Constraint Management in the New Market Systems

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Abstract

The New Zealand Electricity market has operated since 1 October, 1996. At the core of the market operation is the Scheduling, Pricing and Dispatch (SPD) software application. SPD, a DC optimal power flow based application, uses the network configuration at the time of scheduling, load bids or load forecast, offers from the market participants for different products (energy, 6 second reserves, 60 second reserves) and a piece-wise linear loss model to compute a price based dispatch. SPD co-optimises energy and reserves subject to different types of constraints. These constraints are central to both a secure and reliable dispatch and to the ex post nodal spot price that is a result of the constraints applied.

SPD model uses thermal constraints, stability constraints, generator risk-reserve constraints, and mixed constraints, along with numerous capacity and limit constraints, in order to produce a secure and feasible dispatch solution for every 5 minutes. At present the thermal constraints are generated manually, using load-generation and network scenarios (“similar case scenarios”). Inevitably a degree of error is involved in calculating these thermal constraints arising from the limitations of the choice of the “similar case scenario’s”, and manual adjustment of input-output operation.

Transpower’s market system project (MSP) will do much to remove the inherent error of the present constraint calculation methods. The constraint calculation process will become largely automated for thermal constraints. This will be achieved by the introduction of an application known as the “Simultaneous Feasibility Test (SFT)”. SFT is based on an AC decoupled load flow model and communicates iteratively with SPD in order to develop the thermal constraints.

This paper provides a detailed discussion of the operations and functionality of SFT and development of thermal constraints using SPD and SFT. In addition to providing a mathematical description the paper will discuss a range of issues that arise from the employment of SFT in the NZ Wholesale Market. These issues will include a discussion of the benefits and challenges attendant on the introduction of SFT.

1 Introduction

First generation electricity markets came into being in Chile (1978), the U.K (1990), Argentina (1992), Norway (1992), and Colombia (1993). These were followed by more advanced second generation markets in the mid/late nineties in New Zealand, Australia, parts of Canada, the USA, Europe, and now in Asia.

The wholesale nodal price electricity market introduced by the NZEM in 1996 [1] was the first among the second generation of electricity markets throughout the world. The market software SPD and others have served the market well for the last 10 years.

Ten years has witnessed significant change and growth of the power system. The System Operator, Transpower, undertook a review of the changes needed in the market system to accommodate the current requirements for automation, augmentation of software, enhancement of communication systems to ensure reliability, security of power supply and increasing efficiency in market operations in order to comply with the Electricity Governance Rules (EGR) [2]. As a result of the review Transpower initiated a program in 2005 of replacement of the core SPD software and its supporting market systems. This work is expected to be completed in early 2008.

The market systems project will provide for a higher degree of automation in at least 3 areas. First is the introduction of SFT and its iteration with SPD for developing thermal constraints for different dispatch schedules. This kind of iterative application between the two for dispatch solutions is the first of its kind. ISO's in the USA are using "SFT"(the DC non-linear version) in their FTR (financial transmission right) application which is run well in advance of real time application in order to assess the transmission adequacy. The Transpower SFT is an AC SFT and will be used for real time control and operation purposes. There are significant differences between these two applications and the ways they are operated.

In this paper we will restrict our discussion to the operation of SPD and SFT and the interactions between them resulting in the development of thermal constraints and the production of a feasible dispatch solution. Previous papers [3, 5] have introduced the concepts behind this approach to constraint management and these concepts will be further developed in this paper. The paper is organised as follows. Section 2 discusses the current method of development of thermal constraints. Section 3 presents development of thermal constraints in the new MSP using interaction between SPD and SFT. This section also briefly describes the mathematical models for SPD and SFT. Section 4 illustrates the solution convergence issues and other challenges ahead of us in making SPD-SFT work, and the benefit derived out of SFT, followed by conclusions, references.

2 Current Methods for Developing Thermal Constraints

The System Operator operates the power system to meet the Principal Performance Objectives (PPO's) of the Electricity Governance Rules [2]. Central to the PPO's is the requirement for the power system to be operated to avoid cascade failure and to deliver reliability and security of supply. The present method for managing constraint equations is described in detail by the Transpower document Security Constraints Presentation [4] and previous paper [3].

