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Report

Control Challenges and Possibilities for Offshore Wind Farms

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ABSTRACT

Electricity generation from large offshore wind farms is being gradually accepted as a feasible solution to meet the rapid increase in energy demands. However, although the technology is progressing fast, a major drawback with offshore wind energy is the fact that offshore wind farm installations are still much more costly than their land-based counterparts. Among other issues, this cost discrepancy is in large part due to the increased turbine size, complexity, installation and connection to shore over long distances. It is then clear that costs have to be reduced significantly to facilitate offshore wind development. Hence, this report aims to provide insight on how the development of enhanced control systems can contribute significantly in reducing the life-cycle cost of energy from offshore wind farms by using a holistic analysis approach with the focus on overall system performance. The main issues associated with each subsystem and how they interact, are discussed.

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1 INTRODUCTION

Over the last decade wind energy generation has evolved into offshore installations mainly due to restrictions to build onshore (e.g. UK) [1]. Up to now, just under 4 GW of offshore wind have been installed in Europe, and all relatively close to shore using well-known onshore wind turbine technology. However, new offshore wind sites located far from shore, 30–120 km, and in deep waters, 30m+, have been identified, where more cost-effective wind power plants in the 1 GW range are planned to be built [2].

The environmental conditions offshore are very different from those onshore and therefore new design specifications have to be taken into account. This gives a basis for development of novel wind turbine concepts optimised for operation in rough offshore conditions. The distant offshore location and size of installations further calls for development of new systems for O&M, grid connection and system integration [3]. Figure 1 shows the major subsystems comprised by an offshore wind farm installation and Figure 2 sketches the control boundaries between these subsystems (along with the major control objectives). At a first glance it comprises the same elements of a conventional onshore wind farm. However, offshore the picture changes dramatically as the environment inherently plays a much more important role demanding better designs and controls to enhance reliability and performance whilst minimising costs. At the wind turbine level one of the biggest challenges offshore is the design of the turbine structure and foundations. Offshore, reliability becomes essential, hence it is very important to develop new control schemes for load mitigation and minimisation of unwanted swings and motions, which are critical for large offshore wind turbines, especially floaters. Therefore, it is necessary to have a good understanding of the complex dynamics between the power train, structure and foundations in addition to loadings introduced by waves and sea currents. In addition, turbine control philosophy must be consistent and address the turbine as a whole dynamic element bearing in mind trade-offs in terms of mechanical performance and power output efficiency. Also, control capabilities of new generator technology must be fully exploited.

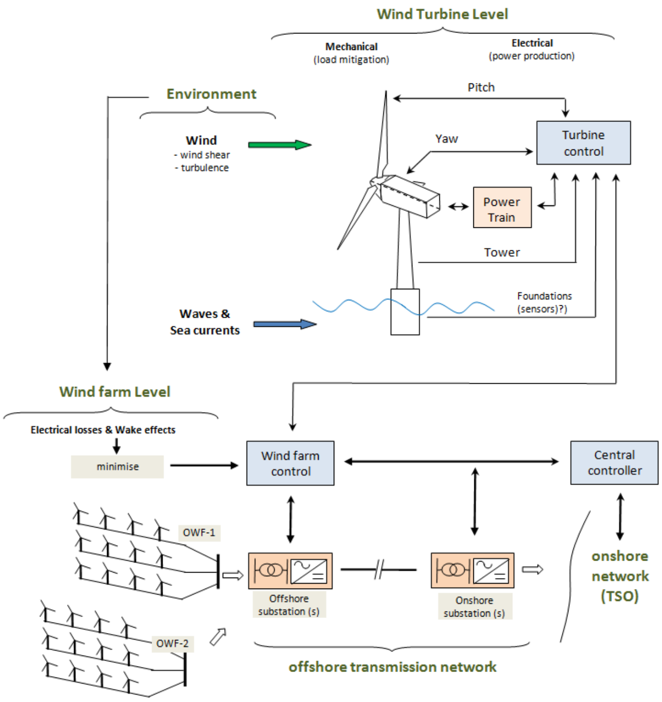

Figure 1. Subsystems of an offshore wind farm installation.

At the wind farm level the array layout and electrical collectors must be properly designed on a site-specific basis to achieve a good balance between losses and the impact of wake effects. For power system studies it is typical to represent the farm by means of aggregated models using a coherent machine (and controller). However, as discussed in the report, more detailed wind farm representations are required in order to take full advantage of control capabilities to achieve a better array design (exploring further coordinated turbine control and operation).

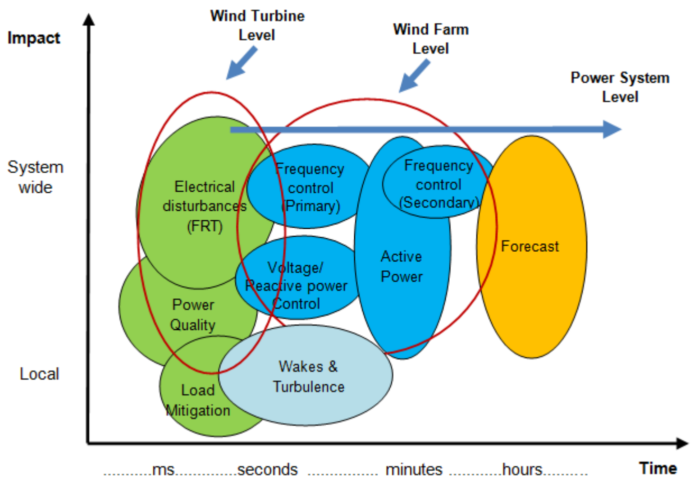

Figure 2. Control boundaries in an offshore wind energy system.

Also, full exploitation of the great potential offered by offshore wind farms will require the development of an efficient offshore transmission network. Great challenges lie then 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 whilst complying with grid codes' requirements for connection of large offshore wind farms. It is anticipated that power electronic equipment (e.g. HVDC and FACTs) and their enhanced control features will be fundamental in addressing these offshore wind integration challenges.

2 CONVENTIONAL WIND TURBINE TECHNOLOGY AND CONTROL STRATEGIES

This section gives an overview of conventional wind turbine technology and typical control approaches as presented in the open literature.

2.1 Turbine operating regions

A general characteristic of all wind turbines is that their output power depends on the wind speed, commonly specified by what is denoted a power curve. The power curve of a wind turbine describes the steady-state relationship between wind speed at hub-height of the wind turbine and the output power from the wind turbine. Figure 3 shows the characteristics. The wind turbine starts producing at cut-in wind speeds, typically around 4-5 m/s, and then the power increases with about the cube of the wind speed until rated power is reached at rated wind speed, typically around 12-15 m/s. Above rated wind speed, the output power is limited either by natural (passive) aerodynamic stall or by actively controlling the pitch angle[1] of the blades. Stall appears when the angle of attack of the effective wind

[1] The pitch angle (including blade twist due to wind force) is defined as the angle between the plane of rotation and blade chord line, see Figure 4.

speed seen by the blades becomes too high (say above 10 degrees or so), and by this, the lift creating the driving torque on the blade is lost. As the effective wind speed is given as the vector sum of the undisturbed wind speed and the speed of the blade element (rotational speed times the distance from the centre of rotation), this means that stall (at the outer parts of the blades) in practice appears at high wind speeds only (see Figure 4).

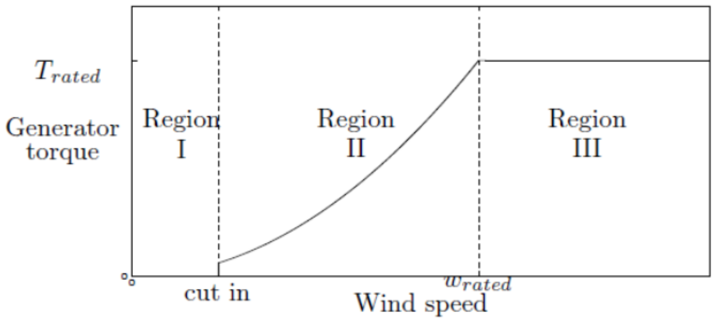

Figure 3. Operating regions of a wind turbine. The graph is for illustration only.

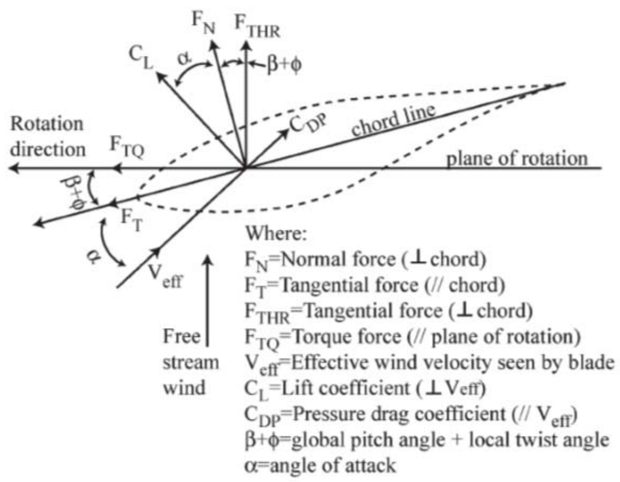

Figure 4. Sketch of forces acting on a rotational blade (cross-section seen from root) of a horizontal-axis wind turbine. Copied from [4].

The active control of the pitch angle can be either "classic" pitch control or active stall control. The "classic" method is to control the pitch angle so that the angle of attack is kept small (out of stall), and continuously adjusted for maintaining constant power at varying wind speeds. In practice this means that the pitch angle is increased as a function of the wind speed. Figure 5 shows how the steady-state pitch angles vary as a function of wind speed in this operating mode when following the constant 1500 kW curve. This type of pitch control is commonly used in combination with variable-speed wind turbines, but has/is also used with fixed-speed wind turbines.

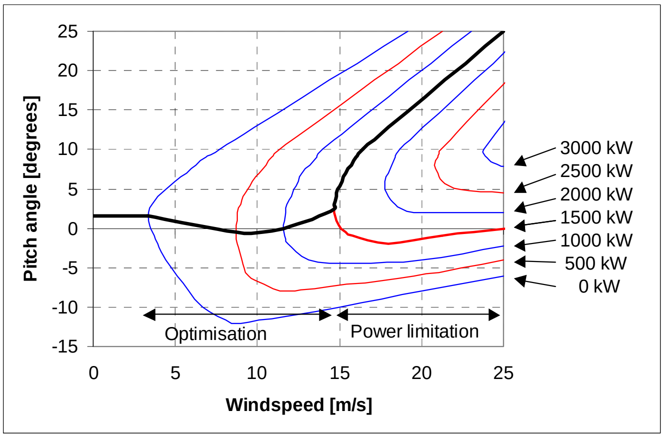

Figure 5. Constant-power curves to illustrate steady-state pitch angles as a function of wind speed for a "classic" pitch-regulated wind turbine with induction generator. Copy from [5]

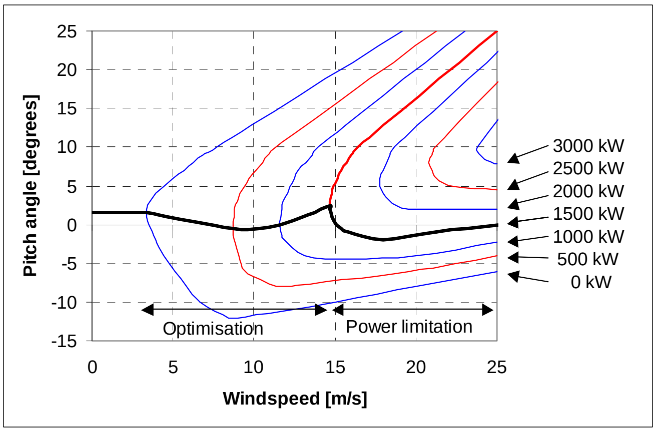

Figure 6. Constant-power curves to illustrate steady-state pitch angles as a function of wind speed for an active stall-regulated wind turbine with induction generator. Copy from [5]

The principle of the active stall method is to limit power output by controlling the degree of stall as shown in Figure 6. This method is applied by Siemens in their fixed-speed wind turbines. The advantage is that it may give less output power fluctuations compared to fixed-speed wind turbines with "classic" pitch control. Comparing Figure 5 and Figure 6 give an indication of this. The drawback of active stall control is that operating in the stall region means operating with increased drag, hence increased trust forces on the construction.

At cut-out wind speed, commonly 25 m/s, the wind turbine is stopped. This is because the mechanical stress on the structure is rapidly increasing with the wind speed, and as such high wind speeds generally seldom occur, the loss in annual generation due to such stopping is anyhow modest. Indeed, an optimum design of a wind turbine for a high wind speed site could yield stopping the wind turbine at a higher wind speed; this would depend on the actual wind distribution and the cost of reinforcing the turbine for operation at higher wind speeds. Gradually decreasing the output power at high wind speeds is an alternative option that is being used by some wind turbine manufacturers (Enercon, ScanWind, possibly others).

2.2 Wind turbine generator technology

Figure 7 shows the main wind turbine generator concepts which are divided into fixed-speed wind turbines (type A) and variable-speed wind turbines (types B, C and D) [6].

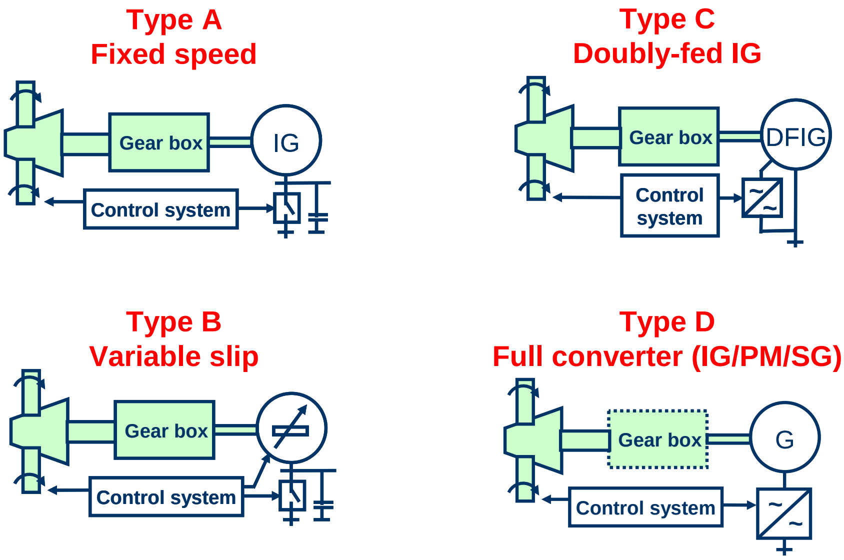

Figure 7. Overview of wind turbine concepts.

2.2.1 Fixed-speed wind turbines

A fixed-speed wind turbine commonly employs a three-phase squirrel-cage induction generator (SCIG) that is driven by the turbine via a gearbox and directly connected to the grid, i.e. without an intervening power electronic frequency converter. Thus, the induction generator will provide an almost constant rotational speed, i.e. only varying by the slip of the generator (typically about 1%). The reactive power consumption of the induction generator is provided via a capacitors bank, whereas a soft-starter limits the inrush current to the induction generator during start-up. At wind speeds above rated, the output power is limited by natural aerodynamic stall or by active pitching of the blades before the wind turbine is stopped at cut-out wind speed, commonly 25 m/s.

Start-up normally takes place at low wind speed, i.e. cut-in wind speed about 4-5 m/s, and then the soft-starter can effectively limit the in-rush current. Connection after a grid or wind turbine fault may however take place at high wind speeds. In this case the inrush current may be significantly higher if the wind-induced torque is not limited by pitching the blades.

The capacitors may be connected in one or more steps. Capacitors for connection in one step commonly provide about zero reactive power consumption at zero active power measured at the wind turbine terminals, and then an increasing reactive power consumption to yield a power factor at rated active power of about 0.9 (inductive), depending on the induction generator characteristics. Modern fixed-speed wind turbines are commonly equipped with more capacitors that are connected in steps, and using electronic switches for fast control of the reactive power compensation. A Static Var Compensator (SVC) can be applied either for controlling the reactive power exchange to a certain value (e.g. zero for unity power factor), or for contributing to voltage control with droop settings just as any other utility-scaled power plant.

Siemens is the only of the top five wind turbine manufacturers (Vestas (DK), Enercon (DE), Gamesa (ES), GE (USA) and Siemens (DE)), that manufactures large fixed-speed wind turbines. The nacelle of a Siemens 2.3 MW fixed-speed wind turbine is shown in Figure 8. The turbine transformer, capacitors and controls are located at the bottom of the tower.

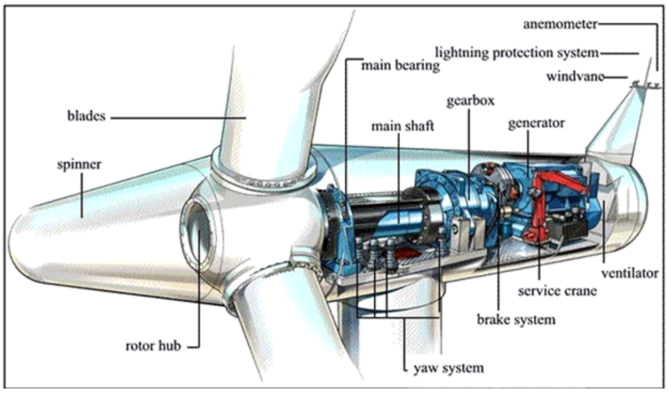

Figure 8. Schematic of Siemens 2.3 MW fixed-speed wind turbine.

2.2.2 Variable-speed wind turbines

Most variable-speed wind turbines employ pitch control, and in the following description only such wind turbines are considered.

Variable-speed operation opens for increased efficiency and enhanced control. The variable-speed operation is commonly achieved either by controlling the rotor resistance of the induction generator, i.e. slip control (Type B in Figure 7), or by a power electronic frequency converter between the generator and the grid (Types C or D in Figure 7). Slip control is offered by Vestas only in what they call OptiSlip, and is mainly marketed in the USA where foreign sales of wind turbines with frequency converters are hindered by patents issues. The variable slip concept (OptiSlip) yields a speed range of about 10%, whereas application of a frequency converter opens for larger speed variations. All variable-speed concepts are expected to yield quite small power fluctuations, especially during operation above rated wind speed. They are also expected to offer smooth start-up.

Hence, the basic difference between the three variable-speed concepts in relation to power quality is that Type B does not have a power electronic converter and thus have reactive power capabilities as a fixed-speed wind turbine, whereas Type C and D have a converter that offers dynamic reactive power control. The reactive power capabilities of Type C and D may differ as the Doubly-Fed Induction Generator (DFIG) concept of Type C uses a converter rated typically about 30% of the generator and not 100% (or more) as is the case for the Type D concepts. The grid-side converters of all major wind turbine suppliers offering Type C or D concepts are based on fast-switching transistors and are therefore not expected to emit characteristic harmonic currents that may significantly distort the voltage waveform. The converters are also full-bridge, meaning that the reactive power can be controlled independently of the active power output (within the apparent rating of the converter).

Vestas, Gamesa and GE all offer wind turbines with the Type C (DFIG) concept.

Enercon has been the pioneer of the top five manufacturers in developing the type D (fully-rated converter) concept. Their system employs a multi-pole (slow rotating) wound synchronous generator directly fixed to the turbine hub as shown in Figure 9. The system is often referred to as a "direct-drive generator system" as the generator is directly driven by the turbine, i.e. not using a gearbox.

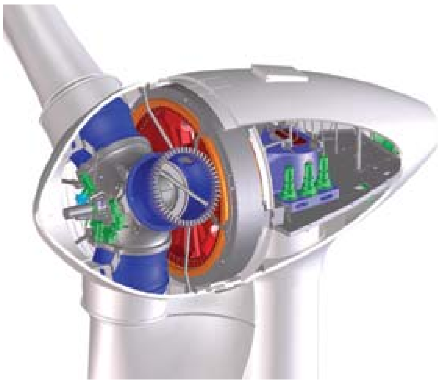

Figure 9. Schematic of Enercon 2 MW wind turbine. (Copy from www.enercon.de)

GE markets an alternative design in their 2.5 MW wind turbines. Here, they use a multi-stage gearbox and a permanent magnet (high-speed) generator connected to the grid via a fully-rated power converter. Siemens has a similar system in their (SWT-2.3-82 VS (2.3 MW) wind turbine and their SWT-3.6-106 (3.6 MW) wind turbine, but applies a standard SCIG connected to the grid via a fully-rated power converter.

The ScanWind turbines are also of Type D. The ScanWind 3.5 MW wind turbine uses a direct-drive permanent magnet generator connected to the grid via fully-rated frequency converter. The generator is from the Finnish supplier The Switch LTD. The first ScanWind 3 MW turbine used a permanent magnet generator from Siemens. The weight of that was about 86 tons, and of the nacelle (including the generator) about 205 tons [7]. The weight of the new 3.5 MW design is unknown to this study, but it is expected to be about the same as for the 3 MW turbine.

The existence of the gearbox or not in the Type D system may not significantly influence the power quality characteristics of the wind turbine. Actually, it is so that wind turbines applying different combinations of power electronic converters and generators may all yield similar power quality characteristics described in qualitative terms, though measurements on actual wind turbines may reveal distinct variations e.g. due to differences in the overall control system or the detailed design of the power electronic converter.

2.3 Wind turbine conventional control strategies

2.3.1 Control of active power

The steady-state active power from any horizontal-axis wind turbine is given by:

$$P = \frac{1}{2}\rho A C_p(\lambda,\beta)u^3 \quad (1)$$

where:

P is the active power output (W)

ρ is the air density (1.225 kg/m^3 at 15°C and 1013.3 mbar)

A is the swept turbine area = πR^2 (m^2); R is the turbine radius (m)
C_p is the turbine efficiency being a function of λ and β
λ is the tip-speed-ratio = $\omega R / u$; ω is the rotational speed of the turbine (rad/s)
β is the pitch angle of the turbine blades (°)
u is the wind speed at hub-height of the turbine (m/s)

This implies that the active power output can be controlled by adjusting: a) the pitch angle, and b) the rotational speed of the turbine.

The control objective is generally to achieve the lowest possible life-time cost per kWh, still respecting any external requirements with regards to operation (e.g. emission of acoustic noise or power system limitations). This can be formulated as:

1. Generation at maximum efficiency up to rated power, thereby maximising generation.
2. Minimising mechanical loading, thereby reducing costs and maximising life-time.
3. Satisfying any external condition.

Objectives 1 and 2 are conflicting, and hence, an optimal control strategy should balance these two. A common assumption is however to give weight to maximising efficiency for wind speeds up to rated power, and for higher wind speeds keep the output power at rated. This results in a power curve (active power output as a function of wind speed, see Figure 3). Control strategies can also include systems for minimising mechanical loading; mainly avoiding operation at critical eigenfrequencies and trying to do so with a minimum loss of energy efficiency. Indeed, the actual control strategies implemented by wind turbine manufacturers are considered of high competitive value and kept secret. Judging from literature a common approach is seemingly along the lines of that detailed in e.g. [8] and [9], though indeed also alternative structure are suggested in e.g. [10].

The schematic in Figure 10 shows the common turbine control loops [11]. The generator often provides the only measurement for both generator torque and pitch control. Supervisory control (not shown) can have additional measurements including local anemometer-based wind speed. More advanced turbines might also include individual blade bending moment/strain measurements and instrumentation for tower/nacelle acceleration.

Also, both the torque and pitch control actions can be modified dynamically in order to reduce certain loads: both by reducing applied loads and by providing additional damping for certain important structural resonances of the system.

2.3.1.1 Wind turbine efficiency

The turbine efficiency C_p being a function of the tip-speed-ratio λ and pitch angle β is a blade characteristic. The actual C_p data may vary depending on the detailed blade design, though normally not much for modern blades. Figure 11 shows one example of C_p data. Note that the turbine efficiency is highest at one specific tip-speed ratio and with pitch angle = 0°. This means that generation at maximum efficiency can be achieved by adjusting the rotational speed of the turbine, ω, so that the tip-speed ratio is kept constant at its optimum value λ_{opt} (in this case 7.8), and keeping the pitch angle constant at zero degrees.

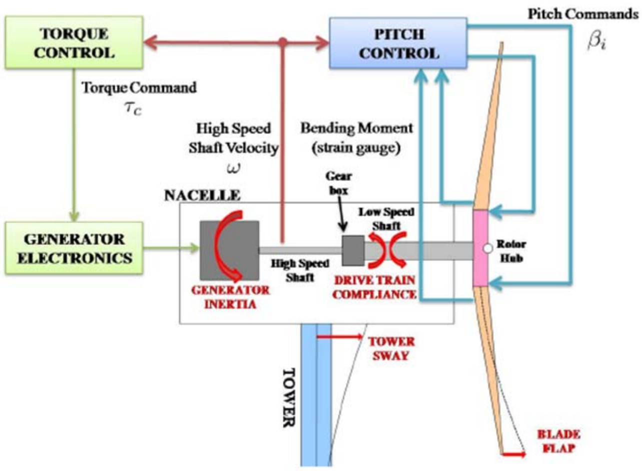

Figure 10. Common turbine control loops [11].

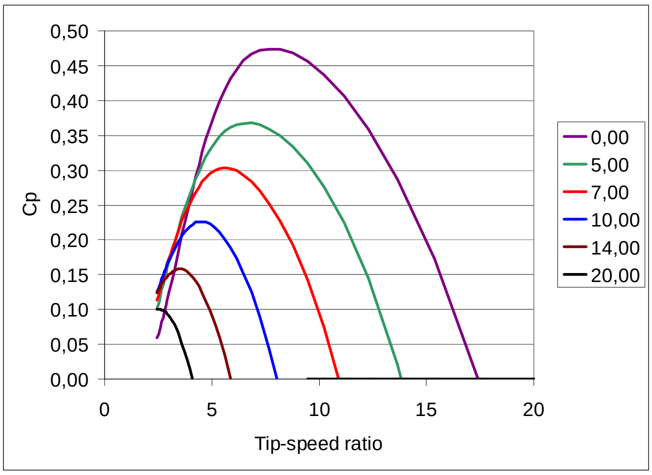

Figure 11. Turbine efficiency C_p as a function of tip-speed ratio for different pitch angles. Example for illustration.

Although it is not evident in Figure 11, note that when the turbine is operated off the optimum tip-speed ratio, small adjustments of the pitch angle (plus/minus one or more degrees) around zero degrees may yield slightly improved efficiency. This is utilised in fixed-speed wind turbines for optimising performance at low wind speeds, and can also be applied in variable-speed wind turbines during operation at (fixed) minimum rotational speed.

2.3.1.2 Converter control for maximum turbine efficiency

In the Type D turbine (see Figure 7) with fully-rated converter, the generator-side converter is normally controlled so that the turbine operates with maximum efficiency up to rated power. As there exists an optimum tip-speed ratio, λ_{opt}, that provides for maximum efficiency, $C_{p,\max}$, eq. (1) gives,

$$P_{opt} = \frac{1}{2}\rho A C_{p,\max} u^3 \qquad (2)$$

Expressing now the wind speed by the tip-speed ratio,

$$u = \frac{\omega R}{\lambda} \tag{3}$$

eq. (2) can be rewritten as a function of the turbine speed:

$$P_{opt} = \frac{1}{2}\rho A C_{p,\max}\left(\frac{R}{\lambda_{opt}}\right)^3 \omega^3 = k\omega^3 = f(\omega) \tag{4}$$

where k is a wind turbine parameter. Accordingly, a simple control structure can be set up for maximising turbine efficiency as outlined in Figure 12.

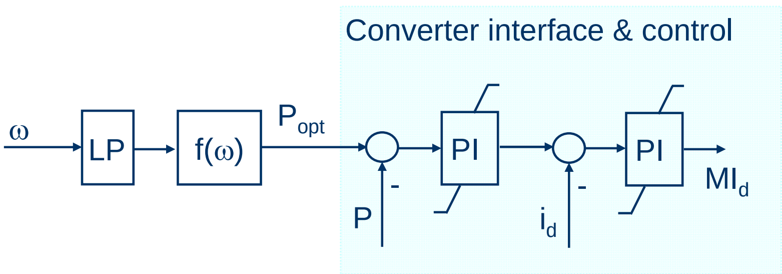

Figure 12. Outline of a control structure using measured rotational speed as input for determining and optimum power set-point signal.

The measured rotational speed ω used as input for the control should be low-pass filtered (indicated by the LP block in Figure 12), in order to damp any speed ripple and high frequency signal noise. Speed ripple may appear as the drive-train, consisting of the turbine, shaft and generator, forms a multi-mass swing system with relatively low damping; hence wind variations may lead to significant torque and speed oscillations (which can be minimised using an active damper).

The shown converter interface and control are indicative only. The structure is similar to the one suggested in [12]; the output of the first PI block gives the reference d-axis component of the current, i_d , and the second PI block gives the d-axis modulation index, MI_d , for the converter[2].

With a speed range that in practice is limited to, say 10 to 20 RPM for a 3MW wind turbine, operation at the theoretical optimum efficiency is not necessarily achieved from zero to rated power, but for a limited power range. The function $f(\omega)$ in eq. (4) may thus in practice look something as shown in Figure 13, i.e. $f(\omega) = k\omega^3$ between ω_1 and ω_2 , and then linear between $\omega_{\min}$ and ω_1 , ω_2 and ω_n (rated speed), and ω_n and $\omega_{\max}$. Here, $\omega_{\max}$ denotes the maximum permitted speed, slightly above the rated speed for allowing some dynamic speed variations, but still keeping the output power at rated.

