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Managing Availability, Quality and Security in a Restructured Electricity Industry with Reference to the Australian National Electricity Market

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Abstract

An AC electricity industry operates by establishing and maintaining near-sinusoidal voltage waveforms at end-user premises. Electricity markets in a restructured electricity industry should replicate this behavior as far as possible. In particular, they should allow end-users to specify the values they place on quality of electrical energy and allow them to manage their future risk levels associated with availability and quality of supply. This property is needed to allocate resources to support a cost-effective flow of end-use energy services in a risk-management context. Our research and experience with the Australian National Electricity Market suggest that the use of a forward-looking but short-term (eg 30 minutes) nodal spot market with associated ancillary service and derivative markets (aggregated to balance nodal precision and liquidity) would support an evolution of this kind subject to greater end-user participation in an enhanced electricity nodal spot market design employing voltage-value functions.

1. The nature of the electricity industry

An electricity industry consists of a very large set of items of electrical equipment, including:

- generators such as alternators that can act as voltage sources within their ratings (described as generator voltage sources in this paper),
- generators that cannot act as voltage sources
- end-use equipment that can provide energy services and that may be able to contribute to maintaining availability and quality of supply,
- network equipment that can complete current paths between the generators and the end-use equipment and/or contribute to maintaining availability and quality of supply.

The industry operates by creating and maintaining current (and electric power) paths and, in the process, providing the conditions under which each item of equipment can contribute to a continuous energy conversion process that supports a flow of end-use energy services.

To operate successfully, each item of electrical equipment except a generator voltage source requires both availability and quality of supply (QOS) at its terminals to be held within the equipment's specified design range, where:

- Availability of supply refers to the existence of a non-zero voltage waveform at a point in an electricity network.
- Quality of Supply (QoS) refers to the collective attributes of the voltage waveform at a point in an electricity network that are required to permit network, generator and end-use equipment to operate in a satisfactory fashion.

In an alternating current (AC) electricity industry, key QOS attributes are voltage magnitude and frequency, sinusoidal waveform purity and, in the usual three-phase configuration, phase balance. In practice, adequate QOS cannot be guaranteed at all network locations at all times. It is sometimes useful to consider unavailability of supply to be simply a limiting case of poor quality of supply.

To manage availability and quality of supply, the supply side of the electricity industry (the electricity supply industry or ESI) operates a number of generator voltage sources each of which can (within its rated capacity) control its terminal voltage and frequency. With the help of network equipment, this allows the supply side of the industry to provide a set of less-than-ideal but still usually adequate equivalent voltage sources at the points of connection to end-users' premises (which could be monitored by electronic meters).

End-use equipment has the capability of delivering end-use energy services (lighting, electrical appliances, space conditioning, motive power, etc), providing the availability and quality of supply is adequate. This is the engineering outcome when the ESI meets its traditional obligation to serve. Due to physical imperfections, there is a practical limit to the ability of the ESI to continuously meet this obligation.

End-use equipment can be designed, at additional cost, to be less sensitive to poor availability and/or quality of supply. An example is a laptop computer with battery and universal power supply (110-240 volts, 50-60Hz) compared to a desktop computer. Thus, the least-cost outcome requires an appropriate combination of supply side and demand side options.

2. Managing electricity industry security

Inadequate availability or quality of supply at any point in an electricity industry may cause an item of electrical equipment to malfunction and thus interrupt the flow of end-use energy services. The electricity industry is particularly vulnerable to this problem because of the lack of cost-effective storage of AC electrical energy, complex dynamic behavior and the importance of exogenous inputs such as weather.

Thus, there are ever-present threats to the ability of an electricity industry to deliver a continuous flow of end-use energy services, which in turn threatens the net economic benefits delivered by the electricity industry. For engineering and economic reasons, the risk of interruption to the flow of end-use energy services cannot be fully eliminated. For engineering reasons, only some of these risks apply to an individual industry participant without affecting other participants. Many of the risks apply to groups of participants defined by their electrical proximity; the most serious risks (widespread blackouts) apply to the industry as a whole.

