2275.000
      QMIN= -49995.00     QMAX=  49995.00
5400    TYPE=NODE  NAME=CNTRGG11   RTYP=UP  U=  302.1000     P= 1588.000
      QMIN= -49995.00     QMAX=  49995.00
5500    TYPE=NODE  NAME=CNTRGG12   RTYP=UP  U=  301.2000     P=  828.000
      QMIN= -49995.00     QMAX=  49995.00
5600    TYPE=NODE  NAME=SOUTGG11   RTYP=UP  U=  303.0000     P= 2378.000
!5603    TYPE=NODE  NAME=SOUTGG12   RTYP=UP  U=  300.0000     P=  100.000
!       QMIN= -9999.000     QMAX=  9999.000     NCON=1
6000    TYPE=NODE  NAME=WESTGG1_   RTYP=UP  U=  301.5000     P= 1129.000
      QMIN= -1000.000     QMAX=  1000.000
6100    TYPE=NODE  NAME=NWESGG1_   RTYP=UP  U=  300.0000     P= 2346.000
      QMIN= -49995.00     QMAX=  49995.00
6500    TYPE=NODE  NAME=MID3GG1_   RTYP=UP  U=  300.0000     P= 1511.000
      QMIN= -49995.00     QMAX=  49995.00
6700    TYPE=NODE  NAME=NOR3GG1_   RTYP=UP  U=  306.0000     P= 2771.000
      QMIN= -49995.00     QMAX=  49995.00
7000    TYPE=NODE  NAME=SO-FGG1_   RTYP=UP  U=  420.0000     P= 5300.000
      QMIN= -49995.00     QMAX=  49995.00
7100    TYPE=NODE  NAME=NO-FGG1_   RTYP=UP  U=  420.0000     P= 1310.000
      QMIN= -49995.00     QMAX=  49995.00
8500    TYPE=NODE  NAME=SJOLGG1_   RTYP=UP  U=  428.4000     P= 1000.000
      QMIN= -49995.00     QMAX=  49995.00
```

```
   ! Transformers RTYP=UFI:
3244    3245     NO=369 TYPE=TREG RTYP=UFI U=420.0000 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000
3359    3360     NO=369 TYPE=TREG RTYP=UFI U=134.2913 FI=  0.000
!  UMIN= 252.0000 UMAX=588.0000
5300    5301     NO=369 TYPE=TREG RTYP=UFI U=420.2604 FI=  0.000
!  UMIN= 180.0000 UMAX=420.0000
5400    5401     NO=369 TYPE=TREG RTYP=UFI U=418.4880 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000
5400    5402     NO=369 TYPE=TREG RTYP=UFI U=422.5284 FI=  0.000
!  UMIN= 180.0000 UMAX=420.0000
5500    5501     NO=369 TYPE=TREG RTYP=UFI U=421.9068 FI=  0.000
!  UMIN= 180.0000 UMAX=420.0000
5600    5601     NO=369 TYPE=TREG RTYP=UFI U=416.6610 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000
5603    5602     NO=369 TYPE=TREG RTYP=UFI U=401.5368 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000
6000    6001     NO=369 TYPE=TREG RTYP=UFI U=419.8320 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000
6700    6701     NO=369 TYPE=TREG RTYP=UFI U=422.9316 FI=  0.000
!  UMIN= 180.0000 UMAX=420.0000

! Transformers defined with RTYP=UFI. CNODE bus voltage is set fixed.
! The CNODE is set as the first node name in order in the data list
3701    3249     NO=369 TYPE=TREG RTYP=UFI TAU=  1.00000 FI=  0.000
   UMIN= 180.0000 UMAX=420.0000 CNODE=3701    U=302.22897
5101    5100     NO=369 TYPE=TREG RTYP=UFI TAU=  1.00635 FI=  0.000
   UMIN= 252.0000 UMAX=588.0000 CNODE=5101    U=415.74121
5102    5100     NO=369 TYPE=TREG RTYP=UFI TAU=  1.00000 FI=  0.000
   UMIN= 252.0000 UMAX=588.0000 CNODE=5102    U=420.00842
5103    5100     NO=369 TYPE=TREG RTYP=UFI TAU=  1.00000 FI=  0.000
   UMIN= 252.0000 UMAX=588.0000 CNODE=5103    U=419.17682
END
END
```

APPENDIX C: HVAC DYNPOW FILE

```
Case fault
**

CONTROL DATA
 TEND=20
 SPL=1.7
 NPRD=3000
 DEND=0.1
 N7=40
 GAM5=0.01
 TETL=100000
END



GENERAL
 NREF=2
 FN 50.0  50.0
 REF= FPCWT_GEN      SV-SGG1_
END



GLOBALS

 FPCWT_REC_IQORD      TYPE=REAL
 FPCWT_REC_IQORD0     TYPE=REAL
 FPCWT_REC_DW         TYPE=REAL
 FPCWT_INV_IQORD      TYPE=REAL
 FPCWT_INV_IQORD0     TYPE=REAL
 FPCWT_REC_PORD      TYPE=REAL

END


SVC
 SVC1 5600 SN=350  REG=100
END


SYNCHRONOUS MACHINES
 FPCWT_GEN  1000    SN = 1060.0  UN = 3.0   TYPE = 2A   H = 5.5
              RA= 0.0025  XD= 1.9  XQ = 1.6  XDP = 0.32  XDB = 0.2
              XQB = 0.21  XA = 0.14  TD0P = 5.0  TD0B = 0.03  TQ0B = 0.07
              TURB=1

 SV-SGG1_   3300    TYPE=1    XD=2.42    XQ=2.00    XA=0.1481  XDP=0.23     XQP=0.4108
```

```
          XDB=0.16  XQB=0.16  RA=0.0    TD0P=10.8  TQ0P=1
          TD0B=0.05  TQ0B=0.05  V1=1     V2=1.2    SE1=0.1089  SE2=0.378
          TURB=40   H=6.0     SN=5000   UN=420    D=0       VREG=24

STCKGG1_  3000   TYPE=1   XD=2.22   XQ=2.13   XA=0.1688  XDP=0.36   XQP=0.468
          XDB=0.225  XQB=0.225  RA=0.0    TD0P=5.0   TQ0P=1
          TD0B=0.05  TQ0B=0.05  V1=1     V2=1.2    SE1=0.1089  SE2=0.378
          TURB=40   H=5.97    SN=5579   UN=420    D=0       VREG=10

STRFGG1_  3100   TYPE=2   XD=0.65   XQ=0.39   XA=0.0877  XDP=0.19
          XDB=0.1169 XQB=0.1169 RA=0.0    TD0P=4.0
          TD0B=0.06  TQ0B=0.1   V1=1     V2=1.2    SE1=0.1024  SE2=0.2742
          TURB=20   H=5.04    SN=1579   UN=420    D=0       VREG=20

SV-NGG11  3115   TYPE=2   XD=0.946  XQ=0.565  XA=0.1108  XDP=0.29
          XDB=0.23  XQB=0.23  RA=0.0    TD0P=7.57
          TD0B=0.045 TQ0B=0.1   V1=1     V2=1.2    SE1=0.1024  SE2=0.2742
          TURB=21   H=4.741   SN=3758   UN=420    D=0       VREG=23

!KRLSGG1_  3200   TYPE=1  XD=1.8   XQ=1.7   XA=0.2   XDP=0.3   XQP=0.55
!          XDB=0.25  XQB=0.25  RA=0.0025 TD0P=8.0   TQ0P=0.4
!          TD0B=0.03 TQ0B=0.05 TAB=1    TURB=3
!          H=6.5    SN=1    UN=420    D=0      VREG=2

SV-MGG1_  3245   TYPE=2   XD=0.75   XQ=0.50   XA=0.1154  XDP=0.25
          XDB=0.1538 XQB=0.1538 RA=0.0    TD0P=5.0
          TD0B=0.06  TQ0B=0.1   V1=1     V2=1.2    SE1=0.1024  SE2=0.2742
          TURB=22   H=3.3     SN=822    UN=420    D=0       VREG=20

SV-NGG12  3249   TYPE=2   XD=1.036  XQ=0.63   XA=0.1154  XDP=0.28
          XDB=0.21  XQB=0.21  RA=0.0    TD0P=10.13
          TD0B=0.06  TQ0B=0.1   V1=1     V2=1.2    SE1=0.1024  SE2=0.2742
          TURB=23   H=4.543   SN=5000   UN=420    D=0       VREG=20

SV-WGG1_  3359   TYPE=2   XD=0.75   XQ=0.50   XA=0.1154  XDP=0.25
          XDB=0.1938 XQB=0.1938 RA=0.0    TD0P=5.0
          TD0B=0.06  TQ0B=0.1   V1=1     V2=1.2    SE1=0.1024  SE2=0.2742
          TURB=22   H=3.3     SN=2811   UN=420    D=0       VREG=25

SV-WGG2_  3359   TYPE=1   XD=2.13   XQ=2.03   XA=0.1453  XDP=0.31   XQP=0.403
          XDB=0.1937 XQB=0.1937 RA=0.0    TD0P=4.75  TQ0P=1
          TD0B=0.05  TQ0B=0.05  V1=1     V2=1.2    SE1=0.1089  SE2=0.378
          TURB=40   H=4.82    SN=874    UN=420    D=0       VREG=22

EASTGG1_  5100   TYPE=2   XD=1.1332  XQ=0.6832  XA=0.1341  XDP=0.243
          XDB=0.1514 XQB=0.1514 RA=0.0    TD0P=4.9629
          TD0B=0.05  TQ0B=0.15  V1=1     V2=1.2    SE1=0.10   SE2=0.30
          TURB=25   H=3.9871  SN=1558   UN=300    D=0       VREG=30

HDALGG1_  5300   TYPE=2   XD=1.14   XQ=0.84   XA=0.2    XDP=0.34
          XDB=0.26  XQB=0.26  RA=0.0    TD0P=6.4
          TD0B=0.05  TQ0B=0.15  V1=1     V2=1.2    SE1=0.10   SE2=0.30
```

```
          TURB=25   H=3.5    SN=2395   UN=300    D=0      VREG=27

CNTRGG11  5400   TYPE=2    XD=1.02   XQ=0.63   XA=0.13   XDP=0.25
          XDB=0.16  XQB=0.16  RA=0.0    TD0P=6.5
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=25   H=4.1    SN=1672   UN=300    D=0      VREG=30

CNTRGG12  5500   TYPE=2    XD=1.2364 XQ=0.6557 XA=0.1619 XDP=0.3741
          XDB=0.2283 XQB=0.2283 RA=0.0    TD0P=7.198
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=25   H=3.0    SN=872    UN=300    D=0      VREG=30

SOUTGG11  5600   TYPE=2    XD=1.0    XQ=0.5132 XA=0.21   XDP=0.38
          XDB=0.28  XQB=0.28  RA=0.0    TD0P=7.85
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=24   H=3.5    SN=2504   UN=300    D=0      VREG=26

!SOUTGG12  5603   TYPE=1 XD=1.8   XQ=1.7   XA=0.2   XDP=0.3   XQP=0.55
!          XDB=0.25 XQB=0.25 RA=0.0025 TD0P=8.0  TQ0P=0.4
!          TD0B=0.03 TQ0B=0.05 TAB=1    TURB=3
!          H=6.5    SN=106   UN=300    D=0      VREG=2

WESTGG1_  6000   TYPE=2    XD=1.28   XQ=0.94   XA=0.2    XDP=0.37
          XDB=0.28  XQB=0.28  RA=0.0    TD0P=9.7
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=24   H=3.5    SN=1189   UN=300    D=0      VREG=31

NWESGG1_  6100   TYPE=2    XD=1.2    XQ=0.73   XA=0.15   XDP=0.37
          XDB=0.18  XQB=0.18  RA=0.0    TD0P=9.9
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=25   H=3.0    SN=2470   UN=300    D=0      VREG=27

MID3GG1_  6500   TYPE=2    XD=1.0679 XQ=0.6420 XA=0.1351 XDP=0.2387
          XDB=0.158 XQB=0.158 RA=0.0    TD0P=5.4855
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=25   H=3.558  SN=1591   UN=300    D=0      VREG=30

NOR3GG1_  6700   TYPE=2    XD=1.1044 XQ=0.6619 XA=0.1474 XDP=0.2548
          XDB=0.1706 XQB=0.1706 RA=0.0    TD0P=5.24
          TD0B=0.05 TQ0B=0.15 V1=1      V2=1.2    SE1=0.10  SE2=0.30
          TURB=25   H=3.5920 SN=2917   UN=300    D=0      VREG=27

