Monte Carlo simulation and its application in modelling electricity market behaviour *

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SUMMARY: *There has been substantial restructuring of the Australian Electricity Supply Industry over the past ten years. At the center of this restructuring has been the introduction of the National Electricity Market (NEM). In the NEM all electricity is traded through a common pool. Market outcomes therefore have a direct impact on the profitability of participants.*

There is clearly a need to be able to simulate the electricity market operation. This paper discusses how Monte Carlo techniques integrated with linear program dispatch algorithms are being used to model the NEM. The paper discusses various applications for these tools. The paper also discusses important aspects of the simulations that need to be considered.

1 INTRODUCTION

There has been substantial restructuring of the Australian Electricity Supply Industry over the past ten years. At the center of this restructuring has been the introduction of the National Electricity Market (NEM). In the NEM all electricity is traded through a common pool. Market outcomes therefore have a direct impact on the profitability of participants.

There is clearly a need to be able to simulate the electricity market operation. This paper discusses how Monte Carlo techniques integrated with linear program dispatch algorithms are being used to model the NEM. The paper discusses various applications for these tools including:

- Forecasting interconnector requirements in documents such as the Annual Interconnector Review and the Annual National Transmission Statement;
- Justifying regulated transmission investment though the application of the regulatory test
- Translation of reliability standards into operational trigger levels
- Forecasting of participant revenues and the impact of investments, regulatory and operational decisions on these.

The paper also discusses important aspects of the simulations that need to be considered. These include:

- load forecasts, including both peak demand and annual energy
- generating capacity of individual units
- transmission configuration for multi-area systems
- Convergence criteria for reliability assessment;
- bidding behaviour;
- network limits;
- planned and forced outages of generation and transmission; and
- energy limits, particularly in relation to short term hydro and gas supply.

2 ROLE OF SIMULATION STUDIES

2.1 Overall objective

Monte Carlo simulation studies of system operation are a major class of simulation techniques. They are a subset of a wider range of power system simulation techniques used to study all aspects of power system performance in time frames varying from fractions of a second through to periods of years. The overall objective of the class of power system modelling

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described in this paper is the planning time frame (1-10 years). In this time frame the performance of the power system, in terms of holistic indicators, such as reliability, production levels and prices, can only be forecast on a probabilistic basis. The Monte Carlo simulation technique surpasses any other mathematical modelling technique in its ability to provide a physical understanding of performance of the system in the future. This is especially the case if the simulation methodology is designed to closely reflect the actual operating characteristics of all essential elements (mainly loads, generators, transmission lines and system dispatch rules) in simulated time sequential steps.

Planning studies, such as Monte Carlo studies, generally do not address operational issues except so far as they will have an influence on future planning decisions. The data used for planning studies is often developed by accessing operational data and converting it to equivalent data. For example, the half hourly forced outage rate data recorded on individual generating units is often converted to other forms such as mean time to fail (MTTF) and mean time to repair (MTTR)[i]. In most cases, all generators in a power station, or all generators of a particular class eg 660MW coal fired units, are assigned the same performance characteristics even though there may have been significant differences in past performance between units of that type.

The modelling task in the planning horizon is therefore to represent all power system elements and their key performance characteristics in sufficient depth to provide a reliable forecasting outcome of the parameters that are of interest. The parameters that are of interest include assessment of reliability at the bulk supply point level, production of generation, statistics on the likely range of flows on interconnectors between regions, and pool prices by region. A knowledge of forecast system behaviour enables decisions to be made now to ensure the future power system is capable of safe, reliable and economic performance in accordance with the National Electricity Code.

2.2 Time resolution

The time resolution of interest for Monte Carlo reliability and production forecasting is typically half hourly for every half hour of the year. In the NEM, this corresponds with the half hourly settlement period for financial transactions. The half hourly outcomes are frequently aggregated to the daily, monthly, seasonal and annual level and analysed using statistical methods.

For some studies, it may be necessary to consider 5 minute resolution, for example where ramp rates may influence the study outcome.