[2] The generator-side converter is in addition to controlling the active power output also applied for controlling the generator AC voltage.

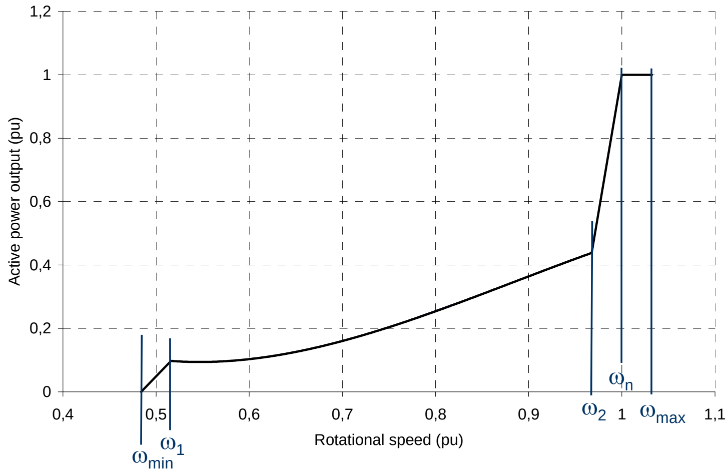

Figure 13. Relation between rotational speed and active power for operation at optimum efficiency between ω_1 and ω_2 .

Alternative control structures to that in Figure 12 can also be set-up. For example, instead of calculating P_{opt} based on measurements of ω, the optimum torque $T_{opt} = P_{opt}/\omega$ could be calculated and compared with the measured turbine torque T . Another alternative could be to calculate $\omega_{opt} = g(P)$ from eq. (4), and then apply the control structure outlined in Figure 14. Here, $g(P)$ is the inverse function of $f(\omega)$, hence Figure 13 also illustrates $g(P)$, but with this control structure, $\omega_{\min}$ can be set equal to ω_1 and $\omega_2 = \omega_n$. Again, possibly torque can be used instead of active power.

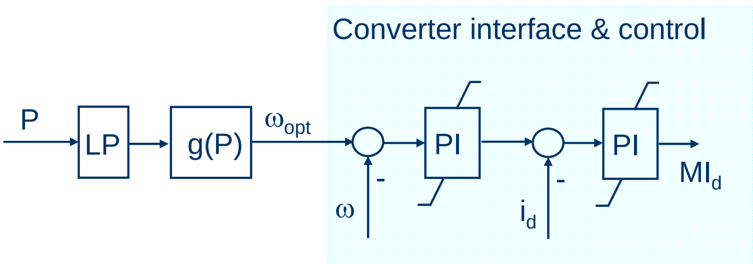

Figure 14. Outline of control structure using measured active power as input for determining an optimum rotational speed set-point signal.

It is thinkable to use also the wind speed as a direct input for the control, though the challenge is to achieve a wind measurement that is representative for the swept rotor area. Due to the difficulty of doing this, using the wind speed as a direct input for the control is not in use by any wind turbine manufacturer. Indeed, the wind speed is measured at the top of the hub, and gives input for when the wind turbine should start and stop (at low (cut-in) wind speed; and at high (cut-out) wind speed). Control for achieving optimum efficiency is however as outlined in this section generally achieved by measuring P (or T), ω and β , and knowing the C_p characteristics; examples of well-esteemed literature describing similar structures are [8] and [9]. These consider wind turbines with DFIG, though still relevant as the overall control issues are basically the same be it wind turbines with DFIG or direct-drive generators with full-scale frequency converters. Ref. [8] suggests a structure similar to

Figure 12, and [9] similar to Figure 14. Neither of these references suggests any gain scheduling for the control of the converter. Comparing the two options, using speed as input to the control (Figure 12 and [8]) has the advantage that this likely will work well also under grid faults (voltage dips or loss of grid), whereas using power as input (Figure 14 and [9]), is likely to pose difficulties in case of grid faults. The actual detailed implementation by the wind turbine manufacturers is not known.

2.3.1.3 Power System Stabiliser

A power system stabiliser (PSS) may be applied for damping torque and speed oscillations in the drive-train. As stated above, such oscillations may appear as turbine, shaft and generator form a multi-mass swing system with relatively low damping; hence wind variations may lead to significant torque and speed oscillations that can be damped by application of a power system stabiliser.

The technique of applying a PSS for damping oscillations in torque (or other power system oscillations) are well-known from use with conventional plants based on synchronous generators, and the same technique can be applied also for wind turbines. A possible scheme for using a PSS in wind turbine control is shown in Figure 15.

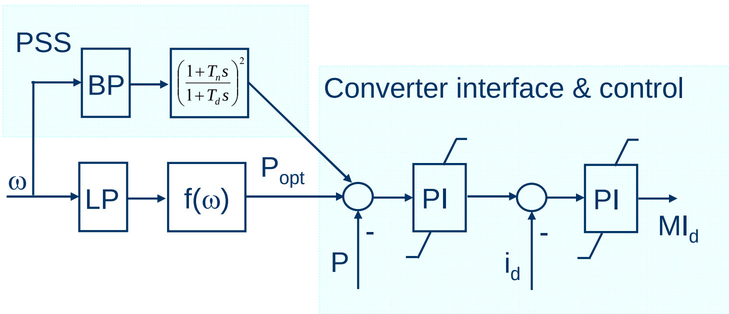

Figure 15. Outline of control structure for the generator-side converter with a PSS for damping torque oscillations.

The measured rotational speed is band-pass filtered (denoted BP in Figure 15), so that all frequencies except for the oscillation of interest are well damped. Thereafter, the oscillating signal is fed into a lead-lag filter that phase-shift the signal so that it is in counter-phase with the original oscillations. Adding this to the reference output power provides damping of the speed oscillations, but still keeping the wind turbine operating at (around) maximum efficiency.

Another alternative could be to apply the PSS on the grid-side converter that control the DC link voltage and the reactive power output to the grid. This is suggested in [12] by adding the output of the PSS to the reference signal for the DC link voltage. The result of this would be a fluctuation of the DC link voltage around its reference voltage, charging and discharging the DC link capacitor, and by this, damping the torque oscillations. A pro of this approach compared to the alternative of controlling the reference power signal as outlined in Figure 15, is that the power fluctuations are kept on the DC link and not transported to the grid. The con is that it requires a sufficiently large capacitor on the DC link to absorb the fluctuations.

2.3.1.4 Pitch control for limiting the rotational speed

The pitch control for limiting the rotational speed to the maximum permitted can be implemented as outlined in Figure 16, as suggested in [8].

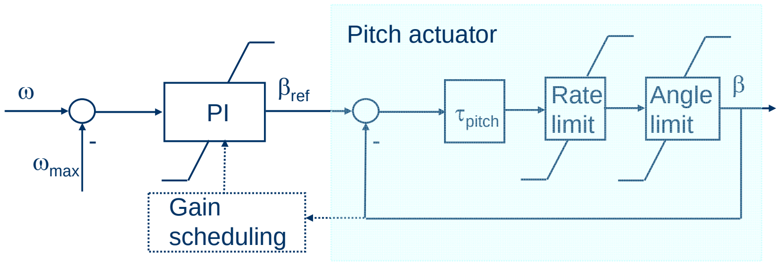

Figure 16. Outline of pitch control for limiting active power to rated.

Here, the measured rotational speed ω is compared with the maximum permitted speed $\omega_{\max}$, and the difference is fed into a PI controller giving a reference pitch angle, β_{ref}, as output. The limiter on the PI controller ensures that $\beta_{ref} = 0$ as long as $\omega < \omega_{\max}$. Gain scheduling is proposed in [8] to compensate for the nonlinear aerodynamic characteristics of the turbine, i.e. at high wind speeds and high pitch angles the system is much more sensitive to changes in the pitch angle than at low wind speeds.

Similarly to the alternatives for converter control outlined in Section 2.3.1.2, alternative control structures can also be assumed for pitch control. For example, instead of determining β_{ref} based on measurements of ω, it could be based on measurement of the active power P and compared with the rated power. This is done in [9]. It can also be considered that instead of comparing the speed with $\omega_{\max}$, the speed could be compared with ω_n. Again, the actual detailed implementation by the wind turbine manufacturers is not known.

All considerations above assume collective pitching of the wind turbine blades. Individual pitch control of each blade is an alternative, and most large modern wind turbines have this capability as each blade is equipped with a separate pitch actuator. The individual pitch control would then assume the same overall control (for limiting the speed), but can in addition be varied individually to reduce fatigue loads on the structure. This is currently a subject of R&D, though expected to be used commercially in the future. By using the latest control techniques combined with reliable load measurements throughout the life of the wind turbine, it is possible to improve its structural efficiency, cope with a wider range of adverse flow conditions and/or permit a larger, higher yield rotor for a given nacelle and support structure. Example publications on individual pitch control are [13] and [14]. An overview of aspects of control for reducing the fatigue loads on the wind turbine is given in [15].

Blade pitching, wind load, varying rotor speed, tower vibrations and gravity are examples of effects that in reality will interact with each other, and result in a dynamic pitch response that may differ from the steady-state relation in eq. (1). For the design of the overall control structure this is however not considered critical as long as the objective is to maximise the efficiency for wind speeds up to rated power, and for higher wind speeds keeping the output power at rated (and avoiding over-speed of the rotor). Example references considering the dynamic interaction of pitch and blades are [16] and [17].

It is thinkable to operate a wind turbine with variable speed, but without any pitch control [18]. The paper concludes that it is possible, and may be an option, but gives increased weight and cost of the generator system compared to a system with pitch control.

2.3.2 System for Fault Ride-Through

A braking resistor may be used for protecting the converters during voltage dips and other power system transients (see Figure 17). The braking resistor may be connected with a power electronic switch over the DC link allowing for fast switching On and OFF, possibly many times during a voltage dip.

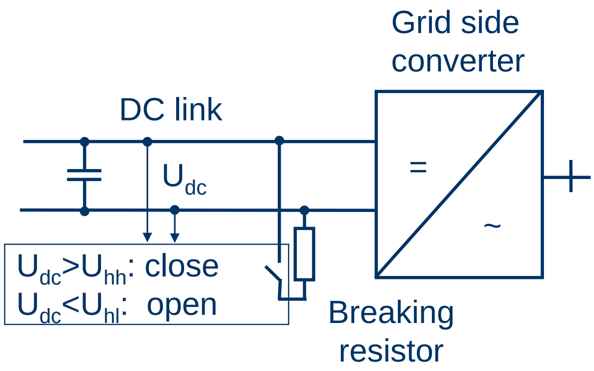

Figure 17. Outline of braking resistor control.

The operation may be as follows: In case of a voltage dip the DC link voltage will increase as the wind induced power will be greater than the power being fed to the grid. As soon as the DC link voltage is increased above a certain threshold value (U_{hh} is say 1.2 pu), the braking resistor is connected. The power going through the braking resistor together with the power being fed to the grid will now be greater than the wind induced power, and the DC link voltage will decrease. At a certain value (U_{hl} is say 1.15 pu) the braking resistor will then disconnect. This cycle with hysteresis of connection and disconnection of the braking resistor will continue until the grid voltage is back to normal. This system with breaking resistor is also described in [12].

2.3.3 Reactive Power Control

An outline of a system for controlling the reactive power output from the grid-side converter is shown in Figure 18. Here it is assumed that the reactive power is controlled according to a given voltage droop function, so that the reactive power output reference value (Q_{ref}) is depending on the measured grid voltage (U). An alternative could be to control Q_{ref} to provide for a fixed value, e.g. $Q_{ref} = 0$, or according to a fixed power factor.

The converter interface and control is as suggested in [12], where the output of the first PI block gives the reference q-axis component of the current (i_q), and the second PI block gives the q-axis modulation index (MI_q) for the converter.

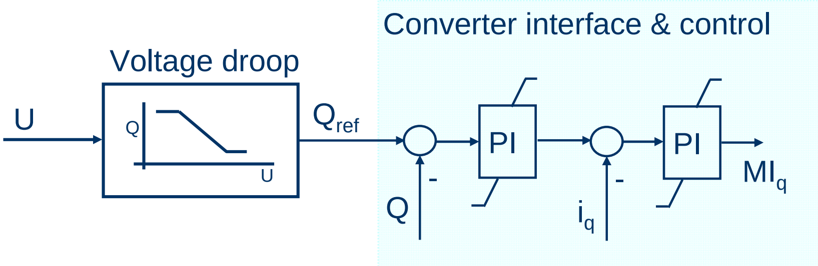

Figure 18. Outline of system for controlling the reactive power output from the grid-side converter.

3 OFFSHORE WIND FARM CHARACTERISTICS

3.1 Environment

In the offshore environment, additional load sources impart new and difficult challenges for wind turbine analysis.

For offshore wind turbines (OWT), the environmental loads are induced by wind, waves, currents and in some cases floating ice; Accurate estimation of these loads, especially for wind loads, are very important not only for design of OWT structures but also for wind power forecasting and control strategies applying. The International Electro-technical Commission (IEC) has issued the 61400-3 standard (2009) [63], which defines 32 different design load cases for ultimate analysis and 9 different design load cases for fatigue analysis. Proper combination of wind and wave loads needs to be addressed for the design purposes, preferably in an integrated analysis. However, the detailed information of wind, waves and currents needs to be collected and predicted at the specified wind farm sites before we do the dynamic response analysis of OWTs.

The integrated design of an offshore wind turbine and its support structure represents a challenge. On one side the on-shore wind industry has developed design methods for wind turbines with regard to their aerodynamic load and response. On the other side, the offshore industry has developed design methods for conventional offshore structures. However, the successful design of an offshore wind turbine not only requires a matching of the two technologies, but in many cases also a focused further development [20].

The key issue is how to combine the highly nonlinear and dynamically responsive rotor/nacelle and tower system with a substructure and its foundation. Add to this the complexity that the substructure may also respond dynamically, and behaves as a nonlinear system due to the nonlinearities in the hydrodynamic loading and response of its foundation. In some areas sea ice, in combination with wind, may also constitute a design driving load combination, but mainly the wind/wave case is considered. The designer is therefore faced with a complex, dynamic system exposed to two different (although correlated) environmental loads, namely aerodynamic load (rotor/nacelle and tower) and the hydrodynamic load (substructure).

Ideally, the total system composed of rotor/nacelle, tower, substructure and foundation should be analysed using an integrated model.

3.2 Wind turbine

Offshore, wind turbines become larger, with longer blades. To maximise the opportunities of working offshore, larger turbines tend to be used with longer blades and mounted on taller towers (giving hub heights of up to 130 metres) than onshore products.

There is no consensus on how large offshore wind turbines will become, although most agree that no physical limit prevents building 10 MW or larger turbines. But the technology to develop these ultra-large turbines has not yet been proven and several significant challenges and development risks may exist. Today, land-based machine size growth may be slowing, and future wind turbine size growth may be paced by offshore development. A critical issue in developing ultra-large machines is that the physical scaling laws do not allow some components to be increased in size without a change in the fundamental technology. New size-enabling technologies will be required to extend the design space for offshore wind turbines beyond the current 5 MW size. Some of these technologies may include a variety of stiffer, lightweight composite material and new composite manufacturing methods; lightweight, low-maintenance drive-trains; lightweight, high-speed downwind rotors; direct-drive generators; and large gearbox and bearing technologies that can tolerate slower rotational speeds and larger scales [21].

Typical wind turbines for the offshore market are GE Energy's 2.5 MW, Siemens' SWT-3.6 (3.6 MW), the Repower (owned by Suzlon Energy since 2009) 5M (5 MW) turbine with a rotor diameter of 126.5 metres, and AREVA's M5000 5MW turbine, with a rotor diameter of 116 metres. As well as the physical size of the rotor, with each blade of the AREVA turbine weighing 16.5 tonnes, the difficulty of transporting and assembling the turbine and the mast in an offshore location can be readily appreciated. Evident in Siemens' turbines, for example, are the necessary adaptations for operating in the marine environment.

The main components, such as the main shaft, the gearbox, and the yaw system, are all strengthened and are larger and heavier than the equivalents on onshore turbines. Other features reflect the interruptions that may occur to regular servicing, with automatic lubrication systems having redundant lubricant reserves to enable continued operation even if scheduled maintenance is severely delayed by weather.

A radical departure from conventional wind turbine design can be seen in the NOVA offshore vertical-axis wind turbine. Developed by a consortium including QuinetiQ, WPL, OTM and the Universities of Cranfield, Sheffield and Strathclyde, a full-scale 5 MW demonstrator of the NOVA aerogenerator is scheduled for 2015. The NOVA turbine is particularly suited to offshore application as it has a very low overturning moment. Generally, offshore vertical-axis wind turbines are of great interest since they are insensitive to wind direction and have a reduced component count. The siting of the generator at base level potentially allows large-scale direct drive, and the relatively low centre of gravity makes the turbines highly suitable for offshore installation.

3.2.1 Advanced rotors and turbine control strategies

The rotor represents only a small fraction of the total cost of the offshore system, but transfer most of the aerodynamic loads and all of the energy; therefore, this is one of the best places to look for system cost improvements. Turbine rotors can be enlarged to increase the energy capture in ways that do not increase structural loads, costs, or the requirements of electrical equipment. A significant amount of R&D has been devoted to this approach for reducing the costs of land-based turbines, and offshore turbines can benefit from the same strategy [21].

Concepts such as active variable diameter rotors, bend-twist coupled blades, two-bladed rotors, or active control surfaces could have a higher economic value offshore, as long as they can also contribute to higher reliability. Structural loads caused by turbulence can be reduced using both passive and active controls to allow for longer blades and greater swept area.

3.2.2 Direct drive alternative to gearboxes

The gearbox drives the generator, converting the slow rotation of the large rotor into the much faster rotation needed by the generator. The components in wind turbine gearboxes are subject to extreme stresses as a result of wind turbulence and are generally the first to fail, damaging the gearbox and putting the whole turbine out of commission. Since wind speeds are higher and turbulence more pronounced offshore, a very ruggedised (and heavier) gearbox is required to give acceptable mean times between failures. Hence, schemes to eliminate the larger, heavier and vulnerable gearbox in offshore applications focus on various direct-drive technologies. Direct-drive, being introduced by companies like Enercon and Siemens, eliminates the gearbox and means the generator rotates at the same speed as the wind turbine shaft. To make up for a direct-drive generator's slower spinning rate, designers increase the radius of rotation, effectively increasing the speed with which the magnets move around the coil. Thus in the Siemens' direct-drive SWT-3.0-101 turbine, the generator has a diameter of 4 meters, and increasingly powerful turbines will require even greater diameters. This accounts for the attraction of vertical-axis turbines where the size of the generator, which is at the base of the turbine, presents far less of a problem. Siemens limits the weight of the large diameter generator by using permanent magnets.

3.2.3 Controls and Condition Monitoring

The control features in an offshore wind turbine are similar to those in onshore turbines, that is, pitch control, and generator torque control. Another challenge in offshore turbines is associated with floating turbines, and that is to maintain platform stability in addition to the conventional control objectives.

One trend is to equip operators remotely with intelligent turbine-condition monitoring and self-diagnostic systems to manage operation and maintenance. Systems that monitor turbine operating conditions can be used to inform smart controllers of needed operational changes or parameter adjustments. They also alert operators to schedule maintenance at the most opportune times. Because offshore turbines are larger, they offer new opportunities that are not as practical at smaller sizes. The cost of the control system and health-monitoring sensors that diagnose turbine status will not increase substantially as turbine size increases because the hardware is independent of size. For the same cost fraction, larger offshore turbines will enable a much higher level of control, maintenance management, and condition-monitoring intelligence [21].

Much of the controls research for land-based systems can also apply to offshore machines, including new algorithms to increase power production and decrease blade loading. Some unique offshore applications may offer opportunities for enhancing these solutions, especially for floating systems that can use the rotor to help manage overall system displacements and loads.

If an existing commercial wind turbine is installed offshore in deep water[3], the cost of energy will be higher than that of a typical onshore wind turbine. There are three unavoidable reasons for this:

- a more elaborate support structure is required,

[3] A depth greater than a few tens of meters (e.g. >60m)

- the electrical power may need to be transmitted over a long distance,
- installation, maintenance, and repair involve costly marine operations and require a favourable weather window.

Thus, it is worth exploring the 'corners' of design space, with the thought of minimising these additional costs. The most economical offshore turbine is likely to be different from existing onshore turbines.

3.2.4 Offshore wind substructure technology

The substructure of the offshore wind turbine is defined as the supporting system that begins at the lower flange of the tower and extends to the structural elements that attach it to the seabed. Offshore wind substructure technology can be divided into three major technology classes based on water depth, such as those shown in Figure 19. Shallow water is defined in this reference as between zero and 30 m. This definition captures the water depth of most of the projects installed today, as well as the bulk of industry experience. Transitional depths range between 30 m and 60 m. Beyond 60 m depth, several floating concepts derived from the oil and gas industry have been developed. These depth bands only approximate the break points for the three technologies, but not enough experience exists to know if they are chosen accurately. They serve as good guides, however, for estimating the resource and the need to develop new solutions [21].

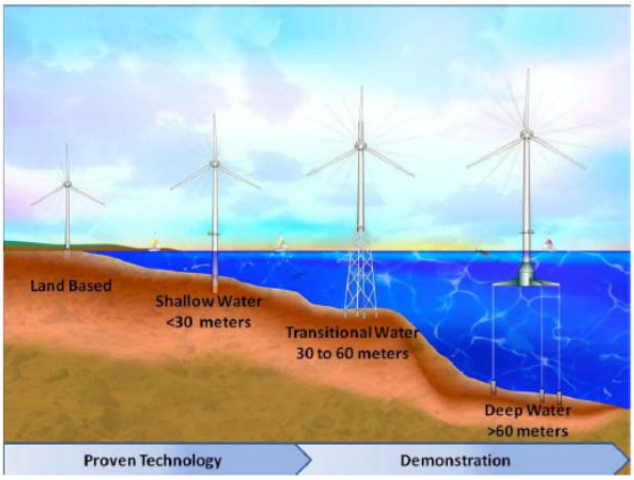

Figure 19. Substructure technology classes for offshore wind turbines [21].

3.2.4.1 Shallow-water substructures

Figure 20 shows the most common shallow-water foundations being developed today. They include monopiles, gravity-base, and suction-bucket substructures, with the latter in the experimental stage. There is no technical reason why some of the transitional substructures would not also perform well in shallow water, but a full analysis of all conditions has not yet been performed [21].

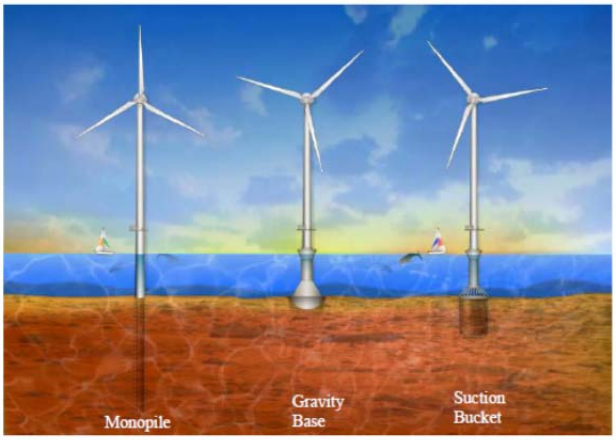

Figure 20. Shallow-water foundation technology [21].

Monopiles generally have a larger projected area toward the wave front, which can increase the loading from waves in general. In some shallow-water sites (between 10 m and 15 m deep), where waves may only break when they reach extreme wave heights, the load contribution from extreme breaking waves can become a design driver for monopiles and must be given full attention. In shallower sites, the waves may break more frequently under storm conditions but the wave attenuation is significant enough to reduce the overall impact on the design.

3.2.4.2 Transitional technology

Transitional substructure technologies are used to support offshore wind turbines in waters deeper than 30 m but shallower than 60 m (see Figure 21). In most cases, transitional substructures use multiple anchor points, using jackets or tripods, and in most cases will results in higher costs and add incremental technology challenges. Not all the concepts shown in Figure 21 have been developed yet, but the figure shows some possibilities. An advantage of transitional water depths is that breaking waves do not occur as easily as they do in some shallow-water sites, which significantly reduces extreme wave loading [21].

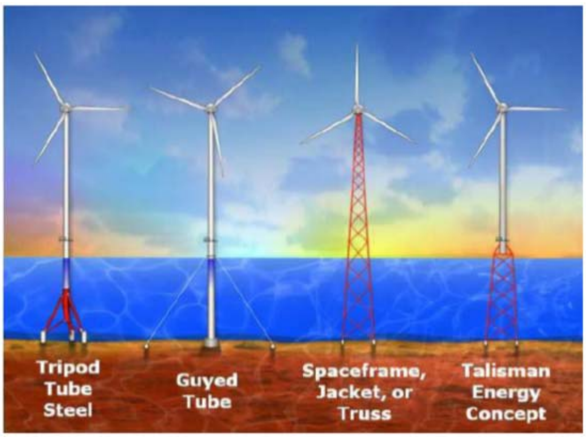

Figure 21. Transitional substructure technology [21].

3.2.4.3 Floating wind turbine technology

At deeper water sites, it might be more economical to use floating substructures, but the technology is at a nascent stage of development. The development of floating wind technology will dictate a new set of wind turbine design specifications to handle the coupled hydrodynamic/aerodynamic forcing, as well as the added weight and buoyancy stability requirements. These new requirements will initially add a higher degree of technical risk but with a potentially high payoff in the long term [21].

A vast number of permutations of offshore wind turbine platform configurations are possible, considering the variety of available anchors, mooring, floater geometry, and ballast options.

Typically, the overall architecture of a floating platform will be determined by a first-order static stability analysis, although there are many other critical factors that will determine the size and character of the final design. To focus the discussion, a classification system was developed that divides all platforms into three general categories based on the physical principle or strategy that is used to achieve static stability [19]:

1. **Ballast**: Platforms that achieve stability using ballast weights hung below a central buoyancy tank which creates a righting moment and high inertial resistance to pitch and roll and usually enough draft to offset heave motion. Spar-buoys apply this strategy to achieve stability.
2. **Mooring Lines**: Platforms that achieve stability through the use for mooring line tension. The tension leg platform (TLP) relies on mooring line tension for righting stability.
3. **Buoyancy**: Platforms that achieve stability through the use of distributed buoyancy, taking advantage of weighted water plane area for righting moment.

Figure 22 shows some examples of floating offshore platform architectures that are being considered. Most concepts shown in the figure have not yet been demonstrated.

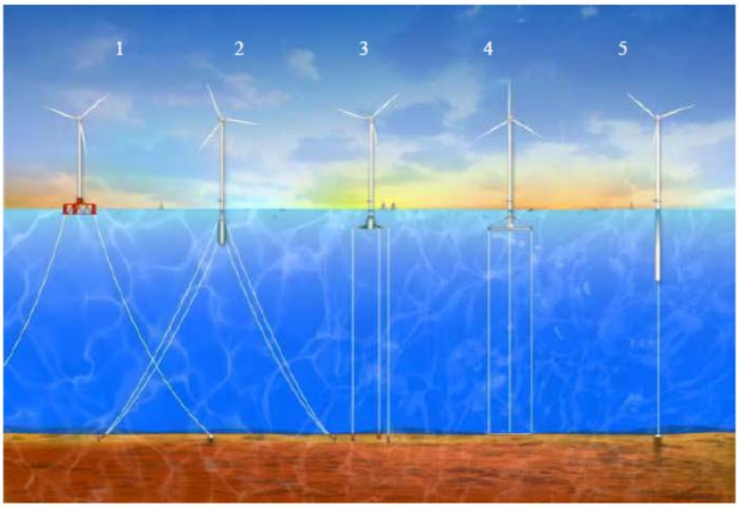

Figure 22. Floating deepwater platform concepts: (1) semisubmersible Dutch tri-floater; (2) spar buoy with two tiers of guy wires; (3) three-arm mono-hull tension-leg platform (TLP); (4) concrete TLP with gravity anchor; (5) deepwater spar (Sway 2010) [21].

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3.3 Wind farm

3.3.1 Wind farm arrangement – wake effects

The arrangement of the turbines within a wind farm depends on the site terrain, wind conditions (velocity and direction) and the size of the turbines. In order to maximize the power output from a wind farm, the wind farm layout needs to be designed in such way that wake effects will be minimized. To reduce the wake effects and hence, increase power output from the wind farm, the simplest option is to space the turbines far apart until wake effects are completely negligible. However, this approach will lead to increased inter-turbine cable cost and land wasting [26][27]. It is therefore important that the turbines are not distributed at unnecessary separations and the economical aspects of site development must balance wake effects and by possible loss in energy production [28]. In addition to the common rectangular layout, some wind farm layout optimization studies have suggested that wind turbines should be arranged in scattered pattern (e.g. [29][30]). In general, in a flat terrain (e.g. offshore sites), wind farm layout is mainly based on the prevalent wind direction. If the wind speed is uniform with no dominant wind direction, the distance between wind turbines in rows and columns could be about 5*D* (where *D* is the rotor diameter) [31][29][27]. However, if there is a predominant wind direction, turbines are generally spaced between about 1.5*D* and 4*D* apart in the cross-wind direction to the prevailing wind direction, and between 5*D* and 12*D* apart in the direction of the prevailing wind [31][29][27].

