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"Integrated Wind Turbine Design"

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Abstract: This document reviews electrical drive-train options for future wind turbines of sizes up to 10 MW, and the implications for compliance with Grid Code requirements.

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STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
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1. Preliminaries

This report forms one of a number of deliverables for the work Garrad Hassan is conducting for the UpWind project. It relates to the electrical aspects of wind turbine technology and how electrical system topologies may be developed such that machines with capacities of 8 to 10MW can be realised.

This report uses technical expressions and assumes the reader is generally familiar with electrical system terminology and basic wind turbine electrical arrangements.

2. Introduction

It is intended and possible that in the future wind turbines could be larger. The aim of this aspect of the UpWind project is to review existing wind turbine technologies and determine which electrical arrangement if any is most appropriately suited to further development, such that wind turbines with ratings in the region of 8 to 10MW may be realised.

The development of wind turbine technology has progressed from wind farms with wind turbines rated at 300kW in the early 1990's to wind farms today with turbines rated at 3MW. At the present time the highest known capacity machines installed are rated at 5MW.

With this rate of development over a period of approximately 15 years, it is conceivable that, in the future, wind turbines with much higher ratings will be available.

Wind turbines are getting larger. Their impact on electricity systems is becoming more perceptible and consequently with large quantities installed to form wind farms, it is important that their presence does not pose a threat to security or quality of supply. Indeed this requirement is laid down in what is (in the United Kingdom) referred to as the Security and Quality of Supply Standard (SQSS). To safeguard the SQSS, the network operator requires all large scale generators to satisfy the requirements of a set of rules called the Grid Code.

Different network operators of different countries or in some cases regions have written and established a grid code. Although most if not all are different, they are all generally aimed at achieving the same objective, that is a stable, safe and secure electricity network able to deliver constant electricity of a defined quality. Thus although with a differing emphasis on parameters, all generally have the same set of requirements.

In brief summary, it is important that however wind turbine technology is developed, it is done so with clear consideration of the requirements of grid codes around the world. Regardless of the technology it is a requirement that all power stations above a defined rating pay due consideration to these rules. Therefore it is clear that wind turbine electrical technology should be developed in a robust manner that is able to competently and confidently address the requirements of grid codes.

This report is intended as a review of the salient issues contained within the grid codes, how these issues are addressed and how wind turbines address them. In understanding how effectively various types of wind turbines address the various grid code requirements, it is anticipated that a path will emerge as to the most appropriate direction for the development of wind turbine technology for larger sizes.

This report excludes consideration of fixed-pitch stall-regulated wind turbine technology. This technology allows very robust and simple rotors and drive-trains. However it does not allow any control of the power produced by the wind turbine, and consequently cannot meet several of the most basic Grid Code requirements. Also, it appears that the concept loses out to pitch-regulated concepts at larger machine sizes, as the mechanical loads on the structures are higher.

3. Grid Code Requirements

The grid codes of most countries are generally aiming to achieve the same thing. Electricity networks are constructed and operated to serve a huge and diverse customer demographic. Electricity transmission and distribution systems serve, by way of example, the following types of user:-

- Large high-consumption industrial factories
- High-sensitivity loads requiring high quality and reliable uninterrupted supplies
- Supplies for (e.g. national) communications systems
- Farms
- Shops and offices
- Domestic dwellings
- (Large) Power stations

In simple terms it is vital that electricity supplies remain 'on'. To do this, the system operator not only balances the system with suitable levels of generation to meet the demand, but also requires larger capacity users of the system including both generation and load, to actively participate in ensuring system security.

To achieve this, the following technical requirements are possibly the most crucial and appear common across most European countries:-

1. Frequency and voltage tolerance
2. Fault Ride through
3. Reactive power and voltage control capability
4. Operating margin and frequency regulation
5. Power ramping

3.1 Frequency and voltage tolerance

The electrical behaviour of the network, in terms of frequency and voltage, due its dynamic nature is continuously changing. Generally these changes occur in very small quantities. It is a requirement that users of the transmission system are able to continue operating in a normal manner over a specified range of frequency and voltage conditions. With respect to frequency and for a 50Hz system this range would be in the range of 49Hz to 51Hz. With respect to voltage, this range could be +/- 10% of the nominal voltage.

However at times the ranges could be wider although it would normally be expected that the user would continue operating under an extreme condition for a defined period of time, for example 47Hz for 15 seconds or +20% of the nominal voltage for 1 hour. Beyond these extremities, the user would normally be required to disconnect from the system.

The table below shows a common range of conditions that a user would be required to operate within:-

	Normal	Continuous operation required	Very Short Term
Frequency	49 to 51Hz	47.5 to 49Hz & 51 to 52Hz	47 to 47.5Hz
Voltage	+/- 5%	+/- 10%	-

Table 1: Example of possible frequency & voltage tolerance requirements

3.2 Fault ride-through

If a defined fault occurs on the transmission system, it is normally a requirement of the transmission system operator that a generating station remains operating and connected to the system; thus it "rides through" the fault. The definition of the fault is derived from the response time of the network protection systems to clear the fault. A normal duration to clear a fault is in the region of 140ms hence the requirement of the user will be to ride through a fault which has a most severe depression in voltage of 140ms in duration.