2.3 Time scale

The time scale of interest is typically from one year to 10 years ahead. This depends on the particular investigation of interest. For example one year ahead may be sufficient to examine the effect of different maintenance patterns on system performance. It is necessary to look several years ahead for reliability investigations of additional generating capacity or transmission capacity needed to ensure that standards will be achieved if growth eventuates. In many cases, the outcomes of these studies are released to the market to provide opportunities for a timely market response.

2.4 Data development

2.4.1 Load forecasts

These are forecast on a half hourly basis throughout the year, generally by region.

An historical half hourly record (historical load trace) for the region for a particular year is used as the starting point for the forecast.

These records are available on an as-generated basis from NEMMCO records.

Peak demand and energy forecasts for each region are obtained by econometric modelling. These forecasts are developed by jurisdictional planning bodies[ii] and are published by NEMMCO annually in the Statement of Opportunities (SOO).[1]

The load traces for future years are ‘grown’ from the historical trace in accordance with the forecast maximum demands and energy to produce a ‘realistic’ forecast.

This is typically done using a goal seeking algorithm in an Excel spreadsheet or similar tool. Since NEMMCO forecasts both summer and winter peaks by region, particular attention has to be paid between the boundaries of the defined winter and summer periods to ensure there is minimal mismatch at the half hourly boundary.

2.4.2 System data

System data includes:

- the dispatch rules used to manage the supply/

[i] The categories of data collected are generally in accordance with the US NERC Generating Availability Data System (GADS) or equivalent system

[ii] The jurisdictional planning bodies are Powerlink Queensland, TransGrid, VENCorp, TransEnd and ESIPC

demand balance at each point in time – in the NEM, dispatch is carried out based on bids submitted by each generator, from the lowest price bid to the highest price bid. The price is set by the bid price of the last tranche of generation to be dispatched in the time interval.

- Dispatch in the NEM is as a single pool, with a single generator setting the price throughout the NEM, if no transmission constraints are binding
- If a single interconnector constraint binds, two generators will set price, one on either side of the constraint. In this way it is possible for several generators to set price at a given point in time
- rules to provide at least the minimum level of spinning reserve of all categories at all time periods
- rules to manage operating constraints, including generator minimum and maximum output levels and transmission limits (particularly interconnector limits between regions)

The NEM is a self dispatch market, hence the commitment of generation is managed by adjustment of bids, and does not have to be explicitly calculated.

2.4.3 Transmission data

If the modelling is at the regional level, the transmission data applies to this level and would include:

- transmission limits (bi-directional)
- expressions for marginal loss factors and transmission losses
- forced outage rates, both full and partial
- planned outage rates

The purpose of the modelling will dictate the level of detail required when representing the transmission network. In some cases simply representing the transmission network with fixed bidirectional limits may be sufficient. In other cases it may be necessary to model the transmission network capability with multi-term constraint equations similar to those used in the NEM Dispatch Engine (NEMDE).

2.4.4 Generation data

Typical generation data needed for Monte Carlo studies includes:

Generator Capacity	Maximum for each season (from SOO) (Captures seasonal derating); Minimum to model minimum stable output of base-load units.
Bid Profiles	Developed from combination of: historical behaviour; SRMC and LRMC. Representative of any energy limitations such as hydro with small storage capacity
Generator Ramp Rates	Extracted from NEM Market systems; Minimum ramp rate in summer applied for each generating unit
Generator Planned Overhauls	Extracted from Medium Term Projected Assessment of System Adequacy. Data extracted from a number of historical years to capture maintenance cycles.
Generator Forced Outage Rate	Historical generator reliability information collected from relevant Market Participants. Regional aggregate MTTR and MTTF calculated from the historical data Partial and full forced outage rates calculated and modeled separately

3 MODELLING METHOLOGY

3.1 Overall

The overall methodology in time sequential Monte Carlo modelling is to proceed through the solution from the first half hour to the last half hour in the study period. This allows the interaction in the various plants being simulated to proceed in accordance with the 'real world' operating rules.