The turbine wake in general, is characterized by streamwise (axial) velocity deficit, which leads to less power available for the downstream turbines. It also causes high turbulence levels which can give rise to high fatigue loads. The wake could have significant effects up to a distance 15*D* downstream of the upstream turbine [32][33]. The effect of these interactions will have severe implications on the downstream turbines which are located in the wake of the upstream ones. Depending on the distance between the turbines and the arrangement pattern in a wind farm, the power losses due to wake effects can be up to 23% [34][35] compared to a farm consisting of unobstructed turbines. In fact, these losses can be considerably higher for the first turbine immediately downstream of the most upstream turbine that is exposed to the undisturbed freestream conditions (e.g., [35]). Similar effect is experienced on the subsequent downstream turbines but the effect decreases slowly downstream. The increase in fatigue loads on the downstream turbine due to wake interference effects can be up to 80% [36] and this may severely shorten the life span of the rotor blades. Turbine wake properties and development depends on many factors which include the wind conditions (speed, direction and turbulence intensity), site topology and surface roughness and, upstream turbines operating conditions. The performance of any turbine operating within the wake of another turbine depends on these parameters as well as the distance between them. The wake of turbine and some of the factors that can affect its properties are schematically shown in Figure 23.

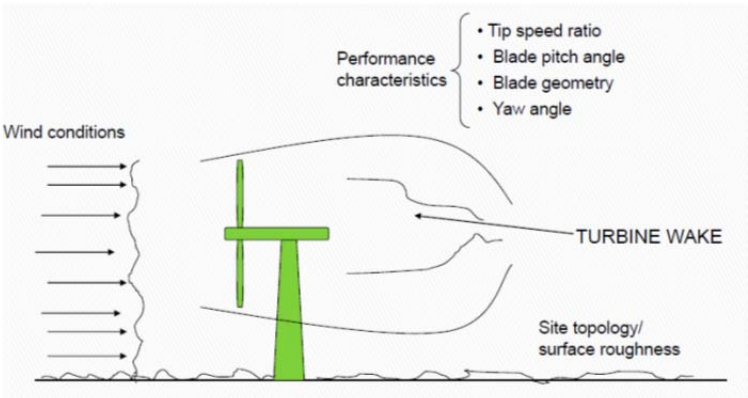

Figure 23. Schematic diagram of wind turbine wake parameters that can affect it.

3.3.2 Wind farm – electrical collectors

The typical layout of an offshore wind farm is shown in Figure 24, and in general, the topology is similar to an onshore wind farm. The most commonly used voltage level in the array is 33 kV. This choice depends on power capacity, cable length and losses, but is also limited by available technology.

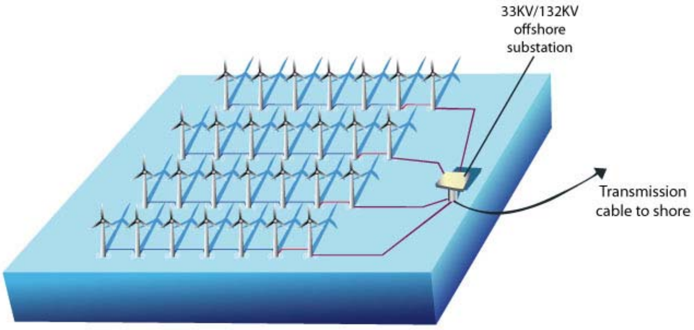

Figure 24. Offshore wind farm layout.

Different topologies may be employed for the collection networks depending on the wind farm size and the desired level of losses and redundancy. Figure 25 shows electrical schematics of the two most commonly used configurations, for which in principal AC or DC could be used [40]–[45].

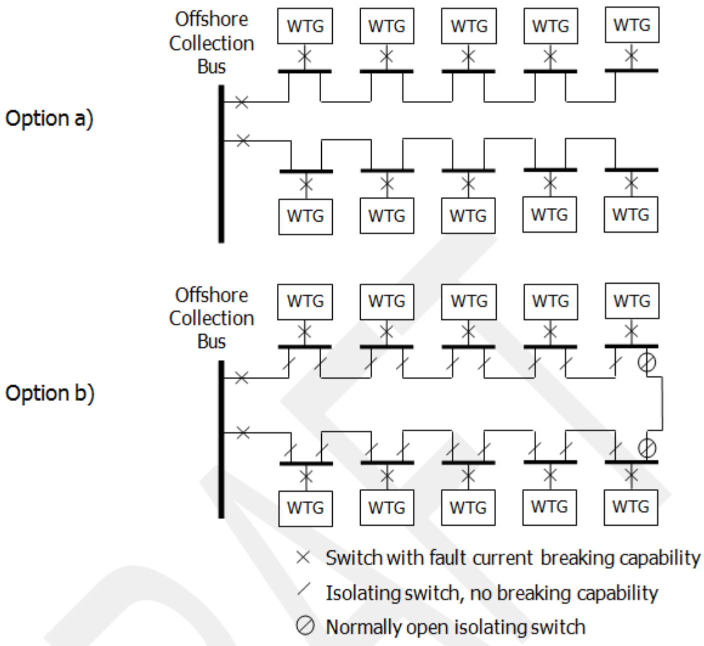

Figure 25. Electrical schematics of most common collection configurations [40]-[45].

Option a - Simple radial strings.

This grid has no redundancy and a fault on any section of a string would take out the entire string for as long as the fault occurs. There are no means to isolate the fault remotely, which is a great disadvantage as an offshore repair can take a considerable amount of time. No part of the power generated along a string can be exported for the duration of the outage. Moreover, supply to the WTGs' auxiliary demand would be lost, therefore diesel generators would be needed on each of the WTGs to provide supply to the essential demands. It could take three months to repair a cable, during which time fuel supplies for the emergency generators would have to be maintained to the WTGs affected and this could be very difficult during winter sea conditions.

Option b - Fully flexible strings.
This array configuration allows the faulted section to be isolated for repair and get the normally open link closed between the two feeders remotely to restore an electrical link with most if not all of the WTGs. The great benefit of this arrangement is that supply to the essential demands of all WTGs can be maintained after a fault on a cable string. In this way, at least a proportion of the generation capacity can also still be exported, depending on the fault location, the selected cable ratings and whether their sizes are tapered (lower rated cables are used for the sections near the end of a string). This is much better than not being able to export any power specially when considering that the load factor of wind generation is often less than 35%.

In practice, the WTG layout is normally given as an input to the collection network design and the cables are routed for connection to the WTGs such that cable costs and conductor losses are minimised. This is achieved by minimising the total cable length and applying a similar utilisation (peak power/rated power) to all cable strings as much as possible.

3.4 Grid connection

The typical connection of an offshore wind farm system is shown in Figure 26. In general, the system consists of the wind turbine generators (WTGs), collection network, collection point, offshore transmission system, and the interface to the point of common coupling (PCC) with the onshore grid [46].

Figure 26. General offshore wind farm layout [46].

All wind turbines have a voltage adjusting unit, comprising an AC transformer and may include power electronic rectifiers and inverters to step up the voltage to an appropriate level. The collection network comprises medium voltage cables that connect the wind turbine units to the colleting point. Today, the collection network operates at a medium voltage of typically 33kV. The choice of the voltage level is driven by the required power flow capacity, and the length of the collection cables, and the requirement to keep the losses adequately low. If proven viable, DC/DC converters could in the future be used to step up the voltage in a DC collection network. At the collecting point the voltage is increased to a higher voltage level suitable for transmitting the power to shore. For onshore wind farms, the standard transmission scheme is an AC network. However, for connection of an offshore wind farms HVDC transmission may be the only feasible option if the cable distance is more than about 100km. However, this is project specific, as the break-even distance also depends on the wind farm size, cost of the AC/DC converters, the offshore substation platforms and environmental factors. In particular, HVDC offers the following advantages (and more specifically in those schemes with cable connections) [46]-[48]:

- Sending and receiving networks are decoupled by the asynchronous connection, such that faults are not transferred between the two AC networks.
- DC transmission is not affected by cable charging currents (therefore there is less of a limitation on distance).
- A pair of DC cables can carry up to 1200 MW.
- The cable power loss is lower than for an AC cable scheme.

There are two different HVDC transmission technologies: Line-Commutated Converter HVDC (LCC-HVDC) using thyristors, and Voltage Source Converter using IGBTs VSC Transmission, as shown in Figure 27.

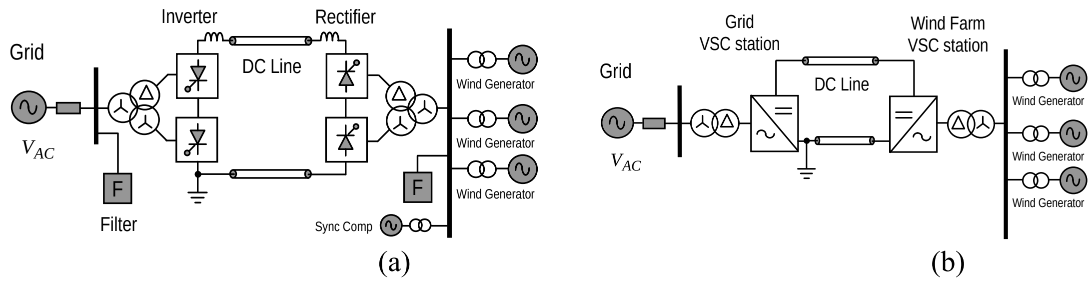

Figure 27. HVDC transmission schemes: (a) LCC-HVDC; (b) VSC-HVDC.

In addition to the HVDC transmission other enabling technologies such as Static Var Compensators (SVCs) or the Static Compensator (STATCOM) may be used to facilitate the integration of wind. An SVC or a STATCOM can provide the dynamic reactive power control required to keep the AC voltage within the connection agreement limits. The SVC/STATCOM can react to changes in AC voltage within a few power frequency cycles, and can thus eliminate the need for rapid switching of capacitor banks or transformer tap changer operations. The rapid response of the SVC/STATCOM can also reduce the voltage drop experienced by the wind farm during remote AC system faults, thus increasing the fault ride-through capability of the wind farm.

Figure 28 illustrates the schematic of the connection of a large offshore wind farm using a VSC-HVDC transmission scheme.

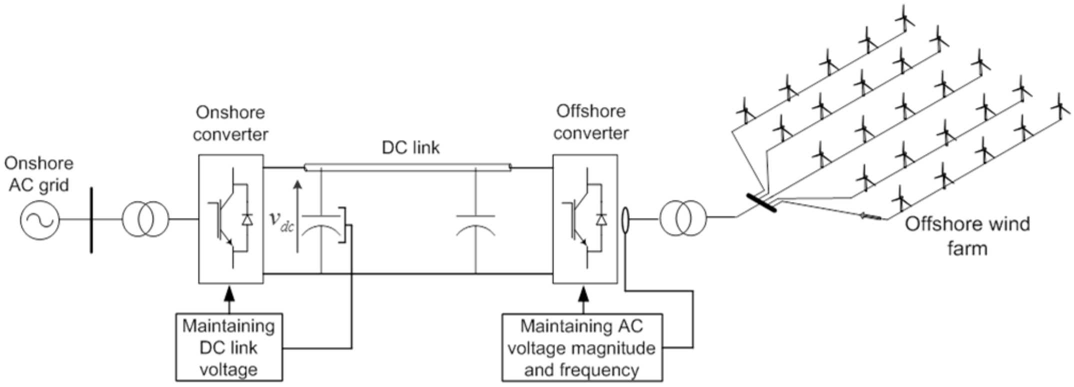

Figure 28. VSC-HVDC transmission for connection of a large offshore wind farm.

4 CONTROL OBJECTIVES

This chapter discusses in good detail the various objectives a control system for offshore wind turbines and wind farms should meet.

4.1 Wind turbine

The minimisation of the energy cost involves a series of partial objectives. These objectives are closely related and sometimes conflicting, and should therefore not be pursued separately, but lead to a well-balanced compromise among them. These partial goals can be arranged in the following topics [49][50]:

- *Energy capture*: maximisation of energy capture taking account of safe operation restrictions such as rated power, rated speed and cut-out wind speed, etc.
- *Mechanical loads*: preventing the turbine from excessive dynamic mechanical loads. This general goal encompasses transient load alleviation, high frequency loads mitigation and resonance avoidance.
- *Power quality*: conditioning the generated power to comply with interconnection standards.

4.1.1 Loads in a bottom-fixed offshore wind turbine

An offshore wind turbine is affected by fluctuating loads from wind and by the fluctuating charge from the ocean waves. The combination of these two effects results in a highly dynamic loading situation, through which fatigue becomes a critical aspect [51]. Figure 29 shows the turbine definition that is used in the following discussion.

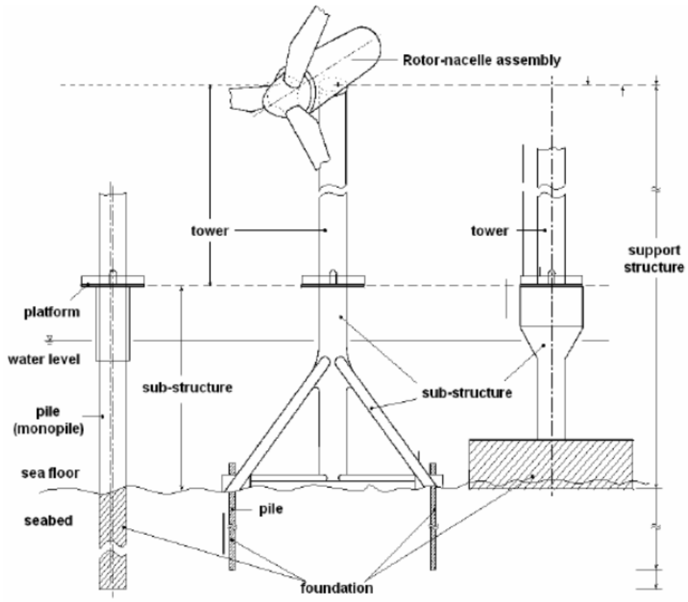

Figure 29. Wind turbine definition [51].

Figure 30 illustrates various impacts on an offshore wind turbine [51]. The figure shows that the turbine has to withstand the influence of many different sources, which results in high requirements of the turbine design.

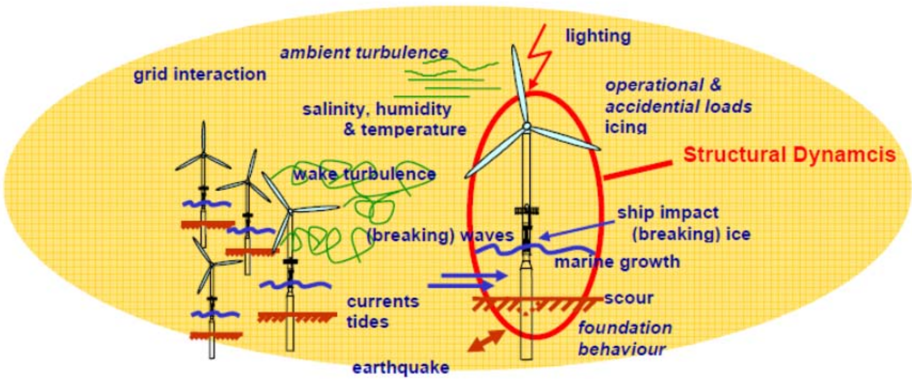

Figure 30. Impacts on bottom-fixed offshore wind turbines [51]

In general, the loads can be sorted according to their variation in time and their origin [51]. The table in Figure 31 classifies a number of example loads in this way.

Load types		Variation in time: Steady	Periodic	Random	Transient
	Operational	• tower and nacelle gravity loads • rotational loads	• loads from mass-imbalance • tower shadow • blade gravity		• stopping and breaking events • yawing • grid failure • pitching •
	Aerodynamic	• mean wind speed	• skewed inflow • aerodynamic imbalance (e.g. pitch misalignment)	• turbulence	• gusts
	Hydrodynamic	• mean currents • tides	• breaking ice	• sea-states	• extreme waves • breaking waves

Figure 31. Classification of load types in an offshore wind turbine [51].

4.1.2 Dynamic response of bottom-fixed offshore wind turbines

The aerodynamic and hydrodynamic loads indicated in the table in Figure 31 have different effects on the response behaviour of wind turbines [51]. Figure 32 illustrates the main dynamic responses of the turbine, which are explained below.

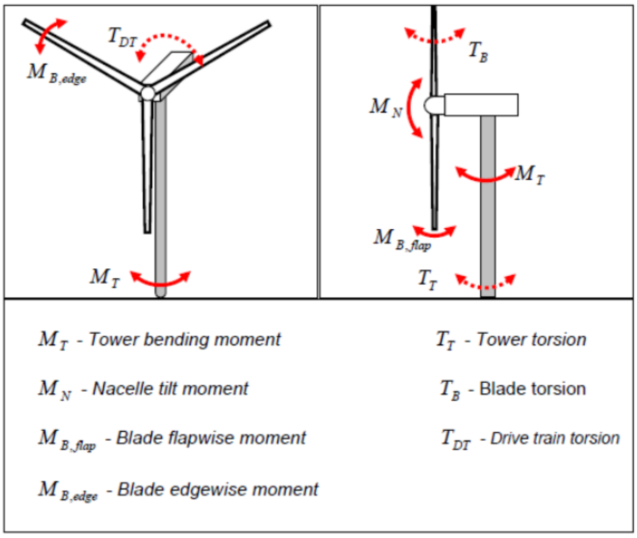

Figure 32. Main responses from a bottom-fixed offshore wind turbine [51].

The blade response can be divided into three components: the flapwise moment; the edgewise moment; and the blade torsion.

The edgewise bending moment is mainly influenced by gravity loads due to rotation, but also the aerodynamic impacts such as the wind profile, turbulence and tower shadow effect result in edgewise loads. For the flapwise moment, these aerodynamic impacts play the most important role. Especially the tower shadow effect lead to rotational-depended moments. Resulting from the nacelle tilt and cone angle, even the gravity loads affect the flapwise bending, but in a subordinate way.

As the lift force, which results from the incoming wind field and mainly the rotation, creates an untwist moment to the blade, the angle of attack changes dynamically. Due to this effect, the centrifugal forces create torsion in the blade when the blade is bended out of its rotation plane.

From the rotor system, the loads are transferred to the fixed nacelle/tower subsystem. Here the rotor acts like a disc that converts and transfer the wind loads. The thrust creates a tilt and yaw moment to the rotor-nacelle-assembly (RNA) with a pressure point moved slightly to the top. Furthermore, this moment is rotational-depended fluctuating, due to the tower shadow effect and the turbulence.

The fluctuating drive torque results from a combination out of the rotor and the counteracting generator torque. This results in the main shaft torsion. Both torques are subject to fluctuations, which enlarge the torsional behaviour. The rotor torque varies due to aerodynamic load fluctuations and rotational periodic effects, where the generator torque is subject to grid coupling fluctuations, control impacts or vibrations induced by the converter.

Until here for the RNA, the hydrodynamic load impacts are not noticeable. Only for the last subsystem - the tower and substructure - these loads have to be considered in response analysis, as they have an impact on the tower top deflection and therefore on the aerodynamic damping.

The tower bending moments are subject to loadings from the tower top (the RNA kinematics) and the lower tower part (the hydrodynamic impacts). Of course the tower is also excited by an aerodynamic drag force, but compared to the other two impacts the influence is rather small.

On the tower top the forces from the thrust act on the system, where again fluctuations due to tower shadow effects, turbulence or sheared inflow are visible. Besides this, a major contributor to tower stresses is the yaw moment. This moment is created by a misalignment between the incoming flow and the position of the rotor. Also, pitch-errors, where for example one blade is pitched differently, have an important impact on the tower top forces.

On the lower part of the tower (i.e. the support structure), the wave induced loads and the tower top kinematics affect the bending of the tower system, where the loads strongly depend on water depth/wave height, currents, direction and period [51].

4.1.3 Load mitigation concepts in offshore wind turbines

The load mitigation concepts discussed in this section aim to reduce fatigue and to increase the turbine lifetime [51]. Basically two fatigue contribution can be distinguished - the aerodynamic and the hydrodynamic fatigue. Many components in an OWT system have to be considered in relation to fatigue but the emphasis here is on the blades and the support structure.

The blades experience all their loads from the aerodynamics - mainly the 1P and 3P loadings. Turbulence is one of the main contributors to blade fatigue loading and approaches such as individual pitch control may be used to address this type of loading.

The support structure is influenced by both environmental impacts affecting an OWT - the aerodynamic and the hydrodynamic. Both influences create vibrations of the structure, which are crucial for the fatigue lifetime of the support structure. Thus, devices to control these vibrations include tower damper systems, and tower feedback control with the aid of cyclic, tower vibrational depending pitching [51].

4.1.3.1 Vibration control systems

With increasing size of wind turbines, dynamic loading of the structures increase. These loads and the resulting vibrations can be reduced with the aid of damper devices. Vibration damping devices can be classified into active, semi-active and passive dampers. The concept of the passive damper is simply to change the structural stiffness and therefore the natural frequencies and the modes shapes. The active damper devices are based on the actual response of the structure and the change in response of the structure.

A wind turbine is a nearly undamped system with many degrees of freedom, which tends to brace if one of the eigenfrequencies is activated/excited. The dominate vibrations in a wind turbine are the first to third tower bending frequencies, the appropriate first to third eigenfrequencies of the blades (edge- and flapwise), and the torsion vibration of the blades, tower and of the whole drive train. Additionally, superposition of these single effects can appear.

4.1.3.1.1 Tower vibration damper

Wind turbine towers are classified according to their relationship between the tower natural frequency and the exciting frequency, which is mainly the rotor system frequency. If the towers natural frequency is greater than the blade-passing frequency (3P), the tower is said to be stiff. If the natural frequency is lying in between the rotational frequency (1P) and the blade-passing frequency, the tower is said to be soft. Finally if the natural frequency is smaller than the rotational frequency, the tower is classified as soft-soft. In cases of variable-speed turbines, these bands between the 1P and the 3P frequency narrows, as the rotational frequency has different ranges of operation as shown in Figure 33 [51]-[53].

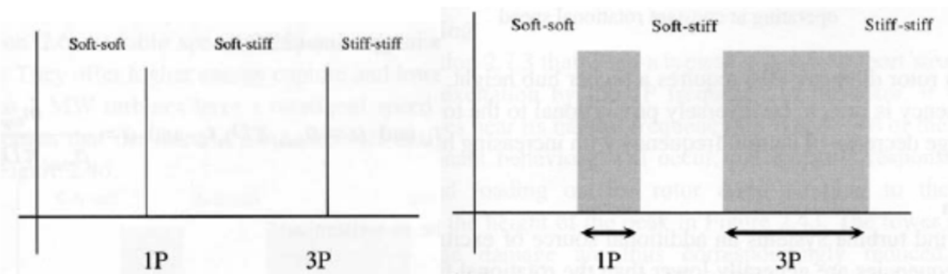

Figure 33. Frequency intervals for a constant (left) and variable-speed turbine system (right) [51]-[53].

The tower vibrations for OWT are induced by the thrust on the rotor disc and the hydrodynamic impacts on the substructure. The natural damping inside the tower consists of different factors - the friction damping in the foundation, the air friction, the friction between the tower segments and finally the friction between the tower and other components (like the nacelle). Therefore, a damping of tower vibration would also have positive effects on the other systems like the nacelle or the blades.

Thus, by placing a damper element into a wind turbine tower, the excitation of the eigenfrequencies can be reduced a lot.

In applications done so far, the damper elements were always right beneath the connection to the nacelle. This makes sense, as the damper should operate in the section with the largest accelerations and deflections, which is the tower top. For conventional passive damping devices the mass of the damper is approximately 2-4% of the total wind turbine mass.

4.1.3.1.2 Drive-train vibration damper

The drive train of a wind turbine with its multiplicity of rotating masses and torsionally flexible connection elements is a very vibratory system. In addition, there are external impacts on both sides of the energy transmission path. The rotor creates rotational periodic variations, which are an ideal vibration excitation. Furthermore, the rotor creates random fluctuations of the driving torque due to wind turbulence. On the other hand there is the electrical generator and its coupling to the electrical grid, which can cause variations in the generator moment. Additionally, there are also the frequencies from the teeth engagement of the gearbox or control impacts (e.g. from pitching), which produce large excitations of the vibrations in the drive train. Vibration resonance in the drive train can have a very relevant influence on the dynamic loading of the components, the quality of power and even on the mechanical noise.

When quantifying the possibilities of drive train vibration damping, it is important to distinguish between the two types of rotational speed turbines.

In the fixed-speed turbine case, the directly coupled induction generator creates a lot of damping, as the generator torque increases rapidly with the generator speed. Here, the damping behaviour is strongly coupled to the generator slip, as the torque-slip curve completely change the dynamics. Thus, the torsional mode of the drive train is well damped.

In the variable-speed case, the damping effects are much smaller. Above rated power, the torque is held constant and therefore nearly no damping can be achieved. Only in the variable speed case - before rated power - little damping is present.

For the vibration reduction in the drive train different possibilities are available. One approach could be to implement a mechanical damper into the drive train, like a coupling or with the aid of rubber mounts. Another possibility might be to influence the moment from the generator with the aid of the frequency converter. Therefore a control device has to be coupled to the DC intermediate circuit. The advantage of the converter control device is the much faster response in comparison to other control devices (like pitch).

4.1.4 Feedback Control Systems

The fundamental control systems in a wind turbine are the pitch control and also the generator torque control in the case of variable-speed turbines. Blade pitch control is primarily used to limit the aerodynamic power in above-rated wind speeds in order to keep the turbine within its design limits. Some optimisation of energy capture below rated is also possible. In variable-speed turbines, generator torque control is used primarily to limit the transmission torque in above-rated winds and to control rotor speed below rated in order to maximize energy capture in this region [54][11][55][56]. Figure 34 shows these basic feedback control loops.

The algorithms used for controlling pitch and torque need careful design. In addition to their effectiveness in meeting these primary objectives, the control algorithms can also have a major influence on the loads experienced by the wind turbine. Clearly, the algorithms must be designed so as to prevent excessive loading, but it is possible to go further by designing them with load reduction as an explicit objective. As the size of wind turbines increases and as cost reduction targets encourage lighter and hence more flexible and dynamic structures, these aspects of controller design become increasingly important [54].

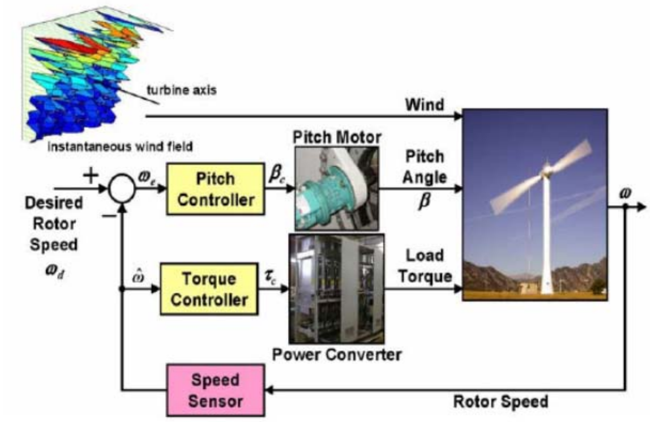

Figure 34. A wind turbine control block diagram. Rotor speed measurements are usually the only measurements used in the feedback loops for both the generator torque control and the blade pitch control [55].

4.1.4.1 Collective Pitch Control - damping of resonances

The control algorithm can have a major effect on the loads on certain parts of the turbine structure. For example, pitch control is used primarily to regulate the aerodynamic torque, but changes in pitch also have a major effect on the thrust load. This in turn affects the blade out-of-plane bending moments. However, the thrust also drives the fore-aft motion of the tower. This in turn affects the relative wind speed seen by the blades, which then feeds back into the pitch control via the aerodynamic torque. This is strong feedback which has a major effect on the stability of the pitch control system. It is easy to design a pitch controller which exacerbates the tower vibration or even makes it completely unstable, with important consequences for the tower base loads [54].

Most pitch-controlled turbines pitch to feather: as the wind increases, the pitch is increased, leading edge into the wind, to reduce the angle of attack and hence also the lift, so limiting the aerodynamic torque. It is also possible to limit the torque by pitching the other way, increasing the angle of attack to cause the blade to stall ('pitching to stall'). This also increases the drag and hence the thrust loading on the turbine. However, both the torque and thrust become more stable, varying more slowly with pitch angle. This means that although the thrust loads are higher, they vary less, so fatigue loads may actually be reduced [54].

4.1.4.1.1 Controlling tower vibration

The first tower fore-aft vibrational mode is essentially very lightly damped, exhibiting a strong resonant response which can be maintained at quite a high level even by the small amount of excitation which is naturally present in the wind. The strength of the response depends critically on the small amount of damping which is present, mostly aerodynamic damping from the turbine rotor. The pitch control action modifies the effective damping of that mode. In order to achieve this, it is sometimes useful to extend the PID controller by including a filter tuned to the tower resonant frequency, which modifies the magnitude and phase of the pitch response at that frequency in such a way as to increase the tower damping [54]. A second-order filter of the following form can sometimes be useful:

$$\frac{s^2 + 2\xi_1\omega_1 s + \omega_1^2}{s^2 + 2\xi_2\omega_2 s + \omega_2^2} \tag{1}$$

4.1.4.1.2 Drive train torsional vibration

A typical drive train can be considered to consist of a rotor inertia and a high-speed shaft inertia (mainly generator and brake disc), separated by a torsional spring. Sometimes it is important to consider also the coupling of the torsional mode with the first rotor in-plane collective mode. In some cases the coupling to the second order tower side-to-side mode, which is characterised by large angular displacements at the tower top, is also important.

In a fixed-speed turbine the induction generator slip curve essentially acts like a strong damper, so the torsional mode of the drive train is well damped. In a variable-speed turbine operating at constant generator torque, however, there is very little damping for this mode, which can therefore lead to very large torque oscillations at the gearbox, effectively negating one of the principal advantages of variable-speed operation.

