Economic Regulation Authority

Inter-Jurisdictional Review of Limit Advice and Constraint Equation Development and Assessment

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Ampere Labs

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Revision History

Revision No	Date	Author	Reviewer	Revision Description
1.0	03/02/2025	J. Bryant	J. Susanto	Draft report
2.0	07/03/2025	J. Bryant	J. Susanto	Final report
3.0	11/07/2025	J. Bryant	J. Susanto	Public report

Executive Summary

This report provides an inter-jurisdictional review of the development, assessment, and oversight of Limits Advice and Constraint Equations in electricity markets, particularly as it relates to the Economic Regulation Authority's (ERA's) oversight role in the Wholesale Electricity Market (WEM). This review specifically looks at the following jurisdictions:

- Australia's National Electricity Market (NEM)
- Ireland's Integrated Single Electricity Market (I-SEM)
- California Independent System Operator (CAISO)
- Electric Reliability Council of Texas (ERCOT)
- New Zealand

We investigate the NEM and I-SEM in detail because the real-time market designs (as relevant to constraints) are most like the WEM, i.e., zonal market—a copper plate model that has a simplified power system representation by treating defined areas as a single node, assuming unlimited transmission capacity and no losses—with linear constraint equations representing thermal and non-thermal constraints. The other jurisdictions (CAISO, ERCOT, and New Zealand) have fully nodal markets but still use linear equations for complex thermal and non-thermal constraints.

No other jurisdiction has explicit obligations for third parties to oversee the development and effectiveness of limits and constraint equations

One of the key findings from this review is that the WEM is unique since there is an explicit obligation for the ERA to provide formal oversight regarding the development of Limit Advice and Constraint Equations. The other jurisdictions surveyed as part of this review do not place direct obligations on a third party to monitor the system operator's work (and, if applicable, the transmission network service provider's) in developing and assessing the effectiveness of limits and constraints. Any regulatory oversight is indirect, such as in CAISO and ERCOT, where the North American Electric Reliability Corporation (NERC) oversees reliability outcomes (the failure of which can arise from poorly formulated or overlooked constraints) but does not directly look at the constraint equations themselves.

There is no evidence of third parties formally overseeing thermal limits

Thermal limits directly relate to the continuous power transfer rating of equipment like transmission lines, power transformers, cables, circuit breakers, and instrument transformers. The ratings are based on the equipment's technical specifications, vendor-specific data, and engineering calculations, accounting for equipment operating conditions (e.g., ambient temperature, wind speed) and other factors (e.g., age, condition, known batch defects).

Transmission network asset owners typically provide thermal limits, and this review did not identify any jurisdiction that systematically assesses these limits via a third party.

There are impracticalities associated with formally overseeing limits

Other jurisdictions may have decided that formal oversight is impractical owing to the sheer volume of limits, the technical expertise required to review limits, and inherent information asymmetries (i.e., the asset owners have intimate knowledge about their assets that is inaccessible to external parties). However, there is usually some transparency of thermal limits (either publicly or to market participants), but these limits are rarely audited by third parties.

All jurisdictions adopt a similar approach to developing constraint equations

While there is a difference between developing thermal constraints in zonal versus nodal markets (i.e., we can directly implement simple thermal constraints in nodal market dispatch engines), a fairly standard approach has evolved across all jurisdictions (including the WEM) to develop complex thermal and non-thermal constraint equations. This “standard” approach uses power system simulations to define secure operating regions—which the power system needs to operate within to maintain security and reliability—and then formulates linear constraint equations using the boundaries of these regions.

Good governance is achieved through a mix of best practices

A set of good governance practices for developing, assessing, and monitoring limits and constraints has been identified across jurisdictions (noting that some jurisdictions only adopt a subset of these practices):

- **Robust and transparent processes** like self-imposed practices that continuously monitor and review limits and constraint outcomes provide governance, accountability, and transparent communication with stakeholders.
- **Regular assessment of binding limits and constraints** as a trigger to review constraints that economically impact the market ensures constraints’ legitimacy, appropriateness, and effectiveness.
- **Stakeholder feedback mechanisms** allow market participants (or the public) to provide feedback or question limit and/or constraint functionality, catalysing investigations.
- **Real-time system security monitoring** by system controllers serves as a backup measure, ensuring constraints imposed by dispatch engines are working correctly. Real-time monitoring includes power system software tools like real-time contingency analysis and dynamic security assessment tools.
- **Periodic business process audits** (either self-imposed or to satisfy regulatory requirements) can help identify risks and improvements in developing, managing, or implementing limits and constraint equations.

- **Reliability compliance monitoring and enforcement** via third parties (e.g., government or regulator)—including launching investigations and imposing penalties when system operators breach reliability standards—ensures power system reliability standards are met.

However, maintaining security and reliability trumps everything else

There is a general sense from the review that maintaining system security and reliability in real-time operations is paramount, i.e., to the exclusion of economic factors. For example, applying the N-1 system security principle in a blanket deterministic fashion without regard for the probability of an N-1 contingency (e.g., based on equipment conditions, weather patterns, or historical observations of past occurrences). As a result, real-time system operations departments around the world are largely left to themselves to operate their power system securely without outside economic scrutiny (though often with third-party oversight for security and reliability outcomes).

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1 Introduction

1.1 Scope

The Economic Regulation Authority (ERA) engaged Ampere Labs to support the ERA's inaugural review of the effectiveness of Limit Advice and Constraint Equations in the Wholesale Electricity Market (WEM) as per clause 2.27C of the ESM Rules. The scope of the engagement is twofold:

i) Undertake an inter-jurisdictional review on Limit Advice and Constraint Equation development and assessment/oversight; and

ii) Develop a framework for reviewing the effectiveness of Limit Advice and Constraint Equations in meeting the principles described in clause 2.27A.9.

This report documents the inter-jurisdictional review's outcomes regarding developing, assessing and overseeing Limit Advice and Constraint Equations. The review covers the following jurisdictions:

- National Electricity Market (NEM)—Australia
- Integrated Single Electricity Market (I-SEM)—Ireland
- California Independent System Operator (CAISO)—USA
- Electric Reliability Council of Texas (ERCOT)—USA
- New Zealand

1.2 Glossary

Table 1 lists the acronyms, terms and abbreviations used throughout the report.

Table 1: Glossary of terms

Term	Meaning
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
BM	Balancing Market
CAISO	California Independent System Operator
DAM	Day-Ahead Market

Term	Meaning
EMS	Energy Management System
EMT	Electromagnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
ERA	Economic Regulation Authority
ESM	Electricity System and Market
EU	European Union
FCAS	Frequency Control Ancillary Service
FERC	Federal Energy Regulatory Commission
GTC	Generic Transmission Constraint
IDM	Intraday Market
I-SEM	Integrated Single Electricity Market
IROL	Interconnection Reliability Operating Limit
ISO	Independent System Operator
LHS	Left-Hand Side
LMP	Locational Marginal Price
LSAT	Look-ahead Security Assessment Tool
MUON	Minimum Number of Units Online
NCUC	Network Constrained Unit Commitment
NEM	National Electricity Market
NEMDE	National Electricity Market Dispatch Engine
NEO	National Electricity Objective
NER	National Electricity Rules
NERC	North American Electric Reliability Corporation
NSP	Network Service Provider
OM	Operating Margin
PUCT	Public Utilities Commission of Texas
RA	Regulatory Authority
RDF	Redistribution Factor

Term	Meaning
RHS	Right-Hand Side
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SCED	Security-Constrained Unit Commitment
SEMC	Single Electricity Market Committee
SEO	State Electricity Objective
SFT	Simultaneous Feasibility Test
SNSP	System Non-Synchronous Penetration
SPD	Scheduling, Pricing and Dispatch
SOL	System Operating Limits
SONI	System Operator for Northern Ireland
SSE	Multinational company (formerly Scottish and Southern Energy plc)
SWIS	South West Interconnected System
TCG	Transmission Constraint Group
TNSP	Transmission Network Service Provider
TOR	Terms of Reference
TSO	Transmission System Operator
VTT	Voltage Trajectory Tool
WDT	Wind Dispatch Tool
WEM	Wholesale Electricity Market
WEMDE	WEM Dispatch Engine
WITS	Wholesale Information Trading System

2 Overview of Limits and Constraints

2.1 What are power system limits?

Power systems have limited transmission capacity—their physics and underlying material properties restrict a transmission element's (e.g., a line or transformer's) maximum power delivery capacity according to thermal, voltage, or stability limits.[1] These three (3) critical limits are summarised as follows[1,2]:

- **Thermal Limit**: Transmission equipment limits are governed by an element's physical properties. Electricity flow through the transmission apparatus heats the equipment. Thus, thermal limits are imposed based on the equipment's operating temperature (e.g., concerning a conductor or transformer). Exceeding these limits can lead to overheating and other unintended effects that pose safety issues and reduce the equipment's lifespan.
- **Voltage Limit**: Transmission system voltages must be maintained close to their nominal (rated) values to ensure safety and reliability. Voltages that are too high (overvoltage) or too low (undervoltage) can damage equipment and affect the network's power transfer capabilities. A well-controlled voltage profile (within technical limits) helps avoid excessive current, reduces losses and prevents overloading, improving the system's power transfer capability and stability. Thus, operators may limit the amount of power transferred across parts of the transmission network, for example, to ensure the voltage drop across transmission lines is not excessive.
- **Stability Limit**: Power system operators may limit power transfer across transmission elements to ensure the system can reliably operate across various scenarios—like when the system is fully intact, and all *N* elements are in service, and under contingencies when *N-1* elements are in service, e.g., following the loss of a transmission line, transformer, or generator.

Typically, short transmission lines (under 80 kilometres) are rated according to their thermal limits, medium-length lines (between 80 and 320 kilometres) are limited by voltage limits, and long lines (> 320 kilometres) are restricted by stability limits.[1] While thermal limits are generally greater than stability limits,[3] they may not correspond to a line's actual power transfer limit since stability constraints can be reached first. Thus, we must consider all three limits to determine a

[1] US Department of Energy, "Advanced Transmission Technologies," accessed online, 2020.
[2] US Department of Energy, "National Transmission Needs Study," accessed online, 2023.
[3] US Department of Energy, "Dynamic Line Rating," accessed online, 2019.

line's (or other element's) actual power transfer limit.[4] The device with the smallest capacity determines the maximum transmittable current for branches with interconnected elements (e.g., a line and a transformer).[5]

Hence, limits relate to temporal factors like power system topology,[6] weather,[7] and transmission element technology types.[8] For example, seasonal weather variations can augment static transmission line limits—cooler seasons facilitate greater throughput, whereas limits generally reduce in warmer seasons. Dynamic line rating takes these static limits further by varying transmission line capacity in real-time via weather and operational conditions. Moreover, temporal variations in renewable energy like solar can locally influence a network's voltage profile owing to fluctuations in power production.[4] Meanwhile, generator and transmission technology types can influence stability limits. For example, power system oscillations can manifest in inverter-rich network areas of low system strength, and hence, stability limits are employed as a prevention strategy.[9]

Overall, various limits exist that represent the physical and operational limits of individual network elements and the overall power system. Such limits represent boundaries that ensure the safe, reliable, and efficient transmission and use of electricity with acceptable error margins. The limits are thus generally identified from apparatus/equipment data, calculations, and through power system studies employing state-of-the-art simulation software like DIgSILENT PowerFactory, PSS/E, and PSCAD. The general forms for thermal, voltage, and stability limits are:

$$|S_{ij}| \leq S_{max} \quad \text{(thermal limits)}$$
$$V_{min} \leq V_i \leq V_{max} \quad \text{(voltage limits)}$$
$$P_{ij} \leq P_{stable} \quad \text{(stability limits)}$$

where $|S_{ij}|$ is a branch's apparent power flow in MVA, S_{max} is the rated thermal limit in MVA, V_i is a busbar's voltage (in per-unit or kilovolts), V_{min} and V_{max} are the minimum and maximum permissible bus voltages, P_{ij} is a branch's active power flow in MW, and P_{stable} is the stability-limited power transfer in MW (e.g., to maintain transient or small-signal stability).

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[4] T. Su et al. "Grid-enhancing technologies for clean energy systems," *Nature reviews clean technology*. Vol. 1, 16-31, 2025.

[5] S. Karimi et al. "Dynamic thermal rating of transmission lines: a review," *Renew. Sustain. Energy Rev.* Vol. 91, 600-612, 2018.

[6] The structural arrangement of a power system—how the power system is "made up".

[7] For example, inherent seasonal variations.

[8] For example, the technology underpinning generators like grid-following inverters, grid-forming inverters and synchronous machines, or different transmission technologies such as high-voltage direct current (HVDC) interconnectors.

[9] Australian Renewable Energy Agency, "The Generator Operations Series. Report One: Large-scale Solar Operations," accessed online, 2021.

2.2 What are constraint equations?

Having identified power system limits, system operators develop constraint equations that encode the limits into a mathematical representation for application in scheduling, dispatch, planning, and real-time operational processes. The constraint equations give purpose to the limits by creating a framework that enforces them, keeping the power system bounded.[10] Generally, a constraint equation is said to *bind* or be *flagged* when a limit has been reached and is impacting system operation.

2.2.1 Constituent components

Fundamentally, constraint equations contain a left-hand side (LHS), an operator, and a right-hand side (RHS). The LHS comprises a linear combination of *controllable elements* from the dispatch engine like scheduled generator dispatch and interconnector flows. The (mathematical) operator is a conditional requirement that provides bounding and can be either $\geq$, $=$, or $\leq$. The RHS can consist of a single term or many terms of different data types like constants, analogue SCADA data values, or regional demand forecast data representing a *limit* for a set of power system conditions.[11]

Figure 1 provides an illustrative constraint equation example comprising the LHS, operator, and RHS components.[11] The a, b, and c terms are weightings, generally referred to as factors, that define the contribution of each generator and interconnector to the constraint.

Figure 1: An illustrative constraint equation with its constituent components highlighted.

$a \times Generator\ 1$ $- b \times Generator\ 2$ $+ c \times Interconnector$	$\leq$	$[Limit - Line\ Flow(s)] \times Scaling$ $+ a \times Generator\ 1\ (current\ val)$ $- b \times Generator\ 2\ (current\ val)$ $+ c \times Interconnector\ (current\ val)$
LHS (Controllable Terms)	**Operator**	**RHS (Limit)**

M*onitored elements* include a single or group of transmission elements whose power transfer is controlled. Hence, they are found on constraint equations' RHS. A *contingent element* is a part

[10] Interested readers can refer to the Appendix for a comprehensive, accessible treatment of limits and constraint equations.

[11] AEMO, "Constraint Implementation Guidelines," accessed online, 2015.

of the transmission system assumed to have experienced an unplanned outage.[12] Contingencies influence how constraint equations bind. In the WEM, AEMO applies operating margins to its constraint equations that align with error, risk consequences, and risk appetite, noting that it may default to applying conservative operating margins.[13]

[12] AEMO, "WEM Procedure: RCM Constraint Formulation," accessed online, 2024.

[13] AEMO, "WEM Reform Program: Constraint Formulation," accessed online, 2020.

3 Methodology and Assumptions

3.1 Approach

Outside the WEM, there are only a few bid-based wholesale electricity spot markets that do not manage congestion using fully nodal network representations[14] (e.g., that value the cost of congestion via locational marginal prices) and instead apply thermal constraint equations, namely:

- Australia's National Electricity Market (NEM)
- Ireland's Integrated Single Electricity Market (I-SEM)

This inter-jurisdictional review mainly focuses on the governance and oversight of Limit Advice and Constraint Equations in these two jurisdictions with "like" congestion management frameworks.

We also assess other jurisdictions with fully nodal markets, such as the California Independent System Operator (CAISO), the Electric Reliability Council of Texas (ERCOT) and New Zealand, to see how generic (linearised) Limit Advice and Constraint Equations[15] are managed and governed.

3.2 Information sources

The following information sources underpin the inter-jurisdictional review:

- Technical literature from credible sources from industry (e.g., NEM, I-SEM, CAISO, ERCOT, and New Zealand), including guidelines, procedures and training materials published on company websites.
- Interviews with industry experts from other jurisdictions that work in the development, management, oversight, and monitoring of Limit Advice and/or Constraint Equations.
- Academic literature research relevant to the development and oversight of Limit Advice and/or Constraint Equations (where applicable).

[14] In fully nodal markets, System Normal (N) and single network contingency (N-1) thermal overload limits can be automatically integrated into the market dispatch engine software without the explicit use of linear constraint equations. For example, refer to the CAISO Technical Bulletin – Information on Modeling of Transmission Constraints.

[15] Note the differences in terminology across jurisdictions, e.g., constraint equations are referred to as "Nomograms" in CAISO and "Generic Transmission Constraints" in ERCOT.