Determining and then maintaining appropriate levels of risk (which may vary with context) are key tasks for an electricity industry [4]. For industry-wide risks, these are often described as power system security management. However, they are better described as electricity industry security management in a restructured industry context.

In a restructured electricity industry, decision-making is largely devolved to industry participants through commercial trading arrangements. However, short-term threats to industry security must still be managed by engineering techniques, using resources often described as ancillary services. One test of the effectiveness of restructuring is the extent to which ancillary service requirements can be minimized and integrated with energy spot and derivative markets to form a coherent centralized and decentralized decision-making framework involving both supply and demand sides of the industry.

There are subtleties to this task. The appropriate levels of risk vary with location, time, system structure and state, the design of the end-use equipment and the nature of the end-use energy services that are being delivered. Also, the impact of imperfections in availability and quality depends on their nature. For example, simultaneous loss of supply over a wide geographical area (a widespread blackout) may have a higher social cost than small blackouts distributed in space and time that result in the same total hours of supply interruption. Also, poor supply quality can cause equipment to malfunction even though supply remains available [3].

In summary, a key challenge for an electricity industry is to manage the uncertainties that affect its immediate to long-term future ability to maintain continuous delivery of end-use energy services. These uncertainties arise from a wide range of stochastic processes that may have location-specific attributes. As these stochastic processes evolve they introduce disturbances to the electricity industry configuration and/or state, with the result that an electricity industry is never in equilibrium. The objective of managing power system security is to avoid those states that are associated with inappropriate levels of risk.

Important stochastic processes that may affect the ability to maintain quality include the following:

- Primary energy fluxes (eg wind, solar, precipitation) and access to stored primary energy forms (eg fossil fuels, such as gas in pipelines): Diversity in the portfolio of primary energy forms used by an electricity industry may enhance system security.
- Generating unit availabilities and related issues such as maximum and minimum outputs, ramp rate limits and commitment lead times: These performance limits may reduce the industry's ability to compensate for equipment failures (outages).
- Network connectivity and network impedances flow constraints: The stochastic processes that influence network connectivity include the behaviour of generators and loads as well as the operation of protection equipment and the outages of network elements themselves.
- Life-styles and weather.

3. The network role in availability, quality and security

A key role of an electricity network is to create useful regions of influence around large voltage source generators, within which they can provide adequate availability and quality of supply. That is, the network contributes to the ability of the ESI to maintain adequate availability and quality at end-user points of connection.

In its physical operation, an electricity industry automatically takes advantage of any diversity between the stochastic demands for electric power that each individual item of end-use equipment presents at its point of connection. As a result, the network need only convey the aggregate power flow.

Thus, while a network should not be viewed as a monopoly service provider in a restructured industry, it is difficult for competitors such as distributed resource to replicate its ability to take advantage of diversity between the stochastic power demands of end-use equipment.

The effects of outages of network elements (network contingencies) depend on network configuration as well as on the way in which the whole electricity industry (including protection equipment) is designed, operated and maintained.

With respect to network configuration:

- In meshed networks, which have parallel network paths, the loss of a network element may reduce quality at end-users points of connection but will not usually cause an immediate blackout. Thus market mechanisms may be able to at least partly manage a reduction in quality following a network contingency.
- In radially connected networks, which have no parallel network paths, the loss of a network element usually results in an immediate blackout. Market mechanisms cannot alter this outcome. However, they may be able to contribute to valuing risks associated with future blackouts and thus to informing investment and maintenance decisions.

4. The relationship between voltage and reactive power

4.1 The key role of voltage

The adequacy of an AC voltage waveform may be defined by reference to its quality of supply attributes, the most important of which are voltage magnitude and frequency. Whereas frequency is a global variable (except for fast dynamics), voltage magnitude varies with network location because of network impedances and flow constraints.

To manage voltage quality in a power system, the starting point is a set of generator voltage sources.

