

Submission to the Royal Society of Edinburgh

Investigation of Response Times for Standby Generation Plant

Summary.

The introduction of intermittent sources of renewable energy, predominately that of wind resource, presents to the Grid Controller a challenge to accommodate fluctuations of output without compromising the integrity and stability of the National Electricity Grid System. The paper describes the circumstance of operation, the problems to be addressed and the need for a clear indication of intermittent capacity that can be accommodated.

Background.

Government policy has introduced a system of subsidy to encourage the development of renewable forms of energy to meet obligations arising from the Kyoto protocol. A framework of challenging targets has been set that together with the terms of subsidy, effectively promotes a single source of renewable power for development, that of wind. There is optimism that wave energy will provide further resource in the future. Both these power sources are unlimited but by their nature intermittent and to a degree unpredictable. (Reference 1)

The most practical means to convert and transmit this resource is through the Electricity Grid System but this accommodation is subject to poorly understood technical constraints. The body of expertise in this area is surprisingly small.

The UK Electricity Grid System.

Electrical power cannot readily be stored. The most effective means to date is by pumped storage, whereby water is pumped to a high head storage pond to be released when required. This conversion efficiency is around two thirds, has topographical restraints, storage limitations and high capital expenditure. Reliability and durability are prime considerations.

Grid operation has to finely balance the generated power with consumer demand. Any mismatch raises or lowers system frequency that by statute must be maintained between proscribed limits. The Grid Controller must continually instruct load changes to maintain balance, backed up by certain automatic and non-automatic features with varying degrees of response. Clearly this factor of response is of crucial significance. The consequence of serious imbalance is to reduce the performance of induction motors sustaining auxiliaries in power stations, thereby aggravating a deteriorating circumstance. (Appendix B). There are other forms of instability that can arise with the failure to maintain correct voltage profiles over the transmission system, leading to uncontrolled power flows and disconnection.

Much routine operation is uneventful but the incidence of fault, often prompted by adverse weather conditions, stretch the capabilities of the system together with its design and operational criteria. Statistical probability of failure, akin to roulette, has to be acknowledged. Understandably, the key ingredient of successful operation is predictability. (Reference 2)

Statistically the loss of supply to consumers from transmission related causes are extremely low but this disguises the severity of any failure with such a dynamic and inherently unstable system. The UK Grid system is much smaller and elongated than the interconnected system on the continent. This circumstance has considerable influence when comparisons are made with diversity and stability.

Wind Turbine Characteristics.

The circumstance of intermittence raises a whole range of problems that are only ameliorated by reduced scale or aggravated expense. These are:-

1. *Standby Power.* Sufficient standby generation must be available to replace or absorb power fluctuations from wind resource. This is above the requirement for coping with demand fluctuations and other generation plant loss. In effect, wind resource behaves as an extension of system demand with the important distinction that unlike demand, the direction of movement is largely unpredictable. German experience stipulates standby cover of 60% of wind capacity and this is on the large interconnected continental Grid System. (Reference 3a)
2. *Installed Capacity.* Wind resource cannot be factored into the requirement for installed generation capacity to meet maximum demands on the Grid System, either daily, seasonally or annually. Neither can it be relied upon for use as standby generation.