SO-FGG1_  7000   TYPE=1    XD=2.22   XQ=2.13   XA=0.1688 XDP=0.36   XQP=0.468
          XDB=0.225 XQB=0.225 RA=0.0    TD0P=10.0 TQ0P=1
          TD0B=0.05 TQ0B=0.05 V1=1      V2=1.2    SE1=0.1089 SE2=0.378
          TURB=40   H=5.5    SN=5579   UN=420    D=0      VREG=11

NO-FGG1_  7100   TYPE=2    XD=0.75   XQ=0.50   XA=0.1154 XDP=0.25
          XDB=0.1538 XQB=0.1538 RA=0.0    TD0P=5.0
          TD0B=0.06 TQ0B=0.10 V1=1      V2=1.2    SE1=0.1024 SE2=0.2742
          TURB=22   H=3.20   SN=1379   UN=420    D=0      VREG=27
```

```
 SJOLGG1_  8500   TYPE=1    XD=2.42   XQ=2.00   XA=0.1481  XDP=0.23   XQP=0.4108
           XDB=0.1706 XQB=0.1706 RA=0.0    TD0P=10.0  TQ0P=1
           TD0B=0.05  TQ0B=0.05  V1=1      V2=1.2    SE1=0.1089   SE2=0.378
           TURB=40   H=7.0     SN=1056   UN=420    D=0       VREG=28

END


REGULATORS


 10   TYPE=DSLS/IEEEX2/
    TR=0    KA=729   TA=0.04   VRMAX=5.32   VRMIN=-4.05
    KE=1.0   TE=0.44   KF=0.0667  TF1=2.0     TF2=0.44
    E1=6.5   SE1=0.054 E2=8      SE2=0.2020   TB=0      TC=0       SWS=40

 11   TYPE=DSLS/IEEEX2/
    TR=0    KA=800   TA=0.04   VRMAX=5.32   VRMIN=-4.05
    KE=1.0   TE=0.44   KF=0.0667  TF1=2.0     TF2=0.44
    E1=6.5   SE1=0.054 E2=8      SE2=0.2020   TB=0      TC=0       SWS=44


 20   TYPE=BBC1
    T1=3.3   T3=13    K=31     T4=0.05   T2=0
    UEMIN=0  UEMAX=4

 21   TYPE=BBC1
    T1=0    T3=0.04   K=10     T4=0.04   T2=0
    UEMIN=0  UEMAX=5

 22   TYPE=BBC1
    T1=2    T3=10    K=165    T4=0.04   T2=0
    UEMIN=0  UEMAX=5

 23   TYPE=BBC1
    T1=3.3   T3=13    K=31     T4=0.05   T2=0
    UEMIN=0  UEMAX=4   SWS=41

 24   TYPE=BBC1
    T1=0    T3=0.04   K=10     T4=0.04   T2=0
    UEMIN=0  UEMAX=5   SWS=42

 25   TYPE=BBC1
    T1=3.3   T3=13    K=31     T4=0.05   T2=0
    UEMIN=0  UEMAX=4   SWS=43

 26   TYPE=BBC1
    T1=3.3   T3=13    K=61     T4=0.05   T2=0
    UEMIN=0  UEMAX=4

 27   TYPE=BBC1
```

```
    T1=3.3  T3=13    K=61    T4=0.05  T2=0
    UEMIN=0  UEMAX=4  SWS=42

 28  TYPE=BBC1
    T1=0    T3=0.04  K=10    T4=0.04  T2=0
    UEMIN=0  UEMAX=5  SWS=42

 30  TYPE=BBC1
    T1=0.00005 T2=0   T3=100   T4=0.5     K=200
    UEMIN=0   UEMAX=4

 31  TYPE=BBC1
    T1=10    T2=0   T3=0.1   T4=0.1     K=20
    UEMIN=-4  UEMAX=4

 40  TYPE=DSLS/STAB2A/
    K2=1  T2=2   K3=0   T3=2  K4=0.55  K5=1  T5=0.01  HLIM=0.03

 41  TYPE=DSLS/STAB2A/
    K2=1  T2=4.5  K3=0.87  T3=2  K4=0.087  K5=1  T5=0.01  HLIM=0.04

 42  TYPE=DSLS/STAB2A/
    K2=1  T2=4.5  K3=0   T3=2  K4=0.55  K5=1  T5=0.01  HLIM=0.03

 43  TYPE=DSLS/STAB2A/
    K2=1  T2=4.5  K3=0   T3=2  K4=0.68  K5=1  T5=0.01  HLIM=0.03

 44  TYPE=DSLS/STAB2A/
    K2=1  T2=1.0  K3=0   T3=2  K4=0.55  K5=1  T5=0.01  HLIM=0.03

 100  TYPE=SVS
    RTYP=2  KP=15  TF=0.02  VPMAX=2  VPMIN=-2  KA=30
    VIMIN=0 VIMAX=0.1     QMIN=-320 QMAX=320

END




TURBINES
 1   TYPE=DSLS/FPCWT_WINDTURB/  NOM_POWER=1060.0  AIRDENS=1.2
              NOM_TURBSPEED=0
              BLADELENGTH=0  LOWCUTOUT=2.0
              GOV=2     WINDCURVE=81

 2   TYPE=DSLS/FPCWT_PICON/  KPP=60  KPC=3  KIP=20  KIC=20
              TP=0.3  BMAX=27  BMIN=0
              DBDTMAX=4.0  DBDTMIN=-4.0   BLOCK=0
              DW=FPCWT_REC_DW
              PORD=FPCWT_REC_PORD
```

```
!!!HYDRO TURBINES

 20   TYPE=DSLS/HYTUR/
     GOV=29      TW=1    AT=1.0022     DTURB=0.5    QNL=0.1

 21   TYPE=DSLS/HYTUR/
     GOV=29      TW=1    AT=1.0577     DTURB=0.5    QNL=0.1

 22   TYPE=DSLS/HYTUR/
     GOV=29      TW=1    AT=1.01       DTURB=0.5    QNL=0.1

 23   TYPE=DSLS/HYTUR/
     GOV=29      TW=1    AT=1.1        DTURB=0.5    QNL=0.1

 24   TYPE=DSLS/HYTUR/
     GOV=28      TW=1    AT=1.1        DTURB=0.5    QNL=0.1

 25   TYPE=DSLS/HYTUR/
     GOV=27      TW=1    AT=1.1        DTURB=0.5    QNL=0.1

 27   TYPE=DSLS/HYGOV/
     RBIG=0.06          RSMALL=0.4
     TR=5.0             TF=0.05      TG=0.2
     VELM=0.2           GMIN=0       GMAX=1

 28   TYPE=DSLS/HYGOV/
     RBIG=0.06          RSMALL=0.3
     TR=5.0             TF=0.05      TG=0.2
     VELM=0.2           GMIN=0       GMAX=1.5

 29   TYPE=DSLS/HYGOV/
     RBIG=0.06          RSMALL=0.4
     TR=5.0             TF=0.05      TG=0.2
     VELM=0.1           GMIN=0       GMAX=1.5

!!!STEAM TURBINES

 40   TYPE=ST2
     GOV=49      K1=0.301    T1=0.4     K2=0.399    T2=8.0
     K3=0.3      T3=0.3      K4=0       T4=0

 49   TYPE=SG3
     T1=0.01     T2=0.0      T3=0.15    K=0
     YMIN=0      YMAX=1

END



LOADS
  3000     NO=  1    MP=1 MQ=2
```

```
 3000     NO=  2    MP=1 MQ=2
 3100           MP=1 MQ=2
 3200           MP=1 MQ=2
 3245           MP=1 MQ=2
 3249           MP=1 MQ=2
 3300           MP=1 MQ=2
 3359           MP=1 MQ=2
 3360           MP=1 MQ=2
 5100           MP=1 MQ=2
 5300           MP=1 MQ=2
 5400           MP=1 MQ=2
 5500           MP=1 MQ=2
 5600           MP=1 MQ=2
 5603     NO=  1    MP=1 MQ=2
 5603     NO=  2    MP=1 MQ=2
 6000           MP=1 MQ=2
 6100           MP=1 MQ=2
 6500           MP=1 MQ=2
 6700           MP=1 MQ=2
 7000     NO=  1    MP=1 MQ=2
 7000     NO=  2    MP=1 MQ=2
 7100           MP=1 MQ=2
 8500           MP=1 MQ=2
END



PWM CONVERTERS
 FPCWT_REC
                TYPE=DSLS/FPCWT_PWM_DYN/ SN=1060.0
                UN=3.0    X=0.3    PL=0.02
                MODE=1      UDCORD=5.0   IMAX=1.04


                PORD=FPCWT_REC_PORD


                IQORD=FPCWT_REC_IQORD


                IQORD0=FPCWT_REC_IQORD0

 FPCWT_INV
                TYPE=DSLS/FPCWT_PWM_DYN/  SN=1060.0
                UN=3.5    X=0.3    PL=0.02
                MODE=2     UDCORD=5.0    IMAX=1.04
                PORD=0.0


                IQORD=FPCWT_INV_IQORD
```

```
                IQORD0=FPCWT_INV_IQORD0
END


MISC
 SPC1  TYPE=DSLS/FPCWT_SPCON/  KS=0.6   KP=3.0   TPC=0.05
                PMAX=0.976  PMIN=0.0  DPMAX=0.1  DPMIN=-0.1  !PMAX=0.976
                WMAX=1.20  WMIN=0.40  WLOW=0.60
                        !A2=-0.4625     A1=1.0902    A0=0.3764   BLOCK=0
                DW=FPCWT_REC_DW
                PORD=FPCWT_REC_PORD
                SYNC=FPCWT_GEN

 VACR  1000 TYPE=DSLS/FPCWT_VACCON/ N=1
                INTMAX=1.0  INTMIN=-1.0

                UACORD=3.0

                IQMAX=0.5    IQMIN=-0.5
                K=1.2   TI=0.05   BLOCK=0


                IQORD=FPCWT_REC_IQORD


                IQORD0=FPCWT_REC_IQORD0

 VACI  1002 TYPE=DSLS/FPCWT_VACCON/ N=1
                INTMAX=1.0  INTMIN=-1.0

                UACORD=3.5

                IQMAX=0.5   IQMIN=-0.5
                K=1.2   TI=0.05
                IQORD=FPCWT_INV_IQORD
                IQORD0=FPCWT_INV_IQORD0
END



TABLES
! 1 TYPE=1 F 0.000 0.00 0.700 0.70
!         0.800 0.80 0.830 0.83
!         0.860 0.86 0.962 0.94
!         0.974 0.95 1.039 1.00
!         1.113 1.05 1.202 1.10
!         1.315 1.15 1.467 1.20
!         1.682 1.25 1.998 1.30
!         2.478 1.35
! Cp/lambda curve for beta=0 deg.
 11 TYPE=0   F    0.0   0.00
```

```
                1.0   0.10
                2.0   0.20
                3.0   0.30
                4.0   0.38
                5.0   0.42
                6.0   0.48
                6.5   0.49
                7.0   0.50
                7.5   0.504
                8.0   0.50
                8.5   0.49
                9.0   0.48
                10.0  0.47
                11.0  0.45
                12.0  0.42
                13.0  0.39
                14.0  0.35
                15.0  0.30
                16.0  0.25
                17.0  0.19
                18.0  0.11
                19.0  0.04
                20.0  0.00
! Cp/lambda curve for beta=7 deg.
 12 TYPE=0   F   0.0  0.00
                1.0  0.02
                2.0  0.05
                3.0  0.16
                4.0  0.26
                5.0  0.30
                6.0  0.31
                6.5  0.31
                7.0  0.30
                7.5  0.28
                8.0  0.26
                8.5  0.24
                9.0  0.22
                10.0 0.16
                11.0 0.08
                12.0 0.00
! Cp/lambda curve for beta=27 deg.
 13 TYPE=0   F   0.0  0.00
                1.0  0.01
                2.0  0.04
                3.0  0.16
                4.0  0.20
                5.0  0.25
                6.0  0.26
                6.5  0.26
                7.0  0.22
                7.5  0.20
                 8.0  0.19
```

```
                    8.5  0.16
                    9.0  0.10
                   10.0 0.05
                   11.0 0.00
! Voltage fluctuations in the grid
 51  TYPE=0    F            0.00   1.0
                            10.0   1.0
                            10.0   0.94
                            10.1   0.94
                            10.1   1.0
              100.0           1.0
! Wind profile
 81 TYPE=0     F  0.0   11.569607734680176
              100.0 11.569607734680176



! or from separate file as

!!! $INCLUDE TEST-FPCWT.TXT

! This text file must look the same as a table given in the Dynpow file.
! It is possible to create a text file from MS Excel if the wind profile is
! stored there, but after export to a text file in the text file, strings edit
! by TABS must be replaced and edit by SPACE