Although it may be possible to provide some damping mechanically as mentioned before, another solution, which has been successfully adopted on many turbines, is to modify the generator torque control to provide some damping. Instead of demanding a constant generator torque above rated, a small ripple at the drive train frequency is added on, with its phase adjusted to counteract the effect of the resonance and effectively increase the damping. A high-pass or band-pass filter of the form:

$$G\frac{2\xi\omega s(1+s\tau)}{s^2 + 2\xi\omega s + \omega^2} \tag{2}$$

acting on the measured generator speed can be used to generate this additional ripple [54].

4.1.4.2 Individual Pitch Control

Offshore turbines for future applications will be equipped with large rotors as the rated power of these machines will be high. Especially because of these large rotor diameters, the turbines are subject to many asymmetric loads across the rotor, which are responsible for a large contribution in fatigue loading. Loadings through the tower effect, wind shear, skewed inflow or turbulence are the main contributors of asymmetric loading. As turbines grow larger, the required pitch value will diminish, since the pitch action required is essential at 1P, the rotational frequency, and this frequency will decrease as rotor diameter increases [50][51]. Thus, the adoption of individual pitch control may be useful.

The idea behind pitch control is to control the pitch angle of each blade referring to conditions experienced by each blade [14][51][54], because in a large turbine the wind speeds seen by each blade at any instant may differ significantly, so it would be desirable to control the pitch of each blade independently to take account of this. This possibility has been suggested many times over the years [57]-[59]. In order to achieve any useful benefit, there must be some measurement available which can distinguish what is happening at the different blades, so that the controller can generate appropriate demand signals for each.

The simplest measure which could be used is the rotor azimuth angle. There are some effects (wind shear, tower shadow, upflow and shaft tilt), which cause a systematic azimuth-dependent variation in the aerodynamic conditions at a point on the blade. In principle the pitch of each blade could be modified as a function of rotor azimuth in order to reduce the loading variations caused by these effects. In practice, however, this is not a useful approach, because the wind speed variations across the rotor at any instant are dominated by stochastic variations due to turbulence.

If the wind vane is also included in the controller, even yaw misalignment could be avoided. But stochastic variations like turbulence may contribute the highest asymmetric loading, which makes it difficult to achieve good results only by controlling azimuth-dependent loadings. Thus a combination of both load reduction concepts has to be included in the controller - the so called individual and cyclic pitch.

Cyclic pitch means that the pitch angle varies cyclic depending on the blade position. This method is useful to reduce especially effects like yaw and tilt moments coming from skewed inflow, large wind shear and tower shadow [51][60].

The block diagram of and IPC control scheme is shown in Figure 35 [61]. The figure shows how the three blade root out-of-plane bending moment signals (usually derived from flapwise and edgewise signals resolved through the pitch angle) are transformed into two orthogonal d and q-axes (which can be thought of as the horizontal and vertical axes) by means of a special transformation, Coleman Transform. A controller for each axis generates a pitch demand for that axis, and the two d and q-axis pitch demands are converted by the reverse transformation to give pitch demand increments for each blade. These are summed with the collective pitch demand (which controls torque and thrust and hence rotational speed, tower vibration, etc.) to give a total pitch demand for each blade **[61]**.

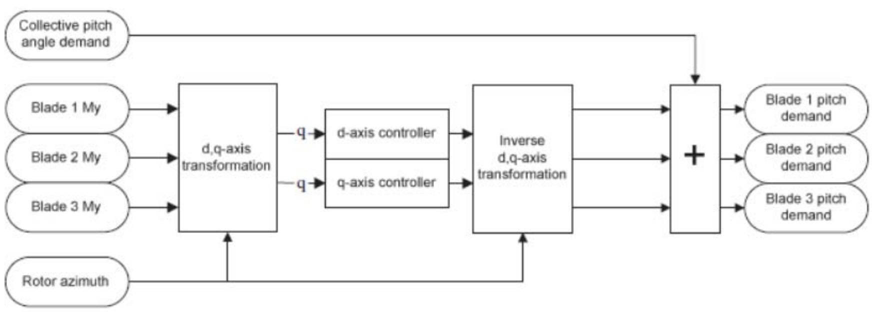

Figure 35. Individual pitch control scheme [61].

The collective pitch control usually responds to measured generator speed and sometimes also to nacelle acceleration. A possible advantage of using load sensors in the blade roots is that, in addition to feeding the individual pitch control, the signals can readily be used to estimate rotor torque and thrust, which can then be included in the collective pitch algorithm to enhance the quality of the collective pitch control loop performance. Figure 36 shows the controller for each axis.

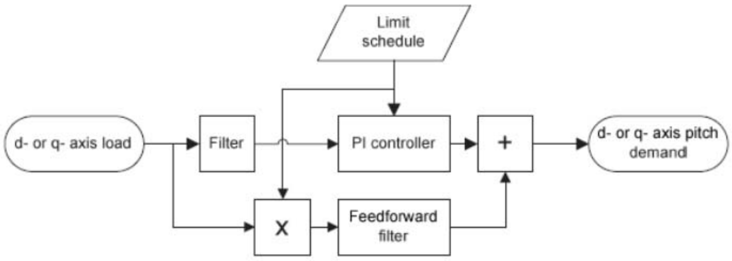

Figure 36. The controller for each axis.

4.1.4.2.1 Advanced controllers

As shown in Figure 36, the control loops are implemented using PI or PID algorithms from classic control. There is, however, a huge body of theory (and practice, although to a lesser extent) relating to more advanced controller design methods, some of which have been investigated to some extent in the context of wind turbine control, for example [11][61][58]:

- self-tuning controllers;
- LQG/optimal feedback and H_∞ control methods;
- fuzzy logic controllers;
- neural network methods;

Recent work using the LQG method (see Figure 37) to generate individual pitch controllers for load reduction on multi-MW turbines has shown considerable promise in simulations [61]. This is a multivariable problem, since several sensors are required to measure the stochastic asymmetrical loadings and there are of course several control actions (individual blade pitch demands).

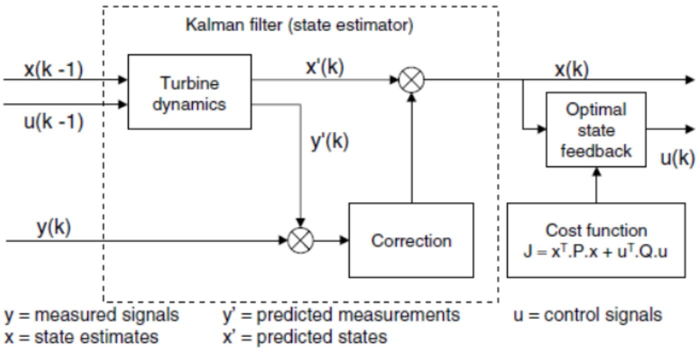

Figure 37. Structure of the LQG controller [61].

4.1.5 Loads in a floating offshore wind turbine

One of the immediate challenges common to all support structure designs is the ability to predict loads and resulting dynamic responses of the coupled wind turbine and platform system to combined stochastic wave and wind loading. In the offshore environment, additional load sources impart new and difficult challenges for wind turbine analysis. Figure 38 below shows the range of different loading sources and additional degrees of freedom needed to model floating platforms [19].

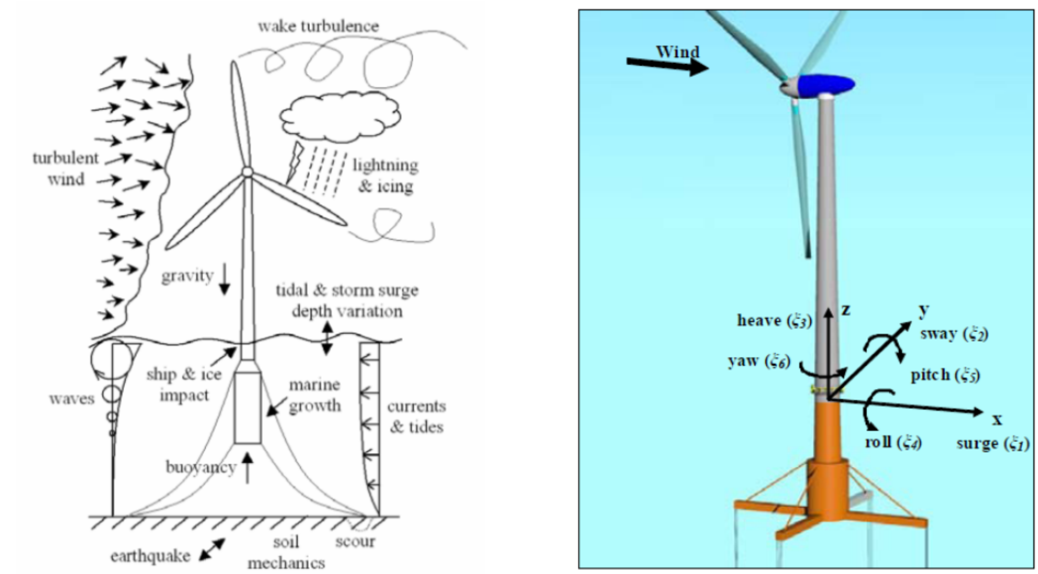

Figure 38. Floating offshore wind turbine loading forces (left); and degrees of freedom in a floating platform [19].

4.1.5.1 Floating structures control complexity

The dynamics of a floating wind turbine can present unique challenges for the design of the power production control system. There are two sources of potential motion of the turbine, namely wind driven motion and wave driven motion. The wind driven motion mainly comes from the thrust force on the rotor and can be easily influenced by the control system through pitching of the blades. A well designed control system will be able to damp out a significant amount of the wind driven motion as well as some of the higher frequency wave driven motion. Low frequency wave driven motion cannot be so easily damped by the control system, and so the job of the control system is then to accept the motion and deal with it in such a way that power quality or loading on the rotor does not suffer too excessively [22].

The type of floating support structure and mooring mechanism will also have a large influence on the design of the control system. For example, a slender spar buoy structure can tilt significantly as the thrust loading on the rotor varies. Dynamically this can lead to periods of low or negative aerodynamic damping. Careful design of the pitching algorithm can introduce additional damping and reduce overall motion. A design which uses mooring arrangements to keep the structure stable will be less sensitive to wind induced loading, and so the design of the control system could be more conventional.

A further consideration for the control of a floating wind turbine is yaw stability. Even a structure tethered with several tension cables will have a much larger degree of yaw flexibility than a bottom mounted structure, leading to larger transient yaw errors than would be common for bottom mounted turbines. It is conceivable that active yaw damping or more intelligent yaw control systems may be desirable [22].

It is common for the offshore turbine designers to focus on the support structure, but the extra motion allowed by floating platforms will significantly affect the turbine designs as well. More active dynamics will be experienced by all the floating concepts resulting in greater tower top motions and coupling between the support structure and rotor. For this reason it is important to include the impact of platform motion with respect to stability classification in overall system design.

In floating platforms it is conceivable that controls would be used to limit the response of the entire turbine/platform system to stochastic wave loading. For example, pitch motions (fore/aft direction) can easily be limited by an intelligent collective pitch control strategy. Similar techniques have already been used to dampen tower motions in onshore turbines. A greater challenge will be in damping roll motions, which are translations of the rotor in the plane of rotation (side-to-side), but researchers are also working on control methods to limit these responses. Some platform choices might introduce dynamics that are more difficult to control than others. Thus, it is important to consider the benefits and challenges posed by this issue [19].

4.1.5.1.1 Controlling platform motions - pitch motions

Several recent investigations have identified potentially problematic dynamics of floating offshore wind turbines, in which excessive loads occur due to large platform pitch motions in above rated conditions. These large motions and loads are a result of a poorly damped mode in the platform pitch direction, which is exacerbated by a coupling between the blade pitch control system (for power regulation) and the platform dynamics. This issue arises not only for a barge-type support structure but for other floating structures as well [23].

The physical explanation for this poorly damped mode can be summarised as follows: as the platform pitches upwind in above rated conditions, the relative wind speed seen by the rotor increases. To maintain constant rotor speed and constant power output, the wind turbine control system increases the collective pitch angle of the blades. This results in reduced rotor thrust, and so exacerbates the motion of the platform in the upwind direction. A similar effect occurs when the platform pitches downwind. In sum, because the rotor thrust decreases with increasing relative wind speed in above rated conditions, a negative damping contribution to the platform pitch motion results [23].

Jonkman [24], uses three distinct approaches to improving the pitch damping of a barge-mounted wind turbine:

- feeding back the tower-top acceleration in an additional control loop (control objectives conflict each other, i.e., power production and platform pitch),
- pitching to stall (damping is made worse),
- detuning the pitch controller gains

Detuning the gains for the collective pitch controller is the simplest and most successful strategy, as it results in improved power and speed regulation, and marginally reduced platform pitch motion.

Overall, [24] results provide significant insight into the problem of using the control system to regulate pitch motion of floating wind turbines, but an effective control strategy is not fully determined.

Namik et al. [25], build on the work of Jonkman [24], utilising the same turbine and barge model, and introduce advanced methods for controlling the platform pitch motion of a floating wind turbine. With an LQR controller, they use the collective pitch angle to control both the rotor speed and the platform pitch motion. The results appear quite successful as the platform pitch motion is reduced by approximately 12%, and the power variability is reduced by approximately 45%. The improvement in both the platform motion and the power quality is presumably due to improved tuning in the LQR case. The only notable drawback in this approach is the increased tower side-to-side damage equivalent load, of approximately 20%.

Namik et al. [25], also implement an individual blade pitch control (IPC) approach, which uses LQR with periodic gains, to control the platform pitch motion. By changing the blade pitch angle of each blade, the net effect of the controller is to generate a tilt moment at the rotor hub, which can then help control the platform pitch motion. Using two different IPC controllers, they are impressively able to reduce the platform pitch motion by nearly 30%, the tower fore-aft loads by 20%, and the power variability by approximately 25%, on average. On the other hand, this improved performance is accompanied by a 10% increase in the blade root flap-wise bending moment fatigue loads. The increase in the flap-wise blade loads is not surprising, given the physical mechanism use to control the platform motion: namely, creating non-uniform thrust loads on the blades so as to generate a rotor tilt moment.

Static inclination during operation, maximum inclination during survival and the behaviour of the mooring system are generally considered important design drivers. Technical challenges are related to minimising the wave-induced motion and understanding the coupling between support structure and the wind turbine, achieving static and dynamic stability. It is recognised that a standard control algorithm for variable blade pitch turbines aiming at constant power output in a variable wind will introduce a thrust force variation that adds negative damping for the pitch and surge motion. Modified control algorithms are thus required. Further, the motions may add complexity to the turbine design. Also, the mooring system involves design and cost challenges [20].

4.2 Wind Farm - Wake mitigation

The *wake* effect of individual turbines has a strong influence on energy production and mechanical loads of other turbines. Understanding these influences strongly supports aerodynamic research programs and allows for the development of optimised control strategies.

With regards to the minimisation of wake effects, two approaches can be distinguished [37]:

- Accept the wake effects as they are and try to optimise the wind farm layout in order to suffer as little as possible from these wake effects.
- Reduce the wake effects using dedicated control concepts.

Reference [38] shows that in order to minimise wake effects, wind turbines in a farm should not be operated in a way that their individual output is at a maximum. Instead, the entire farm, as an energy extracting body should be optimised. It is shown that the output of a farm as a whole can increase by decreasing the power of individual turbines at the windward side. This is explained by two different physical mechanisms: Heat and Flux. It is required to operate the wind turbines at an axial induction factor below the Lanchester-Betz optimum of 1/3. Their analysis shows that the power of the turbines under the lee will increase more than the decrease of the power of the turbines at the windward side, so that the power of the farm as a whole increases. That is, reduction of the axial induction at the windward side of the wind farms is required. This measure can be implemented easily by minor changes in the control algorithms. A more significant change will be the adaptation of SCADA systems to control the induction parameters of the individual wind turbines in wind farms. Nevertheless, the implementation of Heat and Flux is simple since it does not require new hardware. Another benefit is that the turbulence generated by the windward turbines decreases in Heat and Flux-operation. Since turbulence is a major factor in the loading of the first turbines behind the windward turbines this is a valuable property.

The control design for an individual wind turbine is focused at an optimal performance for a solitary wind turbine. But for a group of wind turbines this control system is not necessarily optimal [39]. For example, the aerodynamic interaction is not taken into account in the design of the control. A wind farm control could reduce unfavourable interactions. A wind farm control can also be needed to enhance controllability or quality of the power output of the farm. The main proposition of this reference is that the output of a wind farm can be enhanced by reducing the tip-speed ratios at the upwind side of a farm. Also, it is hardy necessary to develop an overall farm control when and optimal individual control system is being used for uprated wind speeds (the power fluctuations are very small. However, the operation at wind speeds down-rated (partial load) show more power fluctuations, due to the strategy to maximise the power output. A wind farm control could be desirable to reduce fast wind farm power excursion due to a strong gust. This can be done using load control with acting on the blade pitch angle. However, some wind power will then be spilled. After finding a good trade-off between power variations and spilled energy there is the possibility in maximising energy capture for a group of wind turbines down rated. The maximum power tracking strategy is the best strategy for a single turbine, but this is not necessarily the best strategy for wind turbines grouped together. The rotor power is strongly influenced by the wind speed. In a wind farm the wind speed near wind turbines in a wake, depends on the tip-speed ratio of the up wind turbines. If these tip-speed ratios are reduced, Cp of the up wind turbines are also reduced, but the wind speeds in their wakes are higher. This is of benefit for the energy capture of the wind turbines down wind. Hence, a suitable farm control down-rated can (slightly) increase the overall energy capture.

4.3 Grid integration

4.3.1 Grid Code regulations for the integration of wind generation

Grid connection codes define the requirements for the connection of generation and loads to an electrical network which ensure efficient, safe and economic operation of the transmission and/or distribution systems. Grid Codes specify the mandatory minimum technical requirements, that a power plant should fulfil and additional support that may be called on to maintain the second-by-second power balance and maintain the required level of quality and security of the system. The additional services that a power plant should provide are normally agreed between the transmission system operator and the power plant operator through market mechanisms.

The connection codes normally focus on the point of connection between the Public Electricity System and the new generation. This is very important for wind farm connections, as the Grid Codes demand requirements at the point of connection of the wind farm not at the individual wind turbine generator terminals. The grid connection requirements differ from country to country and may differ from region to region. They have many common features but some of the requirements are subtly different, reflecting the characteristics of the individual grids. As a mandatory requirement the levels and time period of the output power of a generating plant that should be maintained within the specified values of grid frequency and grid voltage is specified in Grid Codes. Typically this requirement is defined as shown in **Figure 39**, where the values of voltage, V_1 to V_4, and frequency, f_1 to f_4, differ from country to country.

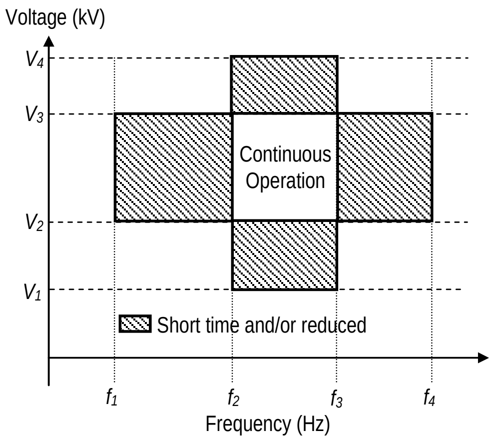

Figure 39. Typical shape of continuous and reduced output regions (after GB&Irish Grid Codes).

Grid Codes also specify the steady-state operational region of a power plant in terms of active and reactive power requirements. The definition of the operational region differs from country to country. For example Figure 40 shows the operational regions as specified in the Great Britain and Ireland Grid Codes.

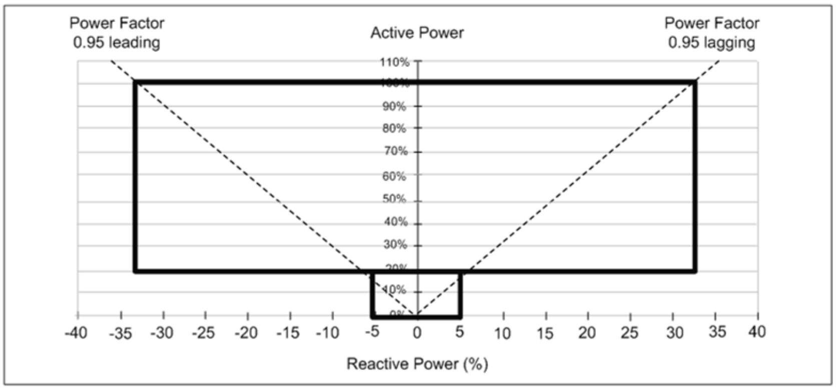

Figure 40. Typical steady-state operating region (after GB & Irish Grid Codes).

Almost all Grid Codes now impose the requirement that wind farms should be able to provide primary frequency response. The capability profile typically specifies the minimum required level of response, the frequency deviation at which it should be activated and time to respond.

Traditionally wind turbine generators were tripped off once the voltage at their terminals reduced to less than 20% retained voltage. However, with the penetration of wind generation increasing, Grid Codes now generally demand Fault Ride-Through capability for wind turbines connected to transmission networks. Figure 41 shows a plot illustrating the general shape of voltage tolerance that most grid operators demand. When reduced system voltage occurs following a network fault, generator tripping is only permitted when the voltage is sufficiently low and for a time that puts it in the shaded area indicated in Figure 41. Grid Codes are under continual review and as the level of wind power increases, are likely to become more demanding.

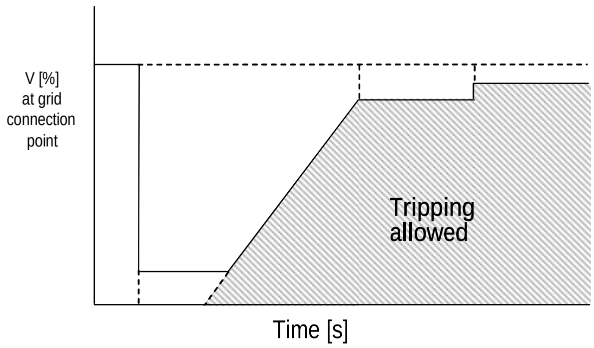

Figure 41. Typical shape of Fault-Ride Through capability plot (after GB & Irish Grid Codes).

4.3.2 Power quality

Two local effects of wind power on voltage power quality may be considered, harmonic distortion and flicker. Harmonic distortion is mainly associated with variable-speed wind turbines because these contain power electronic converters, which are an important source of high-frequency harmonic currents. It is increasingly of concern in large offshore wind farms where the very extensive cable networks can lead to harmonic resonances and high harmonic currents caused by existing harmonic voltages already present on the power system or by the wind turbine converters.

In fixed-speed wind turbines, wind fluctuations are directly translated into output power fluctuations because there is no energy buffer between the mechanical input and the electrical output. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted and annoying fluctuations in electric light bulb brightness. This problem is referred to as 'flicker'. In general, flicker problems do not occur with variable-speed turbines, because in these turbines wind speed fluctuations are not directly translated into output power fluctuations. The stored energy of the spinning mass of the rotor acts as an energy buffer.

4.3.3 Power system dynamics and stability

Squirrel-cage induction generators used in fixed-speed turbines can cause local voltage collapse after rotor speed runaway. During a fault (and consequent network voltage depression), they accelerate due to the unbalance between the mechanical power from the wind and the electrical power that can be supplied to the grid. When the fault is cleared, they absorb reactive power depressing the network voltage. If the voltage does not recover quickly enough, the wind turbines continue to accelerate and to consume large amounts of reactive power. This eventually leads to voltage and rotor speed instability. In contrast to synchronous generators, whose exciters increase reactive power output during low network voltages and thus support voltage recovery after a fault, squirrel-cage induction generators tend to impede voltage recovery.

With variable-speed wind turbines, the sensitivity of the power electronics to over-currents caused by network voltage depressions can have serious consequences for the stability of the power system. If the penetration level of variable-speed wind turbines in the system is high and they disconnect at relatively small voltage reductions, a voltage drop over a wide geographic area can lead to a large generation deficit. Such a voltage drop could, for instance, be caused by a fault in the transmission grid. To prevent this, Grid Companies and Transmission System Operators require that wind turbines have a Fault Ride-Through capability and withstand voltage drops of certain magnitudes and durations without tripping. This prevents the disconnection of a large amount of wind power in the event of a remote network fault.

4.3.4 Reactive power and voltage support

The voltage on a transmission network is determined mainly by the interaction of reactive power flows with the reactive inductance of the network. Fixed-speed induction generators absorb reactive power to maintain their magnetic field and have no direct control over their reactive power flow. Therefore in the case of fixed-speed induction generators the only way to support the voltage of the network is to reduce the reactive power drawn from the network by the use of shunt compensators.

Variable-speed wind turbines have the capability of reactive power control and may be able to support the voltage of the network to which they are connected. However, individual control of wind turbines may not be able to control the voltage at the point of connection, especially due to the fact that the wind farm network is predominantly capacitive (a cable network).

In many occasions the reactive power and voltage control at the point of connection of the wind farm is achieved by using reactive power compensation equipment such as static var compensators (SVCs) or static synchronous compensators (STATCOMs).

4.3.5 Frequency support

To provide frequency support from a generation unit, the generator power must increase or decrease as the system frequency changes. Thus in order to respond to low network frequency, it is necessary to de-load the wind turbine leaving a margin for power increase. A fixed-speed wind turbine can be de-loaded if the pitch angle is controlled such that a fraction of the power that could be extracted from wind will be ‘spilled’. A variable-speed wind turbine can be de-loaded by operating it away from the maximum power extraction curve, thus leaving a margin for frequency control.

5 CONTROL POSSIBILITIES

5.1 Wind farm - Maximize energy output

In existing wind farms, where it is impossible to change the distance between turbines, it is likely that the overall wind farm efficiency can be improved by controlling strategically the power extraction of the individual turbines. This control operation can be achieved by changing the pitch angle, the tip-speed ratio (variable speed rotor) as well as the yaw angle of the turbines. These changes can significantly affect the performance of the turbines and hence, their wake properties and therefore, the performance of the turbines located in their wake. In fact the changes could be more significant if the control systems are applied to the most upstream turbines that are exposed to the unobstructed wind conditions. However, since the wind speed and direction are continuously changing, this may be a challenging task. The data presented in this section is based on a wind tunnel study carried out to investigate the effect of power output from the upstream turbine on the performance of a downstream turbine as well as its implication on the combined power output from the two turbines[62].

Two model turbines with 3-bladed upwind rotors and the same rotor diameter of 0.90 m were used. The hub diameter is 90 mm and its height (above the ground plane) is 820 mm. The effect of change in pitch angle, tip-speed ratio and yaw angle of the upstream turbine on downstream turbine were studied. The distance between the turbines in in-line arrangement is 3*D* and constant free-stream velocity of about 11.8 m/s was used throughout the experiment.

5.1.1 Downstream turbine performance

The effects of these parameters on the maximum power coefficient of the downstream turbine relative to unobstructed turbine are shown in Figure 42-Figure 44. The loss in power from the downstream turbine is about 21% and 26% when the upstream turbine is operating at low and high tip-speed ratio, respectively (Figure 42). This is significantly lower than the power deficit of 35% in the downstream turbine when the upstream turbine was operated at optimum tip-speed ratio. However, as the tip-speed ratio of the upstream turbine is increased even further, its power output will eventually be reduced faster than the gain achieved from the downstream turbine and thus, the wind farm efficiency may be reduced. The effect of change in pitch angle of the upstream turbine is shown in Figure 43. This figure shows that the loss in maximum power coefficient depends on the pitch angle. When the pitch angle is changed from -2^o to +2^o, the loss is observed to change from 46% to 35%. Likewise, by operating the upstream turbine at a fixed pitch angle, the power output of the downstream turbine is expected to change if its pitch angle is varied.

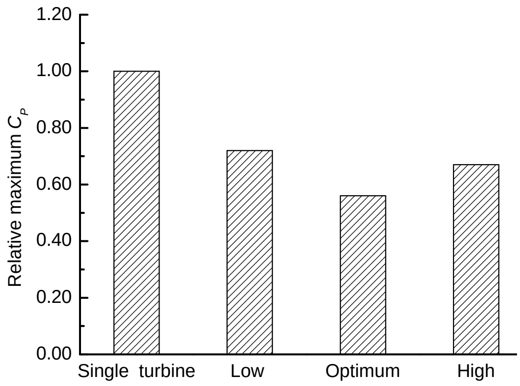

Figure 42 The relative maximum power coefficient when the upstream turbine operating condition effect.

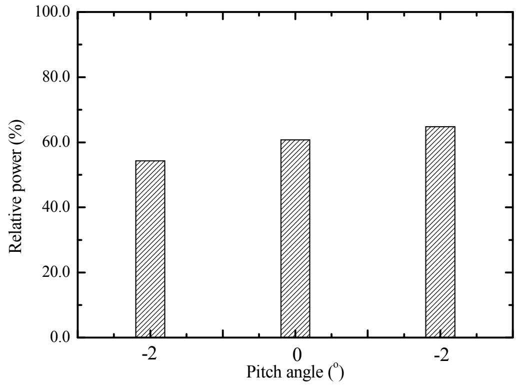

Figure 43 The relative maximum power coefficient as a function of the turbine separation and pitch angle.