The figure below, taken from the E.ON grid code of Germany [1] shows the voltage profile within which a user is required to remain connected. That is, so long as the voltage profile as seen at the high voltage terminals of an installation (or alternatively at the nearest point on the transmission system) follows or is above the profile, the installation must remain operating and connected.

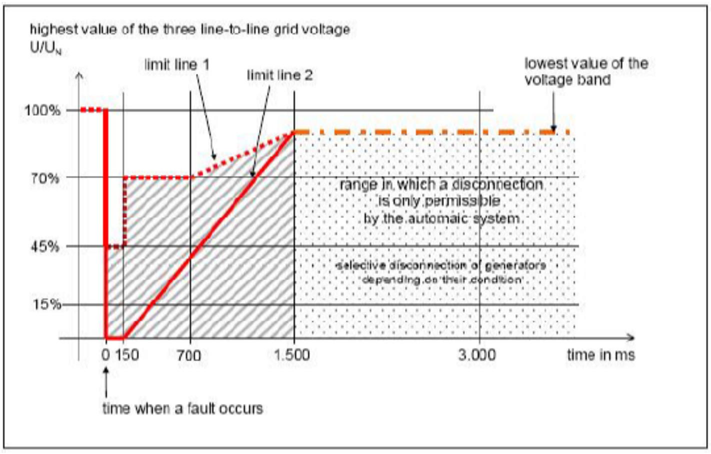

Figure 1: Example of a fault ride-through profile (E.ON Netz)

3.3 Reactive power and voltage control capability

Power factor control

Reactive power is the product of voltage and out-of-phase components of alternating current [2]. To minimise losses and thus maintain high levels of efficiency, generally it is a preference that networks are operated with voltage and current operating in-phase - the power factor is unity. However, users of electricity systems often tend to have inductive loads or generation facilities that operate such that voltage and current are out-of-phase. In addition, power system components including lines and transformers for example, produce or consume large levels of reactive power. From the network user's perspective (looking from the installation towards the network) an inductive load/generation facility is said to have a leading power factor because the current leads the voltage. Put another way the user is consuming reactive power.

As the behaviour of the network is continuously changing, users are required to have the ability to adjust their reactive power production or consumption, in order that reactive power production and consumption is balanced over the entire network. In most cases it is the generators who provide this control ability. The range could be for example from 0.95 leading to 0.95 lagging.

Voltage support

A generating station may be required to operate over a range of power factor to provide or consume reactive power as discussed and shown above. Alternatively the installation may be required to operate in voltage control mode, i.e. to adjust its reactive power production or consumption in order to control voltage on the local network.

If the network voltage reduces beyond the limit of a pre-defined range, it may be a requirement of an installation to supply reactive power to the network to raise the voltage. Conversely if the network voltage increases to a level above a pre-defined upper limit then the installation would be required to consume reactive power to bring the voltage back within acceptable limits.

3.4 Operating margin & frequency regulation

The operating margin and frequency regulation are the capability of an installation to operate at a margin below its rated power output so that it may respond to significant changes in frequency by increasing or decreasing its output. A response requirement diagram taken from the technical regulations applicable to wind farms in Denmark [4] is shown in Figure 2 below:-

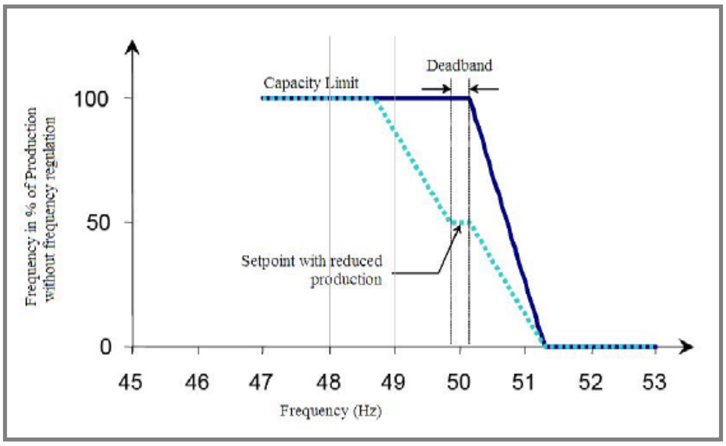

Figure 2: Frequency response characteristic (Energinet.dk)

As shown in the figure above and if frequency regulation is a service that a generator provides, the generator is required to operate at a level below its current capability for a frequency around 50Hz. The installation is required to respond to an increase in frequency by reducing its output, and to a decrease in frequency by increasing its output.

3.5 Power control

Some network operators impose limits on power output. This could be during normal continuous operation and/or during ramping up to an increased output or ramping down to a decreased output.

This requirement might be necessary in the first case to limit output because of limitations in the capabilities of other generators or the transmission or distribution networks. In the latter case this might be necessary so that network control systems and other generators have time to respond to a new operating state.

When a generator comes on-line it is providing the network with an increased amount of power which not only affects frequency, but also requires existing operating installations to adjust their operational characteristics to adapt to the ‘new’ operating state.

With respect to wind power, it is to be noted that for decreasing wind speed conditions there are limitations in the capabilities of wind turbines. If the wind speed is falling a wind turbine may not be able to maintain its output or fully control the rate of decrease of output. However, wind speed profiles can be predicted and so if a controlled ramp down or clearly defined power reduction rate is required, a wind turbine’s output can be reduced early, thus reducing the maximum rate of change of output power.

