INTRODUCTION

With around 50,000MW of wind power generation installed globally, most of the issues relating to connection of individual projects are now well understood. The three key distribution network issues that determine how much generating capacity can be connected to a distribution network are voltage rise, thermal limits and, to a lesser extent for wind, fault levels. Innovations are underway to reduce the impact of these problems and improve the utilisation of traditionally passive distribution networks for generation [1,2].

The key questions under discussion now are how do large wind energy penetrations affect networks, power systems, markets, and current transmission practices? How can these be developed and evolved to accommodate wind energy? This is particularly pertinent in liberalised regulated networks where wind energy is the first technical paradigm shift since liberalisation took place.

The issues of high wind penetration in power systems are not new. There have already been successful small systems running on high penetrations up to 100% wind power [3].

This paper considers the key issues being discussed in the industry and gives some examples to show the relative importance of different issues and how the real problems can be addressed.

HIGH WIND SHUTDOWN

At high wind speeds, wind turbines are designed to shut down. The energy available at these high wind speeds does not warrant the investment in structural materials that would allow the wind turbines to operate safely at these wind speeds over the whole of the machine’s design lifetime. System operators unfamiliar with wind are sometimes concerned that these high wind speed shut downs will occur simultaneously. That is simultaneously across all turbines in a windfarm, and also across many windfarms, causing a loss of generation beyond the capabilities of the system’s available spinning and standing reserve.

The high wind shutdown risk should be compared to the potential loss of a large power station or interconnector infeed on the system. All power systems are designed to cope with a large loss, normally the loss of the largest, or a number of the largest, generating sets, or largest system infeed. However, these credible fault criteria can be exceeded. The power blackout in Italy in September 2003 demonstrated a possible outcome from the loss of power from interconnectors, where the loss of two lines in Switzerland led to unsustainable overloads on the interconnectors to Italy, and their subsequent automatic tripping, resulting in 55million Italians being without power for up to 18hrs [4]. It is uncommon for large modern power systems to have a large infeed loss but, as the Italian case demonstrates, it is quite possible.

The Central European System is designed to cope with an instantaneous infeed loss of 4000MW. Even though there is over 14,000MW of wind installed in Germany the possibility of simultaneous high wind shut down was not raised as a problem in the E.ON Wind Report 2004 [5].

In Scotland and Ireland there have been proposals by System Operators to shut down wind turbines gradually half an hour ahead of an actual high wind shutdown [6]. The forecasting accuracy and capability to achieve an accurate prediction of high wind shutdown is way beyond anything available or envisaged. Therefore, turbines would have to be shut down gradually and preventatively for a large part of the time when they could be operating at peak production. This would significantly increase the cost of wind energy.

In reality even wind turbines in a single windfarm do not shut down simultaneously due to high wind. Machines, which are more exposed and subject to higher windspeeds and turbulence in complex terrain due to topography, or those on the windward side of an array in flat terrain or offshore, will shut down first. In Europe especially, rapid high wind shut down of a windfarm due to a sudden increase in windspeed is very rare, and for this to occur simultaneously with other windfarms, which are geographically dispersed, even rarer.

SUDDEN WINDSPEED CHANGES

In addition to the high wind speed shutdown scenario, System Operators, such as E.ON in Germany [5], have raised issues about sudden changes in wind energy output. On 5&6th November 2003 in the Republic of Ireland there was a dramatic drop in wind energy from the connected windfarms [7]. Power output fell 74% in four hours. In 2010 the expected installed Irish wind energy capacity will be 1000MW. Assuming the same circumstances are repeated, this would result in the loss of 740MW in the four-hour period. However, the Irish system is currently designed to cope with the instantaneous loss of a 400MW genset and
could be partly or largely attributable to the expected costs of £5.5/MWh over wind energy [9]. This price differential is actually a result of a lack of market price mechanisms, which would encourage controllable generation plant to reduce output or shut down and encourage load management or storage.

FREQUENCY RESPONSE

System Operators with large wind penetrations and limited interconnection with other networks are concerned about the ability to provide frequency response. They consider a scenario with low demand and high wind generation (for example on windy summer nights in Europe) where all conventional “flexible” generating plant has been constrained off the system and only wind (and perhaps nuclear) plant remain on line. If there is a large loss of load or generation, the concern is that this remaining generation plant will not be able to respond and a blackout will follow. Wind turbines are now being designed to respond to this challenge. In reviewing the issues it is helpful to consider high frequency response and low frequency response separately.