END


FAULTS
 F1 TYPE=3PSG NODE 5600
END

RUN INSTRUCTION
 AT 1.000  INST    CONNECT  FAULT  F1
 AT 1.185  INST  DISCONNECT  FAULT  F1
END

END
```

APPENDIX D: HVDC OPTPOW FILE

```
SYSTEM BASE = 1000.000 MVA.
Reduced NORDEL power system model
V 3.2, 12.08.97
**
CONTROL DATA
 UBCHECK=NO
 NSEP=NO
 ICPV=4
END
GENERAL
 SN=1000.000
END
NODES
! PSS NAME
!
! Nodes within the wind farm area    10
!
1000         UB= 3.000       TYPE=AC     AREA= 10
1001         UB= 5.000       TYPE=DC     AREA= 10
BUS_1        UB= 300         TYPE=AC     AREA= 10
BUS_2        UB= 300         TYPE=AC     AREA= 10
BUS_11       UB= 3.5         TYPE=AC     AREA= 10
A_1          UB= 300         TYPE=DC     AREA= 10
A_2          UB= 300         TYPE=DC     UI=-1     AREA= 10
B_1          UB= 300         TYPE=DC     AREA= 10
B_2          UB= 300         TYPE=DC     UI=-1     AREA= 10
B_SW         UB= 3.5         TYPE=AC     AREA= 10

!
! Nodes within area     40
!
3000         UB= 420.000     TYPE=AC     AREA= 40 ! STCKH    !
3100         UB= 420.000     TYPE=AC     AREA= 40 ! STRFN    !
3115         UB= 420.000     TYPE=AC     AREA= 40 ! SV-N1    !
3200         UB= 420.000     TYPE=AC     AREA= 40 ! KRLSK    !
3244         UB= 300.000     TYPE=AC     AREA= 40 ! SV-M2    !
3245         UB= 420.000     TYPE=AC     AREA= 40 ! SV-M1    !
3249         UB= 420.000     TYPE=AC     AREA= 40 ! SV-N2    !
3300         UB= 420.000     TYPE=AC     AREA= 40 ! SV-SW    !
3359         UB= 420.000     TYPE=AC     AREA= 40 ! SV-W     !
3360         UB= 135.000     TYPE=AC     AREA= 40 ! KONT_135 !
3701         UB= 300.000     TYPE=AC     AREA= 40 ! SV-N2B   !
!
! Nodes within area     51
!
5100         UB= 300.000     TYPE=AC     AREA= 51 ! EAST3    !
5101         UB= 420.000     TYPE=AC     AREA= 51 ! EAST4-A  !
5102         UB= 420.000     TYPE=AC     AREA= 51 ! EAST4-B  !
5103         UB= 420.000     TYPE=AC     AREA= 51 ! EAST4-C  !
!
! Nodes within area     53
!
5300         UB= 300.000     TYPE=AC     AREA= 53 ! HDAL3    !
5301         UB= 420.000     TYPE=AC     AREA= 53 ! HDAL4    !
!
! Nodes within area     54
!
5400         UB= 300.000     TYPE=AC     AREA= 54 ! CNTR3-A  !
5401         UB= 420.000     TYPE=AC     AREA= 54 ! CNTR4-A  !
5402         UB= 420.000     TYPE=AC     AREA= 54 ! CNTR4-B  !
!
! Nodes within area     55
!
5500         UB= 300.000     TYPE=AC     AREA= 55 ! CNTR3-B  !
5501         UB= 420.000     TYPE=AC     AREA= 55 ! CNTR4-C  !
!
! Nodes within area     56
```

```
!
5600         UB= 300.000     TYPE=AC     AREA= 56 ! SOUTH3A  !
5601         UB= 420.000     TYPE=AC     AREA= 56 ! SOUTH4A  !
5602         UB= 420.000     TYPE=AC     AREA= 56 ! SOUTH4B  !
5603         UB= 300.000     TYPE=AC     AREA= 56 ! SOUTH3B  !
!
! Nodes within area     60
!
6000         UB= 300.000     TYPE=AC     AREA= 60 ! WEST300  !
6001         UB= 420.000     TYPE=AC     AREA= 60 ! WEST400  !
!
! Nodes within area     61
!
6100         UB= 300.000     TYPE=AC     AREA= 61 ! NWEST3   !
!
! Nodes within area     65
!
6500         UB= 300.000     TYPE=AC     AREA= 65 ! MID300   !
!
! Nodes within area     67
!
6700         UB= 300.000     TYPE=AC     AREA= 67 ! NOR300   !
6701         UB= 420.000     TYPE=AC     AREA= 67 ! NOR400   !
!
! Nodes within area     70
!
7000         UB= 420.000     TYPE=AC     AREA= 70 ! SO-FIN   !
!
! Nodes within area     71
!
7100         UB= 420.000     TYPE=AC     AREA= 71 ! NO-FIN   !
!
! Nodes within area     90
!
8500         UB= 420.000     TYPE=AC     AREA= 90 ! SJOLLAND !
END

SREACTORS
5400     5500     NO= 81 TYPE=11  R= 0.890000E-02 X= 0.111000
END



PWM CONVERTERS
  FPCWT_REC     1000    1001   AC2=1000
                    TYPE=DSLS/FPCWT_PWM_OPT/        SN=1060.0
                     UN=3.0      X=0.3        PL=0.02         MODE=1      ORDER=1000.0

  FPCWT_INV     BUS_11    1001   AC2=BUS_11       !BUS_11
                    TYPE=DSLS/FPCWT_PWM_OPT/        SN=1060.0
                     UN=3.5      X=0.3        PL=0.02         MODE=2      ORDER=5   !UN=
3.5

  LIGHT_A       BUS_1     A_1    DC1=A_2
                    TYPE=DSLS/HVDC_LIGHT_OPEN_MODEL_V116_OPT/ SN=1060.0
                        UN=300 BSH=1.5E-3 XL=0.15 PLOSSNOM=0.0165 PLOSSNOLOADPART=0.3
                        PCTRL=1 UACCTRL=0 UACREF=1.0 QREF=0.0 PREF=0.903396

  LIGHT_B       BUS_2     B_1    DC1=B_2
                    TYPE=DSLS/HVDC_LIGHT_OPEN_MODEL_V116_OPT/ SN=1060.0
                        UN=300 BSH=1.5E-3 XL=0.15 PLOSSNOM=0.0165 PLOSSNOLOADPART=0.3
                        PCTRL=0 UACCTRL=1 UACREF=1.0 QREF=0.0
END


SHUNT IMPEDANCES ! Line type 13,14 and 15 are translated as lines type 12.
!                  Corresponding GI,BI,GJ,BJ are translated as shunts !
1001     NO= 81 R=  1E6         C=  1.2381  !2.4E-3
A_1             R=  1.0E9       C=  1.2E-4  !70.0E-6
A_2             R=  1.0E9       C=  1.2E-4
B_1             R=  1.0E9       C=  1.2E-4
B_2             R=  1.0E9       C=  1.2E-4
```

```
5101      NO= 81 R=  0.00000     X=  181.034
5101      NO=810 R=  7910.31     X=  0.00000
5501      NO=811 R=  0.00000     X= -181.034
5501      NO=812 R= -8166.67     X=  0.00000
5102      NO= 81 R=  0.00000     X=-0.176397E+07
5102      NO=810 R=  882000.     X=  0.00000
6001      NO=811 R=  0.00000     X= 0.176397E+07
6001      NO=812 R=  882000.     X=  0.00000
5103      NO= 81 R=  0.00000     X=  13889.8
5103      NO=810 R=  441000.     X=  0.00000
5301      NO=811 R=  0.00000     X= -13889.8
5301      NO=812 R= -588000.     X=  0.00000
5401      NO= 81 R=  0.00000     X=  352800.
5401      NO=810 R= -882000.     X=  0.00000
6001      NO=813 R=  0.00000     X= -352800.
6001      NO=814 R=  882000.     X=  0.00000
5500      NO= 81 R=  0.00000     X= -69230.8
5500      NO=810 R=  300000.     X=  0.00000
5603      NO=811 R=  0.00000     X=  69230.8
5603      NO=812 R= -300000.     X=  0.00000
END
LINES
! See also the second LINES-chapter further below,
! containing all lines of TYPE=11.


A_1       B_1               TYPE=6    R=0.0105     LL=0  L=100

A_2       B_2               TYPE=6    R=0.0105     LL=0  L=100

BUS_11    B_SW              TYPE=0    NCON=0

3000      3115      NO=  81  TYPE=12    R= 0.140000E-01  X= 0.100000
                                       B= 0.300000E-01 L=  10.00

3000      3245      NO=  81  TYPE=12    R= 0.125000E-02  X= 0.170100E-01
                                       B= 0.127460E-01 L=  10.00

3000      3300      NO=  81  TYPE=12    R= 0.113000E-02  X= 0.170100E-01
                                       B= 0.116380E-01 L=  10.00

3100      3115      NO=  81  TYPE=12    R= 0.301000E-02  X= 0.413800E-01
                                       B= 0.775800E-02 L=  10.00

3100      3200      NO=  81  TYPE=12    R= 0.686000E-02  X= 0.561200E-01
                                       B= 0.171790E-01 L=  10.00

3100      3249      NO=  81  TYPE=12    R= 0.108000E-02  X= 0.147400E-01
                                       B= 0.105290E-01 L=  10.00

3100      3359      NO=  81  TYPE=12    R= 0.910000E-03  X= 0.119000E-01
                                       B= 0.221700E-02 L=  10.00

3115      3245      NO=  81  TYPE=12    R= 0.300000E-02  X= 0.500000E-01
                                       B= 0.900000E-02 L=  10.00

3115      3249      NO=  81  TYPE=12    R= 0.150000E-02  X= 0.200000E-01
                                       B= 0.400000E-02 L=  10.00

3115      6701      NO=  81  TYPE=12    R= 0.400000E-02  X= 0.300000E-01
                                       B= 0.500000E-02 L=  10.00

3115      7100      NO=  81  TYPE=12    R= 0.100000E-01  X= 0.700000E-01
                                       B= 0.100000E-01 L=  10.00

3200      3300      NO=  81  TYPE=12    R= 0.125000E-02  X= 0.170100E-01
                                       B= 0.332500E-02 L=  10.00

3200      3359      NO=  81  TYPE=12    R= 0.357000E-02  X= 0.408200E-01
                                       B= 0.775800E-02 L=  10.00

3244      6500      NO=  81  TYPE=12    R= 0.500000E-03  X= 0.500000E-02
```

```
                                    B= 0.100000E-03 L=  10.00

3249      7100      NO=  81  TYPE=12    R= 0.100000E-01  X= 0.700000E-01
                                    B= 0.100000E-01 L=  10.00

3300      3359      NO=  81  TYPE=12    R= 0.740000E-03  X= 0.964000E-02
                                    B= 0.166300E-02 L=  10.00

3300      8500      NO=  81  TYPE=12    R= 0.800000E-02  X= 0.310000E-01
                                    B= 0.300000E-01 L=  10.00

3359      5101      NO=  81  TYPE=12    R= 0.148000E-02  X= 0.192800E-01
                                    B= 0.360200E-02 L=  10.00

3701      6700      NO=  81  TYPE=12    R= 0.100000E-02  X= 0.100000
                                    B= 0.500000E-03 L=  10.00

5100      5300      NO=  81  TYPE=12    R= 0.400000E-02  X= 0.400000E-01
                                    B= 0.500000E-02 L=  10.00

5100      5500      NO=  81  TYPE=12    R= 0.180000E-02  X= 0.150000E-01
                                    B= 0.212800E-02 L=  10.00

5100      6500      NO=  81  TYPE=12    R= 0.150000E-01  X= 0.150000
                                    B= 0.100000E-03 L=  10.00

5101      5501      NO=  81  TYPE=12    R= 0.610000E-03  X= 0.643000E-02
                              B= 0.325920E-01 L=  10.00
                    RNO1=   810  RNO2=   812

5102      5301      NO=  81  TYPE=12    R= 0.750000E-03  X= 0.107900E-01
                                    B= 0.128600E-01 L=  10.00

5102      6001      NO=  81  TYPE=12    R= 0.200000E-02  X= 0.350000E-01
                              B= 0.100000E-01 L=  10.00
                    RNO1=   810  RNO2=   812

5103      5301      NO=  81  TYPE=12    R= 0.170000E-02  X= 0.231200E-01
                              B= 0.675500E-02 L=  10.00
                    RNO1=   810  RNO2=   812