A network region of influence surrounds each of these generator voltage sources. Typically, these regions overlap and the generator voltage sources are controlled jointly to manage network voltage profiles.

The size and shape of the network region of influence of a generator voltage source depends on its rating, the characteristics of the network and the characteristics of electrical equipment connected to the network. The latter may include end-use equipment, non-voltage-source generators and other equipment such as capacitor banks.

Contingencies threaten the size and shape of the network regions of influence and the extent of overlap between them.

The implications of contingencies should be assessed holistically, considering:

- the full set of generator voltage sources and other available resources,
- the full extent of the network and its associated protection equipment,
- the full set of end-use equipment, and
- the manner in which industry structure and parameters may change as a result of contingencies and the operation of protection equipment.

4.2 Real and reactive power

The sinusoidal nature of voltages and currents in an AC electricity industry implies that there are time-varying energy flows between generators and end-use equipment. At some times in the AC cycle, the instantaneous flow of energy usually reverses, that is, energy flows from an item of end-use equipment back to a generator for a fraction of each cycle.

When averaged over a number of periods of the sinusoidal waveforms, these time-varying energy flows can be thought of as being comprised of two components – real (aka active or average) and reactive power. Only real power flows can be used by end use equipment to produce useful work.

Real power is defined as the rate of flow of energy averaged over one or more integral periods of the sinusoidal waveforms in a particular direction at a particular network location (for example, at the terminals of generator or end-use equipment). The electricity industry transforms primary energy flows in generators into real power in an electrical network, which in turn is converted into energy losses or into an end-use energy form in an item of end-use equipment. Thus real power is an important step in the energy conversion chain.

Reversible energy storage devices such as pumped hydro or batteries can act like either generators or end-use equipment with respect to real power.

Reactive power measures the component of the time-varying electrical energy flow that simply oscillates back and forth in each sine wave period between electric and/or magnetic energy storages associated with particular items of generator, network or end-use equipment. Reactive power results in no average energy transfer from one item of equipment to another over one or more periods of the sinusoidal waveform. It does not form part of the electricity industry energy conversion chain.

Reactive power plays an important role in network equipment due to the relatively large magnetic and electric energy storage capabilities of network equipment. Network equipment plays only a conveyance role for real power from generators to end-use equipment apart from network losses. However network elements “create” and “absorb” reactive power in their capacitances and inductances and respectively, as they convey real power.

There is no intrinsic incremental cost or value associated with reactive power because it is neither produced from a primary energy form nor converted to an end-use energy form. However, reactive power has measurable impacts on the generator, network and end-use equipment through which it passes, including on current magnitude, energy losses and voltage drops. Reactive power flows increase current magnitudes without increasing work transfer rates. Thus reactive power flows increase losses and can cause equipment to overload. The relationship between reactive power and electrical losses implies a contribution to industry cost. The relationship between reactive power through a line or transformer reactance and the voltage drop across it has implications for the management of network voltage profiles and voltage-related stability constraints, and for investment decisions. Thus there are measurable costs associated with reactive power.

Power system operators control reactive power flows through the network to improve network voltage profiles and to better manage certain operating constraints, thus obtaining value from an intrinsically free resource. However, the operators’ ability to do this can be severely curtailed following contingencies. In any event, the amount of reactive power consumed or produced by a device is constrained by its rating and other electrical characteristics.

Reactive power behavior must be considered as part of electricity industry security assessment. This is because the pattern of reactive power flows can change dramatically as a result of contingencies, changing the network voltage magnitude profile and in turn influencing the pattern of energy flows. Thus it is important to be able to control the flow of reactive power in a dynamic manner following contingencies.

The “production” of reactive power does not require the conversion of a primary energy flow because reactive power is associated with a purely oscillating energy flow. Thus capacitor banks can be regarded as “sources” of reactive power and inductances can be regarded as “sinks” of reactive power despite having no energy conversion capability apart from the inevitable energy losses.

