

Power factors in the New Zealand power system

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Abstract

Power factor is a measure of how effectively electrical current delivers useful work / real power (megawatts (MW)) relative to the total apparent power (megavolt amperes (MVA)) flowing through the transmission/distribution system. Power factors close to unity (1) indicate effective utilisation of the system without imposing additional load, while lower power factors indicate increased reactive power flows and reduced effective utilisation.

This paper analyses longer term trends seen in power factors at transmission grid exit points (GXPs) using publicly available grid metering data. The study reveals a significant trend: lagging power factors have steadily improved, approaching unity and shifting into the leading region in some instances. This suggests that the connected distribution networks are becoming less inductive and more capacitive.

The trends have generally been good, with increasing power factors seen up to around 2018/2019, after which we observe power factors (especially during low demand overnight periods) starting to reduce again into the leading region. This raises concerns around both overvoltage management as well as increasing electrical losses during these periods.

1. Introduction

This paper is concerned with long term trends of reactive power flows through New Zealand power system grid exit points (GXPs).

Unlike real power, which is the portion of electrical power that does useful work, reactive power is the portion of electrical power that does not perform useful work. Reactive power is measured in volt-ampere reactive (vars) and arises due to the phase angle difference between voltage and current waveforms in AC power systems. These phase angle differences arise due to the fundamental components that make up the power system, specifically, inductors and capacitors. For example, in an inductor, current lags voltage, causing energy to be stored and released in a magnetic field. In a capacitor, current leads voltage, storing and releasing energy in an electric field. This back-and-forth energy flow is called reactive power.

Power factor is the ratio of real power (the power that does real work) to apparent power (the total power, real plus reactive, supplied). A power factor of 1 (or unity) is ideal, meaning all supplied power is real and used for work.

Managing power factor is important in power systems for three fundamental reasons:

- (a) Network capacity: low power factor increases apparent power, requiring higher capacity equipment for the same real power.
- (b) Voltage stability: reactive power helps maintain voltage levels in power systems.
- (c) Efficiency: low power factor increases current flow without doing useful work, increasing power system losses for the same real power.

In this paper we investigate the longer-term trends seen in power factor at GXPs across the New Zealand power system. We see a general trend of increasingly capacitive distribution systems where inductive reactive power consumption of the networks is reducing. During light loading we see networks becoming fully capacitive. This equates to power factors in New Zealand that are trending from lagging (inductive) to leading (capacitive).

Overall, this is a good news story. Power factors have generally trended towards unity and so losses and voltage regulation have generally improved. However, we have started witnessing power factors reaching their apex (unity) with power factors worsening since 2020, predominantly during the overnight, low demand periods. This is concerning as it presents increasingly difficult overvoltage management conditions for the system operator. When all reactive power equipment has been used for managing overvoltage, a last resort is to switch out transmission circuits. This increases losses and can lower power system reliability/security.

The paper is split into seven sections:

- Introduction
- Theory: power factor and the two bus model
- Long term power factor trends
- Overvoltage issues
- Current Electricity Authority work
- Conclusion

2. Theory: power factor and the two bus model

The relationship between real, reactive and apparent power is illustrated in figure 1.

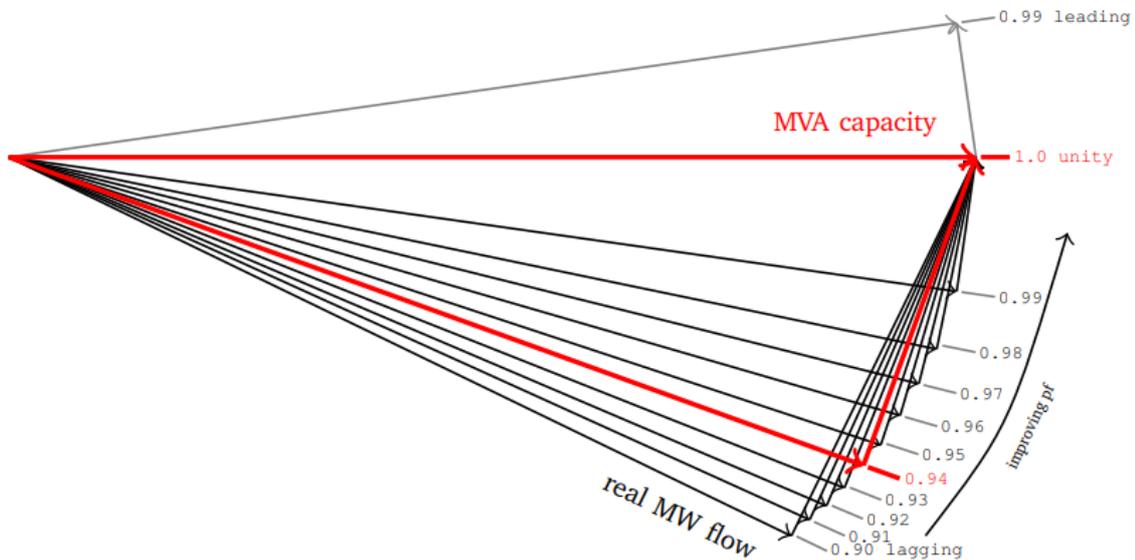


Figure 1 Relationship between real, reactive and apparent power at different power factors

Capacity

The relationship between power factor and total apparent power (MVA) line capacity is illustrated in the phasor diagram of figure 1. For any given distribution / transmission circuit or line of rated MVA capacity, the real and reactive components of the total MVA are illustrated at different power factors.

The length of the phasors is essentially equivalent to power or current flow. Therefore, as power factors improve, more real power can be conveyed within the capacity of the transmission and distribution networks.

Losses

Line losses are the result of heating in the resistive components of the power system.

Losses in the power system have two types:

- fixed or standing losses (that don't change and are essentially the loss from the power system being live through shunt resistance to ground), and,
- variable line losses that are proportional to the total apparent power (MVA) flow, or current. These losses are the (I^2R) losses and are highest during peak demand periods. As illustrated in figure 1, the total MVA (or current) is proportional to $\frac{1}{pf}$ and so losses are inversely proportional to the square of the power factor: $Losses \propto \frac{1}{pf^2}$ So, for example, a 0.9 power factor (lagging or leading) results in variable power system losses that are around 23% higher than what they would be at unity power factor.

