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Integrating wind energy in the Australian National Electricity Market

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Growing concern about climate change is heightening the need for power systems to be able to operate cost-effectively with high levels of wind energy penetration. In a restructured electricity industry such as in Australia, commercial, regulatory and technical challenges must be solved in an integrated and compatible manner. The Australian National Electricity Market has a number of features that together create a unique situation for wind energy integration:

- It extends over 4000 km, with a single power system operator and market rules and with a largely consistent regulatory framework.
- It uses an energy-only market design, with a five-minute market for energy and frequency-related ancillary services with associated derivative markets.
- The system is of small rating, particularly given its geographical size, so that the transmission network is relatively weak and stability can be difficult to maintain.

This paper describes the steps that have been taken to date in Australia to integrate wind energy in this context, as well as research that is currently under way to identify further design enhancements, considering engineering, economic and policy aspects.

Introduction

Electricity industry restructuring in Australia formally commenced in 1991 under an agreement reached by the Council of Australian [Federal and State] Governments (COAG). This process, which has been more extensively implemented in the eastern and southern states than in Western Australia and the Northern Territory, includes the following features:

- Disaggregation and in some cases privatization of the formerly state-owned monopoly supply industry structure
- The creation of new policy frameworks and regulatory regimes
- The introduction of the so-called National Electricity Market (NEM), which does not include Western Australia or the Northern Territory
- Partial or complete elimination of the retail franchise
- A parallel but less radical process of gas industry restructuring.

The outcome has been a largely consistent approach to electricity industry restructuring on an interconnected, multi-state power system that extends over 4000km. In particular, there is a single spot market and system operator for the whole of this system, which is called the National Electricity Market Management Company (NEMMCO). This is fortunate because the large geographical scope of this power system and its relatively small demand (about 30GW) mean that security issues are important and need to be linked closely to electricity trading.

The centrepiece of the NEM is a set of wholesale spot energy and ancillary markets that solve a security-constrained economic dispatch every 5 minutes. Commercial energy trading is based on 30-minute average spot prices and associated derivative instruments, particularly contracts for difference and call options (Outhred 2004).

The transmission network is represented in the NEM spot energy market by a hub-and-spoke approximation to nodal pricing that has the following features:

- Major flow constraints between market regions due to thermal limits or power system security considerations are represented by a set of linear flow constraints, updated as necessary to reflect evolving physical and security constraints.

- Within market regions, network losses are represented but flow constraints are not, except to the extent that they impact on flow constraints between market regions. Otherwise they are managed by market rules and contractual arrangements.
- The market rules provide for market regions to be redefined from year to year to adequately reflect evolving patterns of major flow constraints, although this concept has not been followed in practice due to political sensitivities.
- Settlement residue auctions allow market participants to bid for the revenue streams arising from the "profits" made by regulated interconnections between market regions, which are a form of Financial Transmission Right.

Outhred (2004) contains further information on the Australian electricity industry restructuring process and market design.

Acceptable levels of wind penetration

The output of any generator can vary in an uncertain manner, for example due to equipment failure, and thus should be regarded as a stochastic process. The power output of a wind turbine, which converts an uncertain energy flux to electricity, has an additional source of uncertainty. Wind power density is a stochastic process that is a function of both space and time.

Diversity between the wind power density functions experienced by different wind turbines smooths the power output of a wind farm compared to that of an individual turbine. Likewise, diversity between different wind farms smooths the summated outputs of multiple wind farms compared to that of an individual wind farm. Thus when considering the effects of wind farms on power system behaviour, we need to consider the aggregate behaviour of geographically grouped wind farms, chosen appropriately for considering local, regional or system-wide effects. Without appropriate management strategies, undesirable effects may occur in each case:

- *Local effects:* Wind farms are usually installed in rural areas, which in Australia can have relatively weak networks compared to many other countries, due to our low average rural population densities. Fluctuations in wind farm real and/or reactive power may cause fluctuating real and reactive power flows on local network elements, such as lines, transformers and switchgear. Particularly in weak rural networks, these may cause voltage fluctuations in the vicinity of a wind farm, and excessively high network flows compared to network capacity, which may exceed equipment thermal limits or cause protection schemes to operate. Wind turbines may trip in response to network voltage disturbances, leading to propagating power system disturbances. Wind turbines with power electronic interfaces may limit their short circuit current for self-protection reasons and thus not contribute significantly to local fault level, possibly hampering fault detection.
- *Regional effects:* As with local distribution networks, regional sub-transmission networks in Australia can also be relatively weak, as can interconnectors between state transmission networks. Flow constraints and voltage problems may occur in sub-transmission networks. Likewise, fluctuations in the summated output of the wind farms within a region of the National Electricity Market may cause flows between NEM regions to fluctuate,

possibly causing constraints in the NEM dispatch algorithm to bind and in turn causing prices to separate between regions in the NEM energy and FCAS markets[1].

