Losses in the New Zealand power system

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***Abstract*—Electrical losses in power systems are related to the transport of electrical energy from generating regions to demand centres. The further this energy must be transmitted, and the higher the magnitude of the transmitted energy, the higher the associated electrical loss. New Zealand has a long stringy network with the majority of demand in the North Island and substantial existing hydro and the possibility of future increased renewable generation in the South Island. This means losses play a significant role in both the market in terms of nodal price, and also in the future planning of the New Zealand power system.**

This paper investigates the electrical losses incurred within the New Zealand power system. Specifically, the paper examines the magnitude of these losses for both the high–voltage network, and also the estimated total loss for the power system as a whole (from generation through to end users). It also investigates the dependence that losses have on the generation–dispatch and hydrology conditions, and the locational aspects associated with the nodal price in the market and how this might effect future power system planning.

I. INTRODUCTION

Losses play an important role in the operation and planning of the New Zealand power system[1]. The current market framework utilises a pool market with nodal pricing based on a Scheduling, Pricing and Dispatch (SPD) model [1]. SPD dispatches the system for the least cost and at the same time determines the locational marginal prices, or nodal prices around the network. This paper further investigates the effect nodal prices vary due to transmission losses, and whether this sends appropriate locational signals for generation investment in these regions.

In terms of planning, losses play several important roles. Firstly, transmission investment tends to lower losses and these benefits can be included in the economic case for considering additional transmission investment. In addition to this, losses associated with a generators ability to supply demand is dependent on the generator location and the power system state. This locational dependence is important when considering the economic benefit for transmission to enable generation, and in particular renewable generation that is often remote from major demand centres. In this respect, a key question for New Zealand is: *"Where are the best overall economic renewable generating regions, taking into account transmission losses, additional transmission investment and resource quality"*. This is the key question being identified in Phase II of the Transmission to Enable Renewables Project currently being investigated by the Electricity Commission.

Before describing the effects losses have on system operation and in power system planning, this paper begins by investigating the total loss incurred in the New Zealand power system and how this loss relates to total system demand and system generation–dispatch conditions.

II. NEW ZEALAND POWER SYSTEM LOSSES

The total electrical losses in the New Zealand electricity system, from generation to end user can be estimated by combining the high–voltage network loss with the total distribution network loss. To get some idea of maximum, minimum, and average losses, an estimated loss profile, or time–series, is required. The following sections describe the methodology used to estimate the total New Zealand power system losses.

A. Transpower's network losses

Figure 1 illustrates the New Zealand power system including Transpower's network. Losses are composed of two components, a fixed standing loss, k, associated with the magnetising current of transformers, and a variable component associated with the I^2R losses in the network; or,

$$Loss = k + I^2R \tag{1}$$

The total loss of Transpower's network is reported in their financial disclosure statements. This averages 169 MW (1476 GWh) and equates to around 3.7% of the energy entering Transpower's network. What is unknown is the percentage relating to standing loss and variable loss.

1) Variable losses: Variable losses have been modelled using a power flow solution for every half–hour of the year 2007. An algorithm has been developed that automatically reads half–hourly demand, generation and HVDC transfer data, performs a power flow solution and records the total variable network loss. This is repeated for a series of chronological input data and has been coined the *continuous power flow*. Appendix A describes this algorithm in more detail. Using this technique, the variable losses associated with Transpower's network have been found to average around 128.7 MW (1128 GWh) with a peak of around 280 MW.

2) Standing losses: Standing losses have been estimated by subtracting the total annual variable loss from the total annual losses reported in Transpower's financial disclosure statement. This equates to an average standing loss of around 40 MW (348 GWh) or around 0.87% of the energy entering the system.

3) Total Transpower losses: Figure 2 illustrates the total modelled Transpower system losses for the year 2007. The upper plot shows the actual modelled half–hour loss. The lower plot shows the sorted loss duration curve. The maximum loss is around 320 MW, with an average loss of 169 MW. This is roughly the demand of Aurora Energy (Dunedin + Queenstown regions). These results indicate that, as a rough rule–of–thumb, the standing losses equate to roughly $\frac{1}{4}$ of total annual energy losses.

[1]Note that in the context of this paper losses are considered to be the electrical I^2R real power loss (the heating of transmission assets being used to transport electricity).

