Power System Stability Information Paper

System Operator

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TRANSPOWER

Shifting power system stability landscape

The New Zealand generation mix has historically been dominated by synchronous machines from geothermal, hydro, and thermal generation. This is now shifting to have a higher proportion of solar, wind and battery energy storage systems. These developments change the characteristics of the system due to their intermittency and connection to the grid through power electronic based inverter technology. This is changing the stability risks will see, the way we assess them, and the ways we will manage them.

This paper provides an overview of power system stability, the challenges we foresee under the changing landscape and a high-level overview of work we are doing, in partnership with regulators and industry, to meet these challenges.

What this paper covers

1. Operation and control: the basics of power system operation, frequency and voltage control
2. Stability classifications: the different categories of power system stability
3. Oncoming challenges: the changing landscape and our anticipated system security challenges
4. Our workstreams: a high-level overview of workstreams focused on addressing these challenges

Power System Operation

Secure power system operation requires constant balancing of active power to maintain a stable frequency, and reactive power to ensure healthy voltages across the system. Failure to manage stable frequency or voltage can quickly cause widespread system collapse.

Power systems must also be operated ready for a grid disturbance to occur at any time. Contingencies such as faults on transmission lines, transformers, or generators can occur at any time and will have effects on the system voltage and/or frequency depending on the impact of the contingency. This means that the power system must be operated with enough headroom and corrective control to be able to compensate for a contingency at any given time.

A sudden loss of generation will mean there is more electrical load on the system than the generation input power to supply it (e.g., flow of water driving a hydro turbines). Until that generation input power is restored, the extra electrical load is provided by the inertial response of synchronous machines. Providing this extra energy slows the rotation of the units down which causes a drop in overall system frequency – the more inertia there is on the system, the slower the rate of change of frequency is. Restoring system frequency and restoring generation-load balance go hand in hand and is necessary to avoid cascade failure following the loss of generation on the network.

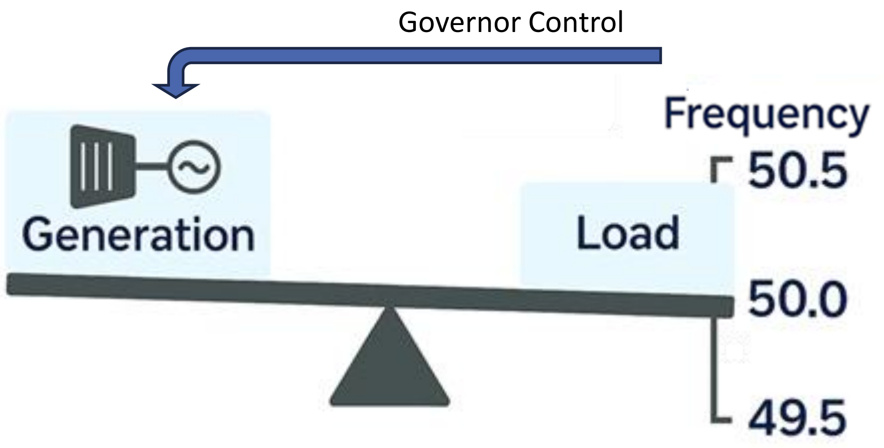
Loss of transmission lines or transformers decrease the available paths for power to flow through the network, increasing the impedance of the system. The increased impedance has a direct impact on voltages on the network, which can increase the reactive power demands on the system, or make voltage harder to control in a higher impedance network. The system must be able to provide adequate reactive power support and have well tuned control systems in order to maintain power system stability.

Frequency Control and Active Power

Given the speed at which a power system can collapse in unbalanced conditions, automated control systems are a fundamental part of secure power system operation. These control systems require careful design to ensure they fulfil their functions while coordinating well with other devices connected to the power system.

Management of frequency is crucial to maintaining a stable power system. In an alternating current (AC) coupled power system, the system frequency is common across the entire network. In New Zealand, the North Island and South Island each have their own system frequency, which is loosely coupled via the high voltage direct current (HVDC) link.

Synchronous generators, which have comprised the majority of the generation mix, are equipped with a speed governor which detects the speed of their physical rotation (directly coupled to the electrical frequency of the power system) and modulates their active power output accordingly. If a speed governor detects a drop in system frequency, it increases the mechanical power output of the machine providing the necessary energy to restore generation and load balance, stabilising the system frequency (and vice-versa).



While newer power electronic devices used in BESS, solar, and wind generation do not have physical rotation coupled to the electrical frequency, they have active power-frequency control that operates with the same principle, modulating active power output based on system frequency.

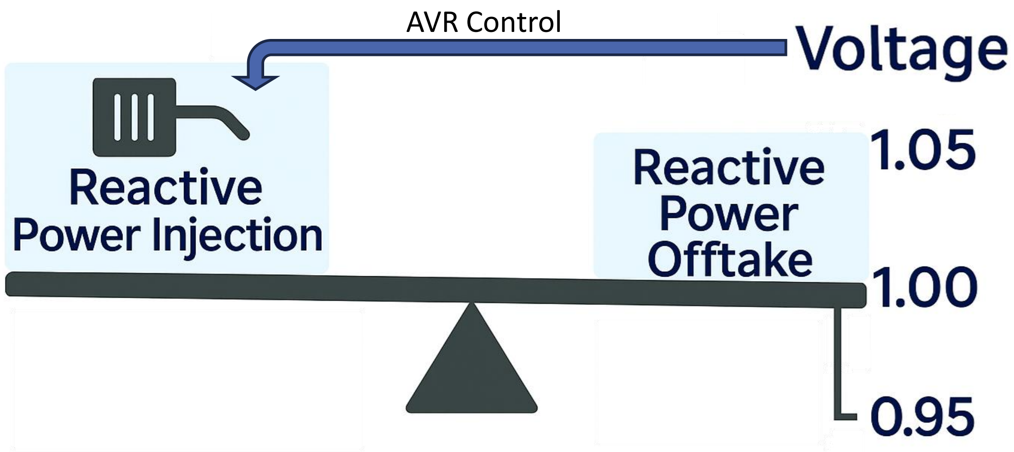
Voltage Control and Reactive Power

Similar to the control of frequency by modulated active power with automated control systems, voltage is controlled on the system by modulated reactive power with automatic voltage regulators (AVRs).

In contrast to frequency management, voltage issues are a localized phenomenon, meaning some areas of the grid may be healthy while other areas are struggling to maintain voltage within operable limits. This also means that voltage support needs to be provided in the location where it is needed – voltage support in Wellington will not assist in the management of voltages in Auckland.