The current method has the following drawbacks, as mentioned in [3]:

- The load, generation and more importantly network configuration can differ from the assumptions used to form the constraints.
- Some contingencies are not identified in planning time resulting in security violations in real time dispatch.

- Currently the thermal constraints are developed in a manual process.
- There are presently some 270 constraints that must be managed and manually selected for appropriate grid dispatch conditions.

3 Development of Thermal Constraints using SPD-SFT

The Transpower SFT application iterates with SPD as shown in figure 1 [5] and produces a set of thermal security constraints required to achieve a security constrained dispatch in SPD. The network, in bus-branch form, is made available to SPD. The generators' offers, load bids, load forecast, and manual constraints are also made available to SPD. SPD calculates the least cost of generation and reserves, satisfying all of the different constraints and numerous limits, and produces a dispatch and accompanying nodal prices. The dispatch (real power only) is passed to SFT. SFT also receives additional data for reactive load, voltage profile, and capacitor switching schedule through the data base. SFT recalculates the set of thermal constraints based on contingency violations, and these are passed to SPD to produce a feasible and secure dispatch.

The iteration between SPD and SFT continues until solution convergence occurs or the maximum number of iterations is reached. Solution convergence occurs when the maximum mismatch of dispatch MW at any bus between the two successive iterations is less than a pre-defined threshold.

3.1 Functionalities of different components in the loop

3.1.1 Transpower SPD Model

SPD is a security constrained DC-OPF based application. It is an optimal power flow program that uses approximate load flow method, and ignores reactive power-voltage equations for AC network analysis. SPD minimises the total cost of generations and reserves subject to given network constraints and limits, and produces secure dispatch, and nodal energy prices and island reserve prices. It ensures feasibility because the dispatch solution space is bounded by the different security constraints used mainly to prevent thermal overload in the event of the failure of one network elements, (N-1 level of security), voltage instability, transient instability and to cover generator and HVDC risks.

The network, which is formed dynamically in MSP, is made available to SPD. Piece wise linear loss model for different transmission elements is used in the SPD. SPD uses the offers from the generators for energy and reserves, and load bids or load forecast and co-optimise these two products.

The major constraints and equations that are incorporated by SPD include the following:

- MW injection at the different buses
- AC Branch flow
- HVDC Branch flow
- AC Branch losses

- HVDC branch losses
- Fixed branch losses
- AC Branch flow constraint
- HVDC branch flow constraint
- Bus Power flow balance constraint
- Bus group generation MW constraint
- Market node group constraints
- Mixed constraints
- Ramping constraints for generators
- Risk reserve constraints including HVDC risks
- Reserve and Capacity constraints
- N-1 thermal constraints
- Voltage and Transient stability constraints.

All these constraints are represented in linear form so that these can be used in SPD which uses Linear Programming (LP) methods to solve the model.