In particular, capacitor banks are often placed at major load centers to locally “supply” some of the reactive power “consumed” by the load equipment and thus obviate the need to transmit it via a network path from a generator voltage source. Loads, for engineering reasons, are more likely to appear inductive than capacitive. The use of capacitor banks at load centers is called power factor correction and it can reduce network voltage drops, network energy losses and loadings on generator voltage sources.

Using capacitor banks for power factor correction does not address another important aspect of power system security, that of keeping the angle difference across a transmission line within an acceptable maximum value. Capacitor banks also require an externally provided sinusoidal voltage waveform at their terminals to produce reactive power.

Capacitor banks are not replacements for generator voltage sources. In system control and planning, they are better thought of as devices that can reduce the burden on, and extend the network region of influence of, generator voltage sources rather than as independent resources in their own right.

Controllable reactive power devices, such as synchronous condensers or static VAR compensators, have additional value compared to capacitor banks because they can contribute to managing power system dynamic behavior. However, a generator voltage source can also produce real power and thus contribute to frequency and angle difference management on a sustained basis.

Because reactive power is associated with purely oscillating energy, the operating costs associated with reactive power production are low. The capital cost of providing reactive power sources (and sinks) are also low compared to real power sources. For example, at the design stage for a power station that uses alternator technology, it is relatively cheap to increase the alternator size and thus its capacity to produce or absorb additional reactive power. This is because the cost of the alternator (the reactive power source) is typically a small fraction of the total cost of the generating unit as a whole (the real power source), and the incremental cost of increasing the reactive power capability of an alternator is a small fraction of the total cost of an alternator. Thus capacitor banks (which are also cheap) are used primarily because they are modular and can be flexibly located and quickly installed to satisfy a local requirement, typically identified by a transmission or distribution network service provider.

5. Commercial and economic issues related to voltage

As part of the regulatory compact, a traditional monopoly electricity supply utility was given responsibility for maintaining adequate availability and quality of supply at end-users' points of connection *(the obligation to serve).* Thus supply-side decision-making was internalised in one organization.

A key objective for the utility decision makers was usually to maintain a relatively "flat" voltage profile throughout the utility's transmission network to enhance robustness of voltage quality management against contingencies and changes in the geographical pattern of demand. The utility achieved this by an engineering design process that resulted in a judicious use of generator voltage sources (which were located for reasons associated with the availability of primary energy resources and other inputs rather than for voltage management), network design, and the appropriate placement of capacitors and other items of equipment such as controllable ratio (tap-changing) transformers.

In a restructured electricity industry, the traditional regulatory compact is replaced by a more commercially oriented framework, in which (ideally) many participants on both supply and demand sides of the electricity industry share decision-making responsibility for maintaining continuous delivery of the end-use energy services that end-users are willing to pay for. *In short, in a restructured electricity industry, the obligation to supply becomes a shared responsibility between all industry stakeholders: - generators, network service providers, end-users, market and system operators and regulators.*

Thus, in a restructured electricity industry, managing security and quality, which were traditionally regarded as purely engineering matters, have become joint engineering, economic and commercial matters. More specifically, there is a need for coordinated design of centralized, automated decision making (engineering control schemes) and decentralized commercial decision making (via electricity markets) to achieve a secure evolution of the electricity industry in the operation and investment timescales.

For example, conditions in the electricity industry can change too quickly to be managed by electricity market clearing processes.

Thus, engineering control schemes must manage availability and quality in the period up to at least several minutes ahead, with the potential for market process to play a role beyond that horizon. Engineering control schemes must manage high bandwidth (rapidly changing) phenomena but markets can manage at least some low bandwidth (slowly changing) phenomena.

It has long been recognized that quality lies at the boundary between the engineering and economic/commercial perspectives of a restructured electricity industry [9] but the issue of how to jointly design engineering control schemes and electricity markets remains a research question to this day.