Unlike active power and frequency, injection and offtake of reactive power is not limited to generation and load. Transmission lines, transformers, capacitors, reactors, harmonic filters, and the HVDC can all inject or offtake reactive power.

Synchronous generators are equipped with AVRs which adjust their reactive power output in response to fluctuations in voltage. If grid voltage at the generator's location drops, the AVR will increase the generator reactive power output to increase the voltage and maintain secure operation levels.



Reactive power-voltage control with power electronic devices differ in their physical characteristics but operate with the same control principle, modulating reactive power output based on grid voltage.

Inverter Based Resources vs Synchronous Generation

Since the inception of the New Zealand power system, the generation mix has been dominated by synchronous machines from geothermal, hydro, and thermal generation. The generation mix is shifting to have a higher proportion of solar, wind and battery energy storage systems (BESS), which inject generation into the power system through power electronic based inverter technology, rather than electromechanically coupled synchronous machines.

Most inverter based resources (IBRs) do not inherently provide system inertia as there is no electromechanically coupled rotating mass. This means that with higher proportions of IBR on the system, our frequency will fluctuate with a higher rate of change when power imbalances between generation and load occur.

Most IBRs do not provide a firm voltage source like synchronous generation, meaning grid voltages can be harder to control where large IBRs connect in regions electrically distant from synchronous generation.

IBRs need to synchronise to the grid via power electronic control rather than a strong electromagnetic coupling, this can create stability challenges where, under certain conditions, IBRs can fall out of step with grid voltage.

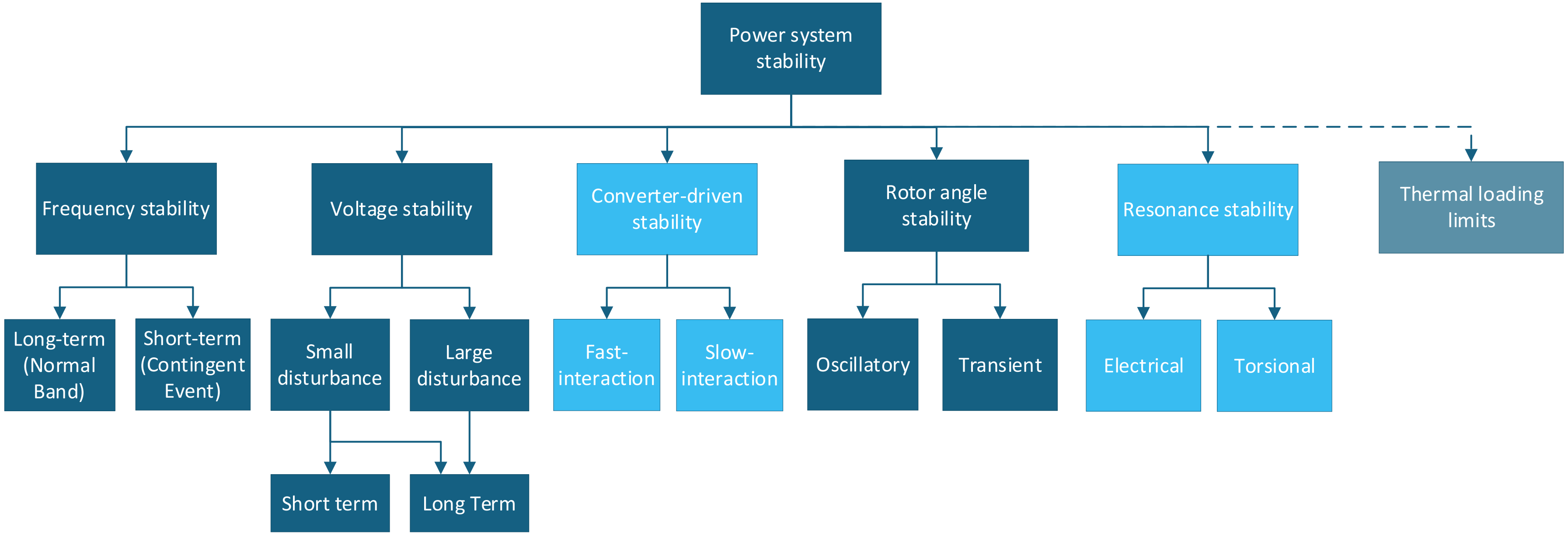
Power electronic control can be very fast with little to no mechanical limitations which slow down the speed of response. This means that while IBRs lack the inherent response to grid disturbances that synchronous machines provide, IBR control action can be much faster as it is not limited by long mechanical limitations (e.g. water travelling down a penstock).

These characteristics are developing as technology improves, for example, grid-forming inverters can provide “synthetic” inertia and firm voltage source characteristics. The shift in characteristics and rapidly evolving technology necessitates a review of established operating practices to manage power system stability.

Power System Stability

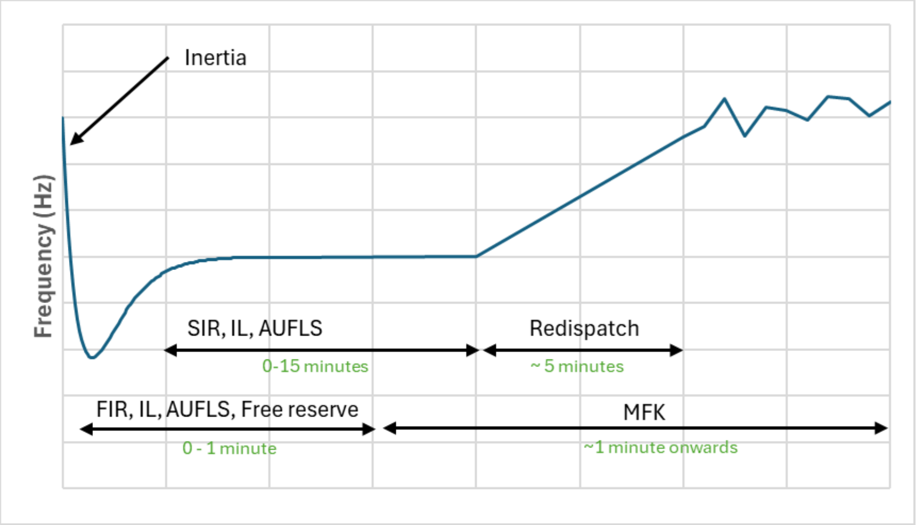
The practice of ensuring that a power system can return to a state of equilibrium following a system disturbance is known as "power system stability". Classifying different forms of stability allows us to diagnose and address system issues in a targeted way, as shown below.