4. Conventional Generation

This section indicates the ways in which grid code requirements are addressed. Different generating plant responds in different ways to the requirements of grid codes. It is important to note that the focus of this section is on the overall objective of the individual requirements.

4.1 Frequency & voltage tolerance

As load on electricity networks under steady state or dynamic conditions are in a state of general continual change, the voltage and the frequency (to a lesser extent) are also continuously changing. Normally the frequency and voltage are held at nominal values. However, at times the voltage and frequency may deviate from nominal values outside of a target bandwidth. Therefore, the network operator requires users of the system to be capable of tolerating and/or responding to excessive frequencies and voltages. This section relates to the ability of generating plant to tolerate excessive voltages and frequencies.

At the extremities of the operating ranges machines are likely to be stressed [5]. This can be an acceptable situation so long as the period of stress is for a short duration. The effects of operating directly connected plant at excessive voltage and frequency ranges is to cause generator and transformer core laminations to overheat – resulting in eventual failure. Life expectancy of insulation is also reduced. The potential for these problems to occur is addressed at the design stage and thus machines are, to a reasonable extent, designed to absorb some level of deviation in voltage and frequency.

4.2 Fault ride through

Conventional generation installations utilising synchronous generators are well able to respond in a beneficial way to network disturbances. They are fitted with exciters and voltage control facilities that respond in the event of a network disturbance by attempting to sustain the voltage at the generation terminals to as close to pre-fault voltages as possible. Furthermore, energy is also stored in the magnetic fields of the rotating machine although this is mostly in the rotor [6].

Synchronous generators are therefore able to supply large levels of reactive power to the network for sustained periods, exactly when the network requires it. Thus the network voltage is supported to a relatively high level and thus the depth of the voltage dip caused by the disturbance is not so severe.

4.3 Reactive power

The requirement for reactive power can be divided into two issues. Firstly, it is important that network operators run an efficient, low loss transmission system. This can be addressed to a certain degree by transporting as much real power as possible whilst minimising the level of reactive power. Thus the network operator requires large network users to operate at a specified power factor. Secondly, during some network conditions, the voltage may be approaching or exceeding defined limits. In such cases, power factor becomes less important and bringing the network voltage back within limits becomes a priority. One way of achieving this is to make use of the reactive power capabilities of load and/or generating station installations. The supply or consumption of reactive power will respectively, raise or reduce network voltages.

Essentially, reactive power service provision is physically addressed through inductive and capacitive plant. Asynchronous generating plant may utilise the inherent inductive characteristics of the generator for reactive power consumption and add banks of capacitors for reactive power supply. In the case of synchronous generating plant, reactive power can be supplied or consumed through the over or under-excitation of the rotor windings.

4.4 Operating margin and frequency regulation

Generally, the network frequency remains consistent at or close to the nominal frequency (50Hz in the case of the European Grid). However, it is possible that this frequency could deviate either up or down. Much deviation either side of the nominal frequency is undesirable and generally a consequence of a load and generation mismatch. Therefore when the frequency is falling the network requires either more generation or less load and conversely when the frequency is rising, the network requires less generation or more load.

There can be a number of stages of frequency response – primary, secondary and tertiary, though terminology is not standardised across all system operators. Primary response times are in the region of seconds, required to be available for approximately 30 seconds and are generally the domain of fast acting generating stations. Secondary response plant is expected to take over from primary response plant and so would be required to be operational at around 30 seconds and available for e.g. 10 minutes. Tertiary or Contingency reserve would not necessarily need to be synchronised with the system, but would be expected to respond within, say 5 minutes and continue operation for approximately 24 hours.

So, it is a requirement of the network operator that generating stations are either operated at a level or 'margin' below their rated output, so that there is spare capacity available to respond in the event of a decreasing network frequency, or on standby (i.e. not generating but available to start) ready to respond to a drop in frequency.

'De-loading' a machine during its normal operation allows a certain level of margin to be called upon if required. Keeping an installation on stand-by allows a reserve to be called upon if required.

4.5 Power control

Power control refers to the control of real power and to what level generating stations can restrict and control their rate of change of output power.

More conventional generation achieves this control over electrical output power as in general there is a reserve of the primary energy source. With reserves available, the fuel input to the generating station can be controlled and in the case of thermal plant, steam stored in the boilers provides significant readily-controllable energy storage.

5. Wind Turbines

This part of the document focuses on wind turbine technology, provides information on the status of present commercially available wind turbines, and explains how wind turbine technology in general addresses the requirements of network operators, including grid code compliance.

5.1 Present commercial concepts

Some examples of large-scale, commercially available and near-commercially available wind turbine concepts are listed in Table 2 to illustrate the range of options currently available.