3. *Must Run*. In practical terms the output from wind resource must be accepted at all times. This is contrary to sound operational practice and creates the forced situation whereby the remaining generation portfolio must accommodate its vagaries. In the event of an island system being created under fault conditions, this characteristic presents an indeterminate delay towards achieving restoration. (There could be an automatic reclosure facility on wind turbines)
4. *Load (or Capacity) Factor*. This is a variable figure and normally considered on an annual basis. Unpredictable variations are influenced by season, region, siting and whether onshore or offshore. Unlike continental practice, there appears to be an absence of high quality data in the UK with current wind output information (Reference 4). Load factor is a critical yardstick of economic viability, frequently overstated by wind promoters. German experience indicates overall load factors of less than 20%. (Reference 3b). Given the preoccupation with targets, any shortfall of production implies a significant increase of capacity. In turn this would have implications for diversity calculations.
5. *Grid Codes*. There is the requirement for wind turbines, being all of international design, to be compatible for the UK Grid System. The problem of widespread tripping with induction machines, leading to Grid instability has been belatedly recognised in Germany but can be overcome with the expense of HVDC technology (Reference 3c and 5).
6. *Volatility*. Continental experience has revealed considerable variations of output within short periods of time. Were these phenomena to coincide with other system fault conditions then grid stability would be placed at risk even with sufficient standby resource. The response time of this resource would be critical (Appendix C).
7. *Reliability*. Development of wind turbines has evolved since around 1990 and only recently have machine sizes been extrapolated to present dimensions. On the continent problems exist with blade and gearbox failure and the risk of type faults cannot be discounted. For reasons of dispersion, this item should not impact on Grid stability (Reference 6)
8. *Governor Response*. All wind turbine installations to date do not have this facility, unlike every other significant generation source on the UK Grid System. Some development of this feature is under consideration (Reference 7).

Transmission. (Reference 8)

All wind farms above 20MW in capacity connected to the electricity grid require to be connected at a minimum voltage of 132kV to towers of lattice steel construction. With projected load factors in the region of 20-25% and Scottish targets aspiring to 40% of electricity being produced from renewable energy by 2020, some 7 to 9,000MW of capacity will require connection in Scotland alone. (To give some perspective, current Scottish maximum demand is around 6,000MW) These numerous and dispersed sources not only need connection but also require the existing infrastructure to be significantly upgraded. The main interconnection between Scotland and England is already used to full capacity so that the implication of introducing additional must run intermittent renewable capacity would be to quadruple the existing interconnection (Appendix A). The option of reducing conventional output to accommodate renewable production would be critically influenced by the rate of response this capacity was capable, to avoid exceeding loading limits. In practice the interconnection could not be continuously fully loaded.

When potential for double circuit tripping is considered together with the level of projected intermittent renewable capacity to be installed, the future investment in transmission infrastructure can be seen to be of considerable scale. Such investment, above the future need for (subsidised?) standby plant provision to an already uneconomic resource requiring significant subsidy, some measure of the economic consequences arising from Government policy can be appreciated.

Operational Characteristics of the UK Grid with Wind Resource.

1. *Governor Response*. A feature of all generation plant providing power into the National Grid is a limited, self correcting, automatic response to variations of system frequency. The absence of this feature from wind resource denies a proportionate correction to frequency deviation. At lower levels of system demand, in combination with inflexible base load nuclear generation, the must run component of wind resource has a significant effect in denying this facility.

2. *Frequency Stability.* At low levels of system demand with limited governor response, in conditions of turbulence and a significant component of must run wind capacity, serious problems of frequency control may be expected.
3. *Transmission Capacity.* The unpredictable variations of output associated with wind generation would be reflected with increased levels of transmission capacity to overcome problems of overload with line outages and fault conditions. This last circumstance would demand careful monitoring and in situations where overload reductions were urgently required, the dominant presence of intermittent resource with its dispersed nature, presents a problem of load reduction. Within the Scottish Highlands many applications for wind developments have already absorbed the full line capacity of existing transmission circuits.
4. *Line Losses.* The utilisation of full transmission capability and the considerable distances power will need to be transmitted from remote locations, will result in significant power losses on the UK Grid System.
5. *HVDC Transmission.* This technology has a number of advantages to offset the problems arising from renewable development. Line losses are reduced, exposure to sympathetic tripping is avoided, and the environmental impact of overhead transmission is significantly less than for equivalent capacity with AC transmission. HVDC cable also offers an alternative routing strategy.
6. *Sympathetic Tripping.* A source of frequency instability that accompanies fault tripping of transmission circuits. Although being addressed within the Grid Codes, it has only become a problem by virtue of the increasing scale of development.
7. *Maintenance and Refurbishment.* The scale and dispersion of transmission infrastructure (as outlined in Appendix A) required to absorb the output of low load factor intermittent renewable resource, has to consider maintenance, another major consideration is refurbishment. Both these conditions introduce operational restrictions, with significant implications for costs and supply restraints.