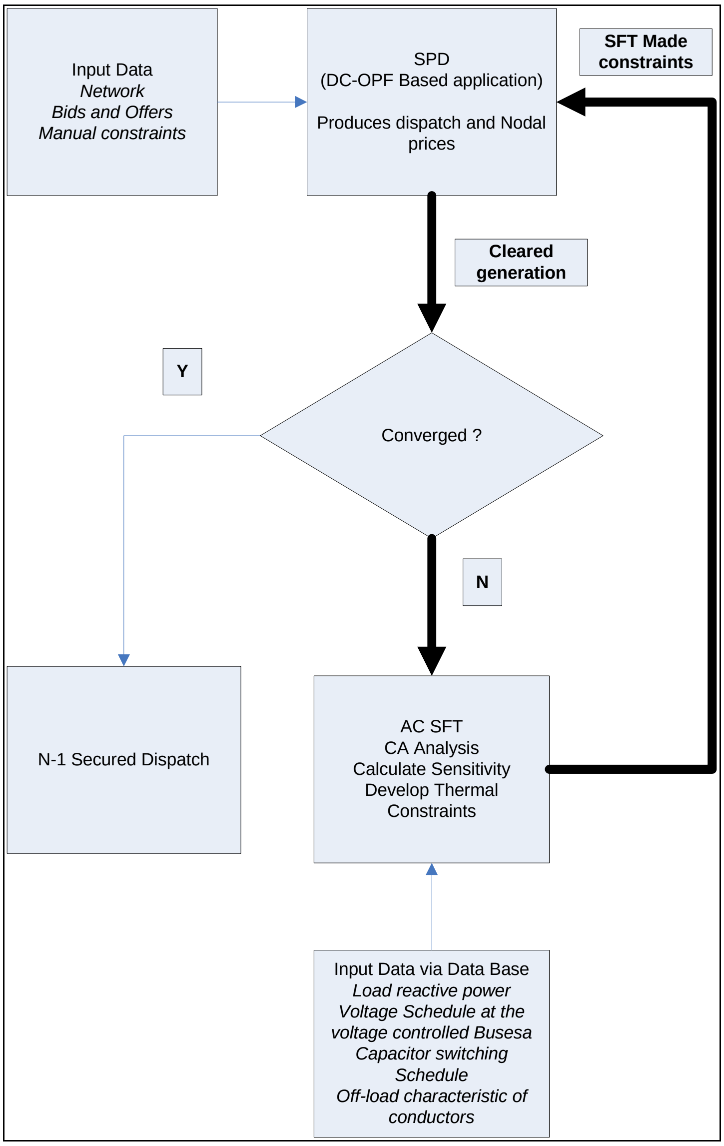

Figure 1: SPD-SFT operating loop showing development of constraints

Functionally it can be shown as in Figure 2.

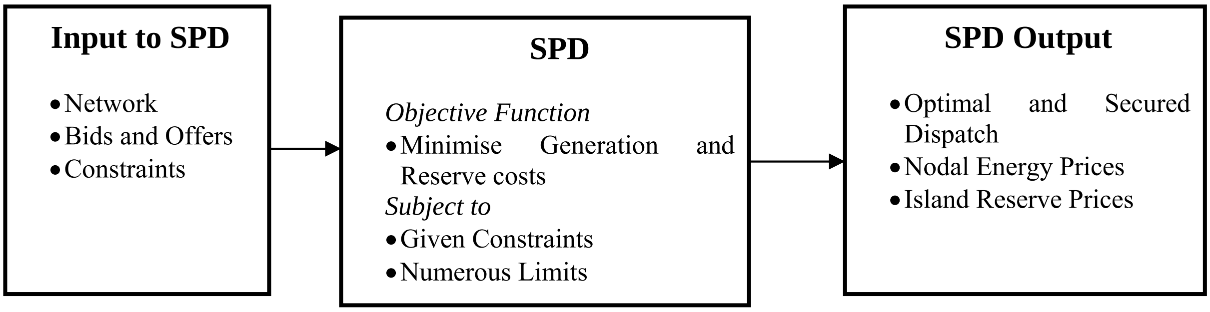

Figure 2: Functional diagram of working of SPD

After the solution, SPD gives the optimal and secure dispatch of energy and reserves, and the bus energy prices and the island reserve prices. In new MSP, the concept of e-node and p-node is introduced inside SPD, but this will not change the way the bus prices are calculated and therefore the issue is not discussed further. The mathematical formulation of the SPD model is available on the EC (NZ Electricity Commission) and Transpower web sites [6, 7]. For further details see [8] where a multiple security constrained dispatch model and dual analyses are presented to show how the price equations are formed and how the binding constraints affect the nodal prices.

There are a number of issues in SPD namely multiple solutions, degeneracy, and restoration of feasible solution by breaking CVP constraints. The global Operations Research and engineering community are still working on some of these issues.