	Manufacturer	Transmission	Generator	Converter	Capacity (MW)	Country
1	Clipper	2 stage gearbox, 4 x output shafts	4 x PM Synch	FC	2.5	USA
2	DeWind D8.2	G +Voith Windrive	PM Synch	None – direct 4kV or 13.8kV conn to grid	2.0	DE/UK
3	Enercon	DD	Multi-pole synch			NL
4	Gamesa	G	DFIG	FC	4.5	DK
5	Gamesa	G	DFIG	PC	2.0	ES
6	Harakosan	DD	PM Synch	FC	2.0	JP
7	Leitner AG	DD	PM Synch	FC	1.2/1.35/1.5	IT
8	MADE	G	4 pole Synch	FC, Diodes/IGCT	2.0	ES
9	Mitsubishi	G	FSIG	None.	1.0	JP
10	Moncada	DD	PM Synch	FC	0.75	IT
11	MTorres	DD	Multi-pole synch	FC, IGBT	1.5	ES
12	Multibrid	G	PM Synch	FC	5.0	DE
13	Nordex	G	DFIG	PC	2.5	DK/DE
14	REpower	G	DFIG	PC	5.0	DE
15	Siemens	G	IG	FC	3.6	DE/DK
16	Suzlon	G	IG, Slip rings/ Resistors (‘Flexislip’)	None	<=2.0	DK/IND
17	Vensys	DD	PM Synch with external rotor	FC, Diodes/IGBT	1.2/1.5	DE
18	Vestas	G	DFIG	PC		DK
19	Vestas	G	Opti-slip	None	1.8	DK
20	Windtec / AMSC	G (Hydraulic)	Synch	None – Direct 11kV conn to grid	2.0	DE/USA
21	Winwind	G	PM Synch	FC	Up to 3MW	FIN

Table 2: WTG Manufacturers & electrical arrangements

Key: G = Gearbox, DD = Direct Drive (No Gearbox), PM = Permanent Magnet, Sync = Synchronous Generator, DFIG = Double Fed Induction Generator, FSIG = Fixed Speed Induction Generator, FC = Full Converter, PC = Partial Converter (Converter accommodates fraction of rated power), IGCT = Insulated Gate Commutated Thyristor, IGBT = Insulated Gate Bipolar Transistor

5.2 Drive train topologies

A number of machine topologies exist and have been tried with varying degrees of commercial success. Although the options and intricacies are extensive (and discussed in more detail in Section 6), the arrangements of electrical topologies may generally fall into the following categories:-

- Fixed Speed Induction Generator (FSIG)
- Variable Slip Induction Generator (VSIG)
- Double Fed Induction Generator (DFIG)
- Variable Ratio Transmission (VRT)
- Full Converter connected generator (FC)

FSIG: The FSIG concept does not allow the wind turbine rotor to operate at variable speed, which results in large mechanical loads on the drive train and other parts of the wind turbine. This is the main reason that the FSIG concept is losing preference amongst developers, especially at large sizes.

VSIG: The variable slip technology is almost an interim design between the standard FSIG design and the more recent DFIG design. Simplistically, the generator rotor circuit is wound with the ends being connected to adjustable resistors. With resistors connected to the generator rotor a small amount of excess slip is possible because the resistors are able to absorb power delivered by wind gusting. This allows a small amount of speed variation, and because of the significant inertia in the wind turbine rotor this is sufficient to reduce the mechanical loads on blades, gearbox and structure **[7]**.

DFIG: From the list, the most prevalent and largest machines being installed today are probably the double fed induction generator. The DFIG arrangement is (at the moment) perhaps the most commonly installed wind turbine, as it allows a relatively wide range of variable-speed operation through the use of a relatively small power electronic converter connected to the generator rotor circuit via slip rings.

VRT: The Variable Ratio Transmission, directly connected synchronous (or asynchronous) generator is an old concept for wind turbines. Many ways of achieving this have been proposed in the past, but have not been widely adopted. Although it is not known whether there is an installed operational machine, it is known that DeWind **[8]** and Windtec **[9]** have developed a variable speed gearbox connected to the shaft of a synchronous generator. Given a variable rotor input speed, the output to the synchronous generator is held constant. In other words, variable-speed operation is achieved mechanically, without using power electronic converters. This saves considerable cost, space and electrical losses. In addition, the generator can also be operated at relatively higher voltages (~11kV) as there is no limit imposed by voltage limits of the power electronic converter. Therefore the wind turbine may be connected directly (without WTG transformer) to the wind farm electrical system or regional distribution network.

FC: The full converter connected machine is, as its name suggests, connected to the external electrical system or the grid by means of a power electronics converter. The converter is sized to accommodate the full rating of the generator because the full power of the generator is passed through it. Although a full power electronics converter is utilised, the generator may take on several forms. The following list outlines the types of drive-trains possible:-

- direct drive (i.e. low-speed generator without a gearbox), wound rotor or permanent magnet synchronous generator
- one or two-stage gearbox, medium speed wound rotor or permanent magnet synchronous generator
- gearbox with large ratio, high speed asynchronous or synchronous generator

The direct drive concept utilises a multi-pole large-diameter synchronous generator arrangement and does not include a gearbox. It may derive its rotor excitation from either permanent magnets or electrical excitation **[11]**. Variable-speed operation is essential with this concept, and this is only possible with a full converter, i.e. all the generator power passes through the converter. The converter is therefore significantly larger and more expensive than for the DFIG.

The medium speed concept utilises, in the case of Clipper Windpower, an innovative 2 stage gearbox “Quantum Drivetrain” with 4 x 660kW synchronous permanent magnet generators with 4 x power electronics converters **[10]**. Other medium-speed concepts exist with a more conventional arrangement using a single generator.