Voltage

The effects power factor has on voltage can be demonstrated by a two-bus power system model (figure 2) and accompanying voltage phasor diagram (figure 3). Though simplified, this model is very powerful in demonstrating power system fundamentals.

A simple two bus system also acts as a simplified model of radial parts of the transmission grid, such as the demand regions in the upper North Island and upper South Island of New Zealand¹.

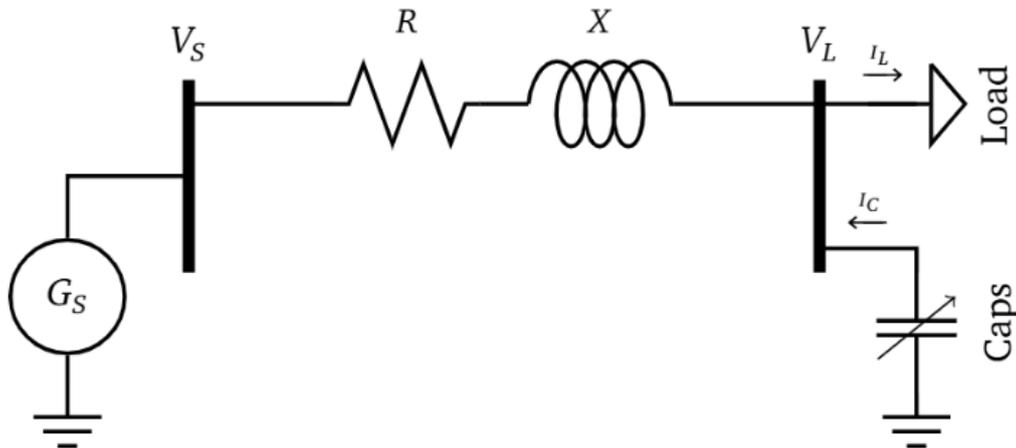


Figure 2 Simple two bus power system model

A strong generation bus at the sending end has a constant voltage V_S (represented by the horizontal black line in figure 3). 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 initially. As the connecting load becomes more capacitive (increasing I_C), the power factor transitions from lagging to unity and then into the leading range.

As illustrated, the voltage drop across the transmission line (V_X and V_R) rotates anticlockwise as the power factor transitions from lagging to leading. This increases the receiving end voltage V_L . Rotating the transmission line voltage drop clockwise (and therefore reducing V_L) can be achieved by lowering either shunt capacitance (for example removing lines with high shunt capacitance, such as high voltage cables), or adding shunt reactance/inductance to consume the excess reactive power of the load.

¹ The shunt capacitance of the connecting load and also the transmission line is represented by the variable Caps with current I_C . For simplicity, the shunt capacitance of the transmission line is not shown separately, and can be thought of as a fixed part of the Caps current I_C . Where reactive controlling devices are present, such as STATCOMs or SVCs, these are able to dynamically control I_C and are important for controlling voltage.

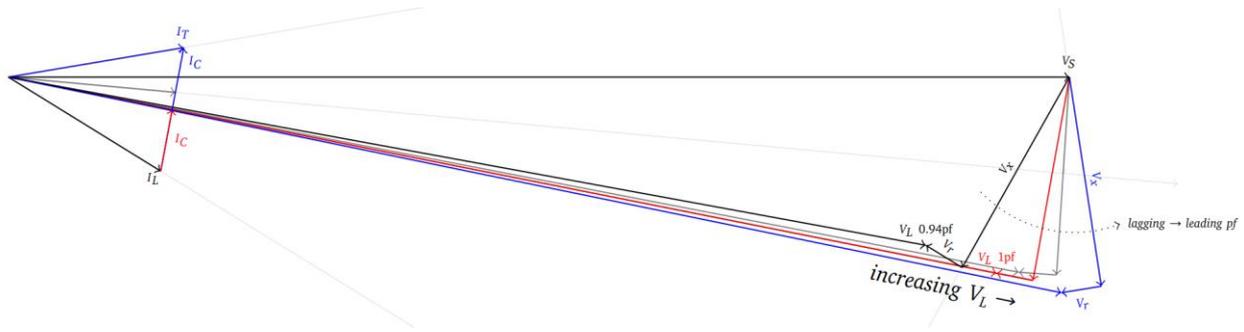


Figure 3 Two bus power system voltage phasors, from lagging to leading power factor conditions.

Lagging power factor

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.

Unity power factor

A unity power factor condition is one where no reactive power flows at the receiving end into or out of the transmission line. 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). The receiving end voltage is improved; as illustrated by the red lines.

Leading power factor

Finally, an example of a leading power factor is shown in blue. For this condition, the receiving end voltage is higher than the sending end voltage. Because of increased shunt capacitance, the transmission line current leads both voltage and reactive power flow from the load, back into and through the transmission line with 'excess' reactive power flowing back into the source or the sending end slack bus.

This case is currently topical during low demand, overnight periods, as will be shown in the following sections. We are witnessing connected distribution networks becoming increasingly capacitive with leading power factor conditions becoming the norm resulting in potential overvoltage conditions that require careful management by the system operator.

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 both increase the transmission voltage drop V_X and V_R , effectively increasing the transmission line voltage drop and the dependence on power factor.
- Additionally, higher capacitance from shunt capacitors or the natural capacitance of transmission circuits (and especially high voltage cables) during light load conditions ensures the voltage drop across the transmission line increases the receiving end voltage magnitude (even if V_X and V_R are smaller due to the lower demand). As such, removing

shunt capacitance, either by switching out circuits, or installing reactive power devices such as shunt reactors and STATCOMs becomes necessary.

The following section (using publicly available transmission grid metering data from the Electricity Authority's EMI database) looks at the trends observed in power factor across the GXP's of the New Zealand power system over the 15 years to 2024.