For example, in the Australian National Electricity Market, frequency-related ancillary services manage system-wide imbalances between supply and demand up to a five-minute horizon, beyond which the five-minute spot energy market begins to take over the task of managing supply-demand balance and angle-related (i.e. real power) security issues.

Spot energy prices are calculated every five minutes according to a security-constrained dispatch to meet a five-minute demand forecast. The security constraints are updated every five minutes according to the operator's understanding of the system state at that time and anticipated future trends. Thus angle-related security issues are internalized in the spot market by flow constraints between market regions. However, voltage related issues remain outside the market framework.

The remainder of this paper focuses on spot market design with respect to voltage and reactive power.

A practical challenge is that meaningful and sophisticated end-user participation in spot and derivative markets for reactive power and other quality of supply resources would be required to achieve effective market-based management of voltage quality. This would also require sophisticated metering that could record key quality of supply attributes as well as market interval energy.

Another challenge is that, in most electricity industries, poor voltage quality is an unusual and unexpected event, with probability and consequences that are difficult to assess. A related issue is that when voltage quality is poor, some market participants may have an increased ability to exercise market power. For example, an adverse reactive power flow might reduce the ability of a line to carry real power thus effectively creating smaller sub-markets. In addition, the shared nature and particular role of network services makes voltage quality difficult to commercialize.

Finally, there is the difficult problem of correctly valuing the contribution that distributed resources can make to managing voltage quality, which includes the problem of defining the extent to which those resources can substitute for services provided by the network.

6. Voltage value functions as a mechanism for voltage quality pricing

In implementing voltage quality pricing in an electricity spot market, it is important to keep in mind that reactive power management is a means to an end, (which might be managing network voltage profiles or contributing to security of supply), rather than an end in itself. Thus prices for reactive power should derive from the values that participants place on risks to voltage quality in the near to long future and, in particular, on the values that they place on the present and potential future voltage magnitude at their points of connection.

One line of research that we have been investigating at UNSW for some years is the use of Voltage Value Functions (VVF) in electricity spot markets [1, 2, 8, 10].

Underlying the concept of Voltage Value Functions is the understanding that an item of electrical equipment is designed to operate satisfactorily when its terminal voltage is within its design range. However, if terminal voltage is outside its design range, equipment performance may deteriorate (eg internal losses may increase), it may malfunction (eg an induction motor may stall if terminal voltage is too low) or it may be damaged (eg insulation may fail if voltage is too high). In practice, these possibilities appear to the equipment owner as commercial risks.

Therefore, a participant's (generator or end-user) willingness to trade in a restructured electricity industry is in principle a function of the voltage magnitude at their point of connection to the network. This can be expressed in a Voltage Value Function (VVF) that modifies willingness to trade if the voltage is outside a preferred range, such that an end-user is not willing to pay as much and a generator wants to be paid more. The key VVF parameters are the preferred voltage range and the intolerance to voltage excursions outside that range. The following VVF was used in [10] to multiply bid and offer functions:

$$\begin{aligned} VVF &= 1+a(V_{min}-V)^3 && \text{if } V<V_{min} \\ &= 1 && \text{if } V_{min}\le V\le V_{max} \\ &= 1+b(V-V_{max})^3 && \text{if } V>V_{max} \end{aligned}$$

Embedding a network model and its associated flow constraints in the spot market algorithm exposes network users to the effect that their bids and offers have on the ability to manage the network voltage profile. Note that implementing this approach requires the use of a gross-pool style electricity spot market that includes a sufficiently accurate AC network model (see [8] for more on this).

To date, we have explored the operation of this concept through computer simulations of the operation of electricity VVF spot markets using simple 5-node and 14-node network models (eg [2]).