4 Market and Governance Structures

This section explores the market and governance structures that influence power system limits and constraint equations—and their associated practices—across the numerous jurisdictions pertinent to this review. Some key findings include:

- None of the jurisdictions studied in this review have explicit obligations for third parties to oversee the development of limits and constraint equations.
- Ireland performs an annual independent audit of its TSOs' scheduling and dispatch process most like the ERA's review of SWIS limits and constraint equations. The audit performs a high-level, process-related assessment of binding constraint events rather than examining constraints' derivation, technical correctness, conservativeness, or economic efficiency. Moreover, New Zealand conducts self-audits related to the management of real-time constraints and the performance of real-time system security monitoring tools.
- Without formal oversight, good governance is achieved through numerous practices:
  - **Self-governance**—occurs across all examined jurisdictions to some degree.
  - **Reliability compliance monitoring and enforcement**—particularly apparent in this review's USA jurisdictions.
  - **Stakeholder consultation and feedback**—occur across all examined jurisdictions to some degree.

4.1 National Electricity Market - Australia

Australia's National Electricity Market (NEM) is an energy-only market whose structure is most like the WEM's real-time market, containing a single pricing/reference node per region and linear equations that represent physical intra-regional and inter-regional system constraints like network, stability, and operational limits.

The NEM's governance is overseen by three (3) major market bodies, viz.:

i) **The Australian Energy Market Commission (AEMC)**—the market's rule/policymaker (in conjunction with federal and state governments).
ii) **The Australian Energy Market Operator (AEMO)**—the independent system and market operator.
iii) **The Australian Energy Regulator (AER)**—the market and network regulator.

4.1.1 Australian Energy Regulator's role in oversight and governance

The National Electricity Rules (NER) has no requirement equivalent to clause 2.27C of the ESM Rules and the AER has no formal obligations for overseeing NEM limits and constraints. Chapter 3 of the NER provides some obligations for AEMO around its dispatch process and the need for alignment with the National Electricity Objective (NEO). For example, clause 3.8.10 concerns network constraints and their treatment in the dispatch process, which contributes to governance in this area.

4.1.2 Australian Energy Market Operator self-governance

AEMO's dispatch procedure,[16] SO_OP_3705, articulates AEMO's approach to self-governing constraint equations. Particularly important sections include:

- **Section 8** describes AEMO's approach to reviewing constraints "*that are overly conservative or not functioning correctly.*" If identified, such constraints can be removed from dispatch (or pre-dispatch), but only thermal constraints are removed (and not non-thermal constraints such as transient or voltage stability constraints).

  While there are no further details on how such constraints are identified, it is implied in Section 20 that these would be identified:

  i) By participants ("*participants should contact AEMO immediately if they suspect that a constraint equation is not performing as expected*"), or
  ii) By AEMO's review of binding constraints ("*When a constraint binds in dispatch, AEMO will, to the extent that is reasonably possible, review the constraint to assess the validity and accuracy of the constraint outcome and use reasonable endeavours to determine if there are actions AEMO can initiate to relieve the network congestion.*")
- **Section 20** describes in more detail the actions that AEMO takes when insecure outcomes or over-conservative constraint equations are identified. In these cases, AEMO typically uses power system studies to confirm the performance of the offending constraint equations.

It is interesting to note that AEMO's policy is to never revoke overly conservative non-thermal constraint equations. Arguably, this is because the control room has limited tools/capacity to

[16] AEMO, "Dispatch procedure," accessed online, 2024.

monitor non-thermal system security in real time and relies on constraint equations to maintain security.[17]

4.2 Integrated Single Electricity Market - Ireland

The Integrated Single Electricity Market (I-SEM) is the wholesale electricity market for the island of Ireland,[18] operated by the Single Electricity Market Operator (SEMO). Developed in 2018 and aligned with the latest European Union (EU) regulations, the I-SEM integrates the existing all-island electricity market with the European Internal Energy Market (IEM).[19] The I-SEM comprises various markets, including[19,20]:

- **The Day-Ahead Market (DAM)**: A daily ex-ante market that closes the day before delivery.
- **Intraday Market (IDM)**: Operates from DAM closure up to one hour before delivery, allowing participants to adjust their physical positions closer to delivery.
- **Balancing Market (BM):** Reflects TSO actions to match supply and demand before and into real-time, with mandatory participation. It operates on a system marginal price structure (i.e., the system price is set at the cost of the final generation unit needed to meet demand).
- **Capacity Market**: Allows generators to recover their fixed costs.
- **Forwards Market**: A financial market that allows participants to reduce their exposure to significant price movements.

The main governance bodies include:

- **SEM Committee (SEMC)**—the market's decision-making authority that governs the I-SEM and oversees its design and implementation.[21] It comprises representatives from the Regulatory Authorities (three from each, see below) and two independent members.
- **Regulatory Authorities (RAs)**—the independent energy regulators in Ireland and Northern Ireland. Each is responsible for local issues like implementing electricity market codes and procedures and monitoring I-SEM operations and participants' conduct.[21]
- **EirGrid and the System Operator for Northern Ireland (SONI)**—operate the transmission system across Ireland and Northern Ireland, respectively.[20] They are responsible for

[17] Unlike thermal constraints, where the control room has access to online network analysis tools (e.g., contingency analysis) to ensure system security in real-time as an alternative to constraint equations.

[18] The contiguous geographical area comprising the Republic of Ireland and Northern Ireland.

[19] EirGrid Group, "Industry Guide to the I-SEM," accessed online, 2017.

[20] EirGrid and SONI, "Quick Guide to the Integrated Single Electricity Market," accessed online, 2018.

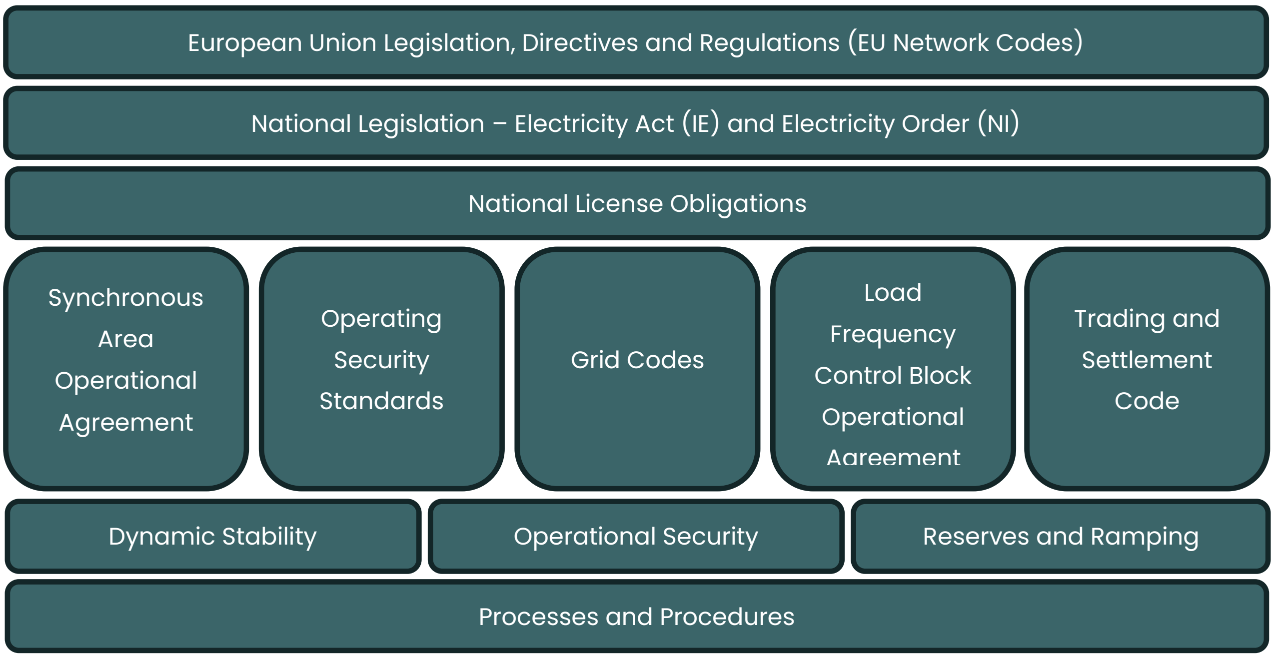
[21] EirGrid and SONI, "Chapter 2: Market Governance, Administration and Operation," accessed online, 2017.

power system security and balancing, operating transmission assets, managing grid connections, and facilitating power system forecasting and planning.

- **European Network of Transmission System Operators for Electricity (ENTSO-E)**—develops and implements network codes and standards for operating electricity markets, ensuring power system security, and integrating renewable energy in Europe.[22] It supports its members (European TSOs) in implementing and monitoring the agreed common rules.[23]

Figure 2 summarises the overarching operational policy framework, highlighting the influence of EU regulation, national legislation, and license obligations.[24]

Figure 2: Overarching operational policy framework



[22] ENTSO-E, "ENTSO-E Mission Statement," accessed online, 2025.

[23] Regulation (EC) 714/2009 stipulates ENTSO-E's tasks and responsibilities.

[24] EirGrid and SONI, "Operational Policy Roadmap 2023-2030," accessed online, 2022.

4.2.1 Oversight and governance of limits and constraint equations

The I-SEM does not have a requirement equivalent to clause 2.27C of the ESM Rules. Hence, there are no explicit obligations about third parties overseeing the development of I-SEM power system limits or constraint equations. However, there are regulatory requirements that assess procedural safeguards, facilitate transparent processes, and provide stakeholder feedback, which are detailed below.

4.2.1.1 Weekly and annual constraints reports

Clause 2(b) of Article 17 of the Commission Regulation (EU) 2017/1485[25] stipulates that each regional security coordinator must prepare an annual report for the ENTSO-E detailing "*the statistics regarding constraints, including their duration, location and number of occurrences together with the associated remedial actions activated and their cost in case they have been incurred.*" As such, EirGrid and SONI publish annual renewable energy constraint and curtailment reports outlining dispatch-down levels of renewable energy[26] for the significant measures taken in curtailing renewable energy sources to guarantee the power system or energy supply's security.[27] The annual reports facilitate constant oversight while providing detailed, transparent information to stakeholders regarding the root cause of wind and solar dispatch-down instructions.

In addition to the annual reporting requirements, Clause 1 of Article 73 of the Commission Regulation (EU) 2017/1485[25] stipulates that TSOs must perform year-ahead and, where applicable, week-ahead operational security analyses to detect constraints, including power flows and voltages that exceed operational security limits, violations of transmission system stability limits, and violations of transmission system short-circuit thresholds. The weekly constraint reports,[28] alongside the annual constraint and curtailment information, likely assist with aspects of self-governance by providing detailed data that can be used to measure

[25] The European Commission, "Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation," accessed online, 2017.

[26] In Ireland, renewable energy sources are given priority dispatch. However, the output of renewable energy can be reduced below its maximum available level (dispatched down) owing to security-based limits related to the local network (referred to as a constraint) or the wider system (referred to as a curtailment).

[27] EirGrid and SONI, "Annual Renewable Energy Constraint and Curtailment Report 2023," accessed online, 2024.

[28] EirGrid, "System Constraints," accessed online, 2019.

performance improvements.[29] The information is publicly available and thus holds the TSOs accountable while ensuring stakeholders are informed.

4.2.1.2 Independent assessment of TSO performance

Under Paragraph 9 of Condition 10A and Condition 22A of the EirGrid and SONI Transmission System Operator Licenses, the TSOs must undertake periodic audits of the scheduling and dispatch process's operation and implementation.[30] The scope of the 2024 and 2025 audits is expected to cover the following items:

1) Priority dispatch
2) Cross zonal actions
3) Dispatch instructions
4) Merit orders
5) Operational constraints
6) Constraint flagging
7) IT general controls required to support the above areas

Previous independent yearly audits have been similar, with operational constraint reviews performed according to Condition 10 and Condition 22A of Paragraphs 4(a), 4(b), and 5(d) of the respective TSO licenses.[31,32] While in-scope items have included, but are not limited to, system reserves, inertia, operating limits and tie-line values, scope exclusions have generally related to areas such as:

- Algorithms associated with optimisation engines that produce the schedules used in the scheduling and dispatch process.
- The Imbalance Pricing process that follows the scheduling and dispatch process.
- Validation of data submitted to the TSOs by participants.
- Inputs like forecasts provided by third parties and transmission and generator outage plans.
- The derivation of operational constraints.

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[29] For example, the following sections of this document highlight that the Irish TSOs currently employ system-wide stability constraints that are an emerging focus of disaggregation in favour of more localised constraints. In this case, the constant performance monitoring will be helpful for both the TSOs and stakeholders by providing a picture of historical baseline performance.

[30] EirGrid and SONI, "Annual Audit of the Scheduling and Dispatch Process," accessed online, 2024.

[31] PwC, "Independent Assurance Report on compliance with specified elements of the Scheduling and Dispatch process for the 12-month period ended 31 December 2022", accessed online, 2023.

[32] PwC, "Independent Assurance Report on compliance with specified elements of the Scheduling and Dispatch process for the 12-month period ended 31 December 2023", accessed online, 2024.

Hence, assessing constraint events has typically been limited to a sample of local constraint events and constraint dispatch instructions to ensure that:[31,32]

1) There was a valid reason for the local constraint event.
2) Before a local constraint event occurred, other options were considered where applicable.
3) Units receiving constraint dispatch instructions were included in the predefined local constraint group that was constrained; and[33]
4) Constraint dispatch instructions issued to priority dispatch units were done on a pro-rata basis.

Historically, the audit's terms of reference (TOR) have generally covered a 2-year period.[30,34,35] A consultation process facilitates feedback on the audit process's proposed scope and period,[36] with the TSOs providing responses and clarification regarding out-of-scope items.[34,35] The consultation process ensures that the audit process is transparent and that stakeholders understand the reasoning behind its scope.

The 2023 audit highlighted numerous risks, including engineering decisions not being the most economical (i.e., merit order deviations) and the potential for errors from manually inputting constraint data.[31] While the process does not interrogate constraints at a low level (i.e., assessing their formulation, correctness, or economic efficiency), it does ensure the governance and processes underpinning the technical aspects associated with their implementation are working and being adequately used while highlighting risks and providing recommendations for improvements. Thus, the audit assesses procedural safeguards as opposed to interrogating technical correctness.

[33] A sample of the remaining wind and solar units which were part of the predefined local constraint group and not tested as part of this point were checked to have been issued a setpoint.

[34] EirGrid and SONI, "Annual Audit of the Scheduling and Dispatch Process: 2020 and 2021 Terms of Reference," accessed online, 2021.

[35] EirGrid and SONI, "Annual Audit of the Scheduling and Dispatch Process: 2022 and 2023 Terms of Reference," accessed online, 2022.

[36] SSE, "EirGrid Scheduling and Dispatch Audit Terms of Reference," accessed online, 2021.

4.3 California Independent System Operator - USA

The California Independent System Operator (CAISO) operates the wholesale electricity system that serves 80% of California and a small part of Nevada.[37] Day-ahead and real-time markets form key parts of the overall wholesale energy market.[38] The DAM is open from seven (7) days before the trade date until the day before, whereas the real-time market opens at 1:00 pm before the trading day and closes 75 minutes before trading hour commencement.[38]

The Federal Energy Regulatory Commission (FERC), an independent federal government agency that regulates and oversees the interstate transmission of electricity, natural gas and oil in the United States, regulates the CAISO.[39] As part of its role, FERC reviews, approves, and enforces mandatory reliability standards developed by the North American Electric Reliability Corporation (NERC) for the bulk power system.[40] Meanwhile, the California Public Utilities Commission regulates investor-owned utilities in the ISO balancing authority area.[39]

4.3.1 California Independent System Operator self-governance

Like the other jurisdictions considered in this review, there are no explicit obligations[41] for a third party to oversee limits and constraint equations in CAISO—hence, governance is largely self-regulated.

Section 3.12 of CAISO Procedure 3610 (the current version is v10.5 from September 2024)[42] briefly describes the formal review process for nomograms, transmission corridors and flowgates—refer to Table 2 for a glossary of these terms—noting that the reviews occur during (i) the seasonal assessment, and (ii) the model database promotion process.

Table 2: Glossary of terms used in CAISO

Term	Definition
Flowgate	A network element or group of elements that act as thermal constraint points on the system, e.g., single lines, transmission corridors, transformers and series devices such as series capacitors or reactors.

[37] Federal Energy Regulatory Commission, "Understanding and Participating in California ISO (CAISO) Processes," accessed online, 2024.

[38] California ISO, "Products and Services," accessed online, 2025.

[39] California ISO, "Regulatory filings and orders," accessed online, 2025.