High frequency response is achievable with wind turbines with variable pitch or active stall control of the rotor, which includes all current large turbines. This service can be provided at virtually no cost to the wind farm operator as the energy lost due to rare high frequency events on large systems is negligible.

However, to provide low frequency response is a completely different matter commercially, even though it is also technically feasible with modern turbines. In low frequency response mode, the wind turbines are deliberately operated inefficiently, spilling available wind energy in the rotor. Should a frequency dip occur, the control system would adjust the blade pitch to achieve increasingly efficient operation and to increase power production. While the turbine is operating at reduced output and efficiency, the value of the lost energy and revenue increases. Unlike fossil fuelled plant there is no fuel cost saving in this mode of operation for wind. If the System Operator is to call on this kind of frequency response, the wind farm operator must be rewarded for the lost revenue.

This will in effect create a market for frequency response. System Operators can be incentivised to make appropriate decisions on despatching or constraining different plant to achieve the most cost effective system operation (including external environmental costs) to achieve the necessary levels of frequency response.

RESERVE & DESPATCH

Reserve is classed as generating plant that can be started up quickly to provide power due to increasing demand or to replace generators that have faulted or have reduced output. Wind does not provide reserve. However, wind power forecasting plays an important role in estimating generation forecasts.
requirements due to changes in wind power [10]. Forecasting is effective at 4 hours and more ahead and several forecasting systems are in operation or undergoing trials, and the field is developing. For 0-4 hours ahead persistence forecasting is the most accurate, i.e. it can be assumed that the wind power will be the same in this period as at present. Forecasts come into their own for periods from 4 up to 48 hours ahead.

### RAMP RATES

In Scotland there has been a concern from Transmission Operators that operating parts of the system at full load may be compromised if spare transmission transfer capacity has to be left for rapidly changing wind power. The most acute issue is restarting the whole windfarm in high winds, for example after a network fault. In this case, following a windfarm shutdown, other generation may have been despatched to utilise the available transmission capacity. The sudden restart of a large windfarm to full power may therefore result in a transmission circuit overload.

In these situations, phasing the restart of a windfarm over several minutes or tens of minutes would not be expected to impact on the windfarm economics, as such events would be relatively rare and the lost energy value therefore small.

However, it has also been proposed to impose ramp rates on windfarms during normal operation [11]. This kind of control is extremely difficult to achieve on a windfarm basis. If it is imposed on an individual turbine the cost of lost energy could be very high. It is unclear what the Transmission Operator is aiming to achieve by this requirement. Fluctuations in wind power due to wind speed changes are stochastic. Therefore, statistically, a sudden increase in power by one wind turbine or group of turbines will be countered by power reductions in other turbines, both within the same windfarm and between adjacent or dispersed windfarms. Transmission Operators must therefore evolve methods to manage and maximise the transfer capacities for high wind generation on their networks without limiting the power output changes of wind farms except during start-up.

### FAULT RIDE THROUGH

Fault Ride Through (FRT) is also referred to as Low Voltage Ride Through (LVRT) and indicates the ability of a wind turbine to survive a network fault and the associated voltage dip. The key concern to System Operators is a 3-phase fault on a highest voltage circuit, which, therefore, propagates widely across the network. Unbalanced faults, although much more common, do not propagate as widely over the network.

Originally wind turbines were connected to distribution networks and it has been a requirement that they must disconnect from the network under fault conditions. This requirement suits the purposes of the Distribution Network Operators. They want to disconnect local generation for a local fault as the quickest, easiest and simplest way of protecting their network and re-establishing supplies where these are lost.

However, for Transmission Operators this policy of disconnection poses a potential threat if the fault is not local on the distribution network but national on the transmission system. If a widespread voltage dip were to propagate to a large amount of the operating windfarm capacity, a common mode effect could occur where, due to their protection settings, these windfarms disconnected. At present there is no published evidence showing such an event, even though the vast majority of connected wind energy was not designed for FRT. It is common for wind turbines to trip for local faults and in general windfarm operators have always preferred protection settings to be relaxed to allow them to ride through these faults. In the UK the Grid Code Review Panel is instigating a project so that the System Operator collects data from the Distribution Network Operators on distributed generation disconnections during major system incidents [12].