3. Long term power factor trends

In this section we look at the general trends seen in power factors at GXPs since 2009. Here we use publicly available data from EMI.² To get a general New Zealand-wide power factor we sum real power and reactive power (over all GXPs) to calculate an average or mean power factor for New Zealand and for each half-hour trading period since 2009.

Power factor trends since 2009

Figures 4 to 7 provide scatter plots of power factors versus real power demand in the New Zealand power system for the years 2009, 2014, 2019 and 2024 respectively.

Power factors above the horizontal unity power factor line are leading power factors, indicating the corresponding distribution networks are net capacitive and producing reactive power that flows back into the transmission grid.

A clear trend of increasingly capacitive networks and leading power factors is evident from the scatter plots:

- In 2009, the mean New Zealand power factor was always lagging (inductive).
- By 2014, this was still largely the case, although overnight periods were nearing unity at times.
- By 2019, we can start to see power factors reaching their apex (ie unity) and starting to lower into the leading power factor region during low demand periods.
- By 2024, this has continued with (leading) power factors lowering further during low demand overnight periods.

This sequence of observations indicates power factors have reached their apex in these periods and hence reactive power flows and power factors are now trending in an adverse direction.

Power factor has reached its apex?

To further illustrate this, figures 8 and 9 show a rolling annual mean power factor for each trading period. Here we see power factors falling below their apex after 2018 for the period between 9pm and 7am with the worst leading power factors occurring around 3am to 5am.

Figure 10 shows annual box plots of the trends in average power factor at both peak demand periods (Trading Period 37, 6:00pm-6:30pm) and a typical minimum demand period (Trading Period 8, 3:30am-4:00am).

These plots illustrate the average power factors over the entire New Zealand network and as such we don't see the variations between regions and individual GXPs.

Recent work completed by the system operator as part of the Electricity Authority's Future Security and Resilience (FSR) project has shown significantly poor leading power factors in overnight periods at certain GXPs. One example of this is illustrated in figure 11.

² Available here: https://www.emi.ea.govt.nz/Wholesale/Datasets/Metered_data

Although demand is low during these periods, poor power factors overnight will be increasing transmission grid losses and making voltage management difficult for the system operator.

This leads us to the following section where we investigate the potential for overvoltage issues in the future.