- *System-wide effects:* Fluctuations in the summated output of all wind farms connected to a power system will cause frequency to fluctuate and may change the anticipated power output of dispatchable generation (affecting dispatch in the next few hours and unit commitment in the next few days). Unexpected sudden changes in the summated output of wind farms, due to either a widespread change in wind conditions or in response to a power system disturbance are contingencies that must be assessed for their implications for reserve requirements.

Provided that advanced wind turbine technology has been used, three factors will determine readily accepted wind farm penetration levels at local, regional and system wide level:

- The fluctuations in wind farm power output aggregated to an appropriate level and the correlation between the time-varying aggregated wind farm power output
- The time varying aggregated demand for electricity, when considered at the same level of aggregation.
- The ability of the wind turbine to contribute to reducing voltage and frequency perturbations.

One factor that reduces impacts of wind variability on a power system the size of the NEM is that wind regimes experienced across the power system are unlikely to be highly correlated even for slow variations. Thus assuming that wind turbines were widely dispersed in the NEM, a situation where they were all operating at full output would be rare, although it would be more common at a regional or local level. At the other extreme, there would be few occasions when none of a set of widely dispersed wind turbines was producing.

Most concerns about wind penetration are thus likely to focus more on local or regional network flow constraints and voltage fluctuations than on system-wide supply-demand balance. These local and regional concerns should be manageable with good network design and operation (albeit at a cost that would depend on circumstances) provided that advanced wind turbine technology had been used.

As wind penetration increased, the incremental economic value of additional wind farms would decline. This would be due to the rising cost of the additional resources and control action required to manage power system frequency and voltage, and the additional operating costs associated with committing and dispatching other generation under increasing uncertainty. Thus, as with any other form of generation, the incremental economic value of additional wind capacity would decline with increasing penetration level. However, there would be no formal “hard” limit to the readily accepted wind penetration level.

Reducing wind energy disturbances

Techniques to reduce the size of voltage or frequency fluctuations can increase the acceptable level of wind farm penetration. These include the following:

- *Siting of wind farms to maximise the diversity between wind farm power outputs.* In general, greater and more uniform spacing of wind farms would enhance diversity.

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[1] This should be regarded as a NEM design weakness rather than a problem due to wind energy per se,

- *Control of groups of wind farms to limit combined power output or rate of increase of output.* Control could be exercised on a local, regional and system-wide basis to depending on need, and it could be centralised or, where appropriate, decentralised in response to a local variable such as voltage, frequency or price of frequency control ancillary service. Intervention strategies could be used for the infrequent occasions when all turbines were at or near their rated output but would be commercially unattractive if used on a regular basis.
- *Control of other resources in response to fluctuations in wind farm output.* Suitable resources include responsive generation such as hydro and standby generators, reversible storage such as a battery, controllable loads such as storage water or space heating, or dump load. Again, control could be centralised or, where appropriate, decentralised in response to a local variable such as voltage or frequency. The more flexible that these resources were, the higher the wind penetration that could be tolerated.
- *Use of wind turbine control systems to provide an "inertial response" to perturbations in power system frequency.* Within limits, the dynamic behaviour of wind turbines with power electronic interfaces (those that use a doubly fed induction generator or an alternator) can be tailored according to power system operating requirements.
- *Use of voltage control devices to reduce voltage disturbances in the vicinity of wind turbines.* Static VAr compensators (SVCs) and the power electronic interfaces associated with the wind turbines can be used to reduce voltage disturbances in the vicinity of wind turbines and to enhance the ride-through capability of wind farms.

The acceptable level of wind energy penetration will depend on the cost of implementing strategies of this kind as compared to the benefits derived from increased wind energy penetration. It will vary from one power system to another and from one type of wind turbine to another.

Doherty and O'Malley (2003) explore the effect of increasing wind energy penetration on reserve requirements, showing that distributing a given wind penetration over a greater number of wind farms and shortening the time horizon for reserve scheduling (for example by using more flexible reserve plant or better forecasting techniques) both reduce the amount of reserves required.

Nunes et al (2003) suggest that wind turbines with doubly fed induction generator (DFIG) are more robust to power system faults than those with conventional squirrel cage induction generators. Koch et al (2003) corroborate these conclusions and illustrate that appropriately controlled DFIG wind turbines can also contribute to frequency control by modulating rotational kinetic energy in such a way as to reduce frequency perturbations.