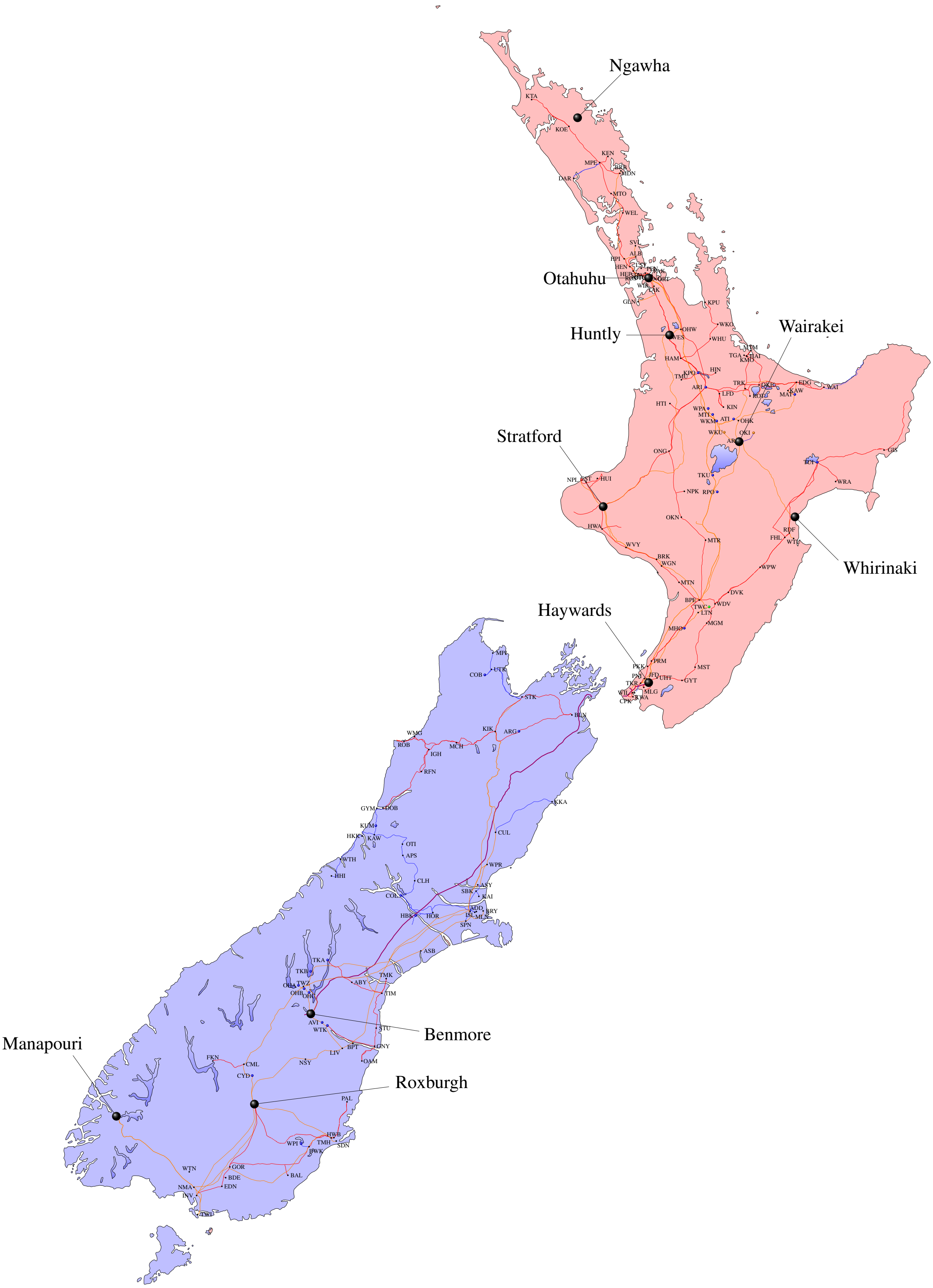

Fig. 1: The New Zealand Power System

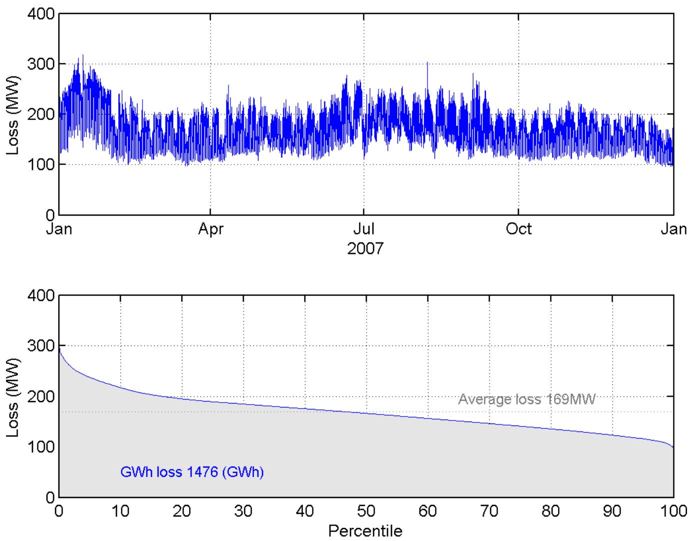

Fig. 2: Losses in Transpower's network – 2007.