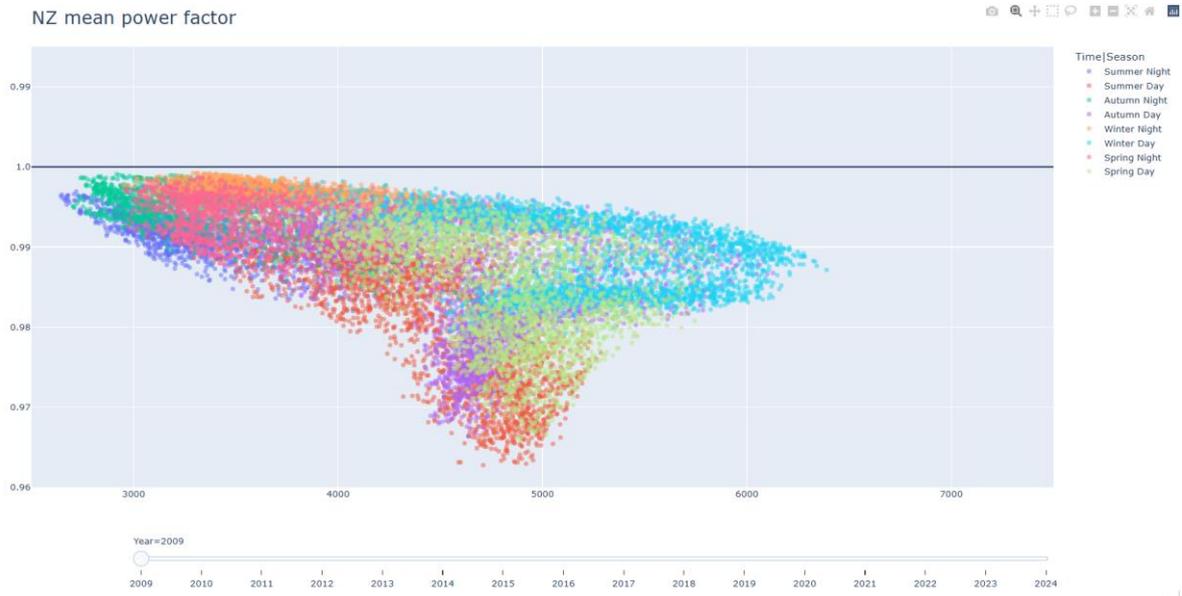


Figure 4 NZ mean power factor vs demand 2009

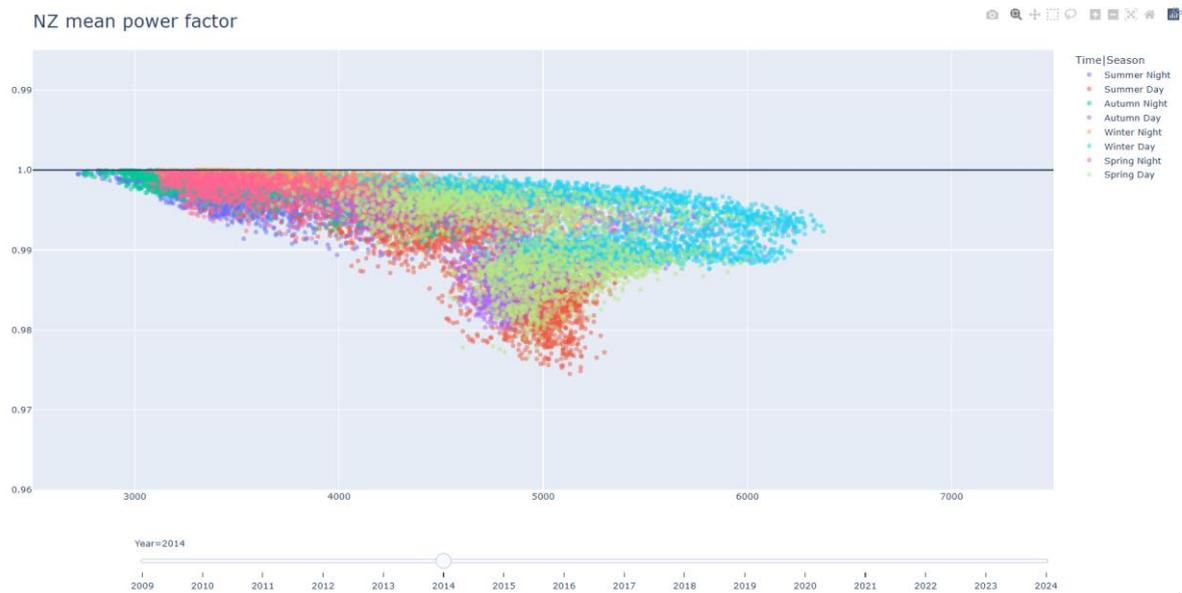


Figure 5 NZ mean power factor vs demand 2014

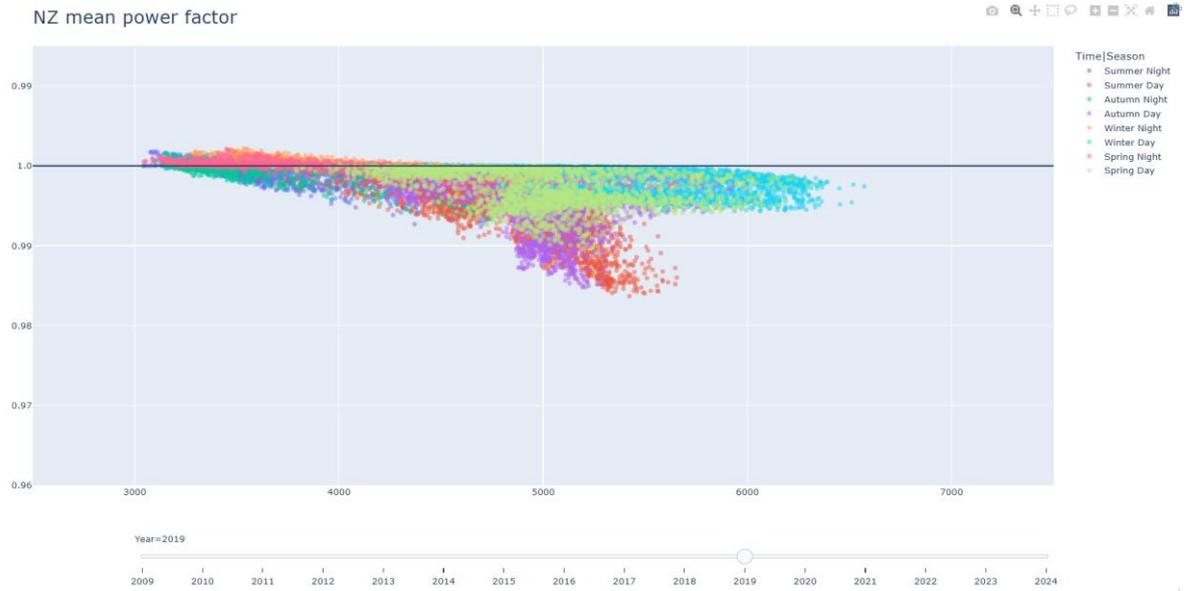


Figure 6 NZ mean power factor vs demand 2019

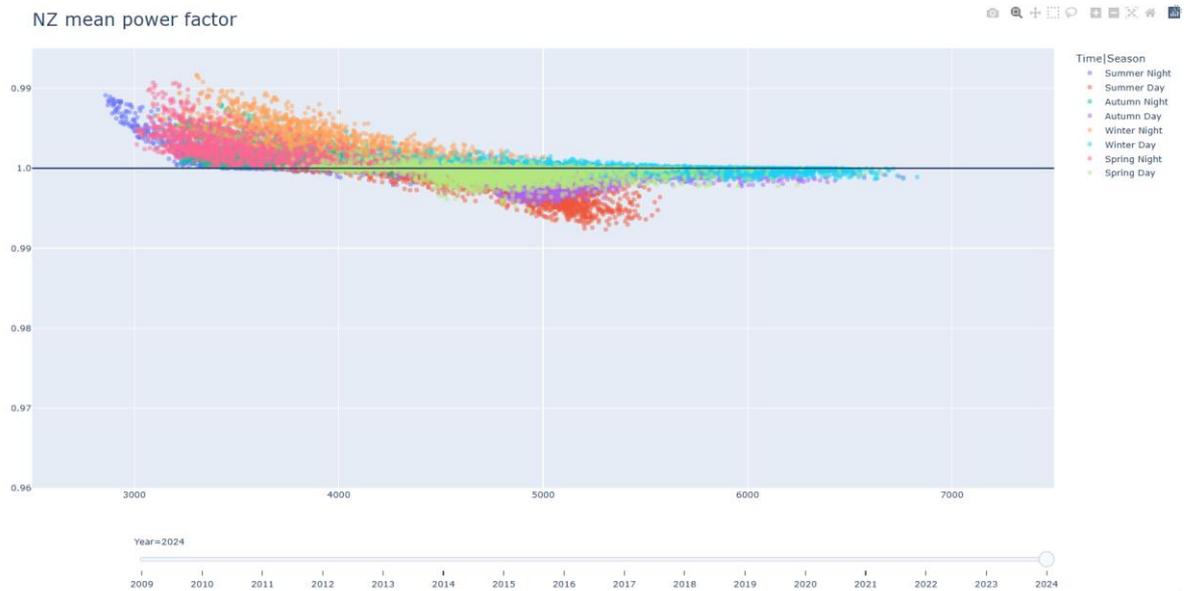