3.1.2 AC SFT Model

The network, which is formed dynamically in MSP, is made available to SFT. It receives cleared generation and reserve at the individual generators connected on different buses, and their limits, and load at the individual buses from the SPD solution. In some cases unit loading conversion from plant level to individual units may be required using a heuristic relationship. It has also available the reactive loads at the buses, capacitor switching schedule and the voltage profile at the voltage controlled buses from the data base corresponding to specific schedule and interval. Receiving the required data, SFT solves the AC load flow problem.

The set of contingencies to be considered is an input to SFT. CA (Contingency Analysis) an application that supports SFT, identifies those contingencies that violate the thermal limits. For the studied scenario and for each violation, the SFT application develops the generic constraints that, when included in SPD model, provides a secured and feasible dispatch. That means SFT finds the violating contingencies and builds constraints that will prevent the system from violating limits when passed on to SPD. The constraints are expressed in terms of branch flow constraints using power distribution factors (pdf's).

The AC SFT uses the "Decoupled Load Flow (DLF)" method which is well established in the industry and is used extensively [9,10]. Using standard notations, power mismatch equations at bus *i* are written as:

$$\Delta P_i = P_i^{sp} - \sum_{j=1}^{N} |V_i||V_j|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \qquad (1)$$

$$\Delta Q_i = Q_i^{sp} - \sum_{j=1}^{N} |V_i||V_j|\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \qquad (2)$$

where,

$\Delta P_i, \Delta Q_i$	Active and reactive power mismatch at bus i
V_i, θ_i	Bus voltage magnitude and angle at bus i
$\Delta V_i, \Delta\theta_i$	Voltage and angle corrections at bus i
$G_{ij} + jB_{ij}$	(i,j) th element of Y bus matrix
P_i^{sp}, Q_i^{sp}	Specified powers at bus i

Linearised load flow equations can be written in matrix form as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}; \qquad (3)$$

where, J = $\begin{bmatrix} \frac{\partial P}{\partial\theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial\theta} & \frac{\partial Q}{\partial V} \end{bmatrix}$ is called Load flow Jacobian matrix and calculated at the operating point.

In DLF, the sub matrices $\frac{\partial P}{\partial V}$ *and* $\frac{\partial Q}{\partial\theta}$ are not considered as (P-V) and (Q-θ) relationships are weakly coupled, and as a result equation for P and Q are decoupled.

$$\Delta P = \left[\frac{\partial P}{\partial\theta}\right].[\Delta\theta] = [H].[\Delta\theta] \qquad (4)$$

$$\Delta Q = \left[\frac{\partial Q}{\partial V}\right].[\Delta V] = [L].[\Delta V] \qquad (5)$$

where,

H, L	Sub matrices of load flow Jacobian matrix

The above set of linear equations can be solved alternately using Newton-Raphson method re-evaluating and re-triangularising matrices H and L at each iteration. This can be used for initial base case solution and for detail analysis for the potential harmful contingencies.

However, further assumptions are made while using for CA analysis for screening the potential harmful contingencies. These assumptions are almost always valid for practical network. The mismatch vectors are now expressed as,

$$\left[\frac{\Delta P}{V}\right] = B'.[\Delta\theta] \qquad (6)$$

$$\left[\frac{\Delta Q}{V}\right] = B^{''}.\left[\Delta V\right] \qquad (7)$$

Both B' and B'' are real and sparse and have the structure of H and L sub matrices respectively and contain only network admittances, and therefore remain constant and needs triangularisation once only at the beginning.

Once the system of linear equations (6) and (7) are solved alternately for $\Delta\theta$ and ΔV, these correction values are applied to update the state vector θ and V. These updated values are used next, to calculate the bus power mismatches using full system equations (1) and (2). The iteration continues until the maximum bus mismatch is less than, or equal to the pre-defined solution tolerances for both active and reactive powers.

3.2 Development of N-1 thermal constraints

N-1 thermal constraints in SPD ensure that should one transmission element fail, the system remains secure meaning there is no overload in the remaining transmission system. Therefore in an N-1 security constrained model, the transmission circuit loading in the base case is significantly less than its rating so that an increase in flow in the circuit can be accommodated in the event of loss of a circuit. These constraints in SPD are expressed in terms of branch flow using "power distribution factor (pdf's)" [4, 11, 12].