The key results of our work to date for the simple networks we have considered are that:

- A VVF spot market with active demand side participants can solve for network voltage profiles without the hard nodal voltage constraints used in the traditional engineering approach. It does this by managing both real and reactive power injections and off-takes according to the values expressed in participant willingness to trade functions.
- A VVF spot market produces consistent reactive power pricing that rewards appropriate operating behaviours with respect to reactive power production and consumption. The reactive power prices are determined by network and participant characteristics and, from an engineering perspective, can be regarded as control variables that assist in voltage management.
- A VVF spot market can correctly discriminate between participants (generators and/or end-users) at the same node on the basis of their voltage preferences.
- A VVF spot market can correctly discriminate between participants at different nodes on the basis of their VVF parameters.
- A VVF spot market can contribute to the management of the low-bandwidth repercussions of contingencies by adjusting participant injections and off-takes according to the post-contingency network and voltage-control capabilities.

These results are illustrated by the following example taken from [10], which uses the simple 5-node network shown in Table 1.

Table 1. 5-node network for VVF example [10]

Line	Nodes	R+jX (pu)
L_{12}	1 to 2	0.021+j0.06
L_{13}	1 to 3	0.084+j0.24
L_{23}	2 to 3	0.063+j0.18
L_{24}	2 to 4	0.063+j0.18
L_{25}	2 to 5	0.042+j0.12
L_{34}	3 to 4	0.011+j0.03
L_{45}	4 to 5	0.084+j0.24

This network has generators at nodes 1 and 2. Under heavy load, it may be difficult to avoid low voltage at node 5. The generator offer and load bid data is set out in Tables 2 and 3 respectively and assumes preference-revealing behavior. This data set permits the effect of different VVF parameters to be explored.

Table 2. Generator offers for VVF example [10]

Node	Block	P (pu)	Pr (c/kWh)	Q_{min}	Q_{max}
1	O_{11}	1.35	2	-0.8	+0.8
1	O_{12}	0.7	4	-0.6	+0.6
2	O_{21}	0.4	3	-0.2	+0.3

Table 3. Load bids for VVF example [10]

Node	Block	P (pu)	PF	Pr (c/kWh)
2	B_{21}	0.2	0.95	6
3	B_{31}	0.3	0.98	7
3	B_{32}	0.15	0.98	6
4	B_{41}	0.25	0.98	8
4	B	0.15	0.98	7
5	B_{51}	0.8	0.98	9
5	B_{52}	0.27	0.98	8

Table 4 shows VVF parameters for the base case. For this power system configuration, voltage upper limits are not binding for load bids and voltage lower limits are not binding for generator offers.

Table 4. VVF parameters for the base case [10]

VVF parameters	V_{min} & a	V_{max} & b
Generator offers	*Not binding*	2000 & 1.05
Load bids	0.95 & 50	*Not binding*

Change cases were run for generators with "b" parameters of 200 and 20,000 and upper voltage limits of 1.0 and 1.1 pu. Change cases were also run for loads, with "a" parameters up to 50,000, increased lower voltage limits of 1.0 and differing bid prices at node 5.

Table 5 shows results for the base case and load change cases. Table 6 shows generator change cases. Marginal variables are shown in bold.

Two marginal resources are required in each of the load change cases, to curtail the lower-value load at node 5 to meet the higher minimum voltage specification at that node.

Table 6 shows that the industry benefit increases when V_{max11} is increased to 1.1. This is because network losses are then reduced (shunt losses are not modeled in this example). In contrast, industry benefit falls, and network losses and the price at node 5 increase when V_{max11} is reduced to 1.0. The node 5 price rise is required to achieve acceptable voltage at node 5.

Table 7 shows the effects of simultaneous changes in generator and load parameters. In all cases, B_{51}=9, a_{51}=50000 and V_{min51}=1.0.

Overall, these results show predictable resolution of bids and offers, which are not restricted to particular nodes due to the shared network.