Frequency, voltage and rotor angle stability are long established classifications within power system management practices (dark blue boxes below). The growth of inverter based resources introduce a new form of instability called converter-driven instability due to their different characteristics compared to synchronous generation. Resonance stability is also a new classification targeting resonance issues on the grid. Thermal loading, though not typically included in stability classifications, has been included here as these limits are an important operational factor in operating a secure power system.



Frequency Stability

Frequency stability is the power system's ability to keep a constant 50 Hz, both during normal operation and following disturbances like load or generator changes. Frequency stability is essential to prevent equipment damage, maintain power quality, and support reliable power exchange. If frequency strays outside acceptable limits due to generation-load imbalance, the system will collapse. We can broadly classify frequency support services into primary, secondary, and tertiary, based on the speed and duration of their response.



Under-frequency curve and response times of various frequency support services on the New Zealand system

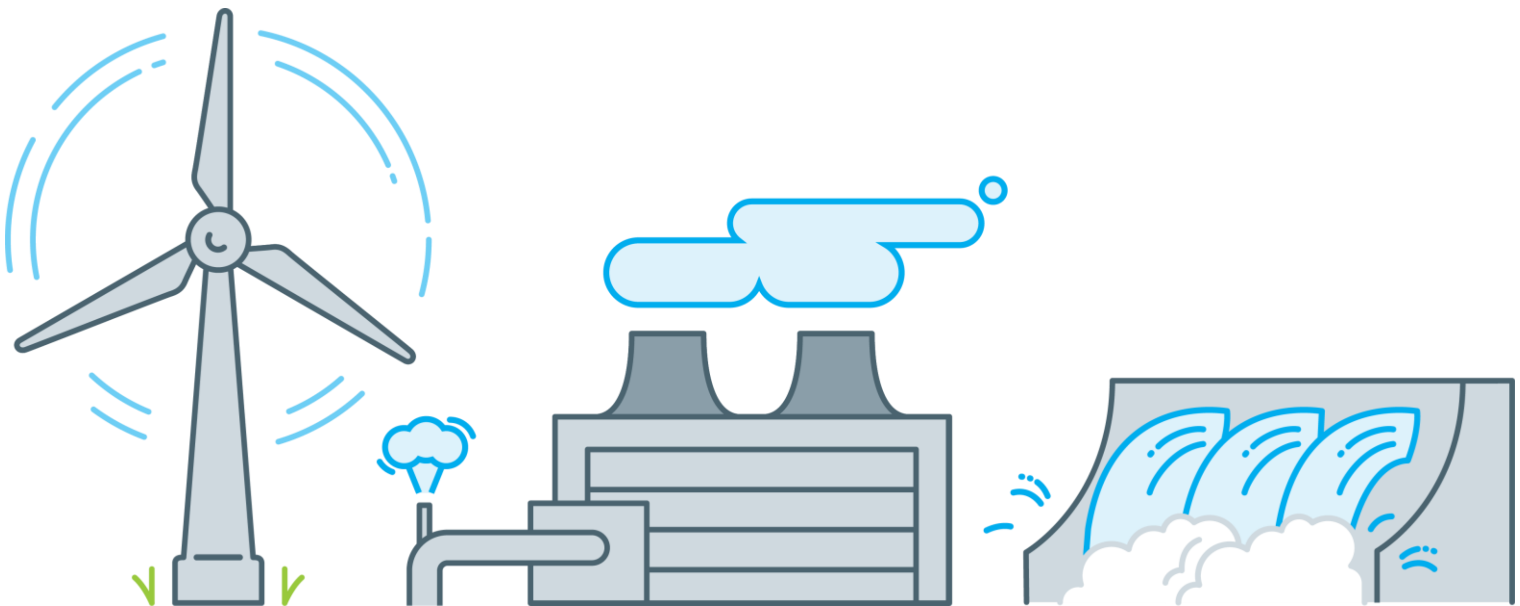
Primary	Secondary	Tertiary
Primary frequency control is fast, typically responding within seconds to arrest the frequency fall and to restore the frequency to a secure operating range.	Secondary frequency control can be a slower and sustained response to ensure the lost energy from the initial frequency event remains replaced.	Tertiary frequency reserve is used to restore frequency back to 50 Hz and returns the power system to pre-fault conditions.
Achieved via fast instantaneous reserve (FIR), Interruptible load (IL), automatic under frequency load shedding (AUFLS).	Achieved via sustained instantaneous reserve (SIR), IL	Achieved through redispatch, and frequency keeping services.

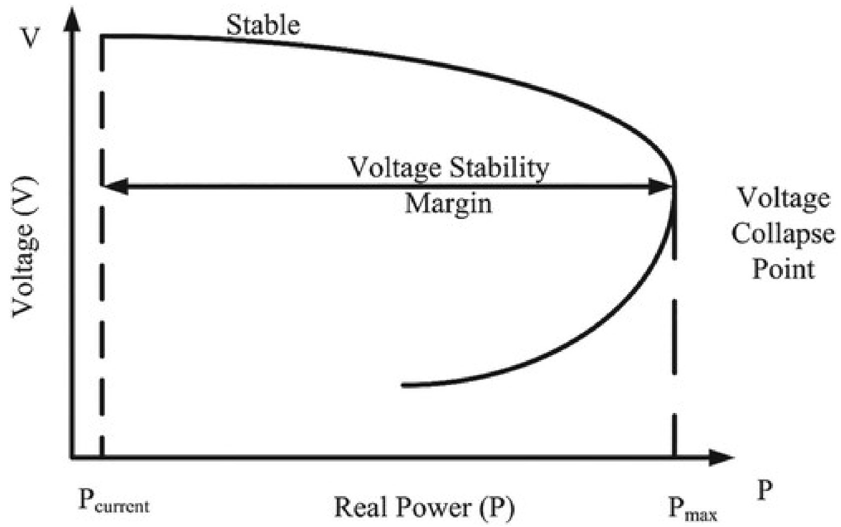
Frequency keeping services have some tertiary reserve benefits, but the primary role is balancing generation and load under normal operation automatically.

Voltage Stability

Voltage stability refers to the ability of a power system to maintain voltage within acceptable tolerances across the system under normal operating conditions and following large disturbances. It is crucial that the power system is operated such that the reactive power demand can be met by voltage support devices on the system.