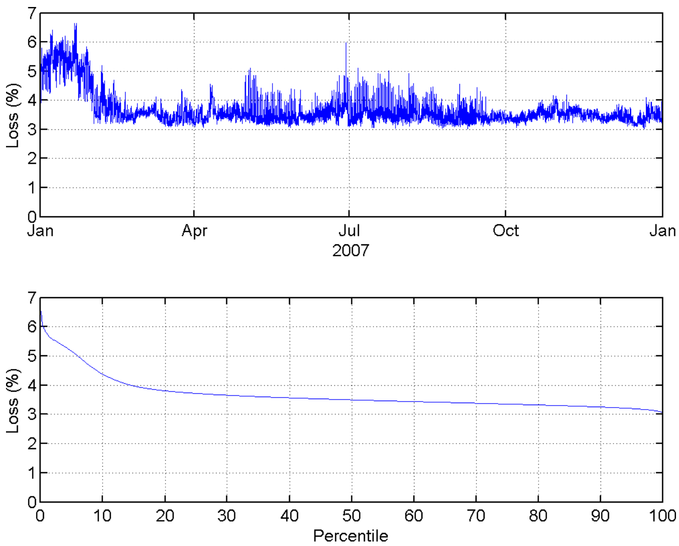

Fig. 3: Losses in Transpower's network (as % of generation) – 2007.

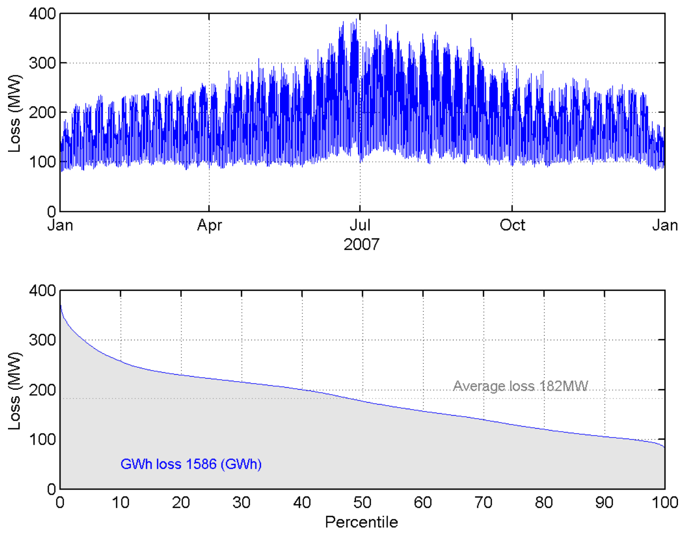

Fig. 4: Losses in Distribution network – 2007.

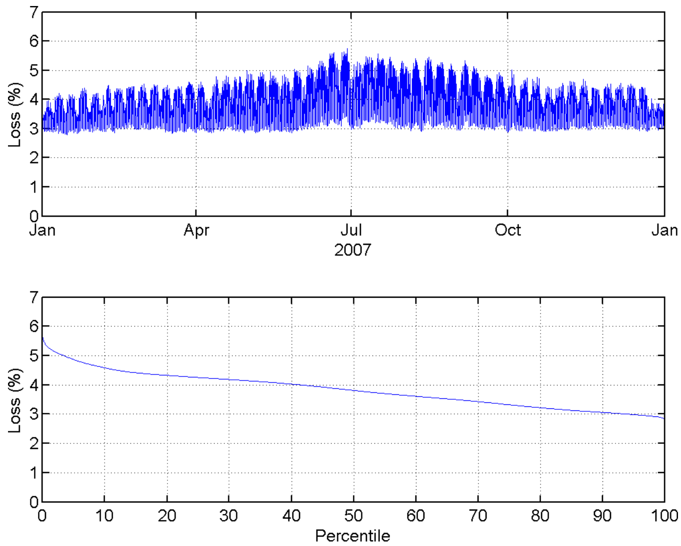

Fig. 5: Losses in Distribution network (as % of generation) – 2007.

Figure 3 again illustrates Transpower's network losses, over each half–hour, but as a percentage of total half–hourly New Zealand generation. Of interest is the flat nature of the loss duration curve. Transpower's total losses vary between 3.0% to 6.7%, with an average of around 3.7%. Table III in Section II-C summarises this data.

Both figures show an increase in losses occurring during the summer months of January and February. Further inspection of the power system data over this period reveals a high northwards transfer on the HVDC link.

B. Distribution network loss

Under the Commerce Commission's Electricity Information Disclosure Requirements (2004), distribution or electricity lines companies are required to publish a number of performance measures. Included in these measures are the published loss ratio, load factor, maximum demand and the total electrical energy entering the system (before losses)[2]. Table I illustrates the published data.

[2]This last measure is a little ambiguous as it appears to be the total measured demand. It appears **not** to be the demand taken off Transpower's grid, which would exclude distributed generation by subtracting it from the total demand.

Along with distributed lines companies, there are a number of direct connect customers on Transpower's network. These customers are assumed to have a loss ratio of 0 (no attributable losses). Table II illustrates the estimated maximum demand and energy for 2007 for some of the larger direct connected customers. This information is made available from the Electricity Commission's Centralised Data Set (CDS).

Each line companies loss ratio represents the average loss over the year[3]. It is unclear what the behaviour of the losses in the distribution network are over time, so the assumption is made that losses behave in a similar manner to that described by equation 1. The rough rule–of–thumb described in the previous section is used, i.e., $\frac{1}{4}$ of total distribution loss is attributable to fixed standing losses in transformers.