Load Response of Conventional Standby Generation Plant.

There are wide variations in the response times for different modes of generation and even within these modes. With thermal plant this extends to their condition as being hot, warm or cold but when fully established, ramping rates of 10MW per minute are common once the initial ten minute notice has been given but this notice can be reduced to five minutes. However bringing plant on from cold can take a full day to reach capacity output with variation to less than half this figure. When hot, a condition related to two shifting, these periods may be halved. An intermediate condition known as warm, can last for around two days with characteristics closer to the hot condition. These restraints, up to synchronising, are boiler related in order to raise steam but once the steam turbine is rotating, the constraint is to contain differential expansion within the turbine. Any departure from full load operation, the cost penalty of part loading becomes progressively prohibitive. Operation at minimum load cannot usually drop below a quarter of full load capability.

Synchronisation to the Grid System is a key step and load dispatch, though usually reliable is not always secure. In conditions of frequency volatility, synchronising delay is not uncommon. Nuclear generation being base load, cannot be considered as standby plant but it is relevant to note the ramping rates for load changes are very gradual and often exceed a full day to reach their full capacity.

Gas Turbines and Combined Cycle Gas Turbines (CCGT) have a quick start up response but are mainly located in England. This fast response would be a major factor to overcome frequency volatility and encourage increased levels of wind capacity on the system but this confidence may well be misplaced. Such a circumstance would introduce volatile power exports across the Scotland-England interconnection.

Hydro-based plant is much more flexible, with full load availability within ten to fifteen minutes, regardless of standing time. With pumped storage plant, designed for quick response, less than five minutes can be achieved for full generation but pumping response is far slower. However caution is necessary. Storage capacities usually have less than 24hours of generation capability and machine operation is processional in that it is impossible to pump and generate at the same time. Once synchronised, loading rates can be very rapid. The UK has only four pumped storage sites with the installed capacity of one site at Dinorwic exceeding the remainder.

Accommodation of Intermittent Renewable Generation.

It should be clear from the text that the ability to absorb intermittent renewable energy becomes increasingly more hazardous with scale. To secure the integrity of the Grid network, there will be an inevitable severe escalation of cost that will not be borne by the developer of renewable resource.

It was in 1999 that in evidence to the House of Lords Select Committee, the National Grid Company stipulated three conditions that would trigger significant extra operational costs. These were:

- a) When installed capacity becomes greater than 20% of peak demand.
- b) When subject to potential instantaneous loss equivalent to greater than 2% of peak demand.
- c) When subject to potential loss over one hour greater than 3% of peak demand.

The analysis in Appendix C indicates these criteria to have been exceeded by current and consented wind turbine capacity, if the second criteria encompassing system faults is accepted.

The question arising from such revelation is at what level does cost deter additional intermittent renewable capacity and who determines that cost. Present structures diffuse this responsibility and indeed provide an incentive for compliance. However the problem extends much deeper to embrace the proportion of capacity required accommodating such issues as variable load factors, diversity criteria, onshore and offshore balance, location and future investment in other intermittent technology.

The introduction of major wind farm projects as on Lewis raises many issues that have a serious economic, operational and environmental impact. Together with the proposed 400kV Beaulieu to Denny transmission line the issues raised are of profound consequence and demand full enquiry. Are institutional structures adequate to contain these varied disputes and do they fully comply with procedures? Does a system of incentive provide the best technical solutions in an industry heavily influenced by strategic considerations?

Strategic Considerations. (Reference 9)

The current direction of development, in the absence of any coherent energy policy, is dangerously exposed to cost escalation, distorted investment decisions and reliance upon a single unproven energy resource. An overview is required of other economic impacts affecting tourism and relief to poor households with no effective institutional voice to protect their interests. When local councils are considering any planning applications, the absence of any policy guidance denies the opportunity for strategic issues to be questioned in the planning process. Indeed there are proposals in place to deny such consideration as a basis for objection, in order to accelerate the procedural process.