Voltage stability is important for avoiding voltage collapse, blackouts, and equipment failures. Voltage stability can be maintained through control and coordination of equipment, such as generators, reactive power compensation, as well as transformers and other voltage regulation mechanisms. Voltage stability is also managed by observing power transfer limits as seen in the curve below.





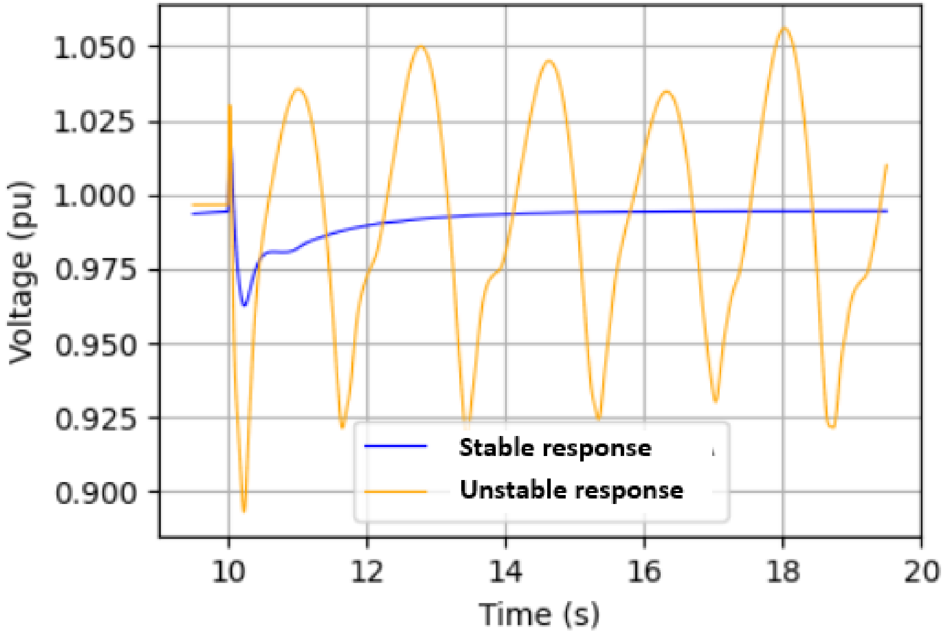
Example PV curve showing power transfer limits for voltage stability [1]

Converter-driven and Resonance Stability

Converter-driven and resonance stability have recently arisen as classifications following challenges arising from the high penetration of power electronic-based devices on the system.

Converter-driven stability deals with inverter synchronisation limitations and control system instability which may arise from either poorly tuned fast control systems or delays in measurement or communication from power plant controllers. Converter-driven stability is heavily influenced by the technology type behind the power electronics and the strength of their connection to the network.

Resonance stability deals with issues related to voltage and current oscillations arising through interactions between control systems and impedances on the power system. This includes inverter interactions and sub-synchronous resonance from generation interacting with series compensated lines.



Example converter driven stability for an IBR connection

Stability classifications

Rotor Angle Stability

This is the ability of a power system to maintain synchronism among all generators under normal operation and severe disturbances, such as short circuits or islanding events. Rotor angle stability is important to prevent loss of synchronism, separation, and instability. Loss of synchronism subjects synchronous machines to large amounts of electro-mechanical stress, which in severe cases can cause irreparable damage to machines.

Rotor angle stability is split into two sub-categories:

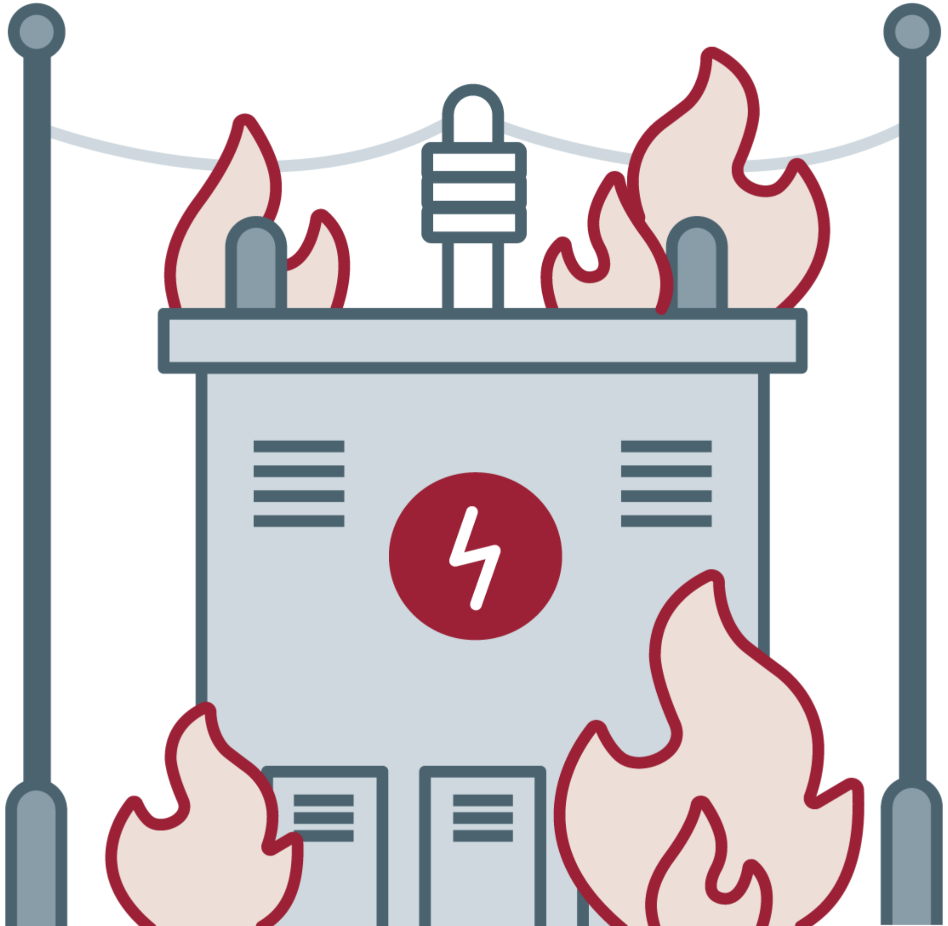
Transient	Oscillatory
Transient stability refers to the ability of a power system to maintain stability under large and sudden disturbances, such as faults, switching, or loss of generation.	Oscillatory stability refers to the susceptibility of the system to sustained oscillations between rotating masses under poorly damped conditions, which may arise from control system behaviour and weakly interconnected power systems.