Furthermore, by increasing the yaw angle of the upstream turbine, there is a corresponding increase in the maximum power coefficient of the downstream turbine (Figure 44). The gain in relative maximum power coefficient of the downstream turbine increases with increasing yaw angle of the upstream turbine. At a yaw angle of $\gamma = 10^o$, the gain is about 4% compared to when the upstream turbine is operating in non-yawed position, but this increases to about 29% at $\gamma = 40^o$. However, since the power output from the upstream turbine decreases with increasing yaw angle, the gain in total power output from the downstream may not necessarily (especially at low yaw angle) increase the overall power output from these two turbines. But, in a wind park with more rows of turbines the strategy used for the first row will affect all downstream rows.

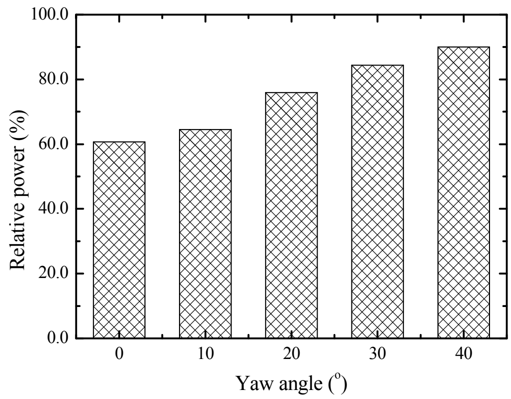

Figure 44. The relative maximum power coefficient of the downstream turbine with the upstream turbine operating at various yaw angles.

5.1.2 Wind Farm Efficiency

Using the total power output from the two turbines operated at their designed conditions as a reference, there is a reduction of about 12% in the wind farm efficiency when the upstream turbine is operating at low tip speed ratio (Figure 45a). However, a gain of about 3% is observed when the upstream turbine is operating at a high tip speed ratio. As the tip speed ratio of the upstream turbine is increased even further, its power output will eventually be reduced faster than the gain achieved from the downstream turbine and thus, the wind farm efficiency will be reduced. The optimum tip speed ratios for the two turbines will need to be carefully selected (controlled) to maximize the output of a given wind farm configuration.

Operating the downstream turbine with blade pitch angle of -2^o gave rise to reduction of about 6% in the wind farm efficiency, however gain of about 4% is observed when the pitch angle is set to +2^o (Figure 45b). This implies that the downstream turbine should be operated at a different pitch angle setting than the one upstream in order to maximize its power output. Likewise, by operating the downstream turbine at a fixed pitch angle, its power output is expected to change if the pitch angle of the upstream turbine changes. This is because the pitch angle of the blade of the upstream turbine affects the power extracted from the air flow and therefore the properties of the wake generated.

With the upstream turbine operating at yawed conditions, the wind farm performance improved and attained a peak increase of about 12% at $\gamma = 30^o$. By operating the upstream turbine in yaw, the effective wind speed component that interacts with the rotor blades and the effective rotor swept area with respect to the wind direction are reduced. Hence, less power may be extracted from the air flow by the upstream turbine. The second effect this has on the downstream turbine is that by yawing the upstream turbine the wake is deflected sideways. Hence the rotor sweeps a smaller part of the wake area. However, this also leads to the adverse effect of increased dynamic loads on the blades. The downstream turbine is therefore exposed to higher wind speed compared to when the turbines are in an in-line arrangement. Operating the upstream turbine at an appropriate yaw angle may not only improve the wind farm power output but will likely reduce the space requirement for the wind farm (Figure 45c). Therefore, by systematically controlling the operating conditions of the wind turbines, the overall performance of a wind farm can be improved significantly.

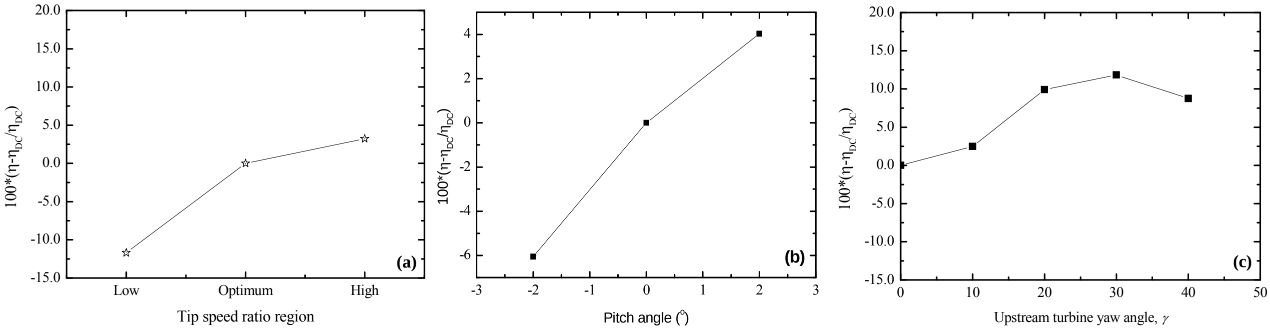

Figure 45. Wake effects on the wind farm efficiency: (a) Upstream tip-speed ratio effect; (b) Downstream pitch angle effect; and (c) Upstream yaw angle effect.

5.2 Load mitigation - advanced control strategies

Typical industry controllers for load mitigation in large commercial wind turbines are designed using simple classical control design techniques such as PID control for generator torque control in Region 2, or pitch control in Region 3. To mitigate turbine structural dynamic loads, and additional generator torque control loop in Region 2 is often used to actively damp the drive-train torsion mode of the turbine. In Region 3, classical control design methods have been used to design controllers to add damping to the tower's first fore-aft mode with blade pitch. The pitch control to actively damp tower fore-aft motion is usually implemented as an additional single-input single-output (SISO) control loop to the basic speed control loop in Region 3.

Another way to mitigate turbine loads is through individual pitch control, where each blade is pitched independently. Both classical control and multivariable control approach may be used to design individual pitch controls to mitigate the effects of asymmetric wind distributions across the rotor disk. A disadvantage of classical control methods is that multiple control loops must be used to add active damping to several flexible turbine modes or to mitigate the effects of asymmetric wind variations with individual pitch (Wright and Fingersh, NREL[63]). If these controls are not designed with great care, the control loops interfere with each other and destabilise the turbine. The potential to destabilise the turbine increases as turbines become larger and more flexible, and the degree of coupling between individual control loops increases.
Using all the available turbine actuators in a single control loop to maximise load-alleviating potential would be advantageous. Advanced multi-input multi-output (MIMO) multi-variable control design methods, such as those based on state-space models, can be used to meet these objectives and use all the available actuators and sensors in a reduced number of control loops.

The control of the blade pitch and rotor speed has not only led to greater power regulation, but also to lighter blade construction due to a lower load spectrum and a lighter gearbox due to reduced torque peaks. Difficulties arise in turbulent winds when excessive loading (both extreme and fatigue loads) occurs, which leads to premature wear on turbine components. Using current technology, it is difficult to mitigate these loads; pitching of the entire blade is too slow and variable rotor speed allows shedding for some of the high loads, but not all. The need to mitigate excessive loads has led to investigations of new methods of control (Johnson et al, SANDIA Report [64]).

5.2.1 Advanced Blade Pitch Control

The traditional method of pitch control uses a collective mode, in which all blades are adjusted simultaneously. Advanced methods of pitch control (cyclic pitch and individual pitch) are being investigated. Cyclic pitch control varies the blade pitch angles with a phase shift of 120° to alleviate the load variations caused by rotor tilt and yaw errors, whereas individual pitch control adjusts the pitch angle of each individual blade independently. This method requires measurement of the local inflow angle and relative flow velocity for each blade. The goal is to create two load-reducing systems (collective pitch and individual pitch) that are independent, where collective pitch is used to keep the power at a desired level by adjusting pitch based on the mean wind speed and the individual pitch regulator is to minimise loads without affecting the power output.

Cyclic and individual pitch control can reduce fatigue loads due to yaw errors, wind shear, up flow and shaft tilt. Not only do the blades benefit from this control strategy, but reductions in loads on the drive train, nacelle structure, and tower are also seen. However, these control techniques are less capable of reducing the loads due to wind gusts and turbulence.

There are three major concerns when considering individual pitch control. First, the entire blade still must be pitched. The flow conditions along a long blade are not uniform and therefore pitching the entire blade may not be ideal. Second, the pitching mechanism may be unable to act fast enough to relieve the oscillating loads due to wind gusts. Third, there is a concern that individual blade pitch will result in over-use of the pitching mechanism. It is important to design turbines to use individual pitch from the start; retrofitting current turbines with individual pitch control will lead to premature failure of the pitch mechanism due to the resulting high duty cycle. Challenges with implementation include response time requirements to counter load perturbations, the need for larger pitch motors, and the power required to operate the system under a new control strategy.

5.2.2 Blade Twist Control

One concept for controlling fatigue loads on a wind turbine blade is to use passive blade bend-twist coupling. The aero-elastic tailored blade is designed so that the twist distribution changes as the blade bends due to aerodynamic loads. This is now possible through the advent of composite materials, which can be implemented in a deliberate fashion to control flap-twist. The transient loads due to wind gusts theoretically could be reduced because the blade would twist towards lower angles of attack, thereby mitigating the loads and potentially reducing pitch activity as well.

Some of the challenges with this concept include reduced energy capture, higher costs, and blade integrity issues. First, reduced energy capture may occur due to altering a blade that is designed for optimum energy capture at rated speed by causing it to twist. Second, higher costs associated with material and manufacturing techniques may make the concept uneconomical. Third, the fabrication technique may lead to decreased stiffness and additional material may be required to counteract additional blade deflection. Active blade twist control can be conceptually achieved by embedding active laminates such as piezoelectric material in the spar caps of the blade. There are several challenges that face this concept, including blade structural integrity, cost of active materials, and actuation power requirements.

5.2.3 Variable Diameter Rotor

This concept is capable of improving energy capture in low wind speeds and reducing loads on the rotor in high wind conditions. Variable diameter rotors operate by extending/retracting a *tip* blade out of a *root* blade to increase/decrease the diameter. During low-wind speed, a large rotor diameter provides more capture area, which results in larger aerodynamic loads and an increase in energy capture. However, this operation generates larger blade root and tower base bending loads. In higher wind speeds, the rotor diameter can be decreased to avoid excessive loads. The tip blade would extend and retract independently of the pitching mechanism and it would respond to gross changes in the wind speed; the pitch control would still be used to regulate power.

The variable diameter rotor has the potential for increasing energy production for a given load spectrum. There are several engineering challenges that must be resolved in order to make this turbine concept successful and marketable. The challenges include complex control strategies, the need to maintain a high aerodynamic efficiency, increased blade weight, and general issues with durability and reliability of the system as a whole.

5.2.4 Active Flow Control

Active Flow Control (AFC) is the control of the local airflow surrounding the blade. The purpose of flow control is often to improve the aerodynamic performance of an aerofoil or lifting surface. However, for utility-scale wind turbines the main focus is to reduce extreme loads, which occur during high wind activity, and to mitigate fatigue loads, which vary along a blade and can occur randomly. To do this, active load control devices or "smart" devices must include actuators and sensors located along the span of the blade. The system must be able to sense changes in the local flow conditions and respond quickly to counter any negative impact on blade loading. This arrangement provides active "smart" control over the rotor. By definition, a smart structure involves distributed actuators and sensors and one or more microprocessors that analyse the responses from the sensors and use integrated control theory to command the actuators to apply localised strains/displacements to alter system response. Numerous investigations on the use of AFC devices show that significant load reduction is possible.

5.3 Wind farm electrical collector option - evaluation

In practice, the wind farm layout is normally given as an input to the collection network design, and the cables are routed for connection to the WTGs such that cable costs, and conductor losses are minimised. This is achieved by minimising the total cable length and applying a similar utilisation (peak power/rated power) to all cable strings as much as possible.

5.3.1 Electrical array system requirements

The electrical array system has to be designed to meet the following general requirements:

- Health & Safety: the system must be designed in a way that minimises the risk of adversely affecting the Health & Safety of personnel and the public, and must comply with all relevant H&S legislation.
- Compliance with all relevant codes - national grid codes, distribution codes, STC (System Operator-Transmission Owner Code) - and standards e.g. IEC, IEEE.
- Export capacity to be at least 100% of wind farm output.
- Minimise CAPEX: material and installation costs.
- Minimise OPEX: losses and maintenance requirements.
- Maximise availability and reliability.
- Low environmental impact (low life cycle carbon emissions, recyclable, de-commissionable).
- Strong supply chain of components.
- Adaptable to different WTGs and wind farm size.
- Redundancy against a single fault to provide power to auxiliary demand.

In addition, bilateral agreements may dictate project specific requirements depending on the location of a wind farm or grid connection point.

5.3.2 AC collection options: fixed or variable frequency

AC fixed-frequency (ACff) operation of the offshore network is normal practice and possible with both synchronous (HVAC) and asynchronous (HVDC) connection of the offshore wind farm. AC variable frequency (ACvf) operation at the collection network would be cost-effective only when the wind farm is connected to the grid through a HVDC transmission system [66][67]-[69]. This is because the offshore HVDC rectifier can control the offshore frequency independently from the onshore grid, whereas for a synchronous AC transmission link an additional AC-AC or AC-DC-AC conversion system would need to be installed. Examples of wind farm configurations using DC collection as proposed in literature are described next [70][71].

5.3.2.1 Examples of variable-frequency collection configurations

The paper by C. Feltes and I. Erlich uses variable frequency operation in the collection network with DFIGs and a HVDC transmission link in order to achieve either one of the following objectives [72]:

1) Reduce the rating of DFIG converters
2) Extend the speed range to maximize the power capture without increasing the rating of the DFIG converters.

D. Jovcic has presented a multi-terminal configuration based on VSC-HVDC transmission that allows variable frequency operation in the offshore collection network [68]. He proposes a similar collection network configuration in [69] but with a multi-terminal HVDC link based on current source converters that use forced-commutated devices such as IGBTs. In the latter arrangement, the authors claim that generator transformers are not needed to step up the voltage to transmission level, because the current source converters are connected in series. In both schemes, it is claimed that no additional converters are required at each WTG terminal, and 2MW permanent magnet generators are synchronised together in a group connected to a centralised converter and all are operating at the same speed. Note that a converter is normally needed to synchronise a permanent generator to a grid comprising other generators in order to maintain stable operation. In reference [68] it is stated that speed regulation is achieved by a novel ‘Blade angle controller’, but it is unclear how this can be achieved in practice given that the wind speed varies at the individual generators.

S. Meier et al [73]-[76], propose a wind turbine topology that allows variable frequency operation with squirrel-cage induction generator over a wide range of operating conditions. The topology replaces the fully-rated back-to-back converter with a single stage cyclo-converter to decouple the frequency at the offshore substation from the wind turbine side, see Figure 46.

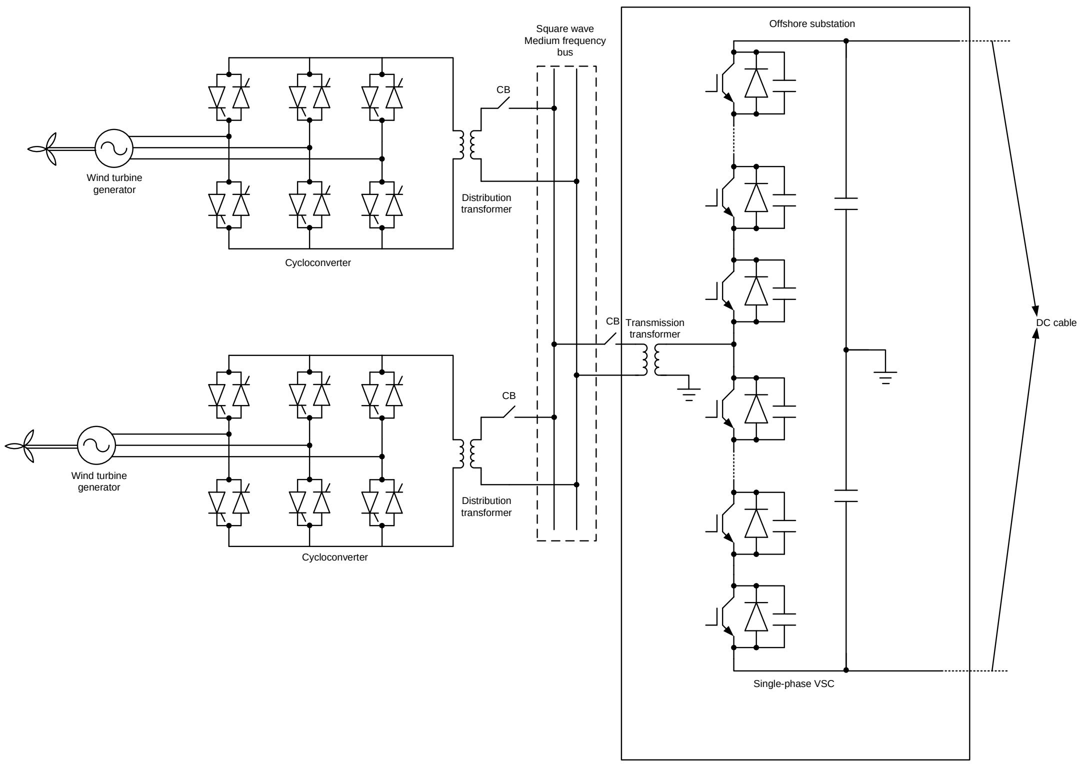

Figure 46. Variable speed operation using cyclo-converter [73]-[76].

The proposed scheme has the following features and claimed advantages:

1) The 50Hz three-phase transformers within each wind turbine generator and at offshore substation are replaced by medium frequency (400Hz-500Hz) single-phase transformers. Although it is claimed in the paper that this may potentially reduce the cost, weight and volume of the transformer, this really depends on the supply chain. A transformer manufacturer would need to be convinced that there is adequate market to develop a production line for such a non-standard design. Also the transformer insulation must be designed to cope with increased voltage stress, and high dv/dt resulting from step changes in the voltage due to the snubber capacitors of the converter.

2) Since only a single-phase converter is required at the offshore substation instead of a three-phase converter, the number of series-connected devices required decreases significantly resulting in significant reduction in cost, conduction and switching losses.

3) Soft switching of the cyclo-converter and offshore converter of the VSC-HVDC reduces the switching losses significantly.

4) The use of thyristors rather than insulated-gate bipolar transistors (IGBTs) in the cyclo-converter reduces the power loss and cost.

One major drawback of using a cyclo-converter could be that it would be very difficult to achieve fault ride through requirements, due to the absence of a DC link serving as an energy buffer. Also, the effect of a medium-frequency square-wave voltage with high harmonic content on the transformers and on the AC cables between the cyclo-converters and the offshore converter needs to be investigated.

5.3.2.2 AC variable-frequency collection evaluation

Variable-frequency operation at the offshore collection network in conjunction with a HVDC transmission link and WTGs of the DFIG type can maximise the power extraction and reduce the overall wind farm cost according to reference [67]. However, the consequences of having variable frequency at the offshore network regarding switchgear and protection, transformer operation, voltage and current rating of the equipment located at the offshore network need to be thoroughly investigated. Standard power transformers are designed for a specific frequency of operation (50Hz or 60Hz), and the normal tolerance of frequency variation is around +5%, i.e. for a 50Hz unit, limits of 47.5 to 52.5Hz. For a lower frequency design of transformer, a larger core would be needed in order to maintain the required voltage ratio, for a specific current rating and a reasonable flux density avoiding saturation. However, this can be overcome by reducing the voltage in proportion to a reduction in frequency. Another aspect to be investigated is how the reactive power flow through the transformers and cables changes with variable frequency.

Any products that are non-standard to allow operation at variable frequency could incur additional costs. Besides addressing the technical uncertainties in the aforementioned variable frequency concepts, a more thorough cost-benefit analysis and supply chain assessment would need to be carried out to evaluate the proposed concepts for practical implementation. Added complexity is likely to lead to increased costs, and lower reliability of the total system.

Operating VSC-HVDC at variable frequency has been demonstrated practically in the gas platform Troll A [66]. In that application, the need for variable-frequency operation by the VSC-HVDC inverter is clear, namely to control the speed of an induction motor. For an offshore wind farm on the other hand, variable frequency is beneficial for the generator rotor only. Further research is required to assess whether it is more economical to achieve this locally at each individual generator than at a collection network level. This is because variable frequency over a wide frequency range in the collection network could add complications to a large number of network components.

5.3.3 DC collection option

The DC collection option may bring some benefits such as the absence of reactive current in the collection network, a reduction of cable materials for the same power capacity, and avoiding the costs of inverters on the wind turbine generators. Some examples of wind farm configurations using DC collection as proposed in literature [71][76] are described next.

5.3.3.1 Examples of DC Collection Configurations

A DC collection network can, in principle, be configured in the same way as an AC collection network. The main difference is that the transformer in the AC collection network is replaced with a DC/DC converter and an inverter, as shown in Figure 47. A rectifier is needed in each WTG, if its output is AC. In a small offshore wind farm located near to the shore as shown in Figure 47, there is no need for an offshore platform, no matter whether AC or DC is used. A consequential difference with a large wind farm located far from an onshore grid connection point is the need for an additional transformation step to increase the voltage from the WTGs to a level suitable for transmission. If the output voltage of the WTG is lower than about 10kV then two steps are probably required as shown in Figure 48. For a large wind farm with two transformation steps, all wind turbines are divided into smaller clusters. All wind turbines within one cluster could be connected as parallel radial feeders to the first DC conversion step. The high-voltage side of that is then connected to the second DC conversion step. If only one step is used then the wind turbines are connected in radials directly to the second DC/DC conversion step.

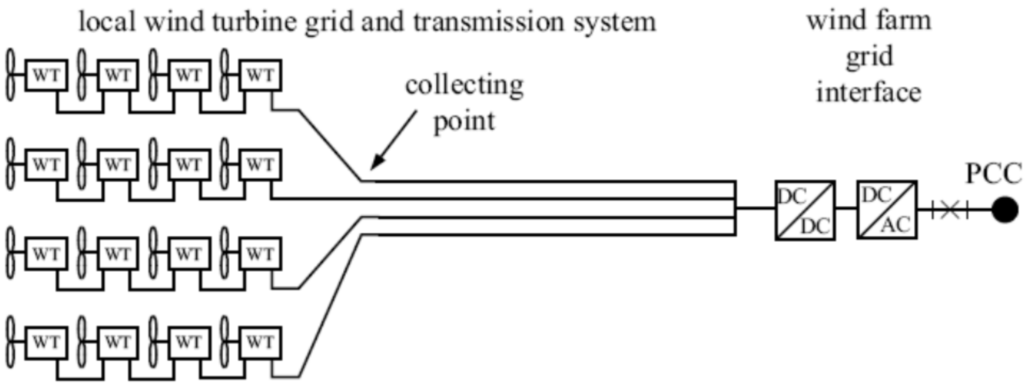

Figure 47. Electrical system for a small wind farm with DC collection [71].

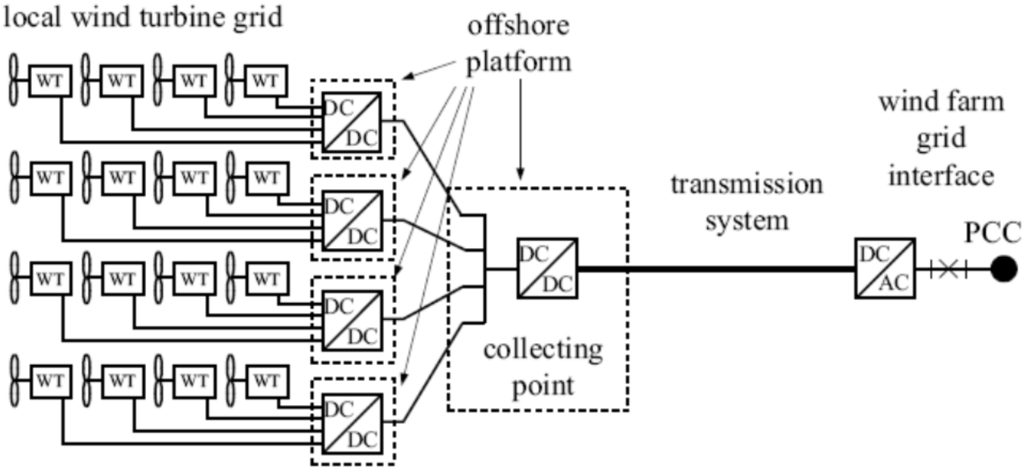

Figure 48. Electrical system for a large wind farm with DC collection using two DC/DC conversion steps [71].

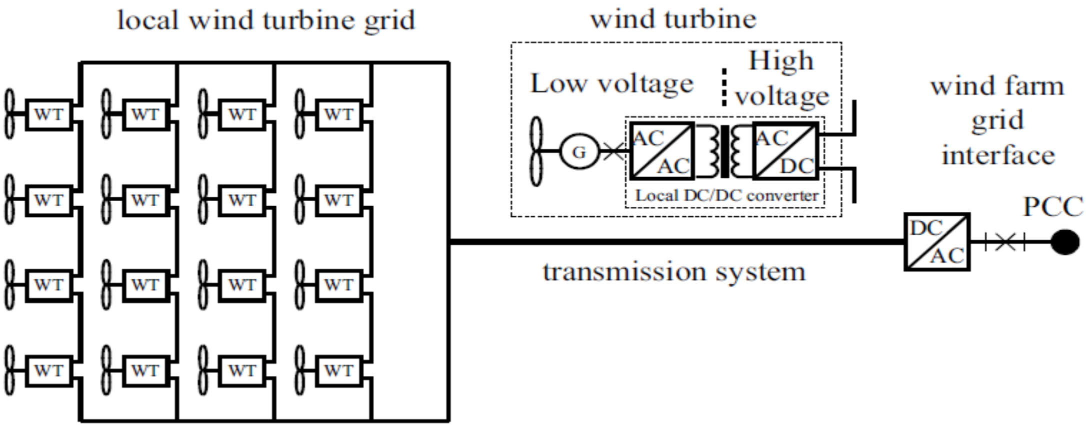

Figure 49. DC electrical system with series-connected wind turbines [71].

A third possible DC collection network for an offshore system is shown in Figure 49, where the wind turbines are connected in series to obtain a voltage suitable for transmission directly. The benefit of this system is that it does not require large DC/DC converters and offshore platforms. The voltage is stepped up partly by the transformers in the DC/DC converters located at each WTG, and by means of connecting them in series. The drawbacks of this configuration are that the collection cables and DC/DC converters must be able to operate at much higher voltages to ground compared with conventional collection network layouts, unless different voltage ratings would be applied to the different stages. Whereas conventional collection networks with radial cable strings are often tapered according to current rating, the collection cables in the series connected layout could be tapered according to voltage rating. Note however, that using a large number of different collection cables would significantly increase the installation and purchase costs.

Finally, if one of the WTGs is out, then one voltage source stage is lost, and the other WTGs would need to compensate for this by increasing their output voltage, adding to higher voltage rating requirements and thus costs. Also, the electrical current needs to be equal within one string of series connected WTGs and it is unclear how this can be achieved exactly given that each WTG will have a slightly different power output due to variations in the wind locally. More information including estimates of the energy production costs for all of these configurations can be found in reference [71].

5.3.3.2 DC collection evaluation

The main obstacle to applying a DC collection network in conjunction with a DC transmission link is presently the absence of commercially available high power DC/DC converters. Such devices should be able to step up the voltage from the generator output voltage (typically 0.69 to 1 kV but may be higher for >5 MW WTGs), to at least 30 kV to achieve the required power capacity in the collection network whilst keeping losses low. It is even more challenging to achieve a DC/DC conversion system that can step up from the collection voltage (e.g. 30 kV) to the transmission voltage (>150 kV) to export the power to shore with minimal losses.

Another uncertainty is the availability and cost of a DC circuit breaker at the collection voltage levels. Even if DC/DC converters would become available on the market, the question is then still how the overall cost of using DC in the collection cables would compare with using AC. The supply chain issues, maintenance and converter losses (of the DC/DC converter as well as the AC/DC converter) need to be considered before a decision is made on implementing a non-conventional DC collection network.

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5.3.4 Evaluation of higher (>33 kV) collection voltage

As wind farms and WTGs have increased in power capacity, the collection voltage levels have increased from typically 11 kV to 33 kV nowadays. The usage of 48 kV or 66 kV cables has been proposed in [77] to connect WTGs to the onshore grid via 48/132 kV or 66/132 kV transformer onshore, instead of using a 132 kV submarine cable and a 33/132 kV transformer offshore. The study showed that stepping up the voltage from 33 kV to 132 kV offshore is most economical for greater distance (>25 km), because the cost of the offshore substation is then less significant compared to the cable costs, and the losses are much more reduced.

Another reason for using higher voltage collection cables is that they can bring the benefit of needing less cable strings in collection networks for large offshore wind farms (>300 MW), because each cable has a higher capacity. Especially for ever increasing WTG sizes, this may become an attractive solution. For example, with present designs of 33 kV cables it would only be possible to connect up to four 8 MW WTGs per cable string, whereas currently in London Array up to nine 3.6 MW WTGs are connected to one string. Higher voltages also reduce fault levels for a given MVA generation and ohmic losses would be less, although the overall losses in a particular design must be considered. In addition, since higher voltages offer a longer transmission distance, the collection cables can be longer, so fewer offshore ‘sub-transmission’ platforms may be needed. These were introduced for example in the 400 MW VSC HVDC linking the BARD Offshore 1 wind farm to the transmission grid in north Germany, where the collection voltage is stepped up from 30 kV to 155 kV on two separate ‘sub-transmission’ platforms. These are linked via 155 kV cables to the offshore 400 MW HVDC substation [78] to transmit the power via DC over a distance of 203 km to onshore grid.

