Power factor, reactive power and voltage stability in the New Zealand power system

EEA Conference 2011
SKYCITY Convention Centre, Auckland, New Zealand, 23–24 June 2011

David Hume, BE, PhD, MIEEE, MIET
Electricity Authority
Email: david.hume@ea.govt.nz

***Abstract*—**
Electricity transmission into the upper island demand regions of New Zealand is arguably one of the most important aspects of the New Zealand power system. Much of the population lives in these regions, there is little generation, and both regions are fed by relatively long transmission corridors. This physical nature means transmission limits are constrained by voltage stability, rather than the more typical thermal (physical) limits of the transmission circuits.

Voltage stability limits are determined using power system analysis. The assumptions used in this analysis therefore play an important role in the determination of appropriate transmission limits.

This paper demonstrates the dependence of transmission limits into the upper island regions on assumptions used in the power systems analysis. In particular, it investigates the dependence of voltage stability constraints on power factor using the Upper South Island (USI) as an example.

The paper then reviews the economics associated with reactive power investment, before briefly outlining the current options for how this investment might be paid for, and by whom. This is part of the on-going Transmission Pricing Review (TPR) which is investigating possible future changes to the Transmission Pricing Methodology (TPM).

***Index Terms*—Transmission Pricing Methodology (TPM), Transmission Pricing Review (TPR), Upper North Island (UNI), Upper South Island (USI), power factor correction, static reactive compensation.**

I. Effects of power factor of transmission constraints

A. Thermal constraint limits

Power factor is a measure traditionally used by electrical engineers to relate the effects of real power to total apparent power. A transmission line (with an apparent power rating, or capacity, of 100 MVA) which feeds a demand with a power factor of 0.94 would be fully loaded when the real part of the demand was 94 MW (the reactive part being around 34 MVAr and the total power being 100MVA). This situation is illustrated in figure 1 by the red lines. Figure 1 also illustrates other power factors, for the same total transmission capacity. As power factor improves, the real (or useful MW) power transfer increases until unity power factor.

Along with thermal capacity benefits, an improvement in power factor towards unity can have additional benefits, including; improved voltage regulation, lower losses, and in networks subjected to voltage stability, significant increases in the stability limit. This is investigated in the following sections.

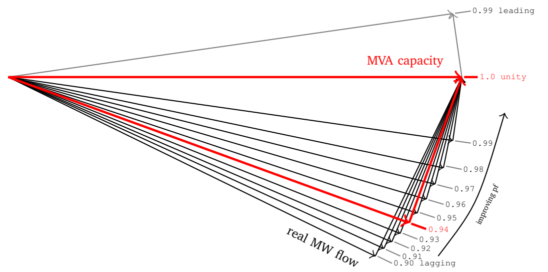

Fig. 1. Relationship between real (MW), reactive (MVAr) and total apparent (MVA) power for power factors between 0.9 lagging and 0.99 leading.)

B. Effects of power factor on voltage

The effects power factor has on voltage can be demonstrated by a two bus power system model, and accompanying phasor diagrams. A simple two bus system is illustrated in figure 2. Though simplified, this has similarities with both radial upper island demand regions in New Zealand.

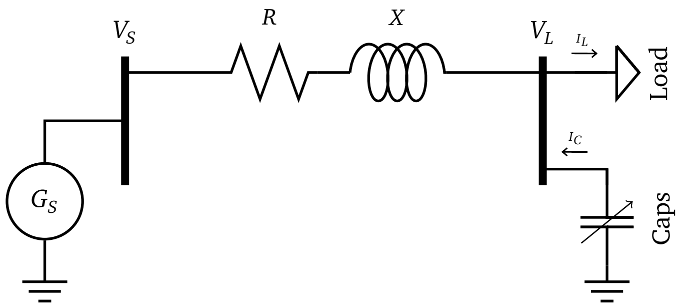

Fig. 2. Simple two bus power system

A strong generation bus at the sending end has a constant voltage V_S. This is connected by a single transmission circuit, represented with resistance R and reactance X to the load bus with voltage V_L. The load, I_L, is assumed to have a power factor of 0.94 lagging[1].

The phasor diagram representation of the two bus system can be drawn with the sending end voltage, V_S, assumed to be constant. In the power flow sense this is the slack bus

[1]A power factor is lagging when the current lags the voltage and the demand has some reactive consumption, likewise, a demand is leading when the current leads the voltage and the demand provides reactive power. There can be confusion over power factors of synchronous machines. A machine is said to be lagging if suppling reactive power and leading if consuming reactive power.