This generally means monitoring a wide variety of parameters. For example, it is possible in this type of modelling to monitor the levels of storages of fuels such as water, gas or coal and change the operating regime as the simulation progresses to suit the available fuel storage.

The simulation process therefore consists of:

- consider time interval n (typically half hour)
- use a Monte Carlo technique to calculate the availability state of each element in the system at time n
- simulate dispatch according to NEM rules for the time n, based on the availability states
- record all dispatch parameters, including dispatch output of all generators, pool prices etc
- increment time interval and repeat.

3.2 System state

The system state in a given period is made up of the operating status of:

- all generators
- all transmission lines.

It is normally presumed that, provided generators and lines are not out of service due to planned or forced outages, they are available for service if dispatched, through market mechanisms such as bid prices, or by direction from NEMMCO if needed to avoid curtailment of loads.

Base load generators, according to the self dispatch principles of the market, will be bid at a negative price up to minimum load to ensure they are dispatched if available.

For cyclable plant, the lowest priced bid is usually a positive value. Cyclable plant will be dispatched at or above the minimum price, if not on forced or planned outage. Time sequential Monte Carlo modelling enables minimum run times or minimum off times for each unit to be observed.

Any generator whose bid is above the market price, will not be dispatched in that time interval.

Transmission line capability is adjusted to account for transmission outages that are forecast to occur for the time period, either scheduled or unscheduled.

3.3 Time sequential Monte Carlo

Time sequential Monte Carlo modelling is the standard. Given the power of desktop computers, there is no reason to leave out the time sequential parameters, which include:

- individual generator characteristics including forced outage rates (MTTR and MTTF)
- energy limited plant, including storage status of hydro plant, pumped storage plant and gas plant (due to pipeline limitations such as depletion of line pack)
- Contractual limitations on generation if any, due to manning levels
- Must run status of generators

Time sequential modelling is typically carried out with combined production (and pool price) modelling and reliability evaluation. Depending on the study objective, bid prices may be based on short or long run marginal costs, historical bidding, or a range of economic bidding profiles.

In the past, Monte Carlo reliability modelling has been conducted without reference to dispatch of generation, to reduce computation time. However, price does have an impact on utilization of plant and therefore on reliability, and is preferable to be modeled on this basis.

4 MATHEMATICAL PROCESSES

Monte Carlo modelling requires close attention to mathematical processes. The following are several issues that need to be addressed:

4.1 Linear program for generation dispatch

The NEM is dispatched to achieve the minimum operating cost in each time interval subject to meeting constraints.

The objective function is $\min(\Sigma\, C_i.P_i,\ i=1,n)$

n = number of dispatched bids, up to 10 bid tranches per unit

The equality constraint is $(\Sigma\, P_i,\ i=1,n = \Sigma\, D_j,\ j=1,m)$

m = number of loads, one for each region (can also be nodal)

Where;

- C_i = bid price for tranche i
- P_i = MW capacity for tranche i
- D_j= MW demand for region j

The inequality constraints include:

- for each generator, $P_{mini} <= P_i <= P_{maxi}$, i=1,n
- for each transmission line $Flow_{min} <= Flow <= Flow_{max}$

Additional terms are included to allow for the effect of transmission losses on interconnectors on regional prices and generation dispatch.

There can be many other constraints, representing other operating criteria such as:

- ramp rates
- minimum reserve levels

Various LP codes are available commercially and non-commercially that can readily solve the above equation set.

Several different levels of complexity in transmission constraint formulation are possible. Radial systems, such as the present NEM, can be solved by including the network topology and accounting for transmission losses by piecewise linearising the interconnector loss equations. Mesh systems can be modelled provided the distribution of flows in the mesh is built into the constraint equations as a ratio of flows on parallel lines.

For full modelling of meshed systems, the network parameters need to be modelled in the LP dispatch. The present state of the art is to include a DC load flow network model, at the regional (or nodal) level, in combination with other constraint equations reflecting voltage or transient stability limits on groups of lines.

