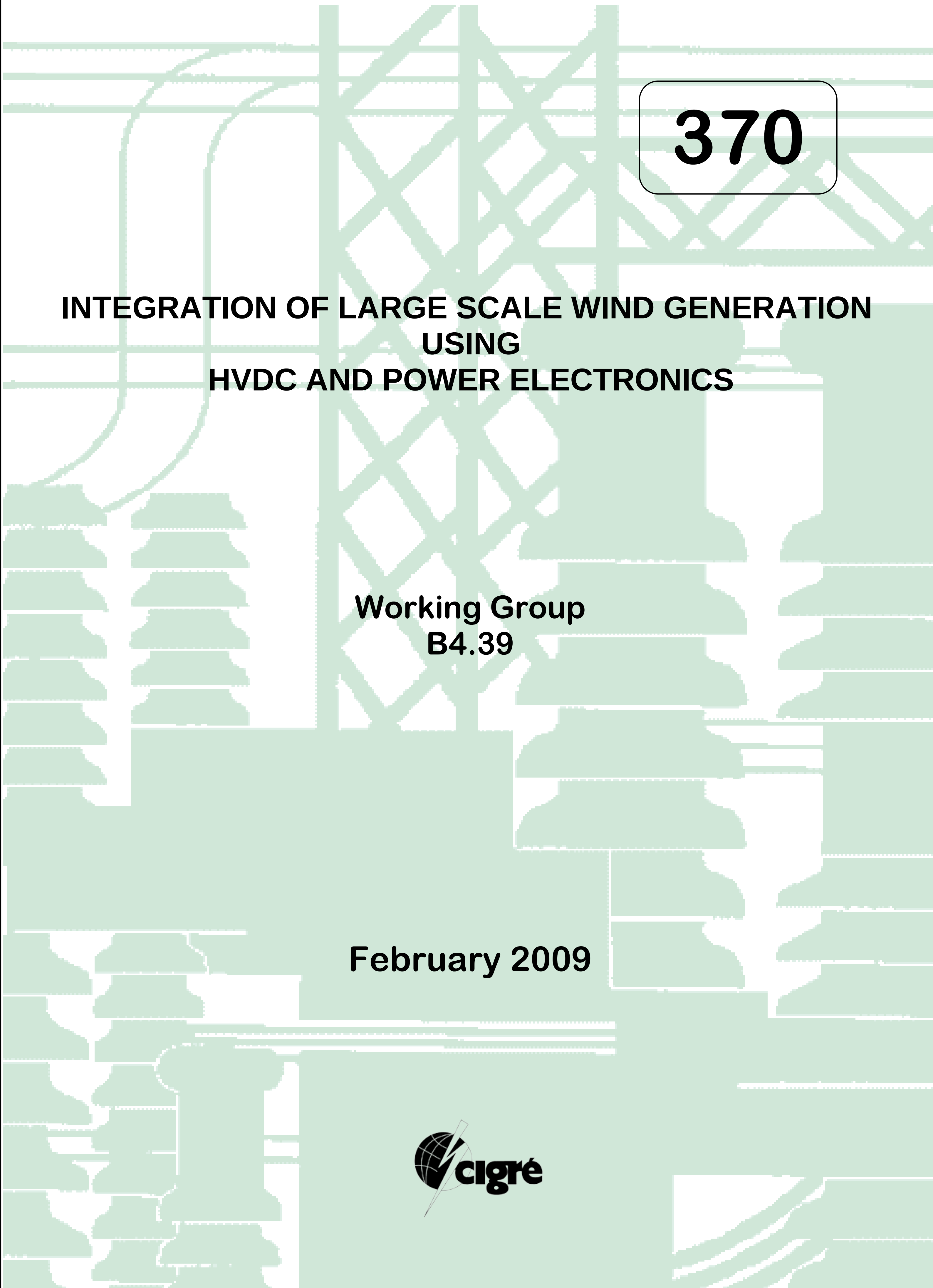

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INTEGRATION OF LARGE SCALE WIND GENERATION USING HVDC AND POWER ELECTRONICS

Working Group
B4.39

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Integration of Large Scale Wind Generation using HVDC and Power Electronics

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EXECUTIVE SUMMARY

BACKGROUND

In recent years, wind generation has been the fastest growing energy generation sector worldwide. Wind farms with capacities of 100-1000 MW or more are being constructed both onshore and offshore. Many of these will be connected to existing power transmission networks using long transmission distances, causing challenges in respect of system stability issues and objections to the building of new overhead lines. Large wind farms also displace conventional power generation plant, resulting in a need for the wind farms to provide system/ancillary services, such as frequency control and ac voltage/ reactive power control. The objective of the WG was to assess how HVDC and FACTS (Flexible AC Transmission Systems) could be used for the benefit of the wind farms and the ac network by overcoming these issues when integrating large scale wind farms into power systems. This executive summary provides a brief overview of the issues discussed in the resulting Technical Brochure.

WIND FARM AC NETWORK INTERACTION ISSUES AND GRID CODES

Wind generation has a number of characteristics which are substantially different from those of conventional power generation stations. The differences arise partly because the “fuel” (wind), depends on the weather, and partly because the generator is rarely a direct connected synchronous generator. The main differences can be summarised as follows:

a) Wind is intermittent, which makes it difficult to accurately schedule the power production from a wind farm. Whilst the accuracy of wind power forecasting has increased substantially in recent years, there are still frequently significant deviations between forecast and actual production capability.

b) Wind turbine generators may not always be available to participate in primary and secondary frequency control. Some, primarily older, types of wind turbine generators do not have the technical functionality. Moreover, the marginal production cost of a wind farm is negligible. This means that there is a reluctance to operate the wind farm below its maximum capability given the actual status of the wind (spilling wind). The range of controllability is also dependant on the level of the wind, e.g. when the wind speed is very low the wind farm cannot generate energy.

c) Some, primarily older, types of wind turbine generators cannot provide reactive power to the ac network, and cannot provide static or dynamic voltage control.

d) Some, primarily older, types of wind turbine generators cannot remain online during a voltage dip (they do not have fault ride through capability), and/or worsen the voltage dip

e) The dynamic system stability of the network may deteriorate if the proportion of power generation from wind turbine generators becomes large, since some types of wind generators tend to decrease the effective rotating mass (inertia) in the system. On the other hand the control action from these generators may be quicker than conventional generators, which tends to improve stability.

Until the 1990s, these issues were not a large issue as the share of wind power in the power system was negligible. Wind generators were exempted from technical requirements and system/ancillary services capability, which were mandatory requirements for conventional power plants. However, as the wind generation reached a significant share in the generation mix, this exemption was found to jeopardize the system security and it became clear that wind farms needed to be subject to more stringent requirements.

In response, several system operators developed and issued grid codes that impose technical requirements on wind generators, to enable system operators to have some control over wind farms. Internationally, there are significant differences between grid codes, reflecting among others different network designs and circumstances. Typically, connection agreements for wind farms demands adherence not only to the grid code, but also contains other site specific requirement, e.g. harmonic limits. To meet these requirements new wind generators generally include power electronics, and the issues b) through f) above are being resolved over time. Issue has not yet manifested itself as a practical problem, and there are mixed views as to whether the correct design of controllers could prevent this issue ever becoming a problem.

Item a), the intermittency of wind energy, has not yet been resolved satisfactorily and forms the subject of a massive research and development effort. Whilst the general accuracy of predictions is being improved, there will still be times when, in the short term, the power supply from wind power deviates drastically from the predicted level due to freak weather conditions. Such conditions may include high pressure zones remaining statically located or a storm front reaching higher wind speeds than predicted, necessitating shut down of the wind generators. Occasional power curtailment of wind farms by the system operator, as specified in an increasing number of grid codes, will limit the danger to the system but will affect wind farm economics unless it is adequately compensated, especially in systems with a significant proportion of wind power. In principle, energy storage devices could help overcome this problem, but today such systems are generally expensive and have low efficiencies.

AC CONNECTION OF WIND FARMS – BENEFITS FROM THE USE OF POWER ELECTRONICS

AC connections are used for the large majority of wind farms, as it is a relatively simple way to connect the wind farm, and for most applications it provides the most economic solution.

Wind farms can be connected to the grid by overhead lines or cables. From offshore sites submarine cables are usually needed to reach land. Long distance overhead lines may be needed on land for the transportation of large-scale wind power to the load centres. Cable sections may be needed also on the land, if planning consent cannot be obtained for the cheaper overhead line option for the complete route.

Reactive power flow can change significantly through an ac network as the level of generation changes, and the wind generators may not be able to solve voltage problems at locations remote from the wind farm. Hence, in some networks there may be a need for additional dynamic reactive power control (e.g. SVCs or STATCOMs) within the AC network, in order to avoid voltage stability problems.

SVCs or STATCOMs may also be used to an increasing extent within a wind farm, and could simplify the design of the wind generators. Effectively, an induction generator based wind farm can achieve satisfactory fault ride through performance by the addition of dynamic reactive power control, as has been shown in the studies performed by this working group. However, the cost effectiveness of this approach is questionable, as power electronics at the wind turbine generator have a function anyway to optimise the maximum wind energy capture, and to reduce mechanical stress in the turbine and the gear box between the turbine and the generator..

DC CONNECTION OF WIND FARMS – BENEFITS FROM THE USE OF POWER ELECTRONICS

HVDC schemes, including LCC HVDC and VSC Transmission, may provide the most economic and technically most beneficial connection for an offshore wind farm located more than say 75km from the AC transmission system connection point.

At the time of writing of this Technical Brochures one project was in construction to connect a 400MW wind farm in the North Sea, and at least two further projects (2 x 335MW and 2 x 550MW) were in the final planning stages. As the size of wind farms and the distance of off-shore wind farms to the shore continues to increase it is confidently predicted that more and more wind farms will be connected in the future using HVDC.

BENCH MARK MODEL AND INTERACTION STUDIES

In order to study and demonstrate some of the issues associated with the integration of a large wind farm in a transmission network, a small 12-bus benchmark model was developed. It is derived from the IEEE12 Benchmark Test System from IEEE Working Group 15.05.02, Dynamic Performance and Modelling of HVDC Systems and Power Electronics for Transmission Systems. The original benchmark model was developed for the investigation of the performance of FACTS devices and represents a network that can only comply with typical network security standards by application of power electronics and/or additional infrastructure.

In order to ensure that studies were focused on system integration issues associated with large wind farms, it was decided to make a number of changes to the original test system, primarily to ensure that the network would satisfy typical network security requirements. The authors believe that the resulting model is suitable for the study of a broad range of static and dynamic stability issues for both AC and DC network connection alternatives for large-scale wind farms.

The interaction studies conducted using PSS/E, Power Factory and PSCAD showed that both for AC and for DC connection, adequate fault ride-through performance can be achieved. For the AC connection case, however, in some cases, significant amounts of reactive power compensation (SVCs, STATCOMs) were found to be required, but it is likely that optimisation could result in reduced ratings, compared with those used in the WG studies.

The number of studies performed by the working group was relatively limited, but it is hoped that the benchmark will be used by manufacturers and researchers for additional studies.

CONCLUSIONS

With the provision of separate SVCs or STATCOMs, and/or the use of HVDC for the connection of large wind farms to the AC network there may be an opportunity for the optimisation of the overall package including the wind generators. Whether this is done may depend on the ownership of the various parts of this system, and on the technical expertise available for this optimisation. It is possible that significant economic benefits could be gained by undertaking the additional work.

Interconnections between network areas which are geographically distant would be very beneficial if a large penetration of wind generation is considered, since the impact of intermittency and unpredictability of wind generation can be reduced by such connections. Therefore, offshore and onshore supergrids using HVDC for long distance transmission and overcoming bottlenecks in the ac transmission networks, may provide an essential element of future electricity provision with a substantial renewable generation content, including wind, solar and tidal energy resources. For such supergrids, multi-terminal DC network configurations should be developed in order to improve the sharing of connections.

Utilising power electronics to achieve satisfactory power quality and efficient transmission of power over long distance will provide part of the solution required to enable renewable resources to provide the large proportion of the total energy supply that is currently envisaged.

Despite significant infrastructure extensions, there may still be times when the power supply from wind power will be drastically reduced compared with the forecast level because of freak weather conditions, which may cause network stability issues. The working group recommends that two key R&D areas are directed towards mitigating this issue:

- Continuation of the on-going R&D in the field of short-term prediction of wind power production. This should enable better scheduling of wind and conventional power sources ahead of e.g. storm fronts. Especially, better predictions will reduce the number of instances of power curtailment required to maintain system stability and thus the amounts of lost energy ("spilled wind"), improving the economics of wind energy

- Energy storage devices to overcome this problem. Much research and development effort is necessary to achieve cost and physical size reductions, to make it attractive compared with traditional methods to achieve the balance between power generation and load.

The consequences of increasing the penetration of renewable power generation using power electronic converters would be that the short circuit level in the ac network and the inertia would both reduce relative to a network with predominantly conventional fossil fuel or hydro synchronous generators as the power supply, while on the other hand primary response speed may somewhat increase. Some planners have great concerns about the satisfactory operation and system performance in such a system. No doubt it would be necessary to re-write the rule book, but with appropriate studies of system performance and due attention to the settings of power electronic controllers it may well be possible to improve on present day performance, even with a much larger penetration of wind generation.

This Brochure presents the power electronic tools which can help facilitate the integration of large scale wind farms in a transmission network. A number of sample studies have been performed to illustrate the performance that can be achieved using these tools, with large wind farms connected via an electrically long transmission line to a weak point in the ac network. The power electronic devices and their controllers were not fully optimised during these studies, because of limited time and resources, and it is highly likely that better results could have been achieved if more work had been done. Nevertheless, the studies have demonstrated the possibilities, and will hopefully encourage others to perform similar studies, and to publish results which surpass the performance shown in our studies.

With reference to future work within Study Committee B4 relevant to the subject of this present Working Group, the following topics are suggested:

- The design and performance of multi-terminal HVDC schemes with more than five terminals.
- The control of HVDC schemes during system dynamics in networks with low inertia.

0. FOREWORD

0.1 INTRODUCTION

In recent years wind generation has been the fastest growing energy generation sector worldwide. This is largely a result of increased environmental awareness creating a drive towards renewable energy sources, but also because of the rapid development of the technology resulting in better technical performance and lower cost. The use of wind generation provides a number of benefits compared to conventional fossil fuel burning power stations, but their use in a network also brings some disadvantages. The benefits include a reduction in greenhouse gasses, reduction in the use of fossil fuels, which may lessen the dependency on imported fuel/energy. Many countries have introduced politically driven targets for the introduction of wind power, encouraging the growth of this generation resource by favourable revenue or other subsidies, when compared to conventional fossil fuel generation. Global increases in energy prices will result in wind power generation becoming increasingly competitive.

The disadvantages are that wind generation is quite different from that provided by a fossil fuel, nuclear or large hydro power generation station. Wind generation obviously depends on the strength of the wind at any one time, and therefore it should be considered to be an energy source, rather than a power source. Persistent and favourable wind conditions are often found at considerable distance from the load centres, necessitating transmission of the wind energy over a long distance. Since the visual impact of the wind turbines is generally considered to be negative, significant objections may be raised if proposals were made to locate wind turbines in heavily populated places, again resulting in long transmission distances. Furthermore, unlike the synchronous generators generally used for power generation, early generations of wind generators had no provision for reactive power control, and had an adverse impact on the voltage stability of the ac network. Although developments in the wind turbine generators have overcome some of the earlier problems to a certain degree,, the integration of large scale wind generation still provides a number of challenges to the network operators.

Network operators and regulators have been putting Grid Codes and connection agreements in place to define a framework within which wind generation can be accommodated without negative impact on the network. Power electronics can play an important role in enabling a wind generator to meet the Grid Code requirements in respect of reactive power control as well as the dynamic and transient response to faults and events in the ac network. Therefore, wind generators are increasingly being provided with partial or full converter systems as part of their interface with the ac network. When a large wind farm is located a long distance from the ac network connection point, HVDC connections or the use of FACTS devices, such as SVCs, STATCOMs, TCSCs, etc may provide a cost effective and attractive way of meeting the Grid Code Requirements.

CIGRE has initiated a number of working groups, which study various aspects of wind generation. Those WGs, which have been active during the period of preparation of this Brochure, and the title of their document are as follows:

- TF B5.08 "Protection and control for dispersed generation and impact on transmission"
- WG C6.01: “Development of dispersed generation and consequences for power systems”
- WG C6.04: “Connection and Protection Practices for Dispersed Generation”
- TF C6.04.01: “Connection Criteria at the Distribution Network for Distributed Generation”
- WG C6.05: “Technical and Economic impact of DG on Transmission and Generation Systems”
- WG C6.08: “Integration of large share of fluctuating generation”
- WG C1.3: “Electric Power System Planning with Uncertainty of Wind Generation”
- WG B4-39: " Integration of Large Scale Wind Generation using HVDC and Power Electronics"

The goal of CIGRE Working Group B4-39 “INTEGRATION OF LARGE SCALE WIND POWER USING HVDC AND POWER ELECTRONICS“ was to study and explore the ability of HVDC and other types of Power Electronics for integrating large scale Wind Power Plants into large power systems. The Working Group has looked at the challenges presented by long distances from the generation to the load centres, the increasing public resistance in many countries to build new overhead lines, the need for operational flexibility, the need for dynamic voltage and frequency support, and the de-coupling between generation and ac network operation.

0.2 GUIDE TO THE BROCHURE

This Technical Brochure provides background technical information concerning the integration of Large Scale Wind Generation with particular emphasis on the use of HVDC and FACTS devices for successful integration in ac networks. The Brochure also include a benchmark model intended for investigation of different wind farm integration methods and the results of some technical studies performed by the WG..

The information presented in this Brochure is aimed primarily at Developers of Large Wind Farms. However other groups of people are also likely to find the Brochure of interest:

- Investors in Large Scale Wind farms
- Project Engineers for Large Scale Wind Farms
- Network Operators and Regulators
- Planning Engineers
- People Interested in the Development of the technology for integration of large scale wind power

In writing this Brochure, the WG has recognised that some readers have a technical interest and some have a non-technical interest. Therefore, the document has been structured such that different needs can be met by reading different chapters.

Readers without interest in the technical detail are expected to find the following chapters of greatest interest:

- Chapter 1 Overview of Wind Generation
- Chapter 6 Large Scale Wind Integration Case Studies
- Chapter 9 Economic Issues

A detailed description of HVDC and FACTS equipment is not provided in this Brochure. However, a brief overview and lists of references to documents providing information about these technologies are included in Chapter 4 “AC Integration” and Chapter 5 “HVDC Integration”.

It is hoped that Manufacturers and Academics will utilise the Benchmark Model (Chapter 7) and the Results of Interaction Studies (Chapter 8) for the testing and development of controls and new technologies for the integration of large wind farms in ac networks.

0.3 OVERVIEW OF THE DOCUMENT

The Technical Brochure consists of 10 Chapters.

Chapter 1 provides a brief overview of the wind generator technology in use today. The chapter starts with a brief description of wind as a power and an energy resource. The basic operation of a wind generator is explained. A description of the different types of wind generators is then provided, covering fixed speed generators and generators with partial or full converters to enable variable speed operation.

Chapter 2 starts with a brief overview of the properties of large conventional power stations based on synchronous generators and a predictable supply of fuel, and the services that are provided from these generators. Issues associated with the remote location of generation and the use of long transmission lines and cables, and the intermittence of wind are then described. The controllability of the active and reactive power of a wind generator is discussed, and this is followed by an overview of the dynamic and transient interactions between a wind farm and the ac network. Some examples of wind farms which were in service at the time of writing are then provided. Finally, issues of islanding and power quality are discussed.

Chapter 3 provides an overview of Grid Connection Requirements/ Agreements (Grid Code) implemented in different parts of the world. The chapter illustrates the different approaches to achievement of satisfactory grid operation, in respect of fault ride through, reactive power control, frequency/active power control and power quality.

Chapter 4 describes the general issues associated with ac power transmission over long distances, including critical cable lengths, and reactive power compensation needs. The system issues of transient stability, voltage stability, harmonic resonance and power quality are discussed. SVC, STATCOM are presented, with an overview of the benefits they can bring to the ac connection of large wind farms. Applications of other FACTS devices are briefly discussed, and the status of energy storage systems available at the time of writing is briefly reviewed. A fault ride through device is briefly described, which could enable wind generators not having this capability to ride through a fault,.

Chapter 5 provides a brief overview of general HVDC transmission and the benefits that it brings. This is followed by an overview of Line Commutated Converter HVDC transmission (LCC HVDC), which has been in service for more than 50 years, and then of Voltage Sourced Converter HVDC Transmission (VSC Transmission), which is a newer technology, and has a number of technical advantages over LCC HVDC. For both technologies the application for the connection of an offshore wind farm is discussed. Most HVDC schemes in service at the time of writing were point to point transmission schemes, i.e. they take power in at one end and deliver it at the other end. However, schemes with intermediate points of connection (multi-terminals HVDC schemes) are also possible. These are described here because this capability may be of particular interest for wind farm applications. Finally, the operation of parallel HVAC and HVDC lines, and the benefits this can bring to the ac system is described.

Chapter 6 provides a number of case studies for large wind farms. Examples of wind farm projects with ac connections, ac connections with SVCs and STATCOMs, LCC HVDC and VSC Transmission are provided, with a brief description of the actual project and the reason for the choice of technology provided for each.

Chapter 7 describes the Benchmark Model which the Working Group used for the studies. The benchmark is based on the IEEE benchmark model developed for the study of different FACTS devices. The WG modified the model, so that it met the usual network security criteria, before the application of faults and tripping of lines. It is hoped that manufacturers and researchers will use the model for studies to demonstrate the capability of new power electronic devices and control algorithms.

Chapter 8 presents the studies performed by the Working Group to illustrate the possible use of SVCs, STATCOMs, LCC HVDC and VSC Transmission for the connection of a large wind farm to a relatively weak point in an ac network. For simplicity in general, and particularly in order to avoid complications due to potential interactions between different power electronic controllers, the wind farm was represented as a simple fixed speed induction generator. Two different ratings of the wind farm were studied.

Chapter 9 discusses the economics of wind farms and outlines the different factors that have to be considered, including capital costs, the revenue from power sales, power losses, availability, operation and maintenance and other life time costs.

Chapter 10 looks at future trends and developments, which may affect the way that power electronics can be used to facilitate the integration of large scale wind generation in an ac network. The chapter describes the potential technical developments both in wind generator technology and in HVDC and power electronics, including the drivers for such development. This chapter considers also the aspect of wind farm production forecasting since one barrier to the growth of wind power may arise from the unpredictability of the exact amount of power that will be generated by the wind generators within a network.

Chapter 11 finishes the report with a brief conclusion which discusses the need for additional work within B4 in relation to the integration of wind power in ac networks.

0.4 WORKING GROUP MEMBERSHIP

The working group has had a large membership, reflecting the high interest in the rapidly expanding energy sector of wind generation. A number of the members undertook the additional responsibility and work associated with leading and co-ordinating a chapter of the report, or participation in the technical studies. My special thanks go to these members, without whose assistance and dedication my task as a convenor would have been extremely difficult.

The members of the Working Group were as follows:

Dr Bjarne R Andersen, AndersenPES, UK - Convenor
Mr Frederik Groeman, Kema, Netherland – Secretary
Mr David Alvira, REE, Spain – Chapter and Study Co-ordinator
Dr Olimpo Anaya-Lara, Strathclyde University, UK – Chapter Co-ordinator
Dr Martin Aten, Eon, UK – Chapter Co-ordinator and study participant
Dr Guangfu Tang, CEPRI, China
Dr Jutta Hanson, ABB, Germany – Study Participant
Dr Michael Haeusler, Retired, Germany
Mr Karim Karoui, Tractabel, Belgium
Dr Peeter Muttik, Areva T&D, Australia – Study Participant
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Dr Marian Piekutowski, Hydro Tasmania, Australia – Chapter Co-ordinator
Mr Javier Ruiz, CENER, Spain – Study Participant
Mr Bogdan Sobczak, Institute of Power Engineering, Gdansk Division, Poland – Study Participant
Mr Kent Soebrink, Energinet.dk, Denmark – Chapter co-ordinator
Dr Torbjörn Thiringer, Chalmers University, Sweden – Chapter Co-ordinator
Mr Dennis Woodford, Electranix, Canada – Study Participant

0.5 ABBREVIATIONS

The following Abbreviations have been used in this Technical Brochure:

AC	Alternating Current

AGC	Automatic Generation Control
CSC	Convertible Static Compensator
DC	Direct Current
DFIG	Doubly Feed Induction Generator
DVR	Dynamic Voltage Restore
FACTS	Flexible Alternating Current Transmission System
FCAS	Frequency Control Ancillary Services
FTR	Fault Ride Through
GTO	Gate Turn Off
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LCC	Line Commutated Converter
PWM	Pulse Width Modulation
PV	Power Voltage
SCR	Short Circuit Ratio
SHEM	Selective Harmonic Elimination Modulation
SSSC	Static Synchronous Series Compensator
STATCOM	Static Compensator
SVC	Static Var Compensator
VSC	Voltage Sourced Converter

1. OVERVIEW OF WIND GENERATOR TECHNOLOGY

This chapter provides a brief overview of wind generator technology, in order to provide the needed background for the analysis and results presented in this report. Since there are many excellent books and papers on wind generation technology, it has been kept fairly short and concise. Readers are recommended to study other literature for more in-depth information [1].

1.1 WIND AS A POWER AND ENERGY RESOURCE

Wind should be considered as an energy source, rather than a power source since its availability will depend on the weather, and cannot be considered to be available all the time. Averaged over a year the produced electric energy can be estimated with reasonable accuracy, but even from one year to another the energy production may vary by ±20 %. In northern Europe around 2/3rd of the energy is typically generated during the winter half of the year, which is convenient since it is during this period that the energy is most needed. By contrast, in warmer climates the maximum electric energy demand can be in the summer due to air conditioning.

In Figure 1-1 below the energy production from an offshore 160 MW wind farm in Denmark during a six month period is presented together with the duration curve. It can be noted that the energy varies considerably during this period, and that the periods with high power production are more frequent during the winter period.

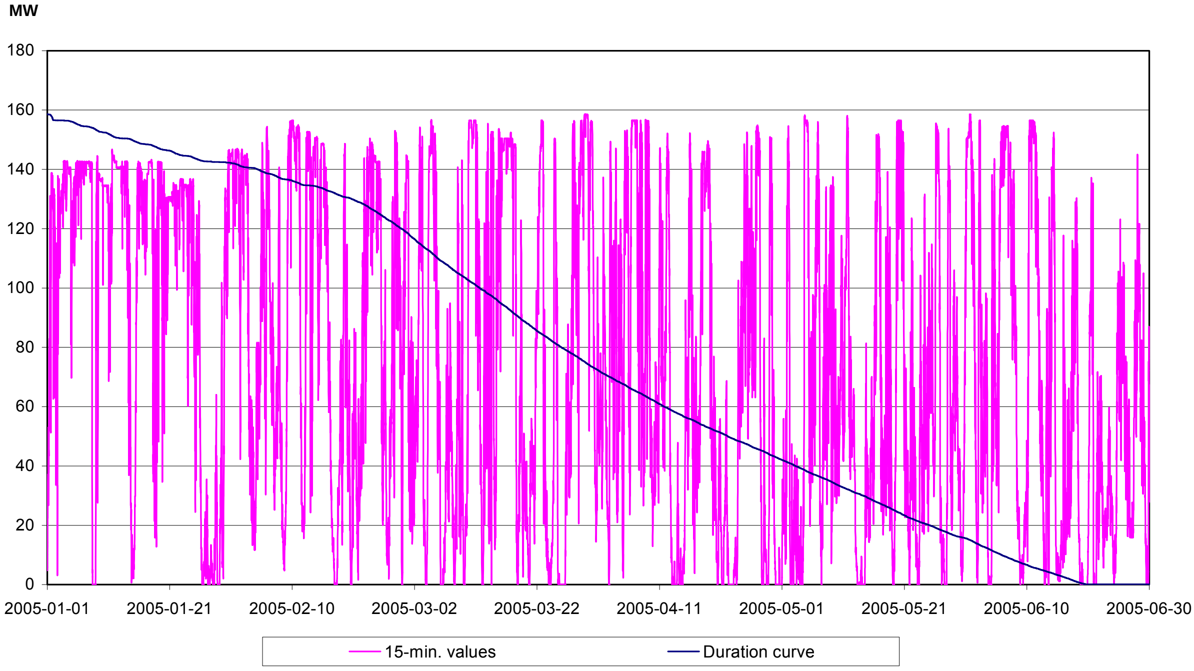

Figure 1-1 Measured wind power production from a 160 MW offshore wind farm

Figure 1-2 shows the variation of the wind speed and the power production from a single wind generator during a period of one hour.

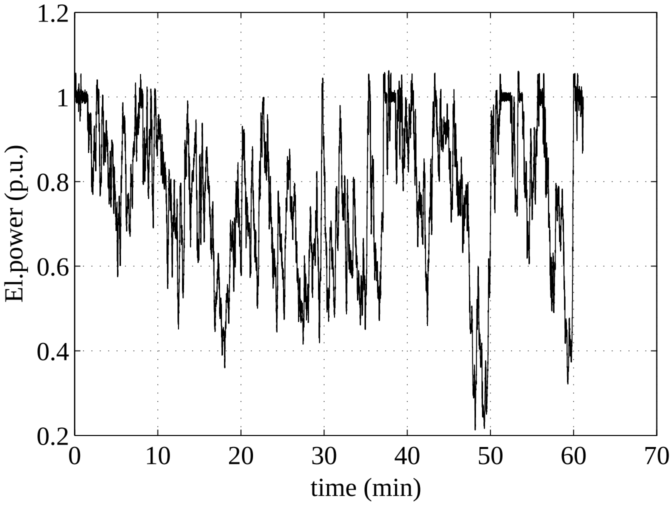

Figure 1-2 Power from a wind generator during 1 hour.

It can be noted that on one occasion the power goes from full power to 20 % power and back again within a 5 minute period, and large swings can also be seen at other times. When a large number of wind generators are connected together to form a wind farm there is some averaging of the output power in the short term. Figure 1-3 shows the power produced by a small wind farm [4] during a time period of 11 days using 1 minute average values. Large daily variations are still clearly visible

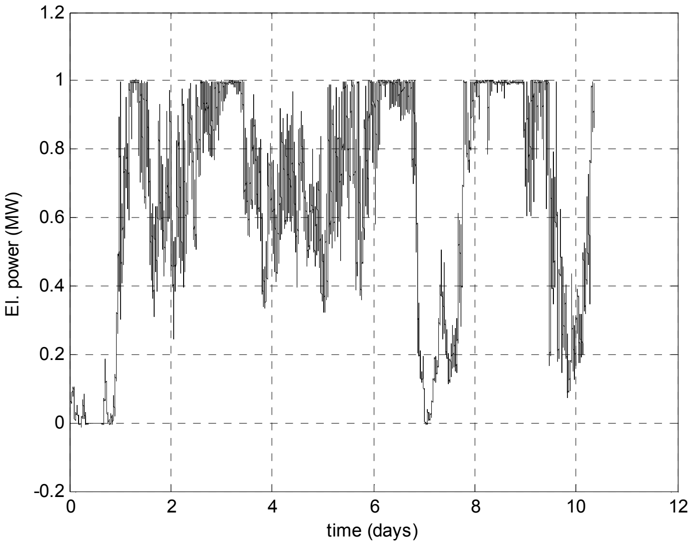

Figure 1-3 Electric power from a 10 MW wind farm [2] during 11 days

In order to plan for the operation of the power production sources within a power network, it is of importance to predict the power that can be anticipated to come from the wind energy installations.

Historically power system planners and operators have successfully managed an intermittent hydro power plant, i.e. generating from a variable water flow through a river with limited water (energy) storage. This was managed either through vertical integration or through bilateral water trading agreements (e.g. Columbia river). However time constants associated with variability of wind generation are shorter than that of hydro power plant which makes operation more complex.

The accuracy of the prediction of produced wind power improves the closer in time the prediction is made [3]. Predictions within 2-4 hours give a high correlation [4]. However, the accuracy of forecast of the generation 1-2 days ahead can sometimes be very poor. An extremely difficult case to predict is when a storm is approaching. A storm could lead to either maximum production or to wind generators rapidly shutting down due to too high wind speed (> 25 m/s).

The difficulties with variability and forecasting are relatively easy to accommodate as long as wind generation provides a relatively small proportion of the overall power generation in the network. A large geographical distribution of wind generation resources within a network is also beneficial, because of the averaging that will occur. The provision of long distance interconnection between networks, to enable mutual support and to take advantage of the diversity that naturally occur between geographically distant areas, would also enable a larger proportion of wind generation to be accommodated, without negative impact on the security and reliability of the ac network.

With the exception of fixed-speed turbines without a pitch control mechanism, wind generation can in principle be used for the purpose of load levelling and spinning reserve, depending on the wind available at a specific time. Naturally, as is also the case for conventional generation used for this purpose, the wind generators are then not operated at their maximum power production capability, but instead with a reduced value. It should be pointed out that an important difference is that in the case of curtailing wind energy, this 'green' form of energy gets lost, whereas in hydro and fossil power plants the energy source is saved and can be used later. The "fuel" costs of the power plant do not decrease during curtailment, which causes some reluctance by wind farm operators towards curtailment as virtually all production costs consist of capital costs. Curtailing of wind generation has not yet been used extensively, however many grid codes, for instance that of energinet.dk, demand that this feature should be available in the control of a wind farm.

1.2 BASIC OPERATION OF A WIND GENERATOR

A wind turbine converts some of the available energy in the moving air mass (wind), into rotational kinetic energy, which is turned into electrical energy by a generator. In order to produce electric energy, there has to be sufficient wind speed for the wind generator to operate. This speed is referred to as cut-in wind speed, see Fig. 1-4. As the wind speed increases, the power production also increases and eventually reaches the nominal power at the rated wind speed. As the wind speed continues to increase further, the power production has to be limited, in order not to exceed the maximum mechanical stresses for which the wind generator has been designed. At an upper wind speed, the cut-out wind speed, the wind turbine is typically stopped, as the mechanical stresses would otherwise be potentially destructive. It should be noted that the design of the wind generator varies depending on the average wind speed (IEC Class A, B, C) and the required survival wind speed (max gust speed).

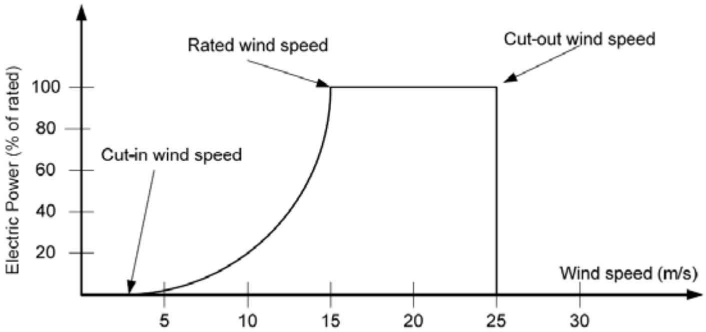

Figure 1-4 Power curve of a wind turbine with pitch or active stall control

The limitation of the output power in the wind speed area between rated and cut-out is achieved by reducing the efficiency of the aerodynamic conversion of wind energy into rotational kinetic energy. This can be done by utilising the turbine blade profile in two different ways. The blades can be designed in such a way that they loose their efficiency as the wind increases; this method is called stall regulation. Alternatively, the blades can be turned out of the wind; this method is called pitch regulation. Stall regulation was mainly used for the earlier wind generators, and is also used today for fixed-speed wind generators, while pitch control is used for variable speed generators.

If pure stall control is used, the power production between the rated and the cut out speed varies slightly with wind speed. Nowadays, large fixed-speed wind generators (>1 MW) are also being equipped with an active pitch mechanism, so that the blade pitch is controlled to provide constant average power in the high-wind speed region. This is called active stall control or combi-stall control.

The pitch of the blades can be changed at a speed of about 10 degrees per second, which means that the aerodynamic production can be reduced from nominal to 0 in a couple of seconds.

The power rating of the wind turbine depends on the swept area of the blades. Approximate rotor blade diameters are 55 m for a 1 MW turbine, 80-90 m for a 3 MW turbine and 120-130 m for a 5 MW turbine.

The rotor speed is decreased as the turbine size increases, so that the tip-speed of the turbine does not become too high. Typically the rotational speed of a 1MW turbine is about 15-30 rpm and for a 5MW turbine 7-12 rpm. In order to have an economical design of the electrical generator, a gear is usually used between the turbine and the generator. However, as the gearbox is the weakest point of the wind generator significant development efforts are being dedicated to large size low speed generators to allow elimination of this equipment (direct drive).

Compared with a conventional power plant, the mechanical drive train structure in a wind energy unit is much less stiff, and consequently the main torsional resonance frequency of a wind generator is typically below 2 Hz. It is also important to note that the converter control provided with variable-speed generators can provide a complete decoupling between the drive train mechanics and the grid side dynamics of a generator. This is of significant benefit in the design of the gear between the turbine and the generator, since it reduces the stresses.

A wind turbine converts the variable speed wind input of the rotor blade system to a fixed frequency electric power waveform, which is then fed to the power grid. This type of conversion system without primary speed governor makes the use of a synchronous generator very difficult as the huge forces between the input and the output could damage the gear box that separates the low and high speed shaft. This has brought application of the induction generator, which with its small slip reduces the torsional forces. The use of variable speed generators reduces these forces even further. Currently some manufacturers use a differential gear box with two output shafts, the first shaft has a fixed speed allowing the application of a synchronous generator and the second shaft with variable speed provides a feedback to the pitch controller.

In addition, a system with a hydrodynamic gearbox can be mentioned. This wind turbine is equipped with a directly connected synchronous generator without power electronics and instead a gearbox with a varying gear ratio, that gives the possibility to have pitch-control and variable speed operation.

The following descriptions of the most used wind turbine systems are a bit short, however, more information can be found in [1, 5-8].

1.3 FIXED SPEED SYSTEM (TRADITIONAL SYSTEM)

This type of wind generator system is equipped with an induction generator which is directly connected to the grid. The turbines are not exactly fixed-speed, the speed varies with the slip of the induction generator (ca 1 % speed variation). Larger wind generators of this type (>1 MW) are typically equipped with pole-changing generators which provide a smaller generator output with a lower fixed speed and a larger generator that has a higher rated power and higher rotational speed. In this way, the energy efficiency is comparable for this wind generator type, given a certain rotor swept area and maximum shaft torque, as for a variable-speed wind generator.

These types of turbines are robust and cheap. In its most basic implementation, the electrical system consists of an induction generator with shunt capacitors for reactive power compensation connected directly to the grid as presented in Fig. 1-5. A drawback is that in the high wind speed region this type of generator has a slightly reduced average power production, due to the uncontrolled aerodynamic behaviour.

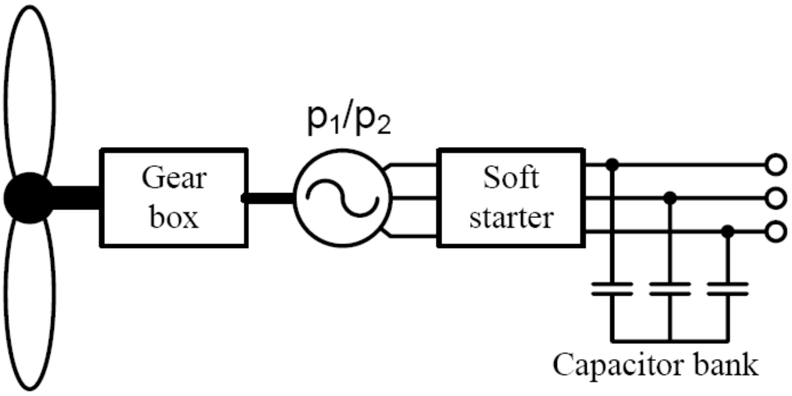

Figure 1-5 Electrical scheme of a fixed-speed wind generator system. p1 and p2 represents different pole-pair numbers in order to obtain two-speed operation.

In order to connect the generator to the utility grid, a soft-starter (consisting of anti-parallel thyristors) is used in order to keep the currents below the rated value, when the generator is being connected to the utility grid. Phase-compensating capacitors are used to compensate for the no-load reactive power consumption of the generator. Nowadays reactive power compensation is often also provided for full-load operation.

An example of the voltage deteriorating property of fixed-speed wind turbines (without the dynamic reactive power compensating equipment) is given in Fig. 1-6 below. The feeder, to which the wind generator is connected, is exposed to a voltage drop down to 0.3 p.u. remaining for 100 ms. The resulting rotor speed as well as active and reactive power is presented in the figure.

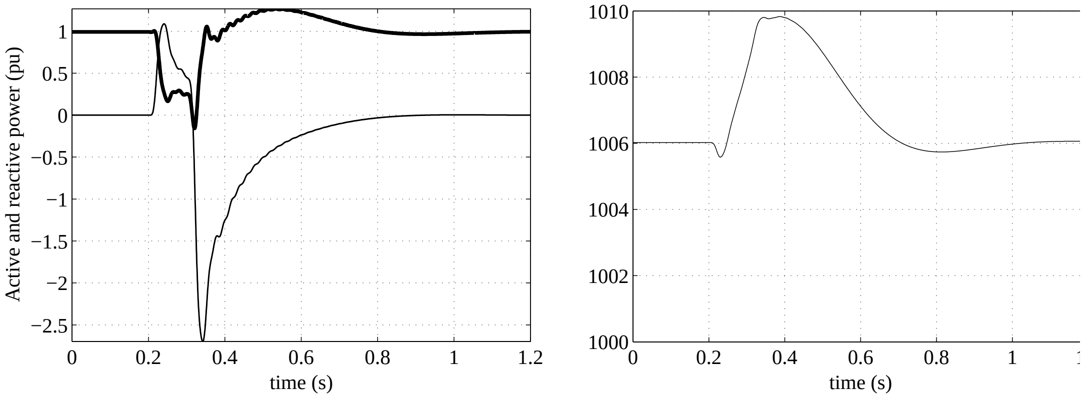

Figure 1-6 Left: Active (thick line) and reactive power response. Right: mechanical speed response.

From the figure it can be noted that during the fault the wind generator initially delivers reactive power to the network, due to the de-magnetisation of the generator. However, once the fault is cleared, the generator absorbs a large amount of reactive power from the grid. This reactive power consumption is caused partly by the re-magnetisation of the generator, and partly because the machine speed has increased during the fault, so that the generator is over-speeding relative to its steady-state operating point. This substantial reactive power consumption causes a delay in the voltage recovery of the grid after a fault has been cleared.

1.3.1 Fixed-speed system with active pitch mechanism

As mentioned earlier, modern large fixed-speed turbines are typically equipped with an active pitch mechanism. This makes it possible to obtain an average power at rated level for all wind speeds above the rated one, in addition to facilitate the emergency stopping of the wind generator.

The fixed-speed systems with active pitching mechanism can also to some extent use the pitch control to provide a varying output that can be used to respond to a need from the grid. It is possible to change from 100 % to 0 % production within a couple of seconds. However, it should be pointed out that such a power decrease will result in substantial stresses on the mechanical construction.

1.3.2 Reactive power control with fixed-speed wind turbine system

The early fixed-speed systems did not have a reactive power control capability. Many modern systems now use capacitor banks switched in stages to keep the power factor close to unity for various operating conditions. In order to obtain better ac voltage controllability, an SVC or a STATCOM can be added in shunt with the wind energy unit, as explained in Chapter 4.

1.4 VARIABLE ROTOR RESISTANCE SYSTEM

This type of wind generator is basically the same as the previous one, but with an additional power electronic converter, which provides control of the generator rotor resistance value, see Fig. 1-7. This addition gives the wind generator a limited variable rotor speed range and some fault current control capability. The rotor speed can be controlled in a speed range about ±2 % from the nominal one. Another difference between this and the previously described fixed-speed wind generators is that the turbine is equipped with pitch control.

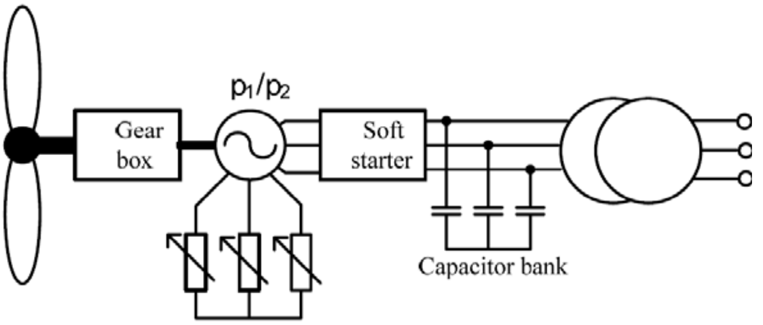

Figure 1-7 Electrical scheme of fixed-speed system with a variable rotor resistance.

The performance difference is that the variation of output power with rapid wind speed changes will be smoother for this type of wind generator than for other fixed speed systems. Moreover, the stresses on the mechanical structure are lower due to the "torque control ability" that the variable rotor resistance control offers. In this way, the incoming power variations are smoothed by the filtering effect of the turbine and rotor inertia. For this purpose, only a limited speed range is needed. A final performance difference is that the rotor resistance control can also improve the under-voltage ride-through capability for this type of system compared with the standard fixed rotor resistance fixed speed wind generators. For instance it is possible to increase the rotor resistance during the voltage dip, increasing the pull-out speed of the generator which results in a higher rotor speed stability margin. Additionally, the reactive currents flowing into the grid during and after the voltage dip can be reduced.

1.5 VARIABLE-SPEED USING DOUBLY-FED INDUCTION GENERATOR

The doubly-fed induction generator (DFIG) was in 2007 the most popular system to be installed in European grids, with more than 50 % of the installations. This type of wind generator system uses a converter which is located in the rotor circuit path. This converter is used to obtain a variable frequency of the rotor currents by exchanging energy between the rotor and the ac network directly. Typically the rating of the converter is 20-30 % of the turbine rating, which translates into a variable speed range of ± 20-30%. The relatively low rating of the converter gives a lower investment cost and lower power losses in the power electronic converter, when compared with a full converter system (See section 1.6). Two simplified electrical schemes of the DFIG system are presented in Fig. 1-8.

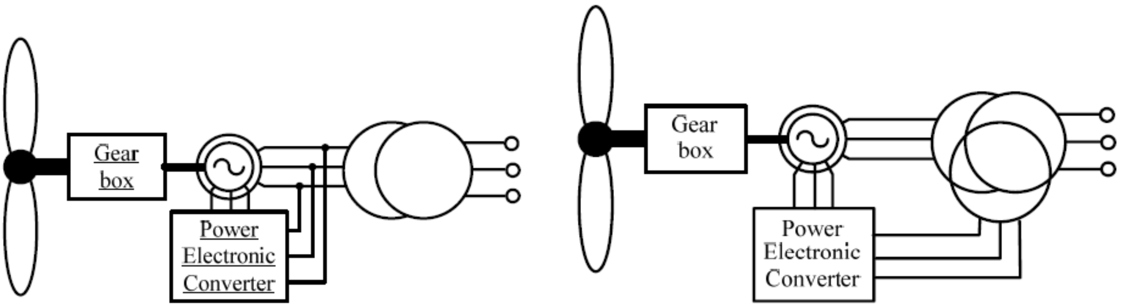

Figure 1-8 Simplified electrical schemes of DFIG systems.

Since the DFIG can be operated with variable turbine/generator speed it can smoothly control the active power output. The converter can also provide variable reactive power output to stabilise the ac voltage. Another benefit of the converter is that the torque acting on the gear-box can be smoothed, which results in reduced stress and possibly less failures of the gear-box. Since it is a variable speed turbine, pitch control is used to control the aerodynamic power.

For minor voltage disturbances, the DFIG-system converter manages to control the current throughout the whole fault sequence. This means that this turbine to a minor disturbance, down to 75-85 % remaining voltage, provides less current disturbances compared to a fixed-speed system. An example of the current as well as active and reactive power responses to a 25 % voltage dip (with 75% remaining voltage) is presented in Figure 2.1.

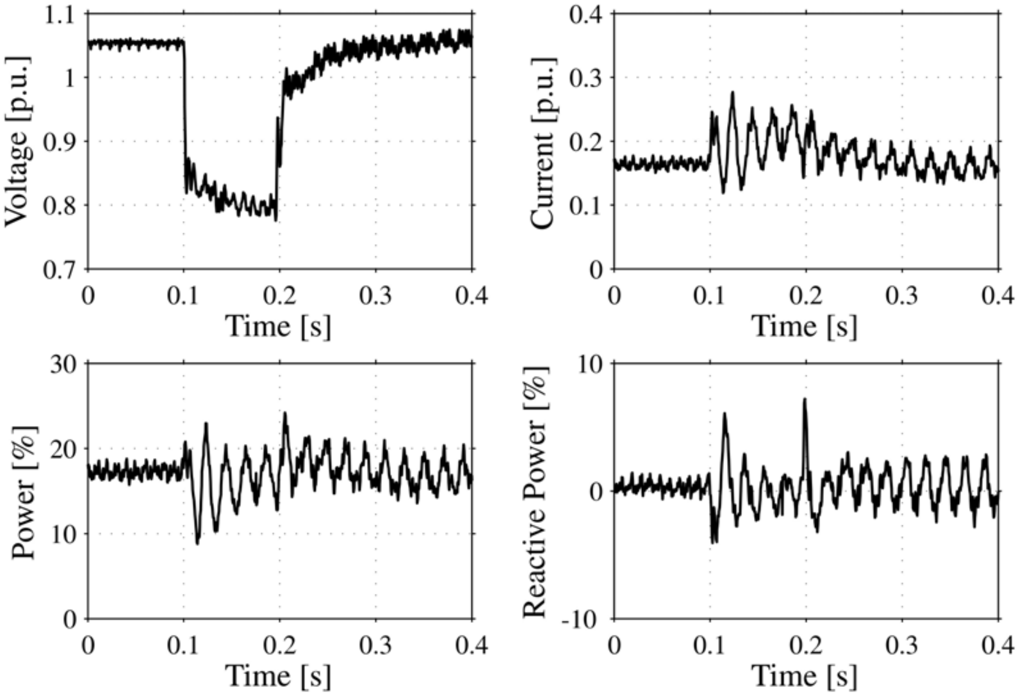

Figure 1-9 Measured response to a minor voltage dip by a DFIG system

Although some oscillations occur, it can be observed that the rotor converter manages to keep a good control over the DFIG system's current. However, for severe disturbances, the small converter cannot control the currents, and the rotor must be short-circuited using a crowbar located between the rotor windings and the converter.

Figure 1.10, shows the electrical system of a DFIG system with crowbar.

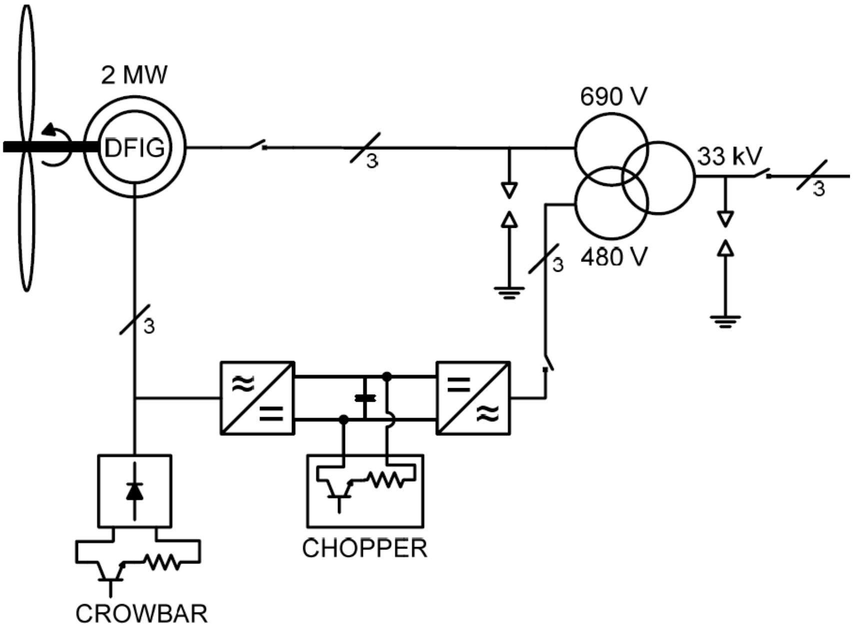

Figure 1-10 Ride-through system of a DFIG wind turbine system.