The high speed concept may use a 4 or 6 pole asynchronous or synchronous generator arrangement and is a relatively new arrangement in terms of wind turbine drive trains. It is connected through a gearbox to a full power electronics converter. This is becoming possible because of the reducing cost of power electronic devices.

5.3 Machine capabilities

This section refers to the requirements network operators place on large scale wind turbine technology and examines specific design solutions various machine manufacturers have adopted to meet the requirements of grid codes. The manufacturers of wind turbines have employed sometimes minimal, sometimes significant differences in their designs. The following is a discussion on both the key network issues applicable to wind turbine technology, and the manner in which wind technology has addressed these issues.

As the behaviour of standard FSIG, DFIG and FC machines is well understood and documented, these machines shall form the focus of this section. However, with an increasing level of industry understanding of alternative topologies of machine, general comments and views with respect to the newer machines/concepts shall also be provided.

5.3.1 Frequency & voltage tolerance

All machines are able to operate satisfactorily over a certain range in terms of both frequency and voltage. For voltage a range of between 90 and 110% of the nominal value is usually considered acceptable without significant adverse effect. With reference to the likely ranges of frequency, it is expected that all machines should be able to operate satisfactorily within the range of (approximately) 47Hz to 52Hz without adverse effect. At the extremities of the range operation should be possible so long as the durations are short – which is as would be expected.

The consequences of operating machines at excessive levels of frequency or voltage are likely to be: heat generated within components, shortened life, and reduced reliability. Heat can be tolerated for short periods of time and even managed through forced cooling. However, the tertiary consequence is that of reduced life of components.

Most of the configurations described below also contain a transformer, to step up from generator voltage to some higher voltage for the wind farm electrical system. The transformer will also experience the frequency and voltage ranges. However this is covered by transformer design standards. In this context, it is not important for comparison of competing drive train configurations.

5.3.1.1 FSIG machine

The fixed speed asynchronous generator with power factor correction equipment and transformer may suffer as a result of the implied higher rotational speeds **[12]**. In general, so long as the durations of extreme operation are short, this should not be a problem.

5.3.1.2 DFIG machine

The asynchronous generator, power converter and transformer will be subject to the excess frequency and voltage range. As with the FSIG machine above, the stator winding of the machine is also exposed to the grid and its potentially wide ranging frequency and voltage variations and so again, so long as the durations of extreme operation are short, this should not be a problem.

5.3.1.3 FC machine

The grid side of the converter and the transformer would be subjected to the potential excess voltage and frequency conditions on the network. The converter is expected to continue operating when exposed to a very wide range of potential frequency or voltage conditions. As the converter decouples the generator from the grid, there should be no impact on the generator.

5.3.1.4 Alternative topologies

Although the VRT concept machine is projected to be quite capable of operating over a range of network frequencies, the direct connection of the electrical generator to the electricity system may, as with the FSIG machine, suffer as a result of possible higher rotational speeds at the extremities of the frequency range. No significant issues are envisaged regarding the ranges of possible voltages.

5.3.1.5 Conclusion

Wide frequency and voltage ranges can be accommodated by all configurations, to achieve the same levels of reliability. Some are less affected than others. If adequately designed, this will show as a cost advantage for some configurations, but the effect is expected to be relatively minor.

5.3.2 Fault ride through

The aim of 'fault ride-through' (FRT) requirements has been explained above. Different machines respond to faults in different ways.

5.3.2.1 FSIG machine

In their standard format with simple power factor correction capacitors, fixed speed induction generator based wind turbines find it very difficult if not impossible to ride through severe network faults which bring about a severe network voltage depression. However, the addition of a sufficient level of equipment can aid the ability of the machine to ride through a severe network fault.

If we assume that at the instant of the fault, the voltage at the fault location is reduced significantly (towards zero), the FSIG machine initially responds by delivering a high peak current. This can be a good thing as it aids the operation of protection systems. Next, as the electrical energy is restricted from entering the network by the reduced voltage, the surplus energy from the wind causes an acceleration of the wind turbine rotor. When the network voltage is restored at the end of the fault, there is a mismatch between the wind turbine speed and the network frequency, causing large levels of reactive current to be drawn from the network, with the effect of further reducing the network voltage.

To counteract this situation, it is understood that suppliers of FSIG machines destined for sites where network support during faults is required provide dynamic fast acting compensation in the form of a Flexible AC Transmission System (FACTS). More specifically, this is likely to be a form of Static VAr Compensator (SVC) or similar, sized in consideration of the rating of the WTG and connected to the LV terminals of each machine. Alternatively a single device may be connected at the network connection point for the wind farm.

The SVC, in this application would generally comprise of a bank of capacitors, switched on/off by means of fast acting (< 20ms) electronic switching **[13]**. Detuning reactors are installed in series with the capacitors to mitigate resonance issues. So, upon detection of the fault the SVC is able to respond extremely quickly by supplying reactive power to the network to support the voltage. Additionally with this arrangement the FSIG induction generator draws its reactive current from the SVC, rather than from the network.

As noted above, the wind turbine may accelerate rapidly during the fault, and therefore requires to be decelerated again after the fault. Large power flows and torques may occur. For a prolonged or deep voltage dip, it may only be possible to keep the turbine stably connected by ensuring that the control of aerodynamic torque through the blade pitch control system is very rapid (so-called 'fast pitching'). This is not cheap or easy to achieve, and may also result in large mechanical loads on the wind turbine structure, adding further to cost.