5400      6000      NO=  81  TYPE=12    R= 0.100000E-02  X= 0.100000E-01
                                    B= 0.100000E-02 L=  10.00

5400      6100      NO=  81  TYPE=12    R= 0.200000E-02  X= 0.200000E-01
                                    B= 0.120000E-02 L=  10.00

5401      5501      NO=  81  TYPE=12    R= 0.150000E-02  X= 0.200000E-01
                                    B= 0.600000E-02 L=  10.00

5401      5602      NO=  81  TYPE=12    R= 0.154000E-02  X= 0.240600E-01
                                    B= 0.879600E-02 L=  10.00

5401      6001      NO=  81  TYPE=12    R= 0.300000E-03  X= 0.500000E-02
                              B= 0.150000E-02 L=  10.00
                    RNO1=   810  RNO2=   814

5402      6001      NO=  81  TYPE=12    R= 0.510000E-03  X= 0.751000E-02
                                    B= 0.235200E-02 L=  10.00

5500      5603      NO=  81  TYPE=12    R= 0.400000E-02  X= 0.450000E-01
                              B= 0.800000E-03 L=  10.00
                    RNO1=   810  RNO2=   812

5600      5603      NO=  81  TYPE=12    R= 0.201000E-02  X= 0.221100E-01
                                    B= 0.208400E-02 L=  10.00

5600      6000      NO=  81  TYPE=12    R= 0.350000E-02  X= 0.350000E-01
                                    B= 0.450000E-02 L=  10.00

5601      6001      NO=  81  TYPE=12    R= 0.137000E-02  X= 0.203100E-01
                                    B= 0.636400E-02 L=  10.00
```

```
6000      6100      NO=  81  TYPE=12    R= 0.220000E-02  X= 0.239400E-01
                                       B= 0.200000E-02 L=  10.00

6500      6700      NO=  81  TYPE=12    R= 0.800000E-02  X= 0.110000
                                       B= 0.100000E-02 L=  10.00

7000      7100      NO=  81  TYPE=12    R= 0.140000E-01  X= 0.100000
                                       B= 0.300000E-01 L=  10.00

7000      7100      NO=  82  TYPE=12    R= 0.140000E-01  X= 0.100000
                                       B= 0.300000E-01 L=  10.00

3359      5101      NO=  82  TYPE=12    R= 0.148000E-02  X= 0.192800E-01
                                       B= 0.360200E-02 L=  10.00

5300      6100      NO=  81  TYPE=12    R= 0.359000E-02  X= 0.382500E-01
                                       B= 0.115200E-02 L=  10.00
    NCON=1
7000      7100      NO=  83  TYPE=12    R= 0.140000E-01  X= 0.100000
                                       B= 0.300000E-01 L=  10.00
    NCON=1
END
TRANSFORMERS
! Transformers with TCR, i.e. with STEP, -NSTEP!

BUS_1     BUS_11   SN=1060.0   UN1=300   UN2=3.5
          ER12=0.00   EX12=0.12
          STEP=0.025  +NSTEP=2  -NSTEP=2
BUS_2     5600     SN=1060.0   UN1=300   UN2=300
          ER12=0.00   EX12=0.12
          STEP=0.025  +NSTEP=2  -NSTEP=2
3244      3245       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00500  EX12=   0.02000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
3701      3249       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.02000  EX12=   0.50000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
3359      3360       NO=369    SN=1000.000  UN1= 420.000  UN2= 135.000
          ER12=   0.00500  EX12=   0.02000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5101      5100       NO=369    SN=1000.000  UN1= 420.000  UN2= 300.000
          ER12=   0.00080  EX12=   0.03050 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5102      5100       NO=369    SN=1000.000  UN1= 420.000  UN2= 300.000
          ER12=   0.00080  EX12=   0.03050 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5103      5100       NO=369    SN=1000.000  UN1= 420.000  UN2= 300.000
          ER12=   0.00250  EX12=   0.10000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5300      5301       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00160  EX12=   0.06100 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5400      5401       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00320  EX12=   0.12000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5400      5402       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00040  EX12=   0.01500 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5500      5501       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00040  EX12=   0.01500 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5600      5601       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00020  EX12=   0.00760 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
5603      5602       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00080  EX12=   0.03050 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
6000      6001       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
          ER12=   0.00040  EX12=   0.01500 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
6700      6701       NO=369    SN=1000.000  UN1= 300.000  UN2= 420.000
```

```
          ER12=   0.00500  EX12=   0.02000 FI=   0.00         TAPSIDE=1
          STEP= 0.63492E-02  +NSTEP= 63  -NSTEP= 63
END
TRANSFORMERS
! 3-WINDING TRANSFORMERS
END
LOADS
! PSS/E load data is translated as follows:
! Constant loads   PSS/E PL,QL defined with exponents MP=0 MQ=0 !
! Constant current PSS/E IP, IQ defined with exponents MP=1, MQ=1 !
! Constant addmittance PSS/E YP,YQ defined withexponents MP=2, MQ=2 !
3000      NO=  1  P=  2500.000  Q=   500.000  MP=0  MQ=0
3000      NO=  2  P=  -500.000  Q=   250.000  MP=0  MQ=0
3100              P=   500.000  Q=   100.000  MP=0  MQ=0
3200              P=   500.000  Q=   100.000  MP=0  MQ=0
3245              P=  2700.000  Q=   500.000  MP=0  MQ=0
3249              P=  1250.000  Q=   300.000  MP=0  MQ=0
3300              P=  9350.000  Q=  1500.000  MP=0  MQ=0
3359              P=  4500.000  Q=   700.000  MP=0  MQ=0
3360              P=   360.000  Q=   180.000  MP=0  MQ=0
5100              P=  4210.000  Q=   692.000  MP=0  MQ=0
5300              P=   201.000  Q=    11.300  MP=0  MQ=0
5400              P=    94.400  Q=     0.000  MP=0  MQ=0
5500              P=  1229.000  Q=   115.000  MP=0  MQ=0
5600              P=  3121.000  Q=   297.000  MP=0  MQ=0
5603      NO=  1  P=   460.000  Q=    45.000  MP=0  MQ=0
5603      NO=  2  P=   940.000  Q=   470.000  MP=0  MQ=0
6000              P=     4.000  Q=     0.000  MP=0  MQ=0
6100              P=  3042.000  Q=   980.000  MP=0  MQ=0
6500              P=  1919.000  Q=   279.000  MP=0  MQ=0
6700              P=  1927.000  Q=   446.000  MP=0  MQ=0
7000      NO=  1  P=  5100.000  Q=  1000.000  MP=0  MQ=0
7000      NO=  2  P=   500.000  Q=   250.000  MP=0  MQ=0
7100              P=  2500.000  Q=   400.000  MP=0  MQ=0
8500              P=  1000.000  Q=  1000.000  MP=0  MQ=0
END
POWER CONTROL
1000      TYPE=NODE  NAME=FPCWT_GEN   RTYP=SW  U=  3.0           FI=0.0
          QMIN= -49995.00      QMAX=  49995.00
5600      TYPE=NODE  NAME=SVC1        RTYP=UP  U=  303          P=0
          QMIN=-320  QMAX=320
B_SW      TYPE=NODE  NAME=SWING       RTYP=SW  U=  3.5          FI=0.0
3300      TYPE=NODE  NAME=SV-SGG1_    RTYP=SW  U=  420.000000   FI=   0.0000
          QMIN= -49995.00      QMAX=  49995.00
3000      TYPE=NODE  NAME=STCKGG1_    RTYP=UP  U=  420.0000     P= 5300.000
          QMIN= -49995.00      QMAX=  49995.00
3100      TYPE=NODE  NAME=STRFGG1_    RTYP=UP  U=  407.4000     P= 1500.000
          QMIN= -49995.00      QMAX=  49995.00
3115      TYPE=NODE  NAME=SV-NGG11    RTYP=UP  U=  420.0000     P= 3570.000
          QMIN= -49995.00      QMAX=  49995.00
!3200      TYPE=NODE  NAME=KRLSGG1_    RTYP=UP  U=  420.0000     P=    0.000
!          QMIN= -49995.00      QMAX=  49995.00      NCON=1
3245      TYPE=NODE  NAME=SV-MGG1_    RTYP=UP  U=  420.0000     P=  780.000
          QMIN= -49995.00      QMAX=  49995.00
3249      TYPE=NODE  NAME=SV-NGG12    RTYP=UP  U=  420.0000     P= 4750.000
          QMIN= -49995.00      QMAX=  49995.00
3359      TYPE=NODE  NAME=SV-WGG1_    RTYP=UP  U=  420.0000     P= 2670.000
          QMIN= -49995.00      QMAX=  49995.00
3359      TYPE=NODE  NAME=SV-WGG2_    RTYP=UP  U=  420.0000     P=  830.000
          QMIN= -9999.000      QMAX=  9999.000
5100      TYPE=NODE  NAME=EASTGG1_    RTYP=UP  U=  300.0000     P= 1480.000
          QMIN= -49995.00      QMAX=  49995.00
5300      TYPE=NODE  NAME=HDALGG1_    RTYP=UP  U=  300.0000     P= 2275.000
          QMIN= -49995.00      QMAX=  49995.00
5400      TYPE=NODE  NAME=CNTRGG11    RTYP=UP  U=  302.1000     P= 1588.000
          QMIN= -49995.00      QMAX=  49995.00
5500      TYPE=NODE  NAME=CNTRGG12    RTYP=UP  U=  301.2000     P=  828.000
          QMIN= -49995.00      QMAX=  49995.00
5600      TYPE=NODE  NAME=SOUTGG11    RTYP=UP  U=  303.0000     P= 2378.000
!5603      TYPE=NODE  NAME=SOUTGG12    RTYP=UP  U=  300.0000     P=  100.000
!          QMIN= -9999.000      QMAX=  9999.000      NCON=1
6000      TYPE=NODE  NAME=WESTGG1_    RTYP=UP  U=  301.5000     P= 1129.000
```

```
          QMIN= -1000.000      QMAX=  1000.000
6100      TYPE=NODE  NAME=NWESGG1_    RTYP=UP  U=  300.0000      P= 2346.000
          QMIN= -49995.00      QMAX=  49995.00
6500      TYPE=NODE  NAME=MID3GG1_    RTYP=UP  U=  300.0000      P= 1511.000
          QMIN= -49995.00      QMAX=  49995.00
6700      TYPE=NODE  NAME=NOR3GG1_    RTYP=UP  U=  306.0000      P= 2771.000
          QMIN= -49995.00      QMAX=  49995.00
7000      TYPE=NODE  NAME=SO-FGG1_    RTYP=UP  U=  420.0000      P= 5300.000
          QMIN= -49995.00      QMAX=  49995.00
7100      TYPE=NODE  NAME=NO-FGG1_    RTYP=UP  U=  420.0000      P= 1310.000
          QMIN= -49995.00      QMAX=  49995.00
8500      TYPE=NODE  NAME=SJOLGG1_    RTYP=UP  U=  428.4000      P= 1000.000
          QMIN= -49995.00      QMAX=  49995.00

     ! Transformers RTYP=UFI:
3244      3245       NO=369  TYPE=TREG  RTYP=UFI  U=420.0000  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000
3359      3360       NO=369  TYPE=TREG  RTYP=UFI  U=134.2913  FI=   0.000
!  UMIN= 252.0000 UMAX=588.0000
5300      5301       NO=369  TYPE=TREG  RTYP=UFI  U=420.2604  FI=   0.000
!  UMIN= 180.0000 UMAX=420.0000
5400      5401       NO=369  TYPE=TREG  RTYP=UFI  U=418.4880  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000
5400      5402       NO=369  TYPE=TREG  RTYP=UFI  U=422.5284  FI=   0.000
!  UMIN= 180.0000 UMAX=420.0000
5500      5501       NO=369  TYPE=TREG  RTYP=UFI  U=421.9068  FI=   0.000
!  UMIN= 180.0000 UMAX=420.0000
5600      5601       NO=369  TYPE=TREG  RTYP=UFI  U=416.6610  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000
5603      5602       NO=369  TYPE=TREG  RTYP=UFI  U=401.5368  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000
6000      6001       NO=369  TYPE=TREG  RTYP=UFI  U=419.8320  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000
6700      6701       NO=369  TYPE=TREG  RTYP=UFI  U=422.9316  FI=   0.000
!  UMIN= 180.0000 UMAX=420.0000