Iranshahr Thermal Power Plant rotor angle instability event 2009 [4]

Thermal Loading Limits

Power system thermal limits refer to the maximum operating conditions a power system can sustain under normal, stable, and balanced conditions without violating operational constraints. These limits ensure the system remains secure, reliable, and within design tolerances during continuous operation.

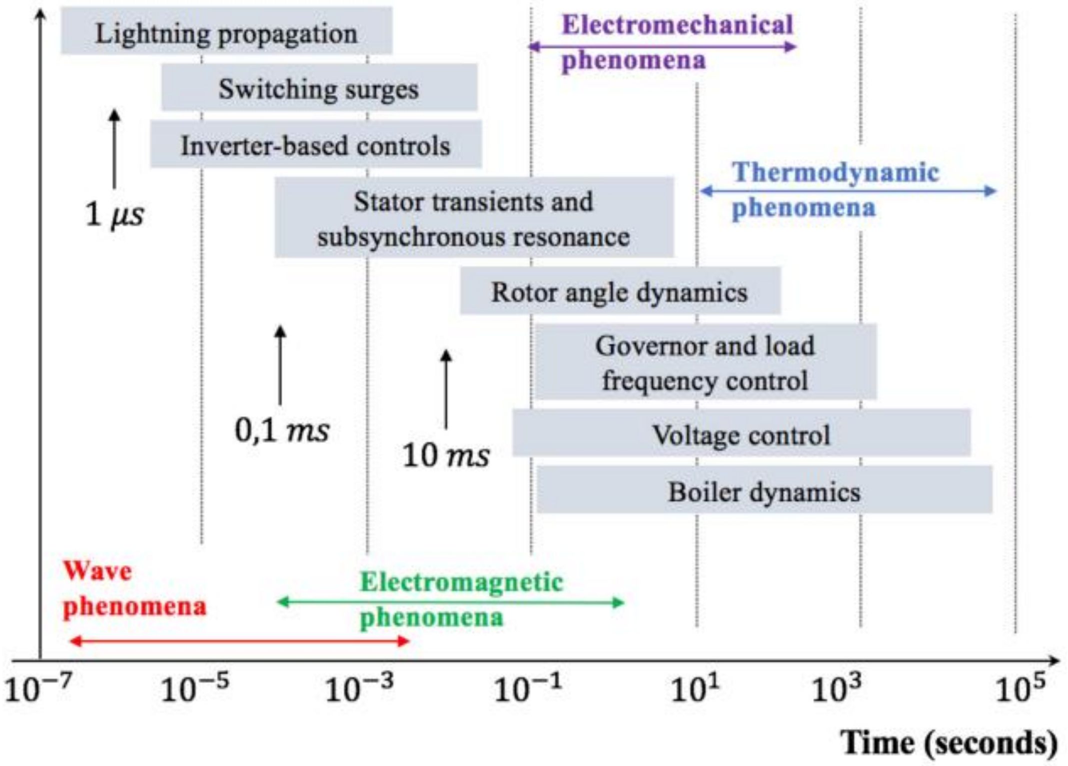
Steady-state thermal limits are important for the secure N-1 operation of the power system, preventing equipment damage, and protecting public safety.



Analysis Techniques

We evaluate different forms of stability with analysis methods and tools over varying timeframes, depending on the influencing factors. Along with understanding classifications of stability, we must also understand the timeframes in which different phenomena occur so we can select the appropriate tool to capture the right level of detail. The figure shows different types of power system phenomena and the timeframes in which they occur.

Although these forms of stability interrelate, we typically study phenomena separately using focused techniques and targeted modelling assumptions.



Power system dynamics phenomena and the time frames in which they occur [2]

The increasing adoption of inverter-based generation requires the use of electromagnetic transient (EMT) analysis techniques for system-wide studies.

Various power system software vendors are now exploring and implementing 'impedance scanning' or 'small-signal eigenvalue analysis techniques', which are more efficient and effective for analysing converter-driven instability phenomena.

Monitoring Techniques

Power system monitoring is a crucial aspect of modern power grid operations, ensuring the reliability, efficiency, and safety of electricity supply. It involves the continuous observation and analysis of various parameters within the power system to detect anomalies, predict potential issues, and enable swift corrective actions.

The importance of power system monitoring can be understood from several perspectives:

Reliability: Continuous monitoring helps identify potential power system risks in order to take preventative measures, thereby reducing the likelihood of power outages.

Efficiency: Real-time data analysis enables utilities to optimize power generation and distribution, reducing energy losses, increasing asset unitisation and improving overall system efficiency.

Safety: Monitoring helps in detecting abnormal conditions that could lead to safety hazards, allowing for timely interventions.

Data Collection

Data collection is the foundation of power system monitoring. Various devices and methods are employed to gather data from different parts of the grid, including:

SCADA (Supervisory Control and Data Acquisition)

- Real-time monitoring of voltages, currents, power flows, and breaker status.
- Used by control centres to operate and supervise the grid.

PMUs (Phasor Measurement Units)

- Provide synchronised measurements of voltage and current phasors.
- Enable Wide Area Monitoring Systems (WAMS) for dynamic behaviour and oscillation detection.

Power Quality Monitoring

- Tracks harmonics, voltage sags/swells, flicker, and transients.
- Important for industrial customers and sensitive equipment.

Event Recorders, Fault Locators and High-Speed Recorders

- Capture high-speed data during disturbances or faults.
- Used for post-event analysis and protection system validation.

System Health Monitoring

The overall vision for power system health monitoring is for an automated, end-to-end power-system data framework that integrates all sources, exposes high-speed dynamics, and produces consistent outputs to support data-driven decisions.

Visibility of system health via data collection and analytics underpins all areas of power system stability as it will allow us to closely monitor trends and triggers for upcoming stability challenges.

Enhancing resolution and spatial density of data

Enhance access to high resolution, continuously streamed data so that the system's dynamic behaviour can be observed and analysed.

Improving the collation of relevant data

Improve access to multiple data sources, align data formats, align time stamps to ensure quality data integration.

Automating data processing

Automate the processing of data ingestion, validation, and transformation of data

Centralising data needed for health monitoring

One data source for all cleansed and transformed data

Standardising the results and visibility of analysis

Standardise the formatting, dissemination and storage of reports and enable visibility through a user-friendly portal

The Changing Stability Landscape

The power system is rapidly changing, thanks to a changing generation mix, new types of load and increased capability for end-customers to be active participants through aggregate solar PV or BESS products.