5.3.2.2 DFIG machine

The DFIG machine in its standard format is unable to remain connected to the network during severe network disturbances. During a severe network disturbance, a large current peak is delivered by the generator. To protect the rotor-side converter from the large currents generated by the rotor circuit, a 'crowbar' operates upon occurrence of a fault. This not only separates the rotor from the converter, but also short circuits the rotor windings **[6, 14]**. During this period, the machine accelerates and draws high levels of reactive current from the network which further exacerbates the grid voltage disturbance.

Only with enhanced equipment is a DFIG based wind turbine able to ride through a severe network fault. This equipment in general is required to address three main issues:-

1. the very high level of current from the machine at the instant of the fault

2. the supply of reactive power to the network to support the voltage
3. relief of the excess energy contained within the wind turbine rotor

Most wind turbine manufacturers have developed their technology to achieve fault ride through capability and supply a form of ‘grid friendly’ package.

There are a number of producers of large scale DFIG machines and a number of solutions have emerged to address the fault ride through issue. Generally the approach is to up-rate the rotor side converter, connect a chopper/resistor circuit to the DC bus and also modify the control system to initiate a fast pitching scheme for the wind turbine rotor blades [19], [20].

Note that the fast-pitching problem is not as severe as for the FSIG concept, as a wider rotational speed range is acceptable.

This is understood in general to be the way most manufacturers of DFIG based wind turbines have dealt with this issue. There are other variations upon this theme which include partial disconnection of the stator circuit using thyristors or a circuit breaker [5, 4].

5.3.2.3 FC machine

Only the full power converter is exposed to the grid in the case of the full converter connected wind turbine generator. During a network fault, although the voltage is reduced, the grid side converter within the wind turbine can deliver (a restricted level of) real and reactive power **[15]**. Furthermore, upon fault clearance and during network voltage restoration, the full converter connected machine is able to support the network voltage by supplying reactive power.

During the network disturbance, the generator side converter continues to allow current to pass through it to the d.c. link **[16]**. This charges the d.c. link capacitor and thus the d.c. link voltage rises. Should the d.c. link voltage increase to excessive levels, the converter will ‘block’ which is in effect disconnection from the network. To alleviate an excess voltage condition on the d.c. bus a chopper/resistor circuit is switched in to consume any excess power.

Whereas significant modifications are required to other technologies to aid the ability to ride through network faults, minimal adaptation is required of the full converter connected wind turbine.

So long as there is energy production from the generator, the converter is able to pass through real and reactive power to the network and thus not trip off and furthermore provide the network with reactive power for voltage support both during and following clearance of the fault.

The wind turbine is still likely to accelerate during the fault, and so some form of fast pitch control is necessary, but this is not as demanding as in the FSIG case.

5.3.2.4 Alternative topologies

It is understood that the VRT concept machines currently of interest utilise synchronous generators. Consequently these machines are unlike the FSIG and DFIG machines in their requirement for reactive current. If the machines are to continue operating, there will be a need to deal with the momentary excess energy being delivered to the network and it may be that the variable ratio transmission system is able to deal with this transient condition. Also, it is expected that a fast pitching mechanism will deal with any possible rotor over-speed, similar to the DFIG or FC concepts.

With regard to the voltage support, and as mentioned previously in section 4.2 relating to the more conventional form of power station generator, the synchronous generator will attempt to sustain the voltage at the generation terminals to as close to pre-fault voltages as possible.

5.3.2.5 Conclusion

Without additional equipment, FSIG based wind turbines are not ideally suited to provide fault ride through capability. However with additional equipment, full fault ride through and network support can be achieved. There are severe demands on the pitch system, which will translate into higher cost.

The DFIG machine with enhanced power electronics equipment and a modified control strategy is able to ride through faults.

Without any significant change in its design, the full converter connected machine including the alternative topology is able to ride through and support the network voltage during and after network faults.

Reservations are held with respect to the VRT concepts. However further work may show these can meet the requirements adequately.

5.3.3 Reactive power

As discussed previously, the issue of reactive power when applied to generating plant can be considered with two aspects. Either the reactive power is used to improve the network and/or the generating station power factor, or reactive power is used to regulate the network voltage when it is either too high or too low. In general, normal operation is likely to be in power factor control mode unless the voltage level approaches the limits of acceptability.

Older fixed speed induction generator (FSIG) based wind turbines that utilise asynchronous machines would without power factor correction and depending on characteristics, operate with a power factor somewhere in the region of 0.89 leading (importing reactive power). Normally this is improved, through the installation of power factor correction capacitors. For simple power factor improvement it is normally improved to close to 1.0.

Although this could be classified as a primitive form of power factor or voltage control, modern wind turbines have developed so that they are able to operate in power factor control or voltage support mode. In power factor control mode they are able to operate with relatively high accuracy over a wide range of power factor from, for example 0.9 inductive through unity to 0.9 capacitive. In voltage support mode they utilise the reactive power capabilities of the machine to supply or consumer reactive power to elevate or reduce the network voltage.

5.3.3.1 FSIG machine

Typically a 1.3MW wind turbine with a controlled approach to power factor correction would utilise capacitor banks with denominations of reactive power values of 45kVAr x 1, 90kVAr x 1, 180kVAr x 4. Using these sizes, the wind turbine is able, using different combinations, to supply 855kVAr of reactive power with a resolution of 45kVAr.