Figure 7 NZ mean power factor vs demand 2024

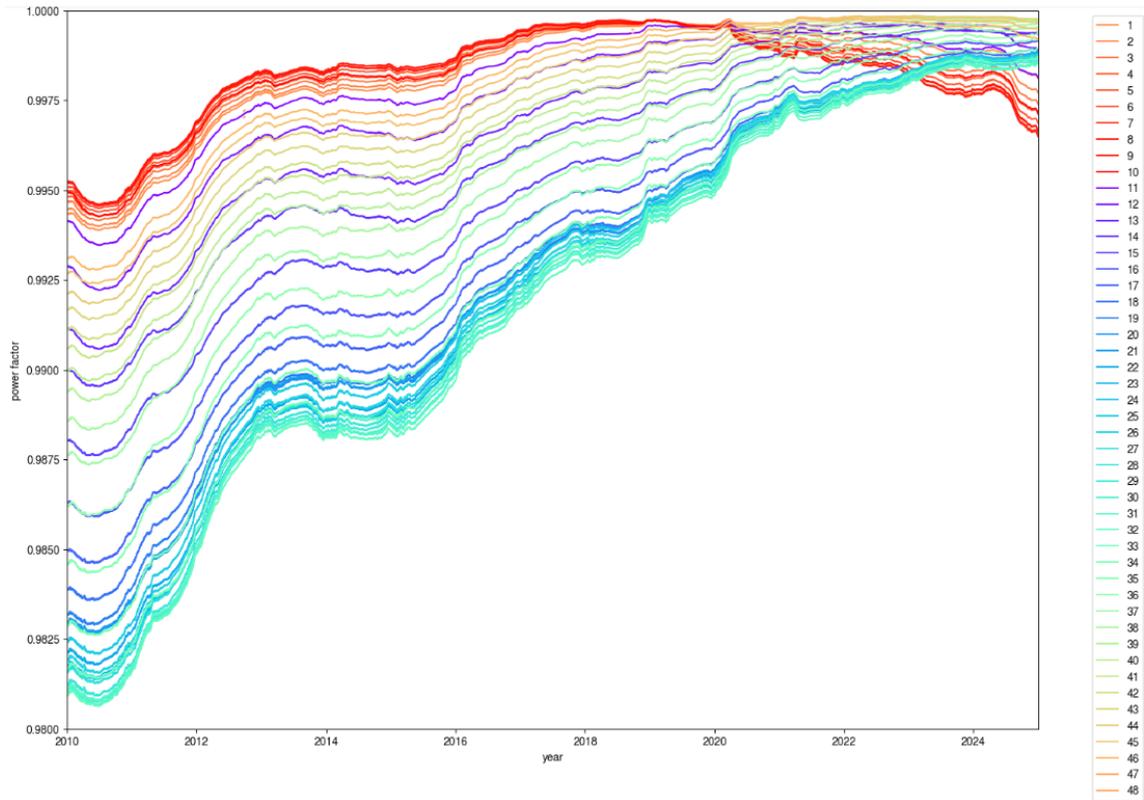


Figure 8 Rolling annual average power factors per half-hour trading period

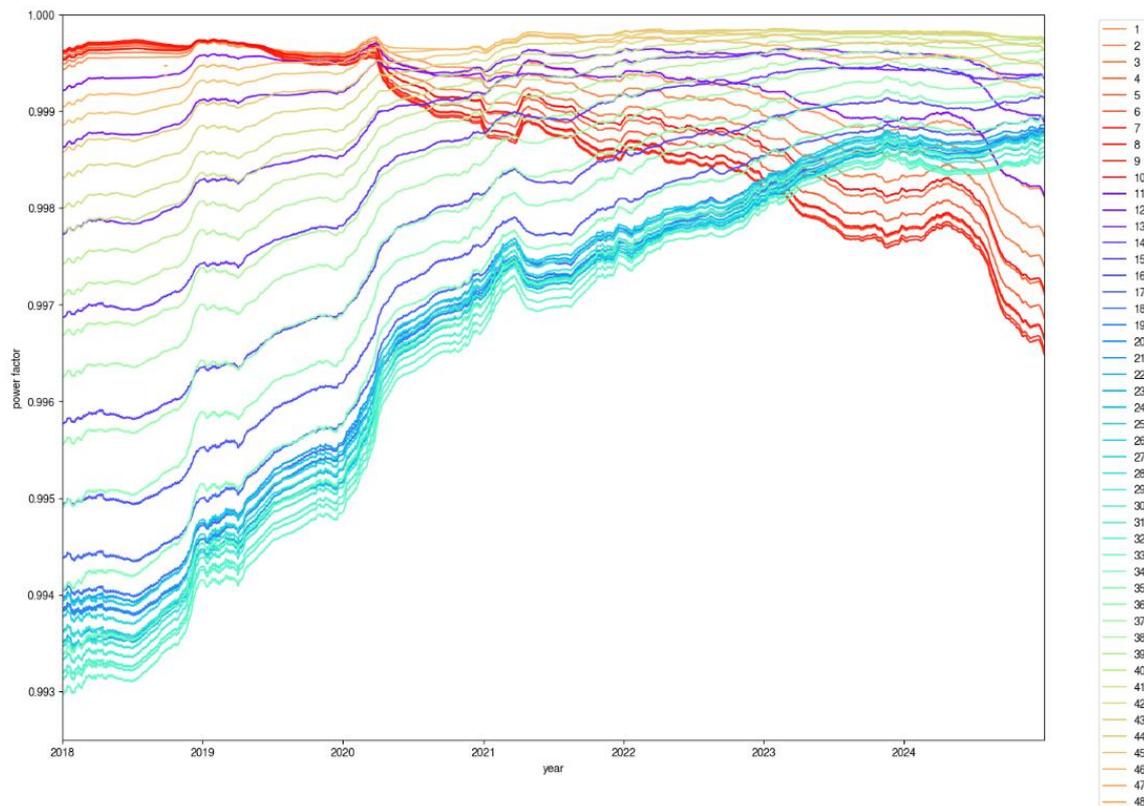


Figure 9 Rolling annual average power factors per trading period (since 2018)