As with terrorism, the long-term nature of energy resource requires cross party consensus.

Suggestion.

Were the Lewis wind farm proposal to become accepted, the output to be directly injected into the National Grid at Merseyside through a HVDC underwater cable connection. The advantages with this proposal would be:-

1. An opportunity for the present day scale of wind turbine development to be proven in hostile conditions and a location having the most favourable load factor. This development presents a considerable technical challenge, as is recognised with offshore wind resource and the consequence of failure needs to be addressed.
2. The avoidance of sympathetic tripping and power fluctuations on the Scottish mainland system, having in consideration the scale of this development with both size of wind turbine and siting concentration.
3. A reduction of transmission losses over such long distance.
4. A reduction with the intended interconnection capacity throughout the northern Grid System of the UK.
5. The proving of HVDC cable transmission over such a distance. A cable of similar length has been ordered to connect Norway to the Netherlands. Operating experience would be an essential precondition before any contemplation of tapping the considerable renewable resource from Iceland and that before other European nations became interested with this resource. Having the cable in place provides a powerful option to obtain this resource that would be non-intermittent in character.

6. The undeveloped hydro potential of the North Western Highlands could complement the cable capacity of the Lewis development and give a more consistent output. It would also provide some assurance were the Lewis development not to succeed. (Current proposals require an HVDC connection, with its associated converter equipment, across the Minch)
7. The HVDC link would avoid the need for the proposed 400kV transmission connection to Beaully from the Minch and re-evaluate the case for the Beaully-Denny 400kV connection, if only by delay. The consequence of future technical reappraisal to limit onshore wind resource could avoid the footprint of unwanted transmission construction in the Highlands.

To summarise, the suggestion would provide an insurance against any failure of the Lewis development and provide options for further reliable renewable resource to be developed.

DGB

22nd August 2005

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Appendix A

Projected Interconnection Capacity Calculations with Assumptions

Current annual production of Electricity in Scotland is 49TWh. (This is in excess of annual demand as there is a substantial export to England through an interconnection of 2GW capacity)

Long term average of hydroelectric generation is 4.5TWh per annum with a capacity of 1.3GW.

Estimate of current wind capacity is 0.4GW producing 0.88TWh per annum for an assumed load factor of 25%..

The Scottish Executive has an aspiration target of 40% of electricity production being derived from renewable power by 2020 that amounts to 19.6TWh. Subtracting hydro production gives 15.1TWh. This equates to continuous generation (100% load factor) of 1.73GW.

With an assumed load factor of 25% this suggests an installed renewable capacity of 6.92GW.

For an assumed load factor of 20% this capacity increases to 8.65GW.

(Both these figures would include the current wind installation of 0.4GW)

An analysis of projected wind capacity in Scotland indicated a total of 14GW to be developed, consented and under consideration. (Reference 10)

Given the must run nature of intermittent renewable generation, standby capacity at minimum load, minimum running of hydro and base load nuclear generation, the interconnection capacity required to export such power would need to be quadrupled.

This domination of a generation portfolio from intermittent sources, widely dispersed and subject to considerable delay were it needed to be disconnected, is a technical nonsense. It would imply significant fluctuations of export across the interconnection, wide variations of voltage levels and part of a general instability with frequency control. The cost implications would be severe, accompanied by a serious reduction with the integrity of the National Grid. Some amelioration of these difficulties would be achieved by a direct HVDC connection from a dedicated major wind farm facility to a major demand node in England, bypassing the interconnection.

Appendix B

The United Kingdom electricity grid system is independent of the far larger European continental system. However there is a 2000MW interconnection with France with virtually consistent import, but this is a DC connection that would only influence the frequency characteristics of the UK system by its provision of electrical power.