The challenges of using voltages higher than 33 kV for the collection network are presently:

- There is a limited supply of commercially available dry type transformers rated above 33 kV and also capable of stepping up from a suitable generator voltage, for example 3.3 kV. They are also more expensive than the more widely available 33 kV transformers. Correspondence with ABB suggests that a 66 kV transformer is about double the price of a 33kV transformer and weighs 42% more for the same MVA rating. Oil-filled transformers at the WTGs are undesirable because of the risk of a spillage at sea which poses an environmental threat. However, the use of the more environmentally friendly Midel oil may be acceptable in combination with using a bund.

- Collection cables at 33 kV and below can be of the ‘wet design’, which do not require metallic moisture barriers surrounding the cable as an outer sheathing layer or around the insulated core(s). The sheathing/bedding layer(s) are made from polypropylene (or jute) string/rope. Seawater fills the empty spaces inside the cable making direct contact with the outside of the insulated core(s). Higher voltage submarine cables presently available are of the ‘dry design’ which use a lead sheath as a water barrier. Their drawbacks are the increased cable capital cost and perhaps somewhat higher installation cost due to the additional weight, and the lead sheath is susceptible to fatigue failure if movement or vibration occurs [79].

For a specific project, a thorough cost-benefit study is required to make an informed decision on whether to opt for 33 kV or higher voltage collection cables because the impact on the overall wind farm design may be profound.

5.4 Offshore transmission technology

There are many large offshore wind farms planned in Europe. The offshore transmission network is used to transfer power from the wind farm to the power network located onshore. The majority of high-voltage power lines use alternating current (AC) with frequency of 50 Hz or 60 Hz. Most operational wind farms are connected through HVAC networks; however, high-voltage direct current, HVDC, may be more cost effective and have lower electrical losses over longer distances. The biggest influence on transmission technology is the distance between the offshore wind farm and mainland, as well as the amount of power transmitted [80][81]. Figure 50 shows transmission technology choices for HVAC and HVDC in relation to distance and power.

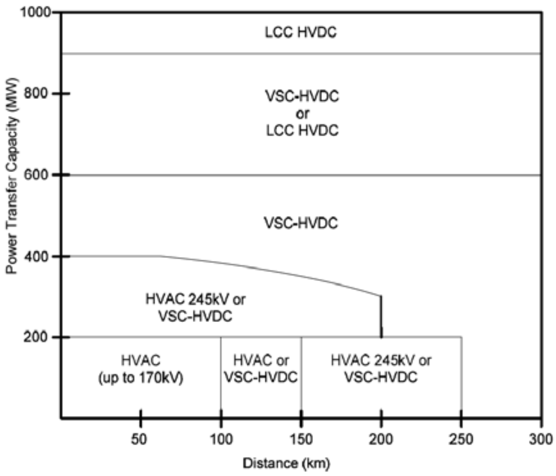

Figure 50. Choice of transmission technology for different wind farm capacity and distance from shore [82].

5.4.1 HVAC Transmission

High-Voltage Alternating Current (HVAC) transmission is used for most wind farm applications and provides a simple and economical connection from large offshore wind farms to the onshore grid but there is a limitation for the cable length. Offshore wind turbine collection network is medium voltage 33 kV [83], then at the offshore substation voltage level is stepped up to 150 kV [84]. And due to several limitations, such as power losses, transmission voltage level, the distance between them should not be larger than 50-75 km for the submarine cable.

To improve the transmission efficiency and capacity, reactive power compensators such as static synchronous compensator (STATCOM), static VAR compensator (SVC) may be incorporated in to the system [84][85][86].

The main components for an offshore HVAC transmission system are [82] (see Figure 51):

- Offshore wind farm
- Offshore substation (step-up transformer)
- Three-core polyethylene submarine cables (XPLE) to shore
- Static VAR compensator
- Onshore substation
- AC submarine cables

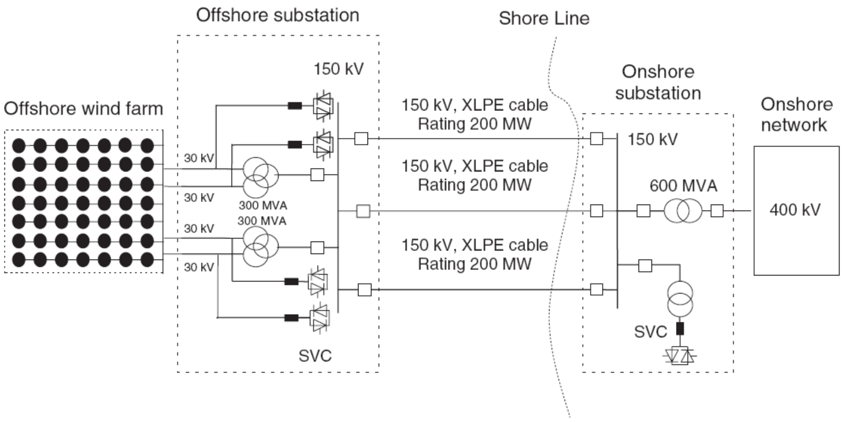

Figure 51. Basic configuration of HVAC interconnection of offshore wind farm to the grid [82].

The main disadvantages of HVAC transmission are [87]:

- Over long distances there are high power losses and large reactive power compensation devices are required at both ends of the line.
- The wind farm is synchronously coupled with the grid and any fault on the side of the wind farm will affect the grid and vice versa, therefore increased risk of blackout.
- High capacitance of the cables, may affect voltage shape.

Thanet (UK) - example of an offshore wind farm connected via HVAC

The Thanet Wind Farm, located 12 km off the cost of Thanet, England, is the largest offshore wind farm connected via HVAC and started producing electricity in September 2010. The wind farm covers $35km^2$ and is located in average water depths of 20-25m.

There are 100 Vestas V90-3MW wind turbines giving 300MW of generation capacity. The Thanet wind farm uses 33kV as a collector voltage, in an offshore transformer station the voltage is raised to 132kV, the offshore substation platform is manufactured by Siemens. Figure 52 shows the Thanet offshore wind farm side plan [88].

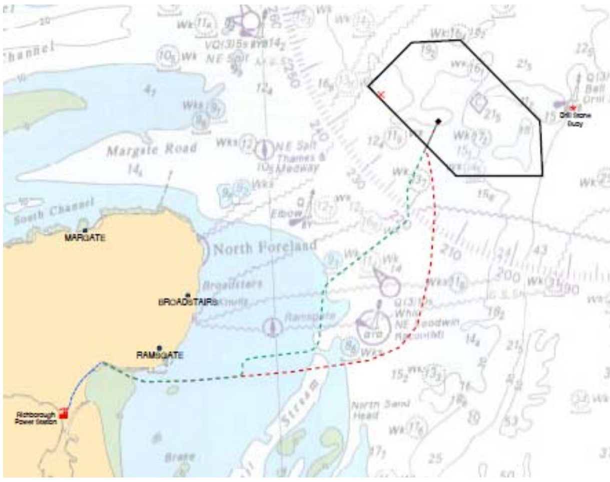

Figure 52. Thanet offshore wind farm site layout [88].

5.4.2 HVDC Technology

High-Voltage Direct Current (HVDC) is used to transmit high powers over long distances, and is an alternative to HVAC transmission. The first prototype of an HVDC system was conducted in the 1950s between the Swedish mainland and the island of Gotland with a rating of 20 MW. Since then, a number of on-land transmission networks have been built all over the world [89]. HVDC transmission is currently considered as an option for large offshore wind farms located far away from an onshore grid.

There are several advantages of HVDC in comparison with HVAC system: the power flow is fully defined and controlled, for distances over 50 km power losses are lower, frequencies are independent, there is no limit for long-distance bulk power delivery, and it is easy to control active and reactive power flow in the HVDC link [90][91]. The HVDC system may be based on two alternative technologies, Current Source systems also know as Line-Commutated Systems HVDC, which have been used in the past on land [92], but for the offshore wind farm applications Voltage Source Converter HVDC system may be more suitable [90].

5.4.2.1 Line-Commutated Converter LCC-HVDC

Line-Commutated Converter High-Voltage Direct Current (LCC-HVDC) transmission is a mature technology with a track record spanning several decades. There are more than a hundred transmission links all over the world [93]. The largest installation with use of LCC-HVDC is the Itaipu link in Brazil with 6300MW ±600kV [94] (see Figure 53). For the LCC-HVDC main components see, also Figure 54:

- Transformers on each side of the line
- Thyristors-based LCC converters
- AC and DC filters
- DC current filtering reactance
- Reactive power compensation, STATCOM or start-up generator.
- DC submarine cables

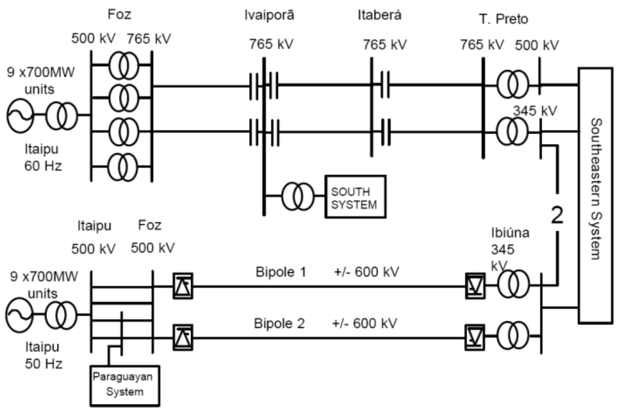

Figure 53. Schematic of the Itaipu LCC-HVDC transmission system [94].

LCC-HVDC transmission technology uses thyristor bridge converters and can be used at very high power levels. They are also known as a Current Source Converters (CSC-HVDC). The operational frequency for LCC converters is 50-60 Hz with power losses no higher than 2%. Because of the line controlled commutation this kind of converter must be connected to a strong AC network since control in a weak AC network is difficult [95].

The LCC converters consume reactive power (VAr) which is about 60% of the active power rating. Therefore, a source of reactive power must be provided, such as capacitors or STATCOM [94]. To remove current and voltage low-order harmonics, AC and DC filters are required. These filters not only remove harmonics but also supply some of the reactive power required by the converters [95].

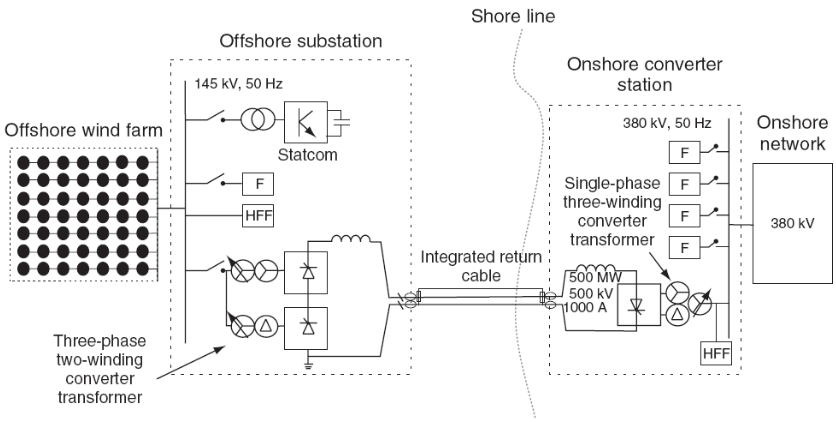

Figure 54. Configuration of LCC-HVDC interconnection of offshore wind farm to the grid [82].

The LCC-HVDC system requires large converter station as large harmonic filters, transformers and reactive power compensation are required, which requires heavy and costly platforms for offshore applications/systems [93].

5.4.2.2 Voltage Source Converter VSC-HVDC

The Voltage Source Converter High-Voltage Direct Current (VSC-HVDC) is a recent technology in power systems, and was first used in the 1990s. VSC-HVDC technology uses self-commutated switching devices such as high-voltage Insulated Gate Bipolar Transistor (IGBT), which is capable of carrying high currents and switch several times during one cycle at high frequencies, e.g. 2 kHz [85].

Gotland in Sweden is the first offshore wind farm which uses VSC-HVDC transmission. The BARD Offshore wind farm located off the German coast is the biggest offshore application commissioned in 2009 which uses Self-Commutated HVDC with total capacity of 400MW and DC 150 kV [96][97]. VSC-HVDC has many advantages such us [98][99]:

- Active and reactive power can be controlled independently
- The wind farm is decoupled from the grid which improves Fault Ride-Through capability, and also the frequency of the wind farm can be different to the frequency of the grid
- VSC can be connected to a weak network
- Black-start capability, discussed in [100]
- No need for start-up generators (compared to LCC)

The typical structure of VSC-HVDC system is shown in Figure 55. The main components are:

- VSC converters
- Transformers
- AC harmonic filters
- DC capacitors
- Phase-reactors
- DC cable or overhead lines

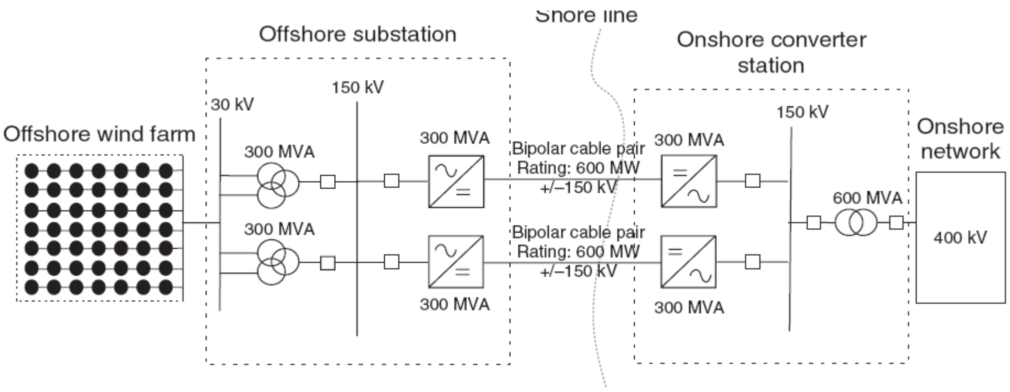

Figure 55. Basic configurations of VSC-HVDC interconnection of offshore wind farm to the grid [82].

BARD Offshore 1 - example of an offshore wind farm connected via VSC-HVDC

The BARD Offshore 1 in the German North Sea is the world first offshore wind farm which uses voltage source converter DC transmission (VSC-HVDC). The wind farm has 80 wind turbines each rated at 5MW with total capacity of 400MW the voltage within the wind farm is 36kV. The power is delivered to offshore

BorWin Alpha substation with an HVDC system, raised to 150kV and transmitted to shore (see Figure 56). The grid connection to the onshore point uses cable length of total 2x203km, which is 406km, where 2x75km is of underground cables and 2x128km is of submarine cables [101]. The wind turbines have doubly fed induction generator with rated power 5MW.

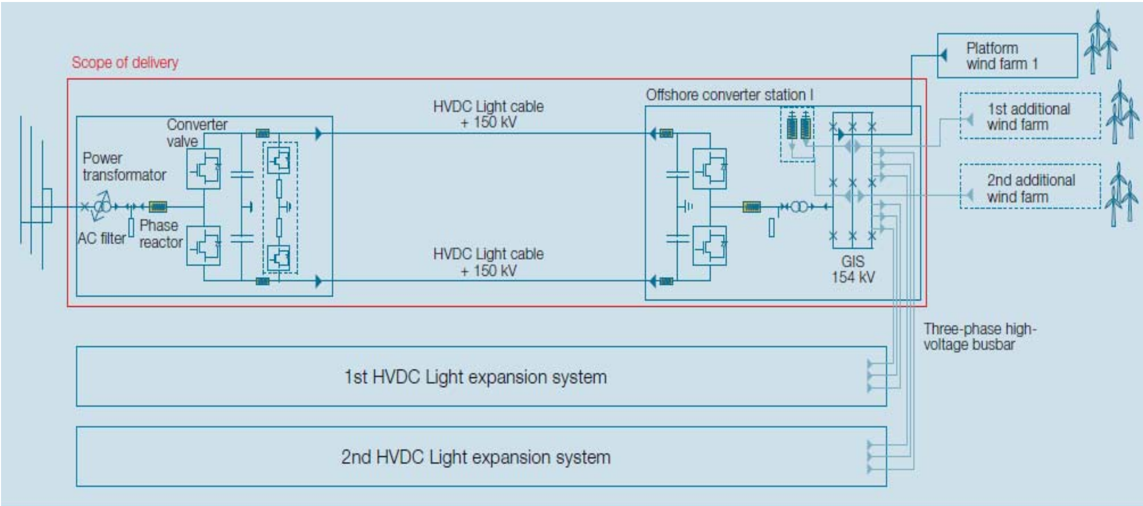

Figure 56. BorWin single-line diagram for HVDC transmission [101].

5.4.2.2.1 Manufacturer options for Voltage Source Converters (VSC-HVDC)

Voltage source converters (VSC) use semiconductor switches such as Insulated-Gate Bipolar Transistors (IGBT), Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET), and Gate-Turn-Off Thyristors (GTO) self- commutated switching devices, which switch several times over one cycle by using high frequencies. VSCs are new technology, used in such products as the ABB developed HVDC-Light and Siemens HVDC-Plus, with converters using Pulse-Width Modulation (PWM) switching techniques.

Currently, two-level converters are used as a standard in industry. By using Pulse-Width Modulation (PWM) the two-level converter changes the output voltage from -Vdc to +Vdc to imitate a sine wave. Due to high switching frequencies, converters have high semiconductor losses. Harmonic content is also very high due to the large step changes.

<u>ABB HVDC Light</u>

Figure 57 shows the basic converter configuration used in the HVDC-Light from ABB. This is a basic configuration for a two-level three-phase bridge converter with six valves. HVDC-Light employs insulated gate bipolar transistors (IGBT) from ABB semiconductors devices. HVDC-Light subsea transmission technology is very attractive for offshore applications it can transfer power over long distances, the gas tubes have been replaced with light-weight and oil-free cables. In the upper range, the technology now reaches 1,200 MW and ±500 kV [102].

The DC transmission HVDC-Light can be used for underground and submarine cables as well as overhead lines; there is control over active and reactive power almost instantly by controlling the phase angle or amplitude. The power is reversed in the HVDC-Light by changing DC current not DC voltage, and this can be obtained without changing the control mode. There is no need for start-up generators like with conventional HVDC system. Also, the HVDC-Light can be connected to a passive network.

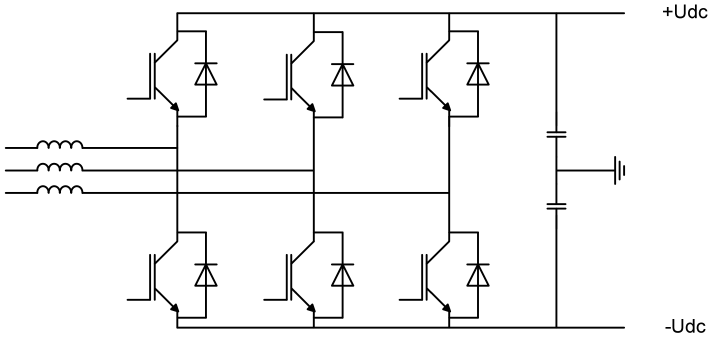

Figure 57. Schematic of a three-phase, two-level voltage source converter.

Siemens HVDC-Plus

Figure 58 shows the HVDC Modular Multilevel Converter Technology (MMC) from Siemens. The basic concept is different from the existing two- or three-level VSC solutions, and it is based on a modular multilevel converter topology. This produces an almost ideal sine wave voltage at the AC terminal and smoother DC voltage that almost eliminates requirements for filters.

Siemens-PLUS and ABB-Light both have many advantages such as:

- Independent control of active and reactive power
- Power can be easily reversed
- Can be connected to a passive network
- Suitable for transmission power over long distances with use of DC cables and over head lines DC.

Siemens-PLUS compared to existing VSC solutions has smaller losses since the individual semiconductors have low switching frequencies which leads to lower switching losses.

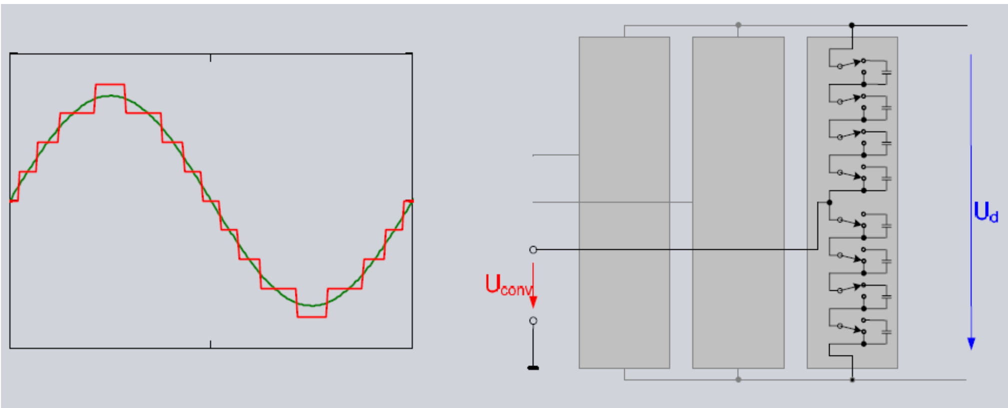

Figure 58. Modular multi-level converter from Siemens [103].

5.4.3 Multi-terminal HVDC

Interconnecting wind farms in multi-terminal HVDC seems to be promising technology for the future North Sea offshore connections. LCC technology requires a huge space for converter station hence the preferred converter technology is VSC-HVDC for offshore application which uses Integrated Gate Bipolar Transistor (IGBT) and employs more than two converter stations.

The VSC-HVDC decouples the wind farm from the ac onshore grid, therefore VSC-HVDC transmission system can use any wind turbine technology for offshore application.

The North Sea has a big potential for developing offshore wind farms. There are different options for potential connection scenarios with VSC-HVDC, in terms of [104]:

- Functionality (power can be transmitted to one or more ac systems)
- Reliability
- Investment cost

Multi-terminal connection can be beneficial in the North Sea connection scenario not only for the wind farms but also for connecting Norwegian oil/gas platforms. This platforms use gas-fired turbines to produce electricity located offshore with much lower efficiency, producing large quantities of greenhouses gases [105].

5.4.3.1 Multi-terminal VSC-HVDC

A multi-terminal VSC-HVDC system has advantages over point-to-point VSC system, in terms of transmitted power, control, reliability, and cost [106]. There are many advantages by connecting wind farms to multi-terminal DC systems (see Figure 59), instead of point-to-point VSC-HVDC system, such as [107]:

- More cost efficient in terms of investment cost, and space required
- Increased power flow control flexibility on wanted routes
- Improvement in system reliability and stability during disturbances

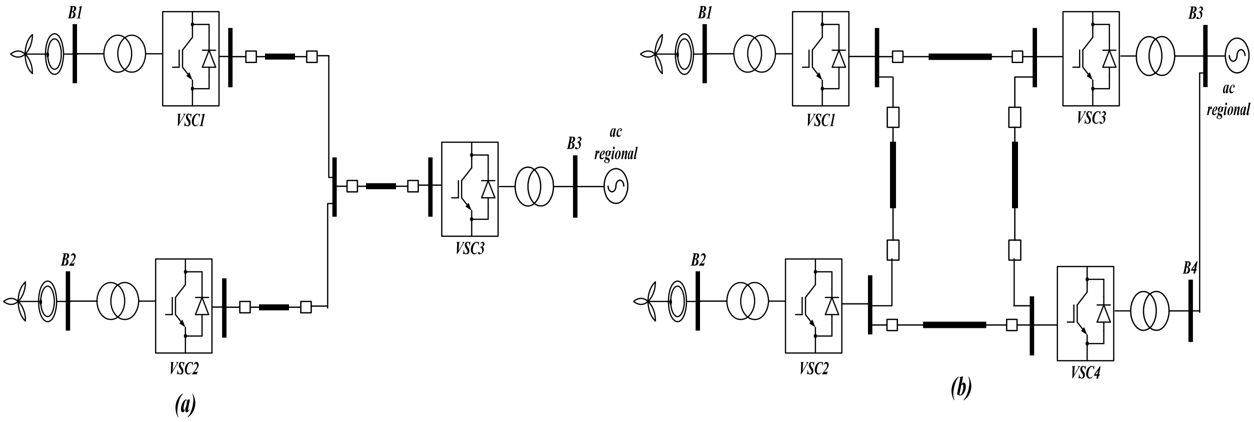

Figure 59. Multi-terminal HVDC: a) double-input, single-output- three terminal system; b) double-input, double output - four terminal system [107].

5.4.3.2 Ring DC network, VSC-HVDC

A ring DC network based on VSC-HVDC (see Figure 60), allows integration of large wind farms and enables penetration of a large amount of offshore wind power. In addition there is an ability to exchange power between regional ac networks which has no influence on system reliability and security of supply. The advantages of connecting networks to a power pool are [107]:

- Easy interconnection between different types of renewable energy.
- Back-up power sharing between ac networks
- Power sharing can be over long distances and capability to supply islanded networks
- Reactive power compensation is provided by VSC converter control

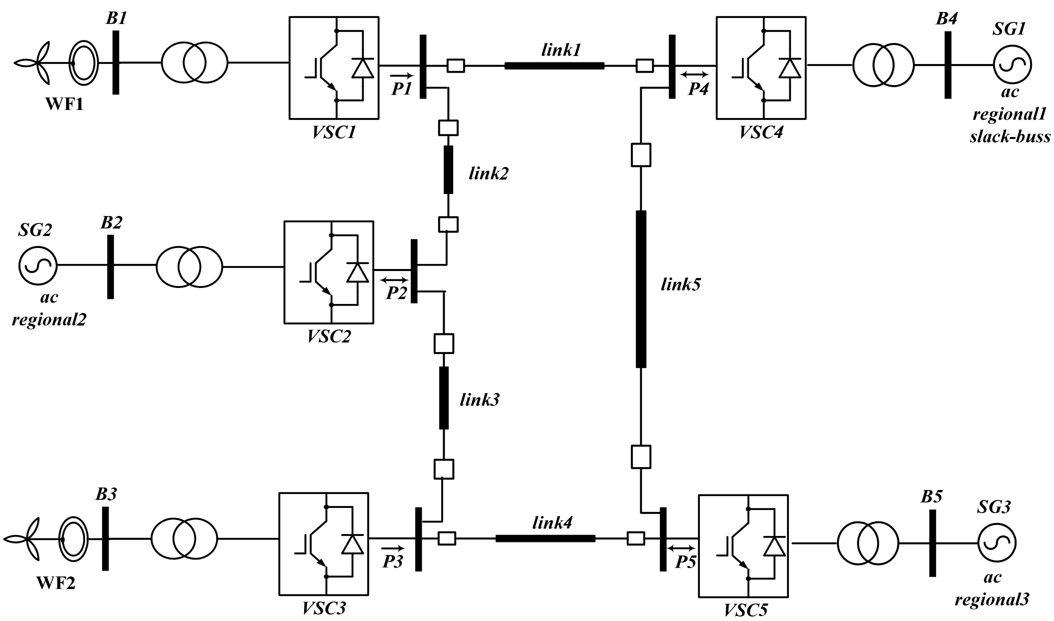

Figure 60. VSC-HVDC ring network [107].

5.4.3.3 Mesh DC network, VSC-HVDC

The DC-ring connection reliability can be increased by using meshed systems (see Figure 61). Interconnecting wind farms with a meshed system is more cost effective than multiple radial connections to shore. A. Hiorns in reference [108] from the UK National Grid operator shows that integrating network in meshed system can save up 25% of capital costs. In comparison to the DC-ring connection, investment cost is higher mainly due to the use of additional cables in the case of maintenance or emergency such as loss of a DC cable [107].

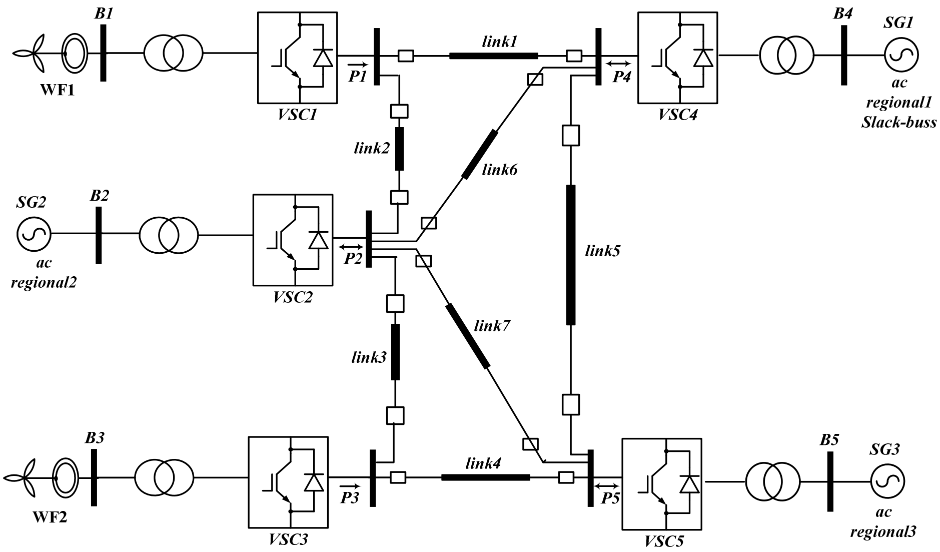

Figure 61. Meshed Multi-terminal VSC-HVDC network [107].

5.4.4 Subsea Cables

To transfer power from offshore wind farms to the onshore grid either AC or DC subsea transmission systems can be used. The selection of subsea cables depends on factors such us: distance to shore, voltage, and transmitted power capacity. Before installation, a comprehensive survey is necessary in order to establish cable routes [109][110].