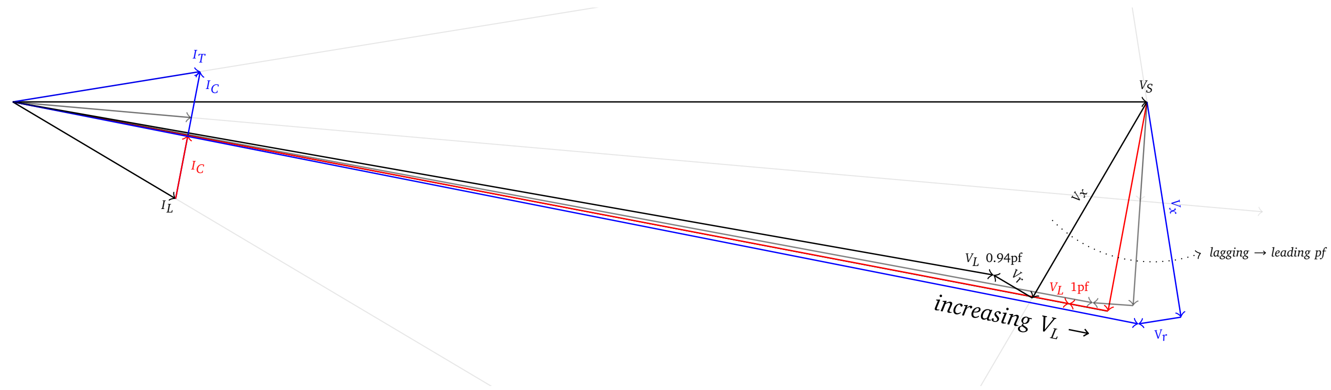

Fig. 3. Phasor diagram of the two bus power system in figure 2, demonstrating dependence of receiving end voltage V_L, with improving power factor from 0.94 lagging, through unity to leading (approximate scale for illustrative purposes).

with a voltage of 1pu. The voltage drop across the transmission line, $V_x + V_r$ is dependent on; the line impedance $R + jX$, and the current flowing through the line, which in turn, is dependent on the demand magnitude I_L, its power factor, and any static reactive power compensation supplied by capacitors.

No power factor correction
This is illustrated by the black lines in figure 3. The magnitude of the receiving end voltage V_L equals the sending end voltage, V_S, minus the voltage drop across the transmission line impedance; V_r across its resistance and V_x across its inductance. At a power factor of 0.94 lagging the receiving end voltage is noticeably lower than the 1pu sending end voltage.

Power factor correction to unity
Improving the power factor to unity is achieved by installing capacitors on the receiving end bus. The current flowing out of the transmission line at the receiving end is the phasor addition of the lagging load current, I_L, (in black) and I_C (in red)[2]. The receiving end voltage is improved; as illustrated by the red lines.

Equally compensated transmission line
Contrary to popular belief the most efficient operation, in terms of I^2R losses, occurs when the transmission line current I_T is lagging V_S and leading V_L. The power factor at the receiving end is slightly leading with the line being compensated from each end. This is illustrated by the light grey lines.

Leading power factor
Finally, an example of a leading power factor is given in blue. Here, the transmission line current leads both voltages and reactive power flows from the load, into and through the transmission line with 'excess' reactive power flowing back into the source, or sending end slack bus.

General observations:

- Receiving end voltage is highly dependent on power factor. Dependence increases with;
  - increased loading I_L; and,
  - higher line impedance, $R + jX$,
  - These increase the transmission voltage drop V_x and V_r effectively levering the dependence on power factor;
- Voltage regulation at the receiving end bus will be most stable when the magnitude of the sending end voltage $|V_S|$ is equal to the magnitude of the receiving end voltage $|V_L|$;
- Most efficient operation occurs when both ends of the transmission line are compensated equally.
- The upper island regions of New Zealand share these characteristics, in particular, the USI which has little generation for the size of its demand.

C. Voltage stability limits

Voltage stability limits are determined using a Power–Voltage (PV) curve analysis. This is accomplished by using a power flow model of the network of interest and iteratively increasing the demand throughout a region, while monitoring the voltages of all buses within the region.

Demand characteristics are important in PV analysis. It is often assumed that all load being modelled (and iteratively increased), is of a *constant power* nature. For a decrease in voltage magnitude, the current of the demand will increase in order to keep power constant. This non-linear behaviour is associated with tap changer operation of supply transformers. As a result, PV analysis is sometimes referred to as being of a longer term voltage stability type analysis (as tap changer operation can range from seconds to minutes). Some power electronic consumer appliances may also have a similar, though much faster constant power characteristics. A constant power characteristic is a fairly onerous assumption. In reality almost all loads will have a better characteristic than this. For example, at peak demand a significant part of the demand will be constant impedance (e.g., electric heating) or constant current (e.g., power electronic appliances).