Power factor control
Most if not all modern large scale FSIG wind turbines have the ability to operate in power factor control mode. Rather than, in the past, where capacitors were installed to improve the power factor to unity, modern wind turbines are installed with smaller banks of capacitors to not only improve the power factor from, for example, 0.89 inductive to say unity, but to have the ability to operate from say 0.9 inductive, in high resolution stages up to unity and on to 0.9 capacitive.

Voltage support
In addition to the above power factor control mode, modern FSIG wind turbines are also able to operate in voltage control mode. The mode is changed by means of either the wind farm or wind turbine supervisory control and data acquisition system (SCADA). The network conditions are monitored at the point of supply or metering point and if, in this case, the voltage deviates beyond acceptable limits, the SCADA system would relay signals to the wind turbines to respond accordingly.

Therefore, in the case of a low voltage at the point of supply, the wind turbine would switch banks of capacitors in circuit so that reactive power is supplied to the network and attempts are made to raise the network voltage.

Aside from the above, if an FSIG based wind turbine installation is called upon to provide FRT then the equipment used to provide FRT is well suited to providing ‘fine’ control of power factor.

5.3.3.2 DFIG machine

The DFIG wind turbine makes use of the converter with the wound-rotor, induction generator to consume or supply reactive power. The rotor circuit is under or overexcited to provide or consume reactive power.

This makes the DFIG based wind turbine with rotor circuit connected power converter very good at providing or consuming reactive power. Additionally if a larger rated converter is installed (for FRT purposes), a wider range of power factor can be achieved down to a lower level of generation. Furthermore, owing to the power electronic switching technology a ‘fine’ control over power factor is possible.

5.3.3.3 FC machine

A full converter connected machine utilising a voltage source converter is able to provide or consume reactive power because the grid side converter can reconstruct the voltage and current waveforms such that the current can be either leading or lagging the voltage waveform. This ability is independent of the generator side converter **[17]**. As the converter forms a complete interface between the generator and the grid, the power electronic switching technology is inherently able to ‘synthesize’ a wide or narrow displacement of voltage and current waveform, be it current leading or lagging the voltage waveform.

Consequently the Full Converter connected wind turbine is very good at operating over a wide range of power factor and providing network voltage control by the provision or consumption of reactive power.

5.3.3.4 Alternative topologies

It is assumed that the synchronous machines with variable ratio transmission systems will consume or provide reactive power through the under or over-excitation of the rotor windings. If this is insufficient, then additional reactors or capacitors may be required. In whatever way the requirement is satisfied, no particular problems are expected.

5.3.3.5 Conclusion

All concepts can meet requirements for adjustable power factor and control of voltage. The FC and VRT concepts provide this at virtually no additional cost. This also applies to the DFIG concept unless a particularly wide range is required. The FSIG concept can only meet the requirements at additional cost.

5.3.4 Operating margin and frequency regulation

Wind turbines may operate with a margin below full output by de-loading. A way of achieving this is to pitch the rotor blades so that the maximum available energy is not extracted from the wind.

If the wind turbine is called upon to increase its real power output following a reduction in frequency, which is outside a range associated with a nominal value, the wind turbine can ‘pitch’ its blades into the optimum ‘lift’ position so that increased energy may be captured.

Similarly, a wind turbine may respond to an increasing system frequency by pitching or ‘feathering’ its’ blades out of the wind in a direction so that less energy is extracted.

This is not the case with fixed pitch stall regulated technology which is unable to influence a wide ranging control over its output. This is discussed further below.

5.3.4.1 FSIG machine

Early fixed speed wind turbines with fixed pitch rotor blades were set up for optimum wind energy extraction in accordance with the local wind regime. The aerodynamic power extraction then depends only on the wind speed, and cannot be adjusted to provide any operating margin for frequency regulation.

With variable pitch rotor blades it is possible in principle to operate a fixed speed wind turbine to provide frequency regulation by pitching the blades. This could provide a reserve margin of power when averaged over a few seconds. However GH is not aware of a manufacturer that provides this facility **[12]**.

5.3.4.2 DFIG machine

Variable speed wind turbines utilising a DFIG with converter technology are able to operate at an optimum level to extract high levels of energy from a wide range of wind conditions. In addition to control of the blade pitch angle, they are also capable of rapid control of the generator torque, and hence the active power output, which means that a reserve power margin suitable for frequency regulation is straightforward to achieve, and can be adjusted with a fast response if necessary.

5.3.4.3 FC machine

The FC connected wind turbine is able to exercise a similar degree of control over the pitch angle and generator torque to the DFIG machine, and is therefore equally capable of providing frequency response, with a fast response if necessary.

5.3.4.4 Alternative topologies

It is assumed that the VRT machine through its ability to control the torque has the ability, if required, to control the torque to the generator to a level below the available rated level. It is also assumed that this torque level can be varied on a real time basis so that the machine may be operated to respond to increasing and decreasing changes in network frequency. This being the case, it is envisaged that the VRT machine with blade pitch regulation should also be capable of providing operating margin and frequency support services.