Early DFIG systems did not have a sufficient rating in the converter to enable a full fault ride through. However, modern DFIG wind generators are capable of riding through the scenario outlined in most, if not all grid codes (see Chapter 3). This has been achieved by enhanced control of the rotor crowbar and increased rating of the dc-link chopper. It should be mentioned that during the short time period when the voltage is very low, there is a risk of high reactive energy consumption during the worst period of a grid fault when the crowbar or dc-link chopper is in operation. Depending on the system strength, this can decrease the grid voltage further, and adversely affect the fault ride through capability..

1.6 VARIABLE-SPEED WIND GENERATORS USING FULL-POWER CONVERTER

The variable speed, full-converter wind generator system gives the highest degree of freedom regarding the control of the electrical quantities as well as the mechanical ones. In this system, all the power flows through a dc-link in the converter, which provides complete decoupling between the generator stator and the grid. The reactive power is also completely decoupled between the machine and grid side of the dc-link and can be produced or consumed separately on each side of the dc-link. The turbine is normally pitch controlled.

Because of the decoupling provided by the full converter, the type of generator that is used, or whether or not a gear-box is used, has no direct impact on the interaction with the grid. Different manufacturers are proposing/developing different solutions, including some without a gearbox, and using different generator types including induction generators, synchronous generators and permanently magnetised generators.

The full converter concept with a direct coupled turbine and generator, i.e. without a gear box, and with a gearbox is presented in Fig. 1-11.

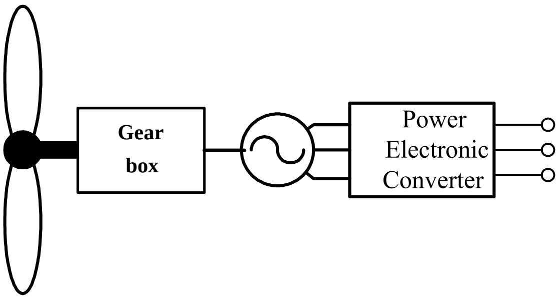

Figure 1-11 Full converter schemes with (left) and without (right) gearbox.

The torque control performance for these systems is as good as for the DFIG system or even better due to the complete decoupling between the generator and grid ac-sides.
It should be mentioned that a large direct drive multi-pole generator (no gear box) turbine may suffer from the drawback of having a very heavy nacelle, due to the weight of the generator. However, with a full converter there is also the possibility to use a low ratio gear box (say about 10 instead of typical 30-40) which can result in a less heavy generator and gearbox system.

1.7 REACTIVE POWER CAPABILITY OF VARIABLE-SPEED WIND TURBINES

The variable-speed systems have an excellent reactive power control capability which can be used for reactive power in-feed during faults and for voltage control. However, when designing the system, the rating of the system must be increased, relative to that required for the pure active power duty, so that the current capacity be sufficient for the required reactive power capacity at all power levels. By over-dimensioning the grid side converter by 8 % (i.e. to be able to handle 1.08 pu current) it is possible to produce or consume more than 40 % reactive power also at rated power operation. In the DFIG-system, reactive power can easily be provided through the generator, while the full-power system needs a larger grid side converter to produce reactive power for the grid.

At lower wind speeds the wind generator can consume or produce reactive power without an over-dimensioned grid side converter.

It is possible to design a DFIG or full-power converter wind generator system to take advantage of the reactive power control ability such that it can act as a STATCOM when the wind generator is standing still due to low wind.

In Fig. 1-12 below, the power capability of a variable-speed (or modern fixed-speed) wind generator is depicted. The thick line in the left figure represents unity power factor (cos □=1) operation. However, with a converter controlled generator it is also possible to absorb or inject reactive power, just accounting for the current limit. The capability diagram on the left depicts a converter rated purely for active power, and the diagram on the right depicts a converter dimensioned also for reactive power control. In this case, there is no need to reduce the active power production in the case that a reactive power in-feed to the grid is needed, even at higher wind speeds.

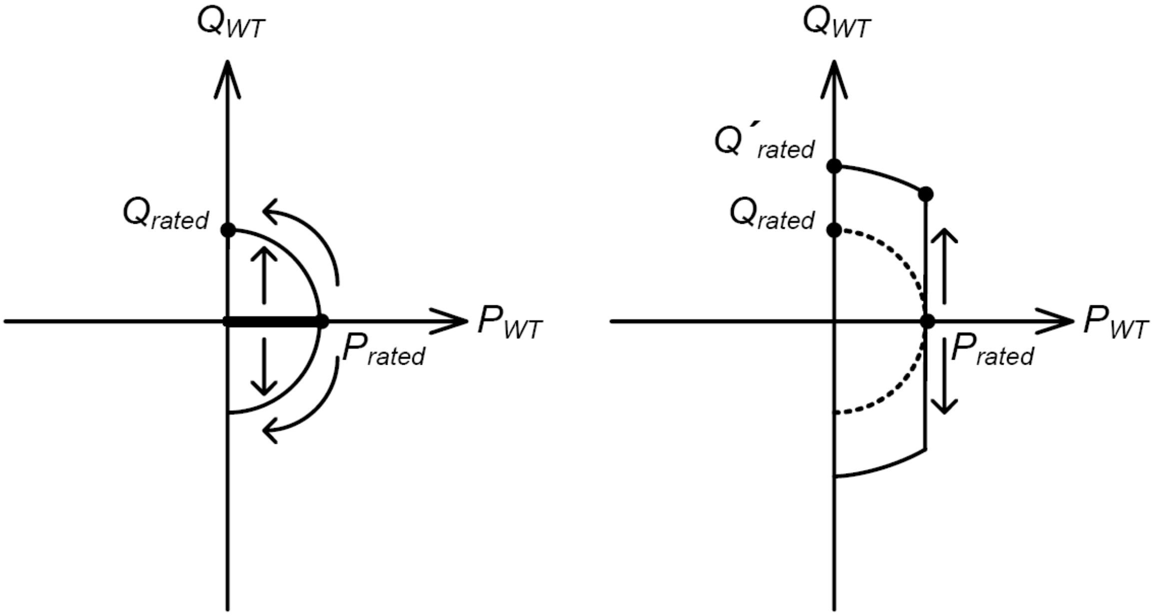

Figure 1-12 PQ Capability diagrams of wind energy systems, left basic rating of the converter system, to the right over-dimensioned converter.

There is still an open question concerning the optimal location of the reactive power source in a wind farm. The above approach postulates over-dimensioning of converters, and in some cases the generators. An alternative approach is to locate dedicated reactive power compensating equipment in the wind farm substation. Some developers favour the use of variable speed wind turbines with little or no compensating equipment at the connection point, while other developers use simple induction generators and adequately selected SVC or Statcom installed at the substation. Note that often the requirement is to provide a certain amount of reactive power at the point of connection with the grid. If there is a large impedance between the wind generators and the point of connection, then a reactive power control system making use of the control capability of the generators would need to take into account the reactive power loss caused by this impedance. In this context, it may be more straightforward or even necessary to have at least some level of reactive compensation located at the point of connection. Finally, there is a question regarding the optimum split between dynamic and static reactive power sources. This will be determined by the required speed of response of reactive power control, and whether dynamic reactive compensation is needed to aid the fault ride through capability of the wind farm. The latter may be applicable to facilitate recovery of the voltage after a fault in the case of connection to a weak grid.

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2. WIND FARM AND AC NETWORK INTERACTION ISSUES

2.1 OVERVIEW

Large wind farms are typically located where good wind resources exist, and are often far away from the main load centres and strong AC network connections. Large wind farms can result in major changes to the load flow within the network, causing real and reactive power flows that were not experienced before. As wind generation becomes an increasing fraction of the overall generation resource the interaction between large-scale wind farms and the AC network becomes a focus for system planners. This brochure discusses a large wind farm, which is defined here as one having an active power capacity greater than 25% of the short circuit power at the point of connection to the transmission network.

Wind power stations have some features that make their operational behaviour different from that of conventional power stations, which since many years have been the main source of electrical energy. This chapter starts by providing a very brief overview of the properties of large conventional power stations.

Next, this chapter discusses the normal operation of an AC network with a large amount of wind generation. The scope includes issues associated with the management of the unpredictability (intermittency) of wind generation in the dispatch process, the impact on quality of power supply and on network reactive power control to achieve the desired power transfer in the network. The performance of the AC network during faults is also discussed, including the impact of the potential reduction in inertia, and the consequences of loss of generation due to lack of fault ride-through capability.

2.2 PROPERTIES OF LARGE CONVENTIONAL POWER STATIONS

Conventional power stations typically use synchronous generators with a highly predictable supply of “fuel”, be this hydro (when based on substantial water reservoir otherwise it can be also intermittent), nuclear, coal, oil, gas or other resources. In addition to providing electrical energy to the network they also provide a number of other services, as described below. The operation of a network with conventional generation has been described in several publications [1, 2], so here we will provide only a brief overview of the operational characteristics of this type of generation.

Scheduled Power Generation: Large conventional power stations can be scheduled for a certain constant power level, provided that there is input energy available. The schedule for individual generators may be decided by the system operator to suit the load demand and taking into account overall economics and system security constraints. In unbundled electricity markets, it is market parties that determine the deployment of generators, however within boundary conditions set by the system operator, and with the system operator arranging for balancing power to compensate for any power shortages or excesses.

Frequency Support and Control Reserves: This is often called Frequency Control Ancillary Services (FCAS). In order to ensure that the network is secure in the event of a trip of a major power station or transmission resource, the total generation resource connected will be increased to provide a margin above the forecast maximum demand (primary reserve). Some of the generators will not be operating at their maximum possible output during normal conditions. Typically, three levels of control ensure that constant system frequency is maintained and the power balance is restored:

- The primary control is an automatic function of each generator governor in the network to quickly adjust the output of the unit in reaction to the frequency change, in order to restore the balance between supply and loads. The balance is restored, but the frequency may deviate from its original value.

- The secondary control is a centralised automatic generation control (AGC) function to regulate the output of one or more generators such, that the frequency returns to its nominal value.
- As a tertiary control loop, power stations may be rescheduled, such that the operating margins in the power system are restored.

Inertia effect: Inertia refers to the stored rotational energy in the generator and it reflects the degree to which rotating masses oppose changes to the power frequency. The rate of change of frequency after a mismatch in demand and supply balance is related to the system inertia. The generators including their prime movers typically have a large rotating mass, which provides a steadying influence on the generator voltage phase angle. This will increase the time constant of swings and disturbances in the ac network and it will stabilise the frequency response to changes in demand/supply balance.

AC Voltage/ Reactive Power Control: The excitation control enables the generator to control the ac voltage at its terminals through the absorption or generation of reactive power. Typically, this vital role for the network is performed through an Automatic Voltage Regulator (AVR) which will have a steady-state control target as well as a sloping characteristic.

Active Power Control (PSS aspect): Some of the generators may be fitted with power controllers (power system stabilisers, which act through the excitation system) designed to damp power swings in the network. This can be particularly useful when the network has distinct areas with large concentration of loads and generation interconnected by long weak lines.

Fault Current Contribution: During a fault in the ac network the generators continue to provide current into the ac network. The fault current that may be experienced by switchgear and other equipment in the network is often one of the key dimensioning design factors, and in some cases it is necessary to introduce measures aimed at reducing the fault current. On the other hand most types of conventional fault protection used in an ac network depend on the presence of high amplitude current during fault conditions for its correct operation.

Fault Ride Through: In the event of a fault in the ac network, the generators may experience large over-currents and power swings both during the fault and after its clearance by the appropriate switchgear. The conventional generators are designed with these stresses in mind and continue to be connected to the network during and after the fault, such that the power supply system can return to normal immediately after the disturbance. Generators very close to a fault are allowed to trip if the critical fault clearance time of that unit is not met, but tripping is then limited only to typically one unit/power plant only, so that the power supply system as a whole is not jeopardized.

The design of a typical ac network depends on the above characteristics. During the planning and ongoing analysis of the ever developing network, its generation and loads, the objective of the network operator is to ensure that secure and stable performance is achieved at all times. The controllability built into conventional generators has developed over many years and form an essential part of the tools used today to achieve the objectives.

2.3 EFFECT OF CHANGED POWER FLOWS

2.3.1 Local Connections

Wind farms are typically located on the fringes of the system and integrated through radial connections. This arrangement leads to changes in the local supply and demand balance as well as changes to the voltage profile as the direction of power flow ebbs and flows as the wind resource varies. A particularly difficult supply arrangement results from wind farms being connected by long transmission lines with a substation along the line supplying local loads. Voltage regulation in such a case can be complicated as the load can be either supplied by the wind farm or the wider system. A common issue is that the original supply network was designed to deliver power to the load and therefore the existing system and connection point transformer have tapping ranges with minimal buck taps to accommodate the reversed power flow that occurs with the wind farm connected and generating. Another related issue is that these transformer tap changers experience an increase in duty over and above that due to a normal daily load cycle, again solely due to the intermittent nature of the wind generation. This has maintenance and life time implications on equipment not specifically related to the connection of the wind farm. The use of separate reactive power control devices, such as SVCs or STATCOMs, may alleviate and/or solve these issues by enabling better control of the ac voltage at the local supply point.

2.3.2 Interconnected Systems

In interconnected power systems, the installed wind capacity may seem relatively small compared to the total installed generation power, but the capacity of interconnecting lines between different areas may limit the degree to which excess wind generation in one area can be transmitted to another area.

Large unscheduled changes to wind generation, larger than the size of typical critical generation contingency, do occur occasionally. Resultant power swings can affect ac interconnection flows. To maintain system security during conditions likely to result in such unscheduled generation changes, the dispatch may constraint the output of intermittent generation.

Limited capacity of interconnectors, and high penetration of wind generation in either or both networks can also lead to the transmission systems being operated very much closer to small signal stability limits and in extreme circumstances close to transient instability limits. This makes it essential to ensure that all of these effects are accurately modelled.

2.4 WIND INTERMITTENCY AND GENERATION SCHEDULING

The interaction between wind farms and AC systems are predominantly influenced by the intermittency of the new resource, applied market rules, and the characteristics of the wind generation technology used. There are also traditional influences associated with selected transmission arrangements.

2.4.1 Generation Scheduling

With a small penetration wind generation can be absorbed by the system and the market can treat it as non scheduled generation. Non scheduled generation wind farms output is typically treated as an offset to the demand curve, thereby reducing the effective demand. With this approach wind generation displaces more expensive sources and lowers the spot price. The disadvantages of this approach are more complex load forecasting and difficulty in specification of adequate ancillary services (real and reactive reserve levels). Usually, large size wind generators now have to supply information about intended output at a pre-dispatch level based on forecasted wind. This information is updated in the dispatch process.

Non scheduled generators, such as wind farms, typically do not provide and do not need to contract ancillary services required to manage system performance. Operationally there is an increasing emphasis on forecasting wind generation. This is acceptable when the generation is small scale but with increased wind penetration this can lead to deterioration in the system security.

In recognition of dispatch problems due to the current treatment of intermittent generation in Australia, the National Electricity Market Management Company (NEMMCO) has recommended [3] the introduction of a new plant category - 'semi-dispatchable' in the grid code. This change has been driven by an increasing risk of violating secure network limits by non-scheduled wind generation located behind the constraint. Under current rules a non-scheduled generator is not obliged to control its output to prevent overloading of transmission plant. Currently to mitigate this risk transmission network service providers (TNSP's) set up conservative operating margins and impose runback requirements on the wind farm. This arrangement was considered by NEMMCO as reducing market efficiency. Under the proposed semi-dispatch arrangement significantly sized wind farms would be required to participate in the central dispatch including submitting daily energy market bids and responding to dispatch instructions. The benefit of the proposed changes will be an improved integration of significantly sized wind farms into the central dispatch process and the transparent management of transmission congestions in cases when both dispatchable and intermittent generation is behind a constraint.

In Germany the rapid expansion of the installation of wind farms in Schleswig-Holstein (Germany) means that on windy days, the grid capacity to accommodate intermittently generated electricity is entirely exhausted. Although E.ON Netz instituted grid expansion measures at an early stage, it must be recognised that it will take several years before the planned power lines are built. In order to be in a position to connect further renewable energy power production plants before the grid expansion is completed, E.ON Netz developed what is referred to in generation management as a transitional solution. The transitional generation management involves temporary reductions of the power fed in by the intermittent plants, in order to protect grid equipment such as overhead lines or transformers from feed-in-related overloads, thereby avoiding supply failures.

In mid 2003, E.ON Netz implemented this generation management in Schleswig-Holstein, together with E.ON Hanse. Plants with a total capacity of at least 700 MW (around one third of the total wind generation capacity installed in Schleswig-Holstein) are currently involved. In 2004, the generation management had to be introduced in Schleswig-Holstein 17 times. The duration of the feed-in restrictions in specific areas was between 30 minutes and 12 hours. Feed-in to the wind farms had to be reduced to levels of between 60 and 0% [15].

The Spanish TSO, REE, established in the Operation Procedure (PO 3.7) the concept of "dispatchable generation" which was later incorporated into the Royal Decree 631/2007. In both documents, a distinction is made between "dispatchable" and "not dispatchable" power plants, regarding their primary power source characteristics. Those power plants whose primary energy source are neither "storable" nor "controllable" such as wind, run of the river hydro, etc. and thus are not able to follow OS instructions are considered "not dispatchable". The Operating Procedure sets out a series of restrictions, which may be activated depending on the system conditions, and that may temporarily restrict the penetration of "not dispatchable" power plant in the power system. However these power plants also have a priority on injecting their production on the grid to minimize energy spill.

2.4.2 Wind Intermittency

An improvement in wind forecasting will reduce the occurrence of unexpected changes in wind farm production and associated changes in power flows in the network. However, the exact performance in the event of high wind will be difficult to predict. During such events the wind farm output can change significantly during a short period of time. Individual wind gusts are hardly visible at the output of a wind farm and are not critical for the system whereas a storm front across tens of kilometres may cause the wind power to rise or fall sharply by hundreds of MW within less than an hour. An initial increase of generation may be followed by the sudden disconnection of wind turbines, if the wind speed increases beyond the cut out level. If this sudden disconnection cannot be forecast adequately, the management of the wind forecasting errors will still necessitate increased reserve levels, compared with a network using only conventional generation. In order to manage the impact of such events additional network control systems may be required to prevent unacceptable overloading of transmission lines from areas supplying balancing power. Future wind farms may be equipped with a wind forecasting system capable of detecting wind fronts and reducing wind power generation before the front arrives.

Forcing wind generators to declare the output of the farm to the market and adhere to this figure would improve market operation however this would result in inefficient and conservative forecasting or constrained operation, “spilling” wind. On the other hand the objective of maximising renewable energy generation to the system may force other generators to operate less efficiently or to use energy storage to minimise operational risks. The forecasting accuracy of wind power production has not yet reached satisfactory levels and forms the subject of a massive research and development effort. Hence, it may be expected that forecast errors will reduce significantly in the long term. The question of what should prevail for the short term, the maximisation of extraction of renewable energy or pragmatic physical market and network management, is beyond the scope of this document.

2.4.3 Connection Agreements with Wind Generators

Initially few requirements were imposed on the performance of wind farms with respect to system connections. Therefore, early wind farms were allowed to connect with little control of voltage and reactive power and no fault ride through capability. This has changed and most countries have now prepared connection requirements and grid codes which takes wind farms into account. Chapter 3 gives an overview of some representative grid codes.

2.4.4 Impact of government subsidies

Most wind farms have relied on some form of government incentive/subsidy to achieve commercial viability. These payments are usually based on the energy generated. Any departure from maximum efficiency operation penalises the wind farm owner, and any need to operate a wind farm at reduced output raises the issue of financial compensation for the energy not produced. Forced reduction of wind farm output represents energy spill unless the wind farm includes an energy storage facility. Even so there will be significant energy spill since the cycle efficiency for energy storage and re-use today is well below 100%. At this stage the most attractive connection for a wind farm is when it is close to a hydro storage plant or to a load that can accept interruptions to its power supply, e.g. a desalination plant.

2.4.5 Provision of Frequency Control Ancillary Services (FCAS)

Participation in the FCAS market attracts a service premium which is usually much lower than the energy price. Conventional plant uses less fuel when operating at reduced output and the penalty is lower efficiency.

Wind generation is unable to provide rise services unless it is intentionally operated at partial output spilling part of the potential wind production, which means that the wind generator suffers the loss of both the value of the spilled energy itself and of other associated incentives.

Wind generation could offer lower FCAS services associated with management of over-frequency. Whilst this would also result in loss of energy production, the periods when frequency deviates from its normal band is relatively small and commercial implications are not significant in this case.

It should be noted that FCAS services are not always available with a wind generator, namely when the wind speed is below cut-in or above cut-out wind speed. For low wind speeds, the lower operating reserve is limited to the actual power produced.

2.4.6 Technology Impacts

Larger sizes of wind turbines rely on the use of variable speed generators in order to reduce mechanical stresses and maximise turbine efficiency. However, the introduction of variable speed generation technologies has created many challenges due to different dynamic performance of these machines, when compared with conventional synchronous generators. The differences include:

- lower contribution to the system inertia,
- limited or no contribution to the fault current,
- limitations in voltage and frequency regulation,
- increased sensitivity to the quality of power supply.

Some benefits of the new technology such as its very fast response and a separation of active and reactive power control have not yet been fully explored. There has also been a recent trend to install induction generators with an SVC or STATCOM at the point of connection with the transmission network to provide necessary voltage control and to keep ownership boundaries transparent.

2.5 ACTIVE POWER WIND GENERATION CONTROLLABILITY

Unlike thermal or hydro generation, wind farms cannot increase their power output on demand at any given moment in time. In the early days of wind generation, this lack of controllability did not seriously endanger the system and wind generators were exempt from contributing to primary and secondary frequency control. However, by the end of the 1990s, in some countries the magnitude of the installed wind capacity could not be neglected any more in comparison with the minimum system load.

During times of high winds and low system load when some of the thermal or hydro generators are switched off, the power system becomes vulnerable to variations in wind power. Therefore it is necessary to increase the generation reserve, such that it can compensate for variations in both load and wind generation. It should be noted that if large scale wind generation is used to offset the demand, it is also necessary to access the impacts of reduced inertia and fault level in the network.

The question defining the largest acceptable wind penetration permitted under the most limiting system conditions is not simple as it depends on the type of generation, interconnections with other systems, availability of energy storage and other regulating devices.

It is important to consider the dynamic response of different types of generators. Synchronous generators provide strong contributions to system inertia and fault level. The characteristics of wind generators are described in Chapter 1. Direct connected fixed speed induction generators cause significant power and torque fluctuations, which are reflected in the quality of the power supply, but offer good inertial contribution and some limited fault current contribution. Variable speed generators do not typically at this stage contribute to the system inertia and their fault contribution is also at best limited, however, they offer significantly smaller variations in their output compared to direct connected fixed speed induction wind generators.

The connection of a wind farm is also affected by its connection to the main network. If the connection is a long weak ac line or cable, the consequences of power swings on the line in the event of faults and disturbances need to be evaluated, since the line may trip due to overloads. If an LCC HVDC link is used, the wind farm connection will not provide a fault current in-feed to the ac network, unless synchronous compensators are used as part of the HVDC solution. For a VSC Transmission solution the fault current in-feed is limited to the rating of the HVDC scheme. Therefore, the combination of high HVDC power transfer and high wind generation could result in the displacement of large number of synchronous generators and a dynamically very weak system.

The operating range of wind turbines is limited by minimum (cut in) and maximum (cut out) wind speed and unlike conventional generation the operating point is limited by the intermittent resource. The minimum wind speed does not have a great impact on a large power system; however the management of wind farm output at high wind speed is important as it may lead to the disconnection of all generation, as described above. Unfortunately at present the instant and the size of the wind speed change can not be (yet) accurately predicted. One solution presently applied is to reduce the wind power output before the expected sharp generation decrease occurs. In an increasing number of countries, the TSO has the authority to control the wind farm power outputs down, see Chapter 3. The impact of wind gust can be at least partially managed on some wind turbines when the wind speed increases. However, the wind speed reduction can not be managed by wind turbines and the provision of additional raise reserves is required.

2.6 REACTIVE POWER AND VOLTAGE CONTROL

Reactive power needs to be balanced in the system in order to keep the system voltage within limits to enable power transmission. The reactive power balance is more localized than the active power balance as reactive power can not be transmitted across significant distances without excessive voltage or energy losses.

Initially, wind turbine generators were exempted from contribution to the reactive power. Now grid codes in an increasing number of countries requires that wind farms take their share in reactive power balance. Wind farm connection point requirements for reactive power are discussed in Chapter 3. The requirements vary from a demand to keep to near zero (unity power factor) to specifically defined leading and lagging requirements at rated output. The point at which these requirements are defined typically depends on the ownership of the interconnector between the wind farm and the grid.

The reactive power capability of wind turbines vary widely from that of induction generators compensated with switched capacitors to generators with full AC/DC converters, with full vector control, offering a variable dynamic response, see Chapter 1. When available, the capability can be used to control the reactive power at the terminals of the wind farm, but only at a remote connection point to the grid if it is electrically very close. Some wind farms operate with secondary voltage control, provided by a wind farm controller, providing target reactive power set points for individual turbines.

Increased requirements for reactive power controllability will lead to changes in the wind farm design and/or lead to the application of switched/controlled reactive power compensation. The application of switched capacitors may have some limitations as capacitor switching tends to have some negative impact on wind turbine gear boxes. Power electronics provide a sophisticated means to dynamically provide reactive power.

It should be noted that the wind generator reactive power control ancillary services may not always be available as typically wind generators are disconnected when the wind speed is below cut-in wind speed. For this reason separate substation based reactive compensation may offer an advantage.

Wind farms will typically be connected to the network using one or more radial high-voltage transmission lines or cables. In the case of ac overhead lines the reactive power characteristics vary from capacitive to inductive as a function of line loading. In the case of an underground or undersea ac cable connection reactive power is supplied to the system and it needs to be absorbed to avoid overvoltage (See Chapter 4). For large wind farms planned today, hundreds of kilometres of high-voltage cables will be connected to the network which will require significant reactive power compensation installations and will lower the system resonance frequency (see Chapter 4). For HVDC connections there are no reactive power issues between the two terminals, and the reactive power requirements at the connection point to the grid will typically be determined either by the grid code, or by specific connection agreements

2.7 OVERVIEW OF DYNAMIC AND TRANSIENT INTERACTIONS

This section provides an overview of dynamic and transient interactions between wind farms and the system reported in the literature. Dynamic impacts are changes to the systems operating state caused by a disturbance. The nature of disturbances is influenced by changes to system design with the connection of wind generation causing changes in system frequency and/or voltage response. Typically changes to system response are due to the following factors:

- Different generation schedule,
- Location of wind farm connections,
- Changes in voltage profile due to reversal of power flows,
- Displacement of conventional generators by wind farm output results in lower fault level and in small systems, lower system inertia,
- Different characteristics of wind generators etc.

Off shore wind farm cable connections with high capacitance also challenge system response. The impact on the isolated part of the system supplied by non synchronous wind farm generation is discussed.

Often wind farm integration problems are due to the characteristics of the connection point, in particular short circuit ratio and weak transmission. Typically at strong connection points the system can supply the required charging currents and absorb the changes in reactive demand caused by variable wind farm output satisfying requirements of applicable codes. In a case of weak supply point the connected wind farm may cause a wide range of voltage variations resulting in poor quality of local power supply. Cable connections with significant charging may be a problem requiring additional stabilisation typically using dynamic reactive power sources such as SVC or STATCOM. In critical conditions harmonic resonances may be excited as described in the next section.

2.7.1 Fault response – voltage dips

Reference [4] provides an example of successful operation of fault ride through. The Bluff Point stage of Woolnorth wind farm in Tasmania, Australia includes 37 off 1.75MW DFIGs connected to the system by a radial 110kV transmission line, the first 50km from the wind farm being single circuit and the next 80km being double circuit. 31 of the wind generators have been equipped with Fault Ride Through (FRT) capability. A single phase to ground fault occurred in the double circuit line section, near the junction with the single circuit. Figure 2.1 shows the fault response as recorded at the wind farm. The rms phase to ground voltage trace, shows that the fault depressed the voltage to about 60% and the fault was cleared within 6 cycles. The voltage remained depressed for 400ms. The long voltage depression was caused by operation of FRT, which is triggered by both under-voltage and over-current, and results in the temporary insertion of a large series resistor at the junction connecting rotor and stator circuits and the step up transformer. The active power transfer before the fault was about 53MWand post fault the wind farm was contributing 28MW. The post fault active power trace shows a 2Hz oscillation which was caused by a torsional oscillation in the wind turbines. Considering that this was the first commercial application of FRT for the type of wind generator, and six of the wind turbines had not been equipped with FRT, and that a couple of turbines were not operational on the day, the performance was considered satisfactory by the TNSP. Since then the operational experience has proven the FRT equipment to be successful and very few turbines have tripped.

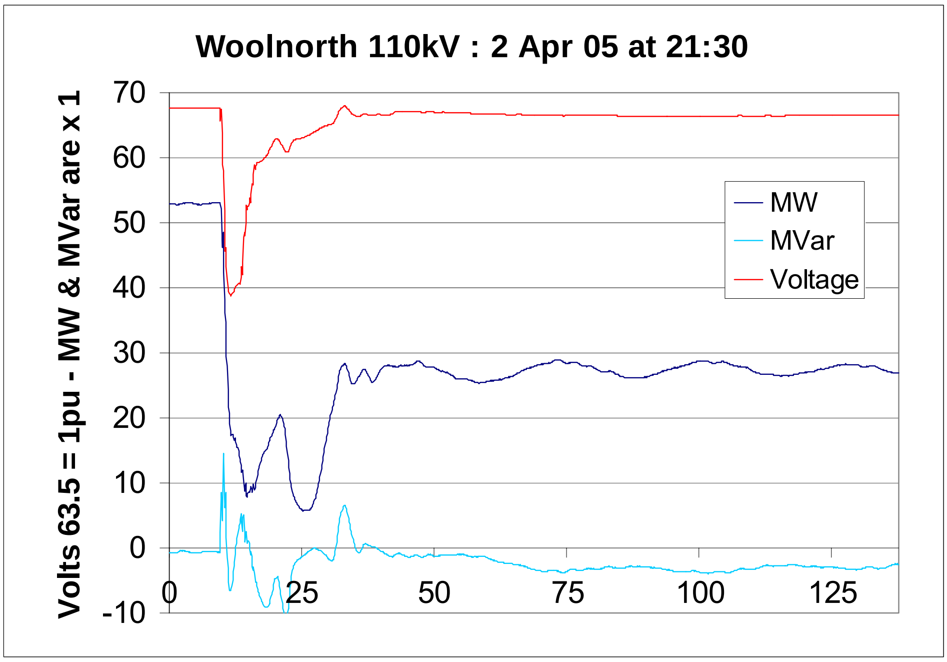

Figure 2-1 **Traces of single phase to ground voltage, active and reactive power during a single phase to ground fault in proximity of the wind farm. The time scale is in 20ms cycles.**

In weak systems remote faults may appear as a voltage depression without drawing a large current contribution. This may be a problem if LFRT is activated by over-current only.

It should be noted that three phase faults are typically easier to handle with electronic equipment than single phase faults. However single phase to ground faults are the most common ones in an ac network.

If the wind farm is connected to the grid through a HVDC scheme it should be noted that an ac voltage collapse does not occur at the wind farm, when a fault occurs in the grid. This makes it necessary to give special consideration to the frequency and ac voltage control at the wind farm, since the wind generators may not instantly be aware that the power cannot be exported from the wind farm. Solutions may involve the use of high inertia synchronous compensators, breaking resistors or other storage or consumption devices.

Faults within the HVDC scheme will also have to be carefully considered, particularly for HVDC overhead line faults which may occur at the same frequency as faults on ac overhead lines. Similar solutions to those mentioned above may be adequate, but fault clearance times of up to 500ms may be necessary, resulting in the need for higher energy storage/consumption. Other faults will be rare and will typically result in a shutdown of the HVDC scheme, and inter-tripping of the wind farm may be required.

2.7.2 Fixed-speed system fault response

As described in Chapter 1 a reduced grid voltage may lead to excessive reactive power consumption by a fixed speed induction generator turbine if the wind speed is high. Simplistically, the fixed-speed system contributes with a fault current according to that of an induction motor, but driven with a negative load.

Wind farms using fix speed wind turbine require significant amount of reactive power support (SVC, STATCOM) to remain connected to the transmission system during a disturbance to avoid stalling or tripping.

2.7.3 DFIG fault response

For minor voltage disturbances, the DFIG-system converter can control the current throughout the whole fault sequence. This means that for a minor disturbance, down to 75-85 % remaining voltage, the DFIG provide less current disturbances compared to a fixed-speed system. An example of the current as well as active and reactive power responses to a 75 % (remaining voltage) dip is presented in Chapter 1.

For larger disturbances the rotor must be short-circuited using a crowbar located between the rotor windings and the converter and the resulting stator currents become several time the rated ones [5].

The double fed induction generators contribute to fault current during system disturbances. This contribution is much smaller than wind generators using directly connected induction generator or induction generator with variable rotor resistance. Typically this value is below 2 pu. With some wind generators the value of the fault current contribution can be selected by the owner, necessitating a trade-off between reduction of active current and increase of reactive current contribution during operation of the fault ride through device. For comparison the fault current contribution of the full size converter (transient over current) is typically limited to about 120% of the rated current.

2.7.4 Full-power converter fault response

This system has a built-in ability to handle dips down to any magnitude. The grid side converter controls the currents to the grid, and, accordingly they can operate at any voltage level with up to rated current. For unsymmetrical faults, depending on the converter design, the current producing ability might be somewhat lower during the fault.

Any fault current up to the rating of the grid inverter but of course the contribution to the short-circuit power of the grid usually is much lower for a variable-speed wind turbine than for a conventional synchronous generator connected directly towards the grid. This means that it will be required to perform a review of the protection settings if such turbines are to be installed into a system in great numbers.

It can be worth pointing out that in some new grid codes, it is stated that wind energy installations should inject reactive power into the grid during voltage reductions.

Full-power converter systems use a breaking resistor on the dc-link and can immediately resume operation at the previous production level when a fault has been cleared.

2.7.5 HVDC Connection of Wind Farms

This type of connection is used when AC transmission is not technically or economically feasible, usually in the case of very long overhead transmission or long undersea cables connecting off-shore wind farms, and are discussed in a little more detail in Chapter 5. In this Chapter some key characteristics relevant to wind farm connections will be mentioned. Examples of wind farms connected using HVDC are provided in Chapter 6.

2.7.5.1 Line Commutated Converter (LCC) HVDC

This type of HVDC requires large ac filters for harmonic control and also for reactive power control. The filters are normally breaker switched, and consideration needs to be given to the impact that the voltage step caused by filter switching may have on the gear box in wind generation units.

Another issue to be considered is the impact of over-voltages during a transient disturbance associated with

HVDC. The typical magnitude of temporary over-voltages (TOV's) can be higher than 1.3 pu, unless the ac network is very strong or special designs are used. The power electronics used in wind turbines do not tolerate such high over-voltages and most of manufacturers limit the maximum operating voltage to 1.2 pu.

Example grid connection studies are presented in reference [6].

2.7.5.2 **Voltage Source Converter**

Voltage Source Converter (VSC) transmission technology is based on self -commutation and therefore does not require an external voltage source for operations. It also eliminates problems associated with voltage regulation, switching of ac harmonic filters, and the need for synchronous compensators for minimum fault levels and provides a black start facility. The four quadrant converter allows independent control of active and reactive power flows.

The results of a study using VSC to connect active stall wind turbines are reported in [7] while reference [6] provides connection examples for wind turbines using double fed induction generators.

2.8 DYNAMIC STABILITY

2.8.1 Mechanical Inertia of Wind farms

The stable operation of power system with synchronous generators depends on the rotational inertia present in the ac system. This inertia influences the behaviour of voltage and frequency waveforms but results in an inherently oscillatory transient response, because of low damping in the mechanical system. Satisfactory power system performance requires a minimum inertia relative to the size of non-synchronous energy sources such as HVDC links, variable speed generators or other sources connected by static inverters [2, 8]. A concept of the relative rotational inertia, defined as the ratio of total AC system rotational inertia to the size of DC link, is defined in [2]. Satisfactory system performance requires this constant to be at least 2.0 to 3.0s [2]. The same concept should apply to some types of wind turbines.

2.8.1.1 **Mechanical inertia of FSIG**

The fixed-speed systems with an induction generator as electrical system, has the mechanical inertia determined by the wind turbine rotor. A typical value for a wind turbine is to have an inertia constant of 3 seconds.

2.8.1.2 **Inertia effect of variable-speed systems**

When a DFIG or full power conversion system is used, the inertia constant looses its traditional definition. In case of variable speed wind turbines the kinetic energy stored in rotating masses does not contribute to the inertia of the system as the rotational speed is decoupled from the system frequency by power electronics. By utilising the built-in speed control of the turbine, a fictive inertia constant can be constructed that can be made smaller or larger than the "natural one". The control system detects a frequency change and determines the power output based on the instantaneous frequency change. However, in order to give the turbine a high fictive inertia constant, it might be necessary to over dimension the power electronic converters. The reaction time can be very short, within 5-10 ms. However, utilising the energy stored in the wind turbine rotor leads to a de-celeration of the rotor, and to restore optimum generation it is then necessary to reduce generated power output so that the rotational speed can be re-established. It is also possible to place an energy-storage (e.g. a battery) on the dc-link that can store a smaller amount of energy that can be quickly controlled. The ability to control power output and use stored energy can be used to increase the transient stability margin on a nearby synchronous generator unit or to damp power oscillations.

Reference [9] provides an example of frequency control system for DFIG wind turbines.

2.8.2 Response to frequency events

Wind turbines offer a reasonably wide range of operating frequencies typically 48 to 51Hz for a system with a nominal frequency of 50Hz. This is acceptable in large systems where the frequency deviations are small. In small size systems Code requirements are often the same as in large systems but frequency variations are larger. The requirement to stay in service at high frequency may not always be met.

Some wind turbines are equipped with frequency controllers including droop power action in response to frequency excursions.

2.8.3 Voltage stability impacts

In [7] the long-term voltage stability problem is investigated using the grid set-up presented in Figure 2-2. At t=1 second one of the 4 long transmission lines is disconnected. The result can be observed in Figure 2-3, taken from reference [11]. The figure shows that from long term voltage stability point, the variable speed wind turbines controlled to unity power factor (System B) are slightly more stable than no-load compensated fixed-speed turbines (System A). The greatest improvement in voltage stability can be obtained by allowing the turbines to inject reactive power into the grid (System C).

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Figure 2-2 Set-up for voltage stability studies.

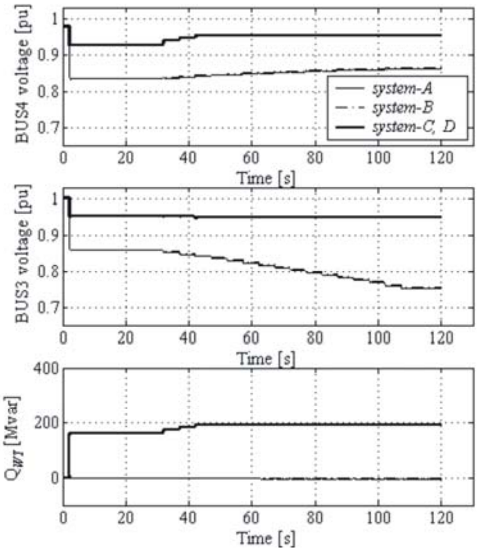

Figure 2-3 Resulting voltages, operation of fixed speed wind turbines and variable speed wind turbines with unity power factor- leads to voltage collapse, while turbines providing reactive current injection improve voltage stability.

It is important to note that all types of wind turbines can have either system, A, B or C function.

Reference [11] considers the impact of high penetration of wind generation on long and short term voltage stability of South Australian system. Long term voltage stability is defined as the ability of a power system to maintain adequate steady state voltages throughout the network. A network exhibiting long term stability problems will have voltages severely depressed. PV curve analysis has been used in order to assess the stability margin. The reference concludes that with increased penetration of wind generation the voltage stability limitation becomes a more dominant constraint than the thermal limitations of transmission equipment. Short term voltage stability refers to the system ability to remain intact after a disturbance such as trip of a large generator, transmission line or voltage control device. The reference notes that there is no discernable trend relating to short term voltage instability with increasing penetration of wind generation. Under high demand and the highest wind penetration level considered the system was clearly unstable and the short term voltage stability was not determined as in this case the dominant constraint was due to thermal limits on the interconnecting transmission line with Victoria.

2.8.4 Impact on transient stability by variable speed wind turbines

A severe fault in an AC grid with synchronous generators will result in oscillations between generators located on opposite sides of the fault. In a critical case when the magnitude of the oscillations becomes too large a synchronous generator can lose synchronism and be disconnected from the system by its protection. Wind generators use either directly coupled asynchronous generators, DFIGs or full AC/DC/AC converter to separate the variable speed generator from the AC grid. Consequently wind turbines respond differently to system swings than conventional synchronous generators. Therefore, an instability associated with wind generators is rare and usually due to problems within control loops or uncontrolled speed (runaway) changes.

New designs of wind generators include controls or additional control plant at the wind farm substation level which will assist in damping of power oscillations. Reference [10] considering system security risks introduced by large scale wind farm development in South Australia has reported improvement in transient stability resulting from such additional controls allowing some increase in power flow in the interconnector to Victoria.

Modern variable speed wind energy units can assist conventional generators to avoid transient instability [11]. If we have the following set-up presented to the left in Fig 2.7, the rotor angle oscillation following a disturbance can be improved from being on the stability limit (system B) to a 20 % margin (System C and D) by implementation of appropriate control strategy. In addition to the systems A, B and C introduced in the section 2.8.2, a system D is considered. In system D the wind turbine is equipped with a supercapacitor or battery energy storage system connected to the dc-link of the turbine. System A performed fairly similar to system B and has therefore been omitted in the figure.

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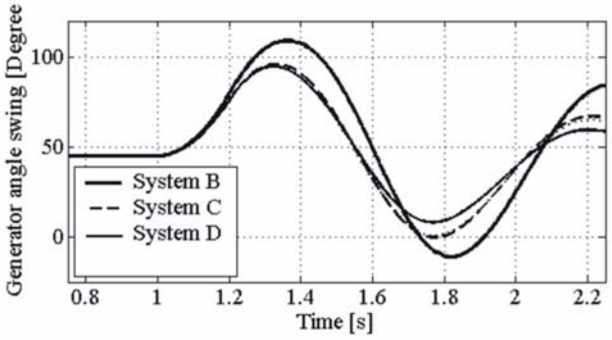

Figure 2-4 Angle swing following a fault, System B operation with PF=1, System C operation mode where the PF is varying and system D with an active energy storage.

2.9 ISLANDING

Spurious islanding can occur in LV/MV networks with distributed generation as the islanded system will not see abnormal conditions until there is significant demand/supply unbalance resulting in a frequency deviation. The condition can be difficult to detect if the islanded part of the system has balanced wind generation and local load. Fixed speed induction generators will trip under such conditions due to shortage of reactive power and collapse of generator flux, however self excited generators using voltage source converters may operate until their protection encounters trip conditions. Some turbines may be equipped with frequency control and in this case the islanded operation will be prolonged. There is a possibility that under such conditions system protection relying on distance protection[1] and fault current may not function correctly. The spurious islanding can be best handled by inter-tripping of the island by a section of the system which was subject to a fault. It is possible that similar conditions can occur on a larger scale in transmission system – for the largest transmission systems, "islanding" capability of a network part is even a desired property.

Reference [4] describes the contingency which has led to islanding of a section of a system containing a wind farm supplying an isolated load. The pre-contingency wind farm output was 48MW. The wind farm was connected radially to the system and in the middle of the connecting transmission line a substation was supplying a small load of about 20MW. The line between the system and the load substation tripped thereby islanding the wind farm supplying the load. Figure 2.8 indicates that the phase to ground voltage rose to just below 80kV i.e. approximately 1.25pu. The duration of overvoltage exceeding 1.1 pu was very short as the system collapsed within 500ms.

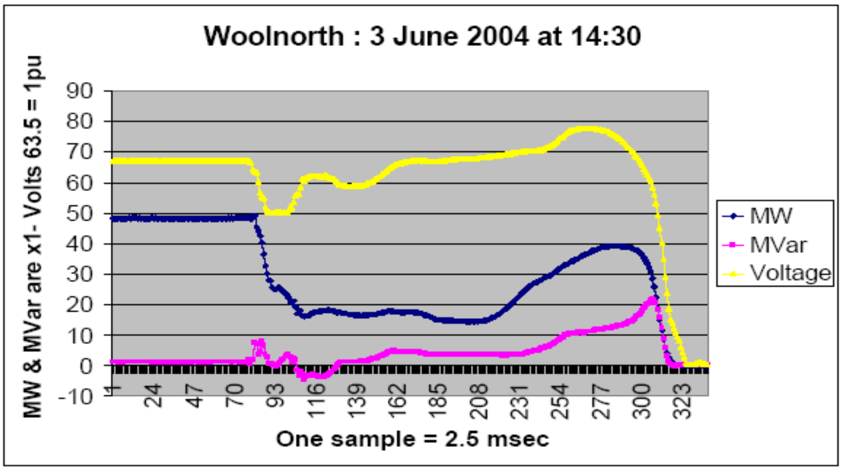

Figure 2-5 Traces of voltage, active and reactive power recorded during islanding of a wind farm with a small load. . The time scale refers to the number of 2,5 ms samples.

The wind farm trip was activated by distance protection sensing variable impedance. The frequency rise from 53Hz to maximum (frequency calculated based on time of zero crossing) took only a 6 cycles (see Figure 2.9). Overfrequency relays installed on wind turbines had a time delay of 200ms (200ms after reaching 53Hz) so it did not have time to act. It is possible to accelerate the action of the rate of rise frequency relay; however, it is unlikely that this relay would have been activated faster than the distance protection.

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[1] The fault recorder shows a dramatic rise in the frequency (16.7Hz in 180 milliseconds – Fig. 2.9). Such high frequency slew rate is well outside the tracking range of the relay. The mho phase distance element uses positive sequence memory polarisation and the high frequency slew rate has caused the high impedance measured by the relay to unpredictably transfer to the zone 3 region. However, had the supply and demand been reasonably balanced the protection would have not operated.

An interesting issue is why the protection operated at all as there was no fault current. The over-frequency protection, although slow, improves the confidence in isolating the wind farm from the load.

The frequency control on the wind farm was disabled, however it is possible to consider a scenario with the wind turbine frequency control enabled and effectively eliminating overfrequency and sustaining operation until there is a reduction in wind generation causing an underfrequency trip. This would be very undesirable due to the possibility of large currents at reconnection of the network part. The best protection arrangement in this case would be direct inter-tripping from any circuit breakers that can cause islanding, and/or connection conditions that explicitly forbid frequency control and cater for verification procedures to ensure this.

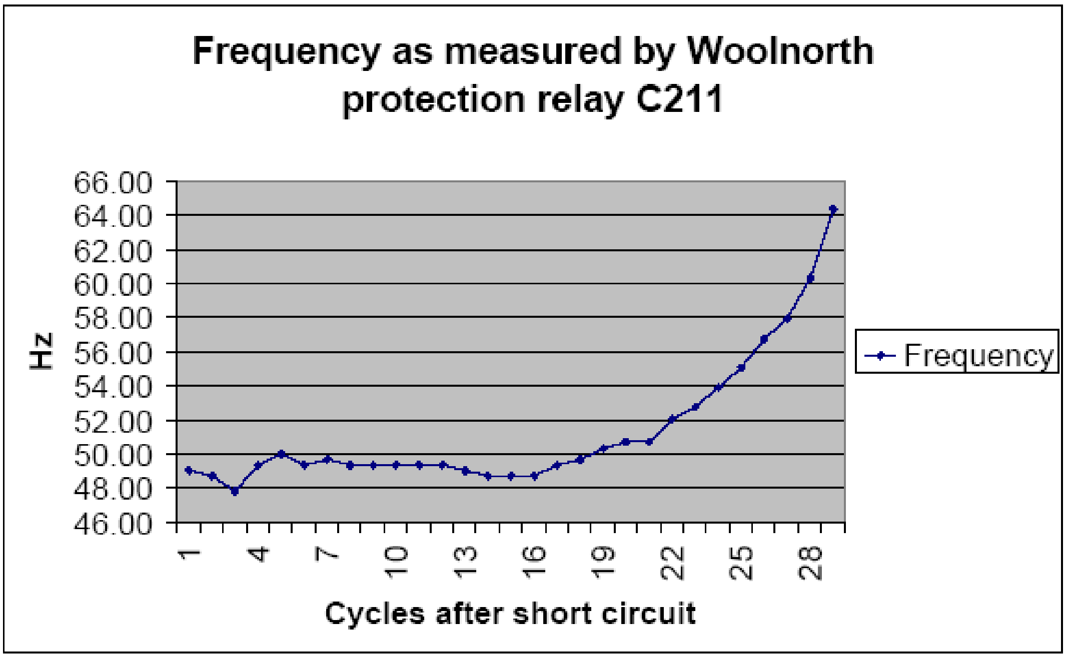

Figure 2-6 Trace of power frequency in the island part of the system with significant unbalance between supply and demand. . The time scale refers to a number of 20ms cycles.

The line which has tripped was equipped with 3 pole auto-reclosure with 5 seconds time delay. If the wind farm had not been disconnected there would have been a danger of out of phase synchronisation.

It can be concluded, that the generator should be equipped with fast over/underfrequency and over/undervoltage protections as an anti-islanding protection,.

2.10 POWER QUALITY

The impact of wind turbines on power quality has long been a source of concern to utilities. This concern was developed based on operating experience of wind turbines with fixed speed induction generators compensated by switched capacitors. These early wind farms were typically connected at sub-transmission level where a weak connection point was shared by the wind farm and local loads. Capacitor switching, wind gusts, wind speed changes in the steep part of the power curve and fast changes of electrical torques caused rapid fluctuations of both real and reactive power. In combination with the short-circuit impedance of the network this causes voltage flicker. The flicker level caused by a wind turbine decreases with increasing network short-circuit power. For wind farms, connected to transmission networks, flicker is not an issue mainly due to the stronger connection point but today also due to the use of variable speed turbines and the diversification of turbine locations. However it needs to be recognised that "transmission" in some part of the world such as Australia includes long, sometimes radial 132 kV circuits that are inherently weak networks with more the characteristics of a distribution network.

2.10.1 Harmonics

2.10.1.1 **Harmonics from fixed speed wind turbine systems**

The wind generator in itself seldom gives rise to problems with harmonics. However, wind generators connected to a local grid with cables, transformers and inductors may as a combination amplify harmonics. Examples from literature [12] show that individual harmonics can be amplified at least three times. High-frequency electromechanical oscillations at resonance frequencies is a possible cause of transformer and generator failures in certain sea-based wind farms. It is considered that in particular the use of vacuum circuit breakers may cause problems due to current chopping.