Assume the load I_L in figure 3 is modelled with a constant power characteristic with a lagging power factor (as indicated by the black lines). In a PV analysis, the load is slowly increased with each iteration of the power flow. As the load increases, the voltage drop across the transmission line increases (the magnitudes of V_x and V_r grow). This causes the receiving end voltage to fall and assuming a constant power characteristic, causes the load current I_L to increase. The situation is improved with increasing power factor.

Figure 4 illustrates the results of a PV analysis on the USI. As power factor improves, the voltage stability limit into the USI also improves[3]. This dependence is quite different to

[2]Note that the current through a capacitor always leads the voltage across it, as such the current I_C is drawn perpendicular to the receiving end voltage.

[3]A general rule of thumb is to use a 5% margin from the collapse point on the PV curve and set this as the stability limit.

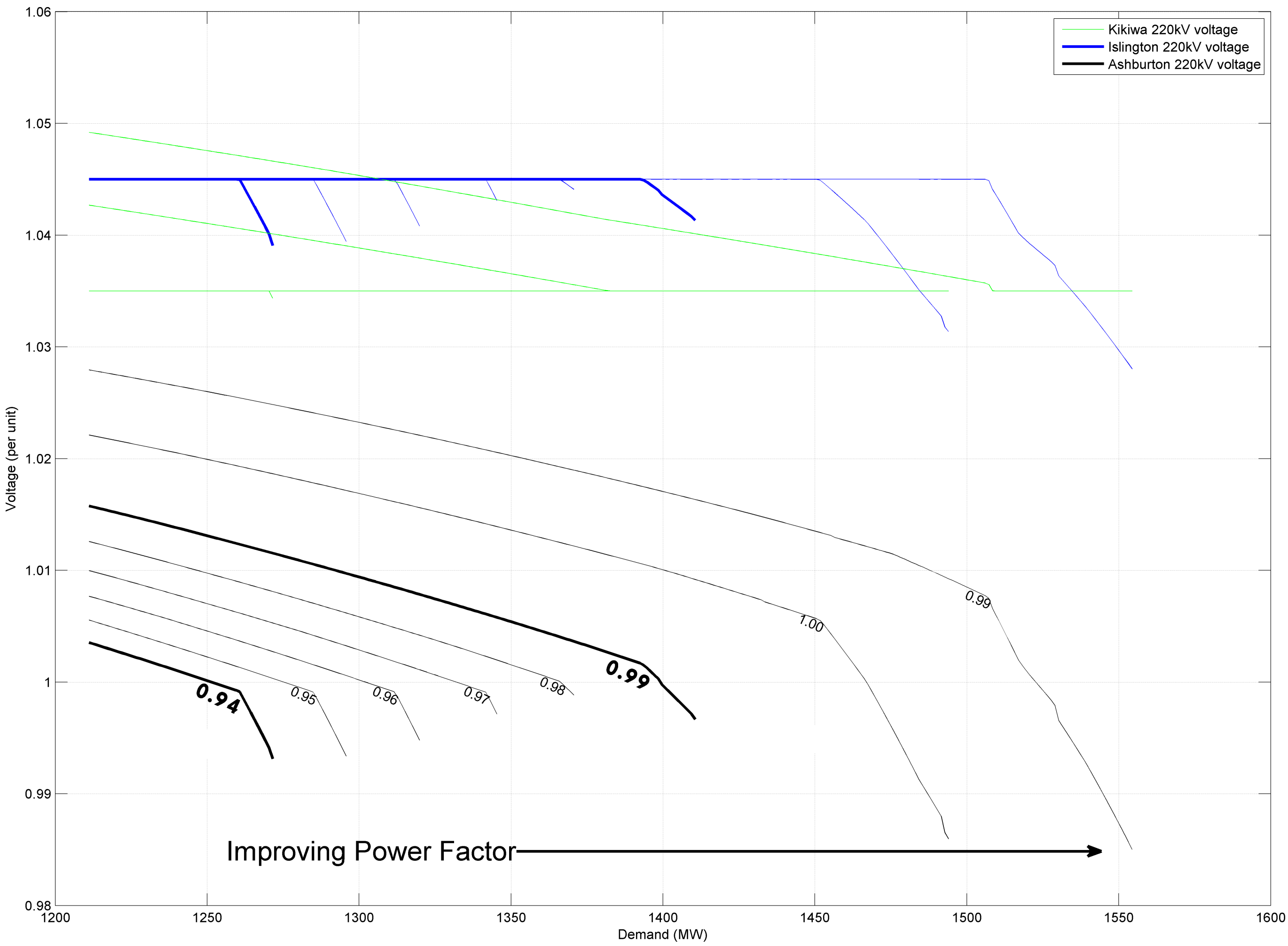

Fig. 4. Upper South Island Power–Voltage (PV) curve illustrating falling voltages with increased demand for different power factors.