In reality the N-1 thermal constraints take a form as follows:

$$DF_{pc} = \frac{P_P^{/} - P_P}{P_c}$$

DF_{pc} = Distribution Factor of flow in protected circuit P when contingency circuit C is out.

$P_P^{/}$ = Power flow in P during post-contingency, MW (AC PF)

P_P = Power flow in P during pre-contingency, MW (AC PF)

P_C = Power flow in C during pre-contingency, MW (AC PF)

$$P_P^{/} = DF_{pc}.P_C + P_P \qquad (8)$$

The effect of off-load time needs to be incorporated in thermal constraints. The asset owner currently provides the 2nd order equation for 15 minute overload time for different conductors. These equations will be generated inside SFT in the new MSP. The equation describes the post-contingency current for different pre-contingency operating currents allowing 15 minutes off-load time. The following steps are taken to linearise the function at the given operating point. Curves corresponding to 5 and 10 minute off-load time are also available. For example, Consider a Zebra conductor strung at 50° C, operating at 500 Ampere (capacity is 765 Ampere). The normalised quadratic curve equation (ZEBRA50C) is: $y = -0.2642x^2 + 0.0353x + 1.2311$.

The linear curve at an operating point x on the curve can be written as, $y = mx + c$

where,

x = Pre-contingent normalised current

y = Post-contingent normalised current

This gives, $\frac{dy}{dx} = m$ = -2* (0.2642)*(500/765) +0.0353 = -0.31006

The value of the function at (500/765), y_{nor} = 1.141309

$c = y_{nor} - m.(x)_{nor} = 1.141309 + (0.31006).(500/765) = 1.343963$

So the equation becomes, in terms of normalised current, $y_{nor} = -0.31(x)_{nor} + 1.343963$

Post contingency current in ampere (multiplying 765 all through) is given by,

$I_P^{/} = -0.31.I_P + 1028$ Ampere

where y_{nor} *765 = I_P' = Post contingency current in ampere

x_{nor} *765 = I_P = Pre contingency current in ampere

Setting both pre and post contingency voltages at nominal value, the equation in terms of power becomes,

$$P_P^{/} = -0.31.P_P + 1028.\,[\sqrt{3}.V_{nom}] \qquad (9)$$

Using (8) and (9), and applying corrections for voltage and power factors, power flow constraint becomes,

$$(1+m)P_P + DF_{PC}.P_C \le 392 * \frac{V_{post}}{V_{nor}} * pf_{post} \;;\; m < 0 \qquad (10)$$