The renewables boom has resulted in increased solar PV, wind and BESS connections. The variability of fuel sources is increasing, as is the use of power electronics at the grid interface. New large-scale connections are emerging in parts of the power system where connections of such scale were absent. These changes will have an impact on power system stability, through reduced inertia due to reduced synchronous generation, increased frequency fluctuations as a result of increased variability, potential voltage in stability in weak areas of the grid, and potential converter-driven instability inverter based resources connect in close proximity to one another.

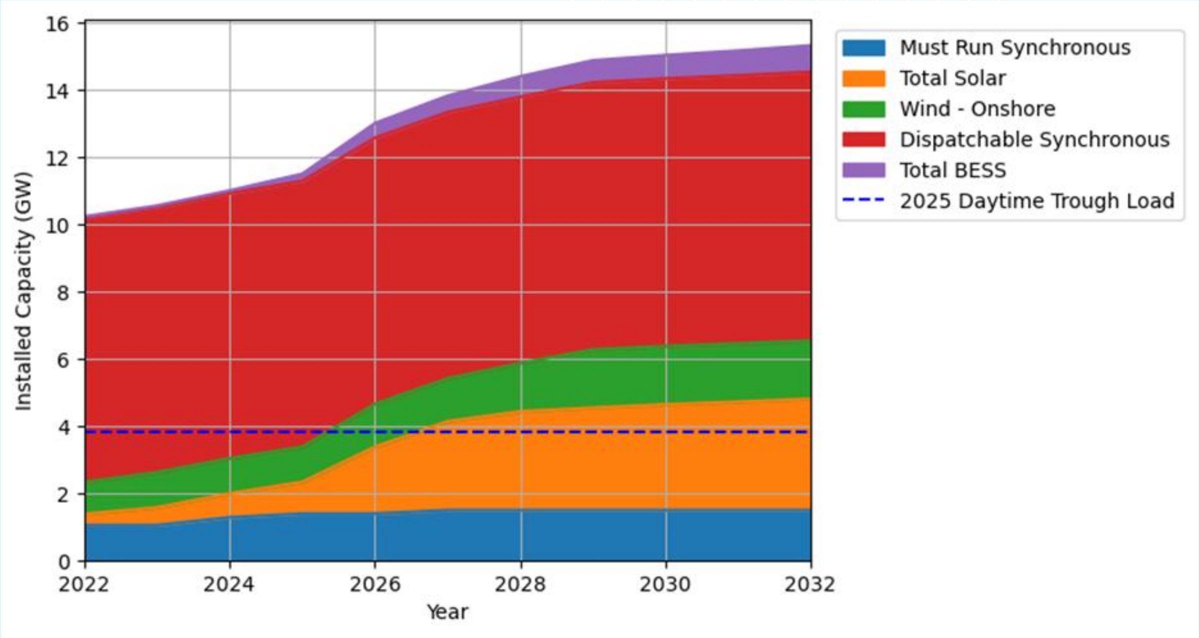
Emerging large loads such as data centres and electrified industry can pose security risks to power system operation. Advanced technologies in large loads will have new characteristics to understand, with potential for large power swings, poor voltage ride through capability, and power quality issues such as power factor and harmonics. The steady uptake of distributed energy resources (DER) can also materially impact power system security as the aggregate amount of household solar PV and BESS reaches into the 100s of MW.

Upcoming Major Stability Challenges	
1	New generator connections mostly intermittent IBR
2	New locations of large generator connections as we generate from previously unused sources of power
3	Emerging large loads e.g. data centres, electrified industrial loads
4	Increased uptake of household DER

System-wide Uptake of Intermittent IBR

Intermittent IBR uptake will increase, as shown by the forecast installed capacity on the power system. The graph also displays the 2025 daytime trough load over the 2024-2025 Christmas-New Year period of 3800 MW. We have grouped generation into:

- Must-run synchronous generation (geothermal)
- Total solar generation (grid-scale and household PV)
- Wind (grid-scale onshore wind)
- Dispatchable Synchronous (all other synchronous generation e.g. hydro, thermals)
- Total BESS (grid-scale and household BESS)



(based on existing generation and upcoming commissioning projects as at December 2025)

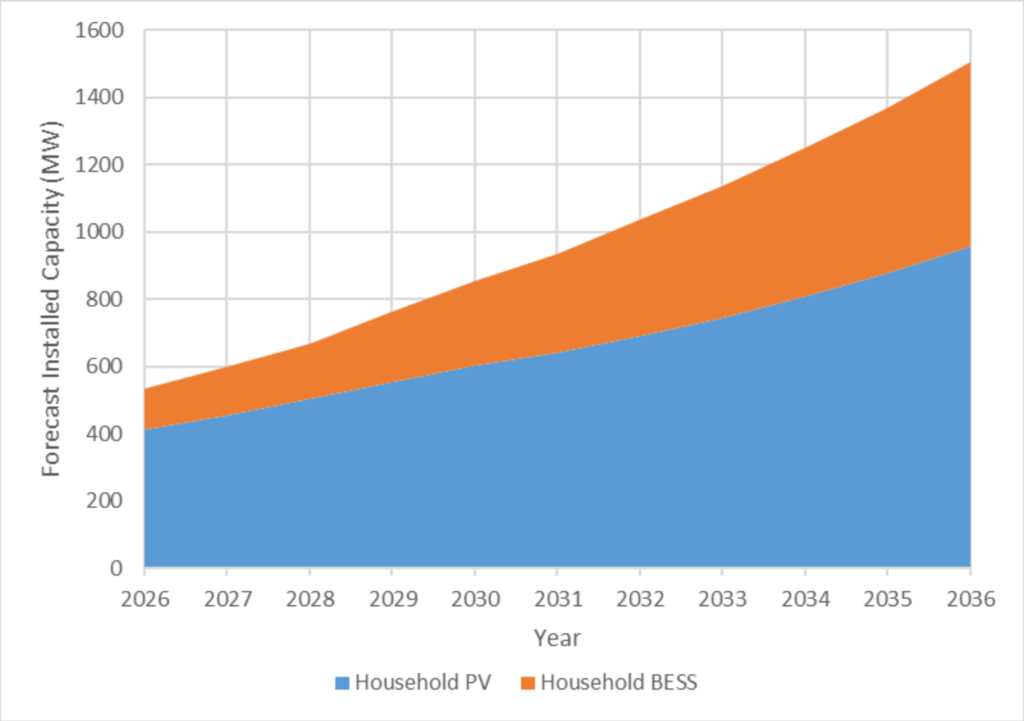
There is a steady pipeline of inverter-based generation, particularly solar. The above graph pipeline shows that the installed capacity of must-run synchronous generation, solar and wind can exceed daytime trough load as early as 2026, increasing the likelihood of operating in low inertia conditions where managing frequency stability can become challenging.