Table 5. Base case & load change cases [10]

Node	Base case	B_{51}=9 V_{min51}=1	B_{51}=8 V_{min51}=1	B_{51}=7 V_{min51}=1
Nodal active power prices (c/kWh)				
1	**4.002**	**4.418**	**4.404**	**4.277**
2	4.262	5.786	5.748	5.306
3	4.406	5.991	5.992	5.490
4	4.441	6.190	6.148	5.638
5	4.648	**8.000**	**7.923**	**6.941**
Total gen'n & load (pu); industry benefit ($K)				
Gen	2.228	2.138	2.138	2.078
Load	2.120	2.048	2.048	1.994
IB	108.0	100.8	93.0	86.0
Nodal voltages (pu)				
V_1	**1.056**	**1.087**	**1.087**	**1.083**
V_5	0.951	**0.995**	**0.994**	**0.995**
Dispatch of marginal resources (pu)				
O_{12}	**0.478**	**0.388**	**0.388**	**0.328**
B_{51}	0.800	0.800	**0.728**	**0.674**
B_{52}	0.270	**0.198**	0.270	0.270

Table 6. Generator change cases [10]

Node	b_1= 20000	b_1= 200	V_{max11} =1.0	V_{max11} =1.1
Nodal active power prices (c/kWh)				
1	**4.001**	**4.406**	**4.000**	**4.401**
2	4.265	4.257	4.202	4.202
3	4.411	4.396	4.337	4.337
4	4.446	4.429	4.365	4.365
5	4.658	4.628	5.199	4.537
Total gen'n & load (pu); industry benefit ($K)				
Gen	2.229	2.225	2.241	2.217
Load	2.120	2.120	2.120	2.120
IB	107.9	108.1	106.6	108.4
Nodal voltages (pu)				
V_1	**1.052**	**1.069**	**1.014**	**1.102**
V_5	0.946	0.966	0.900	1.005
Dispatch of marginal resources (pu)				
O_{12}	**0.479**	**0.475**	**0.491**	**0.467**

Table 7. Generator and load change cases [10]

Node	b_1=200 V_{m11}=1.05	b_1=2000 V_{m11}=1.05	b_1=20000 V_{m11}=1.05	b_1=2000 V_{m11}=1.0
Nodal active power prices (c/kWh)				
1	**4.080**	**4.418**	**4.312**	**4.314**
2	4.477	5.768	5.841	5.408
3	4.619	5,991	**6.000**	5.755
4	4.675	6.190	6.232	5.958
5	5.102	**8.000**	**8.237**	**8.000**
Total gen'n & load (pu); industry benefit ($K)				
Gen	2.218	2.138	1.780	2.101
Load	2.120	2.048	1.721	2.015
IB	107.4	100.8	93.6	98.5
Nodal voltages (pu)				
V_1	**1.096**	**1.087**	**1.066**	**1.084**
V_5	0.998	0.995	**0.994**	**0.994**
Dispatch of marginal resources (pu)				
O_{12}	**0.468**	**0.388**	**0.030**	**0.351**
B_{32}	0.150	0.150	**0.021**	0.150
B_{52}	0.270	**0.198**	**0.0**	**0.165**

6.1 Market design implications of the voltage-value function concept

The outcomes of our research to date are interesting but they are exploratory in nature and do not provide proof of concept. However, they suggest that a gross pool electricity market using an AC network model can, in principle, incorporate low-bandwidth aspects of voltage quality (low-bandwidth frequency and angle-related aspects of security can already be incorporated in gross pool electricity markets by means of security-constrained dispatch as in the Australian National Electricity Market).

If feasible to implement in practice, a VVF scheme would not eliminate the need for engineering control schemes to manage high bandwidth aspects of voltage and reactive power. However, it would reduce the mismatches between economic and engineering decision making in the electricity industry in important ways.

Our research results illustrate an important principle – it is possible in principle to design an electricity spot market that allows participants to express willingness to trade electrical energy as a function of a key aspect of voltage magnitude at their location in an electricity spot market, and to use that information to manage the network voltage profile. That is, to translate an economic measure of quality to a technical quality outcome.

In turn, this opens up the possibility of a market-determined contribution to voltage management, including market valuation of some of the low bandwidth services provided by reactive power resources and by network augmentation.