A more advanced AC load flow constraint set would require the linear programming optimisation technique to be replaced by a non-linear optimisation. This could be the direction of future market development to more faithfully incorporate network effects on market operation.

4.2 Random number sequence

The software to carry out the simulation includes the following modules:

1. Random number generators
2. Distribution functions for plant failure states, which access random number sequences to provide simulated failure patterns

Separate random number generators are used for all generator and transmission elements. This ensures the outage sequences of all plant are independent. Outage sequences may be generated and stored prior to the dispatch simulation for all time periods in the study.

The preferred resolution for outages is the same as the time step.

All random number sequences are chosen to be dependent on a single seed. The seed should be independent of the computer time clock. In that way, if the same seed is used in a repeat simulation at another time, the study can be reproduced exactly, if the user chooses.

4.3 Convergence properties

Monte Carlo simulation aims to accurately estimate parameters such as pool prices, unserved energy [iii] and incidence of transmission constraints. Monte Carlo simulation relies on the Law of Large Numbers to verify the stability of the calculation. This is summarised as follows:

> The **strong law of large numbers** states that if $X1$, $X2$, $X3$, ... is an infinite sequence of random variables that are independent and identically distributed, and have a common expected value μ, then the sample average converges almost surely to μ.
>
> This law justifies the intuitive interpretation of the expected value of a random variable as the "long-term average when sampling repeatedly".

It is possible to determine upper and lower bounds on the mean of the sample parameter by analysing the individual values in the random sequence. These confidence intervals vary with the number of 'simulation years' of study that are repeated in order to gain a reasonable estimate of the parameter of interest.

4.4 Number of iterations

As discussed above, this is also referred to as the number of 'simulation years'.

Unserved energy in the NEM is set to a maximum of 0.002% of energy demand for a given region in a given year, on a long term (probabilistic) basis.[1] Given the relative size of the unserved energy to delivered energy, this can mean that potentially a very large number of simulations is necessary to obtain an accurate estimate of USE[iv].

5 SOME PRACTICAL ISSUES

Sensitivity studies should normally be based on the same random number sequence as the Base Case to ensure that a comparison on a time interval by interval basis to compare differences is feasible.

Adding in a new generator or retiring a generator should have no influence on the random sequence for any other generators.

5.1 VOLL Generators

A convenient way to assemble data on Unserved Energy (USE) is to create a class of pseudo generator called VOLL generators. These bid in at maximum bid price (presently $10000/MWh in the NEM),

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[iii] Unserved energy is a calculated value representing the proportion of system energy that is expected to be curtailed. For the NEM the reliability standard is less than 0.002% unserved energy (USE).

[iv] The traditional Monte Carlo (MC) using (pseudo) random numbers, has a convegence rate of only order N $^1/2$. Note that this rate is independent of the dimension d, it depends only of the number of simulations N.[7]

which represents the Value Of Lost Load (VOLL) or USE. USE provides a forecast of a system’s reliability. Reliability in the NEM is assessed on a regional basis (this is further explained in Section 6.3). Hence, separate VOLL generators are placed in every region (or node). The VOLL generators are made large enough to always exceed the potential MW level of USE in that region (or node) to ensure that all of the USE is captured. In all other respects, VOLL generators are bound by the same requirements as other generators, including adjustment to bid prices to reflect interconnector flows.

5.2 DSM generators

These are another class of pseudo generators that are used to represent the interaction of demand side management (DSM) in the market. Hence, the capacity of these generators is set to the estimated level of DSM in the region (or node) and therefore bid into the market at a price equivalent to the assumed tranches of available DSM (typically in the hundreds of dollars per MWh). While DSM generators are indistinguishable, in all respects, from other generators, they are separately accounted for, as for VOLL generators.

5.3 Aggregation of data to the station level

In some cases it is practical to speed up solution time by aggregating units into stations. This applies when there is no distinction in operation between the generator level and the station level.