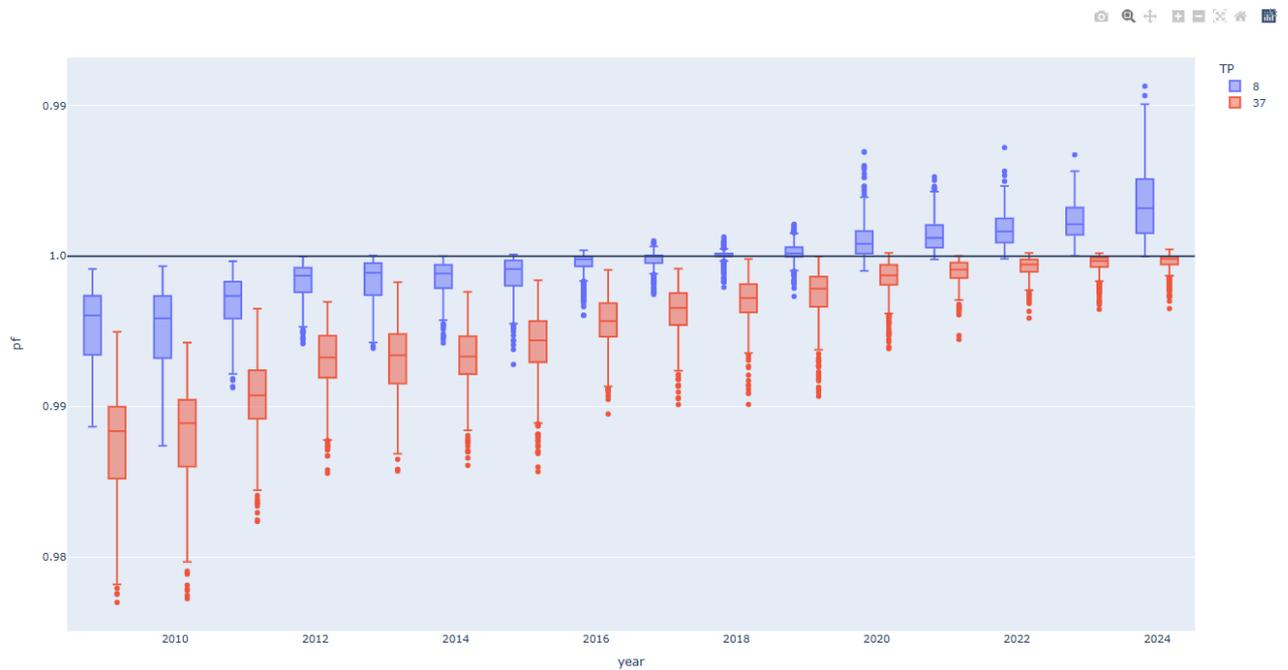


Figure 10 Annual box plot comparing change in average power factor for Trading Period 8 (3:30am-4am) and Trading Period 37 (6:00pm-6:30pm)

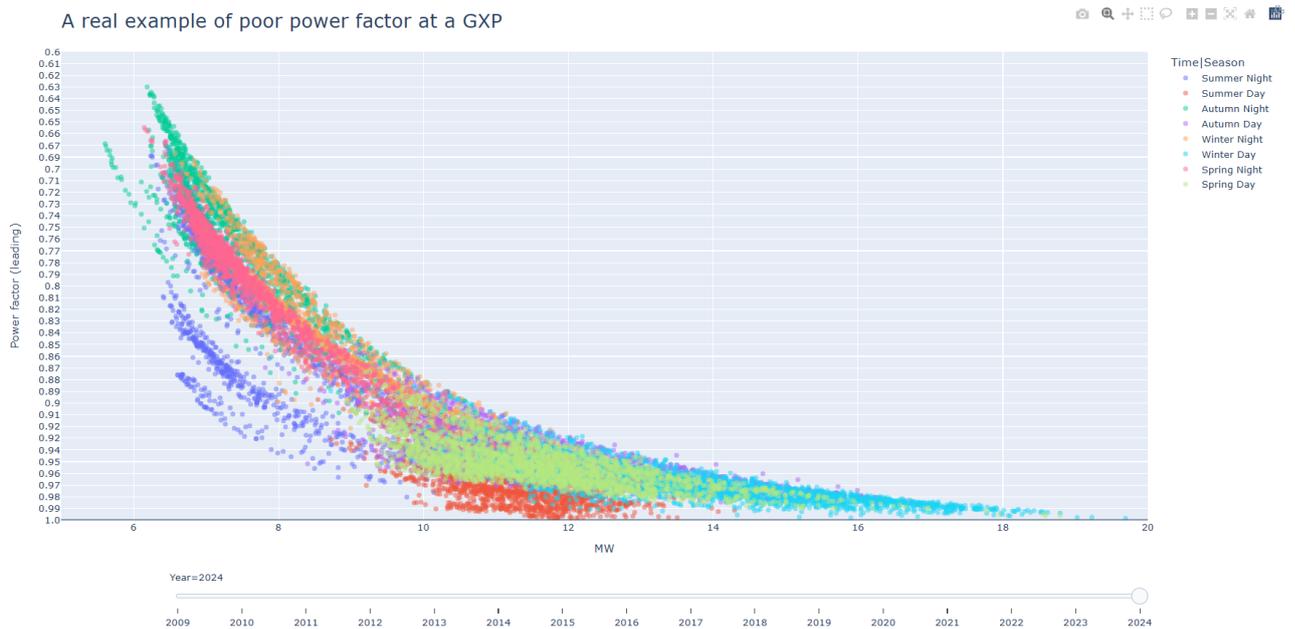


Figure 11 Example of a poor leading power factor GXP

4. Overvoltage issues

An international problem?

Internationally overvoltage is increasingly becoming an issue on many power systems. While several factors contribute to the issue, the most likely factors are:

- 4.1. Increased transmission and distribution network investment in assets that result in increased capacitance, as networks prepare for a future with a broader range of operating conditions.
- 4.2. High levels of distributed generation such as rooftop solar PV reducing transmission system load, leading to overvoltage issues. Although reports are preliminary, overvoltage was a major, if not the primary reason, for the recent Spanish blackout on 28 April 2025 (A.8).