2.10.1.2 **Harmonic contribution from variable-speed wind turbine systems**

With variable-speed turbines there can also be a problem with amplification of harmonics in the local wind farm grid. Examples from literature [13] show that individual harmonics can be amplified at least three times, compared to their original size in the grid. The harmonics originating from the PWM-switchings of the DFIG converter or full size converter are of higher frequency and they are usually filtered sufficiently and have not been reported in literature to be a problem.

2.10.2 Flicker

2.10.2.1 **Flicker emission from fixed-speed wind turbines**

The varying wind speed and also the mechanical design of a wind turbine cause a varying output power. This varying output power then causes voltage variations on the grid to which the generator is connected. National regulations state how much flicker a wind generator may cause at the grid connection.

When several turbines are connected in a group, there is a tendency to even out the power pulsations, and accordingly the result is a lower flicker emission in relation to the total size of the wind energy installation [13]. As a general conclusion it can be said that the flicker emission will rarely be a problem. However, if a single large fixed-speed wind turbine is connected to a weak grid with OH-lines, it is necessary to consider flicker performance in detail.

2.10.2.2 **Flicker emission from variable speed systems**

Since the variable speed turbines have the ability to control the shaft torque of the turbine and accordingly to store a varying incoming wind power by changing the amount of rotational energy stored in the rotor, flicker emission from a variable-speed turbine is seldom a problem. The wind farm "smoothing effect" mentioned above also applies to variable speed generators [14].

2.10.3 Resonances due to long high-voltage cables

In case of underground or undersea AC cable connections, significant amounts of reactive power are supplied to the system. For the many large wind farms planned today, hundreds of kilometres of high-voltage cables will be connected to the network to an unprecedented level.

Resonance is always present in a network and in itself is not critical. However, in combination with a harmonic source (background distortion, in-rush currents due to transformer saturation during switching and current harmonics generated by SVCs or HVDC terminals), resonance may cause unacceptable over voltages and network distortion [14]. Resonance frequencies above the 20th harmonic are very common and seldom cause problems, but resonance frequencies below the 10th harmonic deserve closer attention due to their potential magnitude.

In a simplified approach, the resonance frequency can be estimated from the network short-circuit reactance and the capacitive reactance. In [14] it is calculated that even for a strong 400kV network, the resonance frequency could drop to the 5th harmonic or even lower. From these very low resonance frequencies, it can be seen that harmonics and resonances are certainly a point of concern. These low resonant frequencies are not expected to render AC transmission unfeasible, but the compensation measures required (e.g. passive or active filters) will lower the break-even distance for DC vs. AC transmission.

2.11 SUMMARY

Currently there are three dominating systems for large wind turbines, (full-power converter systems, limited variable speed and fixed-speed systems) all of which are designed to satisfy basic system integration requirements specified in electricity codes. Features such as fault ride through and voltage regulation have become standard. If these features are not provided then reactive power compensation equipment installed at the substation level (DVAR, STATCOM, SVC) can make a wind farm compliant. This equipment may be of particular interest while upgrading the performance of older wind farms. An issue that deserves further studues is the response to grid disturbances, where power electronic controlled turbines can act in a more flexible way.

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3. OVERVIEW OF GRID CODE REQUIREMENTS

3.1 THE NEW AND EMERGING GRID CONNECTION CODES

The requirements for the connection of generation and loads to an electrical network are to an increasing extent being defined by grid codes [1]. The grid connection requirements differ from country to country and may differ from region to region. Their aim is to permit the development, maintenance and operation of an efficient, safe, secure, co-ordinated and economical transmission and/or distribution system. In a deregulated system, their enforcement is intended to facilitate competition in the generation and supply of electricity. They may include basic minimum requirements, and may also outline characteristics, which may be required or provided as ancillary services.

In the past, the technical requirements for connecting a generating plant were specified in terms of large size synchronous machines due to their exclusive use and dominant impact on the grid. However, large scale wind farms are now playing an increasingly important role in many networks, and their fundamentally different operational characteristics when compared with synchronous machines, as explained in Chapters 1 and 2, and in other external documents [2], need to be reflected in modern grid codes. Grid code requirements are typically technology neutral as far as possible, but some have to be specific because of the characteristics of wind generation.

This chapter describes the development of grid codes and the technical requirements which may affect the need for power electronics, either at the wind turbine generators or as separate power electronic (FACTS or HVDC) systems.

3.2 GRID CODE DEVELOPMENT PROCESS

The change in the nature of the generation mix leads to additional or different control requirements to maintain security of supply and power quality. It is therefore not a coincidence that the first countries to encounter large penetration of wind power, such as Denmark [1] and Germany [3], were also the first to develop grid codes applying to wind power. Reference [4] describes in detail how the grid code has been developed in Great Britain, and probably this process was or is similar to that adopted in other countries. The different stakeholders - wind farm developers, existing system users, manufactures and utilities - had originally different opinions ranging from a reluctance to accept any requirements that were perceived to incur high costs, to a demand for stringent requirements to ensure system security and stability under all scenarios. Consensus for grid code requirements was reached as more information became available on better performing technology, economic aspects, impact on market penetration, and realistic needs to achieve network security.

It is recognised that there is a need for non-discrimination between technology types to enable maximum flexibility for wind farm developers. Therefore, the grid codes typically apply at a defined point between the public electricity system and the wind farm, rather than at the terminals of the individual wind turbine generators.

Table 3.1 gives a partial list of countries where grid codes have been issued containing technical requirements applicable to wind power generation. In most countries, these have been published by privatised network operators and approved by an independent government organisation. In some countries government bodies have issued the grid code.

Table 3-1 Partial list of countries and Grid Code Issuers relevant to wind farms.

Country	Grid Code Issuer	Website	Ref.
Australia	AEMC	www.aemc.gov.au	[5]
Canada	AESO	www.aeso.ca	[6]
„	Hydro Quebec	www.hydroquebec.com/transenergie/en	[7]
„	IESO	www.ieso.ca	[8]
Denmark	Energinet.dk	www.energinet.dk	[9]
France	EDF, DIDEME	www.legifrance.gouv.fr	[10]
Germany	EON Netz	www.eon-netz.com	[11]
„	VDN	www.vdn-berlin.de	[12]
Ireland	EirGrid	www.eirgrid.com	[13]
Spain	REE	www.boe.es, www.ree.es	[14]
UK	National Grid	www.nationalgrid.com	[15]
USA	FERC	www.ferc.gov	[16]

The different Grid codes have many common requirements in principle though they sometimes differ with respect to target parameters and their values. This may be explained by differences in network configuration (meshed or radial), grid voltage management, local and historical policies, protection practice, earthing methods, system inertia, and density of wind penetration. Therefore, an ‘universal’ or ‘international’ grid code would not provide an optimum solution for anyone, but would needlessly increase the cost of wind farms.

Bilateral agreements are usually part of the connection agreement for large wind farms, and specify further detailed technical requirements such as fault current contribution, the range of voltages for high voltage connection, the reactive power range, harmonic performance and power runback schemes.

Wind turbine generator manufacturers supply their products to international markets, and are thus faced with the existence of many different grid code requirements world wide. This makes it difficult to develop a standard product that can meet all different requirements, and yet cost effective and fast solutions require some level of standardisation. A standard product which can meet the most difficult requirements in worst case scenarios, would be overrated and unnecessarily expensive for more benign scenarios [17]. An alternative is to have a product with a standard core, to which additional features can be fitted, to meet different requirements. For a particular wind farm two approaches are possible to meet the grid code and connection agreement requirements:

Specify fully customised wind turbine generators that can meet non-mainstream requirements by tailor design of the power electronic controllers inherently present in converter controlled generators.
Add custom designed auxiliary power electronic systems like Static Var Compensators (SVC or STATCOM).

The latter approach may be more flexible, cost effective or reliable in some cases, for example to be able to meet reactive power or voltage control targets at the grid connection point. Wind turbine generators can control these variables at their terminals only, therefore very fast and reliable telecommunications with a centralised controller would be required to control reactive power at the point of connection.

3.3 TECHNICAL PERFORMANCE REQUIREMENTS FOR CONNECTION OF WIND FARMS

3.3.1 Frequency tolerance and operational requirements

Tolerance and operational requirements regarding system frequency and voltage can be found in most grid codes, an example of which is shown in Figure 3.1 for the EON Netz grid code. Continuous operation is required for voltage and frequency ranges within the area of the dotted lines. The times given within the areas of the solid lines indicate the duration after which the generating plant is allowed to trip in this system condition. Obviously for wind farms, such requirements take into account that it is only possible to produce a minimum amount of power if there is adequate wind at that time. Some grid codes also specify that the power may be reduced if grid voltage and frequency fall outside specified ranges.

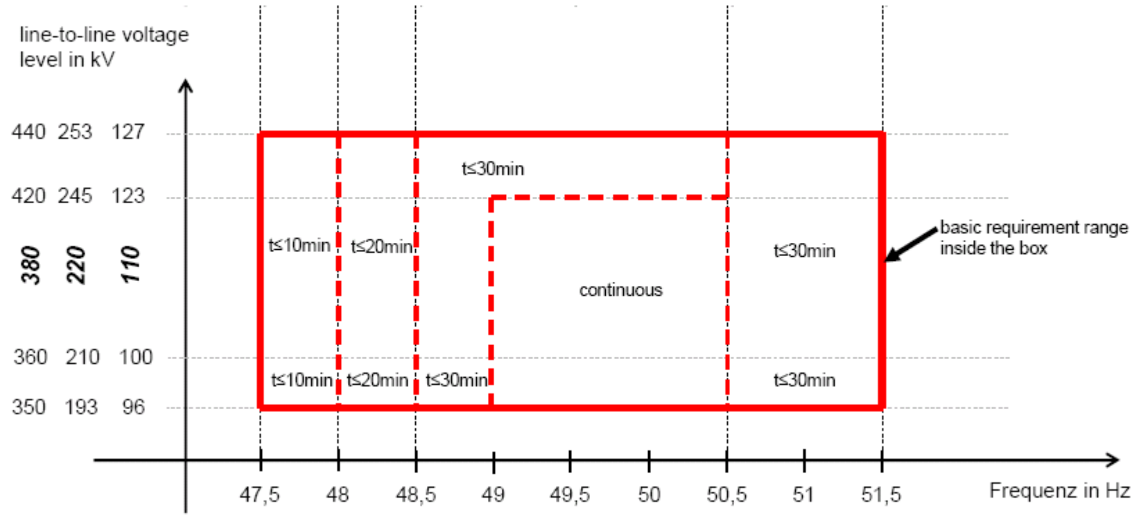

Figure 3-1 EON Netz (Germany) tolerance requirements against variation in grid frequency and grid voltage (quasi-stationary observation, i.e. gradient <0.5% /min, voltage gradient 5% / min.)

3.3.2 Reactive Power Range / Voltage Control

Conventional synchronous generators are required to control the AC voltage and exchange reactive power, in accordance with the needs of the AC system, and according to settings determined by the transmission system operators. They achieve this by varying generator excitation and on load tap changers. It is necessary for the security of grid operation that wind generation can also provide this capability, especially if its penetration in the system is large.

A common requirement is that the wind farm shall be able to operate with a power factor anywhere between defined leading and lagging power factors at the grid connection point. Figure 3.2 gives an illustrative example of the reactive power control demands defined in the EON Netz grid code [11] in Germany. The area within the solid lines shows the power factors with which a wind farm should be able to operate at for a given voltage level. Note that this is just a basic requirement and an extended or different reactive power exchange may be agreed. There may also be incentives or penalties for specific power factor requirements either by bilateral agreement, or by grid code.

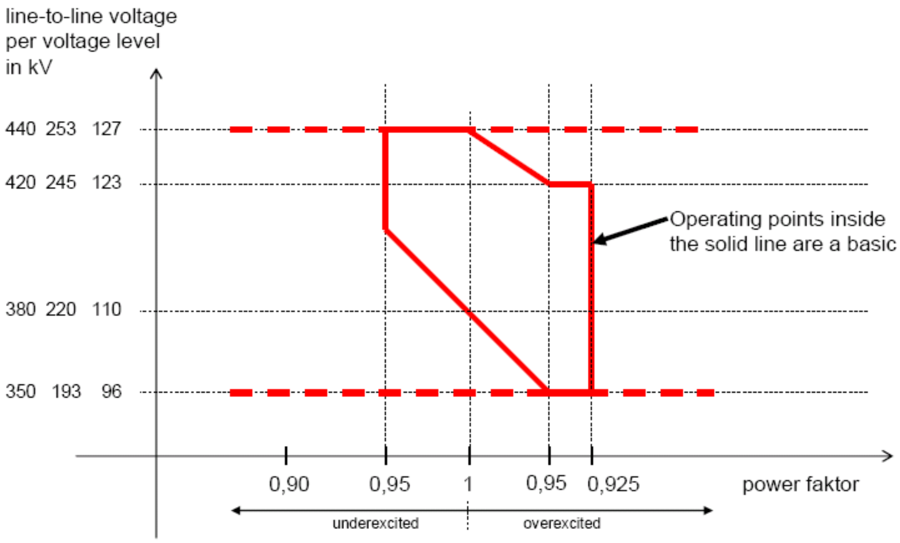

Figure 3-2 **Basic requirements by EON Netz, Germany for the reactive power provision at frequencies between 49.5 and 50.5Hz and without limitation of active power output. [11]**

A different way of specifying requirements on the reactive power control capability of a wind farm is illustrated in Figure 3.3, where the required range of power factors is defined as a function of power output. The decision of the working point in Figures 3.2 and 3.3 is generally commanded by the grid operator.

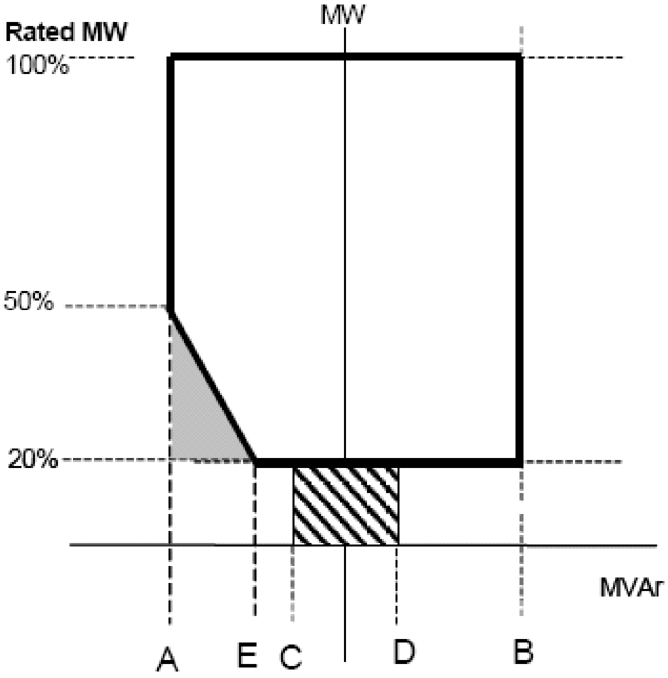

Figure 3-3 **Reactive power requirements in the UK grid code specified by National Grid [15].**
Point A is equivalent (in Mvar) to: 0.95 leading Power Factor at Rated MW output
Point B is equivalent (in Mvar) to: 0.95 lagging Power Factor at Rated MW output
Point C is equivalent (in Mvar) to: -5% of Rated MW output
Point D is equivalent (in Mvar) to: +5% of Rated MW output
Point C is equivalent (in Mvar) to: -12% of Rated MW output

Recently updated grid codes have required the reactive power to be controllable with a specified resolution and accuracy of the target to be met. The emerging trend is to also add AC voltage controllers, with settable droop characteristics. The time response is often specified in the range of seconds or even minutes. Faster response may be specified in bilateral agreements, as the need for fast reactive power or voltage control is very much dependent on the strength of the system at the connection point. For further detailed description is referred to the various published grid codes.

3.3.3 Frequency Control requirements

The requirement to contribute to the system frequency according to a droop (frequency response) tends to be more demanding in low inertia systems such as Ireland and the UK as compared with large inertia systems which are part of the European UCTE.

Wind generators can only contribute to controlling the system frequency in a limited way depending on available wind. However, when there is adequate wind power, which can be forecasted, system frequency control can actually be achieved faster by using pitch blade control of wind generators as compared with the governors of most thermal (coal and nuclear) generators. Also, whereas a coal or nuclear power station may take several hours to start from ‘cold’, wind generators can be activated much faster, subject to wind conditions. In case a wind farm is connected via an HVDC link, frequency control can be implemented via the HVDC controls by varying the DC power flow. Note that this is not necessarily an advantage as ultimately the transmitted DC power has to be balanced with the generated power from the wind turbines, therefore the HVDC frequency controller requires careful co-ordination with the pitch blade control of the generators which may rely on fast telecommunications.

3.3.4 Performance during network faults

One of the most difficult requirements for wind turbine generators to meet is the capability to ride through a fault [17]. Traditionally wind turbine generators were tripped once the voltage at their terminals reduced below 80%, which was acceptable because their impact on the grid was low. However, with ever increasing penetration of wind generation, grid codes now generally demand continued operation when the voltage drops to 15% or even lower. Figure 3.4 shows a plot reflecting the general shape of voltage tolerance that most grid operators demand. Tripping is not allowed during and after a fault causing a voltage drop with a magnitude and duration above the shaded area. The voltage after a fault is unlikely to recover according to the slanted line ‘DE’ in practice, but it indicates the requirement for tolerance against a longer lasting voltage drop if the magnitude of reduction is less.

Table 3.2 gives typical values used in plots for fault ride through requirements as published in various grid codes. The different parameter values have been chosen by the grid operators according to the network topology and line protection settings. The reasons behind these characteristics for the UK national grid code are well described in [4].

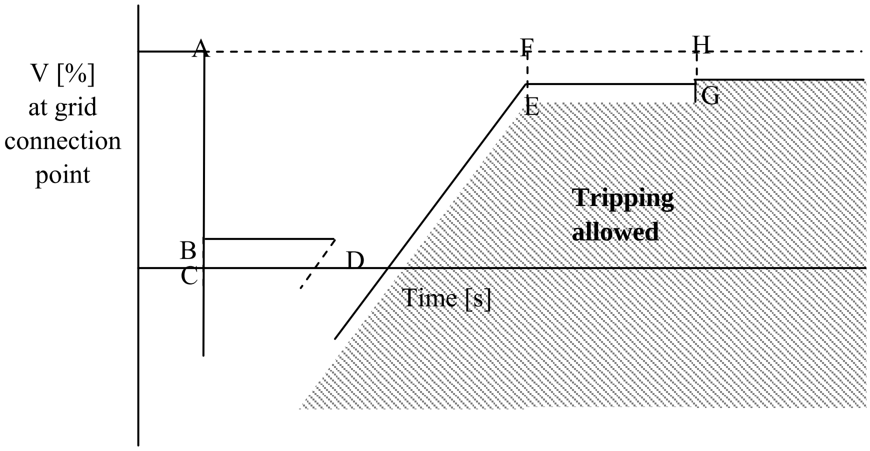

Figure 3-4 Typical shape of Fault Ride Through Capability plot

Table 3-2 Voltage reductions and durations for some Grid Codes, see Figure 3.4.

Grid Code	BC	BD	AF	FE	AH	HG
Denmark	25%	0.1 s	0.75 s	25%	10 s	NA
Germany (EON)[1]	0%	0.15 s	0.15 s	30%	0.7s	10%
Germany (EON)[2]	15%	0.625 s	3 s	10%	NA	NA
Ireland (EirGrid)	15%	0.625 s	3 s	10%	NA	NA
Spain	20%	0,5 s	1 s	20%	15 s	5%
Spain (Canary islands)	0%	0,5 s	1 s	20%	15 s	5%
UK (NG)	0%	0.14 s	1.2 s	20%	2.5 s	15%

[1] For generating unit with large symmetrical short-circuit current component.
[2] For generating unit with low symmetrical short-circuit current component.

Besides the fault ride through requirements some grid codes specify the following demands for wind generation during a voltage drop:
Active power must be provided in proportion to the remaining voltage during a fault, and active power generation should be restored to a certain level within a specified time after fault clearance.

Reactive current in proportion to voltage drop may have to be provided during the fault (and immediately after the fault) for the purpose of voltage support and to enable co-ordination with protection operation [3]. It is to be noted that a thyristor based HVDC link cannot provide fault current, therefore in the UK Grid code for example there is no fault current requirement if a wind farm is connected via conventional HVDC [15].

Some grid codes specify separate requirements for balanced and unbalanced faults.

The requirement for wind generators to remain connected and in service during brief periods of ac over voltage, as may occur as a consequence of a load rejection or similar, is generally not included in grid codes. However, it should be noted that reports have been received that some wind farms may trip in the event of a step voltage rise of 10% lasting less than a few 100ms. Such performance is indicative of a fragile wind generator design, and may reduce the security of an ac network.

3.3.5 Power Quality

As is the case for any type of generation, it is important that wind generation does not adversely contribute to power quality issues such as flicker, harmonics and negative sequence, which ever way it is connected. For these issues, international standards apply, such as IEC61000-37, IEC61000-4-15, IEC61400-21, IEEE 519-1992.

3.3.6 Modelling & Data Provision

System modelling and simulation are the most efficient and practical tools for power system design and evaluation of compliance with grid codes. For this purpose, most grid codes demand models of the wind generators/farms that are representative and validated by the supplier. Results of simulation studies may also be required.

Models for conventional synchronous generators including governors and automatic voltage regulators have been well established and validated over the many years that they have been in existence, however wind generator models have been developed only much more recently. Although good progress has been made for most wind generator models and their aggregation into wind farm models in some simulation software packages, further development in this area is ongoing [18]. One difficulty is that because the technology is still developing quite quickly, details of the implementation of the different types of converters and their control systems are the subject of secrecy and confidentiality agreements.

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4. AC CONNECTION OF WIND FARMS USING FACTS

4.1 INTRODUCTION

This chapter describes the issue of the AC connection of wind farms and gives a brief overview of power electronics (PE) which can be used to integrate wind farms to the AC grid so that the performance of the wind farms can meet the requirement of applicable grid codes.

AC connections are used for the large majority of wind farms, as it is a relatively simple way to connect, and for most applications provide the most economic solution.

Wind farms can be connected to the grid by overhead lines or cables. From offshore sites submarine cables are typically needed to reach land. Long distance overhead lines may be needed on land for the transportation of large scale wind power to the load centres. Cable sections may be needed also on the land, if planning consent cannot be obtained for the cheaper overhead line option for the complete route.

Whether power electronics is required or provide economic benefits depends strongly on the length of the lines, and on the strength of the ac network at the point of grid connection of the wind farm. Due to their different electrical parameters a cable is considered long if its length exceeds about 100 km whereas an overhead line is labelled “long” with a length of typically more than about 400 km.

Whilst an ac connection is often convenient and simple, it is necessary to ensure that issues such as ac voltage control, dynamic and transient stability limits, resonances and power quality have been adequately considered. Power electronic equipment may provide significant benefits for the interconnection of large scale wind farms, helping to overcome any of these issues.

Power electronic equipment can either be designed for shunt compensation i.e. connected between phases of the AC grid or for series compensation i.e. connection in series in the phases of the AC grid or a combination of shunt and series compensation. In this Brochure a brief overview is provided of the following types of power electronic equipment:

- Static Var Compensators (SVC)
- Static Synchronous Compensator (STATCOM)
- TCSC, SSSC and DVR
- Energy Storage Systems

For more information about the above equipment the reader is directed towards the references, which provide significantly more details.

4.2 OVERVIEW OF TRANSMISSION VIA AC LINKS

Overhead lines and cables have four parameters which are the conductor series resistance R and the series conductor inductance L, the shunt conductance and the shunt capacitance. These parameters influence the performance of the lines whether electric power is transmitted at ac or dc. The series resistance and the shunt conductance provide losses and heating at both ac and dc, whereas the series inductances consume reactive power at ac only, not at dc, and the shunt capacitance provides reactive power at ac only, not at dc. The capacitances of cables are much greater than for overhead lines because cable conductors are insulated with a dielectric capable of withstanding much higher stress than air, and therefore much close to the return path (the screen or return conductor) than is the case for an overhead line. For a general understanding of the influence of reactive power generated by the line capacitance a lossless T-equivalent of a line is considered, because it is a simple way to represent the line behaviour as seen from the line terminals.

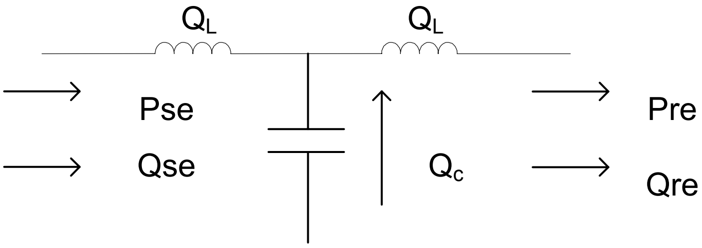


Figure 4-1 Lossless simplified T equivalent of a transmission line

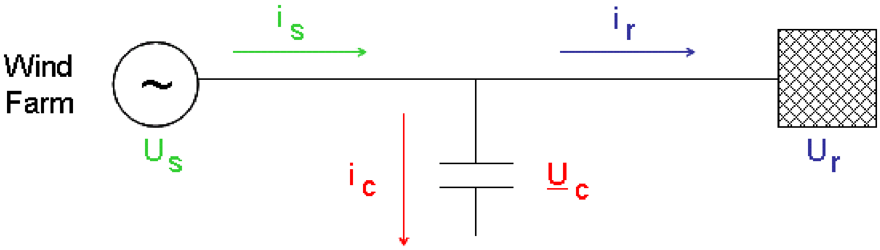
In Figure 4-1 Qc is the reactive power generated by the line capacitance and QL is the reactive power absorbed in the line inductance.

The reactive power generated by the line QC depends on the line voltage and the line capacitance QC = U2 / XC and may therefore be considered as a constant value at a give line length. The reactive line absorption QL depends on the current amplitude and the line series reactance QL = XL•I2 and depends therefore on the transmitted power. The resulting reactive power (QC – QL) is therefore dependent on the transmitted power. The reactive power generated by an overhead line is only significant a higher voltage levels and long lines, however for cables reactive power generation is 20 to 50 times higher than for an overhead line and may therefore be significant even for short cable lengths.

The overall values of the parameters of a transmission line are dependent on its length. Therefore a critical transmission distance could be reached due to the increase of these parameters. Under these conditions compensation equipment including power electronic devices could be applied to extend the transmission distance further.

4.2.1 The critical cable length

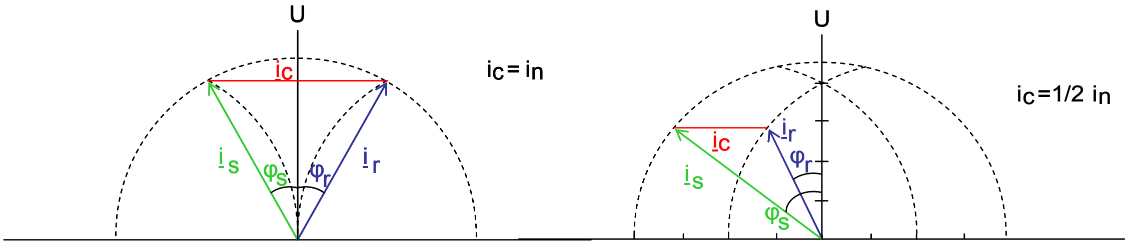
The large capacitances of ac cables results in a flow of a large magnitude of capacitive current (reactive power). This capacitive current flow creates a power loss. The longer the cable the larger capacitive cable current. The cable length at which the charging current is equal to the nominal current of the cable is designated the critical cable length lcritical. The total current in the ac cable is the vector sum of the load current and self generated capacitive current. When the resulting total current is equal to the cable current rating no more power can be transmitted on the cable.



Uc = Us = Ur Voltage phasors
Is = Ic = Ir Current phasors

Figure 4-2 Simplified equivalent. AC cable model with lumped cable capacitance

For simplicity the total cable capacitance are lumped together and represented by a large capacitor in the middle of the cable (Figure 4-2). The voltage drop in the cable is usually small therefore it can be assumed that the voltages in the sending end, in the receiving ends and the voltage at the lumped cable capacitor are equal i.e. Uc = Us = Ur. In addition the capacitive charging current IC in the cable is 90 ° ahead of the voltage UC which is depicted in Figure 4-3.



(a) (b)

Figure 4-3 (a) cable length equal to critical length (b) 1/2 critical cable length

If it is assumed that the cable length is equal to the critical length, then the charging current is equal to rated current of the cable, ic = in. For this case the voltage Uc and the current phasors ir,is and ic are shown in Figure 4-3 (a). The charging current Ic is 90 degree ahead of the cable voltage Uc. Phases angles φs and φr are the angles of the current Is in the sending end and of the current Ir in the receiving end. The maximum power that can be transferred is when the two angles are equal (i.e angles φs = φr = 30º because the length of the current phasors are equal, see Figure 4-3 (a).The maximum power that can be transmitted to the receiving end is 87 % (Uc•In •cos(30º)) of the nominal power.

Figure 4-3 (b) shows the situation at half the critical cable length where the cable charging current is equal to half the nominal cable current (Ic = ½ •In). In this case the maximum power that can be transferred is 97 % of the nominal power.

The maximum power transmitted to the receiving end is calculated by P = Ur• Ir•cos(φr). As can be seen in Figure 4-3 the phase angle at the receiving end goes from zero to 90°. Therefore the maximum power that can be transmitted on the cable decreases with increasing cable length. At a short cable length φr = 0º the full power can be transmitted on the cable and at two times the critical cable length φr = 90º (half of the charging current flows to each end of the cable) then no power can be transmitted on the cable. The cable transmission capacity describes a quarter-circle (or a quarter ellipses depending on the scaling of the axis) if the cable length is increased from zero to two times the cable length.

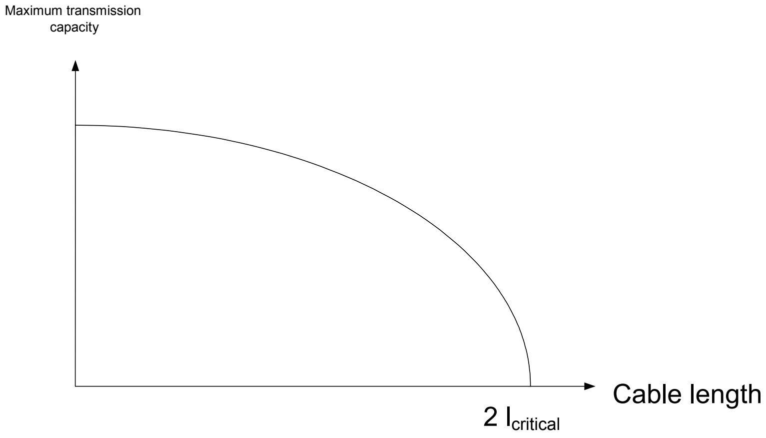


Figure 4-4 The transmission capacity of an ac cable as function of cable length

This is illustrated in Figure 4-4: it shows how the maximum possible transmitted power on an ac cable decreases with the increasing length of the cable. At a cable length twice the critical cable length no power can be transmitted unless reactive power compensation is provided along the cable line.

Data and diagrams for critical cable lengths can be obtained from the cable manufactures.

At the wind farm terminal or at the generators terminals, power converters or shunt reactors could be used to compensate the charging current of the cable.

For operational reasons, cable lengths longer than the critical are not desirable since the charging current creates additional cable losses and reduces the efficiency of the transmission. Therefore, it would be economical to provide intermediate compensation at shorter distances e.g. at half the critical length or less, where this is possible. This possibility may not be available for sub-marine cables.

The critical cable length depends on the cable capacitances, on the cable technology (oil filled cables have problems with pumping etc.) and the cable voltage. Cables with low capacitance per m (low εr) will have longer critical cable lengths than cables with high capacitance per m. The critical limit of the cable length decreases with increasing transmission voltage.

Reactive power compensation should be installed as close as possible to where it is consumed (generated). The compensation ratio for the cable should be optimised so that the power loss in the cable is minimised, and therefore the compensation ratio depends on the mean active power flow. If the reactive power compensation shall be installed only at one location along a cable line, the minimal power loss will be achieved by installing it in the middle (for an unloaded cable line). If there are two locations - it should be installed at both ends (ratio 0,5/0,5). If there are three locations the ratio of the compensation should be 0,25/0,5/0,25. If there are four locations it should be 0,165/0,33/0,33/0,165; etc.
Compensation of the cable has to be performed carefully in view of possible resonances between the capacitance of the AC cable, the grid impedance and the reactors used for reactive power compensation.

4.2.2 Voltage and reactive power control

When the voltage levels of the internal wind farm connections, the link and the grid are different, transformers are used to adapt the different voltage levels. Transformer tap-changers can be used to keep the steady-state voltage at the connection points within permitted limits. The tap changer control is typically co-ordinated with the voltage control provided by varying reactive power compensation e.g. by switchable shunt reactors/capacitors or SVC etc.

In general it is not desirable to transmit reactive power on transmission lines because reactive power flow causes active losses in the line resistances and voltage drop in the line reactance. In order to minimise flow of reactive power in the grid the reactive power should be provided as close as possible to the points in the grid where it is needed, for example at the terminal of loads, and at the point at which a wind farm is connected to the grid.

Line charging capacitive current flowing through the line series inductance results in a voltage rise. This phenomenon is called the Ferranti effect, and is most pronounced if the line is supplied from one side and the other side is left open. Since the cables have much larger shunt capacitance comparing to overhead lines, the Ferranti effect may be more pronounced. The voltage will be higher if the supplying grid is weaker because the capacitive current will cause additional voltage rise on the equivalent inductance of the system. Figure 4-5 shows a voltage rise in a cable line in relation to an overhead line and a cable line with 50% reactive power compensation installed in the midpoint.

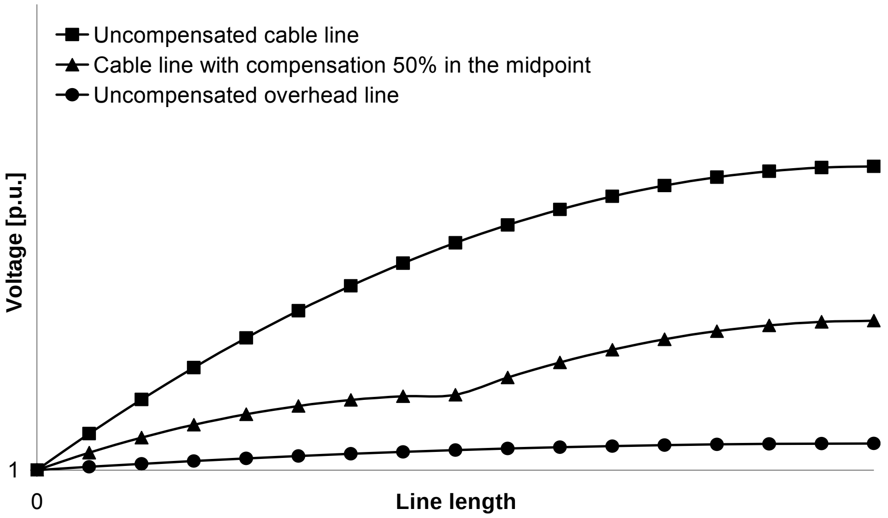


Figure 4-5 The voltage rise in open end transmission lines due to Ferranti effect

The steady state current through an AC link to a wind farm is determined by the capacitive current of the cable/overhead line and the active current generated by the wind turbines. The maximum active current is limited by the pitch control of the turbines.

Because the reactive power of the cable changes with the load current, part of the compensation may need to be variable, if the voltage changes resulting from changes in load flow are unacceptable. This can be accomplished with a Static Var Compensator (SVC) or similar equipment as described in section 4.5. Such equipment will under normal operating conditions keep the power factor of the wind farm at the grid connection point within limits prescribed by the Transmission System Operator (TSO). It should be mentioned that if the connection point is not too far away, then a Full Converter system or a Doubly-Fed Induction Generator (DFIG) system can compensate the variable reactive power of the cable.

4.2.3 Reactive shunt compensation by switched reactors or capacitors

Shunt reactors consume reactive power and can therefore be used to absorb reactive power generated by ac lines and cables. Typically, a shunt reactor will be designed to absorb 50 to 60 per cent of the reactive power generated by an idle ac line or ac cable. The ac line and ac cables are normally not fully compensated because their series reactances consume reactive power, and thereby make up for some of the reactive power generated by the line capacitances. The surge impedance load of ac lines and cables is the load when the reactive power generated by the shunt capacitances is fully absorbed in the series reactance.

If the loading of lines or cables varies considerably from very low to very high load, shunt connected Breaker Switched Reactors (BSR) may be used for the for control of the grid voltages. If the changes can be very rapid and frequent, dynamic reactive power compensation may be required in order to meet the power quality requirements.

Shunt capacitors generate reactive power and may be used to provide reactive power close to loads with high reactive power consumption, thereby providing voltage support.

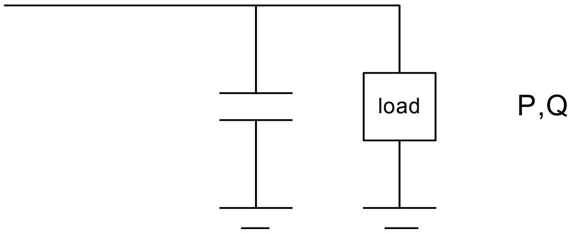


Figure 4-6 Compensation of reactive load with shunt capacitor.

Wind turbines with induction generators consume reactive power, which is why the reactive power to the induction generators is provided with capacitor at the generator terminals. The shunt capacitor may be switchable such that the capacitors can be switched in and out depending on the induction generators' need for reactive power.

4.2.4 Reactive series compensation

If loaded with reactive current long distance lines suffer from a significant voltage drop due to the conductor series inductance L. For long overhead lines it is state-of-the-art to apply series compensation (SC) to improve the voltage profile and to increase the stability of the transmission line. A simplified diagram of a controllable series capacitor compensation scheme is shown in Figure 4-7.

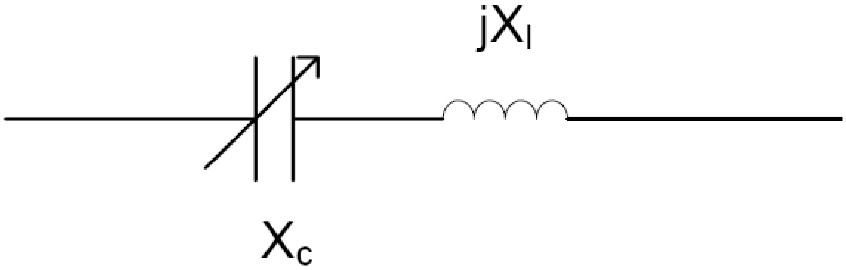


Figure 4-7 Series Compensation (SC) with variable series capacitors

A series compensation installation consists of series capacitors which may be installed at several substations in series with the transmission line. SCs are for example applied in the 10 GW transmission system in Quebec from James Bay to Montreal. The compensation degree is between 16 and 44 % of the series impedance of the lines [1][2]. When the compensation degree increases beyond 40%, consideration needs to be given to sub synchronous resonance risks in the network, as serious damage could be caused to generators if suitable counter measures are not taken. One counter measure may be to make the series capacitance variable, by the provision of power electronics, in which case the controls can be designed to dampen sub synchronous oscillations in the ac network at frequencies that may be critical to nearby generators.

4.3 BENEFITS ARISING FROM THE USE OF POWER ELECTRONICS

A variety of power electronic equipment for application in transmission and distribution systems has been developed over the last few decades. The incentive has been the need for better utilisation of the existing transmission lines, improved system dynamics and better voltage control.

It may be expected that the needs for power electronic equipment for continuous ac voltage control in ac grids will increase in the future as the use of distributed generation and wind power replaces conventional synchronous generator based power stations, which today perform the primary voltage control [8].

As explained in Chapter 2, primary voltage controls is performed by automatic voltage controllers (AVR) on synchronous generators at central power plants. At weak points in grids where continuous voltage control has been needed, dynamic voltage control has been obtained by installation of synchronous compensators, SVCs or STATCOMs. Today, new applications of synchronous compensators for ac system control have been very few, since often the requirements can be met using Static Var Compensators (SVC) or STACOMs.

The next sections of this Chapter describe how these devices can facilitate the integration of large wind farms in a transmission network.

4.4 WIND FARM CONNECTIONS COMPENSATED USING A SVC

4.4.1 Brief overview of SVCs

Over the last three decades, utilization of large pulsed type loads such as arc furnaces, welding equipment, rolling mills has increased with the growing need of steel. The increasing number and size of those fluctuating loads caused power quality problems such as flicker, harmonics and unbalance. Static Var Compensators have been used in the factories to reduce flicker and unbalance. Some 900 SVC applications are running to date around the world [9].

An SVC comprises a combination of shunt connected Thyristor Controlled Reactor(s) (TCR), filters and in some cases Thyristor Switched Capacitors (TSC) or Breaker Switched Capacitors (BSC). The technology, based on TCR is mature. Its exploitation to improve reactive compensation and grid voltage control for a wind farm is shown in Figure 4-8.

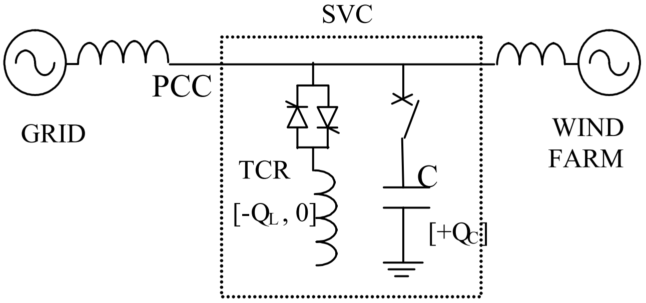


Figure 4-8 SVC at connection point between grid and wind farm

The TCR consists of a shunt reactor in series with a thyristor controller with two thyristor switches in anti-parallel. Each of the two parallel thyristor switches conduct for a period of up to one half period of the reactor current. By controlling the trigger instant of the thyristor switch, the reactor current, and thereby the reactive power absorbed from the ac grid, can be controlled continuously between zero and rated power.

In Figure 4-8 a SVC has been inserted between the grid and a wind farm, which can be seen from the grid as a fluctuating user. The SVC has a TCR and a Fixed Capacitor (C). The supply of reactive power to the ac grid is smoothly controlled by the TCR. By control of the thyristor the TCR provides a variable inductance capable of continuously absorbing an amount of reactive power from zero to QL. Filters extend the control range of the SVC into the capacitive range, but reduce the inductive range.

In the simplest design, the star-connected 3-phase capacitor bank produces a fixed amount of reactive power : +QC. Since the TCR generates harmonics which require filtering in order to provide a proper voltage quality, the capacitor bank is typically implemented as a harmonic filter. The capacitor bank may be split into many branches, in order to provide appropriate filtering and at the same time avoid harmonic resonances between the SVC and the ac network.

Depending on the need for reactive power for the wind farm and/or the ac network, the TCR adjusts automatically its absorption, thereby performing reactive power control or voltage control at the connection point. The TCR is often connected in Delta in order to eliminate 3rd harmonics.

In a variant of the SVC, the capacitor bank may be split into 4 steps that can be switched in or out as the need for capacitive support varies. Switching may be either by breakers, if high speed is not necessary, of by thyristor switches, if instant response is required. The advantage of the subdivision of the capacitor bank is that the size of the TCR can be smaller, and or the power loss of the SVC can be reduced.

The control of an SVC can be designed to provide fast reactive power support and voltage control. This feature can be very important in case of network disturbances. However, the drawback of an SVC is that its supply of reactive power varies with the square of the ac grid voltage. Therefore, at low ac grid voltages, the SVC suffers from lack of reactive power, which is a situation where voltage and reactive support is most needed.

Figure 4-9 shows a SVC installed in Australia for the support of a relatively large wind farm.

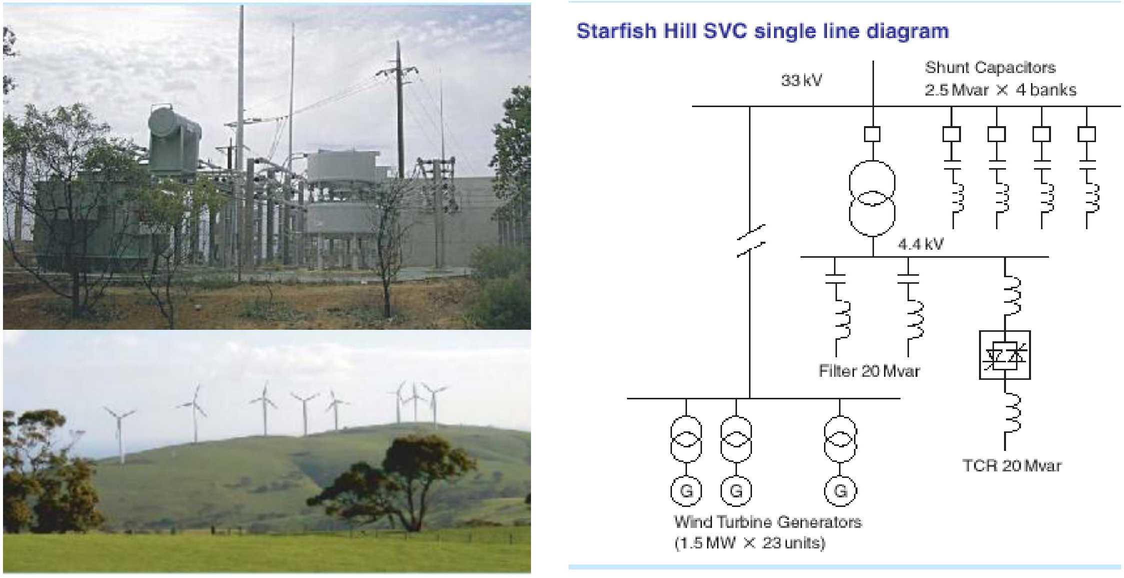


Figure 4-9 SVC in the Starfish Hill / Australia wind farm

The limits of SVCs are related to the inherent time delay of the TCR, the dynamic interactions between the LC filter of the SVC and the TCR, and the SVC inability to compensate active power fluctuations.

4.4.2 Benefits of a SVC for a large AC connected wind farm

Wind farms equipped with variable speed machines associated with full or partial converters can have a built-in VAR management, however, all wind farms using fixed wind speed turbines require separate VAR management. Moreover, traditional VAR management by capacitor banks may have a negative impact in the context of wind generation because frequent starting and stopping will often provoke voltage step changes. Employing dynamic var devices, alone or in combination with switched capacitor banks, eliminates the negative consequences of the traditional solution. Both the wind farm developer/owner and the utility benefit from this approach.

From the wind farm viewpoint:

- The wind farm remains connected thanks to mitigation of voltage transients coming from the grid. So grid connection requirements are met, power output and revenues are also maximized.
- Capacitor-bank switching events are minimized, and step-voltage changes that they cause are eliminated.

From the utility viewpoint:

- Voltage variations due to uncompensated wind farm operation as well as large reactive power demands are cancelled.
- To control the voltage at the connection point, there is no more a need to install breaker switched capacitor banks on the transmission system.

Given the continuing growth of wind power generation, the need for maintaining system reliability and security remains an ongoing concern. Upon appearance of a system fault especially near a wind generator, the rotating machine speeds up and its slip increases. In order not to loose stability of the system, many grid codes require that the generators remain in operation and continue to supply power after clearance of the fault.

Rapid reactive power control during and after a system fault provides a means of restoring the generator slip to its normal value, and thereby prevents the wind generator from tripping. Therefore, after the fault is cleared, the generators remain connected and are ready to supply power to the system.

By providing reactive power control and support for the ac network voltage, an SVC can increase the fault ride through capability of a wind farm. The ability of the SVC to provide continued reactive power control both during the and also after the fault period can be of great benefit to the ac network. For example, power system swings may result in the rise and fall of the system voltage and the SVC can be designed to dampen such swings, subject to the limitations of its rating.

When long radial ac connections are necessary from a wind farm to the grid or the load centre, then a SVC may provide stabilisation of the voltage on the line, and can be used to extend the distance over which the power can be transmitted.

During normal system conditions the SVC can also provide reactive power ancillary services to the ac network, no matter the operation status of the wind farm. This means that the converter ratings within the wind farm (if any) can be minimised, to only consider the need for active power transfer.

Reactive compensation devices, such as the SVC can also help to suppress voltage fluctuations due to generator starting and stopping action, or changes in wind velocity, and can therefore remove voltage quality issues, e.g. flicker.

4.5 WIND FARM CONNECTIONS COMPENSATED USING A STATCOM

4.5.1 Brief overview of STATCOM

A static synchronous compensator (STATCOM) [9] and its distribution system variant, the D-STATCOM are Voltage Sourced Converters (VSC) used solely for reactive power absorption or generation.
Figure 4-10 shows a STATCOM at the wind farm LV connection point to the transmission grid.

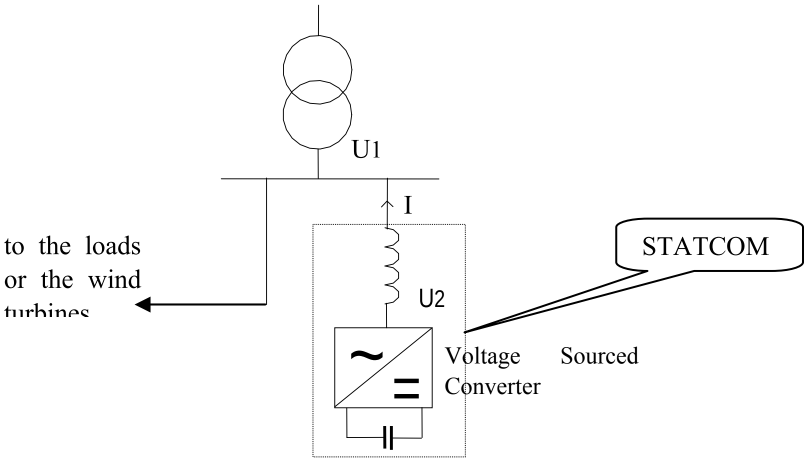


Figure 4-10 Connection of a STATCOM at the grid connection of a wind farm

Unlike thyristor based solutions (TSC and SVC), VSC power electronic systems are based on IGBT (Insulated Gate Bipolar Transistor) or GTO (Gate Turn Off Thyristor) technology, which intrinsically enables a faster response than thyristors. The VSC uses the semi-conductors to switch a dc capacitor to the three ac terminals at high speed, such that a sinusoidal fundamental frequency voltage (after filtering) appears to the ac network behind a large reactor (the converter reactor). By controlling the phase angle between the converter ac voltage source and the network emf the active power flow is limited to that which is required to keep the dc capacitor voltage to a desired value. By controlling the amplitude of the converter ac voltage relative to the network emf, the flow of reactive power from the converter can be controlled. The reactive power flow is determined by the difference between the two voltages and the impedance between the two. The converter is connected to the ac network through a large converter reactor, which together with the stepdown transformer, if any, to a large extent determines the impedance between the converter voltage source and the network emf.

The STATCOM can operate within its current range from full capacitive to full reactive current from the normal voltage range and down to a low value of typically 10- 20% of rated voltage. Capacitive current is achieved when the converter ac voltage source is greater than the network emf. The reactive power varies proportionally to the ac grid voltage. If reactive power support to the network is important at very low ac voltage, a STATCOM may require significantly lower rating than an SVC for the same performance.

Continuous progress in the STATCOM technology industry now makes it possible to build and operate high power STATCOM (in excess of ±100 Mvar), with a very good dynamic response, i.e. time constants in the millisecond range [10].

The STATCOM can be combined with breaker switched capacitors or reactors, or a TSC. Among the available products, the one referenced in [11] can be mentioned: it consists in a small STATCOM that sends orders to adjacent switched capacitor banks. This coordinated operation of the STATCOM and the switched capacitor banks allows a wider range of continuous supply and/or absorption of reactive power.