For each Distribution Lines Company (DLC),

$$Ave.\ Variable\ Loss_{GWh} = k \sum_{hh=1}^{17520} I_{hh}^2 \tag{2}$$

$$Ave.\ Fixed\ Loss_{GWh} = \frac{1}{4} \times Loss\ Ratio \times DLC_{GWh} \tag{3}$$

[3]These losses also include non–technical losses, including theft, un-metered demand and reconciliation or metering errors.

TABLE I: Published Distribution Company data for 2007[a]

Company	Loss Ratio	Load Factor	Peak Demand	Energy (GWh)[b]
Top Energy	7.30	64.3	64.0	362.6
North Power[c]	3.50	76.7	144.0	967.2
Vector[d]	4.73	57.2	2241.8	11226.9
Counties Power	7.19	55.6	85.8	418.1
Well Networks	5.40	54.5	231.0	1166.2
Waipa Networks	6.39	67.4	58.1	343.0
Powerco	7.42	67.2	753.0	4435.6
Horizon Energy	4.33	74.3	94.1	612.5
Unison	5.19	60.1	318.9	1679.6
The Lines Company	7.00	64.4	58.4	329.5
Eastland Network	6.19	59.8	59.2	310.1
Scan Power	6.76	63.0	17.6	97.1
Central Lines	8.91	68.3	19.0	113.8
Electra	6.20	50.0	98.0	405.9
Marlborough Lines	6.90	64.6	63.2	357.4
Network Tasman	4.50	62.7	140.0	768.8
Nelson Electricity	4.46	56.6	31.7	157.0
Main power	5.11	66.2	84.7	491.7
Orion Energy	4.90	59.6	630.0	3286.6
Electricity Ashburton	4.02	57.0	99.6	497.2
Buller Electricity	9.78	66.0	7.9	45.6
Westpower	5.80	62.1	42.1	228.9
Alpine Energy	6.40[e]	68.7	112.8	678.5
Aurora Energy	4.60	56.3	275.5	1359.6
OtagoNet	6.40	78.8	54.5	375.8
PowerNet	6.30	69.9	113.9	697.8

[a] Most data from the year 2007.
[b] Annual energy supplied, before losses.
[c] In comparison to other lines companies, North Power has a very low loss ratio.
[d] Vector sold its Wellington network to Cheung Kong Infrastructure Holdings (CKI) in 2008, now called Wellington Electricity Lines. These figures include the Auckland plus Wellington demand.
[e] Based on the 2006 figure, Alpine Energy's loss ratio for 2007 was 2.9% and for 2005 was 10.0%

where the $Ave.\ Variable\ Loss_{GWh} = \frac{3}{4} \times Loss\ Ratio \times DLC_{GWh}$ and hh indicates each half–hour.

Solving for k gives a constant for each lines company that can then be used to estimate the variable portion of the half–hour loss, or;

$$Variable\ Loss_{hh} = kI_{hh}^2 \qquad (4)$$

TABLE II: Some of the larger direct connected demands

Company	Peak Demand	Annual Energy(GWh)
Pacific Steel[a]	49.9	205
Glenbrook[b]	116.5	493[c]
Kinleith[d]	79.3	585[e]
Kawerau[f]	155.4	970[g]
Winstone	47.9	281
PanPac	72.0	450
Tiwai	609.4	5321

[a] Pacific Steel is owned by Fletcher Building whose total electricity usage over all its operations is much higher than this.
[b] The Glenbrook steel mill is owned by New Zealand Steel.
[c] Glenbrook uses around 1100GWh annually, but has substantial (approximately 60%), internal generation capacity.
[d] The Kinleith mill is a pulp and paper mill owned by Carter Holt Harvey Ltd.
[e] Kinleith used around 829GWh in total, including around 244 GWh produced by its biomass co-generation plant (operated by Genesis Energy) in 2007.
[f] The Kawerau mill is a pulp and paper mill owned by Norske Skog Tasman. In 2008 Mighty River Power completed construction of a 100MW geothermal power station on this site.
[g] A small geothermal power station has historically provided around 230 GWh.

Repeating this process for each lines company and summing the data for each half–hour gives an indication of the estimated variable distribution losses and how they vary over the year. Figure 4 illustrates the estimated total distribution loss. The average loss is around 182 MW (or 1586 GWh) with a minimum of 81 MW and maximum of 390 MW. Fixed standing losses are assumed to be around 45 MW, or 397 GWh. As a percentage of generation, the distribution losses average 3.8% with a minimum of 2.8% and maximum of 5.7%.