5.3.4.5 Conclusion

All the concepts under consideration use pitch regulation, and therefore in principle can be operated to meet the requirements of frequency regulation. With the ability to utilise the energy stored in the wind turbine rotor, the variable-speed concepts will be able to meet these requirements more readily than the FSIG machine.

5.3.5 Power control

Power control requirements specified in grid code documents generally relate to the rate at which generation schemes are required to control their real power output. This could be during normal operation or when ramping their power up or down. Rates are normally specified in MW per minute **[18]** or per hour and rates of e.g. 10% of output per minute and 4 times the installed capacity per hour are normal. In Ireland for example the Grid Code specifies that a grid code compliant wind farm installation should be able to vary its ramp rate over the range of 1MW to 30MW per minute [3].

So long as the (wind) resource is available, modern large scale wind turbine technology is readily able to control the positive ramp-up rate of its output. The situation with respect to negative ramp rates or ramp-down is not so straight-forward. At high wind speeds, wind turbines need to be protected from high loading and so will automatically shut-down. The shut-down is usually fairly rapid – however the desirability of shutting down more slowly is increasingly being recognised, and there is little technical reason why this cannot be done: this is a topic to be investigated later in the project. However, if the wind speed drops quickly, the output may drop more rapidly than desired. Improved wind forecasting for wind farm sites can help in both of these situations, as the output of the wind turbines can be reduced at an acceptable rate in advance of the event.

Note that the requirements are stated over timescales of minutes or longer: therefore fast and accurate control is not required.

All pitch-controlled wind turbine concepts are in principle able to achieve these requirements, given suitable communications capabilities. The variable-speed concepts will be able to achieve the requirements more easily than the FSIG.

6. Future grid code requirements

6.1 Introduction

As wind penetration increases in electricity systems, it is likely that new issues will emerge which have not yet been considered. These are likely to emerge as the capacity of conventional generation reduces, taking with it certain characteristics that are inherent in large fixed-speed generators. These characteristics will then have to be provided by the wind generation.

It is not possible to accurately predict what may emerge, but two possible requirements have been discussed.

6.2 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 FC 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 requirement 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.

It is concluded that an inertia effect is available in principle, but may have implications for wind turbine design and cost. It is not clear if some of the VRT concepts may provide the necessary control.

6.3 Power system stabiliser function

Power system stabiliser functions (PSS) can be provided by conventional generators. In essence, the output power of the generator 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.

Again, because of the tight control of generator torque provided by the DFIG and FC concepts, and possibly also VRT, this function should also be able to be provided if required.

However, it should be pointed out that because variable-speed wind turbines have very little synchronously-connected inertia, the risk of such resonances actually reduces as wind penetration increases. Therefore there is an argument that PSS functions should be provided only by conventional generation.

7. Summary

The objective of the assessment contained within this document is primarily intended to show the appropriate direction for the development of electrical topologies of large scale commercial wind turbine technology.

Electricity generated from wind is expected to increase substantially over the forthcoming years. Therefore the share of wind generated electricity in the power generation mix and thus impact on electricity systems is expected to be significant.

Transmission network operators have a responsibility and are usually answerable at government level to operate electricity systems that are safe, reliable and secure. To achieve this, they specify rules generally called grid codes which define how users of the transmission system should operate their plant.

To gain an appreciation of the direction of future wind turbine topologies, it is important to realise the demands and expectations that are going to be placed on wind generation. This report demonstrates by example, the salient grid code issues that are applicable now to wind turbine technology. It also shows generally how these issues are addressed generically and then finally where wind technology satisfies, exceeds or falls short of satisfying these requirements.

The table below summaries briefly and in a very basic manner how well wind turbine technology satisfies the basic requirements of network operators:-

	Wind Turbine Type			
Grid Code Req.	**FSIG**	**DFIG**	**FC**	**VRT**
Voltage & Frequency Range	✓	✓✓	✓✓✓	✓
Fault Ride Through	✓	✓✓	✓✓✓	✓✓
Reactive Power	✓	✓✓	✓✓✓	✓✓
Operating Margin & Frequency Regulation	✓	✓✓	✓✓✓	✓✓✓
Power control	✓✓	✓✓	✓✓✓	✓✓✓

Table 3: Scoring of WTG types against Grid Code requirements

The above table suggests that the use of a full power electronics converter as part of the wind turbine installation and separating the wind turbine rotating system from the external electrical system has distinct advantages. Indeed it is concluded that the use of the power electronics converter provides an excellent ‘electrical’ interface between a variable power source and the grid with its clearly defined requirements.

However, the emerging technologies such as the use of the variable ratio transmission system also provide what appears to be a good ‘mechanical’ interface between the variable wind resource and the electrical network. Little experience in the wind industry has been gained with this topology and so perhaps with more widespread use and experience, this may well prove to be a beneficial arrangement.

Future grid code requirements may well emerge which cannot be predicted now. However, it is likely that the great flexibility offered by power electronics will allow the FC concept to meet these requirements, and possibly also the DFIG and VRT concepts.

It is emphasised here that this document is a focus on the electrical systems contained within wind turbines and does not address other issues such as mechanical, structural, civil engineering and importantly cost.

Furthermore it is also emphasised that this document relates to machines only. If collections of wind turbines are treated more as power stations then solutions to addressing network operator requirements may be dealt with not necessarily at wind turbine level but by other means such as the location of additional equipment within a central substation.

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