5.4 Energy limited plant

In the present NEM, some 5000MW of energy limited hydro plant is installed. This requires considerable effort to model. The operating rules for such plant are developed by reference to typical hydrological parameters such as average seasonal flows, and expected plant capacity factors.

Since the hydro plant is normally available under emergency conditions, (subject to forced and planned outages) for which it has been designed to replace failed base load capacity, such emergency operation is factored by making plant available at high bid prices. Then the usage of the plant can be monitored within the simulation or as a post process to ensure that the short term production (hourly, daily and weekly) levels are not exceeded.

5.5 Backcasting

The quality of Monte Carlo simulation is vitally dependent on establishing the validity of the simulation outcomes. This is done in a variety of ways. However, one valuable technique is the practice of backcasting. Backcasting enables a past series of events to be replicated by simulation to determine the correlation between the actual event and the simulated event.

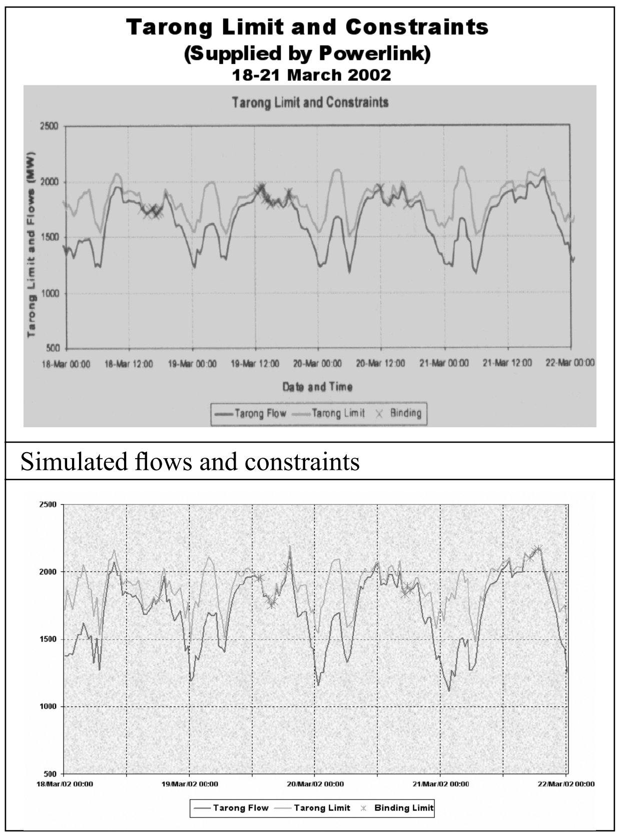


Figure 1: Example comparison of actual and forecast transmission flows and constraints.

Figure 1 shows, as an illustration, a comparison between actual and simulated flows and transmission constraint events on the Tarong to Brisbane lines, which have been of particular interest to the market in the past few years. The second figure shows the simulated results whilst the first shows the historical market outcomes.

Backcasting requires reconstruction, by time interval, of generating patterns, load profiles, forced and planed outages and the dispatch methodology.

6 APPLICATIONS

6.1 Forecasting flow path requirements

The Annual National Transmission Statement (ANTS) forecasts the need for augmentation of major transmission flow paths across the NEM[1]. Monte Carlo based market simulation studies are used to forecast future network utilisation and highlight the need for augmentations. A detailed representation of the transmission network is required for the ANTS.

Multi-term constraint equations based on those used in NEMDE are used to model the capability of the transmission system.

The market simulations conducted for the ANTS attempt to forecast the likelihood of individual network limits constraining flows in the future, and the market impacts caused by these constraints such as constraint residues. These arise due to the price difference that occurs across a binding constraint. Settlement residues are quite volatile as they depend on both the magnitude of the constrained flow and the resulting price difference. As a result the simulations performed for the ANTS require a significant number of iterations (>50).

A forecast period of 10 years is required for the ANTS. The ANTS simulations represent the existing transmission network and any committed network augmentations.