C. Total New Zealand Losses

The total New Zealand loss time–series can be obtained by combining the results of the previous two sections. Figure 6 illustrates the total New Zealand loss for the year 2007. As illustrated, the average loss is around 350 MW, or over 3050 GWh, almost the annual demand of Orion Energy (Christchurch/Canterbury). A maximum loss of around 663 MW has been estimated to occur on the 6th of August at 6:30pm. During this time period the HVDC link was on 97

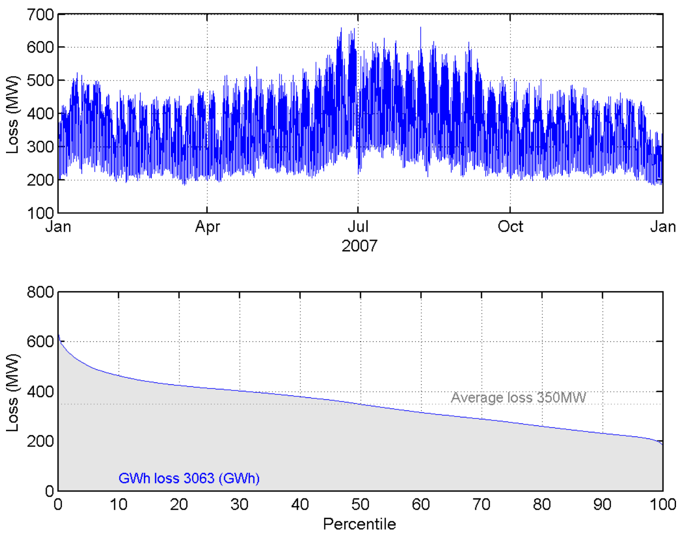

Fig. 6: Total New Zealand losses (in megawatts) – 2007.

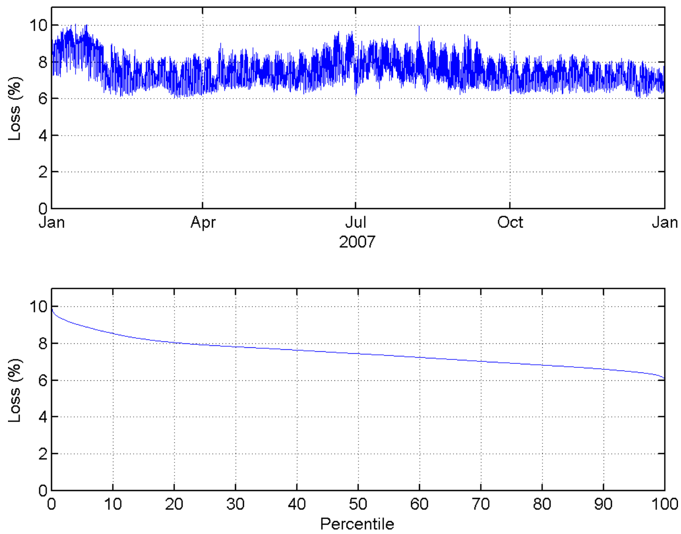

Fig. 7: Total New Zealand losses (as percentage of generation) – 2007.

TABLE III: Modelled New Zealand losses for 2007

	Transpower		Distribution		Total	
	MW	%	MW	%	MW	%
Ave.	169	3.7	182	3.8	350	7.5[a]
Max.	320	6.7	390	5.7	663	10.1
Min.	97	3.0	81	2.8	183	6.0

[a] This equates to around 3063 GWh of the 39720 GWh generated by grid connected generators for the 2007 year.

MW southward flow. The maximum percentage loss occurred at 10am on the 15th of January with an HVDC flow of 408 MW northward flow.

As a percentage of total New Zealand generation, the total New Zealand network losses are estimated to have averaged around 7.5%, with a minimum of 6.0%, and a maximum of 10.1% over the year. Table III summarises the results of losses that occured for the year 2007.

III. Losses in the market

In New Zealand, wholesale electricity is priced in terms of bids from retailers and offers from generators into a 'pool' market. Nodal prices are set half–hourly and differences in the nodal price, if no transmission constraints are binding, are set by the losses in the network. When transmission constraints arise for one reason or another, there can be price separation in the market.

The year 2007 witnessed relatively few transmission constraints (at least comparatively with 2008) with the bulk of the difference in nodal prices around the network being set by transmission losses. Many market participants believe lack of transmission investment is causing significant transmission constraints and price separation in the market[4]. However, HVDC aside, there appears little evidence to support this view. It is more likely that in an energy constrained market the nodal prices are high which correspondingly exacerbates the effects of losses in the market.

An important question then is: *"What quantifiable effect do losses play in the market?"* and in relation to this: *"How much total New Zealand demand can any single generator provide?"* These questions are not easily answered as they depend on generator location and the state of the power system which is continuously varying. Using the continuous power flow model a sub–routine has been developed that perturbs a number of individual generators around the New Zealand network. For each generator perturbation the total New Zealand demand is increased and HVDC transfer magnitude changed until both the North and South Island slack buses have the same pre and post perturbation values (within a preset tolerance). The demand served from the generator perturbation depends on the location and the power system state, or generator–dispatch combination. To give an indicative measure of the demand served a *loss factor* has been derived as the percentage difference of the demand served, or:

$$loss\ factor = 100 \times \frac{pert - \Delta demand}{pert} \tag{5}$$

where, $pert$ is the perturbation magnitude of a single generator and $\Delta demand$ is the change in demand served. Loss factors can be both negative and positive. A negative loss factor indicates that the generation perturbation actually lowers total New Zealand losses. For example a 10 MW perturbation, in the right location, and with the right power system dispatch combination, could actually lower total New Zealand losses and serve 12 MW of demand. The loss factor in this instance would be -0.2 or -20%. On the other hand, the same generator perturbation, with some other power system state or dispatch combination, may increase losses in the power system and serve only 8 MW of total demand. The loss factor in this instance would be 0.2 or 20%.