Supply and demand of power on the UK Electricity Grid has to be in balance. Any deviation results in an increase or decrease of system frequency that by statute must be maintained between certain limits. Grid practice is to operate within much tighter tolerances. There are various means by which correction can be given:-

- A. *Governor Response.* All conventional generating plant feeding the National Grid gives what is known as 'governor response', an automatic limited correction feature that reduces or increases power dependant upon the rate of change of this deviation.
- B. *Load Dispatch.* The Grid Operator would instruct load changes to generation plant to correct imbalance. The degree of response varies with the generation source instructed and whether or not that source is connected to the system. Clearly some dispatch can be anticipated.
- C. *Demand Dispatch.* Certain tariffs to industrial consumers enable disconnection to be instructed at varying degrees of notice.
- D. *Automatic Dispatch.* When frequency deviation exceeds operating limits, certain rapid response generation (pumped storage) can automatically cut in.
- E. *Voltage Reduction and Disconnection.* A further action that can be taken by the System Operator is to lower network voltages to consumers thereby reducing overall demand before a final option of disconnection.
- F. *Low Frequency Relays.* Certain selected sections of the system can be automatically disconnected at pre selected values when the frequency falls, to reduce demand in stages.

A final involuntary consequence of frequency drop results in a reduction in performance of induction motors that sustains the auxiliaries of power stations, in turn reducing their output, so aggravating a deteriorating circumstance.

Imbalance of voltages across the system affect power transfers that in extreme cases can lead to voltage collapse and disconnection, so reactive control can be as significant as frequency control in maintaining grid stability. With such a dynamic and unforgiving system, once balance is lost, a very rapid fall into collapse can follow where time is of the essence and certain of the above corrections cannot be applied in sufficient time. Operator control is vital, in turn dependent upon communications to instruct corrective action and to receive information, essential to form judgements upon which decisions are based.

It is the huge inertia of the system that provides its resilience. An action taken in time avoids numerous consequential actions were the initial action not taken. Therein lies the problem of handling unpredictable power on any scale, especially in turbulent conditions. The assimilation of information has a time constraint that can effectively exclude all of the above Operator controls in certain situations.

The circumstances of major concern are generation loss without warning, tripping of transmission circuits and failure of communications. The effect of generation loss is enhanced at both periods of low system demand and daily peak demand. With low system demands the proportionate effect of generation loss is much greater and the nuclear base load component with its inflexibility far higher. At daily system peaks, available plant reserves are at their minimum. Transmission tripping can not only result in generation (and demand load) loss but prevent available generation from contributing towards restoration. The probability of such losses are considerably increased during periods of storm (and particularly blizzard) conditions. Nor should the effects of ongoing maintenance and refurbishment with transmission lines be overlooked.

Appendix C

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28th May 2004

The Managing Editor,
IEE Review,
Michael Faraday House,
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For the attention of Dominic Lenton

Dear Sir,

Stability Issues on the UK Electricity Grid

I would refer to the article 'Assimilating Wind' published in the IEE Review on January 2002 where the author suggests 8800MW of wind capacity could be installed before significant additional costs would be incurred on the UK Grid System (p12). His article makes reference to evidence submitted by the National Grid Company to the House of Lords Select Committee where three criteria would determine the threshold when intermittent renewables such as wind would be likely to trigger significant extra operational costs. The three criteria were:-

- a) When installed capacity becomes greater than 20% of peak demand.
- b) When subject to potential instantaneous loss equivalent to greater than 2% of peak demand.
- c) When subject to potential loss over one hour greater than 3% of peak demand.

Given his assumption of maximum demand being 50,000MW the first criteria suggests 10,000MW. The second criterion is discounted for reasons of dispersion and the third criterion suggests an excursion of 1500MW to be permissible. Drawing on the Danish experience over the first quarter of 2001 with 1860MW of wind capacity he then suggests 17% would be the maximum hourly power swing that translated to the UK would represent an installed capacity of 8,800MW.

What appears to have been overlooked is the potential for an instantaneous loss elsewhere on the grid system impinging with the third criterion. Extending the argument would reduce this installed capacity to 2,940MW.