6.2 Application of the regulatory test

Transmission augmentations in the NEM must be demonstrated to satisfy the regulatory test, promulgated by the ACCC.[2] The regulatory test requires the market benefits arising from an augmentation be compared with its costs to arrive at the net market benefit for the augmentation. The augmentation is justified if it offers a higher net market benefit than alternative proposals. Monte Carlo based market simulations are used to forecast the benefits of particular augmentation options and these benefits are used in applying the regulatory test.[3,4]

The following benefits of transmission augmentations are determined from the market simulations:

- Reductions in fuel costs (this converges quickly and does not require a large number of iterations)
- Deferral of capital investment in generation plant;
- Improved reliability through reduction in USE. USE is typically slow to converge and requires a significant number of iterations.

A forecast period of 10 years is normally adopted in the market simulations used for the application of the regulatory test. These simulations may need to model a range of alternate network augmentations and one of the key challenges is developing a model of the transmission system that correctly represents how the capability of the transmission network is affected by each augmentation.

Table 1 is an extract from simulation studies conducted to evaluate the reliability (USE) benefits of alternative planned or hypothetical upgrades.

Table 1: Hypothetical example of reliability benefit of several alternate upgrades

04-05	USE NSW	USE QLD	USE SA	USE Vic
NEM base case (minimum required reserve)	0.00031%	0.00288%	0.00349%	0.00183%
QNI +200MW	0.00030%	0.00132%	0.00343%	0.00180%
Basslink	0.00025%	0.00290%	0.00066%	0.00002%
NSW-SA DC link 250MW	0.00022%	0.00281%	0.00064%	0.00079%
NSW-SA DC link 500MW	0.00019%	0.00279%	0.00021%	0.00040%

6.3 Reliability studies

The reliability standard for the NEM is set by the Reliability Panel and requires that, over the long-term, the annual customer demand at risk of not being supplied be no more than 0.002% of the annual regional energy consumption. NEMMCO is responsible for determining minimum reserve levels (consistent with the Reliability Standard) for each NEM region.

Minimum regional reserve levels are determined by:

- Estimating an appropriate minimum reserve level;
- Assessing whether the resulting unserved energy (USE) with installed capacity exactly delivering that reserve level, meets the Reliability Standard; and
- Iteratively adjusting the installed capacity and hence the reserve levels until the Reliability Standard in satisfied in each region.

Monte Carlo based market simulations are used in this process to determine the level of USE that would result with the installed plant consistent with a particular reserve level. As USE is slow to converge these studies generally require a minimum of 100 iterations. USE will generally occur when the power system is most stressed therefore an accurate assessment of USE requires accurate modelling of system behaviour under peak demand conditions. A more approximate model of the system at other times can be employed without affecting the accuracy of the result.

Reliability studies of the type used to assess minimum reserve levels generally have a 2 to 3 year outlook. Reports regarding recent reserve level assessments performed by NEMMCO are available on the NEMMCO web site.[5,6]