Figure 8 illustrates a subroutine procedure that fits into the 'Additional PSA' block of Figure 11 in the Appendix. It enables the automatic calculation of loss factors for multiple generators (demands if required) for every half–hour in a modelled year.

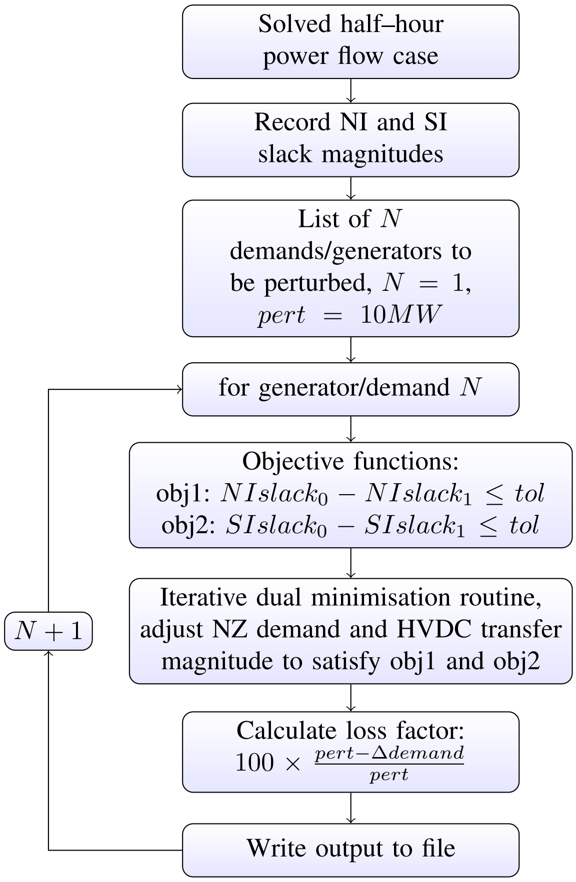

Fig. 8: Generator perturbation subroutine

In this instance the dual minimisation routine requires an average of four iterations to satisfy the two objective functions[5]. A convenient proxy for the power system dispatch–combination is the HVDC transfer magnitude. Plotting the loss factors, for several different generators against the HVDC transfer provides insight into the variation of losses with the power system state for different locations.

Figure 9 illustrates the results of the modelled loss factors for ten generators, as identified in Figure 1. The light pink and light blue scattered points are the modelled Ngawha (in the far North) and Manapouri (in the far South) loss factors, plotted

[4] This is true to some extent and was witnessed on a daily basis in early 2009, with Tiwai aluminium smelter on $\frac{2}{3}$rds output, wet hydrological conditions and transmission constraints north of Roxbrough and on the HVDC link resulting in three price separated regions.

[5] 58 different generators around the New Zealand power system were perturbed equating to $58 \times 4 \times 17650 = 4\ million$ power flow solutions.

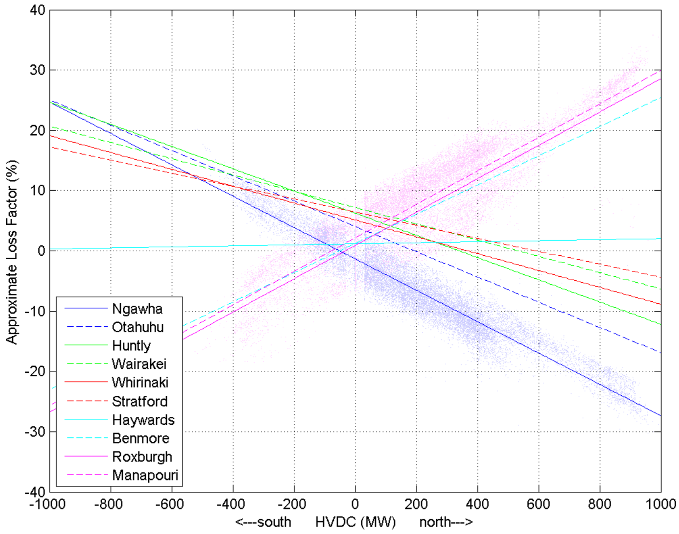

Fig. 9: Approximated (straight line fit) loss factors for ten locations (see Figure 1) vs the HVDC transfer magnitude.