Wind power forecasting techniques

Reliable wind power forecasting has the potential to considerably improve the cost-effectiveness of wind farms in main grid applications by reducing dispatch and commitment errors and by reducing the need for spinning reserve. Accurate forecasts a few hours ahead would reduce the costs of maintaining short-term reserves and accurate day-ahead forecasts would reduce costs associated with inappropriate unit commitment. Accurate longer-term forecasts would assist in network planning and in generation investment. Because of the effects of diversity, it is important to be able to predict changes that affect wind farms in a correlated manner. In particular:

- Accurate prediction up to one day ahead of the timing of large increases or decreases in output would assist in making unit commitment and spinning reserve decisions[2]
- Accurate prediction of diurnal patterns would assist in unit commitment
- Accurate prediction of seasonal patterns would assist the management of hydro reservoirs and fuel stockpiles
- Accurate prediction of multi-year variability and trends would assist investment decision making for wind farms and other generation resources.

Experience with wind forecasting techniques suggests that persistence techniques (extrapolation of past behaviour) are appropriate for prediction intervals of up to about three hours and that techniques based on weather forecasting models have better predictive accuracy for longer prediction intervals. This is because changes due to weather pattern effects may not always be predictable merely by extrapolating past behaviour.

Integrating wind energy in the NEM

NEMMCO has identified several issues that must be managed with increasing wind penetration:

- **Forecasting:** "the variable nature of intermittent generation presents a new dimension to the central forecasting processes managed by NEMMCO for the operation of the market and management of supply adequacy" (NEMMCO, 2003: 3). As previously discussed, forecasting techniques can reduce the uncertainty surrounding the future output of groups of wind farms. It will be important to determine how effective such techniques are in the context of the NEM.
- **Frequency control ancillary services (FCAS):** "as the amount of intermittent generation in the power system increases, there is likely to be an increase in the usage and cost of these ancillary services" (NEMMCO, 2003: 3). Because FCAS deals with short-term fluctuations, diversity between wind farms should considerably reduce the need for additional frequency control ancillary services compared to that predicted by observing the output of a single wind farm alone.
- **Voltage control:** "the variability of intermittent generation causes additional variability of voltage, particularly in connected to distribution networks that may be more sensitive to load variations" (NEMMCO, 2003: 3). Wind turbine control systems or complementary devices such as Static VAr Compensators (SVCs) should be able to reduce the voltage disturbances in the vicinity of wind farms. However, wind farm developers will always wish to minimise their expenditure on network connection assets due to competitive pressures.
- **Network management:** "increased variation in generation is likely to result in increased sub 5-minute variation of flows on network elements and interconnectors" (NEMMCO, 2003: 4). There will be significant sub 5-minute variations in flows on network elements within NEM regions, and the associated voltage fluctuations may have to be ameliorated by control action (eg SVCs). However, diversity between wind farms should reduce (in relative terms) sub 5-minute variations at the level of aggregation equivalent to regional

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[2] Spilling a small amount of wind energy could ameliorate a rapid increase in wind farm output.

interconnectors as currently modelled in the NEM[3].

- **System inertia:** "some intermittent generation technologies also have the potential to reduce system inertia by displacing plant with higher inertia" (NEMMCO, 2003: 4). As discussed previously, the control systems of modern wind turbines can, in principle, be programmed to emulate an inertial response. This capability may be important in some situations.

Thus, while the issues raised by NEMMCO are of great importance, they can be managed at least to some extent by installing appropriate wind turbine technology and control schemes, and by exploiting diversity. Generator connection conditions in the NEM require these issues to be investigated prior to approval to connect being granted.

Commercial issues must also be addressed. Increasing levels of wind penetration will increase the volatility in spot prices for energy and ancillary services and in the associated derivative markets. All market participants will be interested in understanding and predicting those volatilities. Thus, it will be important to develop suitable forecasting services, which may focus as much on price behaviour as on wind behaviour. NEMMCO is developing a wind forecasting capability for its own purposes but it is not yet clear what services will be available to market participants.

Conclusions

A high level of wind penetration would create new commercial, regulatory and technical challenges that the Australian restructured electricity industry would have to meet. These challenges must be solved in an integrated and compatible manner.

To date, considerable progress has been made on resolving the technical challenges, primarily through generator connection requirements and the imminent procurement by NEMMCO of a state-of-the art wind-forecasting package.

In parallel with these developments, companies that provide weather forecasting services to market participants are expanding their services to include wind forecasting.

In addition, the design of retail markets is continuing to evolve and may in future be able to harness responsive load to assist in managing the variations in wind energy flow. Thus it appears that a modern restructured electricity industry may be able to evolve to successfully manage an increasing level of wind penetration.

References

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[3] Variations in interconnector flows at timescales > 5 minutes may cause variations between the spot prices in neighbouring NEM regions and price separation may occur. These are matters for the market to resolve and may lead to complementary investment in flexible generation or reversible storage.