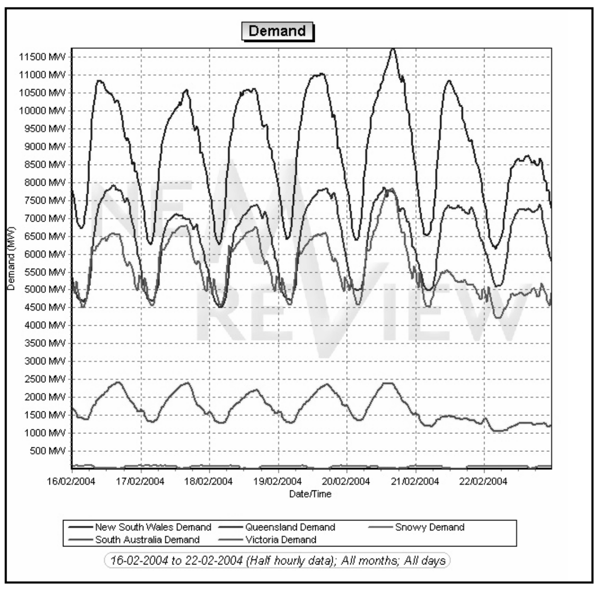
6.4 Participant revenue forecasts

Monte Carlo simulations have become an important decision making tool for a wide range of market participants. Generators use them to establish pool price forecasts by season, by day of week and by time of day. This assists in developing hedge contracts to manage market risk. Generators are also concerned to establish generation production estimates on an annual, seasonal and shorter term basis. It is fully appreciated by generators that their production volumes are determined by the performance of all other generators in the NEM, together with the performance of the transmission system. By accessing this information it is possible to make informed decisions on production planning.

Similarly fuel suppliers, retailers, and transmission network service providers are intensive users of Monte Carlo modelling to understand their business in a market context.

7 KEY DATA TO BE FORECAST

The following Figure 2 shows half hourly records of actual system behaviour for a peak demand week in the NEM in 2004. This representative week gives some indication of the volume of information that is accessed in the NEM and stored. Only one week is shown, and the data is aggregated to the station level for ease of viewing. The data parameters shown, ie demand, generation by station, interconnector transfers, and pool prices, are the key data also produced in Monte Carlo simulations. The volume of data in a single Monte Carlo simulation may be 100 simulation years of half hourly parameters for each half hour of the year or at least 5000 times the information content of Figure 2. When conducting a large number of simulation studies with different assumptions, the issues of data volume become significant and require a systematic methodology for data storage, retrieval and analysis.



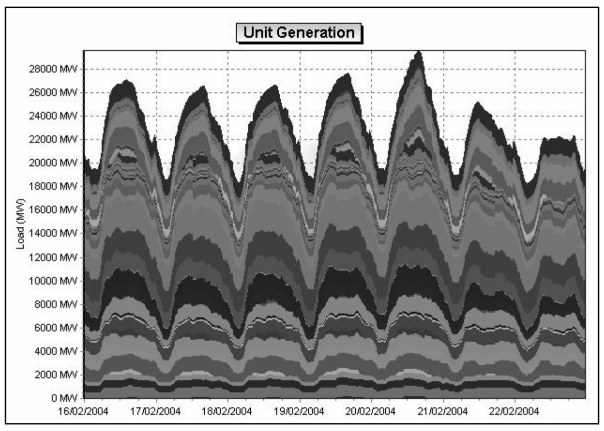
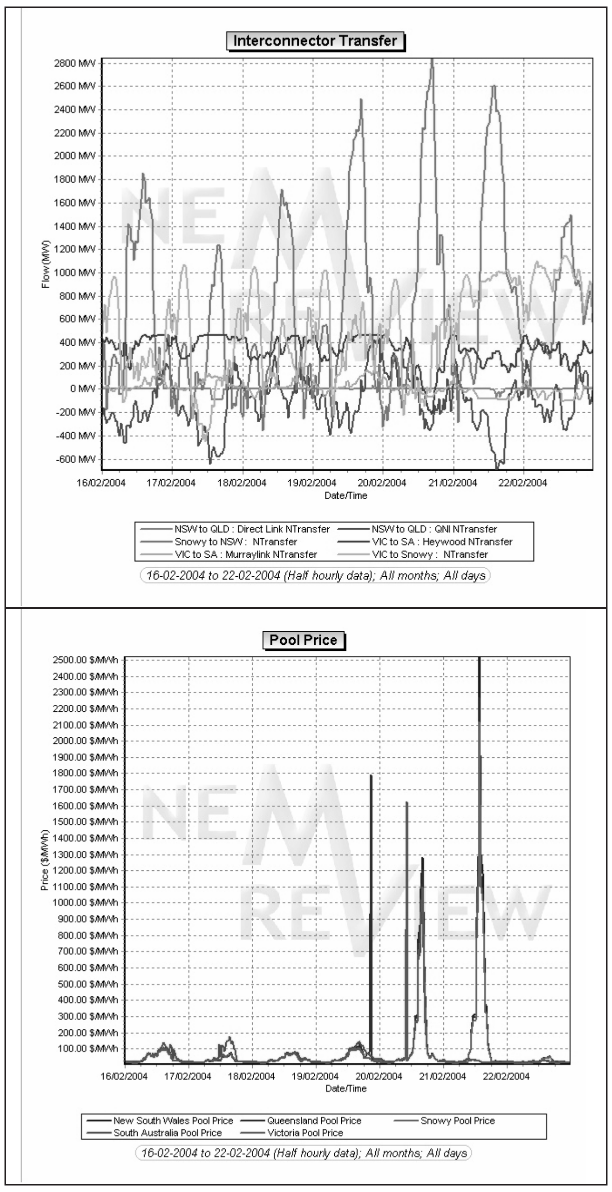