[40] FERC, "Reliability Explainer," accessed online, 2025.

[41] In CAISO's FERC-approved tariff arrangements.

[42] CAISO, "Nomograms, TCORs, Flowgates, Contingencies and MOC," accessed online, 2024.

Term	Definition
Intertie	A transmission corridor that interconnects the CAISO Balancing Authority Area with another Balancing Authority Area. Equivalent to an inter-regional interconnector in the NEM.
Nomogram	CAISO term for a linear constraint equation. Nomograms must be piece-wise linear and convex to be compatible for use in the market dispatch engine.
Transmission corridor	Refers to the physical pathway for electricity flow, e.g. a single transmission line, set of lines or a combination of lines and transformers.

There is also evidence of CAISO reviews leading to proactive changes, for example, in retiring the Southern California Import Transmission nomogram in 2018 after finding transient stability issues that originally necessitated the nomogram's development were no longer present.[43]

4.3.2 North American Electric Reliability Corporation oversight

While having no explicit governance role concerning constraint equations, NERC indirectly oversees CAISO as the FERC-appointed federal Electric Reliability Organisation. NERC must develop and enforce compliance with mandatory reliability standards.

Limits and constraint equations are intended to maintain system security—and ultimately reliability (i.e., to prevent the unintended loss of supply and unserved energy)—so NERC's oversight is designed to ensure that CAISO operates securely and reliably. Moreover, the threat of FERC enforcement for breaches of NERC standards provides strong incentives for CAISO to manage system constraints rigorously.

For example, following a 2011 blackout in the Pacific Southwest that left roughly 2.7 million customers without power, NERC (in conjunction with FERC's Office of Enforcement) investigated CAISO for potential violations of its reliability standards. The investigation found that CAISO had failed to identify a cascading stability risk along a transmission corridor (Path 44), leading to enforcement action that ended with CAISO agreeing to a civil penalty of $6m.[44]

Finally, it should be noted that NERC's oversight is asymmetrical as it only concerns the system security aspects of limits and constraints but has no interest in the economic efficiency side of the equation.

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[43] See the CAISO Market Performance and Planning Forum from April 2018.

[44] Refer to the FERC docket IN14-10-000.

4.4 Electric Reliability Council of Texas - USA

ERCOT is an independent system operator (ISO) responsible for reliably operating a standalone power system covering most of Texas, USA, while facilitating competitive wholesale and retail markets. It operates a day-ahead market (DAM), and a real-time market based on 5-minute intervals. Bilateral contracts facilitate load purchase ahead of these markets to hedge risks associated with potential volatility.[45] The wholesale markets employ zonal locational marginal pricing (LMP) across the system. The Public Utility Commission of Texas (PUCT) oversees market participants and contracts with an Independent Market Monitor, Potomac Economics, to assist with oversight and enforcement activities.[46]

4.4.1 Self-governance and market participant feedback

NERC Reliability Standard FAC-011-4 stipulates that each reliability coordinator must have a documented methodology for establishing system operating limits (SOLs).[47] Under ERCOT's SOL methodology,[48] market participants can request retiring a stability SOL. In such cases, ERCOT assesses the need for a real-time interface or stability limit using operational observations or predicted operational conditions (e.g., topological system changes that could render a limit or constraint invalid).[48] Theoretically, these measures provide a degree of pressure for economic efficiency.

Moreover, like other jurisdictions such as the NEM and I-SEM, ERCOT publishes an annual review that touches on constraints aspects.[49,50] The review is part of an annual planning assessment that looks at region-wide reliability and economic transmission needs as well as angular, voltage, and frequency stability issues using stability studies. There is also an annual independent report on the wholesale market by Potomac Economics, provided to the PUCT.[51] While the report looks at transmission network congestion and constraint costs, there is no requirement to assess the specific formulation of constraints/limits or their technical soundness. However, the report does outline violated constraints and the frequency of binding constraints,

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[45] ERCOT, "ERCOT's Market Structure and Oversight," accessed online, 2019.

[46] ERCOT, "Compliance in ERCOT," accessed online, 2025.

[47] NERC, "FAC-011-4-System Operating Limits Methodology for the Operations Horizon," accessed online, 2021.

[48] ERCOT, "ERCOT System Operating Limit Methodology for the Operations Time Horizon," accessed online, 2024.

[49] ERCOT, "Report on Existing and Potential Electric System Constraints and Needs: December 2023," accessed online, 2023.

[50] ERCOT, "Report on Existing and Potential Electric System Constraints and Needs: December 2024," accessed online, 2024.

[51] Potomac Economics, "2023 State of the Market Report for the ERCOT Electricity Markets," accessed online, 2024.

indirectly highlighting the efficacy of current practices. Moreover, the costliest real-time constraints are also detailed.[52] The 2023 report provided recommendations like increasing the shadow price cap on constraints in real-time (where appropriate) in response to existing price caps being too low and not appropriately valuing constraint violations.

4.4.2 North American Electric Reliability Corporation oversight

Like CAISO, NERC oversees ERCOT's ability to maintain system security and reliability. NERC standards also clearly permeate ERCOT's methodologies, as highlighted above in the SOLs' formulation. Hence, NERC's oversight is asymmetrical in that it only pertains to how limits and constraints provide system security (without considering economic efficiency).

4.5 New Zealand

New Zealand's national electricity system spans the country's North and South islands, with Transpower acting as the transmission network service provider and the system operator.[53]

The wholesale electricity market comprises spot and hedge markets.[54] The spot market facilitates real-time supply-demand matching on a merit-order basis, with electricity prices calculated half-hourly.[55] In contrast, the hedge market relates to electricity futures, where participants can hedge risk against spot market price volatility.[56] The Electricity Authority, an independent Crown entity, oversees and regulates the electricity market.[57]

4.5.1 Electricity Authority role

While the Electricity Authority oversees Transpower, there are currently no direct oversight obligations regarding constraint equation development by the system operator.

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[52] The economic value of real-time congestion is calculated by multiplying each constraint's shadow price by its flow, where the shadow price is the marginal cost of redispatch needed to manage the constraint.

[53] Transpower, "Optimising the transition," accessed online, 2024.

[54] Electricity Authority, "Wholesale market," accessed online, 2025.

[55] Electricity Authority, "Spot market," accessed online, 2025.

[56] Electricity Authority, "Hedge market," accessed online, 2025.

[57] Ministry of Business, Innovation and Employment, "Energy markets regulatory system," accessed online, 2024.

4.5.2 Transpower self-governance and market participant feedback

Limits and constraint equations in New Zealand are self-regulated by Transpower through published procedures, information and market participant feedback.

There is arguably a higher level of transparency in the publicly available information published by Transpower on the development of constraints (vis-à-vis other jurisdictions), with detailed flow charts describing the constraint development process.

Market participants can request Transpower to perform and publish a Simultaneous Feasibility Test (SFT) constraint[58] assessment for particular outages or grid configurations, which can indicate the limiting security constraints that may emerge during such scenarios.

Transpower procedure PR-OC-204/5.0 "Security Constraints Process"[59] articulates the specific triggers for amending constraint equations, summarised as follows:

- Change to transmission network or operating policy
- Change to generation capacity
- Change to load or load growth
- Change to operational configuration
- Change to the SPD (market dispatch engine) model
- Violations in real-time operation

It is noted that, like in most other jurisdictions, economic efficiency (e.g., over-conservative constraints) is not a consideration for amending a constraint equation.

Transpower also conducts internal audits on its SFT constraints and real-time system security monitoring tools (like the Voltage Stability Assessment Tool) as part of its risk and business assurance processes.[60,61] Although, to the best of our knowledge, details on the audit's scope are not publicly available.

[58] In New Zealand, SFT software automatically creates security constraints that are applied in the scheduling and dispatch process. These constraints will be discussed in detail in the following sections.

[59] Transpower, "PR-OC-204 Security Constraints Process," accessed online, 2020.

[60] Transpower, "Quarterly System Operator and System Performance Report: January to March 2023," accessed online, 2023.

[61] Transpower, "Quarterly System Operator and System Performance Report: April to June 2023," accessed online, 2023.

5 Limits

This section explores limits, the development of limits and, where applicable, limit margins across the numerous jurisdictions pertinent to this review. Some key findings include:

- Transparency for stakeholders is important and generally facilitated by regularly publishing documents related to system limits. For example, many jurisdictions (e.g., NEM, CAISO, ERCOT) publish detailed procedures concerning limits' development and application.
- All jurisdictions pertinent to this review employ a "standard" approach for defining secure operating regions through power system simulations to understand the region the system needs to operate within to maintain security and reliability.

5.1 National Electricity Market - Australia

5.1.1 Transmission equipment ratings (thermal limits)

Per clause S5.1.12 of the National Electricity Rules (NER), Network Service Providers (NSPs) "*must, on reasonable request, advise AEMO of the maximum current that may be permitted to flow (under conditions nominated by AEMO) through each transmission line, distribution line or other item of equipment that forms part of its transmission system or distribution system.*"

AEMO provides further guidance on the types of information required to formulate thermal constraint equations in section 5.3 of ESOPP_06 Limits Advice Guidelines.[62] The transmission equipment ratings (in MVA) provided by the NSPs and used by AEMO are also published on AEMO's website.[63]

5.1.2 Non-Thermal Limits Advice

Per NER clause 3.13.3(l5), the Transmission Network Service Provider (TNSP) is responsible for providing "*network limit advice*[64] *relating to power system stability limits to AEMO under clause S5.1.2.3.*" It is noted that clause S5.1.2.3 only relates to inter-regional power transfer capacity, but

[62] AEMO, "Limits Advice Guidelines," accessed online, 2012.

[63] AEMO, "Transmission Equipment Ratings," accessed online, 2025.

[64] Note that "limit advice" is not a defined term in the NEM.

in practice, limits advice is also developed for intra-regional stability issues, e.g., system strength limits in North Queensland.[65]

These NEM arrangements are equivalent to the WEM, where Western Power (as the TNSP) is responsible for developing non-thermal Limit Advice and then providing this information to AEMO for implementation in the market dispatch engine.

Limits advice is typically developed for System Normal, credible contingencies and planned outage conditions (as required by NER clause S5.12.3). AEMO guides the TNSPs on developing limits advice in ESOPP_06 Limits Advice Guidelines[62] (albeit more process-oriented and limited in technical detail). Further guidance on developing non-thermal stability limits is provided in section C.4 of AEMO's Power System Stability Guidelines,[66] describing their expectations for stability studies that need to be performed to arrive at a limit. The guidelines also state that AEMO performs "*a due diligence assessment of the limit advice, using a selection of power system operating conditions.*"

In the NEM, limit equations are typically formulated in terms of power transfer/flows through a specific cutset (e.g., an inter-regional interconnector or intra-regional transmission corridor):

$$\text{Power flow through a cutset (MW)} \leq \text{RHS terms.}$$

Limits advice and the supporting studies used to develop them are generally not publicly available (i.e., there is no NER obligation to publish them). However, AEMO (acting as the jurisdictional planner for Victoria) publishes limits advice for Victoria and oscillatory stability, Frequency Control Ancillary Service (FCAS), and system strength advice for all NEM regions on its website.[67] The published limits advice contains descriptions of each limit (e.g., what the limit is for and why) and the limit equations themselves (including coefficients and terms).

5.1.3 Determining non-thermal limits

AEMO's Power System Stability Guidelines[66] provide a relatively comprehensive treatment of the process for power system stability assessments (including the development of non-thermal stability limits), with considerations around modelling, range of operating conditions, assessment criteria and interactions with NSPs. At a high level, the process for determining non-thermal (stability) limits in the NEM is shown below in Figure 3.

Initial study cases reflect different operating conditions (e.g., high load, low load, northbound or southbound flows). These study cases are then assessed for their stability properties using

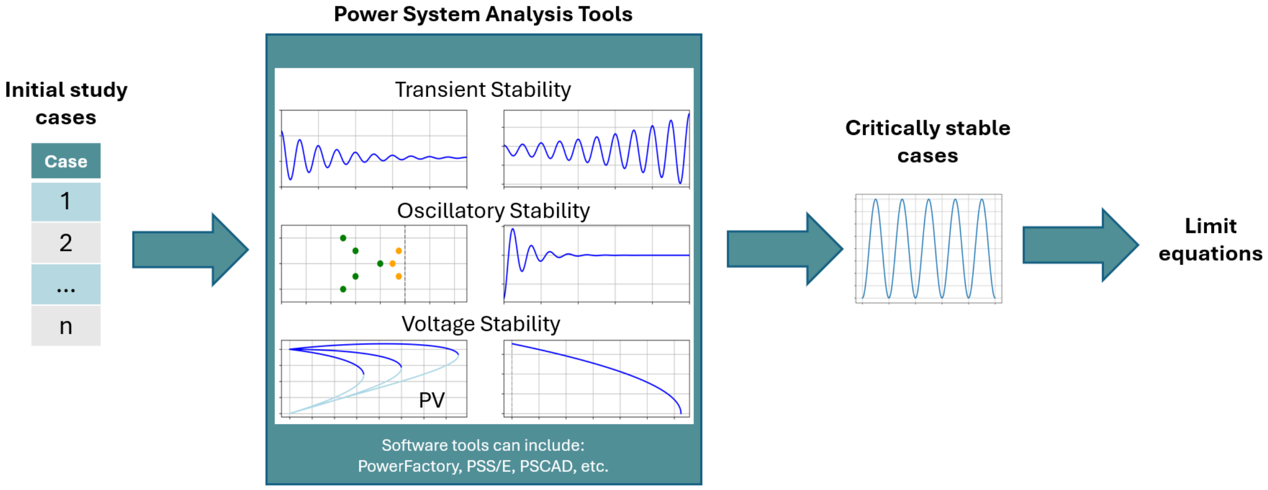
[65] Powerlink, "North Queensland System Strength Constraints," accessed online, 2024.

[66] AEMO, "Power System Stability Guidelines," accessed online, 2022.

[67] AEMO, "Limits advice," accessed online, 2024.

power systems analysis software tools like DIgSILENT PowerFactory, PSS/E, or PSCAD. Due to the volume of study cases that may need to be assessed (> 1,000), automation is often employed using Python scripts.

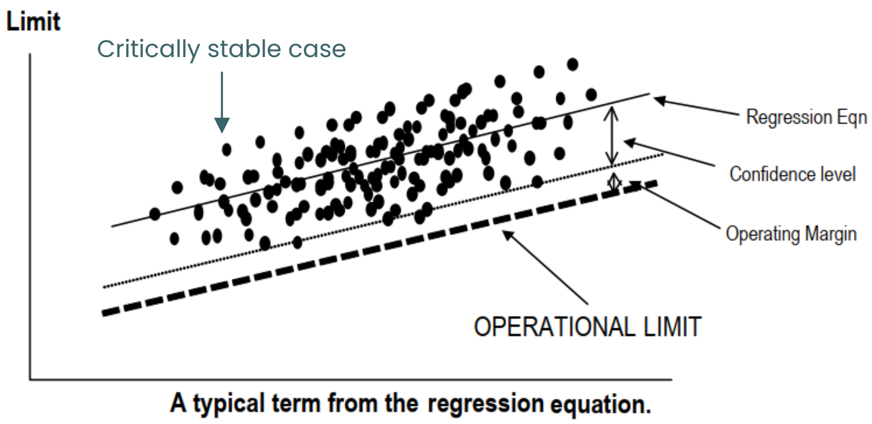
Figure 3: High-level process for determining non-thermal limits in the NEM



From the power system stability assessments, **critically stable cases** are identified. These cases are stable but are at the "edge" of the stability frontier, e.g., one additional MW of power flow would tip it over the edge. The limit equations are developed by applying a linear regression over these critically stable cases, taking the 95th percentile confidence level,[68] and then applying an operating margin (this process is graphically depicted in Figure 4).

[68] Except for Transgrid, where an offset is applied to cover all critically stable cases.

Figure 4: Formulation of limit equation from a linear regression.[69]



Operating margins are calculated based on the following error sources:

- **Modelling approximation error:** accounts for assumptions and uncertainties inherent in the modelling process (e.g. assumptions around system conditions and control system behaviour).
- **Dispatch error:** accounts for generator non-conformance, the effect of voltages on actual MVA flows, and variations in RHS terms over a 5-min dispatch interval.
- **Measurement error:** accounts for errors in metering (e.g., biases, defective transducers, saturation effects).