Distributed Energy Resource (DER) Uptake

As the plot below shows, household PV and BESS are forecast to rise steadily. By the end of 2027, we expect that the total household PV will reach 500 MW at the national level, with about 70% in the North Island. These levels mean that North Island household PV matches the typical CE risk for frequency, and at the regional level, a lower end of possible CE risks in the North Island.

The impact of this DER uptake will distribute across New Zealand regions so it is important to understand the type of aggregate response we could potentially see at a national, island and regional levels.

By 2036, we expect household PV to double the forecast 2027 figure, totalling 1 GW across the system. Work is needed to determine the system impact that these levels of DER might have on power system stability.

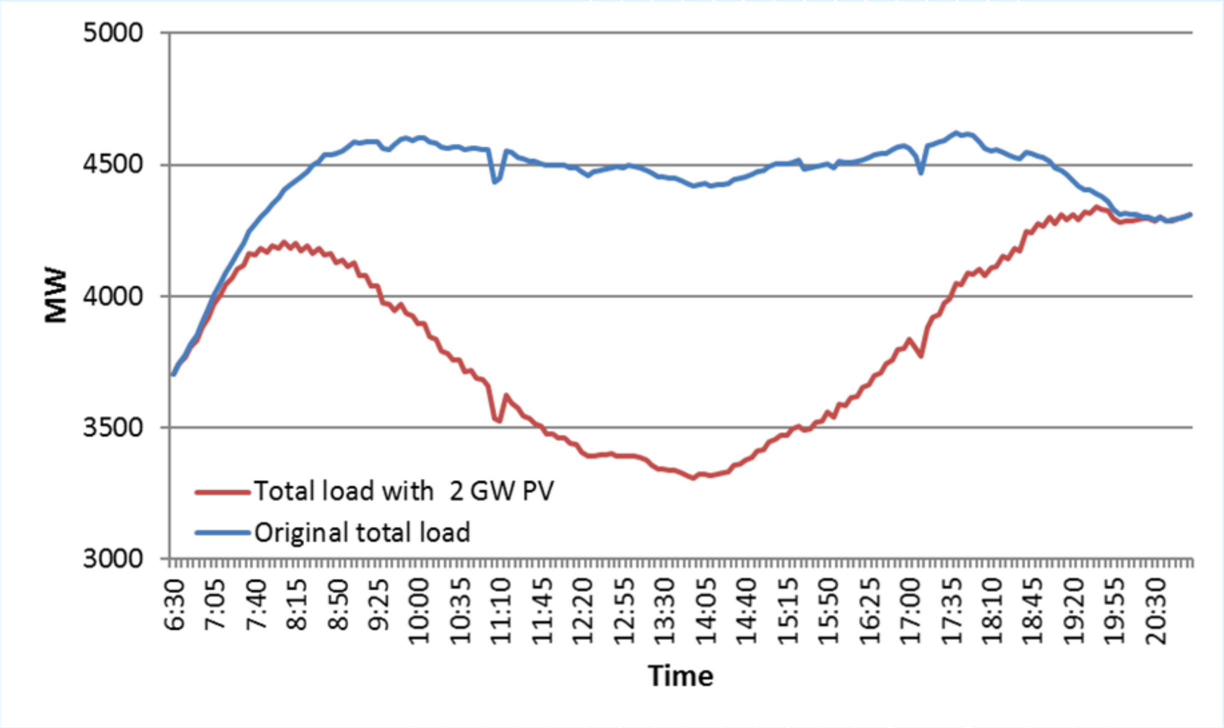


Projected NZ household DER and BESS installed capacity

Overall trend of periods of decreased synchronous generation

As DER and intermittent IBR increase in capacity on the power system, the amount of synchronous generation online at any given time will decrease as hydro and thermal generation are displaced by cheaper solar and wind generation. This is a particular risk overnight when load is low and wind may be high, and during the daytime trough when load is low and solar and wind may be high.

The inverter-based nature of these connections mean that the system is overall weaker. Synchronous machines provide physical inertia which resists changes to system frequency, and provide a firm voltage source which stabilizes system voltage. Reducing synchronous machines online at any given time means the system is less secure against voltage and frequency disturbances.



Effect of 2GW of solar PV installed capacity on the load required to be supplied by synchronous generation

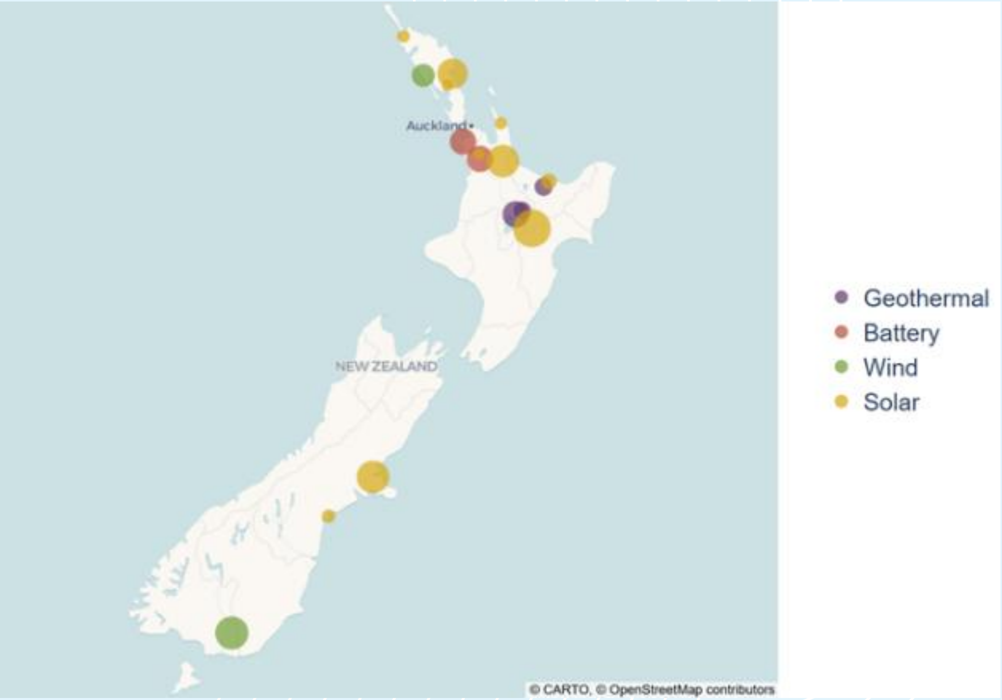
Connection Locations of Grid-Scale IBR Projects

The connection location of IBR projects can have a significant impact on their stability. Most IBRs rely on a strong grid voltage to maintain a stable injection into the grid. The “strength” of the grid voltage can be understood as “the support provided by firm synchronous machine voltage sources at this point of connection”.