$$pf_{post} = Cos[\tan^{-1}\{\frac{MVAR_{post,P}}{MW_{post,P}}\}]$$

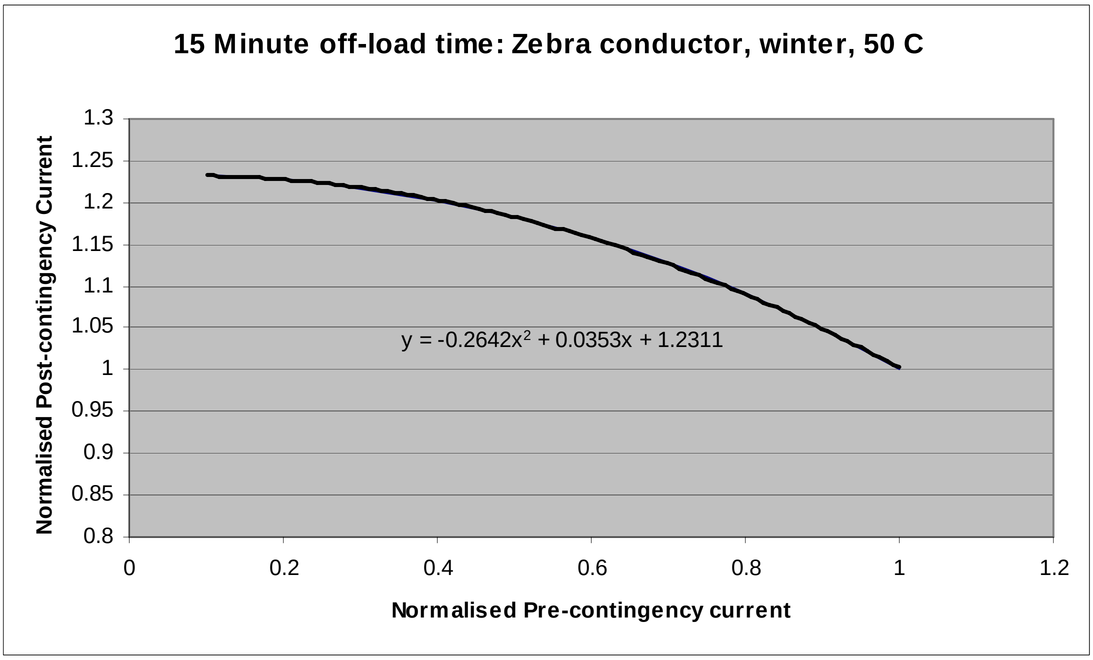

Figure 3: Normalised pre-post current characteristic for 15 minute off-load time

Finally, the equation (10) takes the form:

$$k_1.P_P + k_2.P_C \le c \qquad (11)$$

where

$k_1 = 1 + m, m < 0$

$k_2 = DF_{pc}$

$m = -2 * (a) * (x) + b$

$c =$ RHS limit as discussed above

The development of thermal constraint is automated inside SFT and expected to bring significant benefits to the market. The constraints thus formed are at most ½ hour old, and usually the constraints built in SDPQ (Schedule of dispatch and price) schedule will be used in RTD (real time dispatch) schedule.

3.3 Development of constraints using bus injection sensitivities

Injection sensitivity or generation shift factor determines the sensitivities of flows with respect to generation (injections). We assume that the change in generation is exactly compensated by the slack bus, and all other generations remained constant. Transpower SFT could also use "distributed slack buses" to compensate the loss of generation. DC load flow equation in matrix form can be stated as [13]:

$$\Delta\theta = [X]\Delta P \qquad (12)$$

$$\Delta\theta = [X]\begin{bmatrix} +1(k \textbf{ th row}) \\ -1(slack \textbf{ row}) \end{bmatrix} \qquad (13)$$

The $\Delta\theta$ values in the above equation represents changes in θ when 1 pu bus power is increased at bus k and is compensated at the slack bus. The sensitivity of flow in circuit (i,j) to injection at bus *k* can be written as [13],

$$S_{ij,k} = \frac{\Delta P_{ij}}{\Delta P_{g,k}} = \frac{1}{x_{ij}}\left[\frac{\partial\theta_i}{\partial P_{g,k}} - \frac{\partial\theta_j}{\partial P_{g,k}}\right] \qquad (14)$$

where,

$\frac{\partial\theta_i}{\partial P_{g,k}}, \frac{\partial\theta_j}{\partial P_{g,k}}$	Elements of $\Delta\theta$ vector
x_{ij}	Circuit reactance

The new flow in circuit (i,j) for an injection of $\Delta P_{g,k}$ at bus k is,

$$P_{ij,c} = P_{ij} + S_{ij,k}.\Delta P_{g,k}\,. \qquad (15)$$

where

$P_{ij,c} =$ Flow after the injection

$P_{ij} =$ Flow before the injection

This type of injection sensitivities are required to make a decision to remove generation unit from generation block offers as per block dispatch agreement to avoid overload in circuits in a most effective way.

4 Challenges and Benefits

Challenges

- There are a number of issues in SPD, that were discussed earlier. The treatment of deficit/surplus generation needs to be resolved in SFT with adequate care possibly through a number of slack buses where the deficit generation can be apportioned in proportion to a given set of participation factors or by other means. In case of transmission infeasibilities, related to thermal overload violation in SPD, SFT will also see it as a violation, and SFT will create suitable constraints to get around this transmission infeasibility problem.