Offshore submarine cables have various types of insulation systems such as extruded-polymer insulation, mass-impregnated cables and self-contained fluid-filled cables. There are two types of extruded insulated cables: cross-linked polyethylene (XLPE) and ethylene-propylene rubber (EPR), which are lighter and because of that, they are easier to handle and to install on site. In addition, these cables are environmental-friendly due to the lack of oil and associated risk of leakage. Figure 62 shows extruded-insulation cables for HVDC and HVAC [109].

Figure 62. Extruded insulation cables for HVDC and HVAC [109].

Mass-impregnated cables (Figure 63) are suitable for voltages up to 600kV DC and power 1000MW, ABB cables can transmit up to 2000MW at bipolar operation [111].

Self-contained fluid-filled cables (Figure 63) are suitable for high voltages up to 1000kV AC and 600kV DC systems [109].

The main manufacturers for subsea cables are: ABB, Nexans, Prysmian, LS Cable&System, JDR, NSW and Parker.

Figure 63. Mass-impregnated cables and self-contained fluid-filled cables [109].

5.4.4.1 AC Subsea cables

Normally for HVAC systems, XLPE subsea cables are used for offshore applications. Currently, available options for offshore wind farms are three-core cables carrying from 60kV to 225kV or single-core design carrying up to 420kV shown in Figure 25 [112].

Three-core designs have three cores where each one is separately insulated and combined together in one cable, which can be used to transfer smaller amounts of power. To transmit a large amount of power three separate single-core subsea cables can be used, each cable will carry one phase of the three-phase system. Commonly the fourth cable is added in parallel in case of fault/damage on one of the cables [110].

Figure 64. Three-core, and single-core submarine cables for AC [112].

5.4.4.2 DC Subsea cables

Offshore wind power is going towards higher voltages; HVDC cables are more efficient for long distances for offshore wind farms than HVAC cables. For LCC-HVDC mainly mass-impregnated cables are installed, and for VSC-HVDC systems extruded-insulated cables will be installed [110]. The BARD Offshore 1 in Germany is the first offshore wind farm connected to shore by HVDC-Light [113].

5.5 Emerging technologies for wind integration

This section provides a brief introduction to a number of technologies that are considered relevant to the integration of bulk offshore wind power into the grid.

5.5.1 Energy Storage Systems (ESS)

Energy storage systems (ESS) can mitigate against issues associated with the high penetration of wind energy such as inadequate control over generation and low power quality [114]-[116]. In addition, ESS can potentially provide voltage and frequency regulation services. The optimal location of the ESS depends on its purpose.

The main applications of energy storage systems are [114]-[119]:

1. Power quality: In such applications the stored energy is applied for only a short period of time in the order of seconds or less to assure continuity of quality power. Related to this, in a grid with intermittent (non-controllable) and less flexible (nuclear, critical coal) generation, ESS could offer the service of primary (fast) frequency control. In this case, the ESS may be located anywhere in the grid where there is adequate network capacity, and it does not need to be owned by the wind farm operator.

2. Bridging Power: Here the stored energy is used to balance power demand and generation over time scales in the order of seconds to minutes. Also in this case the ESS can be located anywhere in the grid where adequate network capacity exists.

3. Energy Management: Stored energy in these applications is used to decouple the timing of generation and consumption of electric energy over longer time scales i.e. hours. A typical application is load levelling (balancing). If an ESS is located at the PCC then the power generated from a wind farm can be stored at times when a local line in the grid would otherwise get thermally overloaded, unless the wind power is spilled. This however would only make sense if the total cost of the ESS would be lower than reinforcing the line in question, or the cost of spilling. Cost-benefit analysis has indicated that this is highly unlikely unless the line in question would be extremely long (>80km), or planning permission would inhibit reinforcing the line and a long cable would be the only alternative [120]. Another possible application would be to locate the ESS offshore to peak shave wind generation, thereby minimising the rating of an export cable. This would only make sense if the cost of paying for a higher-rated or additional export cable would be higher than the cost of the ESS and additional platform space required, which is again unlikely.

Most energy storage technologies still have considerable disadvantages such as high cost, low efficiency and size, which make their practical applications limited, but they may be gradually improved by further R&D efforts. The main energy storage technologies are [114]-[116]:

5.5.1.1 Batteries

Batteries used for relatively small storage systems are nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lead acid (Pb acid), Sodium-Sulphur (Na-S) and Na-NiCl2 (Zebra) and Lithium-ion (Li-ion). The Li-ion battery has a high energy density which is particularly attractive for mobile applications. All these batteries however require major technological advances before they can be scaled up economically for the purpose of balancing the intermittent power generated from large offshore wind farms. A more promising usage for them in the short term is to provide auxiliary power to the wind turbine generators, and offshore substation components (switchgear, transformers, converters and control equipment).

5.5.1.2 Super-Capacitors

Super-capacitors, also known as ultra-capacitors, offer higher capacitance, and higher energy density compared to conventional capacitors. Their energy density is still much lower than that of batteries, but their power density is much higher. Compared with batteries, super-capacitors can also be charged and discharged with much higher currents and for many more cycles without compromising their life-time. Whereas some super-capacitor technologies use electrolytes that are safe and not harmful to the environment, others are highly flammable and toxic.

One major drawback of super-capacitors is that their energy stored is proportional to the voltage squared, which means that the voltage drops as more energy is taken out, requiring an increase in current to maintain a constant power export. This means that the extractable energy and power from the energy storage system may be a compromise, unless the current rating of the power electronic interface (DC-DC or DC-AC) could be increased, adding to its cost. Another drawback of super-capacitors is that they are made up of many low voltage (<3V) cells and serial connections are needed to create higher voltages. This requires voltage-balancing circuits adding to the complexity, reducing the reliability and increasing the no-load losses. In addition, self-discharge rates are considerably higher than that of an electrochemical battery.

5.5.1.3 Flywheel Storage System

Flywheel-based energy storage systems, unlike batteries, are sustainable technology solutions that do not use hazardous materials in their construction, nor create them during operation. They are suitable for high power applications, but their energy density is relatively low. Despite higher initial costs, it is claimed that flywheels offer a cost-effective long-term and reliable energy storage alternative [116]-[118].

The company Beacon Power have got a 100kW/25kWh flywheel available as a commercial product, which is designed specifically for frequency regulation [117]-[119]. Note that this has a very low energy rating compared to the needs of a large offshore wind farm of several hundreds of MWs, but Beacon Power promote this product as a 20 MW/5 MWh plant, comprising two hundred of their 100 kW/25 kWh flywheels. Note that these flywheels provide ‘up and down’ regulation as they can export and import power, hence this is equal to a 40 MW swing. The viability of employing large-scale flywheels will depend on how the capital investment costs compare with the market to provide frequency regulation in the future. More R&D work is required to achieve improved efficiency, higher energy density and lower cost.

5.5.1.4 Pumped-Hydro Storage

Although this is not an emerging technology, the role that pumped-hydro storage plays within future power systems will almost certainly evolve as requirements for mitigating the impact of wind variability grows. Conventional pumped-hydro uses two separate water reservoirs at different heights. During off-peak hours (when the generation exceeds the demand), water is pumped from the lower reservoir to the upper reservoir. During the peak hours where more power is required, the water flow is reversed to generate electricity. Pumped-hydro is available at almost any scale with discharge times ranging from several hours to a few days. Their efficiency is in the 70% to 85% range. Pumped-hydro storage plants are characterized by long construction times and high capital expenditure. Pumped-hydro storage is the most widespread energy storage system in use on power networks. In the context of intermittent energy sources such as wind power its main applications are energy management, frequency control and provision of reserve [116],[121]. The main drawback is that sites are limited since pumped-hydro storage requires large reservoirs in mountainous areas, which may be far from generation and demand.

5.5.1.5 Compressed-Air Storage Systems

Compressed-air storage technology has received significant attention recently as a means to addressing the intermittence problems with wind power. When surplus energy is available during off-peak, it is used to run air compressors and store compressed air in the storage tank. When electricity is needed during peak hours, the compressed air is used to generate electricity through conventional gas turbines. The first compressed air storage power station has been in operation since 1978 with a capacity of 290 MW located in Bremen, Germany, capable of delivering full output power for up to 4 hours [122]-[125]. Compressed-air is usually stored in artificial salt caverns underground made by dissolving salt from strata of rock salt at least 100m thick and several hundred meters underground. Consequently this method is limited to locations where there are large amounts of suitable rock salt underground.

5.5.1.6 Superconducting Magnetic Energy Storage (SMES)

SMES technology exploits the fundamental property of a superconductor having negligible resistance to electrical current, to store energy in a superconducting coil in the form of magnetic field that can be created by flow of current. A typical SMES system includes three parts: a superconducting coil, a power conditioning system and a cooling system to maintain the superconducting temperature below its critical value. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conditioning system uses a power electronic interface such as an inverter/rectifier to allow power exchange between the superconducting storage system and the power network. The inverter/rectifier accounts for about 2-3% energy loss in each direction. Therefore, superconducting energy storage systems are highly efficient devices with round-trip efficiency greater than 95%. The use of SMES systems is limited to power quality applications due to their high cost, and their energy storage capacity is relatively low [126]-[128].

5.5.2 Fault-Current Limiters (FCL)

Development of medium- and high-voltage fault-current limiters can contribute to reduce fault levels at the collection network of large-scale wind farms. It may also facilitate the connection of large offshore/onshore wind farms to high-voltage networks without the need for replacement of the existing switchgear at the point of common coupling (PCC) [129][130].

Fault-current limiters may provide a cost-effective solution, if there is a problem of excessive fault levels and if they are cheaper than the cost of higher rated switchgear that would otherwise be needed due to excessive fault levels. Fault-current limiters are also an enabling technology that could allow increased load or generation or increased paralleling of feeders, which would otherwise not be possible due to limitations of the rating of available switchgear.

The most common types of fault-current limiters are reactors, and high-impedance transformers. Other devices being developed are solid-state fault-current limiter circuit breakers and high-temperature superconducting fault-current limiters, but these are not commercially available yet.

Superconducting fault-current limiters are designed to decrease fault levels by inserting impedance into the circuit only in the event of a fault, without adding impedance to the circuit during normal operation. This is achieved by the fact that the super conductor switches to a non-superconducting state when the current through the superconductor exceeds a critical value. Superconducting fault-current limiters are being developed by several manufacturers around the world; and a commercial device is expected to be available within the coming decade. However, the first commercially available fault-current limiters would be limited to medium-voltage levels with maximum operating voltage up to 40.5 kV with current interruption of 140 kA (peak).

Examples of the companies developing high-voltage fault-current limiters are [129]:

- American Superconductor: maximum operation voltage and current of respectively 138 kV and 1200A. During the first testing in December 2008 a fault current reduction of 20-50% was achieved. This device is expected to be commissioned by 2012.
- SuperPower: maximum operating voltage and current of respectively 138 kV and 1200A.
- Zenergy: maximum operating voltage and current of respectively 138 kV and 4000A.

5.5.3 High-Temperature Superconducting (HTS) Cables

Development of HTS cables may enable large-scale power transmission over long distances without the need for extra-high voltage. It may therefore also facilitate grid connection of remote large onshore or offshore wind farms using an AC option with reduced power losses. As high-temperature superconducting cables transmit power with essentially no electrical resistance, it may enable utilities to increase power-carrying capability of existing power corridors. This increased capacity is appealing for locations where there are space constraints for conventional lines or cables.

The main benefits of HTS power cables are [131]:

- Current-carrying capability of 3-5 times that of conventional cables.
- Low load power losses.
- Use of environmentally friendly liquid such as nitrogen for cooling.
- No leakage of electro-magnetic field to the outside of the cable resulting in low impedance.
- As power loss is extremely low, HTS cables may eliminate the need for high voltage (400 kV) and extra high voltage for long transmission distances.

However, HTS cable technology is still at the development stage, extremely expensive and reliability is unproven. One further aspect of concern is the requirement to have a cooling system that would have to be located approximately every 2 to 5 km, which would be very costly if not impractical for a submarine cable. Moreover, such a cooling system would add to no-load losses, which offsets the benefit of low load losses.

5.5.4 Gas-Insulated Transformers (GITs)

Gas-insulated transformers (GITs) that use SF6 as an insulator without the need for oil are a mature technology and are available up to 300MVA. Their advantages are [132][133]:

- Large power rating in small size. Combined with the switchgear the size of a substation can be reduced to about a third.
- Non-flammable and non-explosive (safe).
- Higher reliability with simple internal structure.

GITs have been implemented in some niche applications where there are severe space constraints, for example in big cities like Tokyo. It is therefore logical to consider them for offshore substations where space is also at a premium. The main drawbacks of GITs are however their high costs and the fact that in practice there is always a small leakage of SF6, which is an extremely harmful greenhouse gas (22,200 times more so than CO2).

5.5.5 Gas-Insulated Lines (GILs)

Gas-insulated lines (GILs) are composed of pipes that house conductors with SF6 gas used as the insulator. Although the first GIL was commissioned in 1979 the technology is still at the demonstration stage and would only be better than conventional cables at powers above several GWs. Further development of GILs for long distances may improve system efficiency when used with large-scale wind farms. Since the shunt capacitance of GILs is small, the problems associated with reactive power are less than in the case of the XLPE submarine cable. Power losses are low and a high transmission capacity (several GW) can be achieved.

As for the GITs the disadvantages of GILs are the high costs and the harmful greenhouse gas SF6 used. The cost of installing GILs on the seabed would be extremely expensive. They are less flexible than cables for routing and jointing pipes on the seabed is more problematic than jointing cables, as the latter can be done above the water. Jointing pipes undersea is familiar to the offshore oil and gas industries and similar technology could be applied to GILs, however the relatively high cost would be prohibitive in the wind farm industry. The largest GIL with capacity of 3500 MVA, 550 kV and maximum current-carrying capability of 4000A is scheduled to go into operation in 2012 in China [134][135].

5.5.6 Developments in Condition Monitoring

Condition monitoring systems can detect the potential failures of different electrical and mechanical components of an offshore wind farm, and are capable of predicting the mean time to failure and enabling a degree of remote maintenance of the wind farm. Condition monitoring systems based on supervisory control and data acquisition (SCADA) have been used extensively to monitor and to control numerous aspects of the wind farm operation, such as adjustment of the turbine blade pitch and power output, monitoring the condition of bearings, vibration of the drive train, generator winding temperature and recording switchgear operations.

The applications of condition monitoring for offshore wind farms have increased in the last decade, because of the following reasons:

- It can aid maximising the energy yield from the turbines while minimizing operational and maintenance costs.
- It allows effective system management by remote control and a degree of remote maintenance that may increase the productivity of the wind farm and reduces downtime.

In the context of the offshore electrical array system, SCADA also plays a vital role in monitoring cables, switchgears and transformers at the offshore network to facilitate remote fault detection and schedule maintenance in order to reduce downtime and increase productivity [139]. With further development and improvement of the current condition monitoring techniques, it may play a major role in improving system reliability and availability, which can deliver large operational savings in the future [136]-[139]. The next sections describe developments in condition monitoring in more detail for network components.

5.5.6.1 Partial discharge monitoring in HV cables

The condition of high-voltage cables can be determined by monitoring the level of partial discharge (PD) activity in the cable. This is of interest to network operators in the UK, who have a significant amount of cable approaching the 60-year design life of the cable, and need to know how to prioritise cable replacement [140]. Presence of PD can be detected by attaching high-frequency current transformers to the cable, with the discharges appearing as spikes of current. The energy of the pulse can be determined by integrating the pulse current – this is more accurate than simply recording the pulse magnitude as the pulse shape will change depending on how far along the cable the detector is from the pulse location [140].

It is possible to estimate the remaining lifetime of XLPE cables from analysis of the PD activity, but this requires a large number of parameters to be measured for each discharge, and complex analysis techniques [141]. XLPE cables are designed for a lifetime of at least 60 years, and are tested for partial discharge due to manufacturing defects before leaving the factory, with a requirement of being completely free of discharge activity at a voltage considerably higher than the working voltage [142]. PD monitoring equipment can be easily added to a cable installation later in the lifetime, when the cable is more likely to suffer from age-related failure, and once the presence of PD is established further equipment can be used to locate the source of the discharge [140].

5.5.6.2 Transformer condition monitoring

For early failure detection, it is necessary to measure the transformer load current and operating voltage, which will give indication of overload currents which could damage the windings mechanically, and over-voltages which would damage the insulation [143]. Measuring the oil temperature and load current allows the transformer hotspot temperature to be estimated, which determines the rate of insulation degradation. The presence of various gases in the oil of an oil-filled transformer can indicate problems with the transformer [144]. Gases such as hydrogen (H2), methane (CH4), ethane (C2H6), ethylene (C2H4), and acetylene (C2H2) indicate a breakdown in the oil, caused by overheating, partial discharge, arcing, sparking, etc., and the ratios of each gas can be used to determine the precise cause [145]. Presence of carbon dioxide (CO2) and carbon monoxide (CO) indicate breakdowns in the paper insulation while presence of oxygen (O2) and nitrogen (N2) indicates leaks in the system. This has been shown to be the case for both mineral oils and the newer ester transformer fluids [146]. Sensors such as the Hydran can be fitted to the transformer to continuously monitor the level of combustible gases. The Hydran sensor consists of a membrane which allows only gases to pass through it, and a combustible gas detector. It is most sensitive to smaller molecules, with 100% sensitivity to hydrogen, 15% to carbon monoxide, 8% to acetylene and 1% to ethylene, and will only give the total level of combustible gases detected. It is useful for detecting the presence of a breakdown, with a laboratory analysis of the transformer oil used to determine the precise cause [147]. If the cause is a partial discharge, then PD monitoring equipment can be attached to monitor the level of discharge.

At the most basic level, the health of an on-load tap-changer can be monitored by having the tap-changer in a separate compartment of the transformer tank, and monitor the temperature in the compartment [144][147]. An unusually high temperature in the oil would indicate a degradation of the tap-changer contacts. Another method has been proposed where the load current of the tap-changer motor is monitored. Problems with the tap-changer would cause higher peak currents at various points in the tap-changing sequence, and this has been demonstrated in simulated faults [147].

Studies on the economics of offshore wind farm condition monitoring have concentrated on monitoring the turbine systems, particularly the gearbox and generator [147][148]. A study of the benefits of transformer condition monitoring used a failure rate of 1.63% a year, based on reliability of 245 and 400kV transformers in Germany, along with estimations of the probability of a condition monitoring system detecting a fault early to estimate the benefits of installing a CM system [143]. If the early detection of a fault means that a transformer can be re-wound at half the cost of a new transformer, rather than installing a new transformer, a saving of 0.58% of the cost of the transformer per year could be made. For a CM system with a 10-year life, such a system would have to cost less than 5.8% of the transformer cost, and it was found that the cost was between 1% and 7.4% depending on the installation. This does not take into account the impact of lost generation while waiting to replace the transformer, which could be considerable in an offshore installation.

5.5.6.3 Gas-insulated switchgear condition monitoring

The insulation effectiveness and breaking capacity of switchgear insulated with sulphur hexafluoride (SF6) depends on the density of the gas. An improved gas density sensor based on micro-machined quartz tuning forks has been proposed, which offers better accuracy than conventional sensors [150]. The density of the gas varies with temperature in a complex manner, which depends on the movement of gas and distribution of temperature inside the circuit breaker. This makes it difficult to detect small leaks of gas until a large quantity of gas has leaked, although complex models have been developed which will accurately detect small leaks of gas [151].

Presence of partial discharges in the circuit breaker indicate a degradation in the insulation effectiveness, and can also cause the SF6 to degrade into other substances, some of which are corrosive and damage components of the circuit breaker. Switching of the circuit breaker will also cause degradation of the SF6. Analysis of the gas will show the level of degradation, and indicate the cumulative effect of partial discharge and switching, and simple spectrometers based on the Ion Mobility Spectrometer can be used on site, or installed permanently to monitor the gas composition [152]. The level of partial discharge can be monitored by monitoring the RF radiation in UHF frequencies [153], which will also detect partial discharge inside solid insulating materials such as spacers, which gas analysis and other PD detection methods cannot do. However it has been suggested that PD detection cannot detect low level discharges, which can still cause degradation of the SF6 gas over time, so online PD detection would need to be combined with periodical gas analysis.

5.5.6.4 Power electronics condition monitoring

Condition monitoring for power electronics has concentrated on monitoring two components: electrolytic capacitors, and switching devices in conventional power modules. Both of these have been found to be significant sources of converter failure [154], but the degradation and failure mechanism for electrolytic capacitors is much better understood. Because of this, capacitor banks can be designed to achieve a desired life-time, given expected load conditions [155], and any failures are usually due to unexpected operation conditions, or a capacitor bank which is deliberately undersized to give lower cost with reduced life-time.

Electrolytic capacitors degrade due to the loss of electrolyte, the rate of which depends on the temperature inside the capacitor, which depends on the ambient temperature and the capacitor loading [156]. The loss of electrolyte leads to an increase in the equivalent series resistance (ESR) of the capacitor over the lifetime, which can be measured. ESR can be measured using dedicated current and voltage sensors attached to the capacitor bank [157], or can be estimated from the other measurements of current and voltage in the converter [154]. In the latter case, the ESR estimation would need to be built into the control software of the converter. ESR varies with capacitor temperature and ripple current frequency, and this must be compensated for in software.

Switching devices, such as IGBTs, in conventional power modules usually fail due to one of two degradation mechanisms: lifting of the bond wires from the surface of the silicon chips [158] or void formation in the solder attaching the chips to the copper substrate [159]. Both of these are fatigue effects, due to different coefficients of thermal expansion of the different materials involved, and are related to thermal cycling. There is a small thermal cycling effect from the converter input and output fundamental frequencies, e.g. the generator and grid frequency, and a larger effect from variations in the total power output of the converter [160].

Condition monitoring of switching devices is relatively immature, and many possible methods have been investigated. These can be divided into three main types:

- Measurements of switching device parameters which would indicate device degradation. For instance, bond wire lift-off can be detected by measuring the on-state voltage [161][162], and various device parameters can be used to estimate the junction temperature to calculate the thermal resistance, which indicates the level of void formation in the solder [163][164].

- Embedding sensors in the device package. For instance, additional terminals can be added to measure the bond wire resistance [161], or sensors to measure the junction temperature [165].

- Determining device degradation from changes in the system dynamic performance, e.g. the reaction to certain stimuli [166][167].

The first method requires additional sensors to be installed, and often changes to the gate drive circuit and control software. The second method requires custom designed power modules while the third method requires significant signal processing, and detailed knowledge of how the changes in device parameters will affect the system response.

The trend for higher power fully-rated converters in wind turbines larger than a few MW, is to move towards medium voltage converters [150][168]-[169][170]. These often use press-pack modules, which do not suffer from the same failure modes as conventional power modules [169]. Converters based on IGCTs, in which the gate drive circuit is soldered to the switching device, are available from ABB and Siemens. While the reliability of the switching device in an IGCT is claimed to be greater than that of an IGBT [169], overall reliability is reported to be significantly lower, due to the complexity of the gate drive circuit [170]. Monitoring the health of the gate drive circuit could be achieved by monitoring the switching time of the switching device [165], although it would be difficult to accurately calculate the remaining life.

Anecdotal reports on the reliability of fully-rated converters in wind turbines have indicated a high failure rate on the grid-side converter. This is believed to be due to unexpected events leading to the switching devices operating outside their safe operating area, possibly due to problems with the converter control action, which causes chip-level damage, rather than through continuous degradation mechanisms. While this is potentially detectable using condition monitoring apparatus, failure of the device would occur fairly rapidly, giving insufficient time to replace the device before failure. At best, condition monitoring would allow the converter to be shut down, preventing the device failure from damaging other parts of the converter. Furthermore, while failures of the converter and control electronics in a wind turbine are significant in number, the resulting downtime is usually small compared with other components such as the gearbox or generator [149].

5.5.7 Sub-Sea Substations

Platform-based substations are used at present for the connection of offshore wind farms. As deep waters (>40 metres) are explored for the deployment of WTGs and non-fixed devices for the capture of wave and tidal energy, then subsea substations may become a competitive alternative to platform-based substations. The technologies for subsea substations have so far been developed for offshore oil and gas industrial installations. The electricity generation industry is only recently becoming involved especially for tidal and wave energy generation. The major obstacle to using subsea technologies so far are the (i) high costs, which is less of a problem in the oil and gas industry; (ii) health and safety risks associated with installation and maintenance; and (iii) most subsea technologies are still limited in voltage levels. The following sections briefly review the essential components required for a subsea substation.

5.5.7.1 Sub-Sea Transformers

The largest voltage rating of a constructed and tested subsea transformer to date is 50 kV and has been developed by ABB. Higher voltage levels will be needed for longer transmission links. There are developments to increase this voltage level to a rating of 145kV for a Norwegian gas field project in 2011.

5.5.7.2 Sub-Sea Connectors

Subsea connectors can be split into two categories; ‘wet mate’ where the physical connection can be made whilst submerged, and ‘dry mate’ where the connection must be made above the surface before submerging the connector [172]. This would require a ship, platform or similar. A wet mate connection cannot be made whilst the line is energised; however, cables can be connected without regard for water ingress as the connectors contain a system for ejecting the water from the connection area.

Wet mate connector designs are far more complicated than dry mate versions and therefore are more expensive. However, costs may be offset against the simpler cable design and installation, which does not need to include making the connection to the item of plant above the surface before lowering both the cable and plant to their subsea positions. Dry mate and wet mate connectors have been demonstrated up to 33 kV. Future designs are in place for dry mate connectors at 145 kV however no such plans are in place for wet mate connectors.

5.5.7.3 Sub-Sea Circuit Breaker

The oil and gas industries have operational subsea switchgear at 24 kV which utilise a magnetic actuator system. The significant benefit of this system is that it is largely maintenance free. VetcoGray (a GE Oil & Gas business unit) have a 24 kV subsea circuit breaker commercially available [172][173]. There are proposed designs for 33 kV subsea circuit breakers, but early indication is that a motorised spring charge actuator system will be used. Such a system requires periodic maintenance and is therefore not ideal.

5.6 Grid integration issues

5.6.1 Future Grid Code Requirements

The seamless integration of additional wind generation capacity into existing grids and the growing needs for ancillary services in distribution and transmission systems are requiring further, more advanced functional capabilities from wind power plants (WPPs). Present demands from System Operators (i.e. TSOs or DNOs) generally include reactive power capability and controllability for grid voltage control; ride-through capabilities against common contingencies; and active power control to support grid frequency deviations. These interconnection standards involve bespoken solutions and enhanced control techniques. The large deployment of large offshore WPPs/cluster in the North Sea will potentially involve various wind turbine providers, introducing different turbine designs, with varying specification and performance characteristics. It is hence envisaged that this will introduce additional control challenges demanding novel approaches and control mechanisms. A big control requirement is to explore how a wind power plant can be controlled to provide similar network services as from conventional power plant based on synchronous generators

5.6.1.1 Active power and frequency control requirements

Increasing penetration of wind energy in power systems will require its participation in the power frequency control and balancing procedures, which are already performed by conventional generation. The fulfilment of power and frequency control schemes in case of high wind penetration also implies the provision of primary, secondary and inertial energy (spinning reserve) from wind generators [174]. In some EU countries there are plans to implement in a new operative procedure strengthen requirements for the power and frequency control contribution from wind generators. This includes the participation in the power and frequency control schemes and in addition requirements for inertia provision by emulation from wind farms. With an increasing wind penetration and bigger power ratings wind turbines and wind farms will have an important role to assure the frequency stability of the system. Therefore, it will be expected in future grid codes the obligation of wind generation to provide this ancillary service.

5.6.1.2 Inertia

Most wind turbine concepts utilise variable rotor speed, as this has major advantages for reduction of drive train and structural loads. All conventional generators are fixed-speed, i.e. the entire drive-train rotates at synchronous speed, and therefore provides a substantial synchronously-rotating inertia. Rotating loads also provide such inertia, though the generators dominate. This inertia provides substantial short-term energy storage, so that small deviations in system frequency result in all the spinning inertias accelerating or decelerating slightly and thereby absorbing excess energy from the system or providing additional energy as required. This happens without any control system, effectively instantaneously. Without this, modern power systems could not operate.

In addition to this 'smoothing' effect in normal operation, the spinning inertia also provides large amounts of energy in the event of a sudden loss of generation: the rate of decrease of system frequency in the first second or so after such an event is entirely governed by the amount of spinning inertia on the system. Variable-speed wind turbines have less synchronously-connected inertia, and in the case of the FRC concept, none at all. As wind turbines displace conventional generation, there will be less spinning inertia, and therefore the system will become harder to control and more vulnerable to sudden loss of generation. It is feasible that future grid codes will require all or some generators to provide an inertia effect. This can in principle be provided by variable-speed wind turbines, but requires a control function rather than occurring without intervention. The control function will sense frequency changes and use this to adjust generator torque demand, in order to increase or decrease output power. The effect is similar to the frequency-regulation function discussed above, but is implemented by generator torque control rather than pitch control. A more complex implementation could also include pitch control.

It is possible that wind turbines would not need to provide this function for the small-scale frequency deviations, as conventional generation capacity may still be sufficient. Instead, the requirements could be limited to responses to the large-scale deviations associated with a sudden loss of generation. Initial studies show that, in principle, variable-speed wind turbines can provide a greater inertia effect than conventional synchronous machines, because generator torque can be increased at will, extracting relatively large amounts of energy from the spinning wind turbine rotor. This decelerates the wind turbine rotor rapidly and so may not be sustained for very long before aerodynamic torque is reduced. High generator torque also results in high loads on the drive train, which may add significant cost. So, in principle, the inertia effect is available, but may have implications for wind turbine design and cost. Also, load-following and frequency response can in principle be delivered by appropriate control of wind farms, but much of the detail is unexplored.