There are three basic flaws with this reasoning. Firstly the article only makes reference to England & Wales whereas the Scottish grid system must be included (as it soon will be, under NGC control). For 2002 this system maximum demand is approximately 54,000MW. Secondly my understanding of the maximum designed permissible loss on the UK grid system for a single transmission fault is 1250MW and it may be slightly higher. It used to be 1000MW before privatisation. The third flaw is the reference to the Danish experience. On the 29th October 2000 *under storm conditions* a wind output of 1715MW was reduced to 951MW over a one hour period. Taking the above installed capacity as 1860MW, this represents a swing of 41%.

Using the same reasoning as above but with the modified parameters the 8,800MW figure reduces to 3,950MW. If my proposition of the second criterion fault be accepted this reduces to 900MW. Currently the operating wind capacity is around 640MW with consent granted for over 2,000MW, half of which is offshore. What is significant is how susceptible these calculated figures become with variations of maximum system demand. With domestic electricity price increases of 30% being forecast, coupled to economic recession, a reduction in maximum demand cannot be ignored. For instance with a maximum demand of 50,000MW, the non predictable renewable capacity reduces to 3,660MW and 610MW where the second criteria is being imposed.

2.

As a retired grid control engineer my instincts react against all thought of unpredictable renewable power on the scale proposed, sloshing around the system. Predictability is the key to secure grid operation. The Electricity Grid is a dynamic beast and unforgiving, it is inherently unstable. Wind resource does not provide any governor response to assist the automatic correction of system frequency deviations. Its exploitation on any scale would deter the introduction of new replacement capacity by soaking up available demand, the basis of payment within a market driven structure. At minimum levels of system demand with fixed base load operation of nuclear plant, in turbulent conditions, the control of system frequency would become a nightmare.

Yours faithfully,

Derek G Birkett (Member - reference no 120357)

Addendum to Royal Society of Edinburgh Submission

Transmission p.2

On the 22nd July 2005 the Scottish Executive announced that the renewable energy targets of 40% by 2020 were in future to be expressed in terms of installed capacity and related to Scottish Electricity demand rather than generation.

A recommended assessment of 3.4GW of additional renewable power projects beyond those already built and consented would be required to meet that target, now expressed as a total of 6GW.

This reassessment is an inevitable consequence of the unsustainable criteria chosen with the original definition as outlined in Appendix A. Whilst appearing to maintain the 40% target, in reality it represents an energy reduction to 60% of the original target. Installed capacity (GW) is an expression of capability only. The period of time that capability is exercised, otherwise known as production (TWh), is the only credible basis that can be employed if conversion to tonnes of CO₂ equivalent is to be calculated.

Definition

- A generator of 1kW installed capacity if run for one hour would produce 1kWh of energy (a unit).
- A generator of 1kW run for a year continuously would produce 8760kWh (units) or 8.76MWh
- A generator of 1MW run for a year continuously would produce 8.76GWh or 8.76 million units.
- One thousand generators of 1MW (or 1GW) run for a year produce 8.76TWh

Conditions

Scotland has an installed generating capacity of approximately 10GW producing 49TWh of electricity each year. A substantial export of power to England across a 2GW interconnection is additional to the Scottish annual demand of 34TWh.

Long term average of hydroelectric production each year is 4.5TWh from an installed capacity of 1.3GW.

Remaining renewable power assumed to be intermittent, must run capacity. (ie wind)

Calculation

| | |
|---------------------|---|
| Original Definition | 40% of Scottish annual generation of 49TWh is 19.6TWh. Less 4.5Twh of hydro give a residual figure of 15.1TWh. |
| Revised Definition | 40% of Scottish annual demand of 34TWh is 13.6TWh. Less 4.5Twh of hydro give a residual figure of 9.1TWh. |

9.1TWh divided by 15.1TWh give a percentage of 60%.

6GW less 1.3GW of hydro suggests 4.7GW of intermittent renewable capacity.

9.1TWh is equivalent to an annual continuous generation of 1.039GW (ie 100% load factor)

4.7GW of intermittent renewable capacity would therefore require having a load factor of 22% to provide the revised target definition of 40% of Scottish demand.

A current estimate of Scottish wind capacity is 0.4GW that with a load factor of 22% would provide 0.77TWh per annum.

DGB

6th September 2005