- The AC SFT uses the decoupled load flow method and solves the model using Newton-Raphson (N-R) algorithm. In DLF, the number of iterations is slightly increased compared to full N-R method but the computation load per iteration is significantly reduced. For most system conditions the DLF method provides rapid solutions with good accuracy. However for system conditions with very large angles across lines and with special control devices that strongly influence active and reactive power flows, full N-R formulation may be required [10]. A Non-linear DC SFT has been provided as a “stand-by” to the AC SFT so that it can handle the non convergence situations, particularly arising due to the reactive power and voltage problems. The conditions that will necessitate the use of the DC-SFT must be identified and established.

Benefits

- SFT can use up-to-date and accurate network and injection data for developing constraints, and is therefore providing optimal application of security constraints [3].
- All possible contingencies are considered automatically.
- The process is automated removing a considerable manual burden with attendant risks.
- SFT allows efficient and cost effective use of grid capabilities.

5 Conclusions

The new market systems will ensure the reliability and sustainability of the operation of the New Zealand's wholesale electricity market. The systems will continue to provide the services required under the Electricity Governance Rules and Regulations. The opportunity has also been taken to update the tool sets available to the System Operator to maintain and enhance capabilities in the transmission constrained environment that we now find ourselves [3].

It will take time to understand fully the operation of SPD-SFT loop for developing constraints which is the first of its kind. The constraints built through this process will bring a number of benefits including, accuracy in building constraint using almost real time case, automation (with minimum manual intervention, so less human error) in populating constraints into SPD, maximisation of the use of grid capacity, enhanced reliability and security of the grid. The bus prices are dependent on the binding constraints and therefore the formation of accurate constraints will contribute to ensure accurate bus price. The application of SFT will thus allow the System Operator to provide better management of constraints in real-time operation while enabling a secure the efficient and cost effective use of grid capabilities.

6 References

[1] T. Alvey, D. Goodwin, X. Ma, D. Steriffert and D. Sun, "A Security Constrained Bid-Clearing System for the New Zealand Wholesale Electricity Market," IEEE Transactions on Power Systems, vol. 13, 1998.

[2] Electricity Governance Rules and Regulations (EGR), September 2006. Available at http://www.electricitycommission.govt.nz (Electricity Governance Regulations 2003).

[3] D.G Goodwin, R R Hardy ; "Operating a Constrained Grid – Future Directions" Proc. ESA conf 2006, Wellington.

[4] Transpower "Security Constraints Presentation" http://www.transpower.co.nz/?id=4451

[5] Bhujanga Chakrabarti; "Constraint Building Function (SFT)" Transpower Internal Memo, 25 October 2005.

[6] EC Web site: http://www.electricitycommission.govt.nz

[7] TP Web site: http://www.transpower.co.nz

[8] Bhujanga Chakrabarti; "Modeling of Wind Generation Fluctuations in a Dispatch Model" IEEE Power India conf, April 2006, New Delhi.

[9] B Stott and O. Alsac; "Fast Decoupled Load Flow" IEEE Trans., Vol PAS-93 pp 859-869 May/June 1974

[10] P Kundur; "Power System Stability and Control (Book)" McGraw-Hill, Inc, New York 1993

[11] The Development of Security Constraints" http://www.transpower.co.nz/?id=4451

[12] Bhujanga Chakrabarti; "Process for Calculating N-1 thermal Security Constraints" Transpower Internal document, November, 2005.

[13] A Wood and B F Wollenberg; " Power Generation Operation and Control (Book)" 2nd ed, John Willey & Sons, Inc., New York, 1996.

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An Electrical Engineer Doug has worked since 1979 for the New Zealand Electricity Department and it's successors, Electricity Corporation of New Zealand and Transpower New Zealand Limited. Currently he is the System Operator Development Manager.

Since 1994 Doug has been closely involved in the design development, implementation and operation of the wholesale market. His involvement has included:

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