The STATCOM tends to occupy significantly less space than an equivalently rated SVC, since it does not require as large ac harmonic filters.

4.5.2 Benefits of a STATCOM for a large AC connected wind farm

The benefits obtained by using a STATCOM at the grid connection of a wind farm include all those mentioned above for the SVC, plus the following:

- As the STATCOM appears to the network as a voltage source it is capable of injecting current into a fault in the network. This can be beneficial for the protection system.
- Because of the larger reactive power support capability at low ac voltage, when compared with a SVC, a STATCOM with a lower rating is typically able to provide at least equivalent performance to that of a SVC.
- The STATCOM can help mitigating the flicker due to variations of reactive power absorbed by induction machine-based wind farms. Due to its faster response, when compared with a SVC, the STACOM provides a more powerful reduction of flicker. The reactive power required by the farm is evaluated and a controller drives the STATCOM inverter so as to generate the adequate quantity, making it possible to reduce drastically the reactive power flows towards the grid and therefore, the associated flicker.

In recent years an increasing number of STATCOMs have been used in conjunction with wind farms, probably because their superior technical characteristics make them overall competitive with SVCs. Some of these examples are described in Chapter 6. Figure 4-11 shows an example of an application in Denmark.

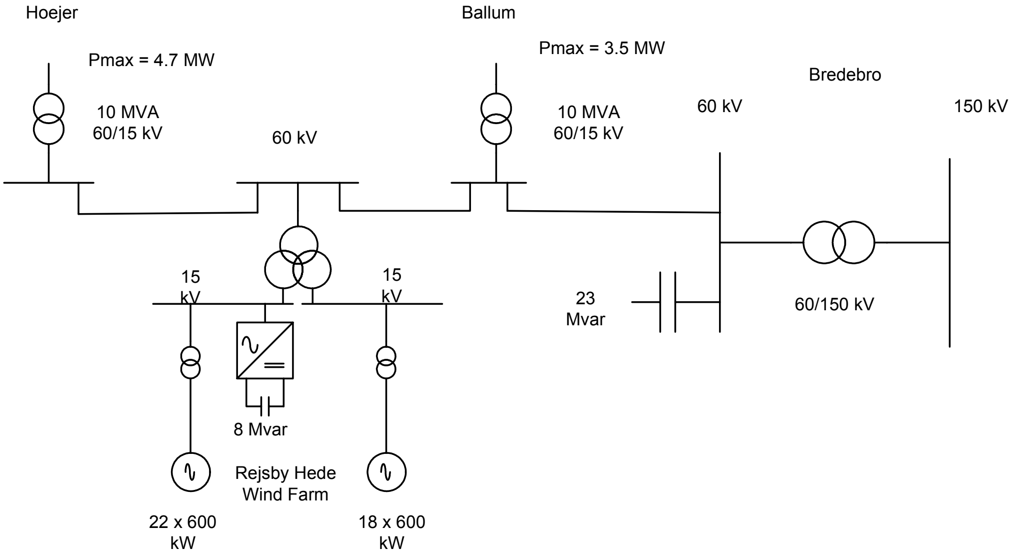


Figure 4-11 An 8 Mvar STATCOM at the Rejsby Hede wind farm (24 MW)

Figure 4-11 depicts the single line diagram for the connections of an 8 Mvar STATCOM in the Rejsby Hede [12] wind farm in Western Denmark. The capacity of the wind farm is 24 MW consisting of 40 wind turbines with induction generators with double stator windings. The rating of each induction generator is 150 kW (low wind) /600 kW (high wind) and they are compensated with 3 times 50 kvar capacitors corresponding to 68 percent of the no load consumption. The STATCOM makes up for the reactive power consumption at full load and maintain the power Factor at unity. When the wind farm production is higher than the local load in Højer and Ballum (maximum 8.2 MW) the power is fed into the 150 kV grid in Bredebro. The STATCOM consists of two 4 Mvar three levels converters with GTO-thyristor valves in a 12 pulse configuration. This ensures that the total harmonic distortion (THD) is kept below 2.5 percent as required, without the need for additional AC filters.

4.6 OTHER FACTS DEVICES

Other power electronic equipment for application in power transmission and distribution systems have emerged over the years, and are generally aimed at increasing the flexibility with which a power network can be operated and/or at increasing the power quality within parts of the network. At the time of completing this Brochure none of these equipments had been applied with the explicit objective of benefiting the integration of a wind farm. However, for completeness a brief description of the available equipment is included in this section. The equipment includes:

- Thyristor Controlled Series Capacitor (TCSC)
- Dynamic Voltage Restorer (DVR)
- Unified Power Flow Controller (UPFC)
- Static Synchronous Series Compensator (SSSC)
- Convertible Static Compensator (CSC)

As mentioned above series capacitors can be inserted in long transmission lines in order to decrease their series impedance, enabling higher power transfers. However, when the level of compensation increases above 40%, a risk of sub-synchronous resonance may arise within the network. The adverse effect of such a resonance can be avoided by making part of the series compensation controllable. This is achieved by bypassing part of the series capacitor with a thyristor controlled reactor, the reactor being controlled such as to stabilise the power flow through the line, damping out sub-synchronous oscillations. This equipment is referred to as a TCSC, and may find applications where long ac overhead lines are required between a wind farm and the grid connection.

The DVR [13] is a power converter with energy storage. The DVR is connected in series with the power supply feeder to a sensitive load, typically an industrial process such as a semiconductor fabrication facility or a paper mill. The purpose of DVR is to protect the sensitive process against voltage sags in the network, caused by faults and switching operations. It does this by injecting active and reactive power on the load side of a blocking impedance. In principle the DVR could be used to facilitate fault ride through of wind generators, which have been designed without the fault ride through capability which is now demanded by most grid codes.

The UPFC [14] is a grid controller composed of a converter connected in series with the line and a converter connected as a shunt to the line. The UPFC is for application in meshed power transmission grids, and its primary function is active and reactive power control. The converter connected in series with the line performs active power flow control, and the converter connected as a shunt to the ac line performs reactive power and voltage control. The UPFC can also be designed for improvement of transient stability, power swing damping and for voltage stability.

The SSSC uses a voltage sourced converter to create an ac voltage that is inserted in series with a transmission line, in order to control the power flow on the line. The SSSC can be used in conjunction with a conventional series capacitor installation, to extend the level of series compensation of the line. The SSSC can be controlled such that it suppresses sub-synchronous resonances caused by the series capacitance.

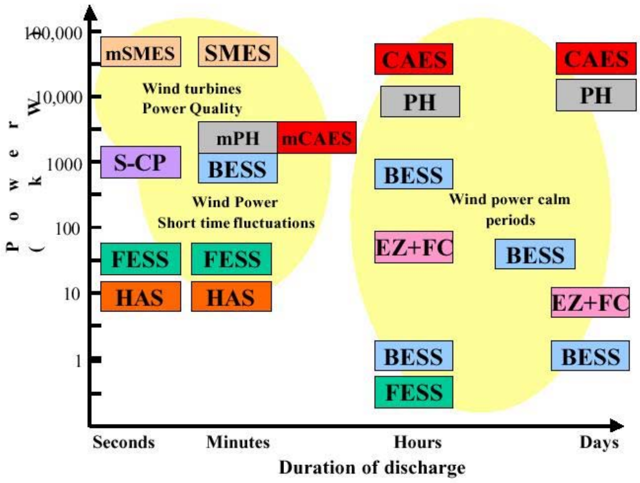
The CSC uses the components of a UPFC, but is designed such that the two voltage sourced converters can be reconfigured such that they can act as either a UPFC (i.e. one converter in shunt and one in series), a pure STATCOM (with both converters shunt connected to one or two lines) or a pure SSSC (with both converters series connected in series with one or two lines).

4.7 WIND FARM CONNECTIONS USING ENERGY STORAGE

One of the problems with a large penetration of wind generation in a network is the uncertainty of the amount of generation that will be available at any specific time [15], particularly if high wind is expected. In an ideal world it would be possible to store part or all of the energy produced from the wind farm, such that it could be fed back to the network when needed. Therefore, the availability of plentiful, efficient and cheap energy storage would be of great value for a network with high penetration of wind generation. This is utilised in some system with flexible hydro storage where water flows can be aligned to compensate for variations in the output of wind generation and allowing to achieve higher penetration levels of wind generation. However there are not many systems where such storage is available. More research, development and design work is still necessary in order to achieve the characteristics of efficient and low cost energy storage, which is an essential precursor to its availability as a plentiful resource.

4.7.1 Brief overview of Energy Storage

There are numerous types of energy storage systems [16] based on different technologies and for various time scales. Available energy storage systems range from short term (seconds to minutes) to long term (hours and days) storage, as shown in Figure 4-12.



LEGEND
m – prefix used to indicate small scale
BESS = batteries
CAES = compressed air energy storage
EZ+FC = hydrogen and fuel cells
FESS = flywheels energy storage system
HAS = hydraulic accumulator system
PH = pumped Hydro
S-CP = supercapacitor
SMES = superconducting magnetic energy

Figure 4-12 Energy storage systems

Energy storage using pumped storage has been used for decades. Systems for pumped hydro storage can be found in many countries and compressed air energy storage (CAES) has been in operation in the Germany (Huntorf, 1978) and USA (McIntosh Alabama, 1991). The installation of both of these storage technologies depends on suitable geology formations. Their efficiency is about 70%.

A large number of different types of battery technologies with different characteristics are available today. The largest electricity storage based on nickel cadmium batteries (40 MW in 15 minutes) is the Golden Valley Electrical Association (GVEA) installation in Alaska. Installations using flow type batteries with large tanks for the electrolyte to create long term storage have been developed, but large scale application of these systems has not yet taken place. This storage technology has been successfully implemented in Castle Valley (250kW, 1000kWh), Utah on small scale to manage peak flows in distribution feeder. Other installations are in Japan and Australia. The overall efficiency of the charge/discharge cycle is about 65%. The technology offers fast response and good short term overload capability (50 to 100% for 60 seconds) and quick recovery to support next the next overload cycle (also 60 seconds) making it suitable to manage wind intermittency. However the technology is limited to about 5MW output and to be economically viable and to provide increased ratings requires a more cost-effective battery technology with higher energy density.

In principle, the DC/AC inverter required to interface a battery storage system with a network, is based on the same concept as a STATCOM with the only difference that in the latter the DC-side comprises a low energy capacitor instead of a battery. A STATCOM complemented with sufficient electricity storage can provide load levelling, frequency control, system damping, improvement of transient stability, fault ride through, black network start, etc.

4.7.2 Benefits of Energy Storage for a large AC connected wind farm

Depending on the technology and on the rating of the energy storage systems, they can:

- improve power quality,
- smooth the voltage and power variations due to wind turbulences,
- smooth power variations in a time scale of minutes, hours or even days,
- solve steady state current constraints in the interconnection,
- participate in voltage and frequency control of the ac network,
- help wind farms to withstand voltage dips,
- guarantee the active power supply to the network.
- enable generation to be shifted from low spot price periods to high spot price periods,
- be used to manage transmission constraints and to minimise energy spill.

4.8 CONCLUSIONS

Wind generators with power electronics converters (DFIG and full converter solutions) provide a number of benefits including:

- An ability to control the voltage and reactive power at their terminals,
- An ability to smooth active power variations and the resulting voltage variations by modifying the rotor kinetic energy.
- They can be designed to povide a limited short circuit current contribution to the ac network.
- The modern designs provide Fault Ride Through capability.

These characteristics may in some cases be sufficient for the successful and satisfactory integration of large scale wind farms in an ac network.

However, if the network connection is at a very weak point, or if a long distance interconnection is required, the application of a separate SVC or STATCOM may provide the most effective and economic solution to specific integration issues.

For wind farms based on induction generators a SVC or STATCOM may be required in order to achieve satisfactory fault ride through performance, as well as for the stabilisation of the ac voltage and the avoidance of power quality problems.

Energy storage solutions are already commercially available, and could significantly improve the technical performance of a network with a high penetration of wind generation. However, with the present status of the energy storage technology the cost of storage systems is too high and their efficiency too poor to make them appropriate for anything but special cases. It is hoped that the continuing R&D efforts in this area will result in future generations of energy storage systems being able to support increased penetration of wind generation, in an economic manner.

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5. HVDC CONNECTION OF WIND FARMS

This chapter gives a brief overview of HVDC systems which can be used to integrate wind farms to the ac grid. An HVDC scheme can be designed so that the performance of the wind farm meets the requirement of the applicable grid codes. An HVDC scheme may be the most economic option for connection to the ac grid, e.g. if a long submarine cable or a very long overhead line is necessary between the wind farm and the grid connection point. Indeed for very long submarine options and for connection between asynchronous networks, HVDC provide the only technical solution for the interconnection.

Only the most basic characteristics of HVDC suitable for wind power integration in grids are described in this Chapter. For a more comprehensive description the reader is referred to the references listed at the end of this Chapter.

The following AC/DC transmission (HVDC) systems are considered:
- HVDC transmission using Line Commutated Converters (LCC-HVDC)
- HVDC transmission using Voltage Sourced Converters (VSC-transmission)
- Multi terminal HVDC transmission
- HVDC and AC transmission lines in parallel.

5.1 BRIEF OVERVIEW AND BENEFITS OF GENERAL HVDC SYSTEMS

There are three main reasons for using HVDC transmission instead of AC transmission:
- **Economy**: HVDC overhead lines are cheaper to build than AC overhead lines for the same transmission capacity. However, HVDC stations are significant more expensive than a corresponding AC substation. Therefore, there is a breakeven distance beyond which HVDC transmission is more economical than AC transmission. Similarly HVDC cables comprising only one high voltage conductor and one low voltage return conductor or alternative sea/earth electrodes are cheaper than AC cables (one three phase or three single phase cables). The break even distance depends on the rating, as well as on local circumstances including ground conditions and market forces. For HVDC overhead lines the break even distance is typically quoted as 500 to 1000km, whilst for cables the break even distance is much less, and is typically quoted as 50 to 125km. In the case of DC transmission, there is no reactive power flow so the submarine cables are not de-rated by AC charging current. High voltage AC cables have a high shunt capacitance in comparison to overhead lines. As the length of the cable increases, so does the capacitance of the cable and the charging current. The capacitive charging current increases the overall current flow through the cable and thus increases the power loss and reduces the power transfer capability of the cable due to the thermal limitation. Shunt inductors at either end of the cable relieve the problem up to a certain limit, but they get more spacious and costly with larger connection distance and power. For long distance power transmission the power loss may also be lower when using HVDC than ac transmission, because the line loss is lower.
- **Technical**: There are two technical main reasons that dictate the usage of HVDC. The first reason is that two power systems which are not synchronised can only be interconnected by HVDC. The second reason is that AC cable transmission beyond the critical cable distance is not feasible without compensation. In the case of a submarine cable compensation along the route is not practical, whereas HVDC does not have a critical cable length, thus providing an effective solution.
- **Environment**: The visual impact of HVDC overhead lines are less than for an AC overhead line for the same transmission capacity. If the society only accepts cable transmission for new lines, then for distances beyond the breakeven distance HVDC cable transmission is more economical. It is typically also possible to transmit more power by HVDC than AC in a given transmission corridor.

HVDC schemes provide a number of benefits to the ac networks to which they are connected. These can be summarised as follows:

- The interconnection by HVDC is asynchronous, such that the two networks can be operated independently of each other.
- The power flow is fully controllable. This feature can be used to provide swing damping for one or even both network areas, subject to the consequences of the change in power flow being acceptable at the other terminal. This feature can also be used to benefit the power flow in the ac network, maximising the power capability of ac lines that may be in parallel with the HVDC line.
- Faults and ac voltage dips are not transferred through an HVDC link. This feature was one of the main reasons why the 2003 black out in NE America did not spread into Quebec.

Two types of HVDC transmission are available, (i) LCC HVDC using line commutated converters and (ii) VSC Transmission using Voltage Sourced Converters. These will be reviewed in the following sections.

5.2 OVERVIEW OF LCC HVDC

LCC HVDC was introduced in the market in 1954 and is a fully matured technology, with many years of experiences gained from about 70 installations world wide, including HVDC overhead lines and submarine cables. The total rating of LCC HVDC schemes in service at the time of writing of this Brochure is in excess of 70GW.

5.2.1 Basic equipment for a LCC HVDC station

Figure 5-1 shows a typical land based 600MW HVDC converter station connected to a 400kV ac overhead line. Several books have been written describing HVDC schemes, which should be consulted for further detailed information [1].

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Figure 5-1 Layout of a 600 MW LCC HVDC monopolar onshore station

The basic equipment in an LCC HVDC converter substation comprises the following:

- Line commutated converter
- Converter transformer
- AC filters and Reactive power compensation
- DC smoothing reactors
- DC filters
- Control & Telecommunication.

5.2.1.1 Line Commutated Converters (LCC)

The ac/dc converters for LCC HVDC use thyristors, which are capable of conducting current in one direction only (the forward direction), and which are triggered into action by a gate signal. When they have been triggered, they will conduct current provided that the external circuit drives the current in the forward direction. When the current tries to reverse direction the thyristor will turn off, and will then withstand voltage until it is triggered again. Thus the converter relies on the external voltage in the ac network for its proper operation. Another main characteristic is that LCC converters always consume reactive power both in rectifier operation (conversion from ac to dc) and in inverter operation (conversion from dc to ac).

The basic building block of the LCC is a six-pulse thyristor bridge (three phase Graetz bridge) which provides six pulses on the dc side. By connecting one six-pulse converter to a YY converter transformer and another six-pulse converter to an YD converter transformer, the two converters can be connected in series on the dc side and in parallel on the ac side so that a 12-pulse LCC is obtained which has a better harmonic performance requiring less filtering than a six pulse converter. Nevertheless, AC filters are required to limit the impact of harmonics on the AC network. The 12 pulse LCC is the standard configuration for modern LCC HVDC schemes.

The reactive power of each converter typically reaches about half of the transmitted active power. The AC filters provided for harmonic filtering provide reactive power, which offset the reactive power demand of the converters.

Commutation failure may occur in a LCC HVDC link due to AC grid voltage disturbances caused by faults in the AC grid. Commutation failure is when the current fails to commute from one thyristor valve to the next valve in an LCC HVDC converter. Commutation failures occur only in LCC HVDC converter when it is operated as inverter (conversion of power from the dc to ac side). LCC HVDC converters are usually designed to operate without commutations failures at temporary AC voltage disturbance down to about 85% of the rated AC voltage.

5.2.1.2 **Converter transformer**

The converter transformers interconnect the ac grid and the thyristor bridges. The converter transformers for LCC application are of a special design, in order to cope with the mixture of ac and dc voltage stresses which occur across the internal and external insulation. The transformer also has to be designed for high levels of harmonics. The converter transformers are provided with tap changers which are controlled by the converter control in order to obtain optimal control of the HVDC link.

5.2.1.3 **Reactive power compensation**

Whether the LCC operates as a rectifier or as inverter, the thyristor bridge will always consume reactive power due to phase displacement between current and voltage. The reactive power consumed by the LCC may be compensated by ac harmonic filters, separate shunt capacitors and in weak ac grids by SVC, STATCOM or synchronous compensators. Reactive power compensation can also be achieved by the use of series capacitors between the converter transformer and the thyristor bridge, and this technology is known as Capacitor Coupled Converters (CCC).

5.2.1.4 **AC filters**

The LCC converters generate harmonics on the ac side, which must be filtered in order to provide acceptable power quality. The ac filter capacitors also contribute to the reactive power and voltage support in the ac grid.

Large AC filters banks in weak AC systems tend to lower the eigen value frequency of the AC system which could contribute to a resonance at the second harmonic. Therefore the AC filters have to be designed carefully to avoid critical grid resonance conditions.

5.2.1.5 **DC smoothing reactor**

The LCC also generates harmonics on the dc side and in order to reduce the ripple in the dc current smoothing reactors are installed in series with the dc line.

5.2.1.6 **DC filters**

In order to prevent telephone interference in nearby open wire communication circuits, which may be caused by harmonics on the dc line, dc harmonic filters line may be provided at the converter station. The filters may be passive LCR circuits or active dc filters.

5.2.1.7 **LCC control and telecommunication**

The dc power transmission is varied by controlling the trigger instant of the LCC thyristor valves and thereby the dc voltages at the sending end and at the receiving end of the dc line. If the dc voltage at the receiving end of the dc line is kept constant, the dc current is indirectly controlled by controlling the dc voltage at the sending end.

The control can be divided into various functions such as valve firing control, converter control, pole control, converter transformer tap changer control and reactive power control. The controls can be arranged to provide ancillary services, such as damping of oscillations in the ac network. The controls may also contain various protection functions. The LCC controls at the sending and the receiving ends are coordinated via telecommunication.

5.2.1.8 Operational characteristics of LCC HVDC

Satisfactory operation of a line commutated converter (LCC) requires a sufficient short-circuit ratio (SCR) in the ac grid. The SCR [2] is the ratio between the short-circuit power at the connection point in the ac grid in relation to the rated power of the LCC HVDC link. If the SCR is too low, the LCC may suffer ac voltage instability or commutation failures – typically the SCR is kept higher than 2.5[3]. The short circuit level at the point of connection can be increased by the use of synchronous compensators or the voltage stability improved by SVCs or STATCOMs [4].

In the event of a short circuit in the ac network close to the inverter, the LCC HVDC scheme does not provide any fault current contribution. This may be of benefit in strong ac networks. However, when connected to a very weak ac network this may be a problem, because conventional protection systems rely on a certain fault current level for their correct operation. If synchronous compensators are used to increase the short circuit ratio, these will contribute to the short circuit fault in the event of a network fault. In addition synchronous compensators will increase the rotational inertia in the power system, which is not the case for SVCs or STATCOMs.

The dc current direction for an LCC is always the same, because the thyristor valves can conduct current only in one direction. Reversal of the power is therefore obtained by changing the dc voltage polarity.

The LCC in both ends consume reactive power of 50-60 % of the transmitted dc power[1].

A LCC HVDC cannot typically operate at a power level of less than 5 to 10% of its rated power. This is because the harmonic current on the dc side can then exceed the direct current level, resulting in the thyristor valves turning off prematurely.

5.2.1.9 DC cables

At power reversal the voltages on the dc cable change polarity. The change of polarity results in higher dielectric stresses internally in the cable immediately after the reversal, when compared with the normal operating stress. The HVDC cables have to be tested specially to demonstrate that they are capable of withstanding these stresses. For LCC HVDC transmission mass impregnated dc cables are normally used, since the XLPE cables currently available are not suitable for application in schemes where polarity reversal of the direct voltage occurs. Mass impregnated HVDC cables with voltage and current capability up to 500 kV dc and 1500 A d.c have been designed [5].

5.2.1.10 Power Losses

The ac/dc conversion in the LCC HVDC converter station results in a power loss which is typically 0.8% (per end) of the transmitted power. The power loss in the dc line depends on the d.c current and the conductor cross-section, which should be optimised to provide the most economical cross section, i.e. to trade off between power loss capitalisation and cable capital cost.

5.2.2 LCC HVDC systems

5.2.2.1 **Power rating**

The power of HVDC systems in service at the time of writing are in the range from about 150 MW (as monopolar system at 180 kV DC voltage) to 3000 MW (as bipolar system at 500kV DC voltage). UHV DC transmission using overhead lines with ±800 kVdc and up to 6000 MW transmission capacity (bipole) is being developed for bulk power transmission. Higher power transfers can be achieved by using more HVDC bipoles in parallel

LCC HVDC may be designed for different modes of operation. :

- Monopolar system with earth/sea return
- Monopolar system with metallic return
- Bipolar system

Figure 5-2 shows some typical system configurations. The top left configuration is a monopolar system with earth/sea return. The bottom left configuration is a monopolar system with return. The configuration on the right is a bipolar system. These systems are described further below.

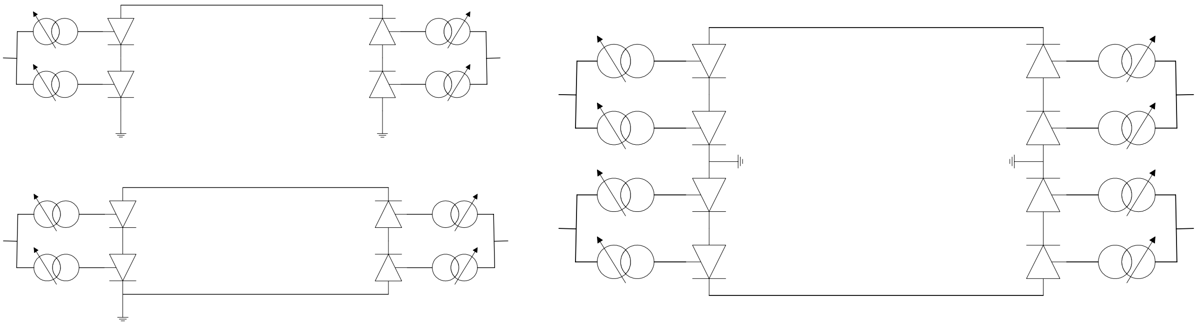

Figure 5-2 HVDC System configurations

5.2.2.2 **Monopolar systems with sea/earth return**

Originally all LCC HVDC cable transmission schemes were designed to operate in monopolar operation. In this operation mode the return current passed between the converter station via earth and sea using earth or sea electrodes. This operating mode is simple and efficient, since the power loss in the earth return is much lower than that in a cable. In recent years environmental lobbying has made it difficult and in some countries impossible to obtain permission for the construction of schemes using earth or sea return.

5.2.2.3 **Monopolar systems with metallic return**

Because of environmental pressures many recent LCC cable projects with only one converter pole have been designed and built using an additional low voltage cable providing metallic return, thus avoiding any possible influence on the environment including uncontrolled corrosion of metallic structures in the ground.

5.2.2.4 **Bipolar system**

The bipolar system consists of two independent poles, and is often considered equivalent to a double circuit ac line. If continuous operation with earth return is allowed only 50% of the transmission capacity is lost for a converter or cable failure, with the healthy pole remaining in operation in monopolar configuration. If earth return is unacceptable, the HVDC system has to be completely shut down in the event of a cable failure, unless an additional low voltage cable is connected between the midpoints of the converter stations at the two ends. In the event of a converter failure, the scheme can continue in operation using the other HVDC cable as a metallic return, provided that appropriate dc switchgear has been provided to allow such reconfiguration.

5.2.3 (Offshore) Wind Farm Connections Using LCC HVDC

At the time of writing LCC HVDC stations has only been built as onshore installations. A typical layout of an LCC HVDC station is shown in Figure 5-1, and it is clear that the space requirement for a LCC HVDC substation is significant. The space for the AC filters alone exceeds the space needed for the converter equipment. Considerable areas are also required for the AC- and DC switchyard including the DC smoothing reactor.

To construct a platform or artificial island for a LCC HVDC Converter station for an offshore wind farm will be very costly, therefore there is significant incentive for designing it for minimum footprint and space. Therefore, Gas Insulated Substations, cabling between components, the use of a low ac connection voltage and the use of oil paper insulated reactors for filters and smoothing is likely to be attractive. An additional problem for an offshore or islanded application is that synchronous condenser or a STATCOM may be need to enable satisfactory operation, particularly as there will be times when power has to be transmitted to the wind farm to meet its auxiliary power requirements, e.g. when the wind speed is below the cut in speed. Local backup power generation for auxiliary power supply may also be required, resulting in additional space and weight on an offshore plat form.

Until today an offshore LCC HVDC stations has not been built, but by designing for minimum space a relatively compact design of 130 m x 50 m x 35 m (L x W x H) may be achievable for a capacity of 600 MW.

5.3 WIND FARM CONNECTIONS USING VSC TRANSMISSION

5.3.1 Brief overview of VSC Transmission

The basic equipment in a VSC converter substation comprises the following:

- Voltage Sourced Converter
- AC Filters, if needed.
- Interface transformer and phase reactors
- VSC dc capacitor
- DC smoothing reactor
- VSC control system and telecommunication.

VSC transmission systems are generally designed with the mid point of the converter at ground potential, since this minimises the amount of equipment which is subject to dc stress. Thus, one side of the converter is operated at positive voltage and the other at negative voltage.

Figure 5-3 shows a conceptual layout of a 250 to 300MW offshore VSC Transmission converter station. The space required by the offshore module is approximately (W x L x H) 30 x 40 x 20 m, including the transformer [6]. The different components in the converter station are described in a little more detail in the following. Further information can be obtained from [7][8].

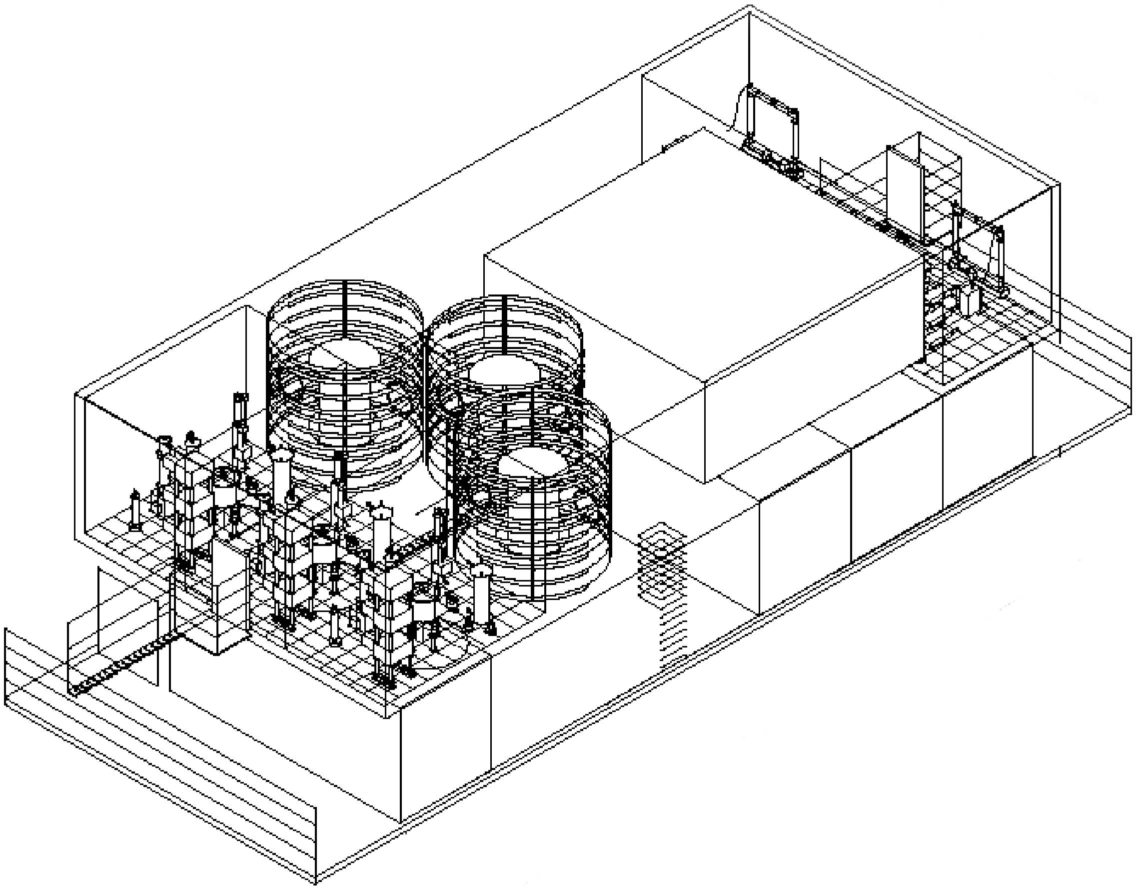

Figure 5-3 Layout of an offshore 300 MW VSC Transmission converter station

5.3.1.1 Voltage Sourced Converter (VSC)

The VSC is a self commutated converter using semiconductors which can be switched on and off in response to a gate signal, independently of the current going through the valves at the time. At the time of writing the Insulated Gate Bipolar Transistor (IGBT) is the semiconductor of choice for this application, because of its low gate power requirements, its high speed and its capability of limiting short circuit currents. The response time of the output from the converter is mainly influenced by the switching frequency (which is typically about 1 kHz for PWM control) and by the size of the AC phase reactors. Because the VSC converters are forced commutated, commutation failures will not occur because of ac grid disturbances, however, they may influence the synchronisation with the ac grid voltage depending on the performance of the phase locked control loop, which tracks the grid voltage vector..

The VSC converts its dc voltage into a three-phase output ac voltage which appears behind the phase reactors and is synchronised with the ac grid. The ac voltage produced by the VSC can be controlled to have any desired amplitude and phase angle relative to the ac grid, subject only to rating limitations in the VSC. If the voltage amplitude behind the phase reactors is greater than the ac grid voltage, reactive current is supplied from the VSC, and if the voltage behind the phase reactor is less than the ac grid voltage, the VSC absorbs reactive power from the ac grid. Similarly, the active power depends on the phase angle between the converter voltage and the ac grid voltage. Thus it is possible to control both the active power and the reactive power flowing in the converter connection, and the control of the two can be performed independently of each other. Naturally, the active power at the sending end and at the receiving end needs to be the same, except for the power loss, since the dc voltage would otherwise change.

Because the VSC can provide controlled reactive output, similar to a STATCOM, there is normally no need to provide breaker switched reactive power banks for the purpose of reactive power control.

5.3.1.2 **Filters**

In order to obtain a satisfactory power quality in respect of harmonics and radio interference, a VSC substation will normally be equipped with ac and dc filters as well as radio interference filters. The VSC valves are switched at about 1 – 2 kHz for a PWM VSC. At a switching frequency of 1450 Hz the two most dominating harmonics are the 29th and the 59th harmonics. Therefore, the harmonics generated by a VSC are of significantly higher order than for LCC. This has the advantage that ac filters for VSCs are smaller than for LCCs. The ac filters are required only for the filtering of harmonics, and are not part of the reactive power control strategy. Therefore, they need not to be switchable.

For a multilevel type VSC with more than 100 levels the output voltage may be so close to sinusoidal that filters are not required.

5.3.1.3 **Interface transformer and ac phase reactors**

The ac phase reactors provide a substantial inductive reactance between the VSC bridge and the ac filter bus, which is necessary for stable operation of the VSC. The phase reactor also plays a significant role in stopping high frequency transients from being imposed on the interface transformer. The phase reactor has to be designed taking into account that in service it is continuously exposed to large amplitude voltage steps, caused by the switching of the VSC valves.

An interface transformer is in principle not needed since the VSC can control the ac voltage by modulation factor control. However, in practise most VSC Transmission uses an interface transformer because it provides convenient adaptation of the ac voltage, thereby providing optimum utilisation of the voltage and current rating of the valves. Typically the interface transformer is also provided with a tap changer, which enables the VSC to meet the performance requirements without substantial overdesign and enables the power loss to be minimised.

5.3.1.4 **VSC dc capacitor**

In order to obtain a constant dc voltage source characteristic, the VSC is provided with a dc capacitor. This dc capacitor is required for the proper operation of the VSC. The dc capacitor smoothes the dc voltage and minimises current ripple.

5.3.1.5 **VSC control system**

The dc power transmission and the reactive power exchange with the ac network is regulated by controlling the VSC valve switching in accordance with a switching strategy, e.g. Pulse Width Modulation or multilevel link switching. Also, other switching strategies are possible depending on specific performance requirements during steady state or during dynamic operating conditions.

Typically, one station will control the dc voltage, whilst the other controls the power flow. Both stations can also control either the reactive power exchange or the ac voltage at its terminals. Because the dc voltage for VSC always has the same dc voltage polarity, telecommunication between the sending end and the receiving end is not necessary for power reversal. However, for optimal operation of VSC transmission or for special control functions, telecommunication is recommended.

5.3.1.6 **Operational characteristics**

The VSC does not consume reactive power; on the contrary, the power of the VSC can be controlled in all four quadrants of the PQ plane. The VSC is self-commutated and need no ac voltage to operate. Therefore, the VSC can be used to energise a passive ac grid.

A VSC Transmission scheme is able to provide a controlled fault current contribution up to the rated current of the converter.

5.3.1.7 **DC cables**

The dc polarity is always the same and the cable is not exposed to additional stress caused by polarity reversal. This makes it possible to use polymeric cables, which are less expensive than mass-impregnated cables. At present the polymeric cables are susceptible to damage in the event of a polarity reversal as occur with an LCC HVDC scheme, and they are therefore not yet used with LCC HVDC.

5.3.1.8 **Power Loss**

The VSC converter losses are higher than for LCC HVDC primarily because the IGBT has a higher conduction loss than a thyristor, and a considerable power loss is incurred during turn-off and turn on of the valve. The development of VSC technology has a high focus on the reduction of the power loss. This can to some extent be achieved by new converter topologies, and by reducing the switching frequency of the VSC valves, through the adoption of new control PWM methods, such as Selective Harmonic Elimination Methods (SHEM), which can achieve good harmonic performance with a lower number of valve switching operations per power frequency cycle. The current and voltage capability of semiconductors with turn off capability is less than that for a thyristor. Consequently, for the same rating a VSC valve contains more semiconductors than a LCC valve.

The VSC conversion losses per end at full load is approximately 2 % of the VSC converter rating. However, the reactive power control capability of VSC Transmission means that reactive power flow in the ac network can be minimised, thereby reducing the power loss in the overall system.

5.4 MULTI-TERMINAL HVDC TRANSMISSION

Almost all HVDC transmission schemes in operation at the time of writing are point to point transmission with just two converter stations at the end of the HVDC line. However, it is possible to build HVDC schemes which have more than two terminals connected to the HVDC lines, and the scheme is then called a Multi-Terminal HVDC scheme. One terminal will be operated in dc voltage control, and the others are operated in current or power control.

Figure 5-4 shows a three terminal HVDC system, which interconnects two power systems A and B and which has a third terminal which may connect a wind farm to the HVDC line. There is no reason why the three terminals could not all be in the same power system.

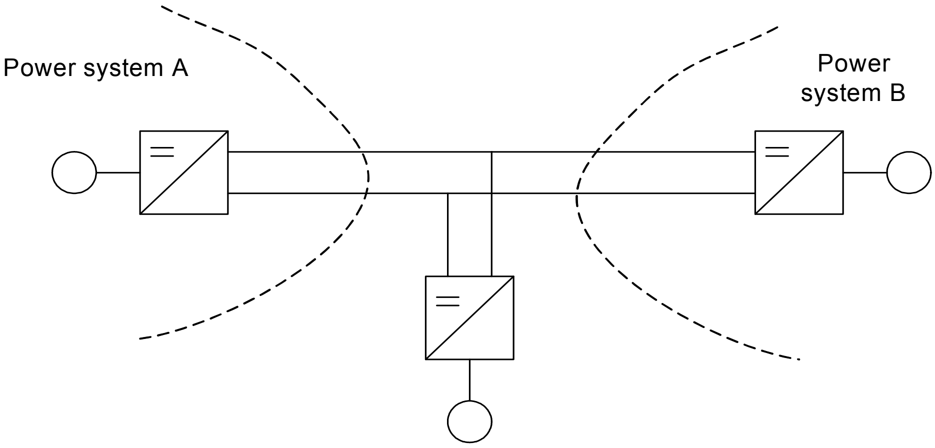

Figure 5-4 Three terminal HVDC system

Multi-terminal HVDC system can be designed using both LCC and VSC HVDC converters. At the time of writing there were two LCC HVDC multi terminal schemes in operation, but no VSC Transmission schemes. However, VSC transmission is more suitable for multi-terminal application than LCC HVDC converters for the following reasons:

- VSC converters do not suffer commutation failure in contrast to LCC HVDC. A commutation failure results in a collapse in the dc voltage, which stops power transmission until all terminals have restarted. This takes longer than in a two terminal scheme.
- The performance of a LCC converter depends on the short circuit level at its terminals. In a multi terminal system the terminal with the lowest short circuit ratio determine the performance of the DC multi terminal system. The performance of a VSC scheme does not depend to the same extent on the short circuit level.
- The power direction in LCC HVDC terminal is changed by changing the DC voltage polarity. Therefore, in a multi terminal system LCC HVDC converters which need to change power direction have to be designed with additional insulation and either dc switchgear to enable the converter to be "turned upside down" or special bidirectional thyristor valves. For a wind farm application it may be necessary for all converters to change power direction. VSC Transmission does not require special designs, because the voltage polarity is never changed.
- In a LCC HVDC multi terminal system communication is needed between the terminals in order to balance the power flow and to coordinate the change of voltage polarity if the power flow in one of the converters is changed. Communication between VSC converters is not necessary for balancing the power in a VSC Transmission multi terminal system.

5.5 PARALLEL HVDC AND AC TRANSMISSION

Both LCC HVDC and VSC Transmission can operate in parallel with ac lines. The share of power between dc and parallel ac lines can be controlled by controlling the power transmission on the dc line. Special power modulation control of the HVDC link can be used to damp power oscillation in the grid and the resulting power transmission capacity of the parallel DC and AC lines can be improved.

As the VSC can control both the active and the reactive power independently, the VSC-transmission can also provide ac voltage control and thereby improve not only the performance of the parallel AC and DC lines but also the total AC grid performance.

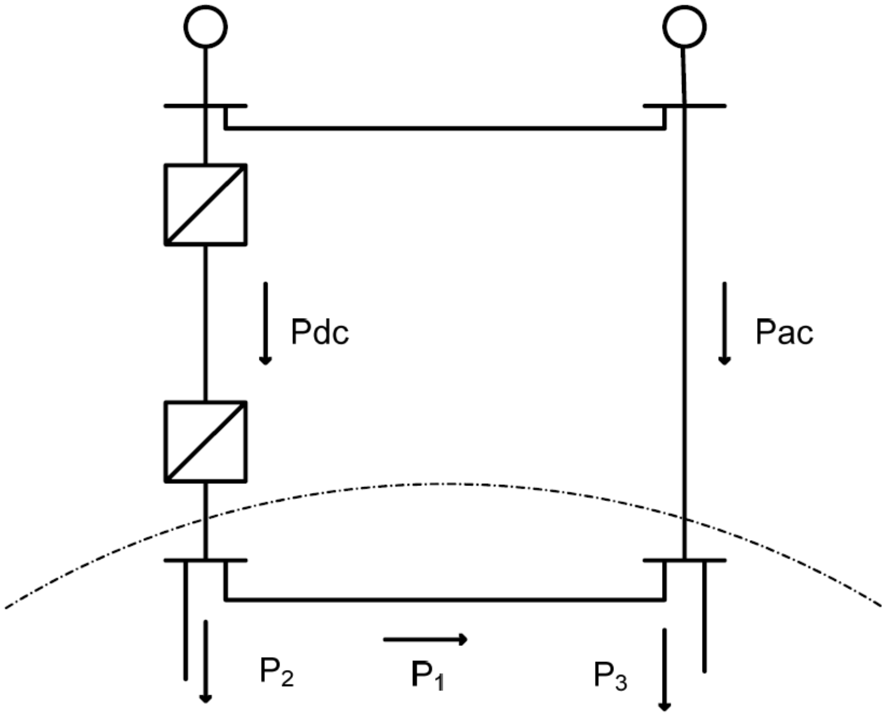

Figure 5-5 Combined AC and DC connection of offshore wind farm

The ac voltage at varying loading of an ac line can be depicted by a circle diagram. This can be used to show how the performance of an ac line can be improved by a parallel VSC line [8].

HVDC is particularly suitable for bulk power transmission. Offshore wind farms may be built gradually in sections over several years. If the first section is build with AC cables and it is later decided to expand the offshore site, then it may be economical to connect the additional sections with DC and operate the AC and the DC cables in parallel as shown in Figure 5-5. This is an advantage because the power flow in the DC link is fully controllable such that no uncontrolled power will flow in the ring constituted by the onshore AC grid and the offshore AC and DC grid. The controllability of the HVDC link will benefit the flow in the parallel AC link, flow in the off shore grid, and the onshore grid, and optimise the e AC grid transmission capacity between bus 1 and bus 2, and generally improve the performance of the power system.. In addition the AC link can provide ancillary power and commutation voltage to the offshore grid, which is an advantage particularly for LCC HVDC.

5.6 BENEFITS OF USING HVDC FOR GRID CONNECTION OF WIND FARMS

The benefits arising from the use of HVDC for grid connection of wind farms include the general advantages of using HVDC as an alternative to AC connections as described in Section 5.1. The asynchronous nature of the HVDC interconnection can be of benefit to a wind farm, particularly if the wind turbine generator does not comprise power electronics itself. For example, a fault in the main ac network is not transferred to the wind farm grid, and the fault ride through capability of the wind farm may be improved. However, this requires appropriate measures to manage the surplus wind power that the HVDC link cannot export to the grid during the fault. This may involve special control features at the HVDC link and/or special control features at the wind generator if it comprises its own power electronic converters. The frequency in the offshore network can be increased during the fault (subject to the wind generator design), storing the surplus energy in the wind turbine inertia, until the fault onshore has been cleared. In the case of an LCC HVDC, some form of reactive compensation combined with energy storage may be needed at the wind farm side of the link. Another possibility is to apply a breaking resistor on the DC side, connected in shunt in the case of a VSC link, or in series in the case of a LCC HVDC link, that can absorb the surplus wind power during the fault. Full export can commence as soon as the ac voltage at the receiving end has returned to normal. Another benefit of faults not being transferred to the wind farm is that fewer faults and disturbances may be seen by the wind farm, which is of long term benefit, since mechanical stresses are caused within the wind farm during grid disturbances.

HVDC converters can be used for power oscillation damping as proven in existing installations. This feature can be used to restore normal operation of the WF quickly and very smoothly and if necessary, to support the AC system for improving its transient stability.

The number of cables required to transmit a given power will depend on the transmission technology. Assuming that 1000MW needs to be transmitted by submarine cable over a distance of say 100km the following solutions would be possible:

- An AC link with 5 parallel three-phase 150kV ac cables with appropriate reactive power compensation onshore and offshore.
- A LCC HVDC link with 2 cables, operated at ± 450 kVdc.
- A VSC Transmission scheme with 4 cables operated at ±150 kVdc or
- A VSC Transmission scheme with 2 cables operated at ±300 kVdc.

5.6.1 Issues associated with LCC HVDC for connection of wind farms

LCC HVDC schemes have not yet been applied for the connection of wind farms at the time of writing this Brochure. A number of issues would have to be considered and resolved for such a connection to become economically and technically acceptable:

- The design of a compact converter station for offshore application.
- Voltage dips of >15 to 20% at the inverter ac terminal may cause commutation failures, which will give a brief interruption in power flow. The wind farm will experience over speeding, and control solutions are required to ensure smooth recommencement of power transmission after recovery.
- Interaction between the wind turbines and the sending end rectifier will need to be carefully studied to ensure absence of future problems, e.g. sub-synchronous torsional interactions.
- Provision of satisfactory commutation voltage for the sending end rectifier. The solution may depend on the type of wind generator.
- Provision of satisfactory commutation voltage for the offshore converter when operating as inverter (during no wind conditions). This operating mode may be required in order to supply auxiliary power to the wind farm. The solution may depend on the type of wind generator, e.g. full converter system may be able to supply some support.
- The ability of the LCC HVDC converter to operate for prolonged periods at very low power, as may be

required during no-wind conditions, for auxiliary power supply and during start up of the wind farm during low wind conditions.

5.6.2 Issues associated with VSC Transmission for connection of wind farms

As has been indicated above VSC Transmission seems to be particularly suited to the connection of wind farms because:

- The VSC does not require a commutation voltage from the network in order to operate satisfactorily.
- The VSC can operate continuously at any power flow.
- The VSC does not suffer commutation failures.
- A VSC Transmission converter station is much more compact than the equivalent LCC HVDC converter station.
- A VSC Transmission scheme will appear to the receiving network as a generator without inertia, but with less short circuit current contribution.

At the time of writing this Brochure two VSC Transmission schemes for the purpose of connecting an offshore wind farm are in the design phase. These projects are described in more detail in Chapter 6.

5.7 CONCLUSIONS

HVDC transmission can offer the most economic connection method for a wind farm which is located electrically far from the connection point in the main ac network. As described above, a break even distance exists beyond which a HVDC scheme becomes more economic than an ac transmission link, the distance depends on many factors, including cable or overhead line, rating and local factors.

For cable schemes it may be possible to use fewer cables with a HVDC solution when compared with an ac solution. This may be beneficial if the cables have to run through an environmentally sensitive area. The maximum power that could be transmitted using LCC HVDC technology with two cables is estimated to be about 1400MW using 500kV cables. At the time of writing VSC Transmission is in service at ±150kVdc, and power would be limited to 500MW, but ±300kVdc schemes are being offered commercially, and would provide power levels up to 1000MW. At the time of writing a 400MW, ±200kVdc multi-level chain link VSC Transmission scheme is under construction.

HVDC may also provide a technically superior solution, because it provides an asynchronous connection and it does not transfer faults from one end of the link to the other. These benefits can be used to optimise the wind farm solution, resulting in lower overall costs. Whether this is possible will often depend on the commercial arrangements between the providers of the power interconnection and the developers of the wind farm. With strict boundaries between the two a full optimisation may not be possible.

HVDC interconnection between asynchronous power systems combined with connection of wind farms as a multi terminal HVDC scheme may also be beneficial if/when the wind power is shared between the two asynchronous systems.

Two projects using VSC Transmission for the connection of offshore wind farms are already in the design stage and the first of these projects may be in service by the end of 2009.

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6. LARGE SCALE WIND INTEGRATION - CASE STUDIES

6.1 INTRODUCTION

This chapter presents a number of case studies, where HVDC and FACTS devices have been employed in transmission networks to facilitate the successful and optimal connection of wind farms.

Unfortunately, many studies, technical reports, and papers that relate to wind farm connection and performance, are the subject of the confidentiality agreements as part of Connection Agreements between the transmission network companies, the wind farm proponents, and the system operators. Wind farms models are also difficult to obtain in the public arena due to the sensitive proprietary technical information contained. Therefore, the information provided about individual schemes may be relatively limited. Where available, references to more detailed documents will be provided.

6.2 GENERAL COMMENTS ON THE CONNECTION OF LARGE SCALE WIND FARMS

Wind farms connecting to and operating in electricity transmission networks around the world have prompted new and original thoughts on the ways generation connection can be facilitated. This is a major shift away from the traditional, “vertically integrated” view of long-term transmission planning. This applies to both large and small-scale generation, and has prompted somewhat of a rethink for both renewable and conventional generation sources.

The increasing penetration of wind generation has necessitated stronger control over the way wind farms are operated and perform during system faults and other events. These additional requirements are specific to individual wind farms, and are laid down in Grid Codes and bilateral agreements between the wind farm developer and the network operator. Fault Ride Through (FRT) requirements vary from country to country, as described in Chapter 3. However, a common theme is for the wind farm to remain on-line during and after a major system disturbance, usually specified as some faulted condition for a period of time followed by a period of recovery. Requirements for the wind farms to be able to participate in system frequency and ac voltage control are also to an increasing extent being applied to large wind farms.

New ideas for generator connection that would never have been considered in the past with conventional generation and transmission planning are now increasingly adopted. T-offs, more complicated to protect, but offering low cost connection without degrading an existing transmission line’s reliability are becoming commonplace. T-offs also add the benefit of shifting the critical fault location from the generators terminals to the remote end substations, in some cases many kilometres away from the wind farm terminals.

Grid Codes have typically set up clear delineations between the requirements of a generator’s performance (usually measured at the generator’s terminals) and the transmission network’s performance requirements. This delineation has led to the development of wind farms with FACTS devices like SVC’s and STATCOM’s inserted in between the wind farm generators and the transmission network to achieve the mandated performance. This approach, which is dictated by commercial reasons, has led to the possible missed opportunity for the development of dispersed, optimally placed FACTS devices throughout a network, rather than the perhaps the sub-optimal placement at the generators.

Importantly, the size of the FACTS device employed to allow the wind farm to meet the FRT criteria can be greatly reduced by shifting the critical fault location. This can apply equally to traditional HVDC and the shifting of critical faults away from the converter terminals further out into the ac system.