! Transformers defined with RTYP=UFI. CNODE bus voltage is set fixed.
! The CNODE is set as the first node name in order in the data list
3701      3249       NO=369  TYPE=TREG  RTYP=UFI  TAU=  1.00000  FI=   0.000
      UMIN= 180.0000 UMAX=420.0000 CNODE=3701     U=302.22897
5101      5100       NO=369  TYPE=TREG  RTYP=UFI  TAU=  1.00635  FI=   0.000
      UMIN= 252.0000 UMAX=588.0000 CNODE=5101     U=415.74121
5102      5100       NO=369  TYPE=TREG  RTYP=UFI  TAU=  1.00000  FI=   0.000
      UMIN= 252.0000 UMAX=588.0000 CNODE=5102     U=420.00842
5103      5100       NO=369  TYPE=TREG  RTYP=UFI  TAU=  1.00000  FI=   0.000
      UMIN= 252.0000 UMAX=588.0000 CNODE=5103     U=419.17682
END
END
```

APPENDIX E: HVDC DYNPOW FILE

```
Case fault
**

CONTROL DATA
  TEND=20
  SPL=1.7
  NPRD=3000
  DEND=0.1
  N7=40
  GAM5=0.01
  TETL=100000
END



GENERAL
  NREF=3
  FN 50.0  50.0   50.0
  REF= FPCWT_GEN       SV-SGG1_    B_SW
END



GLOBALS

  FPCWT_REC_IQORD       TYPE=REAL
  FPCWT_REC_IQORD0      TYPE=REAL
  FPCWT_REC_DW          TYPE=REAL
  FPCWT_INV_IQORD       TYPE=REAL
  FPCWT_INV_IQORD0      TYPE=REAL
  FPCWT_REC_PORD     TYPE=REAL

END

NODES
  B_SW TYPE=1
END


SVC
 SVC1 5600 SN=350  REG=100
END


SYNCHRONOUS MACHINES
  FPCWT_GEN  1000    SN = 1060.0  UN = 3.0   TYPE = 2A   H = 5.5
                     RA= 0.0025  XD= 1.9  XQ = 1.6  XDP = 0.32  XDB = 0.2
                     XQB = 0.21  XA = 0.14  TD0P = 5.0  TD0B = 0.03  TQ0B = 0.07
                     TURB=1

  SV-SGG1_   3300    TYPE=1     XD=2.42    XQ=2.00    XA=0.1481  XDP=0.23     XQP=0.4108
                     XDB=0.16   XQB=0.16   RA=0.0     TD0P=10.8  TQ0P=1
                     TD0B=0.05  TQ0B=0.05  V1=1       V2=1.2     SE1=0.1089   SE2=0.378
                     TURB=40    H=6.0      SN=5000    UN=420     D=0          VREG=24

  STCKGG1_   3000    TYPE=1     XD=2.22    XQ=2.13    XA=0.1688  XDP=0.36     XQP=0.468
                     XDB=0.225  XQB=0.225  RA=0.0     TD0P=5.0   TQ0P=1
                     TD0B=0.05  TQ0B=0.05  V1=1       V2=1.2     SE1=0.1089   SE2=0.378
                     TURB=40    H=5.97     SN=5579    UN=420     D=0          VREG=10

  STRFGG1_   3100    TYPE=2     XD=0.65    XQ=0.39    XA=0.0877  XDP=0.19
                     XDB=0.1169 XQB=0.1169 RA=0.0     TD0P=4.0
                     TD0B=0.06  TQ0B=0.1   V1=1       V2=1.2     SE1=0.1024   SE2=0.2742
                     TURB=20    H=5.04     SN=1579    UN=420     D=0          VREG=20

  SV-NGG11   3115    TYPE=2     XD=0.946   XQ=0.565   XA=0.1108  XDP=0.29
```

```
                    XDB=0.23   XQB=0.23   RA=0.0     TD0P=7.57
                    TD0B=0.045 TQ0B=0.1   V1=1       V2=1.2     SE1=0.1024   SE2=0.2742
                    TURB=21    H=4.741    SN=3758    UN=420     D=0          VREG=23

!KRLSGG1_   3200     TYPE=1  XD=1.8    XQ=1.7    XA=0.2    XDP=0.3    XQP=0.55
!                    XDB=0.25  XQB=0.25  RA=0.0025 TD0P=8.0   TQ0P=0.4
!                    TD0B=0.03 TQ0B=0.05 TAB=1     TURB=3
!                    H=6.5     SN=1    UN=420     D=0        VREG=2

SV-MGG1_    3245     TYPE=2     XD=0.75    XQ=0.50    XA=0.1154  XDP=0.25
                    XDB=0.1538 XQB=0.1538 RA=0.0     TD0P=5.0
                    TD0B=0.06  TQ0B=0.1   V1=1       V2=1.2     SE1=0.1024   SE2=0.2742
                    TURB=22    H=3.3      SN=822     UN=420     D=0          VREG=20

SV-NGG12    3249     TYPE=2     XD=1.036   XQ=0.63    XA=0.1154  XDP=0.28
                    XDB=0.21   XQB=0.21   RA=0.0     TD0P=10.13
                    TD0B=0.06  TQ0B=0.1   V1=1       V2=1.2     SE1=0.1024   SE2=0.2742
                    TURB=23    H=4.543    SN=5000    UN=420     D=0          VREG=20

SV-WGG1_    3359     TYPE=2     XD=0.75    XQ=0.50    XA=0.1154  XDP=0.25
                    XDB=0.1938 XQB=0.1938 RA=0.0     TD0P=5.0
                    TD0B=0.06  TQ0B=0.1   V1=1       V2=1.2     SE1=0.1024   SE2=0.2742
                    TURB=22    H=3.3      SN=2811    UN=420     D=0          VREG=25

SV-WGG2_    3359     TYPE=1     XD=2.13    XQ=2.03    XA=0.1453  XDP=0.31     XQP=0.403
                    XDB=0.1937 XQB=0.1937 RA=0.0     TD0P=4.75  TQ0P=1
                    TD0B=0.05  TQ0B=0.05  V1=1       V2=1.2     SE1=0.1089   SE2=0.378
                    TURB=40    H=4.82     SN=874     UN=420     D=0          VREG=22

EASTGG1_    5100     TYPE=2     XD=1.1332  XQ=0.6832  XA=0.1341  XDP=0.243
                    XDB=0.1514 XQB=0.1514 RA=0.0     TD0P=4.9629
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=3.9871   SN=1558    UN=300     D=0        VREG=30

HDALGG1_    5300     TYPE=2     XD=1.14    XQ=0.84    XA=0.2     XDP=0.34
                    XDB=0.26   XQB=0.26   RA=0.0     TD0P=6.4
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=3.5      SN=2395    UN=300     D=0        VREG=27

CNTRGG11    5400     TYPE=2     XD=1.02    XQ=0.63    XA=0.13    XDP=0.25
                    XDB=0.16   XQB=0.16   RA=0.0     TD0P=6.5
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=4.1      SN=1672    UN=300     D=0        VREG=30

CNTRGG12    5500     TYPE=2     XD=1.2364  XQ=0.6557  XA=0.1619  XDP=0.3741
                    XDB=0.2283 XQB=0.2283 RA=0.0     TD0P=7.198
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=3.0      SN=872     UN=300     D=0        VREG=30

SOUTGG11    5600     TYPE=2     XD=1.0     XQ=0.5132  XA=0.21    XDP=0.38
                    XDB=0.28   XQB=0.28   RA=0.0     TD0P=7.85
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=24    H=3.5      SN=2504    UN=300     D=0        VREG=26

!SOUTGG12   5603     TYPE=1  XD=1.8    XQ=1.7    XA=0.2    XDP=0.3    XQP=0.55
!                    XDB=0.25  XQB=0.25  RA=0.0025 TD0P=8.0   TQ0P=0.4
!                    TD0B=0.03 TQ0B=0.05 TAB=1     TURB=3
!                    H=6.5     SN=106    UN=300     D=0        VREG=2

WESTGG1_    6000     TYPE=2     XD=1.28    XQ=0.94    XA=0.2     XDP=0.37
                    XDB=0.28   XQB=0.28   RA=0.0     TD0P=9.7
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=24    H=3.5      SN=1189    UN=300     D=0        VREG=31

NWESGG1_    6100     TYPE=2     XD=1.2     XQ=0.73    XA=0.15    XDP=0.37
                    XDB=0.18   XQB=0.18   RA=0.0     TD0P=9.9
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=3.0      SN=2470    UN=300     D=0        VREG=27

MID3GG1_    6500     TYPE=2     XD=1.0679  XQ=0.6420  XA=0.1351  XDP=0.2387
                    XDB=0.158  XQB=0.158  RA=0.0     TD0P=5.4855
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
```

```
                    TURB=25    H=3.558    SN=1591    UN=300     D=0        VREG=30

  NOR3GG1_   6700    TYPE=2     XD=1.1044  XQ=0.6619  XA=0.1474  XDP=0.2548
                    XDB=0.1706 XQB=0.1706 RA=0.0     TD0P=5.24
                    TD0B=0.05  TQ0B=0.15  V1=1       V2=1.2     SE1=0.10   SE2=0.30
                    TURB=25    H=3.5920   SN=2917    UN=300     D=0        VREG=27

  SO-FGG1_   7000    TYPE=1     XD=2.22    XQ=2.13    XA=0.1688  XDP=0.36     XQP=0.468
                    XDB=0.225  XQB=0.225  RA=0.0     TD0P=10.0  TQ0P=1
                    TD0B=0.05  TQ0B=0.05  V1=1       V2=1.2     SE1=0.1089   SE2=0.378
                    TURB=40    H=5.5      SN=5579    UN=420     D=0        VREG=11

  NO-FGG1_   7100    TYPE=2     XD=0.75    XQ=0.50    XA=0.1154  XDP=0.25
                    XDB=0.1538 XQB=0.1538 RA=0.0     TD0P=5.0
                    TD0B=0.06  TQ0B=0.10  V1=1       V2=1.2     SE1=0.1024 SE2=0.2742
                    TURB=22    H=3.20     SN=1379    UN=420     D=0        VREG=27

  SJOLGG1_   8500    TYPE=1     XD=2.42    XQ=2.00    XA=0.1481  XDP=0.23   XQP=0.4108
                    XDB=0.1706 XQB=0.1706 RA=0.0     TD0P=10.0  TQ0P=1
                    TD0B=0.05  TQ0B=0.05  V1=1       V2=1.2     SE1=0.1089   SE2=0.378
                    TURB=40    H=7.0      SN=1056    UN=420     D=0        VREG=28

END


REGULATORS

 10    TYPE=DSLS/IEEEX2/
       TR=0     KA=729    TA=0.04    VRMAX=5.32   VRMIN=-4.05
       KE=1.0   TE=0.44   KF=0.0667  TF1=2.0      TF2=0.44
       E1=6.5   SE1=0.054 E2=8       SE2=0.2020   TB=0       TC=0         SWS=40

 11    TYPE=DSLS/IEEEX2/
       TR=0     KA=800    TA=0.04    VRMAX=5.32   VRMIN=-4.05
       KE=1.0   TE=0.44   KF=0.0667  TF1=2.0      TF2=0.44
       E1=6.5   SE1=0.054 E2=8       SE2=0.2020   TB=0       TC=0         SWS=44


 20    TYPE=BBC1
       T1=3.3   T3=13     K=31      T4=0.05   T2=0
       UEMIN=0  UEMAX=4

 21    TYPE=BBC1
       T1=0     T3=0.04   K=10      T4=0.04   T2=0
       UEMIN=0  UEMAX=5

 22    TYPE=BBC1
       T1=2     T3=10     K=165     T4=0.04   T2=0
       UEMIN=0  UEMAX=5

 23    TYPE=BBC1
       T1=3.3   T3=13     K=31      T4=0.05   T2=0
       UEMIN=0  UEMAX=4   SWS=41

 24    TYPE=BBC1
       T1=0     T3=0.04   K=10      T4=0.04   T2=0
       UEMIN=0  UEMAX=5   SWS=42

 25    TYPE=BBC1
       T1=3.3   T3=13     K=31      T4=0.05   T2=0
       UEMIN=0  UEMAX=4   SWS=43

 26    TYPE=BBC1
       T1=3.3   T3=13     K=61      T4=0.05   T2=0
       UEMIN=0  UEMAX=4

 27    TYPE=BBC1
       T1=3.3   T3=13     K=61      T4=0.05   T2=0
       UEMIN=0  UEMAX=4   SWS=42
```

```
 28    TYPE=BBC1
       T1=0     T3=0.04   K=10      T4=0.04   T2=0
       UEMIN=0  UEMAX=5   SWS=42

 30    TYPE=BBC1
       T1=0.00005 T2=0    T3=100     T4=0.5        K=200
       UEMIN=0    UEMAX=4

 31    TYPE=BBC1
       T1=10      T2=0    T3=0.1     T4=0.1        K=20
       UEMIN=-4   UEMAX=4

 40    TYPE=DSLS/STAB2A/
       K2=1   T2=2    K3=0     T3=2   K4=0.55   K5=1  T5=0.01  HLIM=0.03

 41    TYPE=DSLS/STAB2A/
       K2=1   T2=4.5  K3=0.87  T3=2   K4=0.087  K5=1  T5=0.01  HLIM=0.04

 42    TYPE=DSLS/STAB2A/
       K2=1   T2=4.5  K3=0     T3=2   K4=0.55   K5=1  T5=0.01  HLIM=0.03

 43    TYPE=DSLS/STAB2A/
       K2=1   T2=4.5  K3=0     T3=2   K4=0.68   K5=1  T5=0.01  HLIM=0.03

 44    TYPE=DSLS/STAB2A/
       K2=1   T2=1.0  K3=0     T3=2   K4=0.55   K5=1  T5=0.01  HLIM=0.03

 100   TYPE=SVS
       RTYP=2  KP=15  TF=0.02  VPMAX=2   VPMIN=-2   KA=30
       VIMIN=0 VIMAX=0.1       QMIN=-320 QMAX=320