5.6.1.3 Power System Stabiliser function

Power system stabiliser functions (PSS) can be provided by conventional generators. In essence, the output power of the generators is modulated in response to frequency deviations, in order to damp out resonances between generators. These resonances are most likely to occur between two groups of large generators separated by a relatively weak interconnection. It has been argued that this PSS function can also be provided by the DFIG, FRC and HVDC but this still has to be further demonstrated.

SINTEF

5.6.2 Wind farm cluster(s) control

The Wind Farm Cluster concept was created and developed by Fraunhofer IWES as a natural evolution for wind energy management [174]. In the past, wind turbines were grouped into wind farms, and nowadays wind farms are being grouped into Wind Farm Clusters. The aim of this structure is to allow the TSOs to manage wind energy as a conventional power source, avoiding some natural aspects of wind energy as the fluctuating nature of the wind, the distributed location of the wind farms and the existence of different generator technologies, among other issues.

A Wind Farm Cluster is a logical aggregation of existing physical wind farms, which are connected to the same grid node. The main goal of this structure is to allow the large-scale management of wind energy and the operation of wind farms as conventional power plants. The proper management and control of Wind Farm Clusters require of advanced techniques and control strategies combined with high-tech wind energy forecast technologies. These advanced control mechanisms allow wind farm clusters to provide grid operators with active and reactive power control, wind power reserve, congestion management, gradient control, and voltage and power factor control among other issues, in order to fulfil the current and future requirements regarding operational flexibility and security issued by grid operators.

5.6.3 Control of multi-technology offshore networks (wind turbines, transmission, reactive power compensation, energy storage)

The large-scale deployment of offshore wind turbines in the North Sea (e.g. UK Round 3), will potentially involve various wind turbine providers, introducing different turbine designs, with varying specifications and performance characteristics. Additionally, existing concepts and proposed designs for Europe's offshore grids anticipate the use of hybrid networks (LCC-HVDC and VSC-HVDC), and combinations of AC and DC offshore transmission schemes. It is envisaged that control requirements and dynamic performance of these future offshore wind power systems, with such a variety of technology and complex network arrangements, may be significantly different from conventional and comparatively simpler existing power networks. Current offshore network planning, control and operation practices may no longer be appropriate. Hence intensive research is needed in different areas to gain knowledge and understanding on how future offshore wind power systems should be designed, controlled and operated to ensure, technically and economically, the security of the power supply.

5.6.3.1 Reactive power compensation and voltage support

A specific aspect of power system stability concerns voltage. In essence, problems concern local shortages of reactive power and arise out the interaction between loads at times of high demand, the particular paths from generators that serve those loads and the characteristics of network branches. If adequate reactive power is not provided near to where it is needed, the system’s voltage can collapse and demand no longer met. The characteristics of both wind and nuclear power suggest that power conversion facilities are built quite far from demand centres entailing long power transfer paths and large voltage drops. In addition, not all wind turbines have a significant, inherent reactive power capability and grid code requirements may be satisfied by the installation of reactive compensation, which often has quite different performance characteristics in respect of voltage control compared with synchronous generators. This can mean that reactive power support drops of at critical times.

There is another problem that might arise associated with system voltage: an excessive rise that risks breach of insulation limits. The system operator's ability to control such rises has been severely limited by the displacement of conventional generation at critical locations by, for example, wind farms at remote locations. The problem appears to be being exacerbated the changing nature of loads (which seem to have very different responses to changes in voltage to those that have been habitually assumed) and distribution network operators' (DNOs') hitherto generally simplistic approaches to regulation of voltage.
All the above phenomena require attention and the development of new control mechanisms. These are likely to involve more active involvement of DNOs, more precise setting of voltage targets, exploitation of the four-quadrant capability of voltage source converters and, possibly, some degree of hierarchical control of reactive power resources and transformer tap changers at different voltage levels.

5.6.3.2 Integration of energy storage

In the last 50 years significant research has been conducted in energy storage systems. This has resulted in the introduction of several storage technologies into power systems to provide ancillary services. However, more research is needed in scalability and efficiency improvement of storage energy systems. Longer-term energy storage, such as would be used to smooth the power output of the wind farm during variable wind conditions, is bulky and heavy, and as such would be far cheaper to locate onshore at the point of connection to the electricity grid. There are several reasons why short-term storage may be required, and this may or may not need to be connected at the transmission platform. During a transmission cable fault, the wind turbines will be unable to export power, and this must be absorbed somehow. While energy storage could be used, it would be easier to use the established method of allowing the turbines to speed up, while feathering the blades to reduce power capture, and any excess power is dissipated using dump resistors. On re-connection of transmission, the turbine inertia is used to provide power while the blades are un-feathered. During a fault in part of the collection network, the design of the network may mean that a section consisting of several turbines will be disconnected, before isolators are used to isolate the faulted section, and some or all turbines re-connected. Energy storage could be used during this time in order to maintain a constant export of power, and it may be easier to control this function if the energy storage is located on the transmission platform. As the time to clear the fault is likely to be quick, the storage capacity will be small. Due to the use of lower voltages in the collection network, energy storage may be easier to connect at the collection network level, rather than at the converter station onshore, where a step-up transformer will be required.

5.6.4 How development of converter technology affects/influences control approaches

At present, the wind turbines used offshore are based on designs for onshore use, producing an AC output for direct connection to the electricity grid, and complying with the relevant grid codes for power quality and fault response. For a small wind farm, close to shore, the outputs of the turbines are collected and stepped up using a transformer on a transmission platform, with an AC link to shore. Therefore the collection grid represents an extension of the national electricity grid. Many planned offshore wind farms will be of a large size, of up to several GW, and will be located a long distance from the shore. To transmit power over long distances undersea, high voltage DC transmission (HVDC) is required, using converter stations on the offshore transmission platform and onshore at the point of connection to the national electricity grid. In this case, the collection network is not a part of the national electricity grid, and it is the responsibility of the onshore converter station to comply with the grid codes, with assistance from the wind farm hardware. To gain understanding on how wind turbine generator technology may influence control approaches, it is necessary to consider the electrical system as a whole, that is, the turbine topology (converter interface arrangement), wind farm collector, and the offshore transmission type (e.g. HVAC or HVDC). Two cases are discussed next in the context of the converter interface arrangement and location [178].

5.6.4.1 Converters on turbine

AC String
The conventional arrangement is shown in Figure 65. Turbines feature a squirrel cage induction generator (SCIG), or a permanent magnet generator (PMG) connected to a fully-rated converter, or alternatively a doubly-fed induction generator (DFIG) and partially rated converter can be used. The output of the converter is stepped up to the collection network voltage, and the turbines are connected together in strings. The number of turbines on a string is determined by the current and voltage rating of the available cables, and the rated power of the turbines. Voltage is limited by water treeing effect with wet insulation cables, while dry insulation cables with a lead sheath around the insulation would be too expensive. A higher voltage also requires a higher voltage rating for the transformer, which increases the cost and size. Available current ratings are also limited, as the skin depth of the AC current means that conductors with larger areas will be less effective, as the current will not flow in the centre of the cable. For this reason, the cost of AC cables tends to increase exponentially with current capacity.

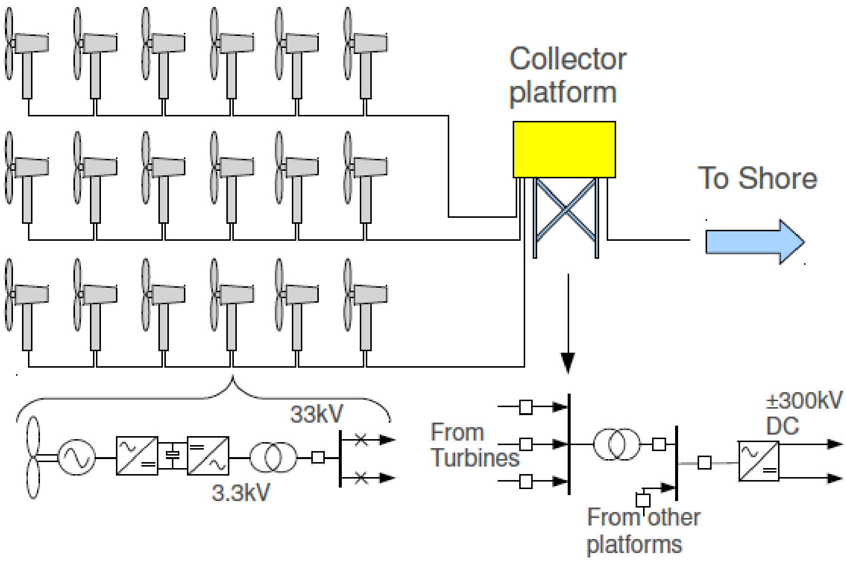

Figure 65. Conventional AC strings.

While the diagram shows strings of turbines, which are connected at one end, the ends of the strings can also be connected together, which allows the end turbines in a string to still export power if a fault occurs in one of the cables of the string. If the turbines are arranged in such a loop, the loop can either be rated such that each connection to the platform can carry the full loop power, giving maximum redundancy, or half power, leading to a loss of power at higher wind conditions. In most cases, the cable reliability is considered to be high, and a loop system is not used. In this case, the cable rating is tapered along the length of the cable to save cost.

DC String
An arrangement using DC in the collection strings is shown in Figure 66. In this system, the turbines output a DC voltage, which is then stepped up to the transmission voltage at the collection platform. In most studies, the turbine produce a voltage of around 40-50kV DC, which requires an AC-DC converter capable of

producing such a voltage, featuring many switching devices in series, or a lower voltage AC-DC converter and step-up DC-DC converter. A solution involving a lower voltage converter, and a DC voltage of 5kV is also possible, which has the advantage of eliminating the turbine transformer and using a conventional 3.3kV 3-level converter. However, the currents in the strings will be extremely high, requiring thick cable and leading to high losses. DC systems are attractive as they could reduce the number of conversion steps between AC and DC, but converters with a high voltage boost ratio will require a transformer, requiring conversion to AC and back.

As DC cables do not suffer from water-treeing degradation, higher voltages could be used without needing dry-insulation cables, while the current in a DC cable can use the entire surface area of the conductor, so the cable cost will increase linearly with current capacity rather than exponentially as with AC. Because of these factors, it could be possible to implement longer turbine strings much more cheaply with DC than with AC collection. However, this is difficult to quantify as there are no commercially available cables with the required configuration and voltage rating, and previous studies of the cable cost have extrapolated the cost for multi-core DC collection cables from the costs for single-core HVDC transmission cables with a significantly higher voltage rating.

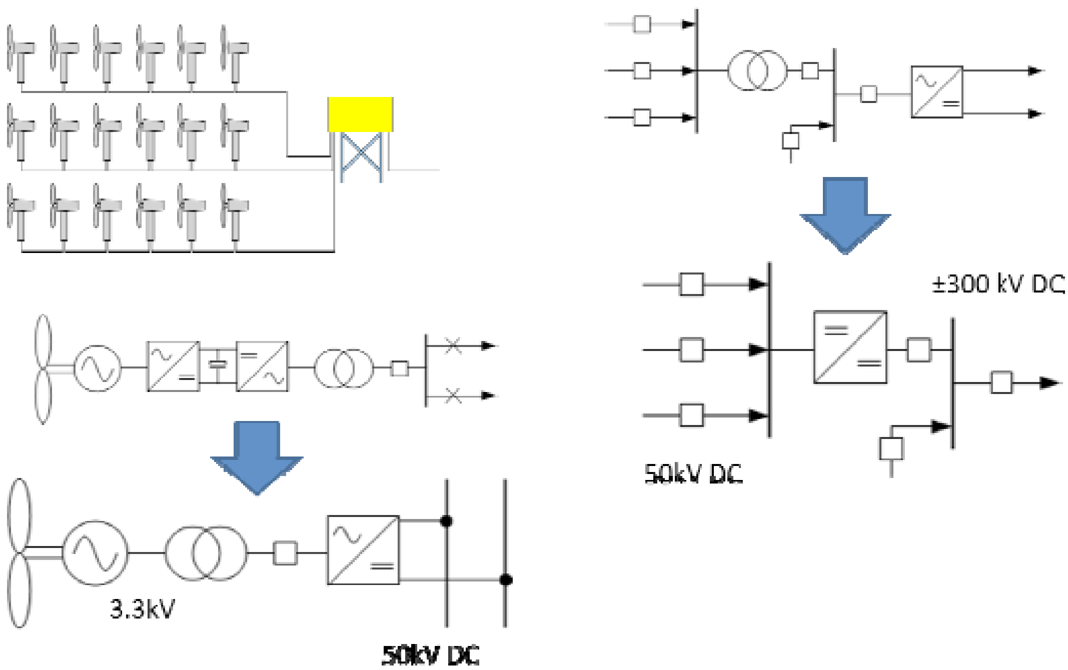

Figure 66. DC Strings Connection.

Another issue with DC collection networks is with fault protection, as the fact that the current does not continually reverse as with AC means that when a circuit breaker opens, the switching arc will not be automatically extinguished when the current reverses. Various DC circuit breaker designs have been proposed, but these become increasingly expensive at higher voltage ratings. DC collection and transmission networks have been designed which use power electronic converters, which are capable of stepping down the voltage as well as stepping up, and these can be used to limit the fault current, but at the cost of extra complexity.

DC Series
An alternative DC collection architecture is to use series DC connection of the turbines shown in Figure 67. Here the DC outputs of the turbines are connected in series, and the turbines connected in a loop. This allows the high collection voltage to be achieved without using high voltage converters, although the converter would need to be isolated with respect to ground. An isolation transformer would need to be used, or a generator capable of handling a high voltage offset. Another option is to use a transformer-isolated converter in the turbine, where the high-voltage side of the converter only consists of a passive diode rectifier, which is much easier to isolate.

This arrangement could reduce the cable costs, as it only uses a single core cable loop, although there is no scope to taper the current rating of the cable. In the event of a turbine fault, the faulty turbine could be bypassed using a mechanical switch, but any cable faults will mean that none of the turbines on the loop would be able to export power.

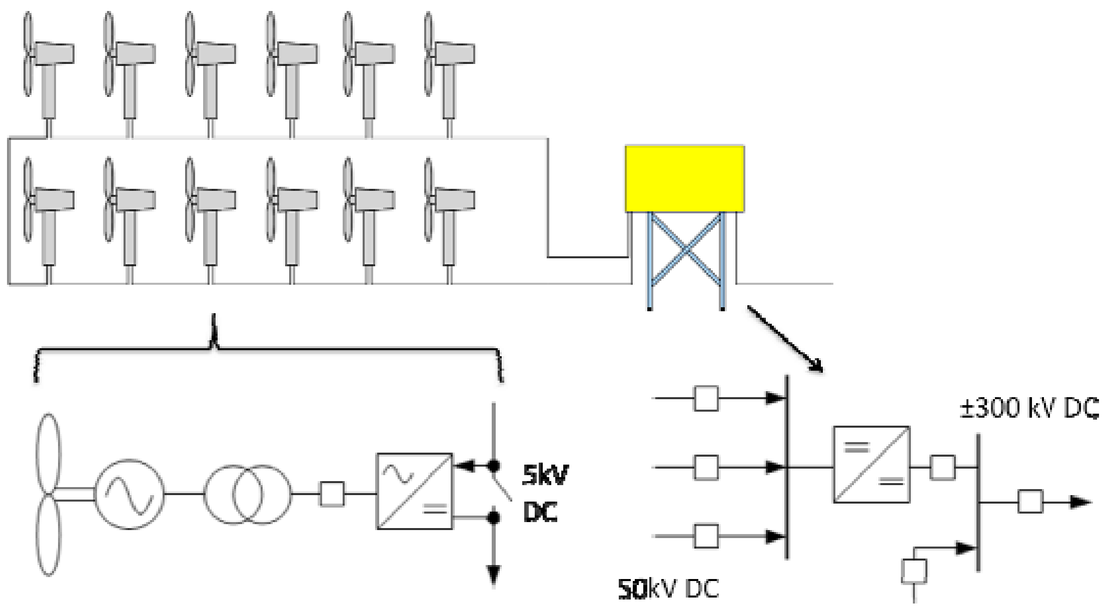

Figure 67. Series DC Connection.

A related idea is to increase the turbine output voltage and the length of the strings, so that the full transmission voltage is produced, eliminating the need for the collection platform. This system has been shown to have the lowest losses due to the high collection network voltage, and the lowest cost due to the elimination of the collection platform. Several strings could be used in parallel to increase fault tolerance. The disadvantage of this system is that the transformer and converter in the turbine must be capable of isolating the full transmission voltage, and high voltage transformers with a low enough power rating are not commercially available.

5.6.4.2 Converters on Platform

AC Cluster
Receiving significant amounts of interest recently is the idea of connecting turbines with fixed-speed induction generators to a variable-frequency AC collection grid, with strings of turbines being connected through a single converter. This places the converters on the collection platform, allowing them to be more easily repaired in the event of a fault, and a single large converter could potentially be cheaper than several small ones. An AC or DC collection system could be used within the collection platform as shown in Figure 68.

The speed of all the turbines in the string can be varied together to track the maximum power point for the current wind speed, but speed control over the individual turbines is lost. The speed of each turbine will be able to vary by a small amount relative to the others, due to the slip of the induction generator, with an increase in turbine speed leading to an increase in slip and an increase in torque. Depending on the number of turbines connected to each converter, this will result in a reduction in the amount of power extracted.

This system could also have an impact on the drive train loads experienced by the turbines, as a turbine experiencing a gust would not be able to speed up to absorb the excess power, leading to a high transient torque, putting strain on the drive train and blade roots. Research on the reliability of turbines in service has shown that the mode to variable speed turbines has reduced the level of blade failure compared with fixed-speed turbines.

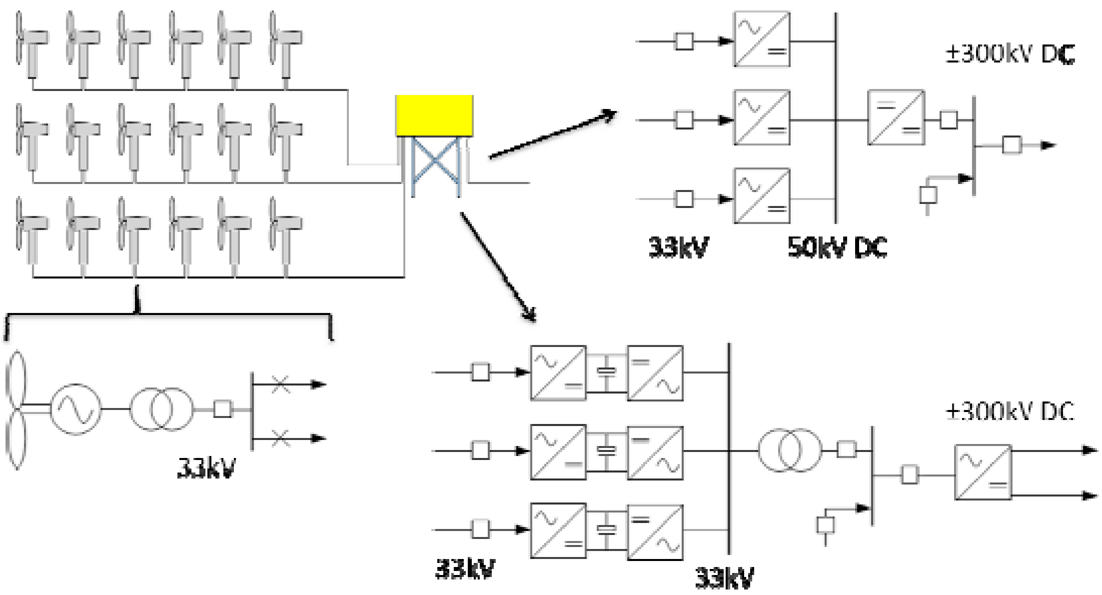

Figure 68. Cluster AC Connection.

Parallel DC Cluster
This method, shown in Figure 69, uses a permanent magnet generator and passive rectifier in the turbine, with a DC-DC converter for each string of turbines. The speed of the turbine will be determined by the DC

voltage of the string, so the system will behave in a similar way to the AC cluster connection system described previously, with similar issues of drive train torque transients during gusts. It is considered that the passive filter will have considerably greater reliability than an active converter.

For a given DC voltage, the amount of possible speed variation of the turbine will depend on the generator inductance, with a higher inductance giving a greater variation in speed. The passive rectifier is unable to supply the generator with reactive power, and if the generator inductance is too high then the maximum torque will be reduced. Inductance is typically much higher in low speed machines, used in direct-drive turbines, and in these cases capacitors can be used between the generator and rectifier to supply the reactive power requirements.

The main advantage of DC over AC clustering is the greater efficiency of the permanent-magnet generator, compared with the induction generator used in the AC system. The greater current and voltage capability of the DC cables could also lead to larger cluster sizes, and a reduction in cable cost, but this could also reduce the power capture. A DC system could also reduce the number of conversion steps, increasing efficiency.

Series DC Cluster
A variation of the parallel cluster arrangement is to connect the turbines in series, in a loop, with each loop controlled by a single converter, as shown in Figure 70. In this case, the converter will control the current within the loop, which will determine the generator torque within the turbine, and will be much more analogous to the conventional turbine control method. As the turbine speeds will be capable of varying individually, transient torque spikes should not be a problem, although this connection method has not been described in literature, so the exact performance is unknown. Speed limitation for the turbines will need to be achieved using pitch control.

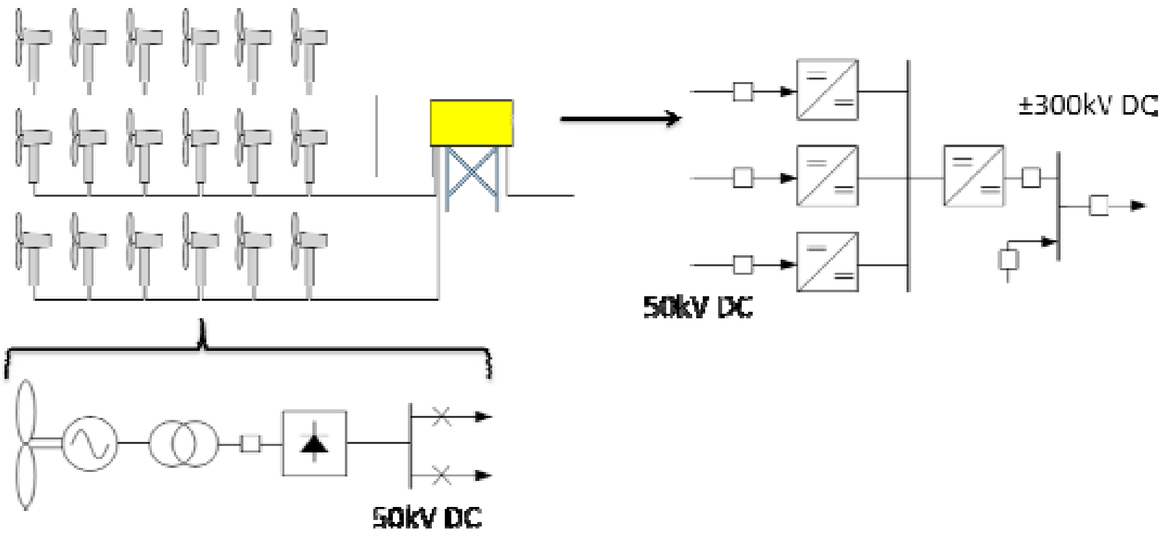

Figure 69. Parallel DC Cluster Collection.

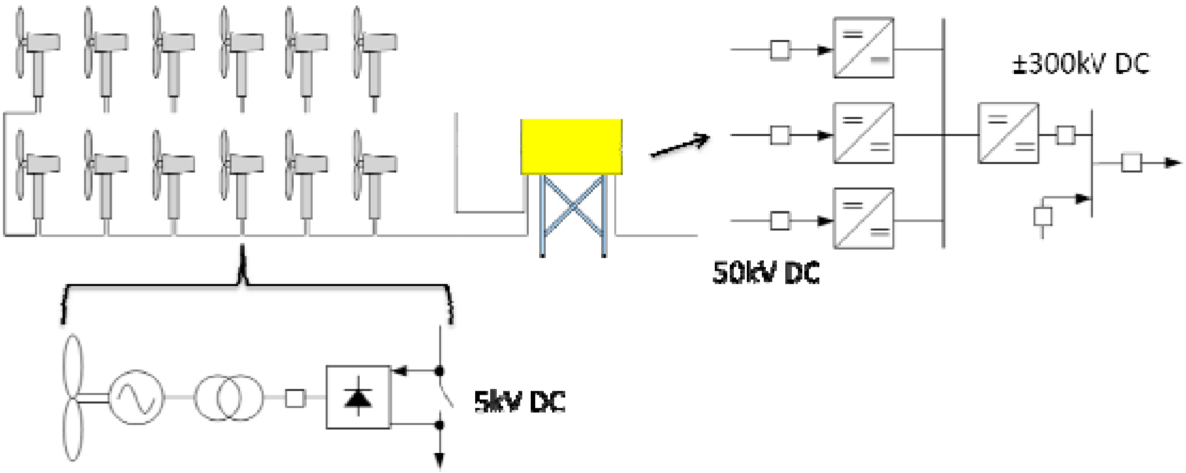

Figure 70. Series DC Cluster Connection.

5.6.5 VPP control approach

A Virtual Power Plant (VPP) mainly addresses the supply side. The basic idea is to connect numerous distributed and renewable power generating facilities via modern information and communication technology (ICT). A central control entity continuously monitors the generation data and can switch individual generators in and out of the system at any time. Thus, the facilities' operation can be scheduled and optimised. By connecting multiple distributed generators, almost the same controllability as with conventional plants can be achieved [175]. Two effects in VPPs contribute to the achievement of this objective: First, a well-chosen mix of volatile generators can offset their inherent unreliability to a certain extent. Following basic stochastic principles, the connection of different volatile systems with different fluctuation patterns may lead to a decreased overall volatility. It is clear that this logic is applicable to power generation from renewable energy sources including both wind and solar. The aggregated control of renewable energy sources executed by the VPP concept can be centralised or decentralised supported by logic control algorithms and communication infrastructure, which then as a whole is treated as a single large power plant [176].

VPPs can be divided into two categories according to the control topology:

1. Centralised VPP

In this category the distributed generation units are centrally controlled by a control coordination centre (CCC), which is located right in the centre of DG units. The loads signals are transmitted to the CCC, and processed by means of a logic algorithm. Then, the control signals are dispatched to each distributed generation controller (DGC), and then the active and reactive power is generated according to the CCC signals. With the CCC, it is possible to execute both technical and economic functions, in order to gain benefit of aggregating distributed generation.

2. Decentralised VPP

In the decentralised system topology, each DG unit is locally controlled by a local controller (LC). In particular, the active power output of the DG is controlled by a distributed generation controller (DGC), and the DGC is controlled by the local controller (LC) based on logic algorithms. To create an integrated system, the local controllers are connected/linked to each other forming a ring network architecture through communication to allow signals exchange, thereby coordinating and thus treated as a single control centre.

Some advantages of the VPP approach and aggregated control of distributed energy sources are:

- Scheduled power dispatch. The power output of distributed energy resources can be dispatch quite rapidly in response to changes in generation and demand conditions, facilitating frequency control.
- Load management. By proper aggregated control DG can be used to supply the load and reduce the demand on central generation as well as local transmission.
- Voltage regulation. Improved voltage regulation is possible by coordinating in the operation of various DG units in a VPP approach.

An ideal VPP has the ability to solve technical barriers (e.g. by maintaining grid stability via load management), commercial barriers (e.g. by providing economic efficiency by energy trading), and regulatory barriers (e.g. by allocating cost and benefits of power consumption and production to various players involved) [177].

6 CONCLUSIONS

Wind energy is an attractive generation technology in many regions where a reasonable wind resource exists, and many countries have committed themselves to substantial capacity investments. However, integration of large amounts of wind generation poses various challenges because the location of the best wind energy resources are often found in locations remote from demand and/or remote from existing conventional generators and Grid Supply Points. Further to the difficulties associated with power transmission over long distances (concerned with the provision of stability, reactive power compensation and voltage control), the connection of large wind farms, whether onshore or offshore, also presents particular questions regarding their ability to meet the connection requirements of present and emerging Grid Codes. Before long, penetration levels will reach levels where power systems will need to be operated differently to accommodate this new generation capacity. This report provided some insight on how the development of enhanced control systems can support the development of offshore wind farms by using a holistic analysis approach with the focus on overall system performance. The report also presented a summarised discussion of the various control challenges and possibilities for large-scale offshore wind farms. Some of the main points that can be concluded are as follow:

- Floating structures should be stabilised without compromising power production and power quality (minimum pitch activity is required, and added control features provided by power electronics should be explored). Tower bending modes become an even more delicate issue.
- Floating turbine performance and control requirements under power grid fault conditions has so far not been explored sufficiently.

- Improved coordinated control of individual wind turbines within the farm is required to minimise wake effects (whilst keeping electrical losses within acceptable technical and economic limits).
- Enhanced controllers are necessary to facilitate wind farm dynamic performance compatible with conventional synchronous plant (i.e. to provide support to power system operation in terms of dynamic voltage and frequency control.
- Holistic/integrated control approaches are imperative

SINTEF

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