There is a considerable effort being put into designing and testing fault ride through capabilities. However there are several different requirements and specifications in different countries’ networks. Not only do the depth and durations of specified voltage dips vary, but also their points of application. Couple this to the varying impedances and network topologies both within the windfarm and between the windfarm and the voltage dip, and factor in the variations in fault level and voltage balance, and the number of scenarios to consider and model becomes onerous.

As a further complication there are differing views in the industry regarding the real and reactive power responses required during and after the fault. In Denmark, for example, the turbine is required to ramp down power during a severe voltage dip, and must not return to full power until 19 seconds later. In Ireland, active power in proportion to voltage should be delivered to the network through the fault. The requirements for reactive power during and after the fault are also subject to different requirements and specifications in different countries.

### TRANSIENT STABILITY

With large amounts of conventional wind turbines the transient stability of the system following a fault has been a concern to some System Operators. The concern has been that turbines remain connected, pulling reactive power from the system, and maintaining the voltage collapse. In practice, older wind turbines disconnect in a fault whilst modern turbines are designed to fault ride through. However, some distribution network connections of windfarms undertaken by Econnect have required particular care. These often involve weak networks and also large induction motor loads.
Modifications to the local protection systems and co-ordination with the windfarm protection scheme have proved an effective method of limiting the impacts of local faults.

A recent paper suggests that voltage rise, not voltage collapse could be a problem following a major system fault, due to wind turbines with high reactive power imports tripping from the grid during a fault [13]. Voltage rise would probably not apply to modern wind turbines, which are more effectively power factor corrected and more immune to tripping.

**DISTRIBUTION AND GRID CODE COMPLIANCE**

Grid and Distribution Codes have been relatively recently introduced as a result of liberalisation to create a set of rules for the various players in electricity supply. The rules for generators were written for synchronous machines, as these were the only machines in large-scale use. With the development of wind energy, revised codes are required for induction generators. However, it is difficult to write one set of requirements that matches the two different machine types. Induction generators as the second comer are generally disadvantaged because the system has evolved to rely on the positives of synchronous machines and manage the negatives.

If power systems had evolved with induction machines, and synchronous machines were now being introduced, the situation would be reversed.

Generation requirements are traditionally written in Grid Codes but with the increasing deployment of distributed generation, these requirements will need to be extended to Distribution Codes. In the GB system it is proposed to apply Grid Code generation requirements to wind farms as small as 5MW in Scotland whereas these only apply to 50MW windfarms in England & Wales, yet the GB network is operated as one system. The whole structure of current Codes and requirements is therefore brought into question.

**DYNAMIC STABILITY**

A limiting factor of transmission system power flows is the dynamic stability of the system. A stable system returns to steady state following a small disturbance. There has been much discussion regarding the impact of wind turbines on dynamic stability, which is influenced by a number of other parameters. A recent assessment has shown that wind turbines with induction generators increase the dynamic stability of the system [14]. Doubly fed induction generators also have a beneficial impact, though to a lesser extent. In particular the power transfer from Scotland to England is often limited by dynamic stability criteria and therefore benefits from wind turbines connected in Scotland.

**TRANSMISSION PLANNING STANDARDS**

Transmission Planning Standards are deterministic standards readily applied by design engineers to new network developments and connections. The Standards are developed from economic optimisations that compare the costs of providing additional circuits with the costs of carrying reserve to cater for the loss of power infeed caused by a conceivable fault.

Work in the UK has highlighted that these standards could be modified for parts of the transmission network that are designed or upgraded to carry large amounts of wind power [15]. Due to the variability of wind, wind energy does not displace conventional capacity on a MW for MW basis. Therefore, other generating capacity is kept available to substitute for unavailable wind power. If some of that wind power were lost or unavailable due to transmission faults or constraints, the cost impacts would be less than for other generation. In addition, wind power operates at full power for less time than other priority generators. It may be, therefore, economically optimum to accept the risk of a greater power infeed loss when operating with wind power. This would require the System Operator to carry more spinning reserve during high wind periods, but this could be more cost effective (and timely) than constructing new additional transmission circuits to meet the current planning standards.

**CONCLUSION**

Wind energy generation is developing and growing rapidly. To successfully integrate it into distribution and transmission networks will require innovation in the technology, management and operation of both the power systems and the generation. This innovation can be incentivised by the regulators of network businesses, by providing appropriate incentives to the monopoly players to successfully integrate wind energy.

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