Voltage control and flicker, especially on weak networks, can also be overcome by the employment of

FACTS devices. Transmission and distribution systems have been designed over many years and incorporate plant and equipment installed specifically to deliver real and reactive power to loads, usually from large blocks of generation. Dispersed wind generation can and has caused concern at time of light load where typical transformer tap changers, which have more boost than buck taps, run out of buck taps, and high transmission and distribution and therefore customer voltages are experienced. Additional fixed and dynamic reactive plant is required in addition to the gradual (more expensive) phasing in of transformers with more suitable tapping ranges.

Coordination of fixed reactive plant and the dynamic range provided by a FACTS device must be coordinated and there are examples of where this has taken some time to achieve this coordination in a practical way.

The development of offshore wind farm projects using relatively long ac cables have promulgated the development of shunt FACTS device topologies (both offshore and onshore) to ensure that the wind farm meets any given connection criteria. With the demand for more offshore wind generation, longer cable distances become necessary, and HVDC transmission, either as LCC HVDC or VSC Transmission, start to provide the most economical and technically optimum means of connection of the wind farm to the grid. At the time of writing only the VSC Transmission technology had been selected for such HVDC connections.

The following Section presents summaries of actual projects that embody these issues.

6.3 LONDON ARRAY

London Array is a proposed offshore wind farm with a capacity of up to 1000MW off shore wind farm. In March 2008, London Array received all of the major consents required for both the offshore and onshore elements of the project. The wind farm will be built more than 20km (12 miles) off the Kent and Essex coasts, in the outer Thames Estuary.

Key elements of the London Array project are:
- Up to 341 turbines, installed over a four year period and spread over some 245km2
- Associated offshore and onshore substations.
- Cabling (between turbines and to shore)

Up to five offshore substations will be installed to collect power from groups of wind turbines before feeding it to shore via the main export cables. The voltage will also be stepped up to increase the efficiency of power transmission in the export cables. Each offshore substation will typically comprise the following key components:
- Transformers
- Electrical switchgear
- Back-up electrical generator and batteries

The offshore substations will be approximately 25m x 25m x 20m high, standing up to 40m above the level of the sea.

Three types of cables will be used:
- Inter-array cables connecting groups of turbines to the offshore substations
- Export cables for transmitting electricity from the offshore substations to shore
- Onshore cables to connect to the onshore substation

The wind turbines will be connected to each other by buried inter-array cables that carry the electricity to offshore substations where the voltage is increased. Up to six export cables will then carry the power from the offshore substations to shore, a distance of around 50km (31 miles). Cables will typically be buried at a depth of between 0.5m and 3m, subject to local conditions. The export cables will be connected to a proposed new onshore substation in Kent. The onshore station will be connected directly to the 400kV transmission. A small diversion of an existing overhead line will be required, resulting in the replacement of three existing towers with new towers of a different design.

SVCs combined with mechanically switched shunt reactors may be used to meet requirements regarding reactive power exchange with the grid, however this concept is still under development at the time of writing.

6.4 BAIHUBAO WIND FARM

Baihubao wind farm is located in the Pinglu district in Shanxi province, northwest of the city Shuozhou, West China. Baihubao wind farm has a design capacity of 100MW, and has been built using 27 sets of DFIG wind generators, each rated at 1250kW, giving a total capacity of 33.7MW.

The arrangement of the wind farms and the collector system is shown in Figure 6-1. The wind generator terminal voltage is 0.69kV, and each generator has a 0.69/35kV transformer. The 35kV terminals of the transformer are connected by cable to a 35kV bus, from where an overhead line is run to the 35/110kV transformer substation. There are two overhead transmission lines, to which 13 or 14 wind generators are connected. The annual electrical generating capacity of the wind farm is 64470MWhr, and the annual equivalent full-load operating hours is 1910h, giving a capacity factor of 0.2180.

The Pinglu power network is composed of 110kV and 35kV transmission line. At the time of writing there are five 110kV substations, with 8 main transformers which have a total capacity of 292MVA. There are seven 35kV substations, with 10 main transformers which have a total capacity of 40.3MVA. In 2005, the maximum supply of electricity was 105MW, and the total delivery was 6.93×105 MWhr.

On the one hand, a grid connected wind farm has some economic and social benefit; on the other hand, it has some effect on the power quality, security and stability of power system.

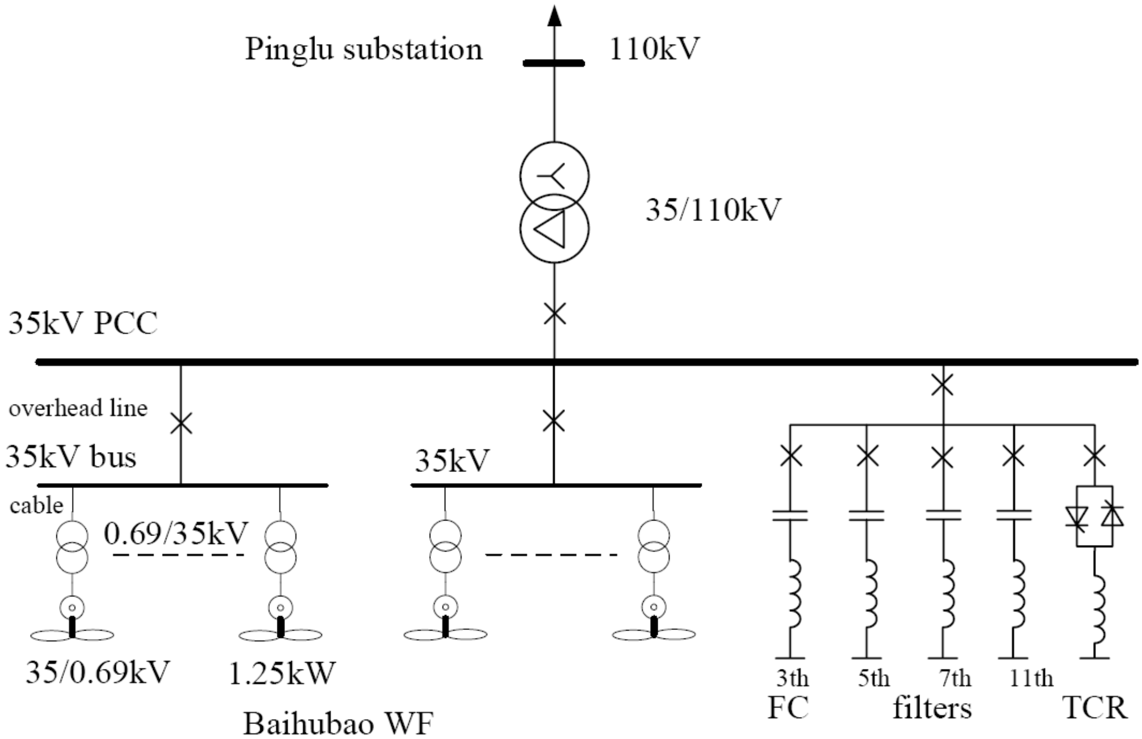

Figure 6-1 Baihubao wind farm interconnection and supporting SVC

The changing wind speed results in fluctuation of output power, and the fluctuation of network voltage. In order to fully utilise the potential wind resource and increase the proportion of energy from wind generation, it is necessary to take effective steps to improve the operating performance of the wind farm. The effective steps must include choosing the right place and method for connecting the wind farm to the power system. It may also be necessary to increase the short-circuit power at the point of connection, in order to minimise interactions. There are two approaches:

- One approach is to choose Doubly-Fed Induction Generators with good and robust performance.
- The other is to use basic wind power generators, and to install a flexible control device, such as a SVC, to improve the system performance.

The Baihubao wind farm has sufficient reactive power compensation devices, such as several Mechanically Switched Capacitors (MSCs), to keep the power factor at the PCC close to 1.0 during normal operating conditions. But in order to meet requirements of reactive power control range, speed of response, and harmonic performance, it was necessary to connect 3th, 5th, 7th, 11th single-tuned filter branches a branch at the PCC, with a total capacity of 12.07MVar; as well a continuously controlled SVC, with a rated capacity of 10MVar. The arrangement of the SVC is shown in Figure 6-1, and it is controlled to keep the voltage at the connection point stable.

6.5 LAKE BONNEY II WIND FARM

The Lake Bonney II wind farm is an addition to the existing wind farm known as Lake Bonney I. Located in South Australia; Lake Bonney II was constructed in two (2) phases consisting of 159 MW DFIG wind generators, each with a generating capacity of 3MW, and was completed in 2007. When combined with Lake Bonney I, the total power output is 239 MW. The owner is Lake Bonney Wind Power.

The wind farm system connects to the transmission grid via two (2) 60/125 MVA 132/33 kV power transformers owned by the transmission utility Electranet. The combined phase 1 and 2 output of 239 MW of power is fed through these transformers to the grid. The wind farm had to meet the following specific interconnection requirements as defined by ESCOSA, the Essential Services Commission of South Australia, and the transmission system operator NEMMCO;

- At full rated output, the generation plant operated by a wind generator must be capable of delivering or absorbing reactive power of 0.395 times its power output (equals +/-93% Power Factor).
- At generation levels below full rated output, the generation plant operated by a wind generator must be capable of delivering or absorbing reactive power at a level at least pro-rata to that of full output.
- At least 50% of the reactive power capability of the generation plant operated by the wind generator must be dynamically variable, with the balance able to be provided by non-dynamic plant.
- The reactive power capability of the generating plant operated by a wind generator must be controlled by a fast-acting continuously variable, voltage control system which is able to receive a voltage set point.
- The wind generator must be able to operate its generation plant to a set power factor if that is the preferred mode of control at any time.
- The generating plant must ride through a 175ms two phase fault and trip of an incoming 132kV line (LVRT).
- The generating plant must ride through a temporary overvoltage of 1.3 times normal operating voltage at the grid connection point decreasing with time as defined in the National Electricity Rules (HVRT).

The reactive compensation system contains two separate D-VAR systems for the two phases of the project. Each D-VAR system consists of a 12 MVAR D-VAR STATCOM, and two (2) 13.5 MVAR capacitor banks. The reactive compensation is located and split at the 33kV level due to the need to suppress temporary overvoltages on both sides of the bus tie which can not normally be closed due to fault level constraints. The output of both of the D-VAR systems is coordinated by a single master controller, which monitors both the transmission and collector bus voltages and the power factor at the 33kV point of connection.

The D-VAR system provides a number of advantages including compliance with ESCOSA and NEMMCO interconnection requirements regarding dynamically variable reactive power capability. The STATCOM units provide fast acting, continuously variable reactive output with the ability to operate at 2.67 x rated current output for up to 2 seconds. This feature is crucial in providing strict high voltage ride through (HVRT) and also assists the wind farm during LVRT transmission system fault events. In addition, the D-VAR control system incorporates coordinated control of the switching of the 33kV capacitors as well as the wind turbine’s reactive output capability in a fully integrated system. This technology was further expanded to leverage the reactive power capability of the wind turbines to meet the overall power factor requirements.

As part of the D-VAR supply, the3 contractor also developed and provided the developer with a detailed user model of the STATCOM and capacitor bank control feature to give to Electranet and NEMMCO for dynamic stability analysis as required by the National Electricity Rules. The simulation model incorporated the actual D-VAR control code including the capacitor switching, allowing very accurately modelling of the wind farm response to system events.

Figure 6-2 shows a single line arrangement of the Lake Bonney connection to the grid, including the D-VAR Reactive power Compensation System.

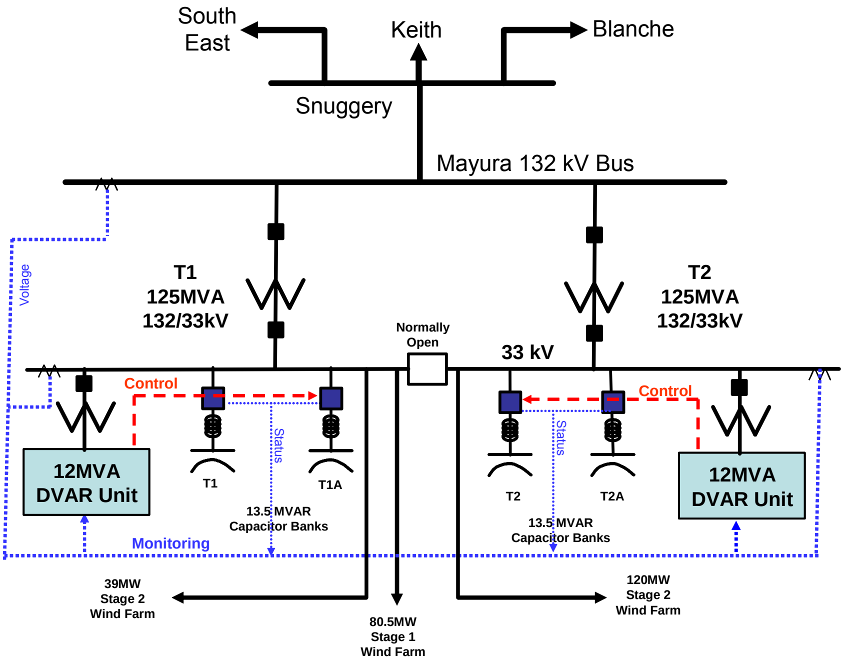

Figure 6-2 The Lake Bonney D-VAR Reactive Power Compensation System

6.6 ENBRIDGE WIND FARM

The Enbridge installation consists of a 99 MW wind farm and a 100.65 MW wind farm located in Ontario, Canada. The two wind farms are adjacent to one another, but are connected to separate 230 kV transmission lines. The 99 MW wind farm consists of 60 x 1.65MW fixed speed, soft start turbines and the 100.65 MW wind farm consists of 61 turbines of the same design. The owner of the wind farm is Enbridge.

The IESO (Independent Electric System Operator of Ontario) non-synchronous generation (wind) interconnection requirements include the following for connection at 50 kV and above.

- Install sufficient reactive compensation such that the net power factor measured at the transmission interconnection point is equivalent to that provided by the same MW sized conventional synchronous generator with 90% lagging (capacitive) to 95% leading (inductive) capability connected to the transmission grid through a13% impedance GSU transformer.
- The reactive compensation system must be fast, dynamic and continuous and must be able to hit either end of the required VAR output range in one second.
- Regulate the transmission bus (230 kV) or the local 44 kV collector bus to a voltage set point supplied by IESO.
- Avoid tripping during temporary high and/or low voltage situations on the transmission grid.

The reactive compensation system consists of two (2) 8 MVAR D-VAR units, four (4) 16 MVAR 44 kV switched capacitor banks, and one (1) 17MVAR switched shunt reactor. The same solution configuration was utilized for each of the 2 wind farms.

The total dynamic range provided by the D-VAR STATCOM (85 MVAR) is slightly larger than the total reactive range of a similarly sized synchronous generator rated +90/-95% PF providing compliance with the IESO interconnection standards. The D-VAR STATCOM provides fast, dynamic, continuously variable

reactive output with the ability to operate in 2.67 x overload. The D-VAR provides the ability to hit either end of the required VAR output range in one second, as required. In addition, the control system incorporates coordination with switched capacitors and reactor in a fully integrated system.
Figure 6-3 shows in the left foreground of the picture a 4 Mvar D-VAR module.

Figure 6-3 4MVAR D-VAR module installed at a wind farm substation

6.7 NANHUI WIND FARM, CHINA

The Nanhui wind farm is located on the coast near Shanghai in East of China. It is connected electrically to two 10/35kV step-up transformers and then to the Dazhi substation via two 35kV overhead lines and cables, which have a power capacity of 2×20MVA. A single line diagram is shown in Figure 6-4. Dazhi substation transmits the wind power to the 110kV network at Nanhui substation, and also supplies local loads.

At present, 11 sets of 1.5MW DFIG wind generators are installed in the Nanhui wind farm. The rated output voltage of these wind generators is 690V. The total wind farm rated capacity is 16.5MW. At the time of writing no devices are installed to improve reactive compensation and grid voltage control.

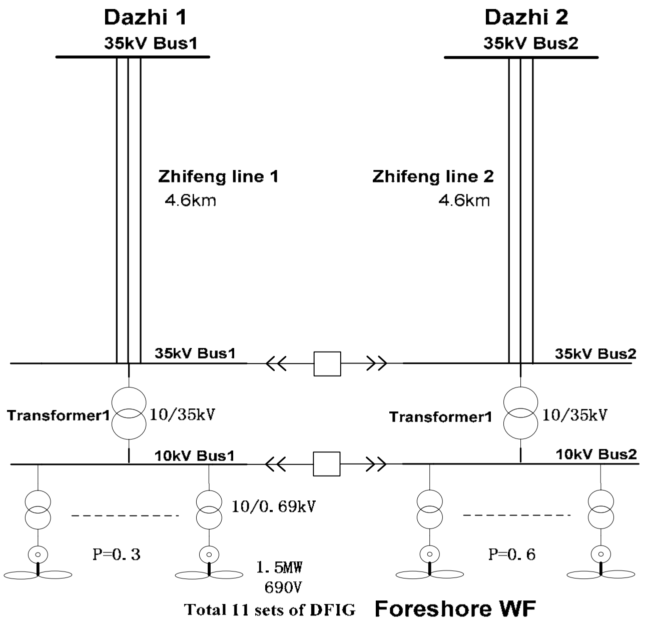

Figure 6-4 Nanhui Wind farm single line diagram

In 2006, the supplied load of Dazhi substation was 10MW. From 2001 to 2006, the yearly load increase of Dazhi substation was 8.5%. It is forecast that in 2010, the local load will be 16MW, and the yearly load increase will be 12%, so that the power from the wind farm power to Dazhi substation almost equals the local loads consumption. Projecting further to 2015, the local load will be 26MW; the annual load increase will be 10.5%. Thus, there is a big problem for the power quality in the future.

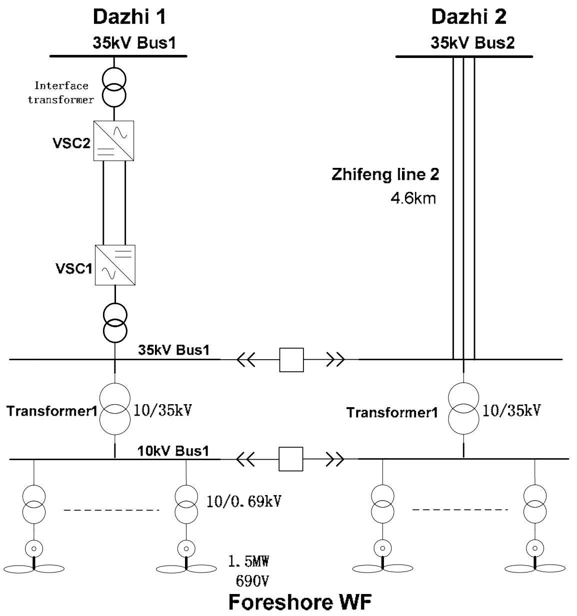

Figure 6-5 New interconnection scheme based on VSC-HVDC system

In order to mitigate the above-mentioned conflict and develop new technology, the State Grid Corporation of China has decided to install a new interconnection scheme based on VSC Transmission as shown in Figure 6-5. The scheme will provide a test bed and demonstration project for the development of this technology in

China. One of AC overhead lines and cable will be replaced by DC transmission cables, and two VSC stations will be added to form a VSC transmission system. This reconstruction of the grid connection will not only enable the VSC Transmission system to control the wind farm power, but will also provide dynamic compensation for the sending or receiving system reactive power demands, thereby increasing the system stability and improving the wind farm FRT. This demonstration project has started and will be put into operation by the end of 2009.

6.8 WESTERN ISLES, SCOTLAND

The Western Isles, off the west coast of mainland have one of the best wind resource anywhere in the world, with an estimated load factor of over 45% for wind turbines installed on the island. At the time of writing go ahead for the Western Isles transmission project was still subject to planning approval and final investment decision, but as it is a good example of how wind power connections can be realized it deserves a description here.

The Western Isles are presently connected to the transmission system via a single radial 132kV circuit from Fort Augustus. The circuit steps down to 33kV for the submarine cable section between Skye and Harris. The submarine cable circuit has a capacity of 20MW. There are two 132/33kV substations on the Western Isles, one on Harris and one on Lewis at Stornoway. A single 132kV trident line links the substations. Supply security is maintained by a diesel power station at Stornoway.

The proposed scheme, owned by Scottish and Southern Energy Ltd, will enable the excellent wind energy resource on the Isles of Lewis to be harvested, and the energy to be delivered to central Mainland Scotland.

The Western Isles HVDC Project would initially consist of two parallel VSC Transmission links, each one with a rated power of 335 MW, with an option for a third link to be added at a later date, see Figure 6-6. On the island of Lewis the first two of the links would be located about 20km South of Stornoway, and the possible third link could be located near Stornoway. The stations would be connected to each other by means of new 132kV circuits. The wind farms would be connected to the converter stations at 132kV. The 132 kV connection between the converter stations would normally only even out the power between the incoming wind farm feeders and would most of the time be very lightly loaded, which would keep its losses low. It is suggested to supply the local network via 132kV connections from the converter station 132kV busbars. This would provide independent feeders to the local network in addition to the existing ac cable from the mainland. The control of the HVDC transmission would give high priority to keep the local network on Isle of Lewis in operation under all possible operating conditions. On the Scottish mainland all converter stations could be located adjacent to the existing Beauly ac substation, near Inverness.

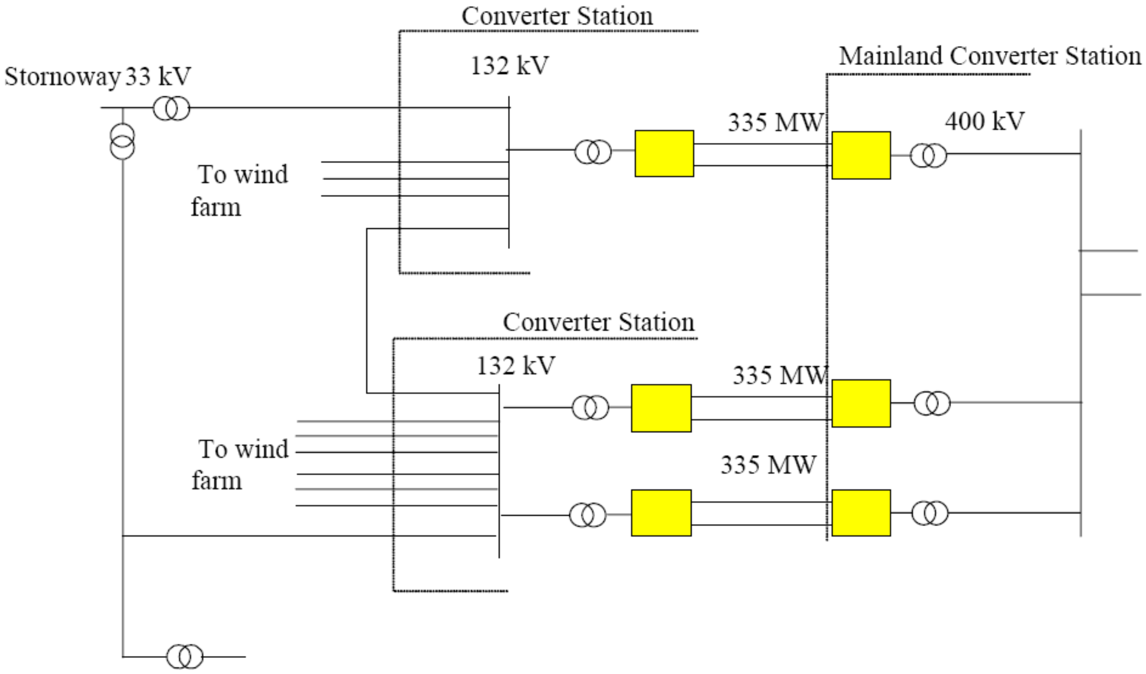

Figure 6-6 Overview of the Western Isles – Mainland transmission

The use of the VSC Transmission technology brings several advantages to the installation and operation of the transmission.

The most important advantage is in the operation in conjunction with the wind power, where successful experiences from earlier installations, such as the Gotland and Tjaereborg projects to connect wind power to consumer areas with a high degree of stability and power quality are described.

The individual links each works with separate controls for active power of the transmission and for reactive power individually in the two stations. Each link has intrinsic reactive power generation and absorption capabilities (+/-), which can be set from the operator or by an automatic ac voltage controller. Inter-station telecommunication for basic operation is not needed. Telecommunication is included to simplify operations and for mainland frequency support. Specifically telecommunication would be needed to control the power on the ac cable connection from the mainland via Isle of Skye.

The proposed layout of one of the converter stations is shown in Figure 6-7. The footprint of the substation is comparatively small compared to a conventional HVDC station being 160 m x 115m for two 335 MW units. The maximum height is 16 m.

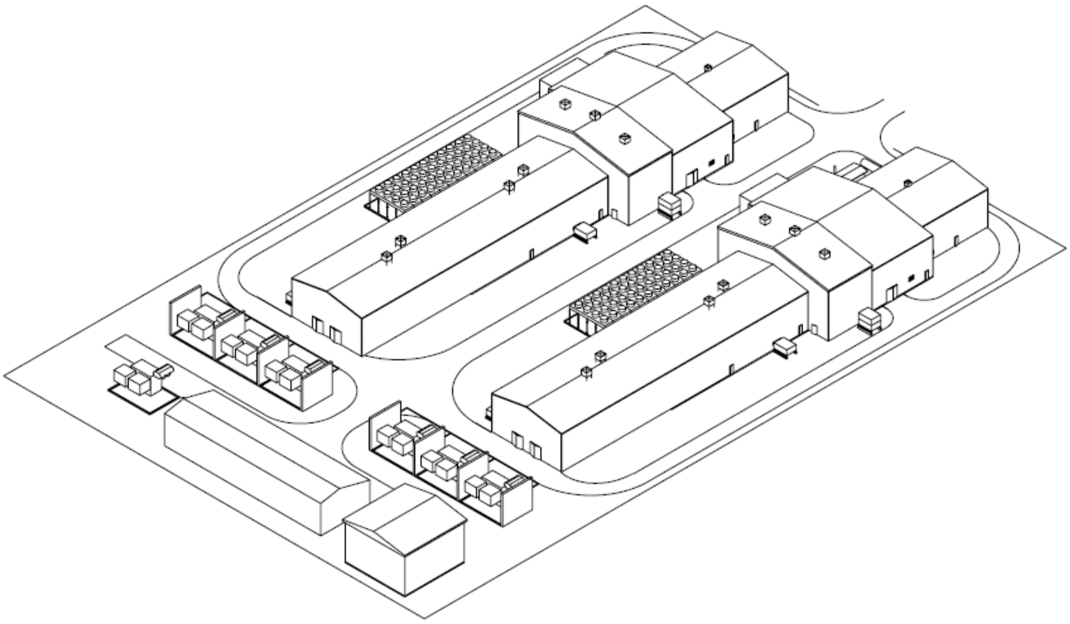

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Figure 6-7 Indicative view of the Isle of Lewis station layout.

6.9 NORD E.ON 1

The NORD E.ON 1 wind farm will have a total generating capacity of 400MW and will consist of 80 wind generators each with a rating of 5 MW located. The wind farm is located in the North Sea, about 130 km North-West from the German coast, as shown in Figure 6-8.

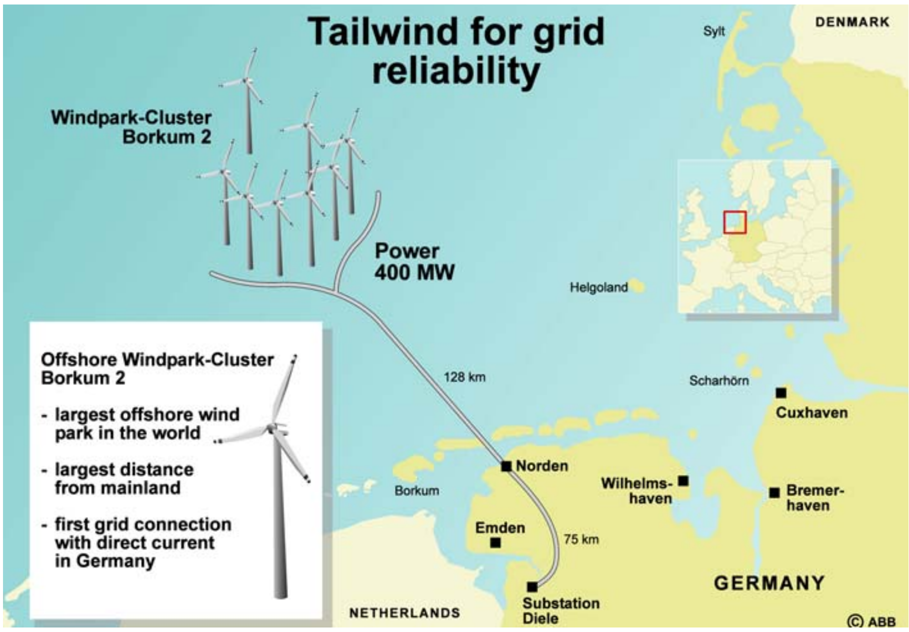

Figure 6-8 The NORD E.ON 1 project

The generators will feed power into a 36 kV AC cable system which will be transformed to 154 kV for the DC transmission in the offshore ac substation. The main reason for choosing HVDC was the total length of the land and sea cables, which have a combined length of 203 km.

VSC Transmission was chosen because it enables independent control of active and reactive power flow, total control of power from zero to full power without filter switching, and smooth and reliable operation of the offshore wind farm.

The wind farm will be connected to the 400 kV AC grid with a bipolar ±150 kV DC cable. The receiving station will be located in Germany at Diele 75 km South from the coast. Full Grid Code compliance of the HVDC transmission ensures a robust network connection.

Most equipment will be installed indoors for both the offshore and the onshore part ensuring safe operation and minimum environmental impact.

Extruded cable technology is used that simplifies installation on land and on sea allowing very short time for cable jointing. The oil-free cables minimize the environmental impact on sea and on land.

Figure 6-9 shows a provisional CAD drawing of the off shore converter station. The HVDC station which is connected to the wind farm controls the frequency of the offshore network by generating a voltage which follows a set reference. The frequency control forces the ac grid frequency of the wind park to follow the reference setting by keeping active power in the offshore grid balanced, thus all available energy is transmitted to the shore.

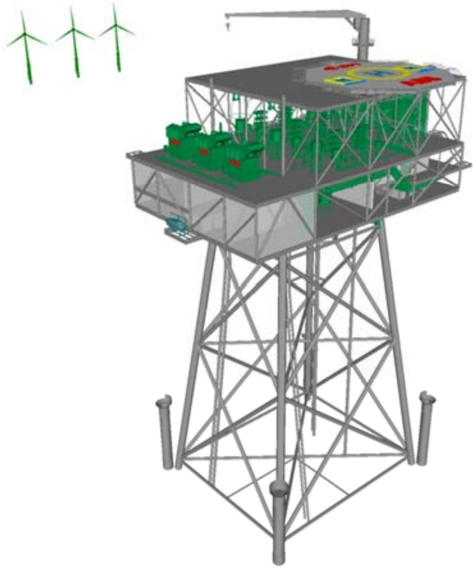

Figure 6-9 Offshore VSC Transmission converter station

The station onshore will deliver the received dc power, less power losses, to the German ac grid by holding the dc voltage constant, i.e. an automatic balance of active power flow between the stations is realized by dc voltage control. The control of reactive power is completely independent for the two stations. The desired reactive power order can be generated by the ac voltage control or set manually.

Black start of the offshore station is an important part of the concept. This is achieved by the VSC system providing active and reactive power to the offshore station with its ac side converter breaker open and generating its own auxiliary power supply. Thereafter, connection to a passive part of the offshore ac network can be initiated by closing the breaker to the ac cables. Thereafter connections to generator or wind power turbines are are made.

The commissioning of this project is scheduled for 2009.

6.10 REFERENCES

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7. BENCHMARK MODEL

7.1 INTRODUCTION

A small test network is proposed for the study of wind farms in electric power systems. It is derived from the Benchmark Test System to Validate HVDC and FACTS Models, prepared by U.D Annakkage, A.M. Gole and Shan Jiang of the University of Manitoba, Winnipeg, Canada. That model was developed as a test system for IEEE Working Group 15.05.02, Dynamic Performance and Modelling of HVDC Systems and Power Electronics for Transmission Systems. The authors would like to see its use proliferated, and its use as a benchmark model for wind generating systems will hopefully fulfil this objective. However, since the objective of this present working group was to investigate the performance of wind farms within a typical ac networks, it was decided to make a number of changes to the original test system, primarily to ensure that the network would satisfy typical network security requirements. The modifications and the modified test system are described in this chapter.

7.2 DESCRIPTION OF THE ORIGINAL IEEE12 BUS TEST SYSTEM

The small test system by the IEEE Working Group, with the addition of a wind farm at bus 12 in place of a hydro generator is shown in

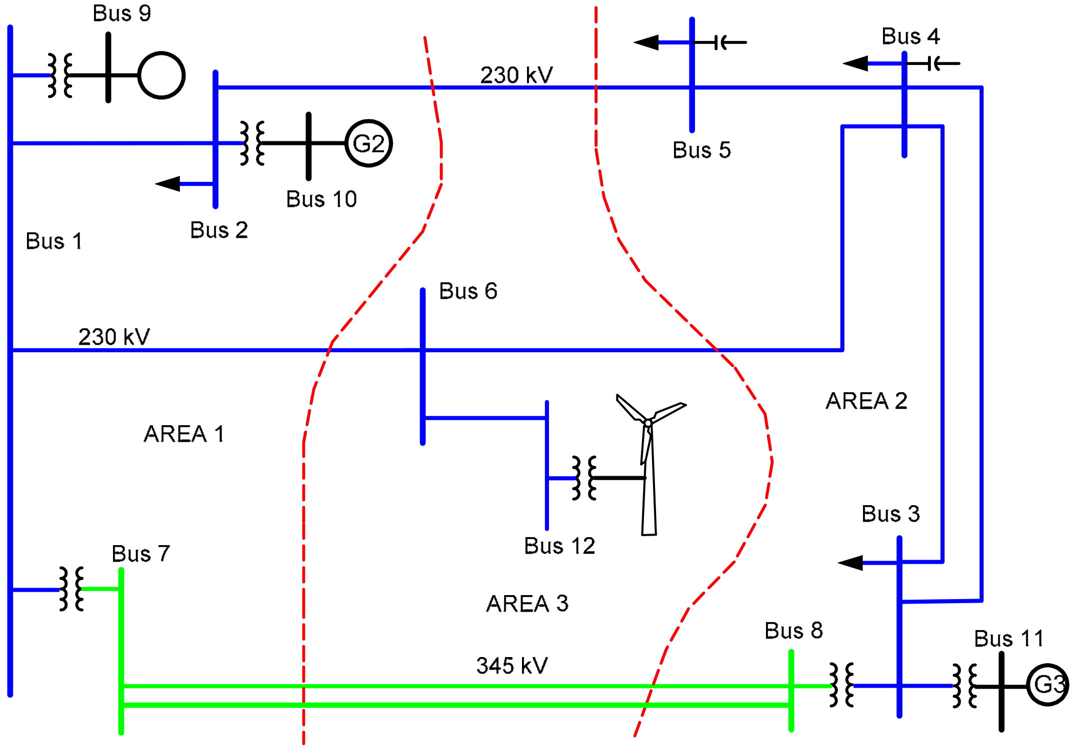

Figure 7-1. It consists of 13 busses (seven 230 kV busses, two 345 kV busses and four 22 kV busses).

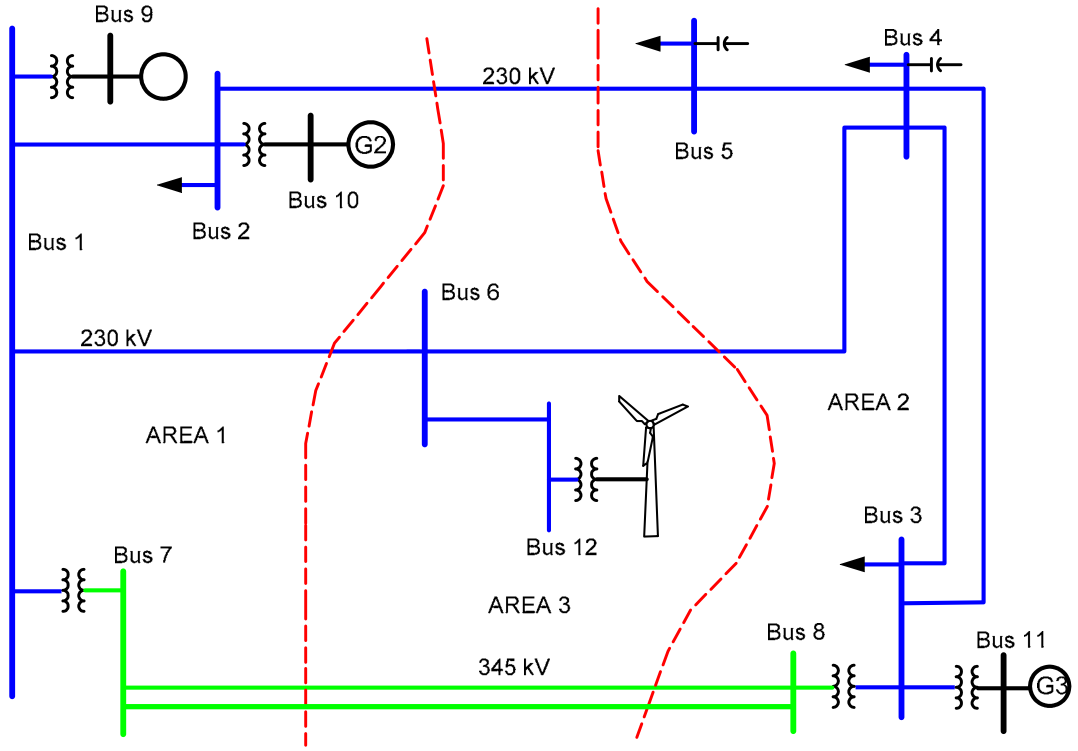

Figure 7-1 One Line Diagram of the IEEE Test System

The test system covers three geographical areas referred to as Area 1, 2, and 3:

- Area 1 is predominantly a generation area with most of its generation coming from hydro power.
- Area 2, situated about 500 km from Area 1, is a load centre with a small amount of thermal generation available.
- Area 3, situated between the main generation area (Area 1) and the main load centre (Area 2), has a 230 kV transmission line between Bus 4 and Bus 9, with Bus 6 being the mid point.

The transmission system is mainly a 230 kV system with one double 345 kV link between areas 1 and 2. Area 2 has switched shunt capacitors to support the voltage in that area. Bus 9 is the slack bus for the power flow solution, and an infinite bus for the dynamic solution.

7.3 ADAPTATION OF THE BENCHMARK MODEL BY CIGRE B4-39

7.3.1 Characteristics of the Original Benchmark Model

The original benchmark model was developed for the investigation of the performance of FACTS devices. Since wind generation is an intermittent energy source the transmission system must be able to supply the demand when the wind generation in Area 3 is unavailable. CIGRE B4-39 tested the model without FACTS devices by performing power flow and dynamic analyses using DigSilent's Power Factory, PSLF and PSS/E software. These studies found that some single line outages in the model resulted in violation of typical security standards. In particular:

- Voltage violations at bus 4 as a consequence of outages of lines 1-6 or 3-4.
- Thermal loading violations of lines 1-6 and 4-6 when line 4-6 or 1-6 respectively was disconnected)
- No solution was found for the power flow during outages of one circuit of line 7-8 or line 1-2

Such a weak grid would be appropriate to show the advantages of using various FACTS devices, but was not considered appropriate to B4-39's activities.

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A rather specific feature of the original model was a very long double-circuit line 7-8. Both circuits of the line had charging generation of around 900 MVAr and at about 50% of loading consumed around 800 Mvar. The net generation/absorption of Mvar by such a long line is very sensitive to changes in voltages and loading, and this was determined to be the main reason for the voltage problems at bus 4 during contingencies.

The initial model is also very "weak" with regard to dynamic stability. The voltage angle at bus 12 (with regard to the reference bus 9) equals 200. After disconnection of line 1-6 the steady state angle at bus 12 is equal to 500 and after disconnection of line 1-2 the steady state angle at bus 10 is equal to 480. This makes it very difficult to maintain transient and small signal stability after faults in the ac network.

These "weaknesses" of the original benchmark model were identified after doing power flow and dynamic analyses using DigSilent's Power Factory, PSLF and PSS/E software.

7.3.2 Requirement for the B4-39 benchmark model

In order to use the benchmark for the objective of WG B4.39 some basic requirements were agreed, for the system without generation at bus 6 (or 12):

- The fundamental frequency is 50 Hz.
- Base voltages are 400 kV, 220 kV and 22 kV.
- The benchmark model should stand n-1 contingencies, which involve lines only.
- Acceptable voltage range, without contingency is 0,95-1,05 p.u.
- Acceptable voltage range during contingency is 0,9-1,05 p.u.
- The benchmark model should also be dynamically stable during single contingencies (lines only).

7.3.3 Modifications to the original model

To fulfil the agreed requirements it was necessary to strengthen the grid. There were two options:

- to duplicate all single lines
- to scale lines.

The second option was chosen in order to keep the topology of the original benchmark. The lines were scaled as shown in Table 7.1.

Table 7-1 New length of lines

Bus 1	Bus 2	Circuit	New length in % of the original length
1	2	1	70%
1	6	1	50%
2	5	1	70%
3	4	1,2	100%
4	5	1	70%
4	6	1	50%
7	8	1,2	75%

The short-circuit reactance of the transformers were kept unchanged.

The line parameters were re-calculated according to the new base kV values.

Other changes made were:

- To avoid low voltage problems at bus 4 after disconnection of one circuit of the line connecting buses 7 and 8 a shunt capacitor of 120 Mvar was connected to bus 4 (the voltage problems at bus 4 occurred when there was no generation at bus 6).
- In the original grid the slack generator is connected to bus 9 behind a step-up transformer. This was changed: in the Power Factory and PSCAD models. The slack generator was replaced by an external grid with given short-circuit power.
- To avoid numerical problems in some programs (i.e. PSLF) with a small reactance of a transformer connecting bus 1 with slack bus 9, the reactance between bus 1 and the external grid was increased to 0,01 pu on 100 MVA base
- Realistic ranges of generator VAR capability was adopted

After these changes the benchmark grid fulfilled the steady-state requirements i.e. it could withstand all single line outages with voltages > 0,9 pu. The voltage following violations of the 0,95 pu minimum voltage were noted:

- Voltage at bus 4 after disconnecting line 3-4, circuit 1 or 2 - 0,929 pu
- Voltage at bus 4 after disconnecting line 2-5 - 0,935 pu
- Voltage at bus 5 after disconnecting line 2-4 - 0,941 pu

It was found that the original simplified set of dynamic parameters for the synchronous generator caused different behaviour of the benchmark model in different programs. It was decided to adopt a full generator data set, which was used in so called 4-machine model (P.Kundur [2]) and available in PSCAD ST1A exciter model. The data is detailed in section 7.5.2.

It was found that the original benchmark model was also very weak regarding dynamic stability. After scaling the lines the model behaviour was satisfactory with one exception: after disconnecting line 1-2 small signal stability was lost. Using a PSS with speed input signal at generator 2 (bus 10) helps to maintain stability.

7.4 SOME COMMENTS TO THE PSCAD MODEL

It is important to note the following characteristics of the PSCAD model used for the group's studies:

- The lines are represented by T-lines (frequency dependant model).
- The parameters for T-lines match quite well typical parameters given in the Kundur book [2] (page 209). All 220 kV lines have the same pu/km values with different lengths.
- The benchmark modeled in PSCAD behaves similarly with the model developed in Power Factory.
- During Power Factory or PSS/E steady state calculations capacitor banks are voltage controlled equipment. In PSCAD connection and disconnection is done manually (it was not considered worth the effort to prepare any control for them).
- For the representation of loads P has been modelled as constant current and Q as constant reactance.
- The settings of the PSS was not optimised. There could be benefits from using a PSS also on the other generator. However, for the purpose of the studies performed the optimisation of the PSS was not considered to be essential.
- The ST1A exciters have transfer function 200*(1+s1)/(1+s10). So they are rather slow. If stabilizers are present it is possible to increase its gain to 500.
- ST1A model does not have limiters (with exception of fast field limiter). Consequently during simulation they can generate reactive power above their ratings. A simple model of an over-excitation limiter could be used if considered necessary, but this was not done for the studies performed by the group.

7.5 BENCHMARK SYSTEM – DESCRIPTION OF PSCAD MODEL

7.5.1 Network and loads characteristics

Frequency dependent line models are used. Double circuit lines are modelled as separate lines. The Resulting line positive sequence parameters based on 100 MVA are given in Table 7.2.

Table 7-2 Line data

Line	Nominal voltage [kV]	Length [km]	Resistance in [pu]	Reactance in [pu]	Susceptance in [pu]
1-2	220	99,14	0,0123	0,0782	0,146
1-6	220	300	0,0360	0,233	0,445
2-5	220	210	0,0257	0,165	0,310
3-4 circuit 1	220	99,75	0,0124	0,0787	0,147
3-4 circuit 2	220	99,75	0,0124	0,0787	0,147
4-5	220	210	0,0257	0,165	0,310
4-6	220	300	0,0360	0,233	0,445
7-8 circuit 1	400	500	0,0087	0,09	3,152
7-8 circuit 2	400	500	0,0087	0,09	3,152

Parameters for transformers are given in Table 7.3. All transformers have tap regulation at their higher voltage windings.

Table 7-3 Transformer data

Transformer	Rating [MVA]	UN of winding 1 [kV]	UN of winding 2 [kV]	Tap ratio	Leakage reactance [pu]
7-1	1000	400	220	0,955	0,1
8-3	1000	400	220	0,955	0,1
2-10	600	220	22	1,05	0,1
3-11	250	220	22	1,05	0,1
6-12	180	220	22	1,045	0,1

Load characteristics and capacitor banks sizes are presented in 7.4.

Table 7-4 Loads and capacitor banks data

Bus #	Load [MW]	Load [Mvar]	Shunt capacitance [Mvar]
2	280	200	
3	320	240	
4	320	240	160
5	100	60	80

7.5.2 Generators

Rated power of generators are: G2 – 588 MVA, G3 – 235 MVA
All generators have the same parameters expressed in pu on the basis of their MVA rating, and are as follows:

- Ra=0,0025, Xp=Xa=0,2; Xd=1,8, Xd'=0,3, Tdo'=8s, Xd"=0,25, Tdo"=0,003s, Xq=1,7, Xq'=0,55, Tqo'=0,4s, Xq"=0,25, Tqo"=0,05s
- Saturation curve: (0,5, 0,5), (0,8, 0,79), (1,0, 0,947), (1,2, 1,07), (1,5, 1,2)
- Inertia constant – H = 4 s.

Parameters of generators are taken from Reference [2].

7.5.3 AVRs and PSSs

All generators are equipped with AVR of ST1A type with independent supply. Generator G2 and G4 have also PSS of PSS1A type using shaft speed as an input signal.

Main AVR parameters are as follows:

- Lead time constant Tc = 1 s
- Lag time constant Tb = 10 s
- Gain Ka = 500
- Exciter limits Vrmax = 7, Vrmin = 0,6

PSS parameters are:

- 1st lead time constant T1 = 0,15s
- 2nd lead time constant T3 = 0,15 s
- 1st lag time constant T2 = 0,04s
- 2nd lag time constant T4 = 0,04 s
- Washout time constant T5=10s

- Gain Ks=1

7.5.4 External grid

The external grid is modelled as a 22kV voltage source with the internal resistance 0,001 Ohm connected to bus 1 by transformer 22/220kV with reactance 0,01 pu on 100 MVA base. That results in bus 1 being a very stiff bus with short circuit power of almost 10.000 MVA.

7.5.5 Verification of models.

The PSCAD benchmark model was checked against results achieved using such power system software as Power Factory (DigSilent) and PSS/E. Both steady states and dynamic results were verified and the results obtained from the different simulation software packages, appeared to match with each other satisfactorily. The bus voltages and power flows for the intact grid and line contingences were tested for the steady state studies, and three phase faults cleared by line disconnection were tested for the dynamic studies.

7.6 REFERENCES

[1] Annakkage, U.D., Gole, A.M. Jiang Shan, “Progress On the Development of the Benchmark Test Systems to Validate HVDC and FACTS Models,” University of Manitoba, Winnipeg, Canada, June, 2004.

[2] Kundur P., “Power System Stability and Control”, McGraw-Hill, 1993.

8. RESULTS OF INTERACTION STUDIES

8.1 INTRODUCTION

This chapter describes the results of the simulations performed using the benchmark presented in chapter 7. The wind farm uses induction generators, and is connected to the grid using different transmission technologies. The event studied is a three phase short circuit to ground on a transmission line close to the grid connection point.

The chapter starts with a brief overview of the study, including the connection methods, a description of the wind farm, an overview of the studies done and the study methodology. This overview is followed by a description of the different signals that can be observed in the plots for the study case. The different study cases are described next, providing details on the interconnection method as well as plots showing the results of the studies. Finally, some brief conclusions are given at the end of the chapter.

8.2 OVERVIEW OF THE STUDY METHODOLOGY

Referring to Figure 7.1 in Chapter 7, the wind farm is connected to bus 12. Studies have been performed with the wind farm connected to the grid at bus 6 using : AC, LCC HVDC and VSC Transmission. In all cases a 100 km cable has been used as the connection between node 6 and 12. For reference purposes the bus where the wind farm is connected is called off-shore and the rest of the grid on-shore.

The wind farm is based on induction generators. This has been done for simplicity and generality of the model and to avoid interactions between power electronic controllers within the wind farm and the inter-connector, which would have complicated the interpretation of the study results. Additionally, the control schemes for DFIGs and Full Converter wind generation systems are subject to continuing development, and generic models of the controllers are not easily available.

It is important to note that the short circuit level at node 6 was determined as 732MVA without any generation connected at node 12.

Two different ratings of the wind farm connected at bus 12 have been studied generally, but some additional studies were performed at intermediate levels to determine the limit at which instabilities occurred, where applicable. The ratings studied were 160MW and 320MW. The 160 MW farm has 124 constant speed wind turbines of 1,8 MVA with a nominal connection voltage of 3,3 kV and compensated each with 0,42 Mvar of capacitors. Each turbine has a 3,3/33 kV step-up transformer. The wind farm is connected to bus 12 via a 180 MVA 220/33kV transformer. A pitch blade controller is assumed to operate if the induction generator speed increases above 1.015pu, and is based on a simple proportional controller, and is rate limited at 10deg/sec.

The fault scenario studied is the application of a solid three phase fault at bus 6, which is cleared after 100 ms by tripping the line between bus 1 and bus 6. Following the tripping of the line the short circuit level at node 6 was 317 MVA without any generation at node 12.

The following generation options connected at bus 12 have been studied:

- A 160MW synchronous generator connected via an ac cable
- A 160MW wind farm as above connected via an ac cable supported by an SVC/ STATCOM.
- A 320MW wind farm as above connected via an ac cable supported by an SVC/ STATCOM.
- A 160MW wind farm as above connected via a dc cable using LCC HVDC.
- A 320MW wind farm as above connected via a dc cable using LCC HVDC.

- A 160MW wind farm as above connected via a dc cable using VSC Transmission.
- A 320MW wind farm as above connected via a dc cable using VSC Transmission.

For the studies involving power electronics, such as SVCs, STATCOMS, LCC HVDC and VSC Transmission some effort was made to identify the rating required of these devices in order to meet the system performance criteria as has been outlined in section 7.3.2 of Chapter 7. However, it should be noted that the controllers were not fully optimised, as would be done in commercial projects, and therefore it is likely that the ratings established during these studies will be pessimistically high. On the other hand, the converter protection was not modelled in the studies, and therefore there could be a risk that some modifications would have to be made to the responses, so that equipment ratings are not exceeded.