5.2 Integrated Single Electricity Market - Ireland

5.2.1 Information relating to limits

Weekly publishing of the all-island system's active constraints details any forecasted significant network congestion or limits that could restrict generation.[70] The analysis employs a base power flow case with a collection of N-1 contingencies using the latest available generation and transmission outage information. The contingency analysis considers the tripping of each transmission plant item, including generator transformers. The studies primarily inform the TSO

[69] S. Boroczky and L. Perera. "Voltage Stability and Transient Stability Assessment Tools to Manage the National Electricity Market in Australia". In: S. Nuthalapati, (eds) *Use of Voltage Stability Assessment and Transient Stability Assessment Tools in Grid Operations. Power Electronics and Power Systems*. Springer, Cham. https://doi.org/10.1007/978-3-030-67482-3_10.

[70] EirGrid and SONI, "Weekly Operational Constraints Update," accessed online, 2025.

of voltage and thermal limits.[70] Thermal transmission limits vary seasonally owing to fluctuations in ambient temperature.[71]

The various limit types and flags published by the TSOs are shown in Table 3. Sets of generators form transmission constraint groups (TCGs), upon which limitations are imposed to ensure system security. MW limits restrict the output of a single generator or a group of generators belonging to a TCG. In contrast, MWR limits account for total power output plus the primary reserve minus the area's demand. NB limits determine the operating status of a single generator or a group of generators within a TCG. The limit flags provide bounds on the power output of a TCG's units.

Table 3: Transmission constraint groups and limit flags.

Transmission Constraint Group (TCG) Type	
MW	Limit MW output of unit or units assigned to a TCG
MWR	Limits (the total MW + Primary Reserve - the area demand) from assigned resources
NB	Limit to the status (On/Off) of the unit or units assigned to a TCG
Limit Flag	
E	Equality Constraint (generation = load)
X	Export Constraint - limit output of a group of units <= max limit
N	Import Constraint - limit output of a group of units >= min limit
B	In-between Constraint; >= min and <= max

The all-island system employs local and system-wide operational limits, as highlighted in Table 4 below, which provides a sample of some limits identified in week 3 of 2025. In this case, system-wide limits relate to the system non-synchronous penetration (SNSP), e.g., the instantaneous amount of solar and wind resources on the system, and the maximum rate of change of frequency (RoCoF), i.e., how quickly frequency changes following a disturbance. The local limits state how many generators must be operating from a specific subset (i.e., local to a power system area) to ensure dynamic stability and provide voltage control.

[71] EirGrid, "Topic: Network Modelling," accessed online, 2019.

Table 4: Sample of published limits for the all-island power system in week 3 of 2025.

Name	Area	TCG Type	Limit Type	Limit	Resources	Description
Non-synchronous generation (S_SNSP_TOT)	System-wide	-	X: <=	75%	Wind, PV, Moyle IC, EWIC IC	Ensures that the SNSP is kept below 75%.
Operational Limit for RoCoF (S_RoCoF)	System-wide	-	X: <=	1 Hz/s	Ireland and Northern Ireland Power Systems	Ensures that RoCoF does not exceed 1 Hz/s.
System Stability (S_NBMIN_MINNIU)	Northern Ireland	NB	N:>=	3 units at all times	B10, B31, B32, C30, KGT6, KGT7	There must be at least 3 machines on-load at all times in NI. Required for dynamic stability.
Dublin Generation (S_NBMIN_DubNB2)	Ireland	NB	N:>=	1 Units	DB1, HNC, HN2	There must be at least 1 large generator on-load at all times in the Dublin area. Required for voltage control.

Like the WEM, the I-SEM uses a Capacity Market to ensure sufficient generation capacity is available to meet demand.[72] An annual Capacity Auction facilitates capacity procurement to meet the requirement set out by the RAs. Locational Capacity Constraints set minimum capacity requirements for certain areas, i.e., a minimum bound (limit), to ensure enough capacity (MW) is available to prevent transmission system constraints and maintain network reliability.[73,74]

5.2.2 Pertinent regulation, codes, standards, and processes

Table 5 summarises some documents shaping aspects of operational security, transmission ratings, and limits in the all-island power system.

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72 SEMO, "Capacity Market," accessed online, 2025.

73 SEMC, "Capacity Remuneration Mechanism 2023/24 T-4 Locational Capacity Constraint Areas Consultation Paper SEM-19-048," accessed online, 2019.

74 SEMO, "I-SEM Capacity Market: Locational Capacity Constraints Methodology," accessed online, 2017.

Table 5: Pertinent codes, standards, and processes.

Document	Item	Relevant content
COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation	Article 20	Stipulates remedial actions in system operation
	Article 21	Stipulates principles and criteria applicable to remedial actions
	Article 22	Stipulates categories of remedial actions
	Article 23	Stipulates the preparation, activation and coordination of remedial actions
	Article 72	Operational security analysis in operational planning
	Article 73	Year-ahead up to and including week-ahead operational security analysis
	Article 74	Day-ahead, intraday and close to real-time operational security analysis
	Article 75	Methodology for coordinating operational security analysis
EirGrid Grid Code	-	Provides definitions for the *Total Transfer Capacity* and *Transmission Reliability Margin* as they relate to interconnectors.
EirGrid Operating Security Standards (OSS)	Clause 7.1	States that: *"All equipment on the transmission system shall be operated within rated capacity, including transitory admissible overload limits, as specified by the Transmission Asset Owner (TAO), so that thermal limits are not exceeded."*
EirGrid Transmission System Security Planning Standards (TSSPS)	Clause 2.3.5	States that: "*Thermal limits on equipment shall be as determined by the assumed ambient conditions. Auxiliary and ancillary equipment (such as switchgear, bushings, instrument transformers, tap-changers, etc.) on a branch shall be adequately rated to permit such overloading; if such equipment in existing branches is inadequately rated and cannot be replaced, the lowest such rating shall be the limiting rating on the branch. No overloading on equipment shall be acceptable in planning either for normal or emergency operation except in the immediate aftermath of a disturbance (while corrective action, either automatic or manual, is being taken).*"

Document	Item	Relevant content
SONI TSSPS	Section 4	The Design of the Main Interconnected Transmission System sets out the system's minimum transmission capacity requirements under various operating scenarios.

5.3 California Independent System Operator - CAISO

CAISO adopts the standard approach for developing System Operating Limits (SOLs), i.e., via power system analyses. The technical methodology and criteria for the power system studies required to determine SOLs are published in CAISO Operating Procedure 3100 (the current version is v8.1 from August 2024).[75] The methodology states that a SOL "represents a value (such as MW, MVar, Amperes, Frequency or Volts) that satisfies the most limiting operating criteria for a specified system configuration to ensure operation within acceptable operating criteria." These criteria relate to limits that include thermal limits provided to CAISO by transmission asset owners, transient stability limits established as pre-contingency SOLs on paths, cut planes or interfaces, voltage stability limits, and interconnection reliability operating limits (IROLs).

CAISO Operating Procedure 3100A provides examples of acceptable thermal performance under various operating conditions (e.g., pre- and post-contingency states).[76] Meanwhile, CAISO Operating Procedure 3100B details the system voltage limits and a list of credible multiple contingencies but is not publicly available since it contains proprietary information.[77] Table 6 summarises the CAISO procedures related to limits.

Table 6: Summary of CAISO procedures relating to limits and system limits.

Procedure Number	Procedure Title
3100	Establishing System Operating Limits for the Operations Horizon
3100A	Acceptable Thermal Performance Examples
3100B	System Voltage Limits and Credible Multiple Contingency List

[75] CAISO, "Establish System Operating Limits for Operations Horizon," accessed online, 2024.

[76] CAISO, "Acceptable Thermal Performance Examples," accessed online, 2023.

[77] CAISO, "California ISO Operating Procedures Index List," accessed online, 2024.

5.4 Electric Reliability Council of Texas - USA

ERCOT employs a similar approach to CAISO since it must also meet the NERC reliability standards. ERCOT's SOL methodology pertains to facility ratings, system voltage limits, stability criteria, and stability limits across pre- and post-contingency states.[48,78] Table 7 provides a sample of pertinent SOL methodology definitions related to equipment ratings and system stability/limits.

Table 7: Glossary of pertinent terms defined in ERCOT's SOL methodology.

Term	Definition
Interconnection Reliability Operating Limit (IROL)	A System Operating Limit that, if violated, could lead to instability, uncontrolled separation, or Cascading Outages that adversely impact the reliability of the Bulk Electric System.
Interconnection Reliability Operating Limit Tv (IROL Tv)	The maximum time that an Interconnection Reliability Operating Limit can be violated before the risk to the interconnection or other Reliability Coordinator Area(s) becomes greater than acceptable. Each Interconnection Reliability Operating Limit's Tv shall be less than or equal to 30 minutes.
Network Operations Model	A representation of the ERCOT System providing the complete physical network definition, characteristics, ratings, and operational limits of all elements of the ERCOT Transmission Grid and other information from Transmission Service Providers (TSPs), Resource Entities, and Qualified Scheduling Entities (QSEs).
Normal Rating	The rating as defined by the equipment owner that specifies the level of electrical loading, usually expressed in megawatts (MW) or other appropriate units that a system, facility, or element can support or withstand through the daily demand cycles without loss of equipment life.
System Instability	The inability of the Bulk Power System, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a Disturbance.
System Operating Limit (SOL)	All Facility Ratings, System Voltage Limits, and stability limits, applicable to specified System configurations, used in Bulk Electric System operations for monitoring and assessing pre- and post-Contingency operating states.
System Voltage Limit	The maximum and minimum steady-state voltage limits (both normal and emergency) that provide for acceptable System performance.

[78] Note that ERCOT's SOL states that the "methodology is intended to address NERC Reliability Standard requirements and does not restrict any entity from applying more conservative or alternative means to establish and communicate SOLs or other limitations as needed."

Section 4 of the SOL methodology relates to the SOL/IROL determination approach and stipulates, amongst other things, that transmission asset owners must provide ERCOT with facility ratings, system voltage limits, voltage-related equipment limits, and any special transfer limits.[48] The ratings are maintained in the Network Operations Model, the primary model used in the operations horizon to determine SOLs, which is accessible to NERC transmission planners and operators. Each documented stability limit must have the following information:

- The stability limit or IROL's offline study-determined value
- Identification of the critical facilities for the stability limit or IROL derivation
- The associated IROL Tv for any IROL
- The associated critical contingency (or contingencies)
- A description of system conditions associated with the stability limit or IROL
- The type and limitation represented by the stability limit or IROL

Real-time stability limits and associated real-time flows are made available to NERC transmission operators within the ERCOT Interconnection, and the limits are automatically recalculated every 10-20 minutes, thus providing continual updates.[47] Table 8 provides pertinent information from ERCOT's SOL methodology regarding equipment ratings/limits and SOLs.

Table 8: Selected pertinent content from ERCOT's SOL methodology.

Section	Pertinent content
4 – SOL/IROL Determination Methodology	"REs and ERCOT TSPs that own transmission facilities shall provide all known information to ERCOT ISO regarding the following: Facility Ratings, System Voltage Limits, voltage related Equipment Ratings, any special transfer limits, and any stability limits. ERCOT ISO shall establish any additional SOLs and IROLs based on the information provided by the REs and ERCOT TSPs and ERCOT ISO's analysis described in Section 4 of this methodology."
4.1 – Facility ratings	"REs and ERCOT TSPs that own transmission facilities shall provide Facility Ratings to ERCOT ISO. ERCOT ISO and ERCOT TOs shall utilize the Normal Rating, Emergency Rating, 15-Minute Rating, and Relay Loadability Rating, as defined in Section 2 - Definitions, in operations. [FAC-011-4 R2]. These ratings shall be maintained in the Network Operations Model by the RE and ERCOT TSP. If Dynamic Ratings are available, Dynamic Rating tables with forecasted or actual temperatures shall be used in operations in accordance with Section 3.10.8 - Dynamic Ratings of the ERCOT Protocols."
4.2 – System voltage limits	"Each RE and ERCOT TSP that owns or represents the owner of a modeled NERC BES bus shall provide to ERCOT ISO any voltage limits it utilizes in its operations that deviate from the default System Voltage Limits identified above…The normal minimum (low) System Voltage Limit shall not be less than 0.9 p.u. The

Section	Pertinent content
	emergency minimum (low) System Voltage Limit shall not be less than 0.85 p.u. [FAC-011-4 R3, R3.4]."
4.3 – Stability criteria	"Steady-state voltage stability: The Voltage Security Assessment Tool (VSAT) is used to determine steady state voltage stability limits. Steady state voltage stability limits are the pre-contingency transfer limits established for an identified critical contingency at the last valid solution point during the maximum power transfer from the source to the sink. Additional margin may be applied in real time operations to maintain reliable transfer. When the solution becomes unsolved, the study condition no longer demonstrates acceptable steady-state voltage stability. [FAC-011-4 R4, R4.1, R4.1.1]."
4.4 – Stability and interface limits	"The Network Operations Model is the primary model used in the operations horizon. The Network Operations Model, Steady State Working Group (SSWG), and Dynamic Working Group (DWG) cases have the known current or expected system topology modeled for the ERCOT Interconnection NERC BES and include non-radial facilities 60 kV and above within the ERCOT Transmission system [FAC-011-4 R4.5]. The 60 kV and above threshold provides additional reliability margin to the study model as it goes beyond the 100 kV BES definition. [FAC-011-4 R4.5]. ERCOT ISO's Network Operations Model consists of transmission lines, transformers, circuit breakers and switches, reactive devices, generation facilities and step-up transformers, loads, and other relevant electrical components. For each Network Operations Model it prepares, ERCOT ISO posts ratings and the ambient temperatures used to calculate any dynamic ratings on the MIS Secure Area when the model is published. The DWG study cases consist of similar information as described above as well as additional details and modeling information necessary to perform dynamic and transient stability studies. The Network Operations Model, SSWG cases, and DWG cases are study models that are used to determine SOLs in the operations time horizon [FAC-011-4 R4.5]. ERCOT ISO performs offline stability studies considering transfers, load and generation dispatch, and system conditions, including any change to system topology, such as facility outages. Generation and load are dispatched in the study case to create a high transfer scenario in the stability studies. Typically, the DWG HWLL (High Wind Low Load) case is used for export stability studies and the DWG SP (Summer Peak) case is used for import stability studies. The stability studies include the planned transmission, where appropriate. The facility outages, which have an impact on the stability limits, are considered in the stability studies. [FAC-011-4 R4.4]."

5.5 New Zealand

Like other systems in this review, Transpower uses seasonal transmission capacity ratings across the Summer, Shoulder, and Winter seasons.[79] According to Clause 12.107(1) of the Electricity Industry Participation Code 2010, the ratings' dates must be provided to the Authority.[80] Clause 12.118 of the Code also requires the system's interconnection asset capacity and grid configuration to be published annually by 30 November. The asset capacities are generally updated monthly on Transpower's website.[81] Variable line ratings, which are employed on thirteen circuits across the system, are also published and thus publicly available.[82]

As Transpower is the sole transmission network service provider and system operator, there is no inter-company exchange of information regarding limits and limit equations as in the other jurisdictions surveyed in this review.

[79] Transpower, "Interconnection Branch Capacity – November 2024," accessed online, 2024.

[80] Transpower, "2023-2024 Interconnection Asset Capacity and Grid Configuration," accessed online, 2024.

[81] Transpower, "Grid capability and configuration," accessed online, 2025.

[82] Transpower, "Variable line rating information," accessed online, 2025.

6 Constraint Equations

This section explores the development of constraint equations across the numerous jurisdictions pertinent to this review. Some key findings include:

- All jurisdictions adopt a similar approach to developing constraint equations—this "standard" approach formulates linear constraint equations using the boundaries of the secure operating regions previously identified through power system simulation studies.
- Maintaining power system security and reliability in real-time operations is paramount, i.e., generally to the exclusion of economic factors.
- Based on the above points, real-time system operations departments worldwide are largely left to themselves to operate their power system securely without outside economic scrutiny but generally with third-party oversight for security and reliability outcomes.

6.1 National Electricity Market - Australia

AEMO develops thermal constraint equations from the transmission equipment ratings/thermal limits provided by the NSPs for each relevant transmission element (e.g., transmission line, cable, transformer). The ratings are described in MVA and converted to a MW limit, i.e., using a notional power factor.[83] The thermal constraint equation is then formulated as follows for a generic N-1 constraint:

$$a_1 \Delta F_1 + \cdots + a_n \Delta F_n \leq \text{Rating} - \text{Flow} - RDF \times \text{Tripped Flow} - OM$$

where ΔF_i is the change in the i^{th} facility output (MW), a_i is the i^{th} facility coefficient, Rating is the rating of the monitored transmission element (MW), Flow is the measured power flow through the monitored transmission element (MW), Tripped Flow is the measured power flow through the tripped element (MW), RDF is the redistribution factor and OM is the operating margin.