Figure 2: One week in the NEM



8 CONCLUSIONS

Monte Carlo simulation is a vital tool for all market participants in the NEM as it allows accurate forecasting of future electricity market operation. These simulation techniques have applications in the following areas:

- Forecasting interconnector requirements in documents such as the Annual Interconnector Review and the Annual National Transmission Statement;
- Justifying regulated transmission investment though the application of the regulatory test
- Translation of reliability standards into operational reserve trigger levels
- Forecasting of participant revenues and the impact of investments, regulatory and operational decisions on these.

Monte Carlo market simulations require compilation of large amounts of data to model the NEM. Care must be taken in setting up the model to ensure accurate results and in general the model may need to be tailored to suit the particular application

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IAN ROSE

Ian co-founded ROAM Consulting in January 2000, to provide specialised advice to participants in the NEM. His position is Managing Director, responsible for marketing and product development. He also consults on the South West interconnected system and North West interconnected systems in Western Australia and the Queensland North West system centred on Mount Isa.

He previously completed 33 years of service with the Australian Electricity Supply Industry. His roles included transmission and generation planning, system operations, power station operations, and design.

His specialist skills are in the development and application of power system simulation techniques, covering reliability assessment, production costing, power pricing, expansion planning, power flow calculations and technology assessment for generation and transmission systems. He has contributed to several significant developments, including software development for the QEC State Control Centre (1980-1984); estimating the benefits of interconnecting Queensland and New South Wales (1990-1992); planning the Callide C supercritical coal fired station (1995-1996); and more recently estimating the minimum reserve levels for all NEM regions, resulting in an approved reduction in minimum reserve levels in the NEM of nearly 1000MW (2004).

He is a Fellow of IEAust (member since 1978), CPEng, and Registered Professional Engineer (Queensland). He has been a Member, IEEE, since 1974. ROAM Consulting is a member of Cigre and he is a member of Cigre Panel APC5, Electricity Markets and Regulation

He holds the degrees of Bachelor of Electrical Engineering (Hons) (University of Queensland) 1971, Master of Engineering Science in Electrical Engineering (University of Queensland) 1974, and PhD in Electrical Engineering (University of Waterloo) 1977

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- the economic assessment of SNI and SNOVIC interconnection proposal;
- reviews of minimum reserve levels for the NEM;
- preparation of Annual Interconnector Reviews, and
- preparation of the 2004 Annual National Transmission Statement .

David has 15 years experience in transmission planning and power system operations. Before joining NEMMCO David worked for Powerlink Queensland, Teshmont Consultants in Canada, ABB Power Systems in Sweden and the Queensland Electricity Commission.

MARGARIDA PIMENTAL

Margarida is currently employed as a Planning Specialist with NEMMCO, based in Melbourne as a member of the power system planning and development team. Margarida has developed her knowledge of monte-carlo market simulations through the following projects:

- preparation of Annual Interconnector Reviews,
- preparation of the 2004 Annual National Transmission Statement; and
- reviews of minimum reserve levels for the NEM in 1999, 2002 and 2004;

Margarida has 9 years experience in transmission planning and design. Before joining NEMMCO Margarida worked for a small energy management consultancy in Melbourne and Hydro Tasmania