END




TURBINES
 1     TYPE=DSLS/FPCWT_WINDTURB/  NOM_POWER=1060.0  AIRDENS=1.2
                        NOM_TURBSPEED=0
                        BLADELENGTH=0   LOWCUTOUT=2.0
                        GOV=2      WINDCURVE=81

 2     TYPE=DSLS/FPCWT_PICON/  KPP=60   KPC=3   KIP=20   KIC=20
                        TP=0.3  BMAX=27  BMIN=0
                        DBDTMAX=4.0  DBDTMIN=-4.0    BLOCK=0
                        DW=FPCWT_REC_DW
                        PORD=FPCWT_REC_PORD

!!!HYDRO TURBINES

 20    TYPE=DSLS/HYTUR/
       GOV=29       TW=1     AT=1.0022     DTURB=0.5    QNL=0.1

 21    TYPE=DSLS/HYTUR/
       GOV=29       TW=1     AT=1.0577     DTURB=0.5    QNL=0.1

 22    TYPE=DSLS/HYTUR/
       GOV=29       TW=1     AT=1.01       DTURB=0.5    QNL=0.1

 23    TYPE=DSLS/HYTUR/
       GOV=29       TW=1     AT=1.1        DTURB=0.5    QNL=0.1

 24    TYPE=DSLS/HYTUR/
       GOV=28       TW=1     AT=1.1        DTURB=0.5    QNL=0.1

 25    TYPE=DSLS/HYTUR/
       GOV=27       TW=1     AT=1.1        DTURB=0.5    QNL=0.1

 27    TYPE=DSLS/HYGOV/
       RBIG=0.06             RSMALL=0.4
```

```
       TR=5.0                TF=0.05       TG=0.2
       VELM=0.2              GMIN=0        GMAX=1

 28    TYPE=DSLS/HYGOV/
       RBIG=0.06             RSMALL=0.3
       TR=5.0                TF=0.05       TG=0.2
       VELM=0.2              GMIN=0        GMAX=1.5

 29    TYPE=DSLS/HYGOV/
       RBIG=0.06             RSMALL=0.4
       TR=5.0                TF=0.05       TG=0.2
       VELM=0.1              GMIN=0        GMAX=1.5

!!!STEAM TURBINES

 40    TYPE=ST2
       GOV=49       K1=0.301    T1=0.4     K2=0.399    T2=8.0
       K3=0.3       T3=0.3      K4=0       T4=0

 49    TYPE=SG3
       T1=0.01      T2=0.0      T3=0.15    K=0
       YMIN=0       YMAX=1


END


LOADS
  3000      NO=  1    MP=1 MQ=2
  3000      NO=  2    MP=1 MQ=2
  3100                MP=1 MQ=2
  3200                MP=1 MQ=2
  3245                MP=1 MQ=2
  3249                MP=1 MQ=2
  3300                MP=1 MQ=2
  3359                MP=1 MQ=2
  3360                MP=1 MQ=2
  5100                MP=1 MQ=2
  5300                MP=1 MQ=2
  5400                MP=1 MQ=2
  5500                MP=1 MQ=2
  5600                MP=1 MQ=2
  5603      NO=  1    MP=1 MQ=2
  5603      NO=  2    MP=1 MQ=2
  6000                MP=1 MQ=2
  6100                MP=1 MQ=2
  6500                MP=1 MQ=2
  6700                MP=1 MQ=2
  7000      NO=  1    MP=1 MQ=2
  7000      NO=  2    MP=1 MQ=2
  7100                MP=1 MQ=2
  8500                MP=1 MQ=2
END



PWM CONVERTERS
  FPCWT_REC
                          TYPE=DSLS/FPCWT_PWM_DYN/ SN=1060.0
                          UN=3.0     X=0.3    PL=0.02
                          MODE=1       UDCORD=5.0   IMAX=1.04

                          PORD=FPCWT_REC_PORD


                          IQORD=FPCWT_REC_IQORD


                          IQORD0=FPCWT_REC_IQORD0

  FPCWT_INV
```

```
                          TYPE=DSLS/FPCWT_PWM_DYN/  SN=1060.0
                          UN=3.5    X=0.3    PL=0.02
                          MODE=2     UDCORD=5.0    IMAX=1.04
                          PORD=0.0

                          IQORD=FPCWT_INV_IQORD

                          IQORD0=FPCWT_INV_IQORD0

  LIGHT_A                 TYPE=DSLS/HVDC_LIGHT_OPEN_MODEL_V116_DYN/ DC1=A_2
                          BLOCKED=0 PTAB=2 QTAB=3 PCTRL=1 UACCTRL=0

  LIGHT_B                 TYPE=DSLS/HVDC_LIGHT_OPEN_MODEL_V116_DYN/ DC1=B_2
                          BLOCKED=0 UTAB=4 PCTRL=0 UACCTRL=1

END


MISC
  SPC1  TYPE=DSLS/FPCWT_SPCON/  KS=0.6   KP=3.0   TPC=0.05
                          PMAX=0.976  PMIN=0.0  DPMAX=0.1  DPMIN=-0.1
                          WMAX=1.20  WMIN=0.40  WLOW=0.60
                          DW=FPCWT_REC_DW
                          PORD=FPCWT_REC_PORD
                          SYNC=FPCWT_GEN

  VACR  1000 TYPE=DSLS/FPCWT_VACCON/ N=1
                           INTMAX=1.0  INTMIN=-1.0

                           UACORD=3.0

                           IQMAX=0.5    IQMIN=-0.5
                           K=1.2   TI=0.05   BLOCK=0


                           IQORD=FPCWT_REC_IQORD


                           IQORD0=FPCWT_REC_IQORD0

  VACI  BUS_11 TYPE=DSLS/FPCWT_VACCON/ N=1
                           INTMAX=1.0  INTMIN=-1.0

                           UACORD=3.5

                           IQMAX=0.5   IQMIN=-0.5
                           K=1.2   TI=0.05
                           IQORD=FPCWT_INV_IQORD
                           IQORD0=FPCWT_INV_IQORD0
END



TABLES
! 1 TYPE=1 F 0.000 0.00 0.700 0.70
!            0.800 0.80 0.830 0.83
!            0.860 0.86 0.962 0.94
!            0.974 0.95 1.039 1.00
!            1.113 1.05 1.202 1.10
!            1.315 1.15 1.467 1.20
!            1.682 1.25 1.998 1.30
!            2.478 1.35

  2 TYPE 0   F   0.0   0.8

                         10.0   0.8

                         20.0   0.9

                        100.0   0.9

  3 TYPE 0   F   0.0   0.0
```

```
                        40.0   0.0
                        50.0   0.05
                       100.0   0.05
  4 TYPE 0   F   0.0   1.0
                        70.0   1.0
                        80.0   0.95
                       100.0   0.95



! Cp/lambda curve for beta=0 deg.
 11 TYPE=0   F       0.0   0.00
                     1.0   0.10
                     2.0   0.20
                     3.0   0.30
                     4.0   0.38
                     5.0   0.42
                     6.0   0.48
                     6.5   0.49
                     7.0   0.50
                     7.5   0.504
                     8.0   0.50
                     8.5   0.49
                     9.0   0.48
                     10.0  0.47
                     11.0  0.45
                     12.0  0.42
                     13.0  0.39
                     14.0  0.35
                     15.0  0.30
                     16.0  0.25
                     17.0  0.19
                     18.0  0.11
                     19.0  0.04
                     20.0  0.00
! Cp/lambda curve for beta=7 deg.
 12 TYPE=0   F       0.0  0.00
                          1.0  0.02
                          2.0  0.05
                          3.0  0.16
                          4.0  0.26
                          5.0  0.30
                          6.0  0.31
                          6.5  0.31
                          7.0  0.30
                          7.5  0.28
                          8.0  0.26
                          8.5  0.24
                          9.0  0.22
                          10.0 0.16
                          11.0 0.08
                          12.0 0.00
! Cp/lambda curve for beta=27 deg.
 13 TYPE=0   F       0.0  0.00
                          1.0  0.01
                          2.0  0.04
                          3.0  0.16
                          4.0  0.20
                          5.0  0.25
                          6.0  0.26
                          6.5  0.26
                          7.0  0.22
                          7.5  0.20
```

```
                      8.0  0.19
                      8.5  0.16
                      9.0  0.10
                            10.0 0.05
                            11.0 0.00
! Voltage fluctuations in the grid
 51  TYPE=0    F     0.00   1.0
                            10.0   1.0
                            10.0   0.94
                            10.1   0.94
                            10.1   1.0
                   100.0      1.0
! Wind profile
 81 TYPE=0      F  0.0   11.569607734680176
                   100.0 11.569607734680176

! or from separate file as

!!! $INCLUDE TEST-FPCWT.TXT

! This text file must look the same as a table given in the Dynpow file.
! It is possible to create a text file from MS Excel if the wind profile is
! stored there, but after export to a text file in the text file, strings edit
! by TABS must be replaced and edit by SPACE

END


FAULTS
 F1 TYPE=3PSG NODE 6100
END

RUN INSTRUCTION
 AT 1.000  INST     CONNECT  FAULT  F1
END

END
```

APPENDIX F: INITIAL POWER FLOW

```
*** BASIC BALANCE REGION    1 AREA   40 ***

 3000     (  40)      1.00000     p.u.
                      420.000     kV
                      30.1386     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3000    3115      81           498.661      -53.9927
            LINE 3000    3245      81          -797.542       68.0472
            LINE 3000    3300      81          -3001.12      -540.372
            LOAD 3000       1                  -2500.00      -500.000
            LOAD 3000       2                   500.000      -250.000
            PROD STCKGG1_                       5300.00       1276.32

 3100     (  40)     0.970000     p.u.
                      407.400     kV
                      34.4729     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3100    3115      81           1006.93      -199.668
            LINE 3100    3200      81          -868.370      -52.8393
            LINE 3100    3249      81           2729.45      -563.566
            LINE 3100    3359      81          -3868.01      -407.839
            LOAD 3100       0                  -500.000      -100.000
            PROD STRFGG1_                       1500.00       1323.91

 3115     (  40)      1.00000     p.u.
                      420.000     kV
                      60.2281     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3000    3115      81          -536.713       83.4253
            LINE 3100    3115      81          -1040.80      -192.805
            LINE 3115    3245      81          -1257.53      -304.111
            LINE 3115    3249      81          -77.3494       25.2032
            LINE 3115    6701      81           168.142       21.0854
            LINE 3115    7100      81          -825.749      -79.7344
            PROD SV-NGG11                       3570.00       446.937

 3200     (  40)     0.964952     p.u.
                      405.280     kV
                      4.28289     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3100    3200      81           813.721      -238.244
            LINE 3200    3300      81          -408.405       228.622
            LINE 3200    3359      81           94.6833       109.621
            LOAD 3200       0                  -500.000      -100.000

 3244     (  40)     0.999840     p.u.
                      299.952     kV
                      22.2758     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3244    6500      81          -76.7740       11.2350
            TR2  3244    3245     369           76.7740      -11.2350

 3245     (  40)      1.00000     p.u.
                      420.000     kV
                      22.3670     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3000    3245      81           789.631      -48.1647
            LINE 3115    3245      81           1207.17      -450.876
            TR2  3244    3245     369          -76.8041       11.1146
            LOAD 3245       0                  -2700.00      -500.000
            PROD SV-MGG1_                       780.000       987.927
```

```
3249     (  40)      1.00000     p.u.
                     420.000     kV
                     59.3385     DEGREES