the typical thermal limits normally associated with power factor. From observation of figure 4 the following can be concluded for the USI;

From 0.94 (lagging) through to unity

- The voltage stability limit increases from 1270MW to around 1470MW;
- This is a 16% increase in real power transfer; significantly more than the 6% if traditional thermal limits applied.

From 0.99 (lagging) through to unity

- The voltage stability limit increases from 1400MW to around 1470MW;
- This is a 5% increase and five times more than expected over the traditional thermal improvements associated with power factor.

General observations

Given the high dependence of power factor on voltage stability limits, any power system analysis should assume power factors that match as closely as possible to those that are known or metered.

A suitable power factor for analysis of voltage stability limits into the USI can be read directly from Centralised Data Set (CDS), as presented in figures 5 and 6. For the USI a power factor of 0.99 (lagging) would seem appropriate and perhaps 0.985 (lagging) for the UNI.

D. Dynamic modelling

In addition to PV analysis, additional dynamic modelling is often required to help determine dynamic load behaviour and voltage issues. This analysis is run in the time domain and typically investigates different types of fault that can help set dynamic 'head room'. I.e., setting the pre-contingent operating point of the reactive devices with fast reactive response (SVCs etc). Once adjusted, the aim is to ensure there is enough dynamic margin to control system voltages within limits following a contingent event.

A major issue with dynamic models are the number of assumptions required. For example, the assumptions relating to the load make-up include many different parameters that try to model the dynamic behaviour of the connected networks. This includes parameters such as the numbers and types of induction machines estimated to be connected.

Load surveys may help in this regard. Transpower has conducted surveys in both upper island regions to help estimate these assumptions[a]. A limiting factor of power factor improvement may be over voltage issues resulting from load or line trips.

[a] One hypothesis is that power factor improvement within the connected network will help the dynamic response/recovery of the network. An improved power factor on a LV bus is likely to mean the voltage stays high helping to prevent connected induction motors from stalling.

However, to-date the author has not found this, perhaps due to the severity of the faults applied, or the equivalent distribution network model used. In any case, this may warrant further work.

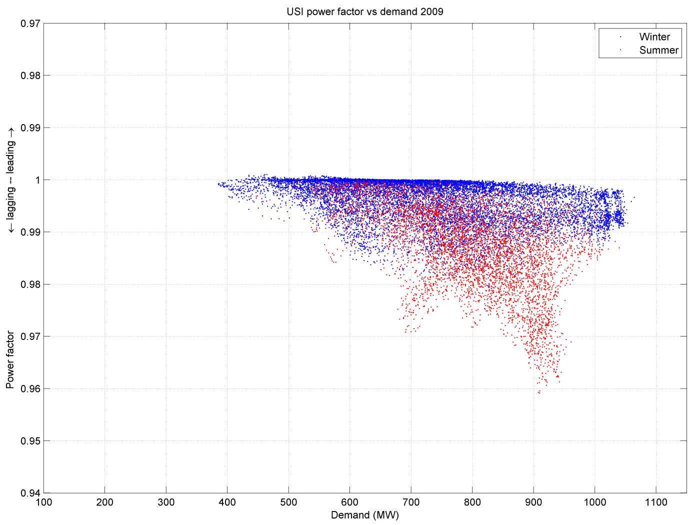

Fig. 5. USI power factor – 2009

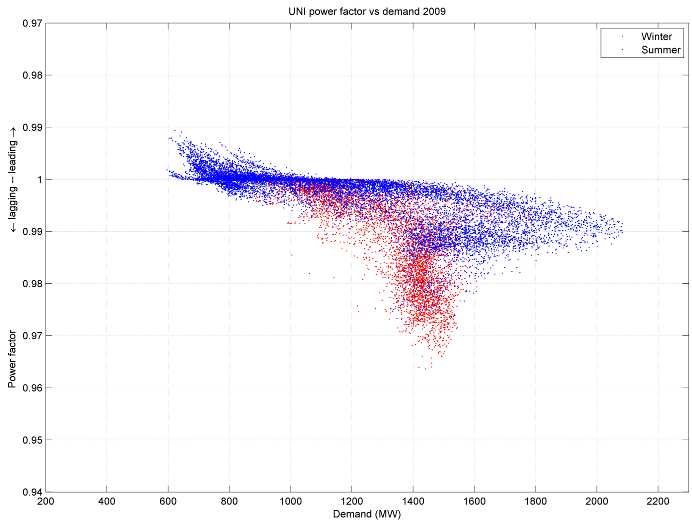

Fig. 6. UNI power factor – 2009

II. The economics of power factor correction

The economics of power factor correction are well documented when considering traditional thermal limits.