The **facility coefficients** are calculated based on the transmission element's power flow sensitivity to a change in the facility's output. For example, a coefficient of 0.5 means that an increase of 1 MW by the facility will lead to a 0.5 MW increase in flow across the monitored transmission element. The coefficients can be readily calculated using power system analysis software based on the network topology and impedances—they are also referred to as *power transfer distribution factors* (PTDF) or *shift factors*.[84] AEMO policy in the Constraint Formulation

[83] The power factor is the ratio of active power (MW) to apparent power (MVA) and is typically very high in transmission systems, e.g., >0.90.

[84] There are standard functions in software packages such as PSS/E for calculating PTDFs / shift factors.

Guidelines[85] is to only consider facility coefficients greater than 0.07 on the LHS (i.e., treated as decision variables).

The **redistribution factor** represents the proportion of power flow across the tripped transmission element that would be redirected through the monitored transmission element. Like the facility coefficients, redistribution factors can be calculated using standard power systems analysis software using the network topology and impedances.

6.1.1 Constraint equations

Per NER clause 3.8.10(b), AEMO is responsible for determining and representing "*network constraints in dispatch which may result from limitations on intra-regional or inter-regional power flows and, in doing so, must use a fully co-optimised network constraint formulation.*" There is a similar obligation for AEMO to develop FCAS constraints in NER Clause 3.8.11.

To achieve this, AEMO converts the transmission equipment ratings and limits advice it receives from the NSPs into a set of linear equations that is compatible for use directly in the NEM dispatch engine (NEMDE). AEMO may also re-arrange the terms in the limit equations provided by TNSPs to ensure that the constraint equation can be formulated in a fully co-optimised manner.

The following table lists the procedures and guidelines available on AEMO's website that are relevant to the development, formulation, application and monitoring of constraint equations.

Table 9: AEMO procedures and guidelines relevant to NEM constraints

Document	Version / Date	Relevant content
Constraint Formulation Guidelines	v12 / Jun 2023	Guidelines on the formulation of network and FCAS constraints, focusing on the principles, structure and lifecycle of constraint equations.
Constraint Implementation Guidelines	v3 / Apr 2023	Guideline on how AEMO implements constraint equations from the limits advice.
ESOPP_06 Limits Advice Guidelines	v1.0 / Mar 2012	Guidance for TNSPs on what AEMO expects from limits advice for developing constraint equations.
ESOPP_08 Confidence Levels, Offsets and Operating Margins Policy	v3 / Jul 2010	AEMO's policy on applying statistical confidence intervals, offsets, and operating margins to constraint equations.

[85] AEMO, "Constraint Formulation Guidelines," accessed online, 2023.

Document	Version / Date	Relevant content
ESOPP_37 Management of Risks on NEM Congestion	v2 / May 2012	AEMO guide describing the sources of risk in managing congestion with constraints and AEMO's approach to mitigating these risks
Power System Stability Guidelines	v2.0 / Dec 2022	Guidance on the development of stability limits and constraint equations.
SC_CM_04 Constraint Naming Guidelines	v8 / May 2013	Guidelines on the naming conventions for different types of constraint equations.
SC_CM_35 Constraint Automation – Closing the Loop – Discussion Paper	v3.1 / Apr 2023	Paper describing how AEMO automates the generation of thermal constraint equations with an Energy Management System (EMS) application.
Schedule of Constraint Violation Penalties	v6.0 / Jun 2024	List and values for constraint violation penalties.
SO_OP_3704 – Pre-dispatch procedure	v17 / Jun 2024	Formulation and application of constraints for pre-dispatch.
SO_OP_3705 – Dispatch procedure	v94 / Jun 2024	General procedure on the application of constraints during dispatch, as well as sections on monitoring and reviewing constraint performance.
SO_OP_3715 – Power system security guidelines	v105 / Jun 2024	Application of constraints to manage power system security, including interactions with TNSPs around limit advice and equipment ratings.
SO_OP_3718 – Outage assessment	v18 / Oct 2024	Development and application of constraints for planned outages.

6.1.2 Formulating non-thermal constraint equations

Non-thermal limits advice from TNSPs are already formulated as a linear sum of terms but not in a manner that AEMO can use in its NEMDE, e.g., facility outputs are only included on the limit equation's RHS and thus cannot be fully co-optimised.

In formulating the non-thermal constraint equations, AEMO must re-arrange the terms so that facilities with coefficients greater than the 0.07 threshold are moved to the equation's LHS. Under some circumstances, AEMO may also linearise RHS terms for facilities not linearly related to facility output (e.g., squared terms, online status).

Finally, AEMO may include an operating margin if not provided by the TNSP in the limit equation (or adjust a margin provided by the TNSP).

6.2 Integrated Single Electricity Market - Ireland

Each TSO of the all-island system (EirGrid and SONI) manages the real-time planning and operation of units on the power system as part of a 24/7 process coordinated by the respective control centres in Belfast and Dublin using common operational systems and processes.[86] Inputs to the scheduling and dispatch process include demand and renewable energy forecasts, system constraints, interconnector technical data, system service requirements, and real-time system conditions.[87]

6.2.1 System constraints

Various constraint types exist in the I-SEM, which can be categorised according to *reserve* (frequency limits), *thermal*, *voltage*, and *dynamic stability*, as shown in Figure 5. Constraints are generally determined through a combination of planning studies and real-time power system analysis and monitoring.[88] Hence, most constraints are known in advance and modelled accordingly in the scheduling tools. Some constraints, such as those relating to frequency, transient stability, and adverse weather conditions are usually observed and dealt with close to real-time.[70]

Figure 5: Example of different constraint types in the I-SEM

Reserve (Frequency Limits)	**Thermal**	**Voltage**	**Dynamic Stability**
All Island OR Requirement	North-South Tie-Line Limit	Coolkeeragh Must Run	Inertia
NI/IRL OR Requirement	Ballylumford Export Limit	Kilroot Must Run	RoCoF†
NI/IRL RR (OCGT) Limitation	Various Dublin Must Run	Various Dublin Must Run	SNSP‡
NI/IRL Negative Reserve	Cork Export Limit	South West Must Run	NI 3 Units Must Run
Ramping		Moneypoint Must Run	IRL 5 Units Must Run

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[86] EirGrid and SONI, "I-SEM Training, Instructor-Led Training, Part 1: TSO Scheduling, Part 2: Imbalance Pricing", accessed online, 2017.

[87] The TSOs are currently working on the Scheduling and Dispatch Programme (SDP), which is a body of work designed to enhance the scheduling and dispatch systems and processes in Ireland and Northern Ireland, and achieve compliance with the EU's Clean Energy Package (CEP).

[88] EirGrid and SONI, "Balancing Market Principles Statement: A Guide to Scheduling and Dispatch in the Single Electricity Market", accessed online, 2022.

An example of the North-South Tie Line constraints is shown in Box 1,[89] with similarities to the constraint equation formulation in Section 6.1.

Box 1: North-South Tie Line Constraints

For positive flows from South to North:

$$T_{S-N} + \min(POR_{IE}, LSI_{NI} - 25\%POR_{NI}) \leq S_{MWR_{IE}} - 20\ MW$$

For positive flows from North to South:

$$T_{N-S} + \min(POR_{NI}, LSI_{IE} - 25\%POR_{IE}) \leq S_{MWR_{NI}} - 20\ MW$$

Where: T_{S-N} is positive scheduled tie-line flow from South to North, T_{N-S} is positive scheduled tie-line flow from North to South, POR_{IE}/POR_{NI} are the scheduled Primary Operating Reserves in Ireland/Northern Ireland, $LSI_{IE}/\ LSI_{NI}$ is the scheduled MW output of the Largest Single Infeed in Ireland/Northern Ireland, $S_{MWR_{IE}}/S_{MWR_{NI}}$ are the maximum allowed flows including rescue/reserve flows that could occur immediately post-fault inclusive of operating reserve requirements, and 20 MW is a margin of safety.

Constraints arising through real-time analysis and monitoring are managed during real-time operation and can appear owing to forced outages (like the trip of a transmission line) or unexpected events, such as wind generation levels exceeding the forecast.[88] The constraints and requirements identified in the weekly forecast, along with any updates from forecast changes and the continuous monitoring of real-time power system status, are inputs to each schedule. The optimisation process for each scheduling run avoids constraint violations by assigning penalty costs, which increases a schedule's overall cost and thus discourages breaches. These violation costs form optimisation parameters that are tuned to give effect to each constraint.[88]

Security analysis is performed every five (5) minutes, which considers circuit loadings, system voltages, and transient stability for various contingencies.[88] The analysis runs in parallel with the scheduling and dispatch process and can lead to constraints that are not reflected in the schedule. This real-time process iterates between the Network Security Monitor, a mathematical model of the power system that aims to ensure each schedule meets security standards, and the unit commitment solver (NCUC) as follows[71]:

[89] EirGrid and SONI, "Information Note on Inter-Area Flow (North-South Tie Line) Constraints," accessed online, 2019.

1. NCUC produces an initial schedule based on factors including, but not limited to, participants' physical notifications, constraints, and commercial and technical offer data.[90]
2. The Network Security Monitor performs N-1 power flow analysis using the schedule.
3. Any violations are reported alongside shift factors.
4. NCUC reruns using the new information.
5. The new schedule reruns in the Network Security Monitor.
6. The iterative process continues until a secure schedule is determined.

Operational studies are critical for determining precise constraint values.[24] For example, the power system's increasingly inverter-dominated nature is driving the need for more detailed and advanced analyses like EMT simulations to study new phenomena. Greater automation will thus be needed to perform relevant analyses more frequently to provide system constraints.

The power system's changing character has also led to global (system-wide, always active) constraints like the minimum number of units online (MUON) and system non-synchronous penetration (SNSP),[24] which are shown in Table 4 and Figure 5. These constraints ensure system security and safety under increasing penetrations of inverter-based renewable energy. However, future power system operation will need to relax these constraints through disaggregation to produce more targeted ones, which is an ongoing body of work.

Table 10 highlights some of the pertinent processes that influence system constraints across the all-island system.

Table 10: Pertinent processes for system constraints in the all-island system.

Document	Item	Relevant content
Business Process BP_SO_2.1 Constraints Changes in Scheduling Runs	-	Details the process for managing constraints within the Market Management System (MMS).
Business Process BP_SO_2.2 System Constraints Calculation	-	Details how system constraints are calculated and the roles and responsibilities into near time and real time.

[90] The Network Security Model employs a DC load flow approximation and thus only analyses thermal/overload issues. The weekly look-ahead constraint studies are an input to the NCUC.

6.2.2 Real-time tools

The suite of real-time monitoring tools currently in use or development that influence (or could influence) constraints include[71,91]:

- **Integrated energy management system (EMS) equipped with real-time monitoring of operational metrics**: A single all-island EMS facilitates total system control from either TSO control room. Numerous operational metrics are monitored in real-time, including the system non-synchronous penetration (SNSP), the rotational kinetic energy from online synchronous units (system-wide and jurisdictional values), and a rate of change of frequency (RoCoF) calculation. These metrics relate to the system's operational limits.
- **Wind dispatch tool (WDT)**: Facilitates control of the all-island system's wind generation in real-time by allowing wind farm setpoints to be directly issued from the EMS. The tool provides dispatch-down instructions to wind generators due to *curtailment*—a global function that allows the system operator to reduce the output of all controllable wind farms at once in situations where the total wind output is considered to be a system security threat (e.g., SNSP exceeding the secure operational limit)—and *constraints* where an individual or a group of wind farm output(s) can be reduced due to local network constraint issues (e.g., thermal limits).
- **Look-ahead security assessment tool (LSAT)**: This state-of-the-art real-time dynamic security assessment tool was developed to support high levels of non-synchronous generation. The tool delivers radar-like guidance for operating the power system safely and securely while minimising wind curtailment and helping maintain power system security under all conditions. It has become a critical decision support tool that allows the system operator to push operational boundaries, particularly the system-wide (global) operational limits.[92]
- **Voltage trajectory tool (VTT)**: Will be used to produce schedules of reactive power resources and voltage set points in the most optimal way over a multi-hour study period to maintain a healthy all-island voltage profile.

6.3 California Independent System Operator - USA

CAISO operates a fully nodal market where all major transmission nodes are represented in the market dispatch engine, and a market clearing price is established for each node (the

[91] M. Val Escudero et al., "Enhancing Decision Support Tools in Ireland and Northern Ireland Control Centres to Facilitate Integration of Large Shares of Wind Generation", accessed online, 2021.

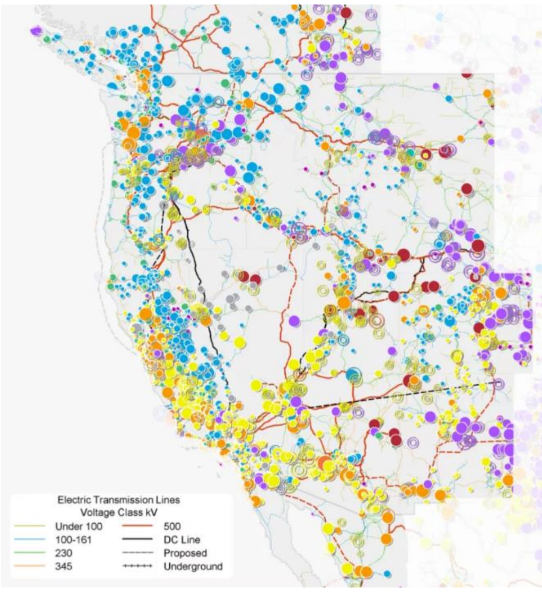
[92] EirGrid and SONI, "Look ahead security assessments: Operations radar to navigate high IBR waters in the journey to Net Zero," accessed online, 2023.

locational marginal price). This contrasts with the WEM—a copper plate model where the underlying network is represented as a single representative node (Southern Terminal).

In the WEM, all transmission constraints must be represented as constraint equations because transmission flows are excluded from the market model. However, in fully nodal markets like CAISO, power flows across all major transmission paths are endogenously solved within the market model. As a result, most simple System Normal and N-1 thermal transmission constraints can be solved directly by the market dispatch engine. Like the WEM and NEM, thermal limits on transmission elements are provided to CAISO by the transmission network owners, e.g., Pacific Gas and Electric Company, San Diego Gas and Electric, etc.

However, CAISO still requires the formulation of linear constraint equations (referred to in CAISO parlance as "nomograms") for non-thermal constraints and more complex arrangements, e.g., transmission corridors and cutsets that span multiple transmission elements such as flowgates and interties.

Figure 6: Full nodal (CAISO) vs single reference node (WEM) markets



(i) CAISO full nodal model representation

(ii) WEM single reference node (copper plate) representation

CAISO adopts the standard approach for developing SOLs and nomograms, i.e., via power system analyses and linear curve fitting. The technical methodology and criteria for the power system studies required to determine SOLs are published in CAISO Operating Procedure 3100 (the current version is v8.1 from August 2024).[93]

[93] CAISO, "Establish System Operating Limits for Operations Horizon," accessed online, 2024.

Applying operating margins to constraint equations is described in CAISO Technical Bulletin 2009-07-02: *Process for Biasing Flowgate/Nomogram Operating Limits for Day Ahead & Real Time Markets.*[94] Additionally, the specific use of operating margins on interties (referred to as Transmission Reliability Margins) is described in CAISO procedure 3620 (the current version is v3.3 from September 2023).[95]

CAISO's justifications for applying operating margins are broadly like the NEM and WEM: to allow for:

i. Errors in calculated market flows against actual flows
ii. Accommodate inherent mismatches between day ahead and real-time schedules
iii. Reliability margins in real-time
iv. Adjustments in flowgates with known telemetry issues.

However, CAISO does not provide any further details on quantifying operating margins.

6.4 Electric Reliability Council of Texas - USA

ERCOT employs a security-constrained economic dispatch (SCED) engine to optimise the generator dispatch process to meet demand with the least cost.[96] The SCED dispatch solution respects each transmission line's thermal limits, ensuring line flows do not exceed thermal limits under normal and credible contingency scenarios. This is the same as CAISO, where transmission constraints are solved directly by the market dispatch engine.

However, the SCED cannot consider other limit types that impact lines' maximum permissible flows in the generator dispatch process. Generic Transmission Constraints (GTCs) are transmission constraints comprising one or more grouped transmission elements used to constrain flows between ERCOT's geographic areas to manage stability, voltage, and other constraints that cannot be modelled directly in power flow and contingency analysis applications.[48] ERCOT uses GTCs in real-time operation to calculate generator dispatch by assigning GTCs a limit that reflects the value of the stability transfer limit.[96,97]

[94] CAISO, "Technical Bulletin 2009-07-02: Process for Biasing Flowgate/Nomogram Operating Limits for Day Ahead & Real Time Markets," accessed online, 2009.

[95] CAISO, "Transmission Reliability Margins," accessed online, 2023.