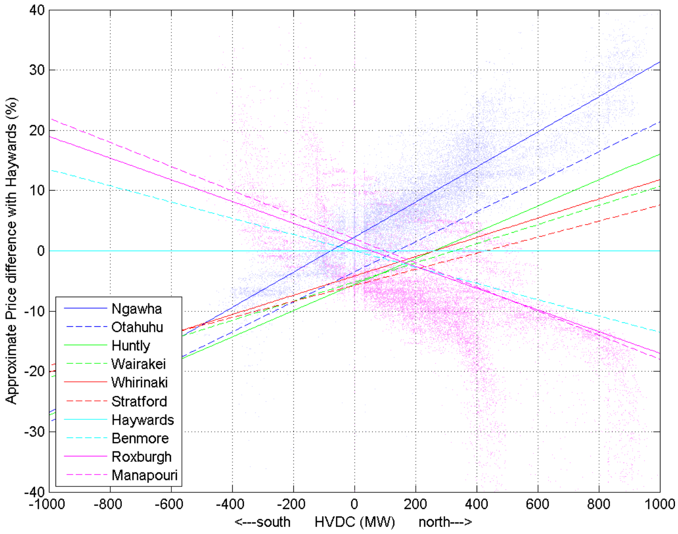

Fig. 10: Approximated (straight line fit) price difference compared with Haywards for ten locations *(see Figure 1)* vs the HVDC transfer magnitude.

against HVDC transfer. The straight lines provide a 'best fit' to this modelled data for all ten generators around the New Zealand system.

This figure helps quantify the effect losses play in the market by illustrating the dependence losses have on location and power system generation–dispatch (as indicative of the HVDC transfer magnitude). A number of insights can be observed, these include:

1) With high northward flow on the HVDC link, South Island generators have relatively high loss factors, or marginal loss. A 10 MW perturbation or increase in Manapouri generation will serve only 7–8 MW of demand during times of high HVDC flow (i.e., a loss factor of 20–30%).
2) Conversely, an additional 10 MW of generation at Ngawha (at the top of the North Island) during the same period will lower losses, serving up to 12–13 MW of total New Zealand demand.

Of course the opposite is true for high HVDC south transfer. Other interesting observations include:

3) The Haywards (Wellington region) loss factor appears to be almost independent of HVDC transfer.
4) Whirinaki (the solid red line) has significant loss attributed to it during periods of high HVDC south transfer. This is not ideal for dry year reserve generation. If Whirinaki were to be moved, or more reserve generation built, then the Wellington region would appear to be an ideal location (with a relatively low loss factor for all HVDC transfers and the ability to provide peak generation support for the North Island).
5) Assuming no transmission constraints, the difference in these loss factors should translate into the comparative difference in nodal prices set by the SPD model.

Figure 10 illustrates the comparative difference in nodal price between nine of the generators and Haywards, against HVDC transfer. Here, the light blue scatter plot is the price difference between Ngawha and Haywards, while the light pink scatter plot is the comparative price difference between Manapouri and Haywards.

As illustrated the price difference reflects the loss factor, inversely. At high HVDC northward transfer the price is likely to be 10–20% lower at Manapouri than at Haywards, and up to 50% lower than Ngawha (as indicated by the percentage difference between Ngawha (blue line) and Manapouri (dashed pink line). This situation occurs when there is surplus hydro in the South Island; prices are low and \$10/MWh at Manapouri would translate to \$15/MWh at Ngawha. In an energy constrained, or dry period, the price is set by the North Island thermal generators. If the HVDC is on high southward transfer, large price differences can result solely from the effect of losses. When prices are high, \$400/MWh at Ngawha could translate to \$600/MWh at Manapouri. Losses can therefore contribute to large nodal price differences around the network, even without transmission constraints binding. A very rough rule–of–thumb to determine if transmission constraints are binding might be when the percentage difference in price between the top and bottom of New Zealand is greater than the absolute HVDC transfer magnitude over 20, or,

$$Price\ Diff > \frac{|HVDC\ Transfer|}{20}$$

Transmission constraints are illustrated in Figure 10 where the historic difference in Manapouri price, versus Haywards price can be seen to diverge off linear at high HVDC transfers. This is the result of constraints on the HVDC link transfer[6].

IV. Effect of Losses on Power System Planning

A. Transmission investment

Additional transmission investment generally lowers losses. This can be recognised in the planning process by costing this benefit into the economic models. Loss benefits have been instrumental in several of Transpower's recent grid upgrade plans, including Auckland's 400 kV project. More recently, the reconductoring of the 110 kV transmission line between Masterton and Woodville was driven primarily by an associated loss benefit.

B. Generation investment

In planning both generation, and transmission investment to enable generation, effects on power system losses should be

[6]HVDC constraints can result because of reserve requirements that ensure the HVDC can act following a large contingent event (such as the largest generator in the receiving island tripping off–line.

TABLE IV: Estimated average loss benefits (%)

Generator	Ave. Loss Factor	Ave. Price diff
Ngawha	-6.8	7.6
Otahuhu	-0.3	0.7
Huntly	2.3	-2.2
Wairakei	4.3	-2.6
Whirinaki	2.2	-1.5
Stratford	4.1	-3.8
Haywards	1.4	0.0
Benmore	6.3	-2.1
Roxburgh	6.7	-2.2
Manapouri	8.0	-4.0

considered. Predicting the future is always fraught with some difficulty but reasonable insight can be gained from the past, as is illustrated with Figures 9 and 10.