In summary, the study results should not be taken as a firm indication of the ratings that would be required for the different technologies, nor indeed of the performance that should be expected. The main objectives of the studies are:

- to illustrate how power electronics can facilitate the connection of large scale wind farms,
- to encourage others to perform similar studies, with different power electronic solutions (FACTS or HVDC)
- to encourage others to do similar studies with different types of wind generation
- to generally encourage research and development for connection of large scale wind farms

8.3 LEGEND FOR PERFORMANCE STUDY RESULTS

The following terminology has been adopted for the variables presented in the study results in the following sections.

Table 8-1 Terminology of variables

Variable	Description
V_BUS6	Voltage at bus 6 (onshore)
V_G4	Voltage at generator G4 terminal
P_G4	Real power of generator G4
Q_G4	Reactive power of generator G4
P_G4_BUS6	Real power from generator G4 supplied to the grid
Q_G4_BUS6	Reactive power from generator G4 supplied for the grid
SPEED_G4	Rotational speed of generator G4
V_BUS12	Voltage at bus 12 (offshore)
P_G12_BUS12	Real Power from the wind farm generator connected at Bus 12 flowing into Bus 12
Q_G12_BUS12	Reactive Power from the wind farm generator connected at Bus 12 flowing into Bus 12
FREQ_G12_BUS12	Rotor frequency of wind farm generator connected at bus 12
SVC_VT	Terminal voltage of 220kV offshore connected SVC or STATCOM
SVC_Q	Reactive Power at the 220kV terminals of the SVC
SVC_ALPHA	Firing angle of the TCR element of the SVC
SVC_TSC_STEPS	Number of SVC TSC steps switched on

Variable	**Description**
SVC_GAIN	Forward gain in one block of the SVC voltage control loop
STATCOM_Q	Reactive Power at the 220kV terminals of the STATCOM
STATCOM_IQ	Quadrature component of STATCOM output current
P_DC_BUS6	Real Power flowing out of the HVDC link and flowing into Bus 6 via the HVDC link, including AC filters and synchronous compensator
Variable	Description
Q_DC_BUS6	Reactive Power flowing out of the HVDC link and flowing into Bus 6 from the HVDC link including AC filters and synchronous compensator
FREQ_SC12_BUS12	Rotor frequency of synchronous compensator connected at bus 12
IDC_BUS12	Direct current at the bus 12 (rectifier, offshore) side of the HVDC link
VDC_BUS12	Direct voltage at the bus 12 (rectifier, offshore) side of the HVDC link
Pitch Angle	Angle of pitch blade controller

8.4 TEST OF THE BENCHMARK USING A SYNCHRONOUS GENERATOR AT BUS 12

This simulation was done to:

- Determine whether the benchmark model would be stable with a synchronous generator connected where the wind farm would be connected.
- Provide a basis to which the studies with different wind farms connected to bus 12 via different interconnectors could be compared.

8.4.1 Results

A three phase solid fault to ground was applied at bus 6, the fault being cleared by disconnection of line 1-6 after 100 ms.

The benchmark grid with a 180 MVA generator (G4) connected in bus 12, and loaded up to 160 MW was able to withstand a three phase solid fault to ground at bus 6, the fault being cleared by disconnection of line 1-6 after 100 ms. Increasing the rating of the generator G4 to a rated power equal to 360 MVA, the benchmark grid could withstand the same fault only for loading up to 252 MW.

Figure 8-1and Figure 8-2 shows the results for 160MW and 252MW generator loading respectively. The system parameters can be seen to provide a typical damped oscillatory result after fault clearance in both cases. The amplitude of the oscillations is greater for the larger generator, and the damping is also slower.

Figure 8-3 shows the results for the case with a generator loading of 259MW. The response is typical of a transient instability, and the generator would be disconnected from the ac network by its protection system.

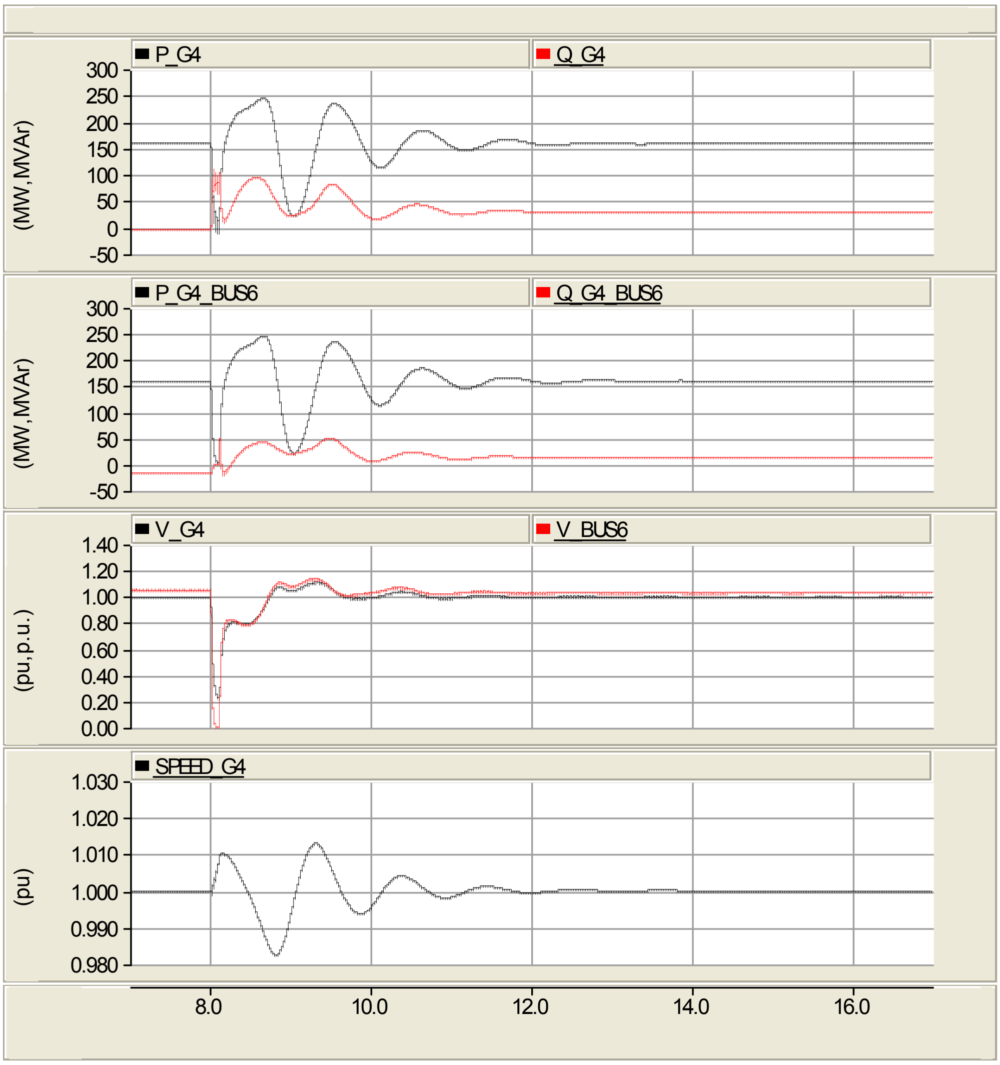

Figure 8-1 Synchronous generator G4 (180 MVA) operating with real power 160 MW

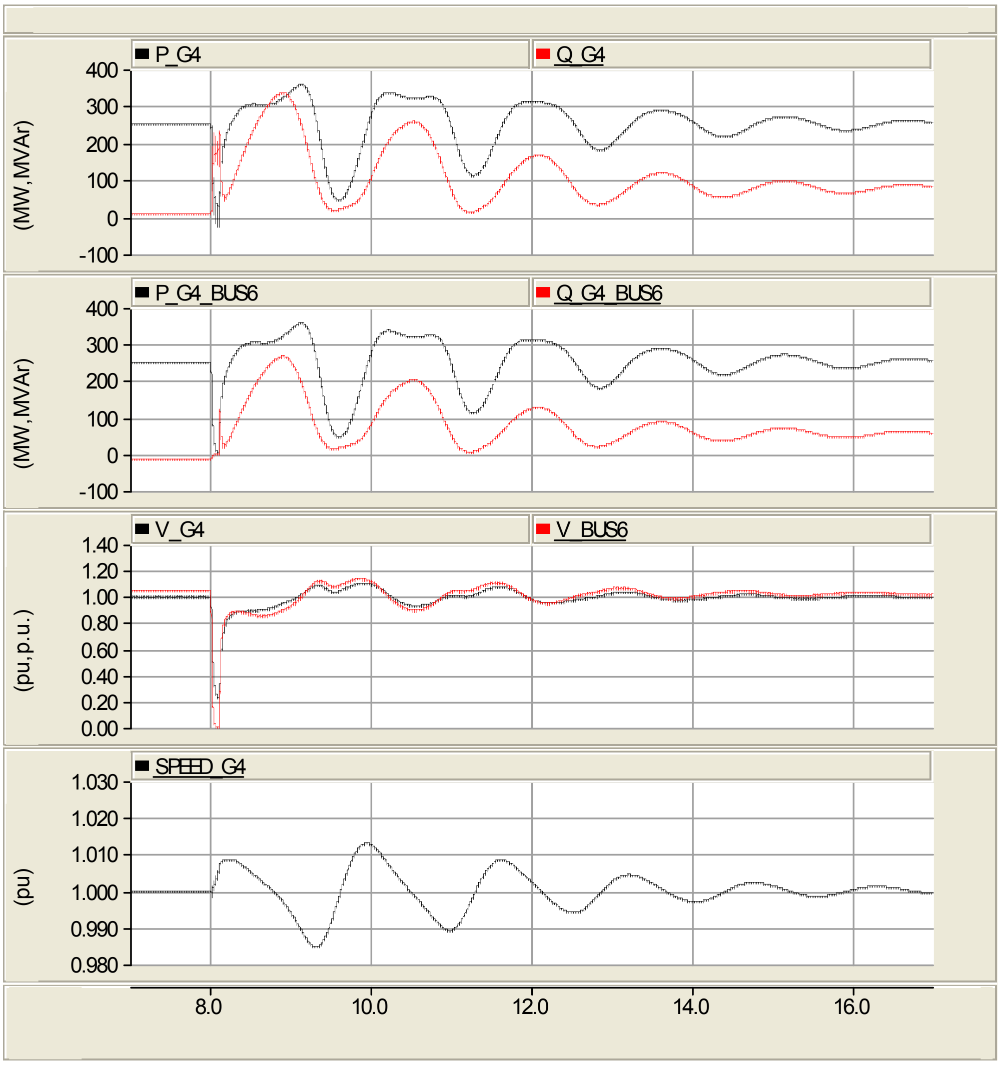

Figure 8-2 Synchronous generators G4 (360 MVA) operating with real power 252 MW.

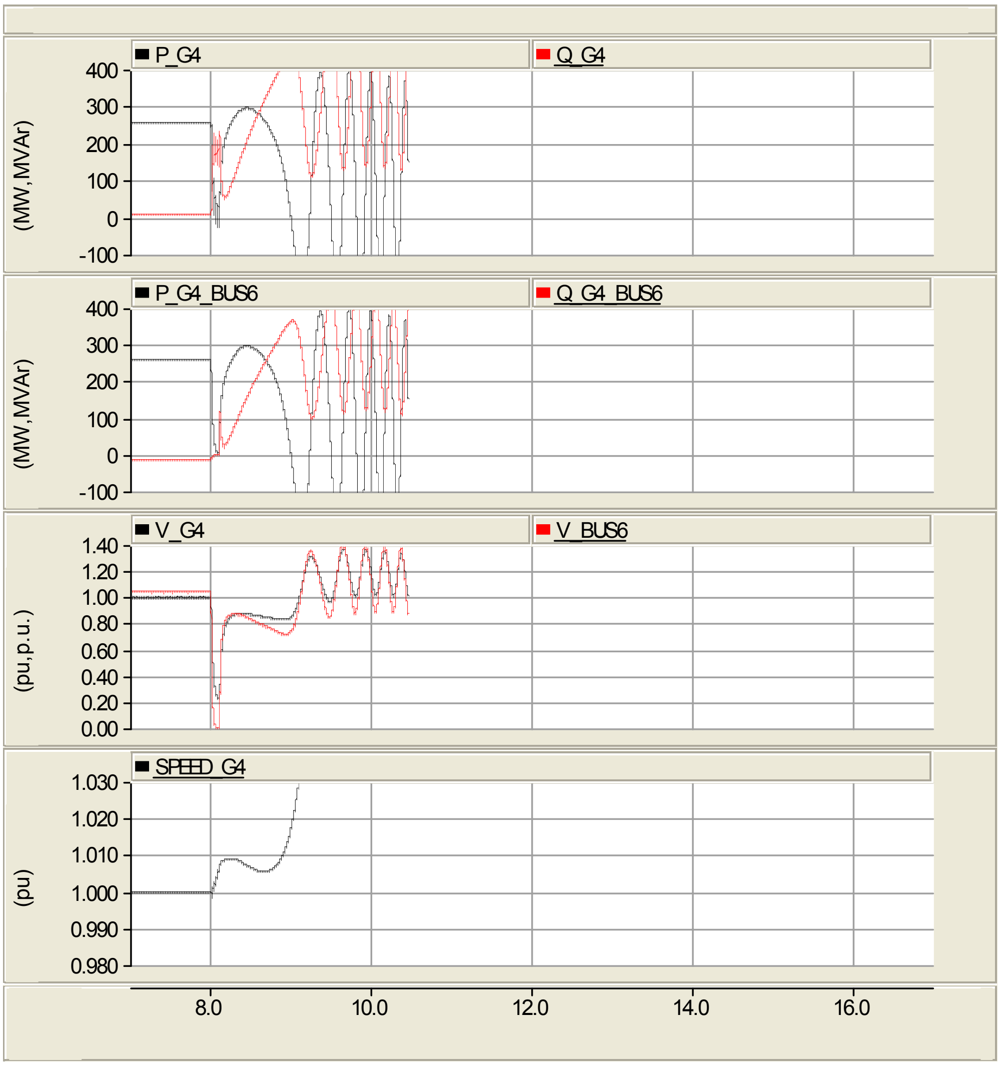

Figure 8-3 Synchronous generator G4 (360 MVA) operating with real power 259 MW

8.5 AC CONNECTION SUPPORTED BY SVC OR STATCOM

In this option a 220kV AC cable is used to connect the wind farm. The ac cable is compensated with shunt reactors at either end to cancel the charging current. An SVC or STATCOM is used on the offshore side to provide control of the AC voltage following an onshore fault. The model of the SVC controls is generic as available in PSCAD. The STATCOM controls are based on [1].

In all cases, a solid three phase fault is applied on bus 6 at t = 4.0 seconds, and the fault is cleared after 100ms by tripping the line between bus 1 and bus 6. The simulation is carried out using a calculation step of 25µs (SVC) or 50µs (STATCOM) with the total duration being varied according to the nature of the results.

8.5.1 160 MW wind farm

Two different options for reactive power compensation at Bus 12 (the offshore busbar) were investigated:

- -50/+250Mvar connected at 220kV and using a TCR and 5 TSC branches
- ±130Mvar STATCOM connected at 220kV

From Figure 8-4 it can be seen that during the fault, the 220kV AC voltage at the SVC and AC cable connection to the network drops to near zero (SVC_VT) hence there is no power transfer. The surplus energy produced from the wind goes into kinetic energy of the rotor inertia of the wind generator and the frequency of the induction generator goes up to 1.023 pu which is well below 1.1 pu, a typical overspeed protection setting for fixed speed induction generators. After fault clearance, the -50/+250Mvar SVC acts to boost the AC voltage to near nominal and the wind farm electrical power output (P_G12_BUS12) is increased to above the pre-fault level bringing the wind turbine generator rotor frequency (FREQ_G12_BUS_12) down to its pre-fault value and stable operation is resumed.

If the offshore SVC size is reduced to -50/+200Mvar, then after initially recovering, the AC voltage falls and the rotor frequency increases to above 1.1 pu, and the generator would trip on over-speed protection, as shown in Figure 8-5.

Comparison of the results in with those of Figure 8-4 indicates that wind turbine pitch control with a maximum rate of change set to typical values currently being applied is too slow to significantly alter the nature of post-fault recovery for first 0.5 second or so and are decisive for the outcome. The pitch control as modelled delays the return to normal operation.

Figure 8-7 shows the behaviour with the lowest possible (±130 Mvar) rated STATCOM for successful post-fault recovery replacing the offshore SVC. It can be noted that after initial post-fault recovery the AC voltage dips to 0.8pu before a 1.1pu overshoot and that this results in a pause and resumption in the recovery of wind turbine generator rotor frequency.

Although the system can be readily made to recover from a solid three phase fault with a 100 ms duration, a relatively large SVC or STATCOM is required, and this may affect the viability of the scheme.

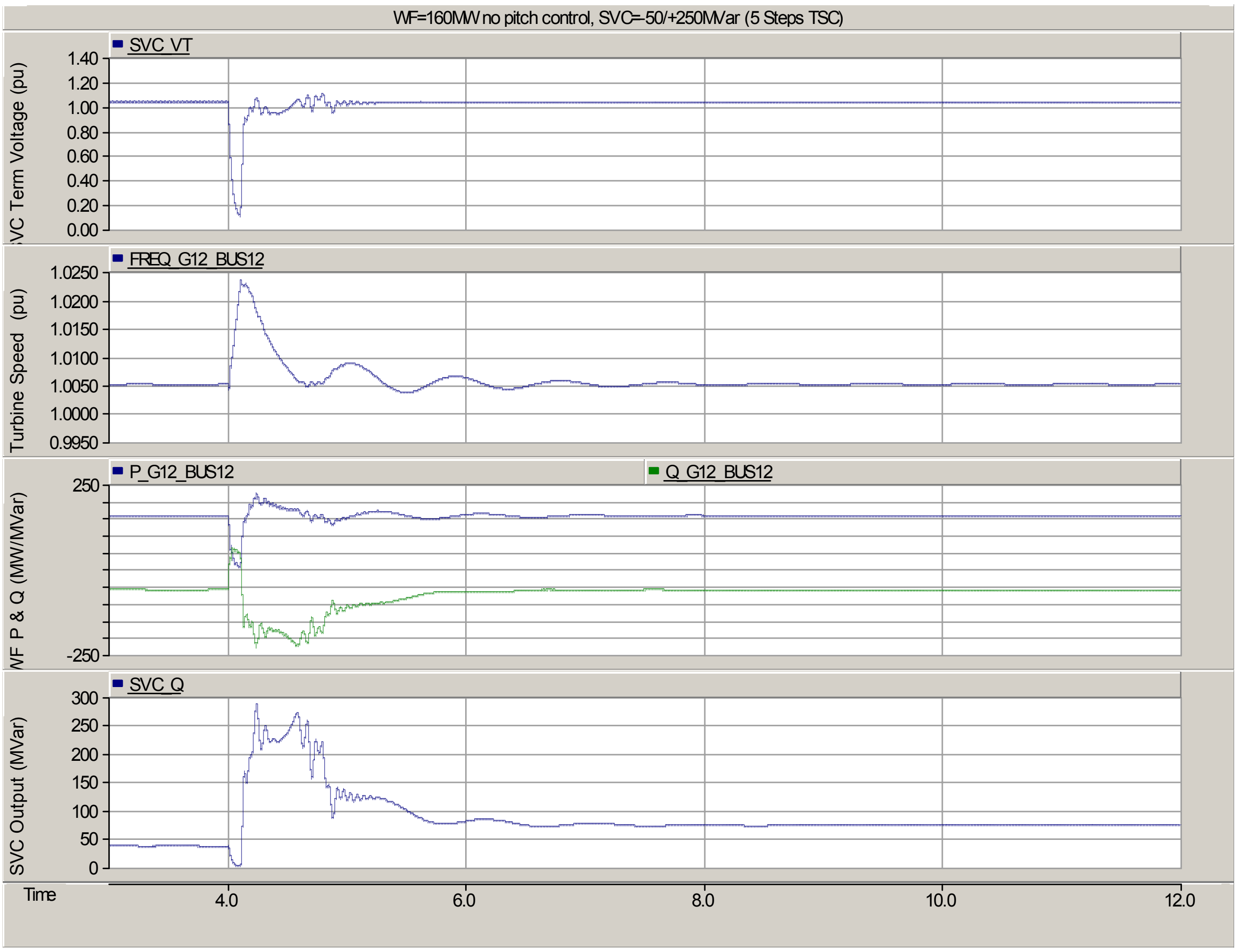

Figure 8-4 Wind farm (160MW) connected via AC with a -50/250Mvar SVC offshore

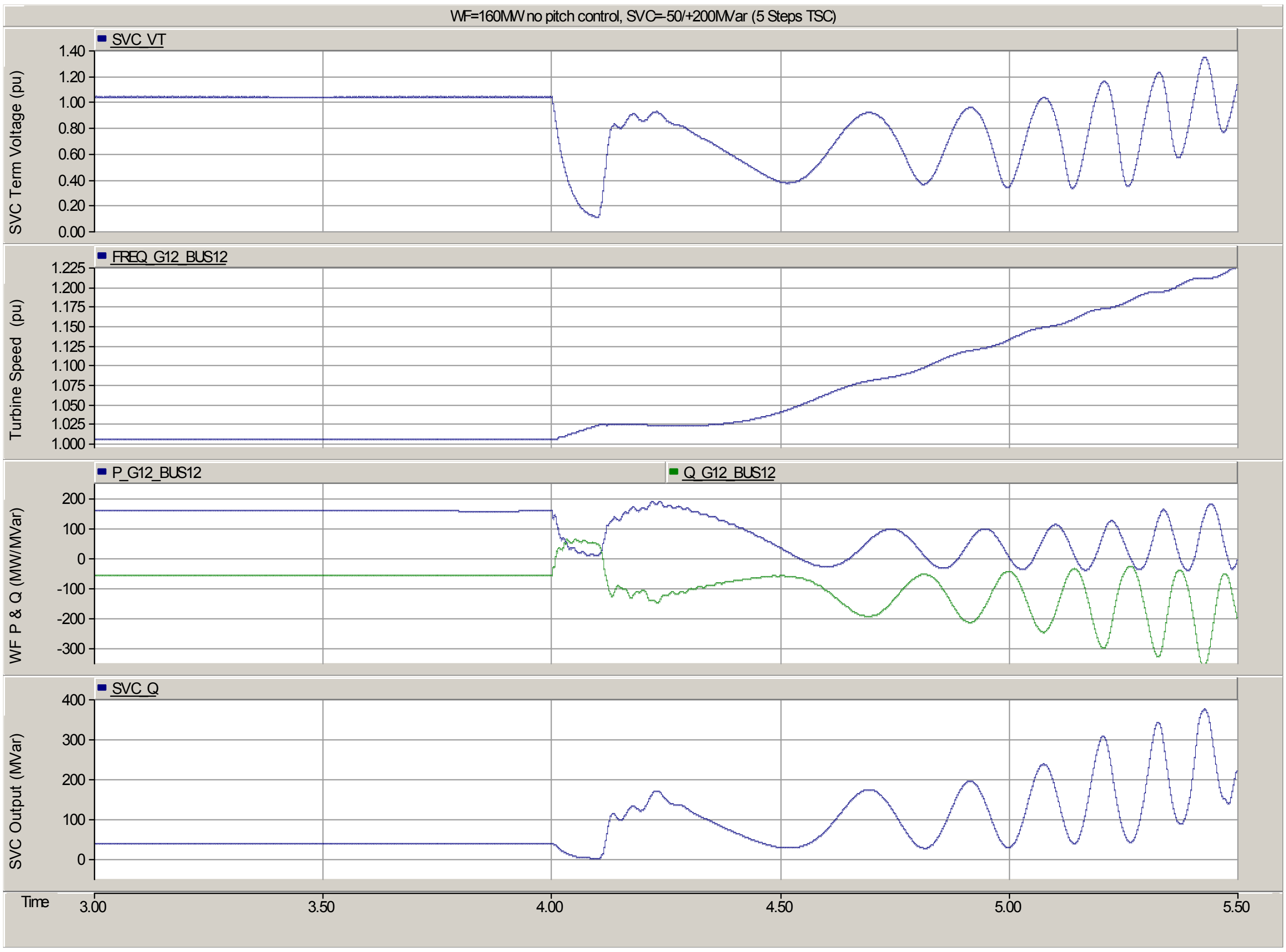

Figure 8-5 Wind farm (160MW) connected via AC with a -50/200Mvar SVC offshore

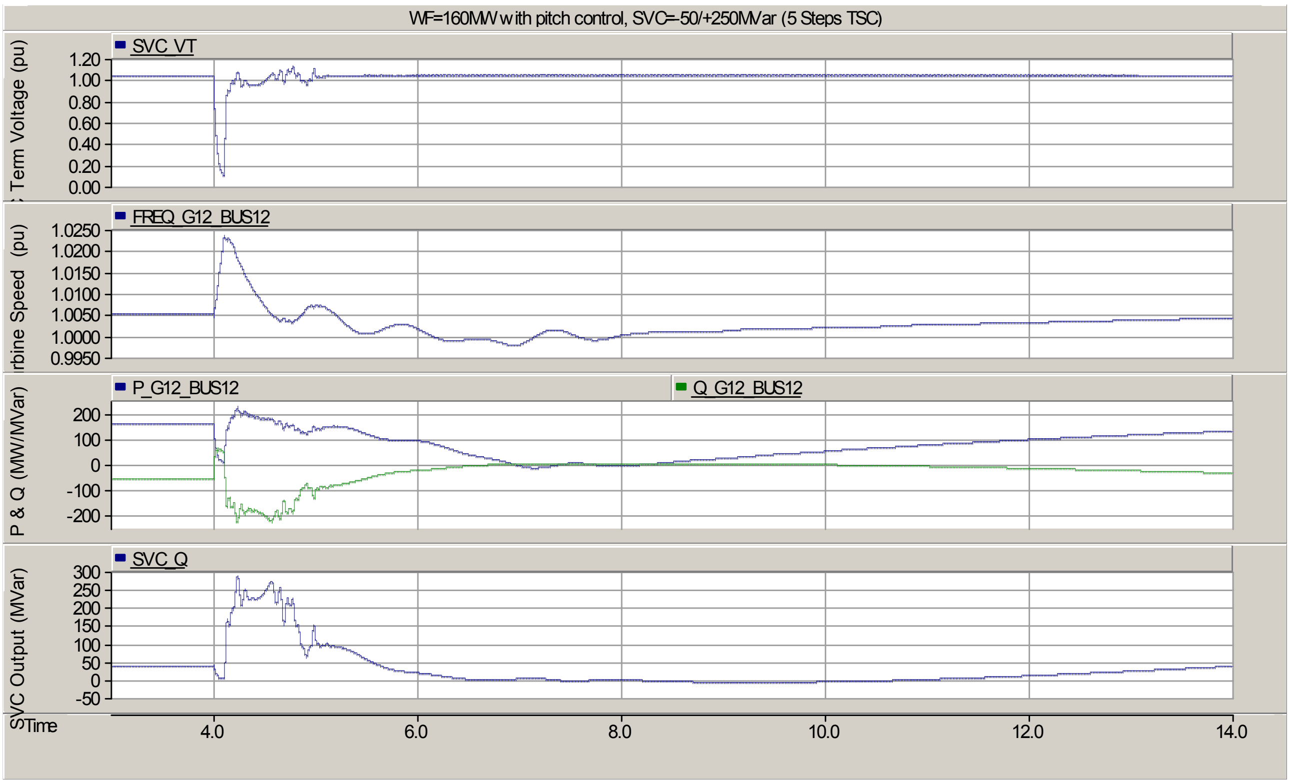

Figure 8-6 **Wind farm (160MW) with pitch control connected via AC with a -50/250Mvar SVC offshore**

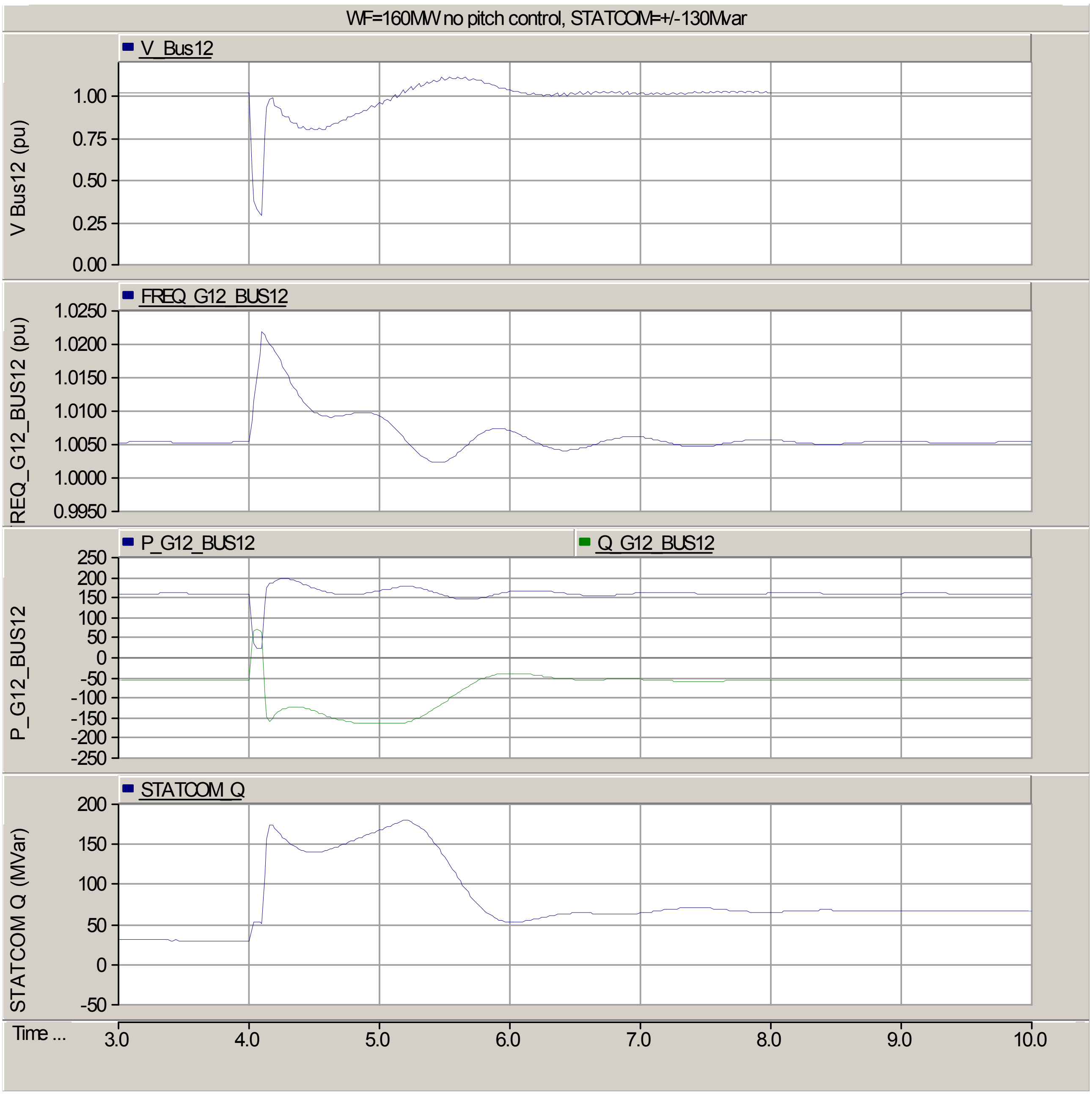

Figure 8-7 **Wind farm (160MW) connected via AC with a ±130Mvar STATCOM offshore**

8.5.2 320 MW wind farm

Four different options for reactive power compensation at Bus 12 (the offshore busbar), and wind generator pitch control were investigated as follows:

A) -100/+500Mvar SVC connected at 220kV and using a TCR and 5 TSC branches, using adaptive control. Wind farm without pitch control
B) -100/+500Mvar SVC connected at 220kV and using a TCR and 5 TSC branches, NOT using adaptive control. Wind farm without pitch control
C) -200/+500Mvar SVC connected at 220kV and using a TCR and 5 TSC branches, NOT using adaptive control. Wind farm with pitch control
D) 390Mvar STATCOM connected at 220kV. Wind farm with pitch control

From Figure 8-8 (SVC A – no pitch control) it can be seen that during the fault, the 220kV AC voltage at the SVC and AC cable connection to the network drops to near zero (SVC_VT) hence there is no power transfer. The surplus energy produced from the wind goes into kinetic energy of the rotor inertia of the wind generator and the frequency of the induction generator goes up to 1.023 pu which is well below 1,1 pu, a typical overspeed protection setting for fixed speed induction generators. During the fault clearance, the -100/+500Mvar SVC switches in TSC steps in an attempt to restore the depressed voltage and this results in a brief 140% temporary overvoltage on fault clearing which results in the wind farm electrical power output (P_G12_BUS12) being increased to above the pre-fault level and reducing the excursion in wind turbine generator rotor frequency (FREQ_G12_BUS_12). The SVC output (SVC_Q) and 220kV voltage (SVC_VT) are very oscillatory indicating excessive gain in the SVC control loop but the voltage is held oscillating around nominal and stable operation of the wind turbine generator rotor frequency down is resumed. The SVC voltage loop gain (SVC_GAIN) is reduced at t = 7 seconds and the voltage oscillations die away allowing overall stable operation of the wind farm to resume.

If the SVC gain is reduced prior to the fault, then after initially recovering, the AC voltage falls and the rotor frequency increases over 1,1 pu, and the generator would trip on overspeed protection, as shown in Figure 8-9 (SVC B – no pitch control). Thus, an SVC with adaptive gain control is desirable for this solution.

Comparison of the results in Figure 8-10 (SVC C and pitch control) with those of Figure 8-8 indicates that wind turbine pitch control with a maximum rate of change set to typical values currently being applied is too slow to significantly alter the nature of post-fault recovery for the first 0.5 second or so to be decisive for the outcome. The mechanical power input to the wind turbine is reduced in a nonlinear way as the blade pitch angle (BETA_G12_BUS12) varies from 0 (maximum) to 28 degrees (zero). The pitch control as modelled delays the return to normal operation and a slightly larger SVC inductive range is needed to limit AC overvoltages during this delay. It can be noted that the oscillations in the SVC voltage control loop disappear when the wind farm power output reduces but reappear as it returns to normal and a reduction in SVC loop gain (at t=15 seconds) is required to suppress them.

Figure 8-11 (STATCOM D, pitch control) shows a failure in post-fault recovery with a 390 Mvar rated STATCOM replacing the offshore SVC. It can be noted that even though the AC voltage recovers to and remains above nominal, the wind turbine generator rotor frequency begins to recover but then suddenly increases due to a rapid fall in the wind farm power output (P_G12_BUS12). This appears to be due to an oscillatory mode that is not present with the SVC.

Although the system can be made to recover from a solid three phase fault with a 100 ms duration, a relatively large SVC or STATCOM is required, and this may affect the viability of the scheme. Due to the large rating of the wind farm compared to the post-fault reduced system strength, the structure and parameter settings of SVC or STATCOM controls have a great impact on the performance. Although successful post fault recovery was not achieved in the studies performed, the result suggests that it should be possible to achieve this using a purpose designed control system with appropriate parameters.

The study results clearly indicate that fault ride through is not the only requirement for successful operation and the interactions between the SVC or STATCOM controller, wind turbine controller and the rest of the network need to be assessed to ensure small and large signal stability.

The required size of SVC or STATCOM depends on the type of wind generator, the presence of fast pitch blade control, the strength of the receiving AC system, and the fault duration.

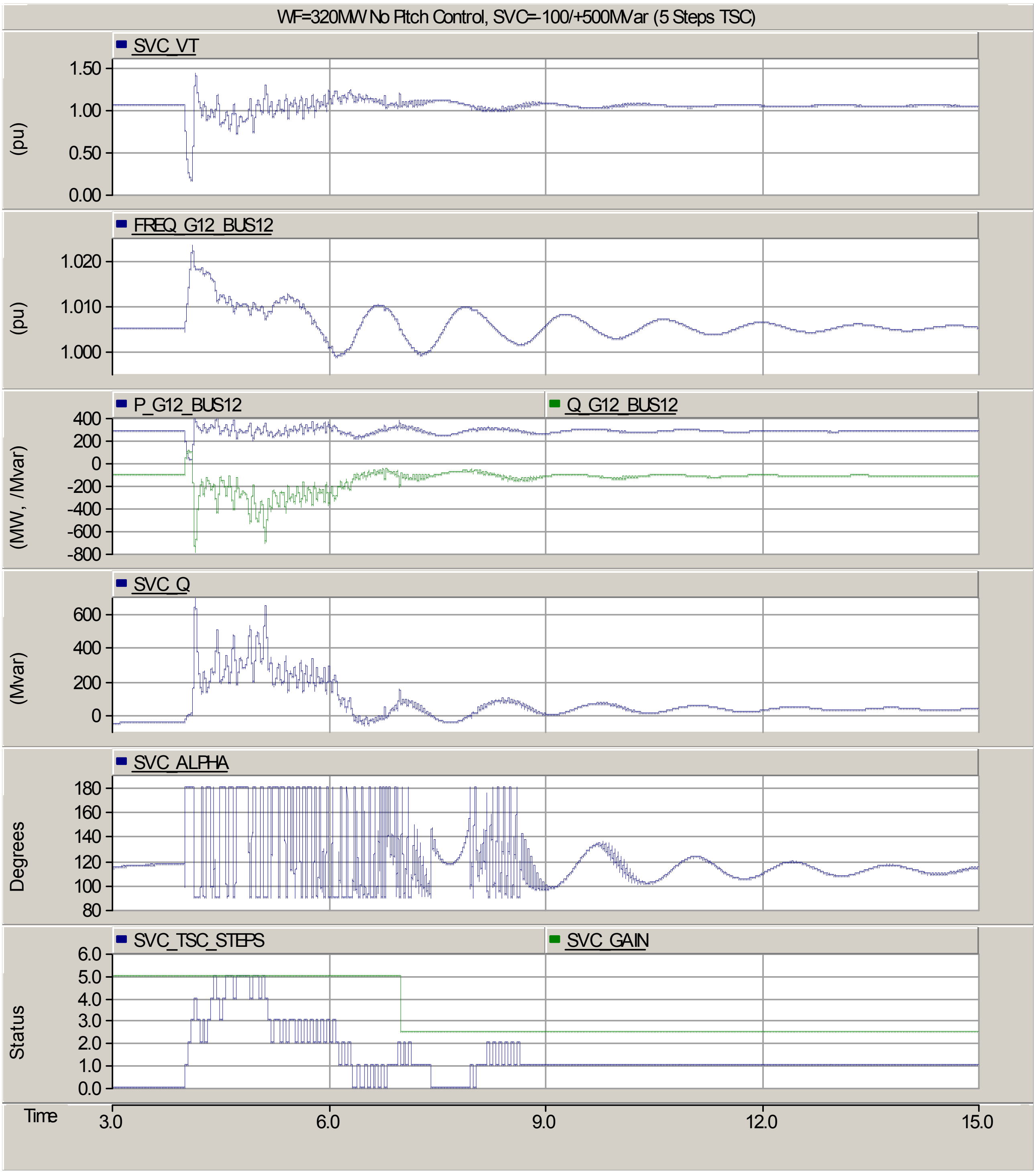

Figure 8-8 **Wind farm (320MW) connected via AC with -100/500Mvar SVC offshore, Adaptive control. No pitch control**

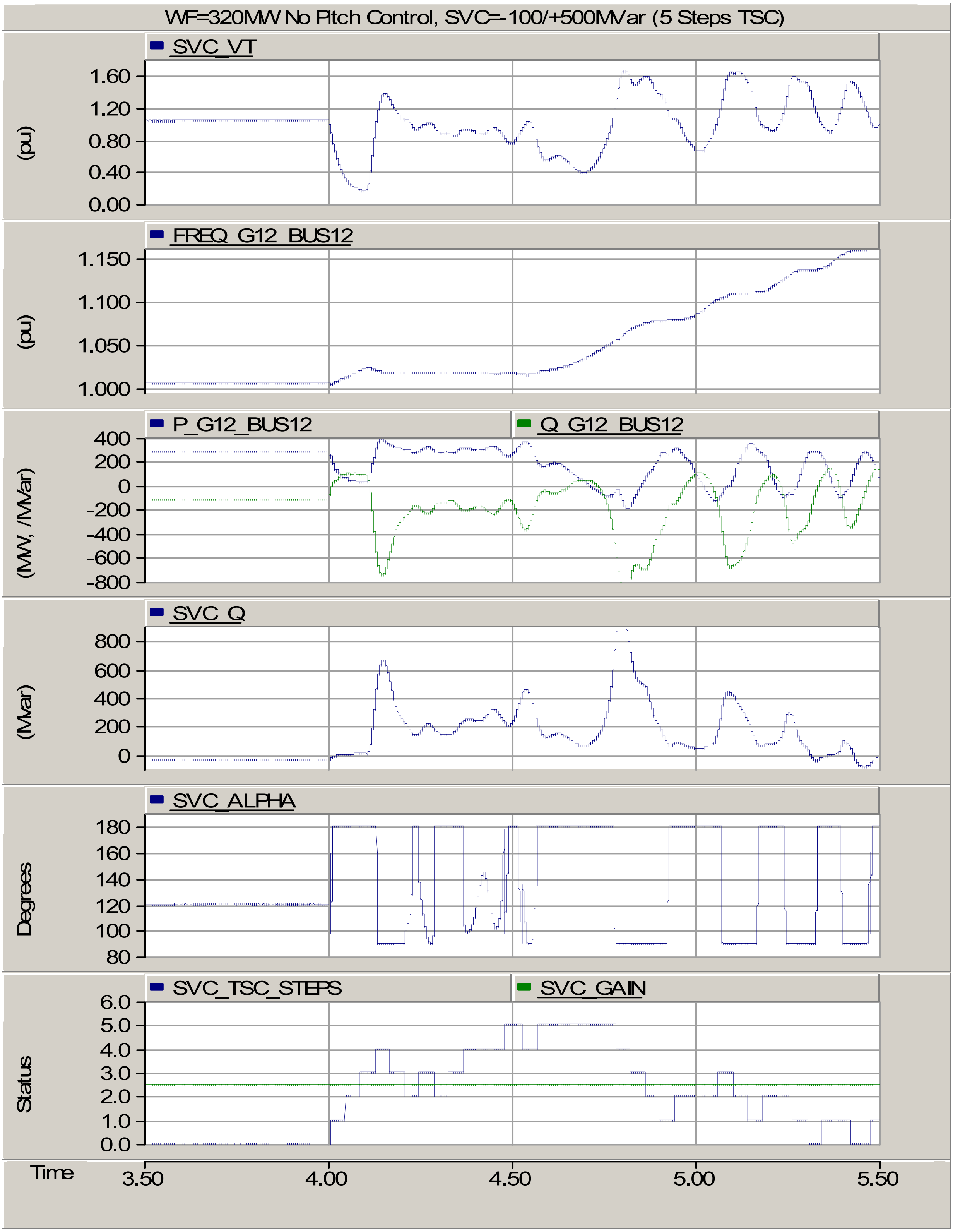

Figure 8-9 **Wind farm (320MW) connected via AC with -100/500Mvar SVC offshore. No adaptive control. No pitch control.**

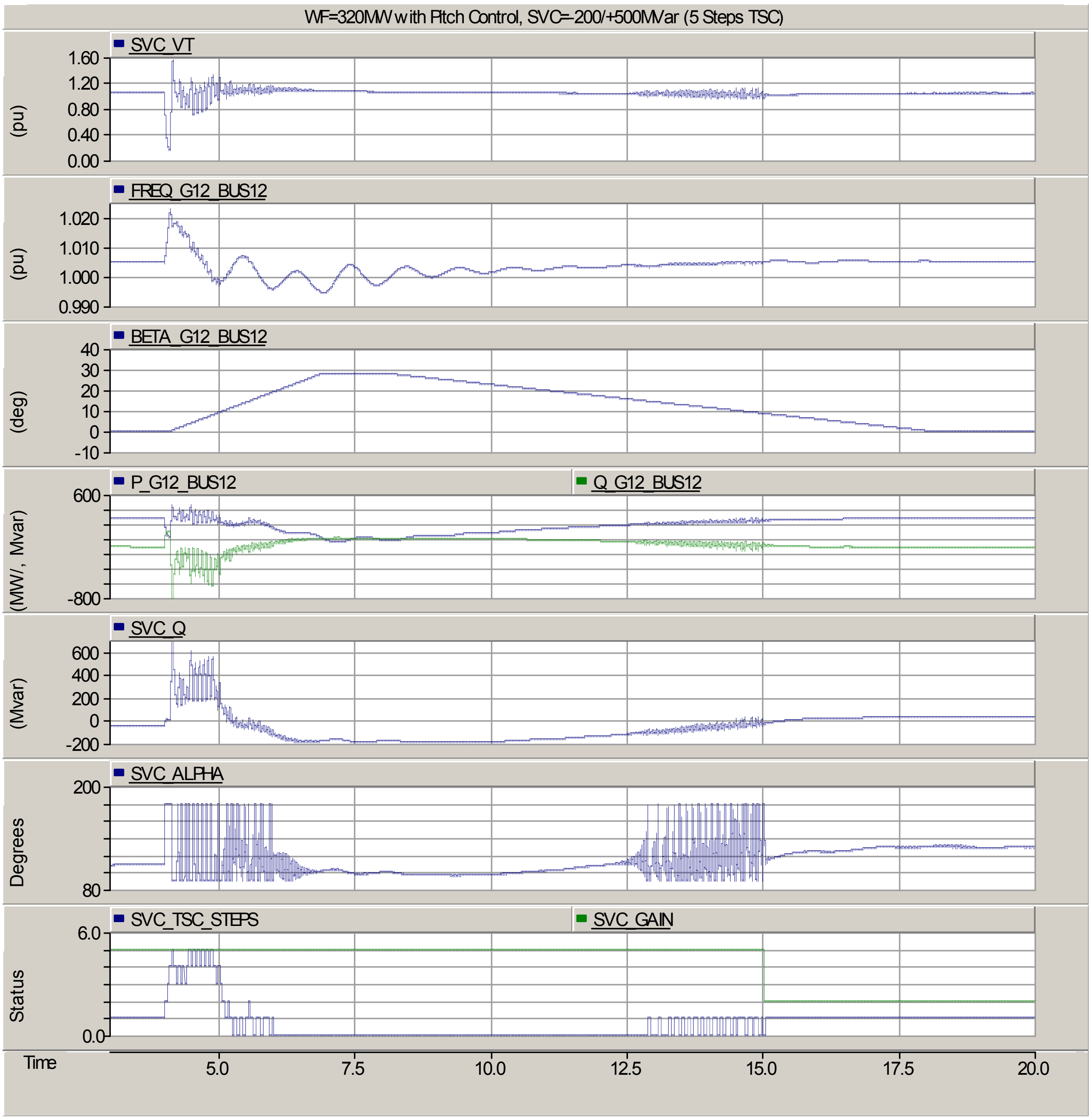

Figure 8-10 Wind farm (320MW) with pitch control connected via AC with -200/500Mvar SVC offshore. Adaptive control

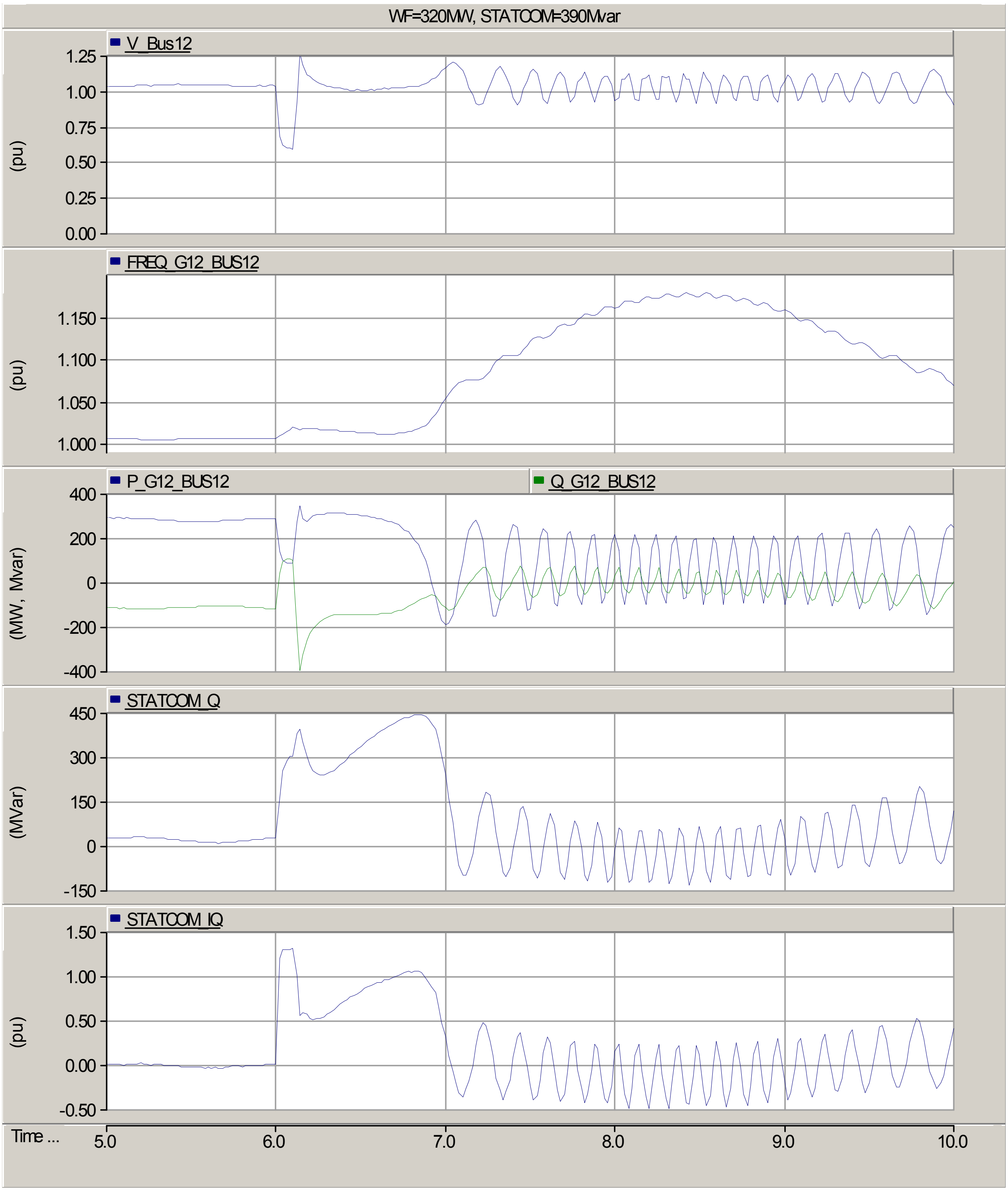

Figure 8-11 Wind farm (320MW) connected via AC with ±390Mvar STATCOM. With Pitch control.

8.6 LCC HVDC CONNECTION

In this option an HVDC link based on Line Commutated Converters (LCC) is used to connect the wind farm. A synchronous compensator is used on the offshore side to provide control of AC voltage and to maintain the power balance during an onshore fault. On the onshore side a synchronous compensator is introduced to increase the short circuit level at bus 6 to stabilise the AC voltage and to prevent repetitive commutation failure, which may occur with LCC HVDC links connected to very weak AC networks on the inverter side. The model of the HVDC controls is generic as available in the simulation software package PSCAD with some modifications for this application, for example the current order is varied as a function of offshore frequency. All synchronous compensators have an inertia of 1,5 s. Table 8-2 lists the scenarios studied for the LCC HVDC option to connect the wind farm.