[96] ERCOT, "ERCOT Trending Topics: Generic Transmission Constraints (GTCs)," accessed online, 2024.

[97] Note that this value is termed a Generic Transmission Limit (GTL)—a value calculated for a given GTC that represents the GTC's SOL for a given set of system conditions.

Hence, the overall process for dealing with constraints is as follows[98]:

1. **Constraint identification**: ERCOT executes its state estimator and performs real-time contingency analysis every 5 minutes.
2. **Constraint Usage**: The SCED market dispatch process runs every 5 minutes and uses the constraints identified through the real-time contingency analysis for congestion management.

The SCED process's objective is thus to minimise the total system dispatch costs while maintaining power system balance and resolving transmission network congestion as specified in the transmission constraint input set.[99] Shadow pricing represents the cost impact associated with tightening constraints—and relates to an increase in system cost if a line limit is reduced by 1 MW in the context of transmission network constraints—thus influencing both total dispatch cost (through penalty costs) and LMPs which are capped based on shadow price limits.

6.5 New Zealand

Transpower's Scheduling, Pricing, and Dispatch (SPD) software builds and solves an electricity market linear program that details the resulting prices and quantities.[100] The SFT software automatically creates most security constraints applied to the SPD engine; however, the system operator also develops some manual constraints through non-automated processes.[101] The automated constraints are published to market participants using the Wholesale Information Trading System (WITS). Planned manual constraints are published at least two weeks before the intended date of first use.[101,102]

The SFT determines branch limits using static and thermal limits and performs contingency screening/analysis to develop constraints of the generic form:

$$K_1 P_m + K_2 P_c \leq c$$

where K_1 and K_2 are constraint coefficients, P_m and P_c are the pre-contingency power flow on the monitored and contingent branches, respectively, and c is the constraint's right-hand side

98 ERCOT, "Real-Time Transmission Congestion Management and Market Effects," accessed online, 2015.

99 ERCOT, "ERCOT Nodal Protocols: Section 22 – Attachment P: Methodology for Setting Maximum Shadow Prices for Network and Power Balance Constraints," accessed online, 2024.

100 Transpower, "SPD_Model_Formulation_v14.0," accessed online, 2024.

101 Transpower, "Security constraints," accessed online, 2022.

102 Transpower, "Manual constraints," accessed online, 2024.

(RHS).[103,104] Table 11 summarises the various constraint categories—automatic constraints are developed across each trading period in alignment with the forecasted topology, and manual constraints have a fixed construction since they cannot be dynamically created.[59]

Table 11: Summary of Transpower constraint types and categories.[59]

Constraint Type	Constraint Category	Summary Description
Automatic	SPD Constraints	Branch type constraints that ensure equipment overloading does not occur pre-contingency. These constraints are applied by the SPD engine in all schedules based on equipment ratings accounting only for active power flows (MW).
Automatic	SFT Constraints	Branch type constraints that ensure monitored equipment overloading does not occur after branch contingencies for which SFT is enabled—considers voltage, and active (MW) and reactive (MVAr) power flows.
Manual	Permanent Constraints	Applied for "normal" grid configurations
Manual	Outage Constraints	Applied for routine outage conditions
Manual	Temporary Constraints	Applied for temporary (not outage related) or one-off situations like temporary grid configurations, e.g., commissioning, or temporary conditions like contingency reclassification owing to weather events or emergency equipment rerating

The initial threshold for SFT constraints is 90%, and 0% for manual constraints.[101] The threshold refers to the "near binding" level at which the constraints are created. For example, for a threshold of 90%, a scenario has reached 90% of violating a limit.

From the Transpower procedures, no operating margins are allowed for in the constraint equations. The performance of manual security constraints is assessed through power system studies to ensure the constraint binds for any scenario where security violations occur (and does not bind for any instances where security violations do not occur).[59]

[103] Transpower, "Simultaneous Feasibility Test (SFT) Process Overview," accessed online, 2022.

[104] Transpower, "High Level Description of Security Constraint Creation Process with SFT Constraint Building (SFTCOB)," accessed online, 2022.

Table 12 summarises Transpower's internal policies, processes, and procedures relevant to constraint development and transparency.

Table 12: Internal policies, processes, and procedures relevant to constraints.

Policy/Process/Procedure	Definition
PR-EA-001	Grid Assets Seasonal Ratings Changeover
GL-OC-202	Security Constraints Development Methodology
UG-OC-210	Build and Update Constraints in ACI
PR-OC-203	Analyse Security Implications and Mitigate Violations
PR-OC-204	Security Constraints Process
PR-OC-215	Determine Conductor Thermal Characteristics for use in Manual Constraint Development
PR-OC-229	Update Registers, Email Notifications, Email CANs, Update Transpower Website
PR-OC-230	Manage SFT-Created Constraints
UG-OC-205	Security Constraint Development Paper
RS-EA-000	Register of Manual Constraints

Note that Transpower provides fairly detailed process flowcharts for the SFT constraint development process[103] and the creation of constraints using SFT Constraint Builder,[104] as well as a full list of manual constraints[102] (those updated and published 2 weeks before new constraints are first used). The flow charts describe the sequence of simulation studies performed and the logic used to create a constraint equation.

7 Academic Literature

An academic literature search for relevant materials (e.g., constraint equation oversight, assessing constraint equation's economic efficiency and effectiveness) was performed. There is a strong focus on transmission constraints' market and economic impacts but sparse information concerning developing and overseeing these constraints.

A preference for confidentiality within system operators (and the electricity industry more broadly) contributes to limited transparency and is likely a principal contributor to the dearth of academic studies in this area, as noted in one paper[105]: *"[R]eliability assessment involves much sensitive market information and ISO operation details which are not available to the public. This is part of the reason why the ISO operation is sometimes referred to as a "black box" operation."*

However, an intellectual predecessor of linear constraint equations used in market dispatch engines is the **secure operating region**—a set of power system operating states known to be secure for steady-state[106] and dynamic[107] conditions. The secure operating region can be expressed as a set of states but can also be graphically depicted, e.g., using nomograms relative to transmission corridor power transfers or generating group outputs. Examples of nomograms depicting secure operating regions are shown in Figure 7.

Linearised limit equations can be derived by calculating line segments along the boundary of the secure operating regions. In the academic literature, secure operating regions are determined in much the same way that limit and constraint equations are developed in wholesale electricity markets, viz.

- Use power systems analysis software tools to explore and simulate a search space of possible power system operating states and check for system security issues, such as:
    - Thermal overloads
    - Transient stability
    - Voltage stability
    - Oscillatory stability

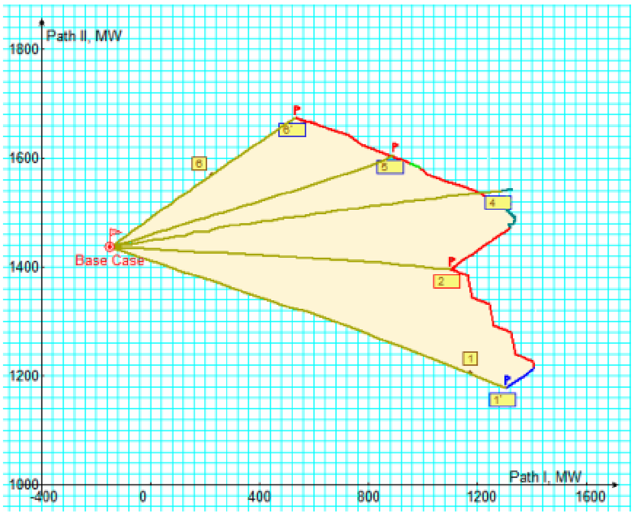
[105] J. N. Jiang and J. Yu, "Reliability in Electricity Markets: Another Binding Constraint?", The Electricity Journal, vol. 17, issue 5, 2004.

[106] F. Wu and S. Kumagai, "Steady-State Security Regions of Power Systems," in IEEE Transactions on Circuits and Systems, vol. 29, no. 11, pp. 703-711, November 1982, doi: 10.1109/TCS.1982.1085091.

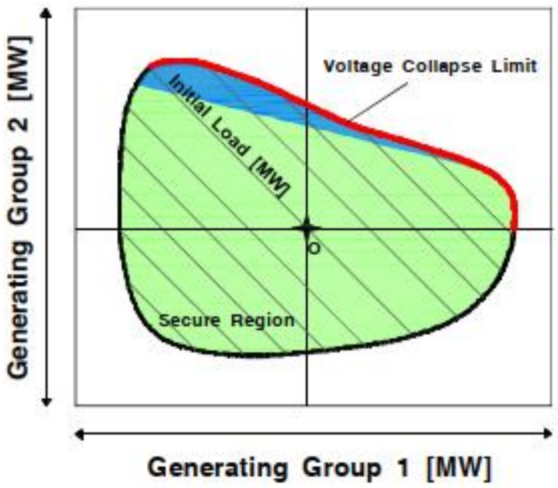
[107] R. Kaye and F. Wu, "Dynamic security regions of power systems," in IEEE Transactions on Circuits and Systems, vol. 29, no. 9, pp. 612-623, September 1982, doi: 10.1109/TCS.1982.1085203.

- Determine the operating region (e.g., a set of feasible operating states) that should be adhered to for secure system operation using the simulation results.

Figure 7: Examples of nomograms of secure operating regions



(i) Secure operating region based on transfers across transmission paths[108]



(ii) Secure operating region based on generating group outputs[109]

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108 M. Papic, M. Y. Vaiman, M. M. Vaiman and M. Povolotskiy, "A New Approach to Constructing Seasonal Nomograms in Planning and Operations Environments at Idaho Power Co," 2007 IEEE Lausanne Power Tech, Lausanne, Switzerland, 2007, pp. 1320-1325, doi: 10.1109/PCT.2007.4538507.

109 H. Sarmiento, G. Pampin, R. Barajas, R. Castellanos, G. Villa and M. Mirabal, "Nomograms for assistance in voltage security visualization," *2009 IEEE/PES Power Systems Conference and Exposition*, Seattle, WA, USA, 2009, pp. 1-6, doi: 10.1109/PSCE.2009.4840049.

8 Inter-Jurisdictional Best Practices

We note from this review that no formal oversight roles are conferred to third parties (e.g., regulators) in the jurisdictions surveyed to ensure that limits and constraint equations are effectively governed. The industry best practices garnered from these jurisdictions are the set of practices (both externally and self-imposed) that best align incentives in balancing risk and economic efficiency while promoting competition.

8.1 Robust and transparent processes

The organisations responsible for Limit Advice and Constraint Equations (e.g., system operators and transmission network companies) adopt self-imposed practices to continuously monitor and review limits and constraint outcomes while transparently communicating information to stakeholders. These practices are encoded in internal-facing and public processes, e.g., in written materials like procedures, guidelines, process flow charts, templates, and worked examples.

Without third-party oversight, some jurisdictions (like the NEM and New Zealand) provide a high level of public transparency around company processes for developing, monitoring, reviewing and updating limits and constraints.

Public transparency around processes aligns with the State Electricity Objective (SEO) of promoting "*efficient investment in, and efficient operation and use of, electricity services for the long-term interests of consumers of electricity*" by clearly communicating how limits and constraints are constructed and applied while supporting independent stakeholder review.

Examples of robust and transparent processes include:

- AEMO's (NEM) Constraint Automation Paper: A highly detailed and publicly available technical document describing the automation of NEM thermal constraint equation development.
- Transpower's (NZ) Security Constraints Process: Detailed and publicly available process flow diagrams and descriptions of the security constraints management processes, clearly articulating individual roles and responsibilities.

8.2 Regular assessment of binding limits and constraints

Binding constraints have an economic impact that can be notionally measured by the constraint's shadow price (i.e., the marginal cost of relieving the constraint by 1 MW). A practice of routinely investigating and reviewing binding constraints (and the limits that make up the constraints) was observed in the jurisdictions with the strongest governance frameworks.

Assessments first confirm that constraints are appropriately formulated and binding legitimately (i.e., preventing insecure operational outcomes). The constraints are then revised or reformulated where errors and/or over-conservative constraints are identified. For legitimately binding constraints, improvements are sought through continuous efforts like implementing measures to increase limits or making operational planning adjustments (e.g., shifting the timing of outages to minimise constraint binding).

Reviews can be conducted periodically (e.g., annually) and/or based on triggers (such as binding constraints meeting a preset threshold).

Examples of binding constraint assessments include:

- AEMO (NEM): Publishes monthly and annual constraint reports providing statistics on binding constraints and the outcomes of any reviews or investigations.
- AEMO (WEM): Publishes a weekly and annual constraint outcomes and congestion reports, with information on both operational and RCM constraints.
- CAISO (California): Formally reviews limits and constraints during (i) the seasonal assessment and (ii) the model database promotion process.

8.3 Stakeholder feedback mechanisms

Stakeholder feedback mechanisms allow market participants, regulatory authorities, or even interested persons in the general public to provide feedback or to question limit and/or constraint functionality, catalysing investigations. Robust feedback mechanisms strengthen the governance of limits and constraints by allowing (and inviting) stakeholder scrutiny and facilitating more opportunities to identify and correct mistakes.

Feedback mechanisms should ideally be a closed loop via an obligation (self-imposed or otherwise) to respond to and address feedback received from stakeholders.

Examples of stakeholder feedback mechanisms include:

- AEMO (NEM): Participants can contact AEMO if they suspect a constraint equation is not performing as expected.
- Transpower (NZ): Participants can request Transpower to perform and publish constraint assessments.
- ERCOT (Texas): Participants can request System Operating Limits (SOL) to be retired.

8.4 Real-time system security monitoring

Real-time system security monitoring includes power system software simulation tools like real-time contingency analysis (typically embedded in the Energy Management System) and dynamic security assessment tools. All jurisdictions employ real-time system security monitoring tools to varying degrees of sophistication.

The monitoring tools provide system controllers with real-time situational awareness of system security. As the tools are based on power system simulations using real-time data as inputs, they are more accurate than constraint equations (which are more akin to simplified estimates of system security). This allows system controllers to identify insecure operational states as they arise in real-time, serving as a backup measure to constraint equations for maintaining system security. For example, real-time system security monitoring tools can flag whether a constraint equation fails to prevent an insecure operational state from materialising, allowing system controllers to act accordingly.

The tools also ensure that constraints imposed by dispatch engines are working as expected. For example, if the same thermal congestion issue is being flagged repeatedly in the real-time system security monitoring tools, then one or more constraint equations (or limits) are not performing correctly and must be revised.

Examples of real-time system security monitoring include:

- All jurisdictions: Use real-time contingency analysis tools to monitor the performance of thermal constraint equations.
- I-SEM (Ireland): The system operator, EirGrid, has numerous advanced real-time system security monitoring tools like the look-ahead security assessment tool (for dynamic security assessment) and the voltage trajectory tool.

8.5 Business process audits

While serving a broader function than the assurance of Limit Advice and Constraint Equations, system operators (and network businesses) perform periodic audits of their business processes, either as a self-imposed practice or due to a regulatory requirement. Business process audits can be self-performed by the organisation or conducted by a third-party auditor.

Examples of business process audits include:

- I-SEM (Ireland): The Transmission System Operators (EirGrid and SONI) must undertake periodic third-party audits of the scheduling and dispatch process's operation and implementation. However, the derivation of operational constraints is excluded from the audit's scope.

- Transpower (NZ): In agreement with the Electricity Authority, Transpower conducts business assurance self-audits and risk control self-assessments, including audits for the management of real-time constraints (i.e., Simultaneous Feasibility Test constraints) and the performance of real-time system security monitoring tools (like the Voltage Stability Assessment Tool).

8.6 Reliability compliance monitoring and enforcement

Reliability compliance monitoring and enforcement by third parties (like the government or a regulator) provides formal oversight of a system operator's performance in meeting power system reliability standards, e.g., limits on major outages and loss of supply to electricity customers.

A compliance monitoring and enforcement framework can include launching investigations and imposing penalties when system operators breach reliability standards. While broader in scope and not specifically intended for limits and constraints, such a framework is still relevant since missing or incorrectly designed constraints can trigger insecure operational outcomes that lead to customer supply loss. The constant vigilance and threat of penalties incentivise system operators (and network companies) to be more rigorous in developing limits and constraints.

Examples of reliability compliance monitoring and enforcement include:

- CAISO and ERCOT (United States): The North American Electric Reliability Corporation (NERC) oversees the respective system operators as the federal Electric Reliability Organisation.

A1 Power System Comparisons

A1.1 National Electricity Market - Australia

The NEM is an interconnected power system encompassing five (5) regions: New South Wales, Queensland, South Australia, Tasmania, and Victoria. The NEM's capacity is roughly tenfold larger than the SWIS, with an installed capacity of ~60 GW and coincident system peak demand of ~34 GW.