Transmission and distribution network investment

Upgrading transmission and distribution networks typically reduces the series reactance (and resistance) and increases shunt capacitance of the connected networks. This is particularly the case when networks opt to invest in underground cabling which can have a large capacitive component, especially if the cables are at higher network voltages.

This increase in the capacitance of upgraded networks, combined with the potential for future light loading on the networks (with increased capacities of commercial- and residential-owned distributed energy resources, including battery energy storage systems) means this issue appears to be a growing technical issue worldwide.

In New Zealand we do not yet have the same penetration of distributed generation as overseas. As such, our lightly loaded periods are currently during the overnight periods, as was shown in the previous section.

It also appears that modern demand characteristics are playing a role in networks becoming less inductive. For example, inverter-based induction motor drives are likely to be a lot less inductive than older directly connected induction machines.

This problem wasn't foreseen (at least by the author!) back in 2011 when concern was expressed at voltage stability constraints on power transfers into the upper island regions during peak demand periods (see references A.2, A.3).

Voltage management by system operators

System operators are required to operate the power system within regulated voltage limits. To do this, a system operator dispatches reactive power devices as a first call. Voltage regulating plant can include generation units, synchronous condensers, SVCs, STATCOMs, transformer tap changers and shunt and series inductors and capacitors. During high voltage conditions when all available (inductive) reactive plant has been dispatched to reduce over-voltages, the final resort is to remove circuits that have high shunt capacitance which, as illustrated by the two-bus model, changes the direction of the voltage drop across the transmission line, reducing the receiving end voltage.

Prior to the recent Spanish/Portuguese blackout, the regional system operators had high voltage circuits removed from service to help manage the high voltages that were being observed. These circuits were then closed to help mitigate a large inter-regional power

oscillation occurring at the time. However, it appears this action may have exacerbated existing excessively high voltage conditions.

Here in New Zealand, we have seen similar overvoltage conditions appear on the transmission grid in recent years. This has led to the system operator removing transmission circuits from service as a last resort effort to reduce transmission voltages.

Using Electricity Authority vSPD market data (the isOpen flag), figure 12 illustrates average rolling monthly overnight (midnight to 6am) outage hours on voltage controlling circuits known to be used by the system operator. The problem started occurring from around 2015 and reached its maximum between 2020 and 2023. Recently it has been alleviated somewhat due primarily to significant transmission grid investments made to help manage it.

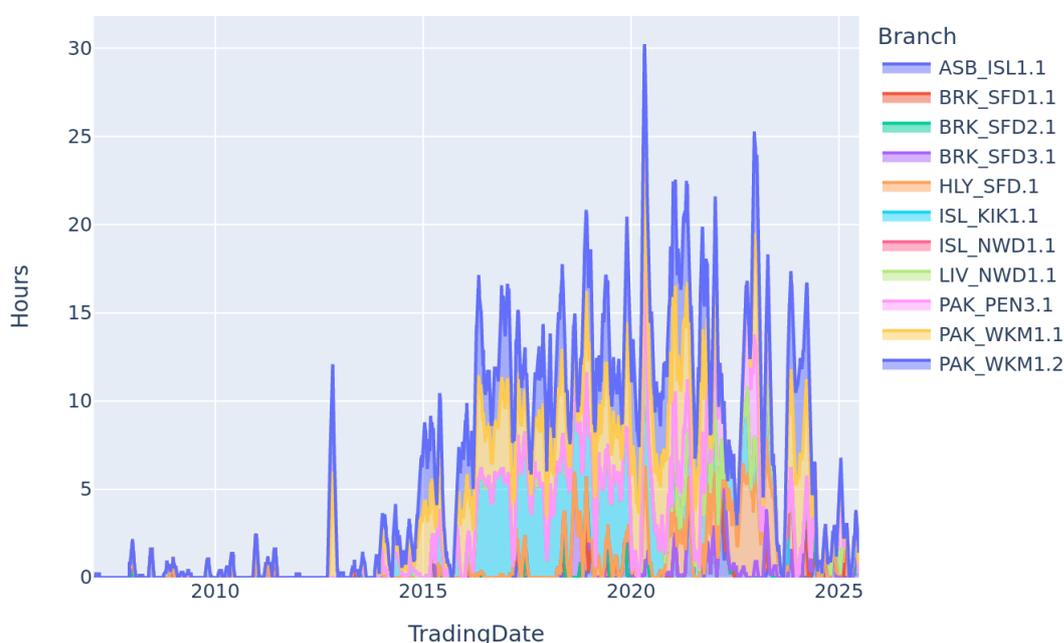


Figure 12 Cumulative overnight (mid-night to 6am) outage hours on voltage controlling circuits known to be used by the system operator

Recent transmission investments to help alleviate overvoltage conditions

In the upper North Island the transmission grid owner has installed several STATCOMS to help manage dynamic voltages following contingent events. These devices are able to produce and consume reactive power in a controlled dynamic way that enables voltage stability. Additional shunt capacitors and reactors help extend the controllable range of these devices. In terms of overvoltage conditions, we have seen several shunt reactors being required and installed in recent years. This includes a 50 MVAR shunt reactor at Otahuhu in 2022 and two 100 MVAR shunt reactors at the Pakuranga substation in 2023 (A.4). Prior to these investments, transmission circuits into the UNI were regularly switched out to help manage overvoltage conditions. Switching out the Pakuranga-Whakamaru 1 or 2 220kV circuits has been restricted due to high transient overvoltages, which likely resulted in a cable joint failure. Currently, one circuit has been removed from service for cable joint

replacement work. Transpower is also looking at further shunt reactors in the central North Island to help manage developing overvoltage conditions (A.4).

In the Upper South Island we have seen recent installation of 50 MVAR and 80 MVAR reactors at Kikiwa and Islington GXPs/substations (A.4).