Table 8-2 LCC HVDC fault recovery study cases

Case	Wind Farm size [MW]	Synchronous Compensator size [MVA]		Pitch Blade Control
		Onshore	Offshore	
1	160	50	30	Yes
2	160	50	30	No
3	320	320	100	Yes

In all cases a solid three phase fault is applied on bus 6 at t = 8,0 seconds, and the fault is cleared after 100 ms by tripping the line between bus 1 and bus 6. A plot step of 1ms is used and a calculation step of 50 µs.

Table 8-3 summarises the main result of each case study

Table 8-3 Summary of study results

Case	Fault ride through successful?	Comments
1	Yes	Successful assuming that overvoltage of 1.2 pu offshore can be tolerated by electrical equipment offshore.
2	No	Not successful, would trip on induction generator overspeed protection.
3	Depends on overvoltage protection setting	The AC network is very oscillatory. Slow response by the synchronous compensator causes overvoltage to reach 1.3pu offshore

In case 1 (Figure 8-12), it can be observed that during the fault, the DC voltage drops to zero (VDC_BUS12) hence there is no DC power transfer. The surplus energy produced from the wind goes into kinetic energy, available in the inertia within the wind generator rotor and the synchronous compensator. The frequency of the induction generator increases to 1,055 pu which is well below 1,1 pu, a typical overspeed protection setting for fixed speed induction generators. As a result of the increased rotor speed the pitch blade controller angle is increased thereby reducing the amount of power flowing into the offshore grid. After fault clearance, the direct current of the LCC HVDC is increased to bring the offshore frequency down to its pre-fault value, and fault recovery is successful, assuming that an overvoltage of 1,2 pu offshore can be tolerated by the electrical equipment offshore.

In case 2 (Figure 8-13), the same scenario is studied but without a pitch blade controller. It can be observed from Figure 8.4.2 that the scheme would trip on overspeed protection. The uncontrolled accelerating speed is due to the fact that the electromagnetic torque is reduced too much due to low AC voltage offshore, whilst the mechanical torque remains the same assuming a constant wind. After the offshore frequency increases above 60 Hz (1,2pu), then the HVDC controls start to malfunction resulting in repetitive commutation failure. If the offshore synchronous compensator size would be increased to 80 MVA, then the offshore AC voltage can be controlled adequately and a successful fault recovery would be possible without a pitch blade controller.

In case 3 Figure 8-14, the increased wind farm size of 320 MW causes the network to become very oscillatory, and it was found that very large synchronous compensators are required offshore and onshore to stabilise the system, and prevent repetitive commutation failure. The system could only recover if the offshore equipment is designed to withstand an AC overvoltage of more than 1,3 pu for a duration of less than 1 second.

Although the system can be made to recover from a solid three phase fault with a 100 ms duration, relatively large synchronous compensators are required affecting the viability of the scheme. Note however that the required size of dynamic reactive power compensation depends very much on:

- HVDC controls. The fact that simplistic controllers have been used means that the required sizes of the synchronous compensators are likely to be higher than would be required in a real scheme with well designed and optimised controllers.
- Type of wind generator, and the presence and speed of a pitch blade controller. The pitch blade controller is particularly effective in this system, because a change in power output by the wind generator has a large impact on the offshore frequency due to the relatively low system inertia offshore. Controlling the offshore frequency in turn has a positive effect on the slip of the induction generator and thereby voltage stability.
- Strength of the receiving AC system. The weaker the system the less stable the AC voltage is at the point of connection and the more chance of repetitive commutation failure of the LCC HVDC inverter.
- Fault dip magnitude and duration. A larger voltage dip and a longer duration, means that more surplus wind energy needs to be absorbed offshore by some form of compensation.

Note that a STATCOM may be used instead of a synchronous compensator. On the offshore side such a STATCOM would require sophisticated controls to co-ordinate with the LCC HVDC link and generators [2]. Energy storage may be required in the form of very large DC-capacitors, or flow batteries, to facilitate the balance of power offshore during faults in the onshore network. Alternatively, a breaking resistor could be used, either implemented as a breaker switched resistor or a thyristor switched resistor. Most of the surplus energy can be absorbed in the rotors of the wind generators, or be reduced by applying fast pitch blade control, however very fast co-ordination (in the ms range) is needed between the STATCOM and HVDC controls, and, if present, the controls of the wind generator to maintain power balance offshore. These measures are required because the AC voltage does not drop at the stator terminals of the wind generator, unlike in the case of an AC connection. Satisfactory ride through capability of the combined generator and DC transmission system needs to be proved by detailed simulation representing the converters with their individual thyristor switch modules.

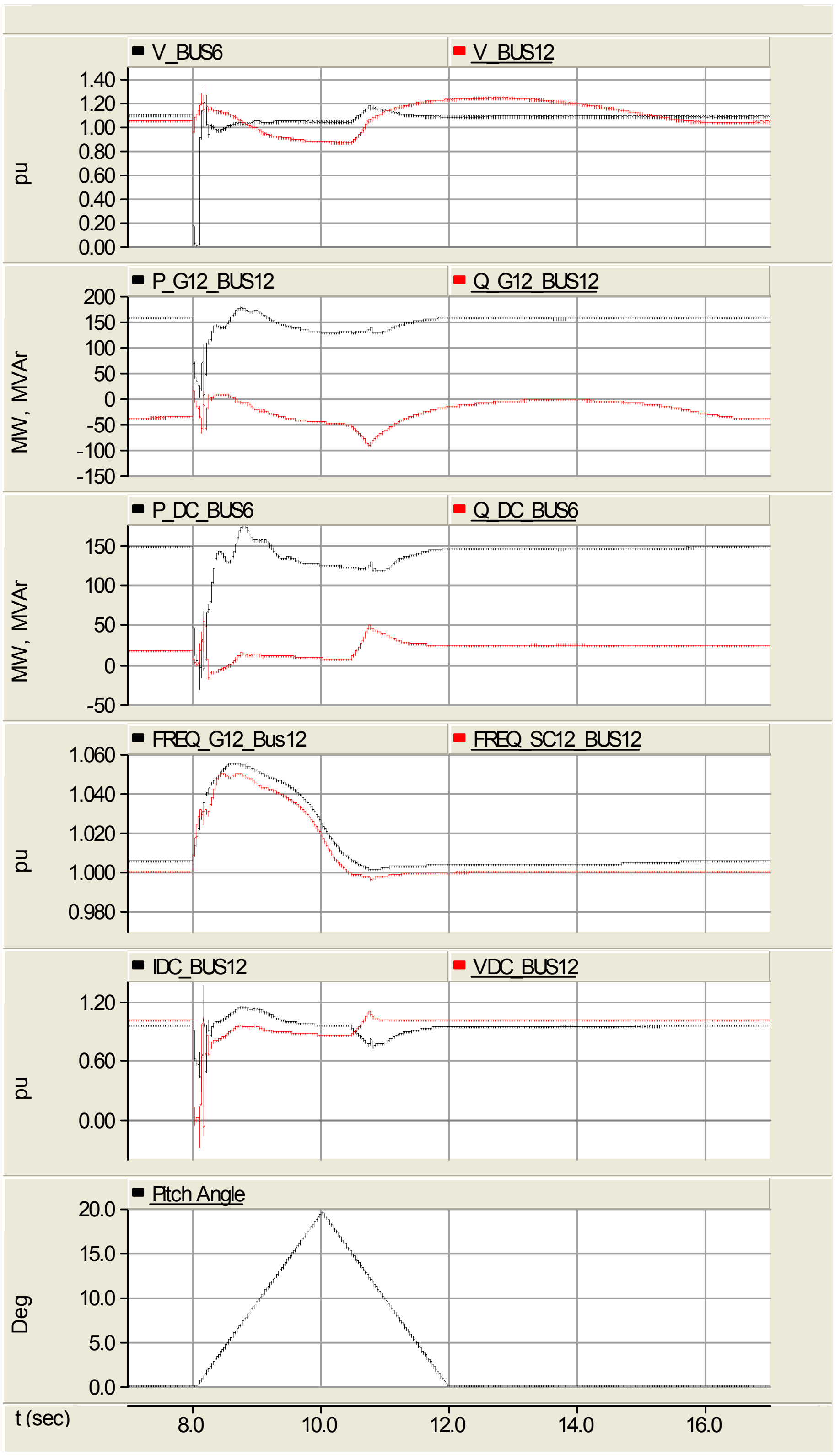

Figure 8-12 **Wind farm (160MW) connected via LCC HVDC with a 30MVA Synchronous Compensator offshore and 50MVA Synchronous Compensator onshore.**

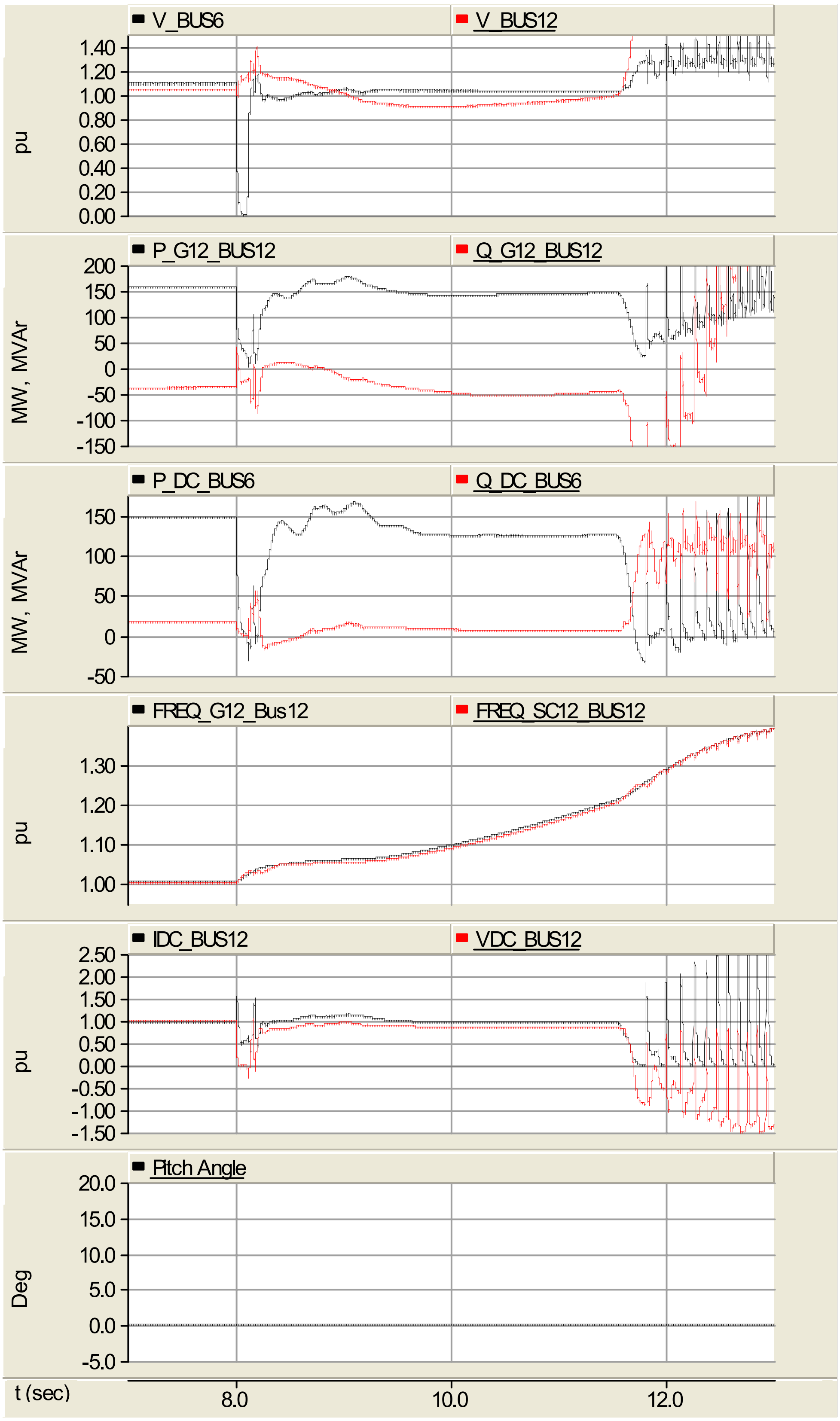

Figure 8-13 As Figure 8-12 but without active pitch blade control.

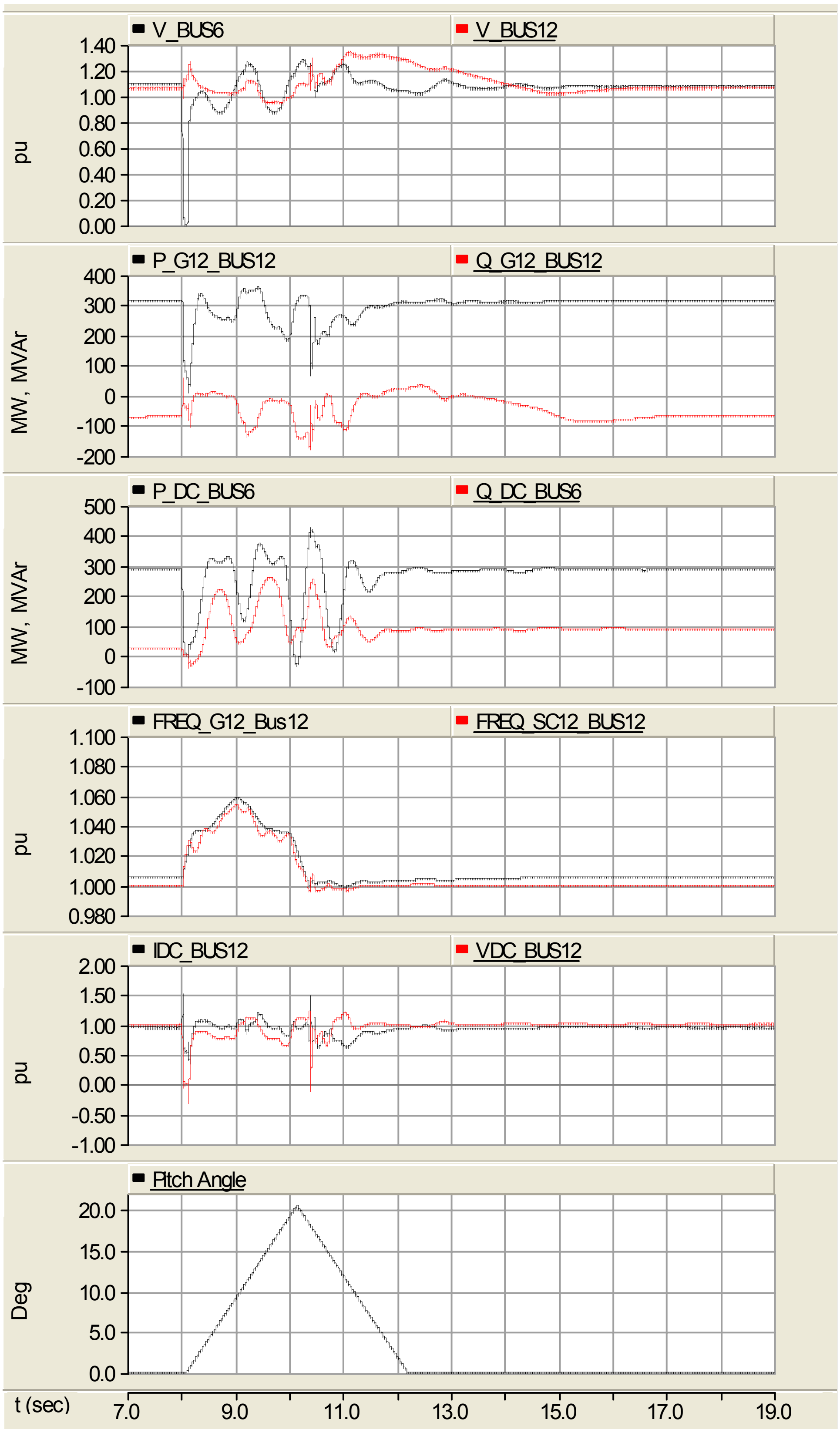

Figure 8-14 Wind farm (320MW) connected via LCC HVDC with a 80MVA Synchronous Compensator offshore and 320MVA Synchronous Compensator onshore.

8.7 CONNECTION WITH VSC TRANSMISSION

In this option an HVDC link based on Voltage Sourced Converters (VSC Transmission) is used to connect the wind farm. Since a VSC Transmission scheme is forced commutated, and provides reactive power control at its ac terminals independently of the active power flow, it can operate with very weak, or even passive, ac networks. Therefore, no synchronous compensators, STATCOMs or SVCs are required to achieve acceptable performance.

This study was performed by a manufacturer, and a control system optimised for a wind farm application was used. Additionally, the VSC Transmission system was modified relative to the standard VSC Transmission, by the inclusion of a dc voltage chopper with dump resistor, such that the energy from the wind could be absorbed by the HVDC scheme, even when a complete ac voltage collapse occurred in the receiving ac network. It is therefore not surprising that the response of this solution is substantially better than that obtained with the other integration methods.

In all cases a solid three phase fault is applied on bus 6 at t = 8,0 seconds, and the fault is cleared after 100 ms by tripping the line between bus 1 and bus 6.

Studies were carried out for wind farms with a rating of 160MW (see Figure 8-15) and 320MW (see Figure 8-16). Both cases resulted in a stable system response, as can be seen in the figures. Because of the dc voltage chopper system, the wind generators would not be exposed to significant transients or dynamics. In particular, no over speeding of the wind generators was experienced in either of the studies. Whilst there were significant power swings within the receiving ac network as a consequence of the system fault and subsequent tripping of the ac line, the VSC Transmission scheme was capable of controlling the ac voltage at the receiving node, thereby assisting the ac network and avoiding voltage collapse and line tripping because of overloads. The reactive power output from the VSC Transmission scheme can be seen to change from approximately unity power factor prior to the fault to capacitive support following clearance of the fault, in order to support the significantly higher loaded remaining ac lines after the tripping of the line from node 6 to node 1.

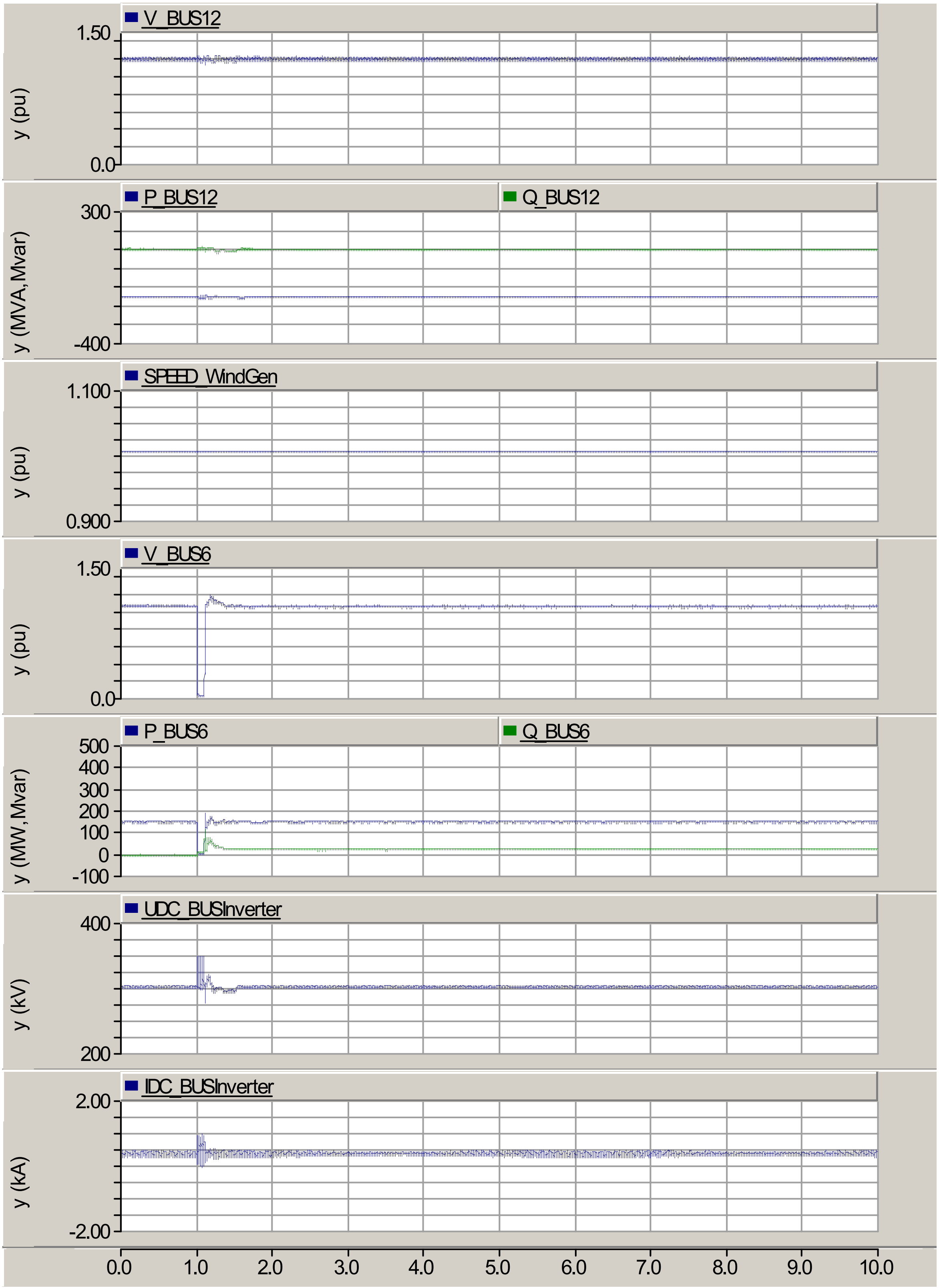

Figure 8-15 Wind farm (160MW) connected via VSC Transmission

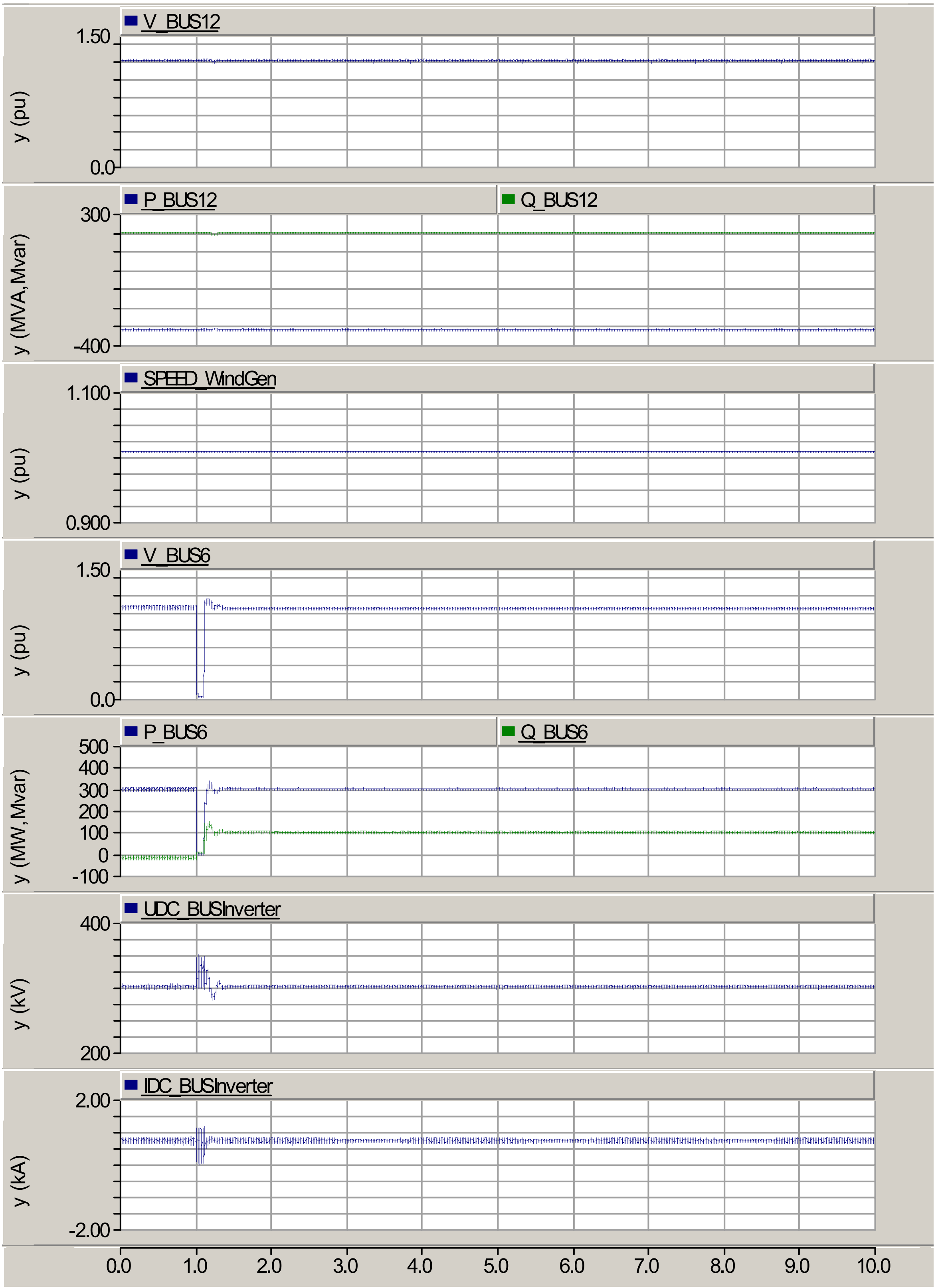

Figure 8-16 Wind farm (320MW) connected via VSC Transmission

8.8 CONCLUSION

The studies performed by the working group have demonstrated that it is feasible to connect a large remote wind farm to a network using either ac or HVDC. The studies have deliberately been performed using a relatively long cable connection and connection to a weak point in the ac network, since such a connection presents much greater challenges than a short distance connection using either over head lines or short cables to a strong node in the ac network. For the latter types of connection the use of power electronics in the form of SVCs, STATCOMs or HVDC connections may not bring sufficient benefits to justify their additional cost.

It was not the intention of the studies to provide definitive guidance in respect of which connection method would be the most financially or technically attractive with the particular parameters chose. The main reasons for not embarking on such a mission was that a proper comparison of the different options will depend on many factors, which are site specific and may well change with time, as market forces and technological developments take place. Some of these factors are:

- The competitive status of the market
- Local factors, including environmental considerations, cost of land, labour etc
- The technology used in the wind generators
- The location of the wind farm, e.g. off-shore or on land
- Availability of auxiliary power
- Etc etc

The technical studies are an important part of the activities that a wind farm developer has to perform as part of his feasibility studies, as they determine the rating of the equipment required to achieve a successful and acceptable integration of the wind farm in the ac network. Thus they feed into the financial studies, which will assess the capital costs, as well as the life cycle costs, as will be described in Chapter 9.

8.9 REFERENCES

[1] Schauder, C. and Mehta, H. "Vector Analysis and control of advanced static Var compensators", IEE Proceedings-C, VOl.140, no.4, pp.299-306, July 1993.

[2] Lie Xu and Bjarne R Andersen, “Grid Connection of Large Offshore Wind Farms using HVDC”, The Fifth International Workshop of Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 7-8 April, 2005, Glasgow, Scotland.

9. ECONOMIC ISSUES

9.1 INTRODUCTION

The historical growth in installed wind power capacities has been driven by substantial subsidies due to the great public and political concern regarding environmental issues on pollution and green house gases from conventional power production on one hand, and desire to lower dependency on conventional fuel on the other hand. Wind power is still driven by subsidies. However, the costs of wind power have been reduced substantially with the size of wind turbines and wind power is becoming increasingly more competitive. The wind power production cost per kWh is an important factor.

The growth in installed wind power capacity in a power system will increase the impact on the total power system. Therefore, it is important that the wind power possesses the same characteristics as the conventional power plants in terms of voltage control, power control and staying on-line at contingencies in the grid. This is reflected in more restrictive grid codes, as discussed in Chapter 3, and more sophisticated wind turbine and generator controls using power electronics. The increasing wind power capacity also demands more ancillary services in the power system, in particular because the forecast of wind power production is encumbered with errors requiring regulating power from other, controllable power sources.

Thus the total cost of a large wind farm project includes a number of components:

- The capital cost of the wind farm itself and the connection to the ac grid,
- The lifetime cost of operation and maintenance of all components and of the additional ancillary services which are necessitated by the wind farm

When evaluating the financial viability of the project it is also necessary to take into account the following factors:

- The wind production possible
- The power loss between the generator and the grid connection point
- The reliability and availability of the wind farm and the grid connection.

These aspects are discussed in the following sections.

9.2 PROJECT COST

The capital cost of the wind farm itself is beyond the scope of this document, but is likely to be the largest component of the overall capital costs. The connection to the grid may also be a large component, particularly if the wind farm is located offshore or a long distance from a suitably strong connection point in the ac grid.

Several approaches regarding cost allocation for the grid connections are possible and they vary in different countries. If the grid connection is considered to be part of the transmission grid, the owner of the transmission grid will pay. If the grid connection is considered as feeders which are parts of the offshore wind farms, the owner of the wind farm will pay. Arrangements are also possible where there will be shared costs amongst a number of different generator owners as well as the transmission grid operator. In any case a connection agreement will set out specific performance criteria which have to be met at the point of connection, and these may impact on the selection of the wind generator technology. Because of the different commercial interests of the wind farm developer and the grid operator an optimal solution for the wind farm and the connection is most likely to be achieved, if the wind farm developer is also responsible for the connection, since he can chose the most applicable wind generator technology for the overall needs.

If the wind farm is built in sections over several years, the choice of cable size and voltage needs to be carefully considered. One option to consider may be to add more cables as required when the installed wind power capacity increases.

Deriving the capital costs for the connection requires a good understanding of the market for the equipment, since the cost depends on the degree of competition.

The cost of AC equipment generally tends to be fairly predictable because the equipment it is highly standardised and because there are many providers of such equipment and therefore a fair competition in the market..

The HVDC converters are customised for each project, and this has some influence on the cost of HVDC equipment. In addition there are only a few providers of HVDC equipment and HVDC and HVAC cables therefore the costs of this kind of equipment are highly depending on the market situation. If all suppliers have their order book full the cost will be high and opposite if suppliers have available production capacity the cost may be lower. However, irrespective of the market situation, the cost of HVDC converter stations will be significantly higher than for similarly rated ac substations, but there is a break even transmission distance beyond which the overall cost of HVDC transmission is less than the cost AC transmission, see chapter 5.

A guide for economical assessment of HVDC transmission is given in the reference list [1]. This guide applies to LCC HVDC transmission however apart from the HVDC cost figures, the described methodology, recommendation and guidance is also valid for VSC transmission, and many of the issues are also relevant to a pure ac connection.

The most significant costs components are briefly discussed below:

a. **Environmental assessment.** The requirement for environmental assessments can be quite comprehensive and demanding depending on the local law and regulation. This may require broad varieties of authorities and public hearings. Environmental assessments will normally be demanding and take long time, which needs to be taking into account at an early state of a project.
b. **The wind farm costs.** A wind farm comprises of a number of wind turbines, in a limited area, where the wind power production is collected such that the wind farm exhibits similar behaviour as one production unit feeding into an AC grid via one or more connections.
   The wind turbines in a wind farm must be placed in relation to the prevailing wind direction with proper distances in between each wind turbine such that they don't shadow over each other and such that the possible yearly production is maximised. The installation time for a wind farm is short once the turbine foundations are made. However the installation may be delayed due to bad weather conditions especially at offshore locations. In the North Sea the sea is calm only 20% to 30% of the time in a year, day and night. The electric collector system may consist of a number of cable radials each connecting a number of wind turbines. The voltage levels of the collector cables are typical lower than the voltage of the transmission system which connects the wind farm to the transmission grid.
c. **Sending end AC substation cost.** The sending end substation collects the power production from the wind farm generators. The sending end substation is placed at the wind farm where it is most suitable with respect to access to the substation and the connection of the wind generators to the substation and the connection of to the grid. For offshore wind farms the substation is installed on an offshore platform which significantly increases the cost of the offshore substation and the cost of operation and maintenance.
d. **Receiving end AC substation.** The receiving end AC substation adapts the voltage level of the transmission line from the wind farm to the receiving AC transmission grid. The receiving end AC substation includes circuit breakers, bus couplers, busbars, power transformers, AC protection and shunt compensation as required.

e. **HVDC stations costs (where applicable).** The HVDC stations includes circuit breakers, bus couplers, AC filters, reactive power compensation, HVDC LCC converters or VSC converters, converter transformers and DC filters on the DC side if required. For LCC HVDC it is also necessary to install a voltage source i.e. a rotating synchronous compensator at the offshore terminal, or a STATCOM with some energy storage capability to provide a three phase AC commutation voltage and short circuit power for the proper function of the LCC converter. This adds costs to the installation.
   The receiving end HVDC station is similar to the offshore HVDC substation. Depending on the performance parameters (e.g. the short circuit ratio) of the AC grid the receiving end LCC HVDC station may be provided with additional reactive power compensation equipment (fixed, breaker switched, dynamic or a combination of these), which increases the overall costs of the HVDC station.
f. **Offshore platform, if any**. The design and costs of an offshore platform for the substation equipment depend on the type of transmission AC or DC and the site of installation in terms of the sea bed, water depth, open sea or interior water and exposure to big waves. Also the content of salt in the atmosphere has a significant impact on the design of the substation and platform and on their costs. A back up diesel generator or some other form of energy storage is generally required to provide an LV supply to auxiliary equipment such as switchgear. Depending on the offshore site additional auxiliary equipment may be necessary. If access is difficult due to high waves a heliport may be necessary on the platform as well as emergency accommodation and other facilities, i.e. if maintenance personnel is stranded due to bad weather conditions.
g. **Cable transmission lines (AC or DC)**The price formation of AC and DC cables follow the economic rule of supply and demand, as there are only a few cable manufactures on the world market and at the time of writing they have several large orders which take several years to produce and deliver. The cable production plants are costly and transports of large cables require special constructed carriers both for sea and land transportation. Only one large contract can suddenly change the cable market from a 'sellers' to a 'buyers' market. Therefore the budgetary costs for cables are encumbered with uncertainties.
h. **Overhead transmission lines (AC or DC)** The price formation for overhead lines are much more predictable than for cables, because of many more supplies and therefore competition on the market. The prices are mostly determined by the terrain, labour costs and the costs of raw materials. For overhead lines it is possible to operate with standard budgetary prices which are updated yearly with the common price development on labour and raw materials.

Example 9.1
This example show the cost of two existing offshore wind farm projects with AC cable connection. Horns Rev I (2002), 160 MW and Nysted I (2003), 166 MW. At these sites, two additional wind farms (Horns Rev II in 2009 and later followed by Nysted II) will be installed each with a capacity of 200 MW and with the possibility to install 15 MW additional wind turbines for demonstration purposes at each site.

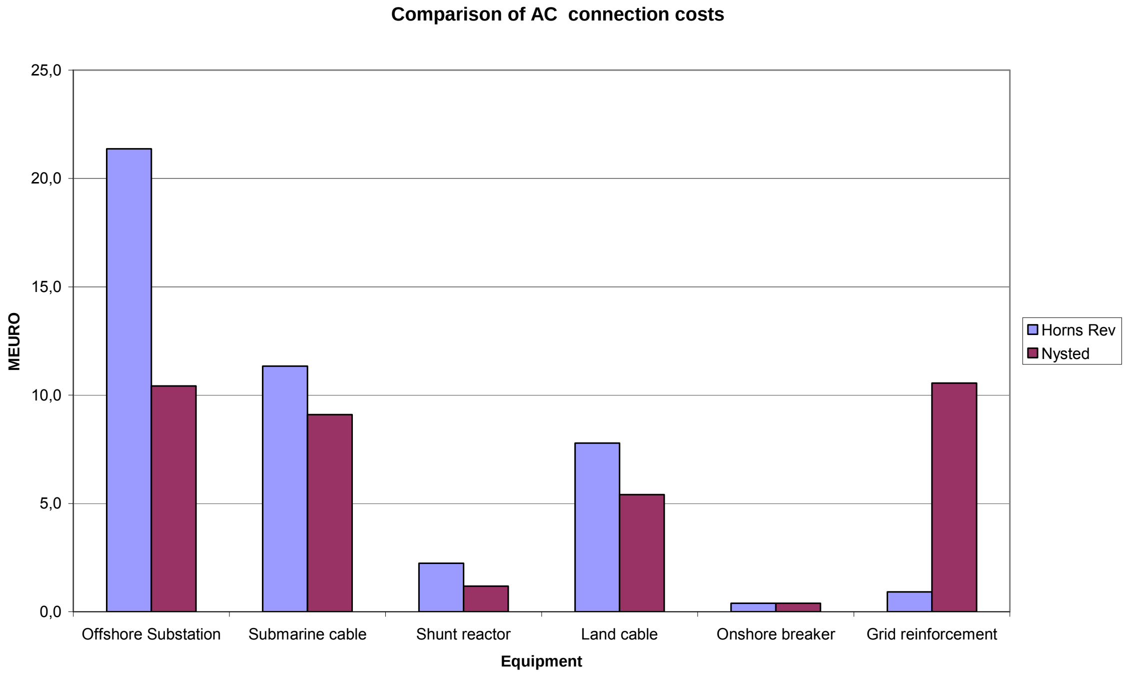

Figure 9.2 **AC connection costs in Millions of Euros for Horns Rev I (160 MW) and Nysted I (166 MW) offshore wind farms.**

Horns Rev offshore substation costs

The total costs of the Horns Rev offshore substation was 21.4 MEURO or 0.134 MEURO per MW. The substation platform accommodates a 200 MVA, 150/33 kV transformer, 33 kV and 150 kV switchgear, auxiliary systems, equipment for maintenance purposes, a boat landing place, a heliport, a 1 MW diesel-generator set, a crane and emergency accommodation for a maintenance team. The platform has a total area of 20 x 28 metres and the total weight is 1200 ton. The transmission line comprises of a 21 km long 170 kV AC submarine cable and a 36 km long 170 kV AC land cable. The transmission cables are compensated with an 85 Mvar shunt reactor at the cable station where the submarine and the land cable is connected together. The reason for having a 1 MW diesel generator set is that each wind turbine needs auxiliary power for heating in order to prevent moisture in wind turbine nacelles due to the harsh environment at the North Sea and for turning the nacelle in a specific position for landing of maintenance personnel from a helicopter while the wind turbine is stopped.

Nysted offshore substation costs

The total costs of the offshore Nysted substation was 10.4 MEURO or 0.063 MEURO per MW. The platform accommodates a 200 MVA 132/33 kV transformer, 33 and 132 kV switchgears, auxiliary systems for maintenance purposes, a 90 kW stand by diesel generator set, fire-fighting equipment and a boat landing place. Due to a much gentler environment where access to the wind turbines by helicopter is not required only auxiliary power for the platform itself is required. The total weight is 700 ton including all equipment.

The higher costs of Horns Rev I offshore substation in the North Sea compared with Nysted I offshore substation in the Baltic Sea is mainly due the harsh environment in the North Sea.

9.3 OPERATIONAL AND MAINTENANCE COST

The operational and maintenance cost generally increases with the age of the equipment in particular for wind turbines, which are exposed to mechanical wear especially on the turbine blades and the gear boxes.

The mechanical wear is dependent on how turbulent the wind is on the site of installation. Offshore wind is less turbulent than onshore where turbulence is highly dependent on the roughness of the landscape. Note however that bringing maintenance people and equipment to offshore sites may require helicopter transportation to the wind turbines and offshore platforms, because of large waves.

The operational and maintenance cost of wind turbines may be either calculated as a yearly fixed percentage of the original investment cost or it may be calculated as a fixed amount per produced kWh.

O&M costs of the connection can be split into:
- AC connection
- AC substations
- AC cables or overhead lines
- Monitoring and ongoing surveys of cable/line
- Reactive power compensation

HVDC connection (if applicable)
- AC substations
- HVDC converters
- AC filters
- DC lines - cables or overhead lines
- Monitoring and ongoing surveys of cable/line
- DC filters

Typically offshore and onshore substations will be unmanned. For offshore wind farms with an offshore substation on a platform, additional cost is incurred depending on whether access by boat or by helicopter is required.

9.4 AVAILABILITY AND RELIABILITY

The availability and reliability of a wind farm and its grid connection influence the total economy of the wind farm due to loss of production. The unavailability of a single wind turbine reduces only a fraction of the production capacity of the wind farm, whereas the whole wind farm production is lost when the connection to the grid is unavailable. Thus, the question arises whether redundant grid connections would pay off. Generally, however, this is not the case and wind farms are typically connected without reduncancy.

Availability of a wind farm includes planned and unplanned outages.

The wind turbine manufactures normally claim an availability of a single wind turbine of 98 %. Although this may have been actually lower in the earlier offshore wind farm applications, valuable practical lessons were learnt, which should help to achieve a high availability in a harsh offshore environment in future.

Also the HVDC manufacturer normally claims an availability of 98 % (for LCC and VSC), and the availability may be increased if more strategic spare parts are kept on stock for fast repair in case of an unplanned outage of the HVDC transmission due to faults. The performance of existing HVDC links in operation world wide is reported bi-annually by Cigré B4 [2]. It is to be noted however that for a true offshore environment there is at the time of writing only experience with one VSC HVDC link that has supplied power to the Troll A gas platform since 2005.

In order to calculate the resulting unavailability of a wind farm and its connection the required yearly shut down period for regular maintenance (planned unavailability) and the statistical failure rate (unplanned unavailability) must be know for the wind turbines and for the connection respectively. The planned unavailability can be minimised by coordinated maintenance of the wind turbines and the connection. The unplanned unavailability can be calculated on the basis of the statistic fault rate for the wind turbines and the connection.

Example 9.2
Due to lack of data for wind turbines only a cable connection is considered in this example. Repair time is dependent on many factors including, weather, availability of repair vessel, skilled resources etc. For submarine cable transmission with a fault rate of 0.1 faults/100 km /year and a four weeks repair time the outage time is calculated as:

Outage time per year for a 100 km cable transmission is: 0.1 [/100 x km / year] x 28 [day/fault] x 24 [hours] = 67.2 hours per year

The unavailability per year is 100 * 67.2/8760 % = 0.767 %

For this example 0.767 % loss of production due to the yearly unavailability must be deducted from the estimated wind power production.

When parallel cables are used the distance between individual cables should preferably be so large that the risk of a common mode failure, i.e. a fault on more than one cable is minimal due to one single event. This is because most cable failures are caused by mechanical interference, e.g. for a submarine cable because of trawling or anchors. In areas close to the shore cables are typically protected by trenching or mechanical covers.

For land cables the fault frequency is higher but the repair times are shorter.

9.5 DERIVED SYSTEM COSTS - POWER REGULATION RESERVES

In order to operate a power system, various ancillary services are required to cope with contingencies in the system. An establish designed criteria is the N-1 criteria which requires that it must be possible that any component in the power system can be lost without jeopardizing the power system security. Within a power system the load demand should be covered by power produced in the system or by generation in a neighbouring power system by a reciprocal agreement. However in power systems with a large share of wind power additional power regulation reserves from controllable power sources are required due to possible errors in the forecast of wind power production.

If the planned generation, planned power exchange and the load demand are not in balance, the power exchange with neighbouring systems will deviate from the plan and the frequency in the power systems may deviate from its nominal value which is unacceptable.

Planning of future generation and power exchange is based on forecast of the load demand. Load forecast is quite accurate, being based on experience and statistics over many years. However in power systems with a large share of wind power a substantial uncertainty in generation scheduling may be introduced because it is difficult to forecast wind power generation.

Figure 9-1 shows the forecast wind output for the Western Danish power network, and the actual wind generation 24 hours later. The shapes of the two curves are somewhat similar but the measured wind appears several hours before it is forecasted leading to a deviation of approximately 600 MW which requires a similar amount of regulating power.

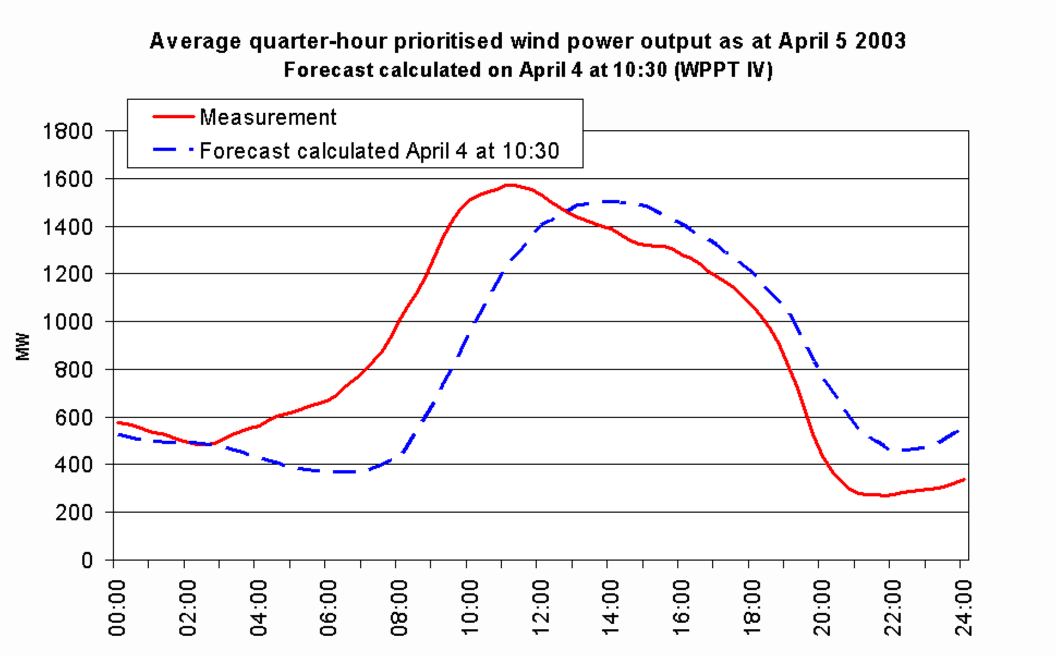

Figure 9-1 Average quarter-hour prioritised wind power output, measured and forecasted value.

Figure 9-2 shows the recorded need for regulating power over a year in the same ac network. Instantaneous values (time series) as well as a duration curve are provided.

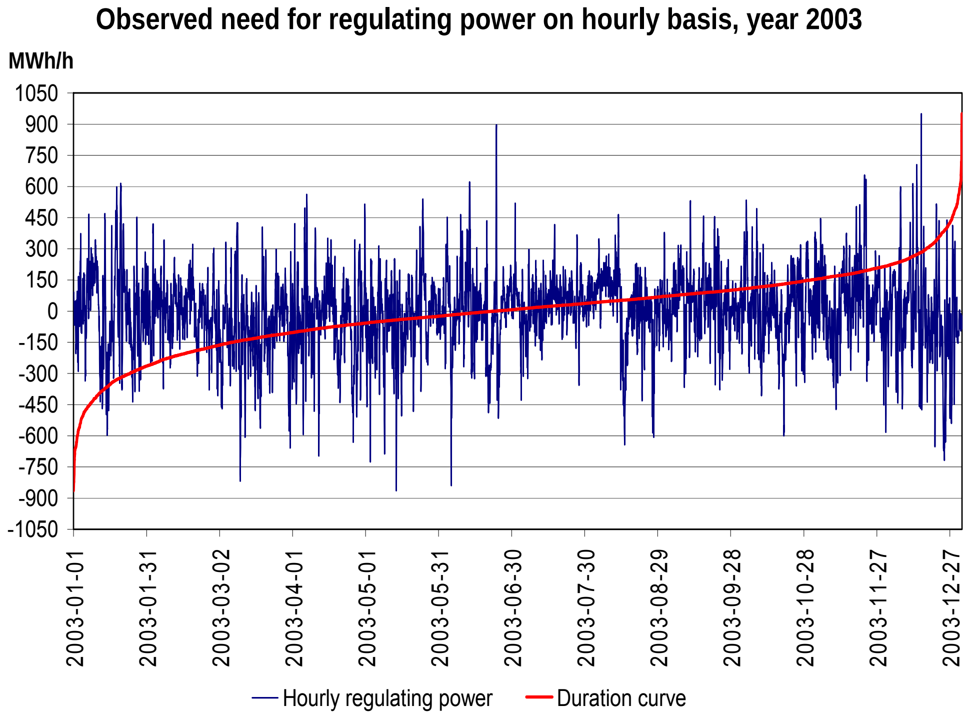

Figure 9-2 Recorded need for regulation power in the Western Danish in 2003.

The area underneath the duration curve is the yearly energy content in up and down regulation of power generation. This regulating power has to be purchased on the regulating power market as a capacity fee and an energy payment; alternatively power has to be kept as reserve on dedicated generation unit at a premium. As seen on the duration curve, the maximum required regulating power was approx. ± 900 MW.

The need for regulating power may be the result of error in the load forecast, in the wind power forecast or due to unplanned outage of generation or loads. For a power system with a substantial proportion of wind power the error in the forecast may be high depending on the distribution of wind power over an area. If it is scattered over a large area an averaging affect may reduce the error. For a large wind farm connected to a single point in the grid the power gradient may also be so high than the regulating power can follow the power variations. In this case it may be necessary to limit the power gradient in the wind farm and thereby reducing the yearly energy production. Estimation of the need for regulating power is rather complex and under study internationally. The cost of regulating power and possible limitation due to high power gradients must be judged carefully and capitalized when calculating the life cycle cost.

9.6 WIND POWER ELECTRICITY PRODUCTION

The electricity production of a wind farm and the transmission losses can be estimated from the measured wind power production and the maximum losses at maximum wind power production. Figure 1-1 in Chapter 1 presented the wind production for a 160MW wind farm. The figure shows the variability of the wind and also the duration curve, which makes it possible to see the amount of time for which the generation exceeded a certain power value. Figure 9-3 shows the duration curve from Figure 1-1, with the power normalised relative to maximum power output. The area under the duration curve corresponds to the total wind energy production over the measured period.

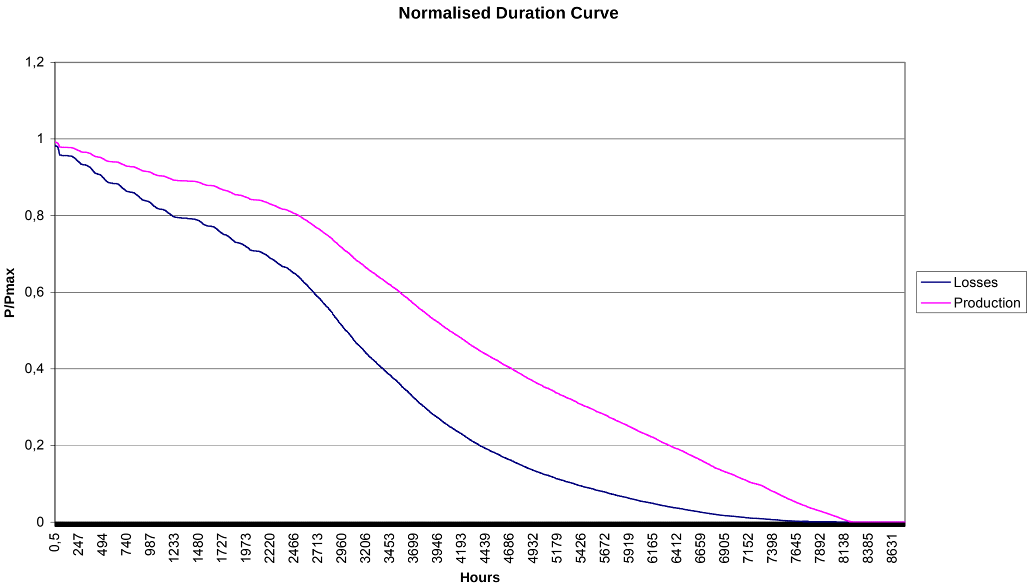

Figure 9-3 The normalised duration curve and the square of normalised duration curve for the recorded production in Figure 1-1.