For example, a VVF scheme would allow end-users to indicate how important it is for them to be "electrically close" to an ideal voltage source – this, of course, would require end-users or their agents to have a sophisticated understanding of the electricity industry and to be able to reflect that in their willingness to trade in spot and derivative markets.

Practical implementation would require a combination of an approximately nodal spot market and a set of approximately nodal derivative markets that each incorporated an appropriate network representation (see [8] for more on the problem of nodal aggregation) and participant willingness to trade electrical energy and VVF parameters. It would also require advanced metering that could monitor availability and quality of supply. In addition, it would require consistent treatment of ancillary services for those aspects of quality of supply management that were not commercialized, for example management of voltage and frequency in the short-term.

7. The Australian National Electricity Market as a case study

References [6] and [7]) describe the key features of the Australian National Electricity Market (NEM) and provide further references. The key features may be summarized as follows [6]:

- Dispatchable generators, market network service providers (trading between market regions) and end users (if they so wish) submit offer or bid functions into a spot market, which sets forward-looking five minute dispatch prices that are then averaged to thirty minute prices for the purpose of settling the market.
- The price-setting process is a linear program that incorporates a regional representation of network losses and thermal and security flow constraints, and implements a hub-and-spoke approximation to nodal pricing.
- Dispatchable market participants can also participate in five-minute ancillary service markets for frequency regulation and contingency management.
- Derivative markets are left to participants to organize apart from auctions of inter-regional settlement residues, which arise when there are flow constraints between market regions.
- The Australian Electricity Market Commission (AEMC) and the National Electricity Market Management Company (NEMMCO) operate a process for determining and implementing a

system reliability and security framework within which the market operates.

- This framework guides the market towards outcomes that are defined as acceptable in the short and long term. However, it seems likely that some cycling between under and over capacity will be an ongoing feature of the market. A total of 4,400 MW of capacity was commissioned in the first 3.5 years of market operation primarily in market regions that were relatively short of capacity.
- Although the National Electricity Rules support competition in the provision of network services between market regions, regulated network service providers provide most transmission and distribution network services.

This design provides close coupling between the spot market and frequency-related ancillary services [5], which has allowed multiple generator contingencies to be managed efficiently and effectively. This is because, within five minutes, contingencies are reflected in the spot market solution, permitting the associated disturbances to be largely managed by market mechanisms.

Network contingencies are also reflected in spot market outcomes within five minutes. However, this is only to the extent that those network contingencies influence the spot market solution through the network model, participant offer functions or security constraints. Recall that the spot algorithm solves a security-constrained dispatch and, if required, security constraints can be changed to reflect the post-contingency context.

Voltage-related ancillary services are still not closely coupled to the spot market in the Australian NEM design. This is partly because a transport model is used to represent the network in the spot market algorithm. It is also because the market prices energy without regard to quality attributes such as voltage.

To incorporate voltage value functions would require a carefully planned evolution to an appropriate market design and more sophisticated participation by both generators and end-users.

8. Conclusions

Electricity industry restructuring is a complex task that involves the creation of a coherent decision-making framework in which some decisions are centralized (e.g. power system operation and economic regulation) and some are decentralized (e.g. unit commitment and investment).

Effective and efficient management of availability, quality and security of supply requires a coherent combination of compatible centralized and decentralized decision-making.

Our research results suggest that it is possible in principle to design an electricity spot market that allows participants to express willingness to trade electrical energy in an electricity spot market as a function of voltage magnitude at their location and to use that information to dispatch real and reactive power resources to manage the network voltage profile. That is, to translate an economic measure of quality to a technical quality outcome.

In turn, this opens up the possibility of a market-determined contribution to voltage management, including market valuation of some of the low bandwidth services provided by reactive power resources and by network augmentation.

For the time being, this concept should be seen as a "light on the hill" rather than one suitable for near-term implementation. Gross pool, short-term spot markets that incorporate a network model, such as the Australian National Electricity Market, lie on a feasible transition path.

The tools of experimental economics could be used to explore these ideas further.

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