Table IV illustrates the average loss factors and also the price difference with Haywards over the year for the ten generators presented in this paper. These results are based on an average hydro year, in this case the HVDC averaged around 210 MW northwards transfer for 2007 (1850 GWh). Similar results could be repeated over multiple years to give a broader indication of locational loss and therefore nodal price benefits for wet and dry periods. Regions that have consistent low or negative loss factors are more favourable for generation investment due to a premium nodal price (i.e., the Northland/Auckland and Wellington regions for 2007).

Consider two wind generation sites of the same resource quality located in the Wairarapa region, and in Southland. On the basis of losses, the Wairarapa region would be more favourable in an average hydro year. However, future loss benefits are dependent on a number of factors including hydrological conditions, transmission and generation builds, future demand, and the size of any planned generator (as the effect of a large generator substantially alters the power system generator–dispatch state and therefore the associated loss factors). Therefore, dry periods such as those seen in 2008 would make the Southland wind farm option more comparable.

V. Summary

This paper has estimated the total New Zealand loss on both the high voltage and distributed networks (Table III). It has quantified the effects losses have on nodal prices and the large variations in price that can result, without binding transmission constraints. This effect is exacerbated during energy constrained market periods when the price is high. Regions with consistent long term negative loss factors are likely to be prime candidates for premium prices and therefore generation investment.

Appendix

The continuous power flow algorithm provides a methodology to iteratively solve a power flow over multiple operating points. It's strength is in its ability to perform continuous power flows over a given (historic) data series. In this instance, the load flow model includes Transpower's high voltage network, including both the North and South Islands and the HVDC link as used for the 2008 Statement of Opportunities[7].

As both islands are included, there are two slack buses for each island[8].

Essentially there are two stages;

Stage 1 Obtain time–series input data for each GXP, modelled generator, and HVDC link. Care is required so that data files relate to what is modelled[9];

Stage 2 Initiate continuous power flow algorithm. For each time–step in the time–series input data, a power flow solution is attempted. Upon solution, additional PSA subroutines are initiated and output written to a file. The time–step is advanced and demand, generation, and HVDC data are read into the power flow. The power flow is solved, and the process repeated.

Figure 11 shows the basic algorithm used for the continuous power flow.

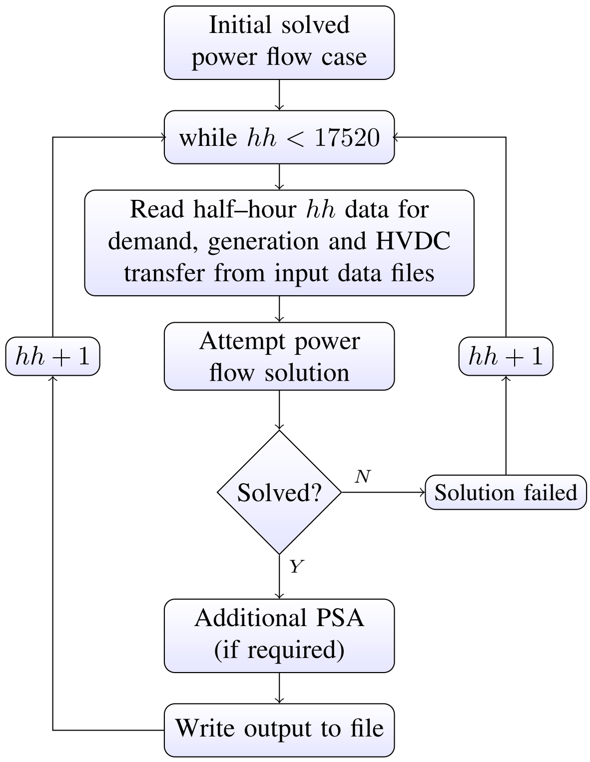

Fig. 11: The continuous power flow algorithm.

In this paper the continuous power flow has been used to estimate the high–voltage network losses and to determine the loss factors at a number of different sites. It has also been used in assessing Transpower's Wairakei Ring Grid Upgrade proposal[10] and could have many more potential applications.

References

[1] T. Alvey, D. Goodwin, X. Ma, D. Streiffert, D. Sun, *A security–constrained bid–clearing system for the New Zealand wholesale electricity market*, IEEE Transactions on Power Systems, Volume 13, Issue 2, Page(s):340–346, May 1998.

[7] http://www.electricitycommission.govt.nz/opdev/transmis/soo/08supportingdocs

[8] Slack buses can be either a known generator or a fictional generator connected to the system that generates what is required to *take up the slack* and solve the power flow.

[9] For example, distributed generation behind a GXP that is **not** modelled in the power flow needs to be included as a negative component of the GXP demand.

[10] http://www.electricitycommission.govt.nz/pdfs/opdev/transmis/gup/2008/wairakei-ring/technical-review.pdf