           POWER FROM                                  MW          Mvar
           LINE 3100    3249      81           -2818.83      -556.968
           LINE 3115    3249      81            77.2575       13.6231
           LINE 3249    7100      81           -805.694      -70.1740
           TR2  3701    3249     369            47.2664       12.4497
           LOAD 3249       0                  -1250.00      -300.000
           PROD SV-NGG12                       4750.00       901.069

3300     (  40)      1.00000     p.u.            SWING BUS
                     420.000     kV
                     0.00000     DEGREES

           POWER FROM                                  MW          Mvar
           LINE 3000    3300      81            2895.98      -930.827
           LINE 3200    3300      81            405.560      -235.234
           LINE 3300    3359      81            1147.14      -144.641
           LINE 3300    8500      81          -0.957295       216.753
           LOAD 3300       0                  -9350.00      -1500.00
           PROD SV-SGG1_                       4902.28       2593.95

3359     (  40)      1.00000     p.u.
                     420.000     kV
                     6.41252     DEGREES

           POWER FROM                                  MW          Mvar
           LINE 3100    3359      81            3721.75      -1484.19
           LINE 3200    3359      81           -95.2452      -40.7748
           LINE 3300    3359      81           -1157.04       32.1969
           LINE 3359    5101      81           -554.319      -21.7842
           LINE 3359    5101      82           -554.319      -21.7842
           TR2  3359    3360     369           -360.819      -183.276
           LOAD 3359       0                  -4500.00      -700.000
           PROD SV-WGG1_                       2670.00       1209.80
           PROD SV-WGG2_                       830.000       1209.80

3360     (  40)     0.994550     p.u.
                     134.264     kV
                     6.04957     DEGREES

           POWER FROM                                  MW          Mvar
           TR2  3359    3360     369            360.000       180.000
           LOAD 3360       0                   -360.000      -180.000

3701     (  40)      1.00744     p.u.
                     302.232     kV
                     60.6685     DEGREES

           POWER FROM                                  MW          Mvar
           LINE 3701    6700      81            47.3142       13.6443
           TR2  3701    3249     369           -47.3142      -13.6443


--------------------------------------------------------------------------------


*** SUMMARY OF RESULT AREA   40 ***

IMPORT(+) EXPORT(-)    MW           Mvar
******************
                    215.456       34.7297     FROM AREA   67
                   -1631.44      -149.908     FROM AREA   71
                   -76.7740       11.2350     FROM AREA   65
                  -0.957295       216.753     FROM AREA   90
                   -1108.64      -43.5684     FROM AREA   51
----------------------------------------
TOTAL              -2602.36       69.2405
```

```
 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         24302.3       9949.72
 NETWORK GENERATION                1167.64
 ----------------------------------------
 TOTAL               24302.3       11117.4

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       21160.0       4130.00
 NETWORK    LOSSES   539.926       7056.60
 ----------------------------------------
 TOTAL               21699.9       11186.6

                        MW           Mvar
 ********************
 SWING     3300      4902.28       2593.95
 SWING BUS  TOTAL    4902.28       2593.95
 TRANSMISS. LOSSES   539.029       7052.01


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   51 ***

 5100     (  51)      1.00000     p.u.
                      300.000     kV
                    -0.897533     DEGREES

             POWER FROM                                MW          Mvar
             LINE 5100    5300      81            568.907      -99.9627
             LINE 5100    5500      81           -101.063       48.6119
             LINE 5100    6500      81            252.221      -77.4994
             TR2  5101    5100     369            634.383      -560.424
             TR2  5102    5100     369            947.600      -37.7610
             TR2  5103    5100     369            427.953      -39.3340
             LOAD 5100       0                  -4210.00      -692.000
             PROD EASTGG1_                       1480.00       1458.37

 5101     (  51)     0.989859     p.u.
                      415.741     kV
                     0.255727     DEGREES

             POWER FROM                                MW          Mvar
             SHUN 5101      81                   0.00000      -954.740
             LINE-REACTOR 5101     810          -21.8500      0.145519E-07
             LINE 3359    5101      81           549.757      -2.01702
             LINE 5101    5501      81          -442.709       420.204
             LINE 3359    5101      82           549.757      -2.01702
             TR2  5101    5100     369          -634.956       538.570

 5102     (  51)      1.00002     p.u.
                      420.010     kV
                     0.760339     DEGREES

             POWER FROM                                MW          Mvar
             SHUN 5102      81                   0.00000      0.100007
             LINE-REACTOR 5102     810          -0.200010      0.227374E-09
             LINE 5102    5301      81           1048.04      -62.9470
             LINE 5102    6001      81          -99.5220       52.5168
             TR2  5102    5100     369          -948.319       10.3302

 5103     (  51)     0.998059     p.u.
                      419.185     kV
                      1.56563     DEGREES

             POWER FROM                                MW          Mvar
             SHUN 5103      81                  0.291038E-07  -12.6507
             LINE-REACTOR 5103     810          -0.398448       0.00000
             LINE 5103    5301      81           428.813      -8.21415
             TR2  5103    5100     369          -428.415       20.8649
```

```
--------------------------------------------------------------------------------


*** TRANSFORMERS OFF NOMINAL *** AREA   51

                          TAU p.u.  FI DEG.  STEP    MW          Mvar
                          ************************
TR2  5101    5100     369  1.0063     0.000      1  -634.956       538.570


--------------------------------------------------------------------------------


*** SUMMARY OF RESULT AREA   51 ***

IMPORT(+) EXPORT(-)    MW           Mvar
*******************
                    1099.51      -4.03403     FROM AREA   40
                    2045.76      -171.124     FROM AREA   53
                   -543.772       468.816     FROM AREA   55
                    252.221      -77.4994     FROM AREA   65
                   -99.5220       52.5168     FROM AREA   60
-----------------------------------------
TOTAL               2754.20       268.675

TOTAL PRODUCTION       MW           Mvar
****************
PRODUCTIONS         1480.00       1458.37
SHUNT CAPACITORS    0.00000      0.100007
-----------------------------------------
TOTAL               1480.00       1458.47

TOTAL LOAD             MW           Mvar
**********
LOAD ABSORBED       4210.00       692.000
SHUNT REACTORS      0.00000       967.391
LINE  REACTORS      22.4485       0.00000
NETWORK    LOSSES   1.75435       67.7537
-----------------------------------------
TOTAL               4234.20       1727.14


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   53 ***

 5300     (  53)      1.00000     p.u.
                      300.000     kV
                      12.5044     DEGREES

            POWER FROM                              MW          Mvar
            LINE 5100    5300      81           -582.396       14.7792
            LINE 5300    6100      81            0.00000       0.00000
            (NOT CONNECTED)
            TR2  5300    5301     369           -1491.60      -18.4380      *
            LOAD 5300       0                  -201.000      -11.3000
            PROD HDALGG1_                       2275.00       14.9587

 5301     (  53)      1.00063     p.u.
                      420.265     kV
                      7.28899     DEGREES

            POWER FROM                              MW          Mvar
            SHUN 5301     811                   0.00000       12.7160
            LINE-REACTOR 5301     812           0.300379     -0.363798E-08
            LINE 5102    5301      81           -1056.37       71.7963
            LINE 5103    5301      81           -431.972       32.7882
            TR2  5300    5301     369            1488.04      -117.301      *
```

```
 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   53 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                   -2070.74       119.364     FROM AREA   51
                    0.00000       0.00000     FROM AREA   61
 ----------------------------------------
 TOTAL              -2070.74       119.364

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS          2275.00       14.9587
 SHUNT CAPACITORS     0.00000       12.7160
 ----------------------------------------
 TOTAL                2275.00       27.6747

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED        201.000       11.3000
 LINE  REACTORS     -0.300379       0.00000
 NETWORK    LOSSES    3.56051       135.738
 ----------------------------------------
 TOTAL                204.260       147.038


 ------------------------------------------------------------------------------



 *** TRANSFORMERS OVER LIMITS *** AREA   53
 TR2  5300    5301     369         S1MAX S  =  1491.72     MVA DELTA=  491.718     MVA
1.49 p.u.

------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   54 ***

 5400     (  54)      1.00700     p.u.
                      302.100     kV
                     0.167178     DEGREES

            POWER FROM                              MW          Mvar
            LINE 5400    6000      81           -158.925     -0.421340
            LINE 5400    6100      81           -418.313      -4.66958
            SREA 5400    5500      81           -313.449      -7.45737
            TR2  5400    5401     369           -326.504      -33.7190
            TR2  5400    5402     369           -276.409      -60.5442
            LOAD 5400       0                  -94.4000       0.00000
            PROD CNTRGG11                       1588.00       106.812

 5401     (  54)     0.996324     p.u.
                      418.456     kV
                     -2.07890     DEGREES

            POWER FROM                              MW          Mvar
            SHUN 5401      81                    0.00000     -0.496331
            LINE-REACTOR 5401     810           0.198532     -0.454747E-09
            LINE 5401    5501      81           55.9813       65.9103
            LINE 5401    5602      81           -680.805      -136.521
            LINE 5401    6001      81           298.465       50.3001
            TR2  5400    5401     369           326.160       20.8067

 5402     (  54)      1.00600     p.u.
                      422.519     kV
                   -0.659512E-01 DEGREES
```

```
           POWER FROM                                  MW          Mvar
           LINE 5402    6001      81           -276.377      -59.3599
           TR2  5400    5402     369            276.377       59.3599
 ---------------------------------------------------------------------------



 *** TRANSFORMERS OFF NOMINAL *** AREA   54

                           TAU p.u.  FI DEG.  STEP    MW          Mvar
                           **********************
 TR2  5400    5401     369  1.0063     0.000      1  -326.504      -33.7190

 ---------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   54 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                    -136.837      -9.48111     FROM AREA   60
                    -418.313      -4.66958     FROM AREA   61
                    -257.468       58.4529     FROM AREA   55
                    -680.805      -136.521     FROM AREA   56
 ----------------------------------------
 TOTAL               -1493.42      -92.2185

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS          1588.00       106.812
 ----------------------------------------
 TOTAL                1588.00       106.812

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED        94.4000       0.00000
 SHUNT REACTORS       0.00000      0.496331
 LINE  REACTORS     -0.198532       0.00000
 NETWORK    LOSSES  0.376035       14.0967
 ----------------------------------------
 TOTAL                94.5775       14.5930


---------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   55 ***

 5500     (  55)      1.00400     p.u.
                      301.200     kV
                     -1.80119     DEGREES

            POWER FROM                                MW          Mvar
            SHUN 5500      81                  -0.363798E-08   1.31042
            LINE-REACTOR 5500     810          -0.302405       0.00000
            LINE 5100    5500      81            100.853      -28.9883
            LINE 5500    5603      81           -418.540      -180.640
            SREA 5400    5500      81            312.586      -3.30341
            TR2  5500    5501     369            406.404       850.061
            LOAD 5500       0                  -1229.00      -115.000
            PROD CNTRGG12                       828.000      -523.440

 5501     (  55)      1.00445     p.u.
                      421.870     kV
                     -1.47001     DEGREES

            POWER FROM                                MW          Mvar
            SHUN 5501     811                   0.00000       983.100
            LINE-REACTOR 5501     812           21.7928     -0.582077E-07
```

```
           LINE 5101    5501      81            441.025      -112.796
           LINE 5401    5501      81           -56.0525      -6.69481
           TR2  5500    5501     369           -406.765      -863.609
 ------------------------------------------------------------------------------



 *** TRANSFORMERS OFF NOMINAL *** AREA   55

                           TAU p.u.  FI DEG.  STEP    MW          Mvar
                           **********************
 TR2  5500    5501     369  1.0127     0.000      2   406.404       850.061

 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   55 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                     541.878      -141.784     FROM AREA   51
                     256.534      -9.99822     FROM AREA   54
                    -418.540      -180.640     FROM AREA   56
 ----------------------------------------
 TOTAL               379.871      -332.422

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         828.000      -523.440
 SHUNT CAPACITORS    0.00000       984.410
 ----------------------------------------
 TOTAL               828.000       460.971

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       1229.00       115.000
 LINE  REACTORS     -21.4904       0.00000
 NETWORK    LOSSES  0.361189       13.5482
 ----------------------------------------
 TOTAL               1207.87       128.548


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   56 ***

 5600     (  56)      1.01000     p.u.
                      303.000     kV
                     -9.15986     DEGREES

            POWER FROM                              MW          Mvar
            LINE 5600    5603      81           -321.643      -370.475
            LINE 5600    6000      81            417.564      -64.5490
            TR2  5600    5601     369            647.080      -18.0862
            LOAD 5600       0                  -3121.00      -297.000
            PROD SOUTGG11                       2378.00       750.110