While transmission investments such as these appear to have reduced the number of transmission circuits being switched out regularly, overvoltage problems and increased losses are likely to continue unless local distributors start improving poor leading power factors overnight.

5. System losses

As we have seen in the previous sections, power factors have reached, and then passed, their apex in the overnight periods. As such, losses during these periods will be increasing, compared to operating with power factors closer to unity. Significant loss savings could be made for New Zealand if local distributors are better able to manage their reactive power and power factor through low-cost changes to distribution network operation.

This section, attempts to very approximately quantify the size of the potential benefits of these loss savings, noting there may be none, depending on the magnitude of the costs involved for distributors to achieve better power factors.

Back in 2009, the author presented an EEA paper attempting to quantify total New Zealand power system losses over both the transmission and distribution networks (A.6). The result was an average loss of around 3,050 GWh, which at the time was close to Orion's annual demand serving Christchurch and mid-Canterbury consumers.

Since then, the Ministry of Business, Innovation and Employment (MBIE) has taken over reporting of losses across the transmission and distribution networks. MBIE makes available an online spreadsheet (A.7) containing relevant data. Current annual losses appear to have changed little since 2009 and sit at approximately 3,000 GWh.

Figure 13 illustrates the current ASX forward market prices. Prices are currently elevated, reaching over \$200/MWh during the winter quarters with an average of around \$165/MWh. This places a greater incentive on improving power system efficiency, including losses, than has been the case in the past.

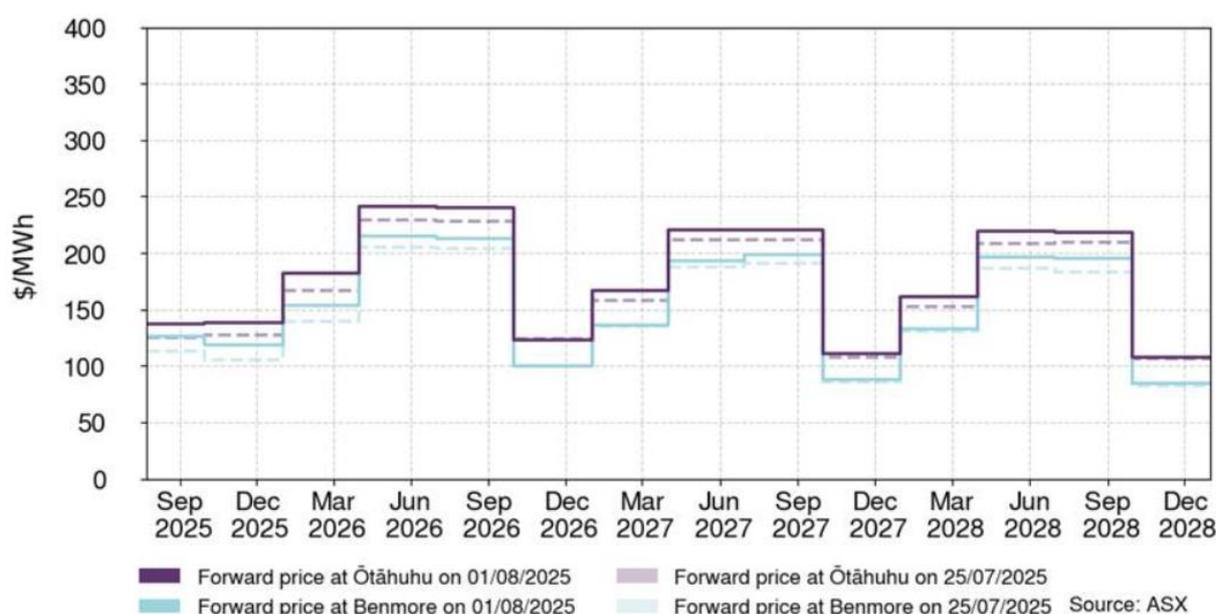


Figure 13 ASX forward market wholesale prices

At current forward market prices, losses in the New Zealand power system cost roughly 3,000,000 MWh x \$165/MWh, or approximately \$500m annually. So, even a small (say 1%) improvement in losses equates to a \$5m outside-of-market benefit to New Zealand.

Although the average power factors in New Zealand look to be reasonable, some GXPs have significantly poor power factors (figure 11, for example), where material levels of local losses can be improved (especially overnight). Accordingly, the author speculates that the benefit in reduced transmission and distribution losses through better reactive power control

and improved power factors could likely be in the range of \$5m-\$50m annually. If this can be achieved through low-cost operational measures, there could be significant savings for New Zealand consumers.

6. Current Electricity Authority work

The Electricity Authority is currently progressing work on reactive power management alongside Transpower, as the system operator, and with input from the Common Quality Technical Group. This work falls within the Authority's Future Security and Resilience (FSR) work programme (<https://www.ea.govt.nz/projects/all/future-security-and-resilience/>).

7. Conclusion

This paper has investigated long-term trends seen in power factors across the New Zealand power system since 2009.

A significant trend has been identified: lagging power factors have steadily improved, approaching their apex (unity) and shifting into the leading region in some instances. This indicates that the connected distribution networks are becoming less inductive and more capacitive.

Although power factors have improved since 2009, the capacitive nature of the observed trends has continued and we now see over-night power factors decreasing again, but in the leading (capacitive) region.

This raises concerns (now, and into the future) around overvoltage management and increasing electrical losses.

An analysis of high voltage transmission outages shows increased high voltage circuit removal over-night in attempts to manage high voltages by the system operator, peaking during 2020-2023. Recent grid investment consisting of shunt reactors in both the Upper North and Upper South islands confirms that over-voltage conditions have been a real issue and, if trends continue, likely to become increasingly problematic.

This paper is intended to help raise awareness of the problem within the industry.

If distribution networks are able to better manage power factor, especially over-night, over-voltage issues and electrical losses will reduce. The Authority is currently investigating the issue in more detail and may prioritise this issue with the help of the system operator as part of the Future Security and Resilience (FSR) work programme.

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