A1.2 Integrated Single Electricity Market – Ireland

The all-island power system that underpins the island of Ireland is relatively small (compared to Australia's NEM), with high non-synchronous renewable energy targets (75%).[110] A new peak system demand of 7,502 MW was set on 8 January 2025 (not quite double the WEM's).[111] Three (3) high-voltage direct current (HVDC) interconnectors link the system to Great Britain: The East-West and Greenlink interconnectors between Ireland and Wales and the Moyle Interconnector between Northern Ireland and Scotland.[112] The TSOs are expecting significant changes in the All-Island power system, including[24]:

- Large solar generation and offshore wind farms
- Hydrogen energy production
- Demand response and energy storage innovations
- Coupling to European markets and market evolution
- Significant demand growth owing to societal electrification and large energy users

A1.3 California Independent System Operator

The California power system is part of the Western Interconnection, which provides electricity to 71 million people in 14 western US states, two Canadian provinces, and portions of one Mexican state.[113] The Californian power system's all-time peak demand is 52.061 GW, which occurred on September 6, 2022.[114]

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[110] EirGrid and SONI, "All-Island Generation Capacity Statement 2022-2031," accessed online, 2022.

[111] EirGrid, "System Demand," accessed online, 2025.

[112] The Celtic Interconnector project is set to deliver a fourth interconnection to France, with planned completion in 2026.

[113] Transmission Agency of Northern California, "The Western US Power System," accessed online, 2024.

[114] California ISO, "Peaks for December 2024," accessed online, 2025.

A1.4 Electric Reliability Council of Texas

The Texas power system's record peak demand stands at 85,508 MW, which occurred on August 10, 2023.[115] A new renewable energy penetration record of 75.67% was set on March 29, 2024, corresponding to 34,958 MW.[116]

A1.5 New Zealand

The New Zealand power system's record maximum demand is 6,924 MW, set on 29 June 2021.[117] High levels of renewable energy characterise the system's electricity generation owing to many hydroelectric generating facilities.

[115] ERCOT, "Fact Sheet", accessed online, 2024.

[116] ERCOT, "ERCOT Monthly,", accessed online, 2024.

[117] Transpower, "Market Operations Insight – 29 June 2021, Record National Demand," accessed online, 2021.

A2 Developing Limit Advice and Constraint Equations

This appendix supplements Section 2, providing a more detailed technical and philosophical overview of limit advice and constraint equation development.

A1.6 Thermal limits and constraint equations

This section covers thermal aspects relating to limits and constraint equations and, where possible, ties these concepts back to simple network topologies or aspects of the WEM.

A2.1.1 Thermal limits, system security, and network congestion – Ensuring transmission system power flows are always within limits

The **thermal limit or rating** of a transmission element (e.g., line, transformer, cable, etc.) is the amount of power (in MW or MVA) that can flow through the element continuously without being overloaded. When a transmission element becomes overloaded, automatic protection systems are designed to "trip" the element, isolating it and taking it out of service. Without this protection, overloading can cause equipment damage and safety risks (e.g. from fires, tree strikes or electrocution).

A transmission system is said to be **insecure** if power flows through any part of the network exceed the thermal limits / ratings of any transmission element. Moreover, a transmission system is said to be **congested** if any transmission element is operating at its thermal limit and cannot transfer any more power without being overloaded. In congested systems, the outputs of one or more generators are typically being capped ("constrained down") to prevent overloading and maintain system security.

Figure 8 graphically illustrates some of these transmission system states using arbitrary values. The *secure and uncongested* state sees the generator's total capacity (60 MW) transmitted through the 80 MW rated line. In contrast, the *insecure* state corresponds to a 100 MW power flow through a line rated at 80 MW (i.e., the line rating is less than the power flow). Last, the *secure but congested* state corresponds to a 100 MW generator transferring 80 MW through the line, aligning with the 80 MW line rating (i.e., power flow and line rating are the same, and the generator output is capped).

Figure 8: Various transmission system states relating to thermal limits.

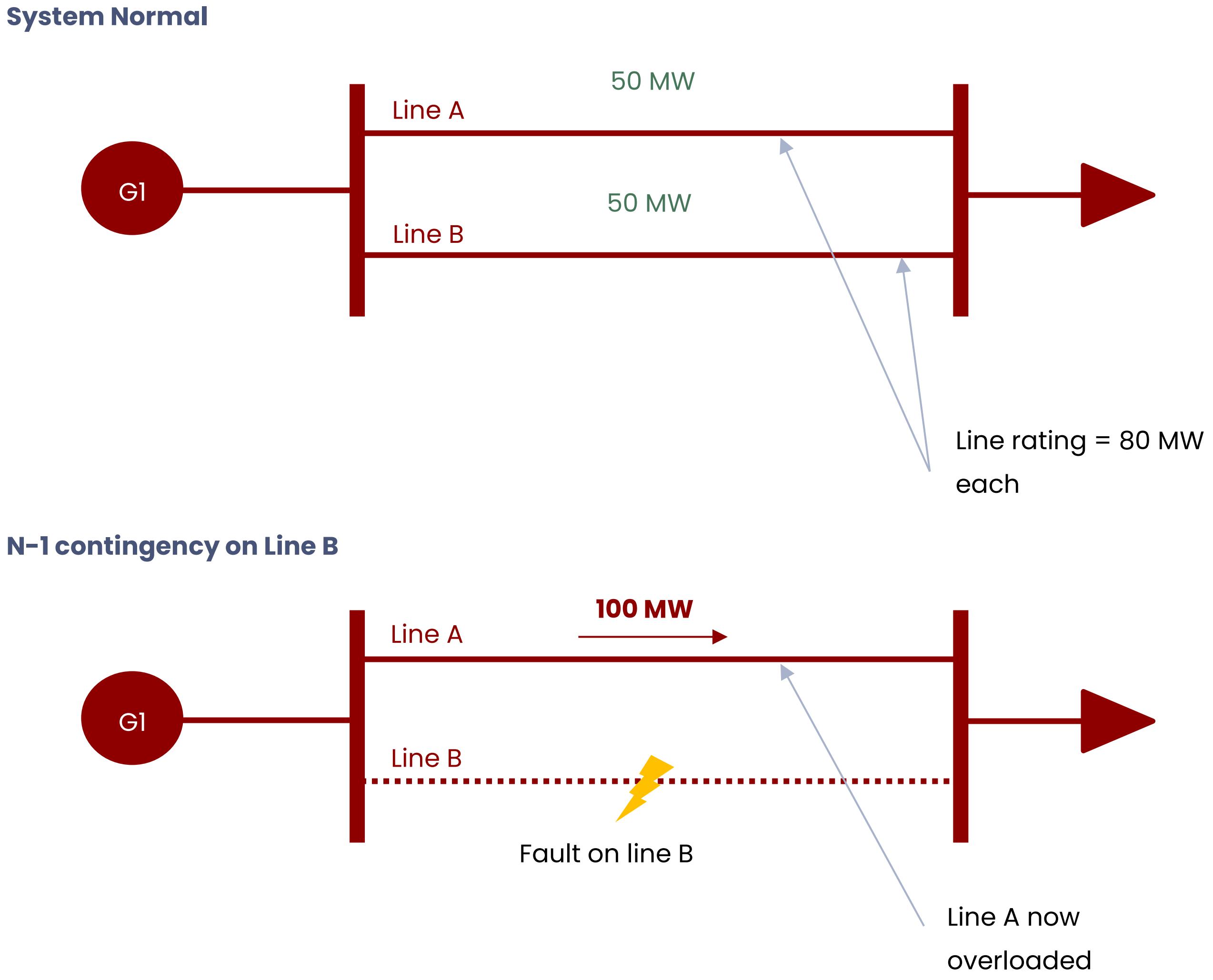
A2.1.2 N-1 congestion – Maintaining system security after the loss of a single transmission element

The term **N-1** refers to a single contingency on a transmission element like the loss of a line, transformer, or cable. After an N-1 contingency, any power flows through the tripped element will be redistributed to working/operational parts of the network.

N-1 congestion occurs when a transmission element is at risk of being overloaded after the trip of another element. This is a system security risk because overloading a line can cause demand to be unserved, or in the worst case, a cascading collapse of the system.

For example, consider the simple system shown in Figure 9 where 100 MW of power is flowing from left to right (generator to load) and the flows are evenly distributed between Line A and Line B. If Line B trips, all its 50 MW flow will be redistributed to Line A, which will then have 100 MW of flow post-contingency. Moreover, if the thermal limit/rating of Line A is 80 MW, then it will be overloaded after an N-1 contingency of Line B. Hence, the flow on the lines would need to be restricted to <80 MW to prevent N-1 congestion.[118]

Figure 9: System normal and N-1 contingency.



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118 N.B. The WEM operates with N-1 system security.

A2.1.3 Facility shift factors – The contribution of a facility's output to the power flow across a transmission element

A **facility's shift factor** is defined as the change in power flow across a transmission element (in MW) for a change in output (in MW) from a given facility. In a more generalised form, they are generally referred to as **power transfer distribution factors** (PTDF). Mathematically, shift factors can be described as follows:

$$a_{i,j} = \frac{\Delta P_i}{\Delta P_j}$$

where $a_{i,j}$ is the shift factor for element i for a change in facility j, ΔP_i is the change in power flow on element i and ΔP_j is the change in output from facility j.

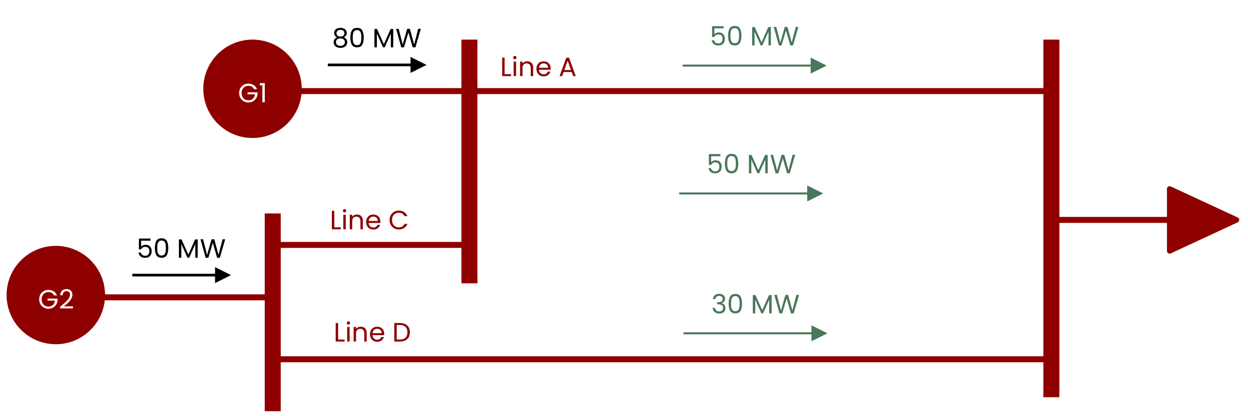
Facility shift factors can be calculated from the network topology and impedances using circuit analysis. If network losses are ignored, they can be computed in a straightforward manner using linear algebra, i.e., from DC power flow equations. However, when considering network losses, an iterative AC power flow solution is required.

As an example, consider the simple system above where two generators (G1 and G2) are supplying a load across three lines. Suppose the generator shift factors relative to Line A are:

- **Shift factor for G1**: $a_{Line\ A,G1} = 0.95$
- **Shift factor for G2**: $a_{Line\ A,G2} = 0.40$

This means that for a change of +1 MW on G1, a corresponding change of +0.95 MW will flow on Line A. This is because G1 is right next to Line A and most of the output will flow across Line A rather than the longer, higher impedance pathway of Line C + Line D. For G2, the shift factor is lower because most of its output would flow across Line D, i.e. the pathway of lowest impedance.

Figure 10: A simple system for considering shift factors.



A2.1.4 Redistribution factors – The proportion of power flow redirected to a transmission element after an N-1 contingency

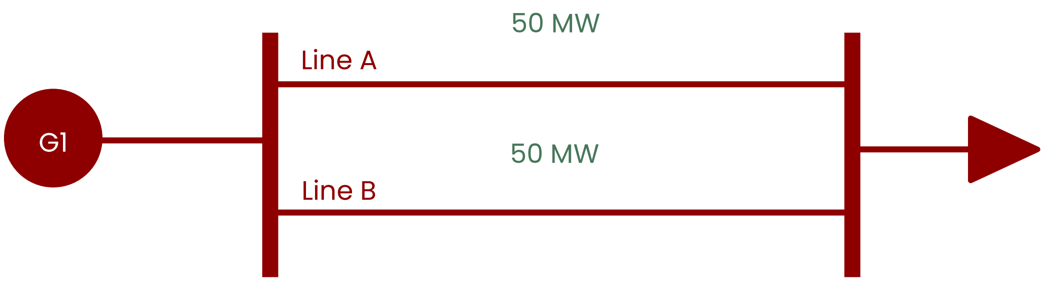
The **redistribution factor (RDF)**—also called **outage distribution factor**—is the proportion of power flow that is shifted to another transmission element after an N-1 contingency. For the simple network topologies shown in Figure 11, we have the following scenarios:

- **Two equal lines:** if Line B trips, all the flow on that line is shifted to Line A, i.e., RDF = 100%.
- **Three equal lines:** if Line C trips, then the line flow is redistributed equally to Line A and Line B, i.e., RDF = 50%
- **N equal lines:** if Line N trips, then the line flow is redistributed equally to all other N-1 lines, i.e., RDF = 1/(N-1)%

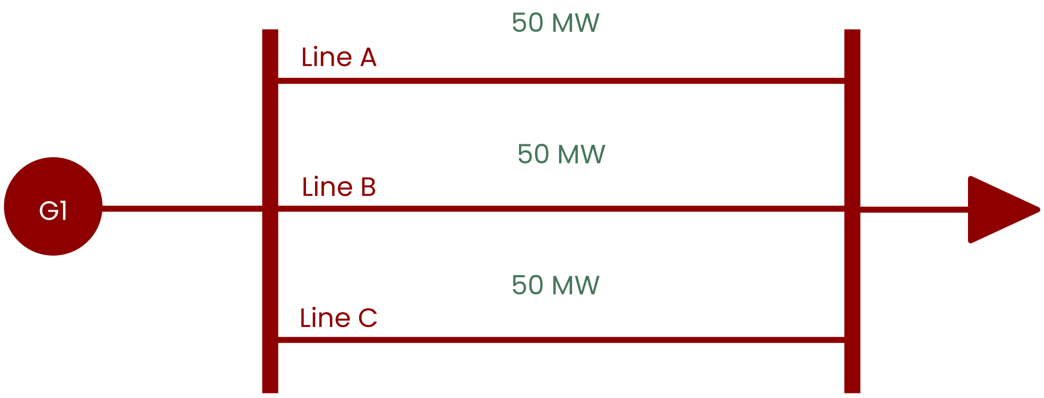
For more complex network topologies that contain parallel lines of different length and impedance or meshed networks, the RDF can be calculated from network impedances using standard electric circuit analysis. Power flows tend to prefer low impedance pathways, leading to the highest RDFs. Similar in calculation approach to facility shift factors.

Figure 11: Simple network topologies to consider redistribution factors.

(i) Two equal lines (RDF = 100%)



(ii) Three equal lines (RDF = 50%)



A2.1.5 Linear constraint equation formulation – Formulating N-1 congestion constraints as linear equations

Using the concepts introduced earlier, we can formulate a linear constraint equation that can prevent the thermal overload of transmission element i on an N-1 trip of element j:

$$a_1\Delta P_1 + \cdots + a_n\Delta P_n \leq Rating - P_i - RDF \times P_j$$

Shift factors and changes in output from n facilities

Thermal rating of element i

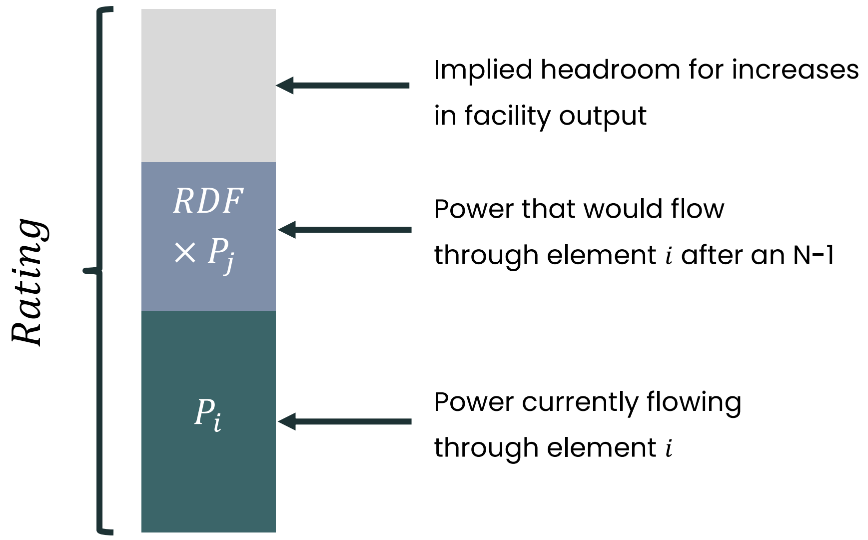
Power flow across element i

Redistribution factor and power flow across tripped element j

The right-hand side (RHS) of the equation represents the total capacity "headroom" available on the transmission element after taking into account the current power flow and prospective power flow after an N-1 contingency. Moreover, the left-hand side (LHS) of the equation represents the total change in power output from all of the facilities that can materially influence the power flow on the transmission element, weighted by the facility shift factors. The "≤" inequality means that the total weighted change in facility output (LHS) cannot exceed the capacity headroom available (RHS), thus preventing thermal overloads.