 5601     (  56)     0.991126     p.u.
                      416.273     kV
                     -8.87280     DEGREES

            POWER FROM                              MW          Mvar
            LINE 5601    6001      81            647.165      -14.8442
            TR2  5600    5601     369           -647.165       14.8442

 5602     (  56)     0.956161     p.u.
                      401.588     kV
                     -11.7764     DEGREES
```

```
            POWER FROM                                  MW          Mvar
            LINE 5401    5602      81            673.155       100.742
            TR2  5603    5602     369           -673.155      -100.742

 5603     (  56)     0.922383     p.u. ** LOW  **
                      276.715     kV
                     -13.0629     DEGREES

            POWER FROM                                  MW          Mvar
            SHUN 5603     811                  -0.145519E-07  -1.10603
            LINE-REACTOR 5603     812           0.255237       0.00000
            LINE 5500    5603      81            410.246       94.7058
            LINE 5600    5603      81            316.750       336.114
            TR2  5603    5602     369            672.750       85.2859
            LOAD 5603       1                   -460.000      -45.0000
            LOAD 5603       2                   -940.000      -470.000
 ------------------------------------------------------------------------------



 *** TRANSFORMERS OFF NOMINAL *** AREA   56

                           TAU p.u.  FI DEG.  STEP    MW          Mvar
                           **********************
 TR2  5600    5601     369  1.0190     0.000      3   647.080      -18.0862
 TR2  5603    5602     369  0.9683     0.000     -5   672.750       85.2859


 *** LOW VOLTAGE NODES *** AREA   56
 5603      0.922383     p.u.


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   56 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                     673.155       100.742     FROM AREA   54
                     410.246       94.7058     FROM AREA   55
                     1064.73      -79.3932     FROM AREA   60
 ----------------------------------------
 TOTAL               2148.13       116.054

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         2378.00       750.110
 NETWORK GENERATION                19.5022
 ----------------------------------------
 TOTAL               2378.00       769.612

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       4521.00       812.000
 SHUNT REACTORS      0.00000       1.10603
 LINE  REACTORS    -0.255237       0.00000
 NETWORK    LOSSES   5.38457       72.5602
 ----------------------------------------
 TOTAL               4526.13       885.666

                        MW           Mvar
 *********************
 TRANSMISS. LOSSES   4.89368       53.8625


 ------------------------------------------------------------------------------


 *** BASIC BALANCE REGION    1 AREA   60 ***
```

```
6000     (  60)      1.00500     p.u.
                      301.500     kV
                    -0.729344     DEGREES

            POWER FROM                                  MW          Mvar
            LINE 5400    6000      81            158.675       8.04928
            LINE 5600    6000      81           -423.782       47.9961
            LINE 6000    6100      81           -282.879       5.56690
            TR2  6000    6001     369           -577.014       67.7403
            LOAD 6000       0                   -4.00000       0.00000
            PROD WESTGG1_                        1129.00      -129.353

6001     (  60)     0.999483     p.u.
                     419.783     kV
                    -1.22774     DEGREES

            POWER FROM                                  MW          Mvar
            SHUN 6001     811                  0.227374E-09 -0.998984E-01
            LINE-REACTOR 6001     812         -0.199793       0.00000
            SHUN 6001     813                   0.00000      0.499484
            LINE-REACTOR 6001     814         -0.199793       0.00000
            LINE 5102    6001      81            99.3094       44.2789
            LINE 5401    6001      81           -298.740      -39.9409
            LINE 5402    6001      81            275.967       76.9693
            LINE 5601    6001      81           -653.015      -8.89008
            TR2  6000    6001     369            576.878      -72.8169
--------------------------------------------------------------------------------



*** TRANSFORMERS OFF NOMINAL *** AREA   60

                          TAU p.u.  FI DEG.  STEP    MW          Mvar
                          **********************
TR2  6000    6001     369  1.0063     0.000      1  -577.014       67.7403


--------------------------------------------------------------------------------


*** SUMMARY OF RESULT AREA   60 ***

IMPORT(+) EXPORT(-)    MW           Mvar
*******************
                    99.3094       44.2789     FROM AREA   51
                    135.902       45.0777     FROM AREA   54
                   -1076.80       39.1061     FROM AREA   56
                   -282.879       5.56690     FROM AREA   61
-----------------------------------------
TOTAL              -1124.46       134.030

TOTAL PRODUCTION       MW           Mvar
****************
PRODUCTIONS          1129.00      -129.353
SHUNT CAPACITORS     0.00000      0.499484
-----------------------------------------
TOTAL                1129.00      -128.853

TOTAL LOAD             MW           Mvar
**********
LOAD ABSORBED        4.00000       0.00000
SHUNT REACTORS       0.00000      0.998984E-01
LINE  REACTORS      0.399587       0.00000
NETWORK    LOSSES   0.135424       5.07660
-----------------------------------------
TOTAL                4.53501       5.17650


--------------------------------------------------------------------------------
```

```
*** BASIC BALANCE REGION    1 AREA   61 ***

 6100     (  61)      1.00000     p.u.
                      300.000     kV
                     -4.58435     DEGREES

            POWER FROM                                MW          Mvar
            LINE 5400    6100      81             414.862      -17.7652
            LINE 6000    6100      81             281.138      -4.41524
            LINE 5300    6100      81             0.00000       0.00000
            (NOT CONNECTED)
            LOAD 6100       0                   -3042.00      -980.000
            PROD NWESGG1_                        2346.00       1002.18


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   61 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 ********************
                     414.862      -17.7652     FROM AREA   54
                     281.138      -4.41524     FROM AREA   60
                     0.00000       0.00000     FROM AREA   53
 ----------------------------------------
 TOTAL               696.000      -22.1804

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         2346.00       1002.18
 ----------------------------------------
 TOTAL               2346.00       1002.18

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       3042.00       980.000
 NETWORK    LOSSES -0.238419E-03  0.800937E-04
 ----------------------------------------
 TOTAL               3042.00       980.000


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   65 ***

 6500     (  65)      1.00000     p.u.
                      300.000     kV
                      22.0527     DEGREES

            POWER FROM                                MW          Mvar
            LINE 3244    6500      81             76.7440      -10.5357
            LINE 5100    6500      81            -262.670      -26.0234
            LINE 6500    6700      81             593.926      -250.390
            LOAD 6500       0                   -1919.00      -279.000
            PROD MID3GG1_                        1511.00       565.949


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   65 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 ********************
                     76.7440      -10.5357     FROM AREA   40
                    -262.670      -26.0234     FROM AREA   51
                     593.926      -250.390     FROM AREA   67
 ----------------------------------------
 TOTAL               408.000      -286.949
```

```
 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         1511.00       565.949
 ----------------------------------------
 TOTAL               1511.00       565.949

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       1919.00       279.000
 NETWORK    LOSSES   0.00000       0.00000
 ----------------------------------------
 TOTAL               1919.00       279.000


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   67 ***

 6700     (  67)      1.02000     p.u.
                      306.000     kV
                      63.2992     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3701    6700      81           -47.3374      -10.8291
            LINE 6500    6700      81           -627.243      -198.333
            TR2  6700    6701     369           -169.420       20.2779
            LOAD 6700       0                  -1927.00      -446.000
            PROD NOR3GG1_                       2771.00       634.885

 6701     (  67)      1.00678     p.u.
                      422.847     kV
                      63.1020     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3115    6701      81           -169.276       20.8518
            TR2  6700    6701     369            169.276      -20.8518
 ------------------------------------------------------------------------------



 *** TRANSFORMERS OFF NOMINAL *** AREA   67

                           TAU p.u.  FI DEG.  STEP    MW          Mvar
                           ***********************
 TR2  6700    6701     369  1.0127     0.000      2  -169.420       20.2779


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   67 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                   -216.614       10.0228     FROM AREA   40
                   -627.243      -198.333     FROM AREA   65
 ----------------------------------------
 TOTAL               -843.856      -188.311

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         2771.00       634.885
 ----------------------------------------
 TOTAL               2771.00       634.885

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       1927.00       446.000
 NETWORK    LOSSES  0.143528      0.573978
 ----------------------------------------
```

```
 TOTAL               1927.14       446.574

------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   70 ***

 7000     (  70)      1.00000     p.u.
                      420.000     kV
                      17.7937     DEGREES

            POWER FROM                                MW          Mvar
            LINE 7000    7100      81            150.000       122.426
            LINE 7000    7100      82            150.000       122.426
            LINE 7000    7100      83            0.00000       0.00000
            (NOT CONNECTED)
            LOAD 7000       1                   -5100.00      -1000.00
            LOAD 7000       2                   -500.000      -250.000
            PROD SO-FGG1_                        5300.00       1005.15


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   70 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 ********************
                      300.000       244.853     FROM AREA   71
 ----------------------------------------
 TOTAL                300.000       244.853

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS          5300.00       1005.15
 ----------------------------------------
 TOTAL                5300.00       1005.15

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED        5600.00       1250.00
 NETWORK    LOSSES -0.476837E-03 -0.596046E-04
 ----------------------------------------
 TOTAL                5600.00       1250.00


------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   71 ***

 7100     (  71)      1.00000     p.u.
                      420.000     kV
                      26.2615     DEGREES

            POWER FROM                                MW          Mvar
            LINE 3115    7100      81            757.417      -303.197
            LINE 3249    7100      81            740.791      -288.459
            LINE 7000    7100      81           -154.104       162.788
            LINE 7000    7100      82           -154.104       162.788
            LINE 7000    7100      83            0.00000       0.00000
            (NOT CONNECTED)
            LOAD 7100       0                   -2500.00      -400.000
            PROD NO-FGG1_                        1310.00       666.080


 ------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   71 ***
```

```
 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                     1498.21      -591.655     FROM AREA   40
                    -308.208       325.576     FROM AREA   70
 ----------------------------------------
 TOTAL               1190.00      -266.080

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         1310.00       666.080
 ----------------------------------------
 TOTAL               1310.00       666.080

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       2500.00       400.000
 NETWORK    LOSSES   0.00000     -0.119209E-03
 ----------------------------------------
 TOTAL               2500.00       400.000


--------------------------------------------------------------------------------


*** BASIC BALANCE REGION    1 AREA   90 ***

 8500     (  90)      1.02000     p.u.
                      428.400     kV
                    -0.296812     DEGREES

            POWER FROM                              MW          Mvar
            LINE 3300    8500      81            0.00000       90.3860
            LOAD 8500       0                   -1000.00      -1000.00
            PROD SJOLGG1_                        1000.00       909.614


 --------------------------------------------------------------------------------


 *** SUMMARY OF RESULT AREA   90 ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
                     0.00000       90.3860     FROM AREA   40
 ----------------------------------------
 TOTAL               0.00000       90.3860

 TOTAL PRODUCTION       MW           Mvar
 ****************
 PRODUCTIONS         1000.00       909.614
 ----------------------------------------
 TOTAL               1000.00       909.614

 TOTAL LOAD             MW           Mvar
 **********
 LOAD ABSORBED       1000.00       1000.00
 NETWORK    LOSSES   0.00000     -0.223517E-04
 ----------------------------------------
 TOTAL               1000.00       1000.00


 --------------------------------------------------------------------------------


 *** TOTAL SUMMARY OF RESULT    ***

 IMPORT(+) EXPORT(-)    MW           Mvar
 *******************
 AREA           40   -2602.36       69.2405
 AREA           51    2754.20       268.675
 AREA           53   -2070.74       119.364
 AREA           54   -1493.42      -92.2185
```

```
AREA           55    379.871      -332.422
AREA           56    2148.13       116.054
AREA           60   -1124.46       134.030
AREA           61    696.000      -22.1804
AREA           65    408.000      -286.949
AREA           67   -843.856      -188.311
AREA           70    300.000       244.853
AREA           71    1190.00      -266.080
AREA           90    0.00000       90.3860

TIE LINE LOSSES     258.637       2443.80
TIE LINE GENERATION               2298.24

TOTAL PRODUCTION       MW           Mvar
****************
PRODUCTIONS          48218.3       16411.0
SHUNT CAPACITORS     0.00000       997.726
NETWORK GENERATION                 3485.38
----------------------------------------
TOTAL                48218.3       20894.1

TOTAL LOAD             MW           Mvar
**********
LOAD ABSORBED        47407.4       10115.3
SHUNT REACTORS       0.00000       969.093
LINE  REACTORS      0.603535       0.00000
NETWORK    LOSSES    810.278       9809.75
----------------------------------------
TOTAL                48218.3       20894.1

                       MW           Mvar
*********************
SWING     3300       4902.28       2593.95
SWING BUS  TOTAL     4902.28       2593.95
TRANSMISS. LOSSES    543.922       7105.87
```