Large IBRs connecting to remote areas of the grid with no nearby synchronous generation can pose a stability challenge if unmitigated by careful parameter tuning, grid-forming BESS, or synchronous machines.

IBRs connecting in close proximity to one another, or close to existing power electronic devices such as STATCOMs, SVCs, and the HVDC, can pose stability challenges due to adverse interactions between these devices.

These challenges require advanced analysis techniques to diagnose and mitigate, especially given the continuous technological advancements of inverter based connections.



Generation projects under construction as at December 2025 [3]

Large Loads and Data Centres

Transpower has received several enquiries related to large loads looking to connect to the power system. Many of these new large load connections are from data centres, a steadily increasing area as we move further into a technological age. New Zealand is an attractive candidate for data centre development due to its high proportion of renewable energy. Though no major grid connected projects are committed at this stage, potential projects on the horizon are in the 100s of MW.

Issues have been encountered overseas with some data centre connections switching to a local uninterruptible power supply under grid disturbances, causing a sudden removal of load from the power system. Which such large installations, this can have a significant impact to the frequency security of the power system.

Additionally, data centres have new load characteristics, which could have complex control which needs to be understood in order to co-ordinate well with existing plant and operational practices.

Example data centre interior

What if we do nothing?

Lowering inertia due to reduced synchronous generation

As inertia drops on the power system, the rate of change of frequency (RoCoF) increases, making frequency security harder to manage. Faster RoCoF means active power response due to a frequency event must act quicker to arrest the frequency fall before upper and lower limits of operation are reached. If left unmitigated, frequency reserves would be over-procured, increasing the overall quantity to realise an overall faster response on the system. This would increase system costs, and would make encountering scenarios with inadequate levels of energy and reserves insufficient to securely meet the demand.

Increasing proportion of generation from intermittent sources

Solar and wind are intermittent sources of energy as they can be disrupted by cloud cover or changes in wind speed any time, in a manner which is difficult to anticipate. As the levels of intermittency on the power system increase, the continuous imbalance of power will affect normal band frequency management, making excursions outside the normal band more common, and increase the burden on frequency keeping services and generators providing frequency support through governor response.

Low system strength IBR connections

IBRs connecting in low system strength conditions, or in close proximity to existing IBR connections, may have challenges maintaining stable voltages and remaining in step with grid voltage. Poorly tuned connections can cause unmitigated oscillations on the power system, potentially involving multiple connections and causing widespread system collapse.

What if we do nothing?

New and rapidly evolving IBR technologies

The continuing advancement of IBR technology means we have to continuously ensure our stability analysis techniques are fit for purpose to adequately capture fast power electronic based phenomena. This goes hand in hand with deepening our understanding of these issues, upskilling with the rest of the international power system community. Continuous review of processes and requirements imposed on IBRs will mitigate the risk of being caught unprepared for system events which may not be captured by existing analysis tools and processes.

Emerging types of large load connections

Depending on their characteristics, large loads can have an impact on power system security. Load characteristics can impact voltage recovery of the network during faults. Poor ride through capability to system disturbances can pose challenges for frequency stability. Understanding large loads on the system, adequately representing their characteristics in power system analysis tools and implementing performance requirements is necessary to continue to maintain voltage and frequency stability on the power system.

Stability Workstreams and High-level Approach

Workstream	Major Outcomes
Frequency contingent event: covers short-term frequency stability.	• Analysis to determine when frequency stability due to low inertia is expected to be a regular issue on the power system • Investigate mitigation options for low inertia scenarios – e.g. minimum system inertia, or additional/enhanced market products to leverage new technology to provide faster reserve and arrest the faster falling frequency.
System strength issues and small-signal stability: covers oscillatory stability, and converter driven stability.	• Having robust models and processes in place to adequately capture system strength and stability issues on the system. Both identified during design phase and as part of ongoing assessment of the power system. • Build our technical expertise, presence and connectivity with wider industry and wider industry experts.
Frequency normal band: covers long-term frequency stability.	• Investigation to determine how fit for purpose existing frequency keeping systems are to continue to maintain normal band frequency in the changing landscape. • Implement potential changes to frequency keeping systems to maintain frequency quality standards.
Transient stability, voltage control and stability, thermal loading issues	• Continuing to leverage and improve existing tools and processes for power system security. • Fit for purpose modelling of embedded generators and the impedances between them and GXPs. • Updated modelling assumptions to feed back into BAU analysis.

Other Workstreams

Workstream	Major Outcomes
System health monitoring	•Build an automated, end-to-end power-system data framework that integrates all sources, exposes high-speed dynamics, and produces consistent outputs to support data-driven decisions, by: •Increasing quality and quantity of high-speed monitoring •Improving collation of all system and market data and automating data processing •Centralising data analysis and storage, and standardising result visibility and reporting •Developing Wide Area Monitoring System, including real-time monitoring of oscillatory behaviour
Large load modelling and performance requirements	•Establish provision of asset capability information from large loads to the System Operator •Determine large load modelling and performance requirements, and produce guidelines for: •Providing models for power system simulation •Performance of large loads on the system (e.g. fault ride through) •Build on guidelines to produce Code changes to implement requirements for projected large loads, with a focus on data centres.
DER impact study	•An investigation into distributed energy resources, particularly household PV and BESS, to determine expected challenges to the system and whether we need to improve our study assumptions or modelling to represent their behaviour.

References

[1] A robust neural network model for monitoring online voltage stability: International Journal of Computers and Applications: Vol 44 , No 12 - Get Access

[2] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9286772

[3] https://www.ea.govt.nz/news/eye-on-electricity/new-generation-projects-flowing-through-the-investment-pipeline/

[4] Iranshahr Thermal Power Plant 4x64 MW-Coupling fatigue_2009