Costs are associated with the installation of capacitor banks, while benefits arise through increases in transmission limits and reduced losses. An improvement from 0.99 (lagging) to unity will increase the real power transfer by 1% in a thermally constrained system. Comparitively, in a voltage stability constrained region the increase can be much higher than this, e.g., 5% in the USI example.

In 2007, the Electricity Commission presented some work on the economics of power factor correction[4]. The work was basic, considering only loss reduction benefits. It failed to consider overall benefits, in particular capacity benefits. Yet, the benefits identified (with the assumptions used) appeared sufficient to help inform the Commission with regard to who should pay for reactive power investment.

The Commission decided a change in the Connection Code was required[5]. The original requirement of 0.95 lagging was improved to 1.0 (unity) and took effect from the 1st of April, 2010. It has since been widely criticised.

The Electricity Networks Association (ENA) consulted SKM to update the Commission's analysis and presented this in a submission to the recent Transmission Pricing Review[6]. The SKM analysis generally improved on the analysis conducted by the Commission. It reflected more detailed cost estimates, but treated power factor in the traditional sense, failing to realise the effects of power factor on voltage stability limits.

A. An USI example

In the USI, an improvement in power factor from 0.99 (lagging) to unity would require 170MVArs of capacitor banks. This would cost around \$17m and lift the voltage stability limit roughly 70MW. Assuming an LRMC of transmission at \$1m/MW, power factor correction would provide a net benefit of around \$53m[a].

[a]Another way of estimating this is to assume an annual peak demand growth of around 1.7%. This would defer a new transmission line from Twizel to Christchurch by three years. If the cost of a new double circuit 220kV transmission line from Twizel to Christchurch is around \$350m, this would save approximately: $17 + \frac{350}{1.07^3} - 350 = \$50m$.

[4]*See http://tinyurl.com/3n3h5n8*

[5]The Connection Code is an attachment (Schedule 8) to the Benchmark Agreement which provides a basis for negotiation of individual commercial agreements between Transpower and its customers. It is available at http://www.ea.govt.nz/document/11646/download/act-code-regs/code-regs/the-code/

[6]http://www.ea.govt.nz/document/11142/download/search/

III. Who pays?

The Transmission Pricing Methodology (TPM) is the method used by Transpower to allocate charges to its customers. With \$3bn of transmission currently approved, Transpower's annual revenue requirement is set to increase from around the current \$680m to an estimated \$1000m by 2015.

Depending on the outcome of the current Transmission Pricing Review this could double off-take customers transmission charges between 2010 – 2015.

As part of the review, a static reactive compensation subcommittee is providing advice to the Transmission Pricing Advisory Group (TPAG) on how to charge for static reactive investment. Three possible options include:

Option 1 (Amended Status Quo Option)
: Amending the current standard in the Connection Code for the USI and UNI regions to unity or leading power factor;

Option 2 (Connection Asset Definition Option)
: Widening the definition of 'connection asset' to include new static reactive power investments;

Option 3 (kvar Charge)
: Determining an appropriate kvar charge to incentivise more cost effective investment in static reactive support; either in the transmission network or in the distribution network in each case, regardless of the power factor at the GXP in question.

All three could be considered 'beneficiary pays' to a greater or lesser extent. These options should therefore help enable better power factor management into the future.

At the time of writing this work is ongoing. The outcome will feed into a recommendation to the Electricity Authority board by the TPAG advisory group.

IV. Conclusions

The high dependence of power factor on voltage stability limits has been demonstrated. This requires careful treatment of;

- the power systems analysis assumptions, where power factor should be modelled as accurately as possible, and;
- the economic calculations, which typically assume a traditional thermally constrained system.

Although small in comparison to the current overall transmission build, power factor improvement during peak demand periods in the upper island regions to unity (and possibly beyond) appears sensible in future years. Current options for the pricing of static reactive compensation should help enable better power factor management into the future.