The transmission losses vary with the square of the current, which is equivalent to the square of the power production (at constant voltage). Therefore, the normalised power loss curve can be calculated by taking the square of the normalised duration curve.

The area under the normalised duration curve (the curved in figure 9.4 marked Production) divided by with the maximum power, Pmax, is the equivalent number of hours that would be required to produce on years of energy production at full wind power, this hours are designated full load hours Ta. For this wind farm the full load hours is 4177hrs or 47.7%.

The area under the loss curve (the curve in figure 9.4 marked Losses) divided by maximum losses (losses at maximum power) is the equivalent number of hours that would be required to produce one year of losses at full wind power production; these hours are designated loss hours Tb. The loss hours for this wind farm is 2973 hours, representing 33.9% of the power loss that would be generated had the wind farm operated at full power for a full year (8760hours).

Example 9.3
In Figure 9-3, the maximum power is Pmax = 160 MW, the full-load hours are Ta = 4177 hours, and the loss hours are Tb = 2973 hours. The yearly wind power production can be calculated as Ta x Pmax = 4177h x 160 MW = 688320 MWh. Likewise if the maximum transmission losses are 1.4 % of 160 MW, the yearly transmission losses can be calculated as are Tb x 0.014 x Pmax = 2973 h x 2.24 MW = 6,660 MWh.

9.7 ELECTRIC POWER TRANSMISSION LOSSES

The electric power losses in connection with transmission of wind power production from an offshore wind farm to the connection point in the AC grid depend on the production profile of the wind farm as discussed above in 9.6 and the parameters of the power transmission system.

Only the electric power transmission losses of a radial line or cable are considered. The losses in the internal collection network in the wind farm are disregarded as they depend on the specific layout of the wind farm and not on the grid connection.

The yearly transmission costs can be calculated from the yearly production profile for the wind farm. The yearly production can also vary from year to year. Therefore, over the life time of the project, an average duration curve based on measurements for the wind velocity must be used in the calculation.

The transmission losses can be divided in two main categories:

- Fixed losses, which are voltage dependent, which includes losses such as dielectric losses, shunt/stray losses, magnetizing losses, corona losses.
- Load losses, which are power losses caused by the active and reactive load current and the charging current for an AC line.

In general the resultant transmission losses can be approximated by a 2nd order polynomial:
Ploss = P 0 + P1+ P2

The first term P0 corresponds to the fixed losses (no load losses) and they are constant independent of the transmitted power.

The second term P1 is a linear term, corresponds to voltaic losses (V·I), these losses are in proportion with the current or the transmitted power at constant voltage. For pure AC transmission the term P1 can be disregarded.

The third term P2 is a quadratic term, corresponds to the resistive heat losses ($R \cdot I^2$), these losses varies with the second power of current or the transmitted power at constant voltage.

When the part losses of the three terms at maximum transmitted power and the wind power duration curve and the associated time factors, i.e. the load hours Ta, the loss hours Tb and the online hours Tc, for a period is known, the total energy losses over the period i.e. a year can be calculated. The total energy losses (Eloss) are calculated as the sum of the three part energy losses, Eloss = E0 + E1 + E2 where the energy part losses are E0 = P0 x Tc, E1 = P1 x Ta and E2 = P2 x Tb.

9.7.1 AC power transmission losses

The AC transmission losses comprise of losses in the AC lines, in the shunt or series compensation equipment and transformer losses.

As explained in Chapter 4 the line capacitances generate reactive power which causes ac lines to have a critical line length and a power loss results from the reactive power flow. As there is no reactive power flow on a dc line, a dc line has no critical length, and there is no power loss from reactive power flow. The critical length of an ac line can be increased, and the power loss reduced, by using reactive power compensation as discussed in Chapter 4.

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Figure 9-4 AC transmission line power losses

The ac transmission line losses comprises of the following components:

		Load losses ($A*I^2$)	**Load Losses ($B*I$)**	**Fixed Losses (C)**
1	AC line	X		X
2	Variable series compensation controlled by PE valves	X	X	X
3	Variable AC shunt compensation controlled by PE valves	X	X	X
4	Fixed or switchable AC shunt compensation			X
5	Power transformers	X		X

9.7.1.1 AC Transmission line Power Loss

The main contributions to losses in AC cables are:

- Resistive loss in the conductors
- Dielectric loss
- Sheath & armour loss.

The main contributions to losses in AC overhead lines:

- Resistive losses in the conductors
- Corona losses

The losses depend on the rated voltage and current. The rated voltage depends on the permissible stress in the insulators and the cable insulation. The limiting factor in the current for AC overhead lines is the conductor temperature, which is related to the permissible sag of the lines. The limiting factor in current for cables is the temperature to which the insulation nearest the conductor can be raised without suffering deterioration of the cable insulation. Cable data may be obtained from the manufacturer's data books.

Example 9.4

Cable data:	
Cable rating	170 kV/800 A
Cable type	XLPE
Conductors	3x1x630 mm2 Cu
Capacitance conductor/screen	0.19 µF

AC cable losses 100 km			
	W/m	km	kW
Conductor losses	16,2	100	1,620
sheet losses	3,7	100	370
Armour losses	7,6	100	760
Dielectric losses	0,06	100	6
Full load losses			2,756

For a 160 MW wind farm using a 100 km ac cable with data as specified above, and with full load hours Ta = 4177 h and loss hours Tb = 2973 h, the yearly production is 160 x 4177 = 668320 MWh and the yearly losses are 2.756 x 2973 = 9194 MWh, which is equivalent to an annual energy losses of 1.4% of the yearly wind farm energy production.

9.7.1.2 **Transformer losses**

Transformers have load losses, no load losses (fixed losses) and auxiliary power losses due to pumps, fans etc. The transformer load losses vary with the loading of the transformer and are caused by current heat losses in the primary and secondary windings in transformers. No-load losses are caused by the current needed to magnetize the transformer core. The no-load losses consists of five components, hysteresis losses and eddy current losses in the transformer core, losses caused by the no-load current, stray eddy losses in core bolts and other core components and dielectric losses. 99 percent of the no-load losses stems from the hysteresis losses and the eddy current losses.

9.7.1.3 **Shunt reactor losses**

Shunt reactors have only no-load losses, similarly to the transformer no-load losses. The no-load losses are almost constant at constant voltage and occur when the shunt reactors are energized. In case of oil immersed reactors also auxiliary losses, e.g. pumps and fans will be present.

9.7.1.4 **Shunt capacitor losses**

Shunt capacitors have only no-load losses. The losses are dielectric losses in the capacitor insulation and current heat losses in the termination of the capacitors. The losses are small and almost constant and occur when the shunt capacitors are energized.

9.7.1.5 **SVC (Static Var Compensator) losses**

The SVC losses vary with the reactive power output. The losses comprise of thyristor valve losses and reactor losses of the TCR (Thyristor Controlled Reactor), losses in the TSC (Thyristor Switched Capacitor), in the MSC (Mechanically Switched Capacitor) and in the AC filters aux power supply for cooling and losses in the interface transformer. The losses in the capacitive range of the SVC are small and nearly constant whereas the losses in the inductive range vary with reactive power. In the capacitive range the ac voltage is supported and the ac losses in the ac grid are reduced. Figure 9.6 shows the SVC loss curve as a function of SVC output, for two different designs. One design uses a large TCR and a fixed capacitor, the other uses a fixed capacitor, a small TCR and two TSCs. Positive current indicates capacitive generation, and negative current indicates inductive absorption.

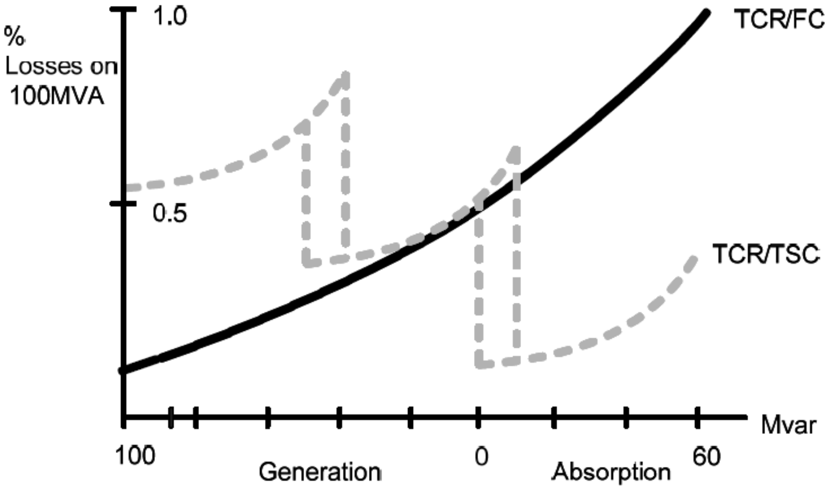

Figure 9-5 Typical SVC loss curve

The power loss in the SVC depends on the implementation, in particular the size of the fixed filter, and the number of TSC's, if any. The SVC should be designed such that it operates for most of the time in a range where the overall losses are minimized.

Capitalization of the SVC losses should be done taking into account the expected operating conditions. For example, if the SVC is expected to operate most of its time (say 90%) in a certain limited range, then the average power loss in that range should be determined. Similarly, the time duration in other ranges should be calculated and the average power loss calculated. The overall power loss for calculation should then be evaluated as the weighted average of the different power loss calculations.

9.7.1.6 **STATCOM losses**

The STATCOM is a voltage sourced converter designed for reactive power output only. The losses comprise of resistive heating losses in the main circuit including semiconductor losses, snubber losses, switching losses, cooling losses and interface transformer losses. The losses increase with reactive power output in both the capacitive and the inductive output range. In the capacitive range the ac voltage is supported and the ac losses in the ac grid are reduced. In general the STATCOM losses are higher than the losses of a SVC of a similar size, due to increased semiconductor and switching losses.

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Figure 9-6 Power loss for STATCOM

The STATCOM losses are a function of the reactive power output. The STATCOM can be supplemented with fixed capacitors or reactors, and even TSCs, and should be designed such that it operates for most of the time in a range where the overall loss are minimized.

9.7.2 HVDC power transmission losses

The HVDC transmission comprises AC to DC and DC to AC conversion and DC transmission lines. The AC/DC conversion losses have to be added to the DC cables losses. If the earth is used for DC current return instead of a DC return line, it is possible to achieve lower power loss and lower capital costs [1].

The absence of reactive power generation in DC cables means that DC cables have no critical cable length caused by reactive power. Consequently, long DC transmission cables will be an increasingly important alternative to long AC transmission cables in places where it is impossible to get permission to build AC overhead lines.

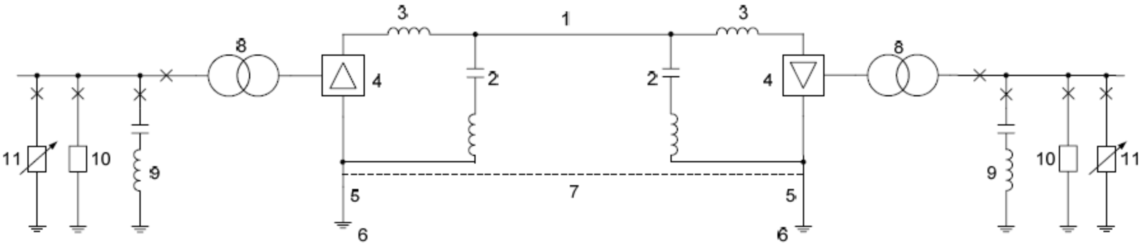

Figure 9-7 HVDC transmission losses

HVDC transmission losses comprise of the following components:

		Load Losses $(A*I^2)$	**Load losses (B*I)**	**Fixed Losses (C)**
1	DC line	X		
2	DC filter			X
3	DC smoothing reactors	X		
4	LCC converters	X	X	X
5	Electrode lines	X		
6	Earth electrodes	X		
7	Return line, if any	X		
8	Converter transformers	X		X
9	AC filters			X
10	Switchable AC shunt compensation			X
11	Variable AC shunt compensation	X		X

9.7.2.1 AC/DC converter losses

The ac/dc conversion losses can be estimated with a second order polynomial representing the losses. This can be used to calculate the yearly energy losses when the duration curve of the transmitted power is known.

A typical HVDC conversion loss function (Ploss) as function of transmitted power is shown in Figure 9-8. The loss function can be approximated by a second order polynomials where Ploss = PA + PB + PC= A*Id2 + B*Id + C. If contribution to the losses at rated power of the quadratic term PA, the linear term PB and the constant terms PC are known and if the full load hours Ta, the loss hours Tb and the online hours Tc are known then the yearly energy losses can be determined as Ta x PA + Tb x PB + Tc x PC, see example 9.5

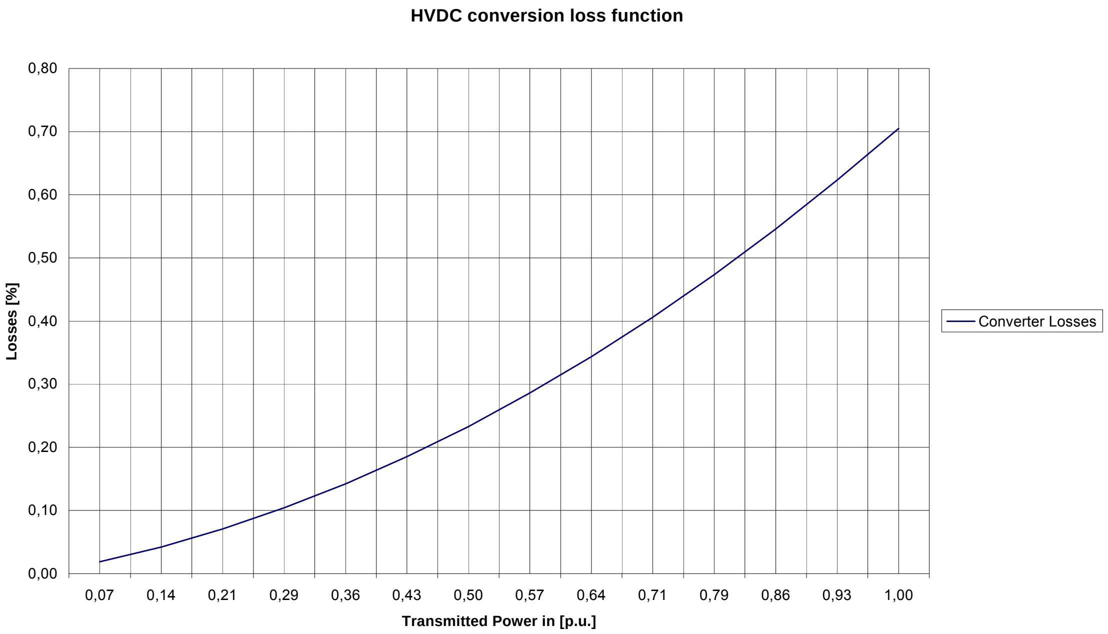

Figure 9-8 Power Loss for a LCC HVDC transmission station.

Example 9.5:
For one 600 MW LCC HVDC converter the assumed power loss at full load operation Ploss may be 4.2 MW or 0.7 % of rated power. If PA at rated power is estimated to 2.4 MW and PB at rated power is estimated to 1.1 MW and the no load losses PC is estimated to 0.7 MW then the yearly energy losses can be calculated.

With Ta = 4177 h, Tb = 2,973 h and Tc = 8760 h (Figure 9-3) the yearly conversion energy losses, for one 600 MW LCC HVDC station with a loss function as in Figure 9-8, are 2.4 x 4177 h + 1.1 x 2973 + 8760 x 0.7 = 19,427 MWh or 19,427 x 100/ 688320 = 2,8 % of the yearly wind power production. In addition the losses of the other LCC HVDC station and the dc transmission line must be added in order to calculate the total LCC HVDC transmission losses.

Similarly for a VSC converter the yearly losses may be calculated when the loss function is known.

Example 9.6:
If the assumed power loss at full load operation for one 376 MW ±150 kV VSC station is 6.15 MW where the first term PA ($A\cdot I^2$) is 65 % of the maximum losses, the second term PB ($B\cdot I$) is 10 % of the maximum losses and the third term PC is 25 % of the maximum losses, the load and the no-load losses is calculated as

Load losses for one VSC station:
- PA = 0.65 x 6.15 MW = 4.998 MW
- PB = 0.10 x 6.15 MW = 0.615 MW
- PC = 0.25 x 6.15 MW = 1.538 MW

The yearly transmission energy losses for one VSC station are approximated to:
- PA x Tb = 4.998 MW x 4,177 h = 20.9 GWh
- PB x Ta = 0.615 MW x 4,177 h = 2.6 GWh
- PC x Tc = 1.538 MW x 2,973 h = 4.6 GWh

In addition the losses of the other VSC station and the dc transmission line must be added in order to calculate the total VSC transmission energy losses.

9.8 CAPITALISATION OF POWER TRANSMISSION LOSSES

In order to capitalise the power transmission losses, the following information is needed:

- The yearly duration curve of the wind power production; see Figure 9-3
- The transmission losses as function of the transmitted power; see Figure 9-4
- The cost of energy losses, see chapter 9.8.1
- The interest rate

9.8.1 The cost of energy losses

The cost of energy losses depend on various parameter such as:

- The expected market price for electric power for the party that pays for the losses
- Year of installation
- Number of years - life time of the project
- Real interest
- No-load losses
- Load losses
- Utilisation per year
- Duration of losses.
- Duration of use

The expected market price for electric power depends on the supply and demand for electric power. If the market is transparent and there is full competition then the market forces will ensure that electricity consumers get the best value for money. However if the market is imperfect for example due to bottlenecks in the transmission system and there is a deficit in the supply, then the price of power may go high.

Due to inflation and the market situation, the basic costs are dependent on the year of installation. Also the cost of energy losses is to be considered over the life time of the project.

The interest may be based on the interest to borrow the money or it may be an internal interest that reflects the interest an investor wants from an investment [4]. If the internal interest is not achievable with a given investment then an alternative investment is preferred by the investor.

9.8.2 The Loss Capitalisation Factor

For comparison of the cost of the same type of equipment with similar characteristics but at different purchase cost and losses, it is common practise to calculate the capitalised value of the losses during the equipment lifetime, say 30 years. The most economical equipment is the equipment which has the lowest sum of purchase costs and capitalised energy loss. The cost of energy 30 years ahead is difficult to predict therefore it is normal to use an estimate of the average yearly energy cost. Also it is normal to carry out a risk analysis taking into account possible variation in the interest and the average energy prices.

Based on the yearly Average Energy Costs (ACE) per MWh and the interest i, the Loss Capitalisation Factor LCF over the life time of the plant (N) can be calculated as

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Where

- N is the lifetime and
- i is the calculation interest.

The cost of the losses over the life time of the project is calculated as:

- Load losses: LCFi, N x (Ta + Tb)
- No-load losses: LCFi,, N x Tc

Fixed losses are constant and occur when a component is energised. The capitalised value of no-load losses is normally higher than for load losses because the on load time Tc is higher than Ta and Tb.

Load losses vary over time depending on the loading of the component.

Example 9.7:
The average spot market price on the Nord Pool power exchange taken over five years (2001 - 2005) was 30.22 €/MWh. At an inflation rate of 2 % and an interest of 6 %, the LCF (Loss Capitalisation Factor) over 30 years of operation is 527.58 €/(MWh/a).

The present value of the cost of no load losses if the equipment is energize all year round (Tc = 8760 h) is LCF €/MWh x 8760 h = 4,621,581 €/MW. If the equipment is only energised 80 % of the time per year, the costs of no-load (Cno-load) is reduced by 20 % to Cno-load = 4,621,581 x 0.80 = 3,697,265 €/MW

The capitalised losses is the penalty to be used for each MW of no load losses when comparing the cost of two components with different no load losses.

Similarly the cost of load losses is LCF x (Ta + Tb) where Ta is the full load hours and Tb is the loss hours. With Ta = 4177 h and Tb = 2973 h (figure 9.4) the cost of load losses is Cload = LCF x Tb = 905.23 x (4177 h + 2973 h) = 3,772,181 €/MW, which is the penalty to be used, for each MW of load losses, when comparing the cost of two component with different load losses.

With the loss figures from Example 9.6 the following cost penalties would apply:

Penalty for load losses is calculated as Cload x (PA + PB) = 4,621,581 €/MW x (4.998 MW + 0.615 MW):
25,940,936 €

Penalty for no-load losses is calculated as Cno-load x PC = 3,692,265 €/MW x 1.538 MW:
5,686,393 €

9.9 FINANCIAL EVALUATION

A proper financial evaluation of a project should take into account all costs and benefits during the project life time. The costs for a transmission system should include capital costs of the transmission system, capitalised costs of losses, maintenances and operational costs. In addition indirect costs derived by the transmission project may also be included such as AC grid reinforcement and compensation of reactive power.

Information needed for the financial evaluation:

- Estimation of the yearly wind production
- Estimated pricing of wind power production
- Capital costs of the transmission system for grid connection
- Capitalisation of transmission losses
- Design life time of the project
- Operation and maintenances cost

- Derived cost of AC grid reinforcement if any.
- Derived cost addition reactive compensation if any
- Refurbishment costs
- Disposal costs

For financial evaluation the net present value (NPV) of the investment may be used.

The NPV is calculated as [4]:

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Where

- N is the life time of the project
- Bn is the benefit stream
- Cn is the cost stream.

9.10 REFERENCES

[1] Cigré Brochure 186, Economic Assessment of HVDC Links, 2001

[2] Cigré AG B4-4: HVDC Performance

[3] Cigré WG B4-44: Planning Guideline on HVDC Environmental Issues, (Planned to be published 2008).

[4] Hisham Khatib: Economic Evaluation of projects in the Electricity Supply Industry (IEE Power & Energy Series 44, ISBN 0 86341 304 9)

10. FUTURE TRENDS AND CONCEPTS

Wind power is presently the most cost effective of the renewable technologies (apart from large scale hydro) and some Governments, world-wide, are actively committed to stimulate the development and utilisation of this energy source. They also recognise that wind energy can provide a continuously growing contribution in the competitive energy market, contributing to climate change goals, energy diversity and security [1]-[5]. However, as described in Chapter 2, wind power plants have very different characteristics to conventional generation plant, and therefore the integration of a large proportion of wind power in a network can be a considerable challenge for the network operator.

In Europe, many large offshore wind farms have been planned. Due to environmental concerns, it is proposed that these offshore wind farms are located some distance from the onshore point of connection. As a result, the distance from the wind farm to the grid connection point is increased. In the USA, India, China and the Sahara desert transmission schemes from wind farms to the transmission grid connection point with a distance in excess of several hundreds of kilometres are being proposed. When transmitting bulk power over such distances, FACTS devices and for very long distances HVDC transmission may offer advantages over conventional AC transmission for both onshore and offshore installations.

The contribution of HVDC and FACTS devices to the interconnection of large scale wind farms may be strongly influenced by power network constraints because of the introduction of generation at new locations, and the advent of new grid code connection requirements. Thus, it is anticipated that in the future power electronic applications (e.g. HVDC and FACTS devices) will play an increasing role in facilitating the efficient and satisfactory connection and integration of large wind farms in an electrical network. On the other hand, the ongoing development in wind turbine and power electronic equipment within wind generators will have an impact on the growth in HVDC and FACTS, as some of the local problems could be solved by power electronics within the generator.

10.1 ENVIRONMENTAL POLICIES

It is generally agreed that over the last two centuries the global climate has been harmfully influenced by the emission of very significant amounts of greenhouse gases, such as carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O). A significant number of countries have already designed strategies to reduce emissions and recognised that these achievements will depend heavily upon the successful stimulation of renewable energy technologies such as wind generation. With Governments encouraging the development of renewable energy sources it is unlikely that future environmental policies will pose a barrier to the continuous development and growth of wind generation in Europe and all around the world.

In Europe and on other continents there is increasing resistance from the population against the construction of new overhead power lines, and long public enquiries are necessary before permission is granted to build a new power line, as may be necessary for the connection of a new wind farm. Frequently the public argues for the under grounding of either the complete route or for sections of the route. For long cable sections, say in excess of 50 to 150km, depending on rating and terrain, a HVDC cable option may offer the most economic option, as described in Chapter 5. For shorter sections, say in the range from 25km upwards a SVC or STATCOM may be required, in order to ensure that the voltage at the terminals is kept well controlled.

10.2 ENERGY MARKET DEVELOPMENT

In Europe wind power could be seen as a great success with growth rates averaging more than 30% annually over the past 5 years. Leading countries such as Germany, Spain and Denmark are not leaders due to superior wind resources, but due to their electricity market policy, in which a fixed minimum price is agreed for energy generated by wind. This seems to have been sufficient guarantee for investors to move into this new sector. In order to enable wind power to reach its full potential not only in Europe but worldwide the wind power industry must continue to develop the technology, such that wind energy can be provided at a competitive level relative to existing technologies. One solution could be in the provision of power electronic solutions which could provide ancillary services, whether or not the wind generators are generating energy.

One barrier to the growth of wind power may arise from the unpredictability of the exact amount of power that will be generated by the wind generators within a network. This unpredictability results in the need for more ancillary services (frequency and voltage control and support), compared with a network which has conventional synchronous generators with a predictable supply of fuel. This need may be reduced by further developments in wind forecasting, or by the incorporation of short and long term energy storage within the wind farms. Additionally, as the amount of wind generation in the network grows further system voltage stability, network power balance and frequency control may become an issue.

It should be noted that some of these concerns could be alleviated by the provision of additional interconnectors between control areas, to provide averaging of wind output over a larger geographical area, and to enable mutual support at times of passing of storm fronts, when there may be a significant risk of wind farms tripping, rather than generating at maximum output.

10.3 FUTURE TRENDS FOR WIND FARM

10.3.1 Wind farm production forecasting

While the fast fluctuations in wind farm output can create problems with respect to voltage flicker and reactive power management, longer term fluctuations in wind farm production appear to be a deep concern for control area operators. More specifically, the uncertainty over what the wind farm production is going to be during the next hour, or hour by hour for the next day is the major question. Conservative planning to cover a possible reduction in wind plant generation results in higher reserve margins and higher cost, than would be the case in a network with conventional synchronous generators. Backing down economic generation to accommodate a sudden increase in wind generation can also increase costs [1], and when operating in conditions with reduced efficiency, there may be impacts on life expectancy for some plant. Much research work is being performed in the area of wind production forecasting. It is expected that new sophisticated meteorological and statistical methodologies for improving the accuracy of production forecasts will be developed in the near future. These methodologies will help to reduce the uncertainties in wind energy production and will be of significant value for wind farm and power system operators. However, the uncertainties associated with weather forecasting can probably never be fully eliminated.

10.3.2 Wind energy costs

Wind farms are being developed as a commercial venture, and therefore investment cost and income are vital factors. The most important factors in determining the cost of wind-generated electricity from a wind farm and therefore its competitiveness in the energy marketplace are:

- The size of the wind farm; the larger the wind farm, all other factors being equal, the lower the cost of energy.
- The wind speed at the site; the higher the wind speed, the lower the cost of energy.
- The cost of installing the wind farm; the lower the construction costs are, the lower the cost of energy.

The cost of the connection of the wind farm to the ac network is another significant factor, in particular for offshore wind farms located at significant distance from the shore.

The factors affecting the cost of wind energy are still rapidly changing, and wind energy's costs will continue to reduce as the industry grows and matures. A strong growth in the demand for energy from renewable sources, coupled to limited supply, may slow down the price reduction.

Wind energy is capital-intensive, so the cost of financing constitutes a large variable in a wind energy project's economics. Although wind turbine technology has steadily progressed to a point where its reliability is today comparable to that of other energy technologies, it is still regarded as 'novel' and 'risky' by many members of the financial community. Lenders therefore offer less favourable financing terms and demand higher return on investment than for more 'conventional' energy sources. As the wind technology matures this trend is likely to disappear.

Transmission and market access constraints can significantly affect the cost of wind energy. Since wind speed vary, wind plant operators cannot perfectly predict the amount of electricity they will be delivering to transmission lines in a given hour. Deviations from schedule may be penalised both for excess generation and insufficient generation, compared to the submitted schedule. At present the cost of providing frequency control ancillary services has not been passed on wind generators however this also may change.

Connection costs can be high when a wind farm is located away from strong parts of the ac network. Utilities may impose stringent requirement on wind plants for connection to transmission lines, or set the connection fee high, to cover the cost of network strengthening, e.g. the addition of reactive power compensation at the point of connection. Wind developers may find that they can provide the equipment at lower cost than the utility, and depending on the commercial arrangement they may take ownership of this required equipment.

10.4 WIND GENERATOR TECHNOLOGY

The evolution of modern turbines is a remarkable story of engineering and scientific skill, coupled with a strong entrepreneurial spirit. In the last 20 years turbines have increased in power by a factor of 100, the cost of energy has reduced, and the industry has moved from an idealistic fringe activity to the edge of conventional power generation. At the same, the engineering base and computational tools have developed to match machine size and volume [1].

There have been gradual, yet significant, new technology developments in direct drive power trains, in variable speed electrical and control systems, in alternative blade materials and in other areas. However, the most striking trend in recent years has been the development of even larger wind generators leading to the current commercial generation of multi MW machines, see Figure 10-1. The data shown in the figure indicates the average annual increase in height and power of wind generators. Local environmental concerns however, may restrict the allowed hub height.

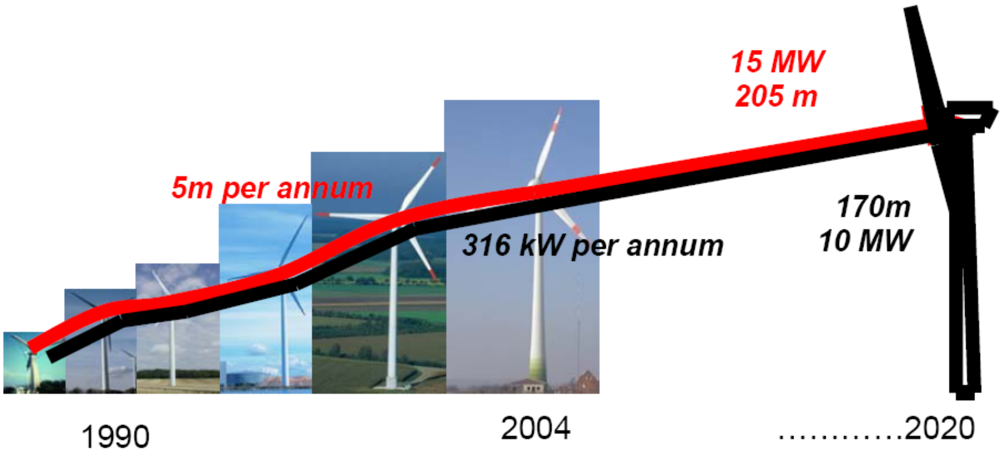

Figure 10-1 Wind generator development.

10.4.1 Improvements in turbine self-diagnosis and condition monitoring

The operational costs of offshore wind parks are very high compared to those of onshore wind parks. For offshore wind, the costs for O&M (Operation and Maintenance) are estimated in the order of 30 to 35% of the Cost of Electricity. Approximately 25 to 35% is related to preventive maintenance and 65 to 75% to corrective maintenance [7]. One of the approaches to reduce the cost for corrective maintenance is the application of self diagnosis and condition monitoring techniques for early failure detection, provided this concept itself can be made reliable. If failure can be detected at an early stage, the consequential damage can be less so the repair will be less expensive. Offshore wind turbines will benefit the most from the fact that with early failure detection, repairs can be better planned. This will lead to shorter downtimes and less loss of revenue.

At present, with the increasing installed power of the wind turbines, the requirements for self-diagnosis and condition monitoring are of high priority. Some components, although designed for the turbine lifetime, fail earlier than expected. This is emphasised by the approach of several insurance companies which simply require application of monitoring provisions. Otherwise, expensive replacements or inspections should be carried out periodically. Also the development of special purpose instrumentation for wind turbines results in more or less off-the-shelf systems for a reasonable price.

10.4.2 Communications and Control

The communications and control infrastructure of current wind farms is highly sophisticated, with high-speed SCADA to each turbine and other critical devices or points within the power collection system. This sophisticated infrastructure has yet to be exploited for purposes of improving the interconnection performance and integration of the wind farm with the power network [1]. In future, this infrastructure can be the foundation upon which many of the advanced features and capabilities will be based. The interface between the wind plant control centre and power system control area operations will also be developed to a much higher degree. Such an interface may facilitate the use of other plant capabilities that could benefit power system security and reliability, such as automatic full- or partial-curtailment of wind generation under severe system contingencies.

10.5 POWER SYSTEM CONSTRAINTS AND NETWORK EVOLUTION

The expected increase in wind generation is likely to result in a number of technical and regulatory constraints for electricity systems:

- The technical characteristics of wind generation do not match the technical characteristics of conventional forms of generation, around which the existing electricity systems have evolved. This will require the implementation of conventional plant characteristics in wind farms to provide support to power system operation. Future large wind farms, hence, may need to be fitted with suitable controllers and fast-response power electronic equipment to provide operational functions such as dynamic control of voltage and frequency, and contribute to system damping and overall system inertia.
- Current predictions are that future wind energy development will primarily concentrate on offshore locations to make use of higher average wind speeds, and to exploit the advantages of offshore wind turbines over onshore ones. The size of onshore turbines is constrained by suitable areas available, environmental constraints restricting the allowable hub heights, and capacity limitations of the available transportation and erection equipment. Transportation and erection problems are mitigated offshore where the size and lifting capacities of marine shipping and handling equipment still exceed the installation requirements for multi-megawatt wind turbines. At a sufficient distance from the coast, visual intrusion is minimised and wind turbines can be larger, thus increasing the overall installed capacity per unit area. Similarly, less attention needs to be devoted to reduce turbine noise emissions offshore. However, the wind farm is likely to require a relatively long submarine cable connection with associated higher cost, in order to connect to the ac transmission grid. The technical issues associated with a long ac cable connection would have to be addressed, possibly by the addition of an SVC or STATCOM (see chapter 4). Alternatively, a HVDC connection may be better (see chapter 5).

10.6 ENHANCED WIND FARM CONTROL

The increasingly wide spread use of wind generation on power network imposes the requirement that wind farms should be able to contribute to network support and operation as do conventional generating stations based on synchronous generators. However the dynamic characteristics of a synchronous generator differ markedly from those of induction generators used in wind turbines, so that the bulk replacement of conventional generation by wind farms will cause changes in the network dynamics and operating characteristics [8]. This situation requires then further research on control methodologies to enable induction generator-based wind farms to exhibit similar dynamic characteristics as those of conventional plant based on synchronous generators.

10.6.1 Synchronising power characteristics

Recent research has illustrated that wind farms based on doubly-fed induction generators can be made to mimic synchronising torque characteristics by suitable generator control [8]. However, further research needs to be conducted in this area to assess the benefits of providing wind farms with this capability.

10.6.2 Provision of power system stabiliser functions

Unlike conventional plant where synchronous generators are provided with power system stabiliser (PSS) functions, the control systems of induction generator-based wind farms are not fitted with this capability. Therefore, more research is needed in this area, and it is already demonstrated in [8], that DFIG-based wind farms can potentially be controlled to contribute positively to system damping.

10.7 SYSTEM INTEGRATION ASPECTS

The full exploitation of the great potential offered by offshore wind farms will require the development of an efficient offshore transmission network. A great challenge lies, therefore, in the design and construction of reliable and cost-effective offshore-grids for collection of power, its transmission ashore and integration with the onshore transmission network.

The increased penetration of wind power may a have a significant impact on reactive power generation and voltage control. The main factor that determines the influence of wind power on these two issues is normally the locations of wind farms which are not the most favourable ones from the perspective of grid voltage control. Additionally, wind turbines are relatively weakly coupled to the system because their output voltage is rather low and because they are often erected at distant locations. This further reduces their contribution towards voltage control. When the output of conventional synchronous generators is replaced by wind turbines at remote locations on large scale, the voltage control aspect and design of enhanced reactive power compensation schemes must therefore taken into account explicitly.

Power electronic equipment will be fundamental in addressing this challenge as HVDC equipment may be considered for transmission, and FACTS devices (SVCs and STATCOMs) may prove essential to implement appropriate reactive power compensation schemes.

10.8 DEVELOPMENT OF POWER ELECTRONIC CONVERTERS

Power electronic converters are used in the wind generator, in the transmission system (HVDC links) and also on specific equipment for power system control (e.g. STATCOMs). It is clear that the continuing developments of power electronic converters is a crucial element in overcoming short and medium term challenges associated with the integration of large scale wind generation within power transmission networks.

The development of new power electronic converter technology for power system applications poses however many challenges which need to be addressed concerning reliability and cost-effectiveness. Additionally, power systems dominated by power electronic converters are also far more complex than traditional systems. The reliability of the converter itself depends on the built-in robustness:

- Power circuit selection and design.
- Reliability and robustness of converter components (power semiconductors, capacitors, transformers, electronic components, etc.) with reference to the specifications given by the manufacture.
- Component de-rating factors (voltage, current, temperature, etc.)
- Selected control strategies and implementation, including state monitoring, local and remote fault handling and self-protection.

Important technical challenges that must be considered to enhance the reliability of converter systems include:

- Advanced switching techniques
- Improved internal and external controllers
- Improved packing and layout
- Reduced thermal stresses.

10.9 DEVELOPMENT OF ENERGY STORAGE SCHEMES

Although penetration of wind power may displace significant amounts of energy produced by large conventional plant, concerns are still raised as to whether this new intermittent generation technology will be able to replace the capacity and flexibility of conventional generating plant [9]. Meeting a variable load with intermittent and inflexible generation (like wind) will be a challenge for secure operation of the sustainable electricity systems of the future. In order to meet this challenge, energy storage has been recognised as a potential technology that may contribute to managing the balance between demand and supply under increased uncertainties due to penetration of wind. Further research work on the development and assessment of energy storage schemes is therefore required. Energy storage options have been discussed in Chapter 4. It should be noted that many of the energy storage systems rely on power electronics for the exchange of energy between the storage medium and the ac network. The power electronics used in VSC Transmission, STATCOM's and in many wind generators, can be adapted to interface also with an energy storage system based on flow batteries for example.

The electricity storage technologies mentioned in Chapter 4 cover a wide spectrum of applications, ranging from fast power quality applications to improve reliability to slow energy management applications to improve profitability.

Thus, for power quality and uninterrupted power supply (UPS) applications, capacitors, flywheels, superconducting magnetic energy storage (SMES), etc., are used within fractions of a second to improve reliability. For energy management applications such as load management, peak shaving and arbitrage; technologies such as pumped hydro, compressed air, flow batteries, etc. are used in daily cycles (hours).

10.10 HYDROGEN

The use of hydrogen is a new alternative to energy storage that covers the needs from maintenance of power quality to energy management over days. Indeed, it does not require placement in an area with specific characteristics, as is required for pumped hydro or compressed air energy storage.

Hydrogen can be obtained from wind by using an electrolyser, taking advantage of the production peaks. It can be stored as a gas until required and transported to the consumption point by pipeline or tanker. In addition it can be converted back to electrical energy by diverse technologies (fuel cells, gas turbines and combustion engines), with all the steps comprising a pollution and emission free process.

In electrochemical systems such as electrolysers and fuel cells, the maximum theoretical round-trip efficiency (from electricity to hydrogen and back to electricity) is limited to some 60%. Moreover, many peripherals (pumps, inverters, heat exchangers, etc.) are required to ensure a satisfactory operation of the different components, thereby reducing the overall efficiency of the system. Currently a global cycle efficiency of 30-40% depending on the system configuration can be expected.

At the time of writing, hydrogen technologies are not fully developed, and therefore their costs are high and their efficiency relatively low. Ongoing research efforts are focused on reducing costs and improving global efficiencies and designs, but the poor round trip efficiency limited by the laws of physics will always remain a limitation, and flow batteries may turn out to be a more suitable technology for utility scale energy storage.

10.11 OFFSHORE DC POWER COLLECTION NETWORKS

Figure 10-2 shows a conventional arrangement of an offshore wind farm with ac connections between the different wind generators. In this example each wind turbine in the AC wind farm has an output voltage of 33 kV AC and each wind turbine is connected with an AC-grid to the HVDC scheme. The transmission from the wind farm to the connection point on the transmission line onshore is made by two ±75 kV DC cables. The grid inside the wind farm consists of 33 kV AC cables. Each wind turbine has a 33 kV transformer and there is one DC/AC converter onshore at the connection point. Naturally, for larger ratings a higher offshore ac grid voltage may be used in future, particularly if distances can be large. Similarly, the dc transmission voltage cn be increased to accommodate larger power ratings.

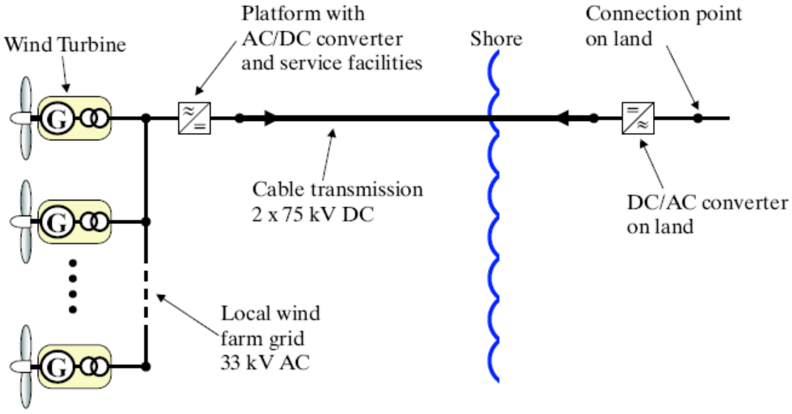

Figure 10-2 Diagram of offshore wind farm with ac grid and HVDC connection to shore

For larger wind turbines with DC links, the scheme above implies four AC/DC conversions: AC/DC/AC in the wind turbine, and AC/DC/AC to the shore. In order to eliminate the intermediate AC stage, arrangements like Figure 10-3 have been proposed. In such concepts, wind generators in a cluster are connected together using dc cables. In this example the wind generators have an output voltage of 15 kV DC and five turbines are connected with a 15 kV DC sub grid to a 15/150 kV DC/DC converter. Several clusters are connected together at 150kVdc by means of dc cables. In this example the transmission from the wind farm to the connection point on the transmission line onshore utilises two ±75 kV DC cables. The subgrid consists of 2x7.5 kV DC cables and the main grid consists of 2x75 kV DC cables. As for the example above, different voltages can be used for different ratings. The connection of clusters using dc cables may be appropriate if long cable distances are necessary between clusters, and the clusters are located far from the shore connection point. Series DC connection of wind turbines within clusters has also been proposed [10]. Development challenges are both technical (series connection, switchgear) and economical (are such concepts economically viable?).

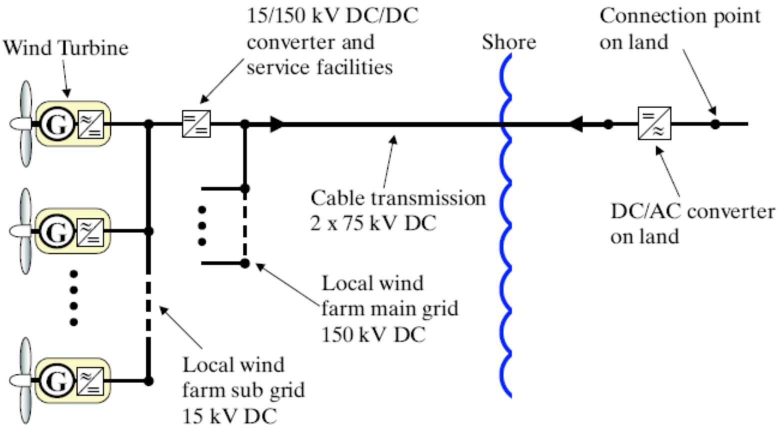

Figure 10-3 Diagram of offshore wind farm with dc grid and HVDC connection to shore

10.12 OFFSHORE DC GRIDS AND SUPERGRIDS

As mentioned in Chapter 3 a substantial part of the problems associated with the intermittency and unpredictability of the actual maximum wind strength can be overcome by the use of interconnections, which enables the wind generated energy to be provided to a larger network and also provides mutual supports between different areas. Similarly, by capturing wind energy over a larger geographic area reduces the problems associated with these issues, because of the averaging effect. Therefore, the future may bring offshore HVDC grids, and Supergrids as explained in the following.

Proposals have been made for the construction of a supergrid for the collections of offshore wind energy, and the transmission of the energy to a number of connection points in different ac network areas, or even asynchronous networks [149]. In addition to providing diversification for the wind energy supply, the proposed scheme also provides additional interconnection capacity between the network connection points, thus enabling other trading and mutual support, whether or not wind is being generated.

Figure 10-4 shows a map of the proposed European Supergrid.

Figure 10-4 The proposed European Supergrid

The Supergrid would use HVDC connections between the different nodes, both offshore and connection points onshore. Since the schemes would be multi-terminal HVDC schemes, i.e. multiple rectifiers and inverters would be connected together on the dc side, the LCC HVDC technology would not be desirable, because of the risk of commutation failures, which would bring the complete grid to a temporary stop in the event of a single phase fault in the ac network close to any of the inverters. Thus, VSC Transmission would be preferable, as these do not suffer from commutation failures. Consideration will have to be given to the performance of the overall network in the event of a dc cable failure. In order to minimise the failure rate of the dc cables it will be necessary to deep trench the cables, to avoid mechanical damage from trawls and anchors, since mechanical damage is the most likely cause of failure for a dc cable. Similarly, dc circuit breakers will be required to ensure that faulty parts of the grid can be disconnected and isolated as quickly as possible and without the need for a complete shut down of the grid. Reliability and availability would be major design criteria for the Supergrid.

The investment required for the construction of a Supergrid as shown in Figure 10-4 would be substantial, and would require political backing from all affected governments. Since the Supergrid connection nodes onshore are located at the fringes of the continental grid the existing 400 kV AC transmission lines will mostly not be sufficient to transfer the large wind power to the load centers. Therefore a substantial reinforcement of the transmission grid will be needed. For this purpose proposals for a combined AC and DC system have been made [12].

10.13 REFERENCES

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11. CONCLUSIONS

Wind generation is the most rapidly growing generation technology worldwide, its increase having been driven initially by environmental concerns over global damage to the world climate because of CO_2 emissions on one hand, and desire to lower dependency on conventional fuel on the other hand. The political backing of the new technology, with favourable tariffs for energy produced fuelled the rate of growth, to the extend that it in some countries the installed wind generation could not be allowed to displace conventional generation any further, for fear of the impact that the wind generation could have on system security. Network operators have developed and are still developing Grid Codes including specific requirements to wind generators in respect of fault ride through, reactive power control and active power control. These grid codes have allowed the proportion of wind generation to increase, without unacceptable reduction in system security.

The growth in wind generation led to substantial investment in the research and development of the wind generation technologies, which have improved their performance to meet the new Grid Code requirements, and has resulted in significant cost reduction of modern wind generators. Wind generators with individual ratings of up to 5MW were available at the time of writing of this Brochure, with predictions of generator ratings of 10MW or more in the near future. The improved performance and increase in rating, is to a large extent due to the inclusion of power electronics within the wind generator, to achieve fault ride through, control of active and reactive power, and minimisation of mechanical stresses within the generator during system transients.

An increasing percentage of new wind generation is being installed offshore, partly because wind conditions are better offshore than onshore, but also because of space restrictions onshore, and public opposition on account of its visual impact on the landscape. Offshore locations of wind farms may necessitate long cable and transmission lines to the point of connection to the transmission network. Furthermore, the best wind resources and possible installation areas for new wind farms are often far away from the load centres, and this introduces additional stress on the transmission network, because the load flows in the system can be very different from those in earlier days without wind generation. Moreover, the load flows can change quite quickly as weather fronts come through wind farms.

Modern wind generators, with their inbuilt power electronics, can control the reactive power at their terminals. However, reactive power flow can change significantly through an ac network, so the wind generators may not be able to solve voltage problems at locations remote from the wind farm. Hence, there may be a need for additional dynamic reactive power control (e.g. SVCs or STATCOMs) within the ac network, in order to avoid voltage stability problems.

SVCs or STATCOMs may also be used to an increasing extent within a wind farm, and could simplify the design of the wind generators. Effectively, an induction generator based wind farm can achieve satisfactory fault ride through performance by the addition of dynamic reactive power control, as has been shown in the studies performed by this working group. However, the cost effectiveness of this approach is questionable, as power electronics at the wind turbine generator have a function anyway to optimise the maximum wind energy capture, and to reduce mechanical stress in the turbine.

HVDC schemes, including LCC HVDC and VSC Transmission, may provide the most economic and technically most beneficial connection for an offshore wind farm located more than say 75km from the ac transmission system connection point.

With the provision of separate SVCs or STATCOMs, and/or the use of HVDC for the connection to the ac network there may be an opportunity for the optimisation of the overall package including the wind generators. Whether this is done may depend on whether the technical expertise available for this optimisation is available, but there may be significant economic benefits in undertaking the additional work.

Interconnections to networks which are geographically distant are very beneficial if a large penetration of wind generation is considered, since the intermittency and unpredictability of wind generation spread across different geographical locations can be significantly reduced by such connections (diversity effect), and the balancing still required can be spread across a larger power system viz. market. Therefore, offshore and onshore supergrids using HVDC for long distance transmission and overcoming bottlenecks in the ac transmission networks, may provide an essential element of future electricity provision with a substantial renewable generation content, including wind, solar and tidal energy resources.

Utilising power electronics to achieve satisfactory power quality and efficient transmission of power over long distance will provide part of the solution required to enable wind power to provide a much larger proportion of the total energy supply, than is currently envisaged. However, even with these measures there may still be times when the power supply from wind power will be drastically reduced compared with the average level because of freak weather conditions e.g. high pressure zones remaining statically located. In principle, energy storage devices could overcome this problem, but much research and development is necessary to achieve cost and physical size reductions, to make it attractive compared with traditional methods to achieve the balance between power generation and load. On the other hand, it is to be noted that the traditional methods are based largely on flexible fossil fuel generation providing standby and spinning reserve, and this will get more and more expensive, with ever increasing oil and gas prices and taxation on CO2 emissions.

The consequences of increasing the penetration of wind power generation by the use of power electronics would be that the short circuit level in the ac network and the inertia would both reduce compared to the levels in a network which has predominantly conventional fossil fuel or hydro synchronous generators as the power supply. Some planners have great concerns or even doubts about the ability to obtain satisfactory operation and system performance in such a system. No doubt it would be necessary to re-write the rule book, but with appropriate studies of system performance and due attention to the settings of power electronic controllers it may well be possible to improve on present day performance, even with a much larger penetration of wind generation.

This Brochure has presented the power electronic tools which can help facilitate the integration of large scale wind farms in a transmission network. A number of sample studies have been performed to illustrate the performance that can be achieved using these tools, with large wind farms connected via an electrically long transmission line to a weak point in the ac network. The power electronic devices and their controllers were not fully optimised during these studies, because of limited time and resource, and it is highly likely that better results could have been achieved if more work had been done. Nevertheless, the studies have demonstrated the possibilities, and will hopefully encourage others to perform similar studies, and to publish results which surpass the performance shown in our studies.

With reference to future work within Study Committee B4 relevant to the subject of this present Working Group, the following topics are suggested:

- The design and performance of multi-terminal HVDC schemes with more than five terminals.
- The control of HVDC schemes during system dynamics in networks with low inertia.