Figure 12 provides a graphical illustration of the rating in the context of linear constraint equation elements.

Figure 12: Graphical illustration of rating in the context of linear constraint equation elements.



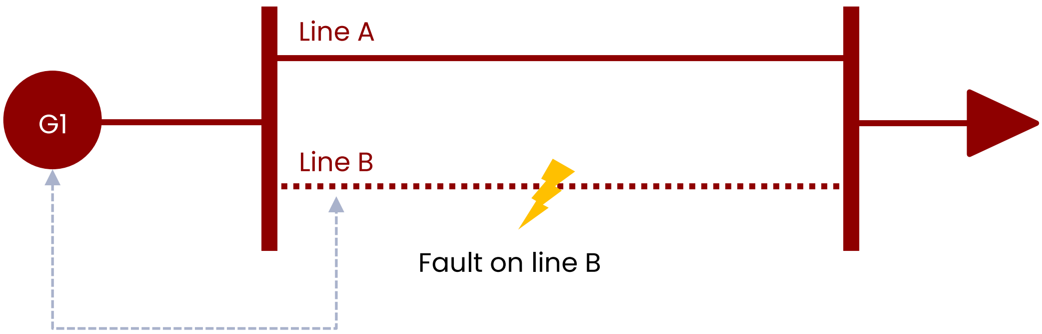
A2.1.6 Effect of special protection schemes – Incorporating special protection schemes into thermal constraint formulations

Some facilities have special protection schemes (SPS) like line overload runback schemes (LORS) that:

- Monitor the status of transmission elements (e.g., are they operating normally or have they tripped?)
- If it detects that a monitored element has tripped, the scheme automatically (and rapidly) reduces the output of the facility to ensure that other transmission elements are not overloaded.

There is a key distinction between N-1 constraint equations and LORS. N-1 constraint equations are **pre-contingent**, which means that they pre-emptively ensure that N-1 thermal overloads don't occur, even before there is a contingency. In contrast, LORS are **post-contingent**, which means that they only act after a contingency has occurred and been detected by the scheme. The post-contingent nature of LORS means their mitigating actions should be incorporated into N-1 constraint equations as otherwise, the headroom freed up from the LORS is wasted. The effect of LORS is typically captured in the RHS of the constraint equation formulation.

Figure 13: Example of LORS operation on a simple network topology.



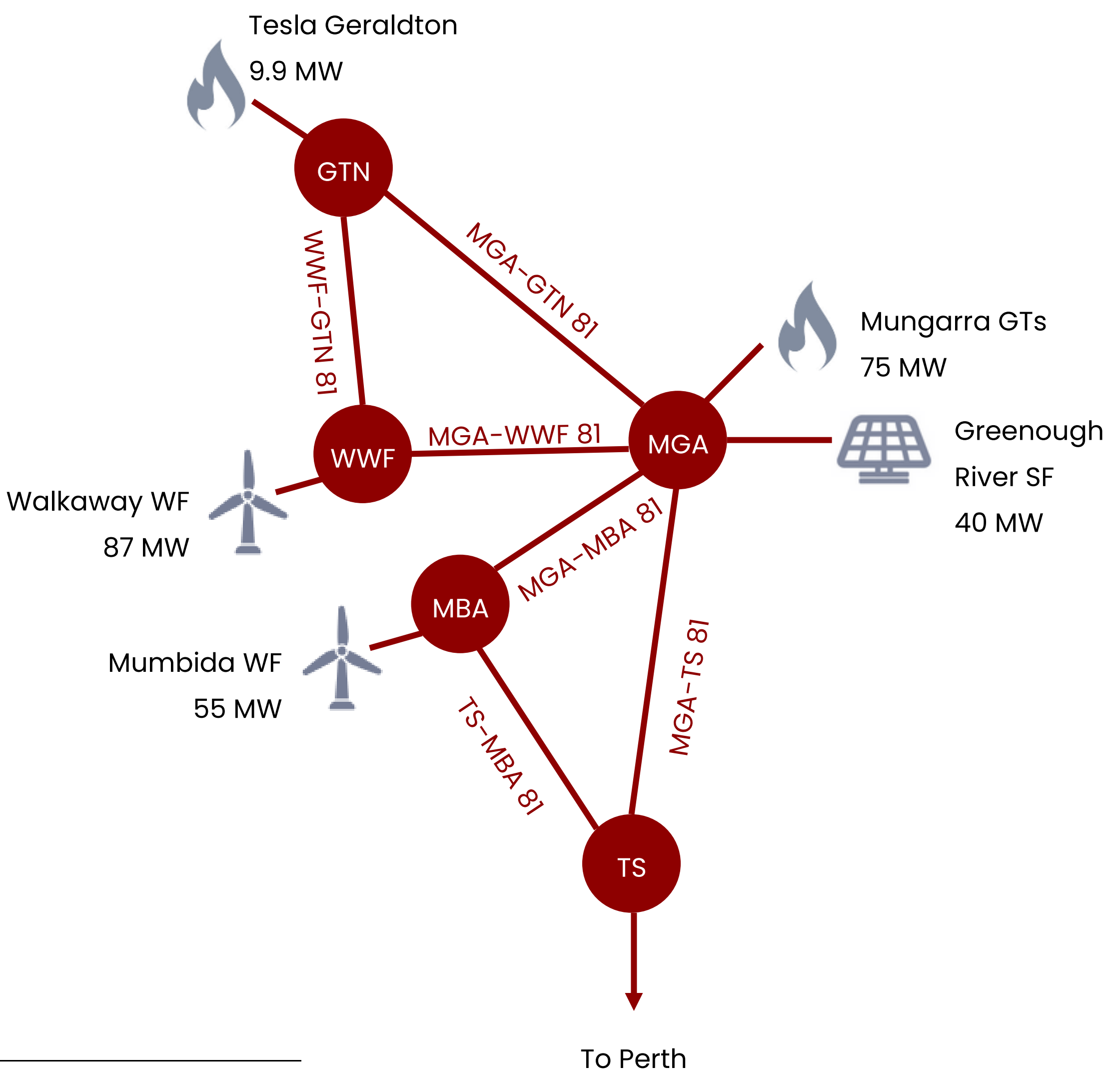
A2.1.7 SWIS network congestion – Example using the North Country 132 kV network

Consider the SWIS North Country 132 kV transmission network, shown in Figure 12. Geraldton (GTN) is the main load centre in the North Country. The power generation from Greenough River

Solar Farm, Mumbida Wind Farm, the Mungarra gas turbines, Tesla Geraldton, and Walkaway Wind Farm will supply Geraldton first, but any excess generation will flow south towards Perth.

However, the weakly linked 132 kV network between Mungarra (MGA) and Three Springs (TS) is a bottleneck for southbound flows. Moreover, a material congestion risk is the trip of the MGA-TS 81 line. After such a contingency, all the flows north of Mungarra must go through the weak TS-MBA 81 line, which is easily overloaded.[119] To prevent the TS-MBA 81 line from being overloaded on a credible N-1 contingency, the outputs of Mumbida WF and Mungarra GTs must be maintained below a level such that the TS-MBA 81 line is not overloaded.[120]

Figure 14: SWIS North Country 132 kV transmission network.



[119] Indicative summer ratings for MGA-MBA 81, MGA-TS 81, and TS-MBA 81 are 139 MW, 84 MW and 84 MW, respectively.

[120] Note that Greenough River SF, Tesla Geraldton, and Walkaway WF are part of post-contingent line overload runback schemes (LORS) and will reduce their output after a contingency, so they do not need to be part of the constraint equation (pre-contingency).

A2.1.8 SWIS network congestion – Example of constraint equation for the TS-MBA 81 line on a trip of the MGA-TS 81 line

NIL > {MGA-TS 81, SPS_MGS, SPS_WWF} [TS-MBA 81 (MBA~)]

Prior network configuration: NIL. Prevent thermal overload of TS-MBA 81 (out of MBA) on trip of MGA-TS 81, including scheme(s): MGS (GRSF Runback Scheme), WWF (WWF Runback Scheme) (MGA-TS 81 measured at MGA)

LHS

+ 1 x MUNGARRA_GT1.energy.setpoint
+ 1 x MWF_MUMBIDA_WF1.energy.setpoint
+ 1 x MUNGARRA_GT3.energy.setpoint

```
def RHS(terms):
  return (                                                                     Capacity headroom
    +0.9500 * terms['MBA.LINE.TS_MBA_81.AMP.RATING.NORM'] * 132 * 1.7321 / 1000   # Thermal Rating term
    -1.0000 * terms['MBA.LINE.TS_MBA_81.MW']                                      # Actual flow term
    -1.0000 * terms['MGA.LINE.MGA_TS_81.MW']                                      # Redistribution term
    +1.0000 * max(0, terms['ALINTA_WWF.pdiSentOut'] - 45.0)                       # Gen runback term
    +1.0000 * max(0, terms['GREENOUGH_RIVER_PV1.pdiSentOut'] - 0.0)               # Gen runback term    LORS
    +1.0000 * max(0, terms['TESLA_GERALDTON_G1.pdiSentOut'] - 0.0)                # Gen runback term
    +1.0000 * terms['MUNGARRA_GT1.pdiSentOut']                                    # Feedback term
    +1.0000 * terms['MUNGARRA_GT3.pdiSentOut']                                    # Feedback term
    +1.0000 * terms['MWF_MUMBIDA_WF1.pdiSentOut']                                 # Feedback term
  )
```

Change in facility output can be re-formulated as the facility output in the current interval (the "energy setpoint") minus the facility output in the previous interval (the "feedback term" and moved to the RHS of the constraint equation).

A1.7 Non-thermal limits and constraint equations

Dynamic, nonlinear limits can only be derived from numerical simulations. This section examines the nature and processes used to develop non-thermal limits and constraint equations.

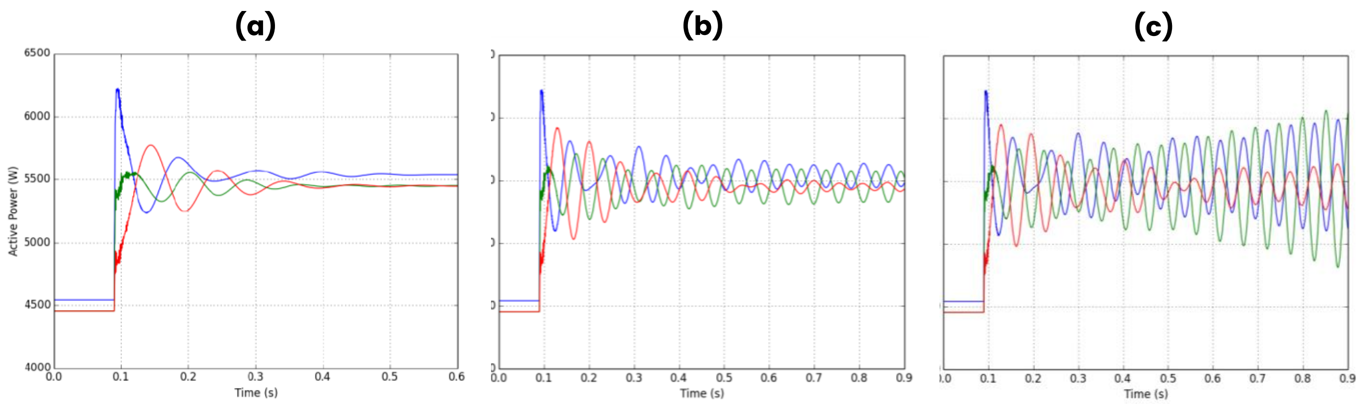
A2.1.1 Nature of non-thermal limits

Non-thermal limits in a power system typically include transient stability, steady-state and dynamic voltage stability, oscillatory stability and system strength limits. While these individual phenomena are generally quite different from each other, a common thread[121] is that these phenomena are dynamic in that they evolve continuously over time (as opposed to thermal limits that are analysed through power flow solutions, which are assumed to have reached a steady-state equilibrium).

Investigating a non-thermal limit typically involves the solution to a set of **differential-algebraic equations (DAEs)**, which can be highly non-linear and in a complex system like an electricity grid, must be solved numerically via simulation (i.e., there are no analytical solutions).

For example, consider the active power step responses in Figure 15. The stable response swiftly settles to a new steady-state value following a transient period, whereas the critically stable response exhibits sustained, bounded oscillatory behaviour. In contrast, the unstable response exhibits undamped oscillations that grow in an unbounded manner and thus do not settle.

Figure 15: Various active power step responses. (a) Stable. (b) Critically stable. (c) Unstable.



[121] With the exception of steady-state voltage stability.

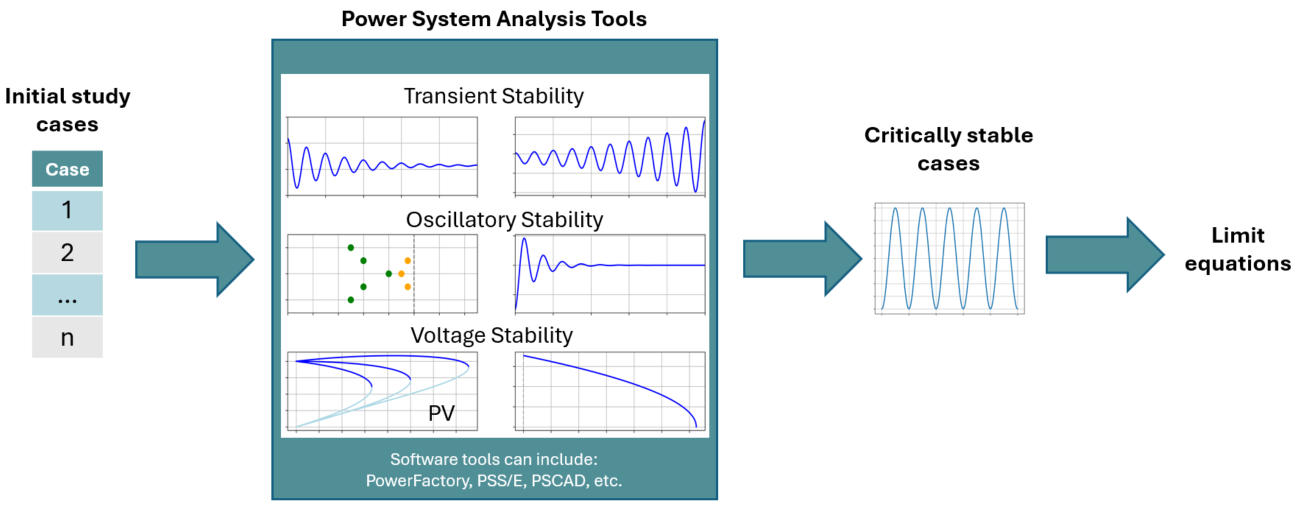
A2.1.2 High-level process for determining non-thermal limits empirically through simulation

While Section 5.1.3 touches on the high-level process for determining non-thermal limits empirically through simulation, we also discuss the process here for completeness.

Initial study cases cover numerous operating conditions such as those relating to high and low load levels or northbound and southbound power flows. We then analyse these cases for their stability properties using power systems analysis tools like DIgSILENT PowerFactory, PSS/E, and PSCAD. Python scripting is typically employed owing to the volume of study cases assessed (> 1000).

We then identify the power system stability assessment's critically stable cases as these cases represent the boundary between stable and unstable operation (refer to Figure 15)—they are stable cases that are at the "edge" of the stability frontier, e.g., one additional MW of power flow would tip it over the edge. The limit equations are developed by applying a linear regression over these critically stable cases and then adding an operating margin. Figure 16 graphically depicts the overall process.

Figure 16: High-level process for empirically determining non-thermal limits through simulation studies.

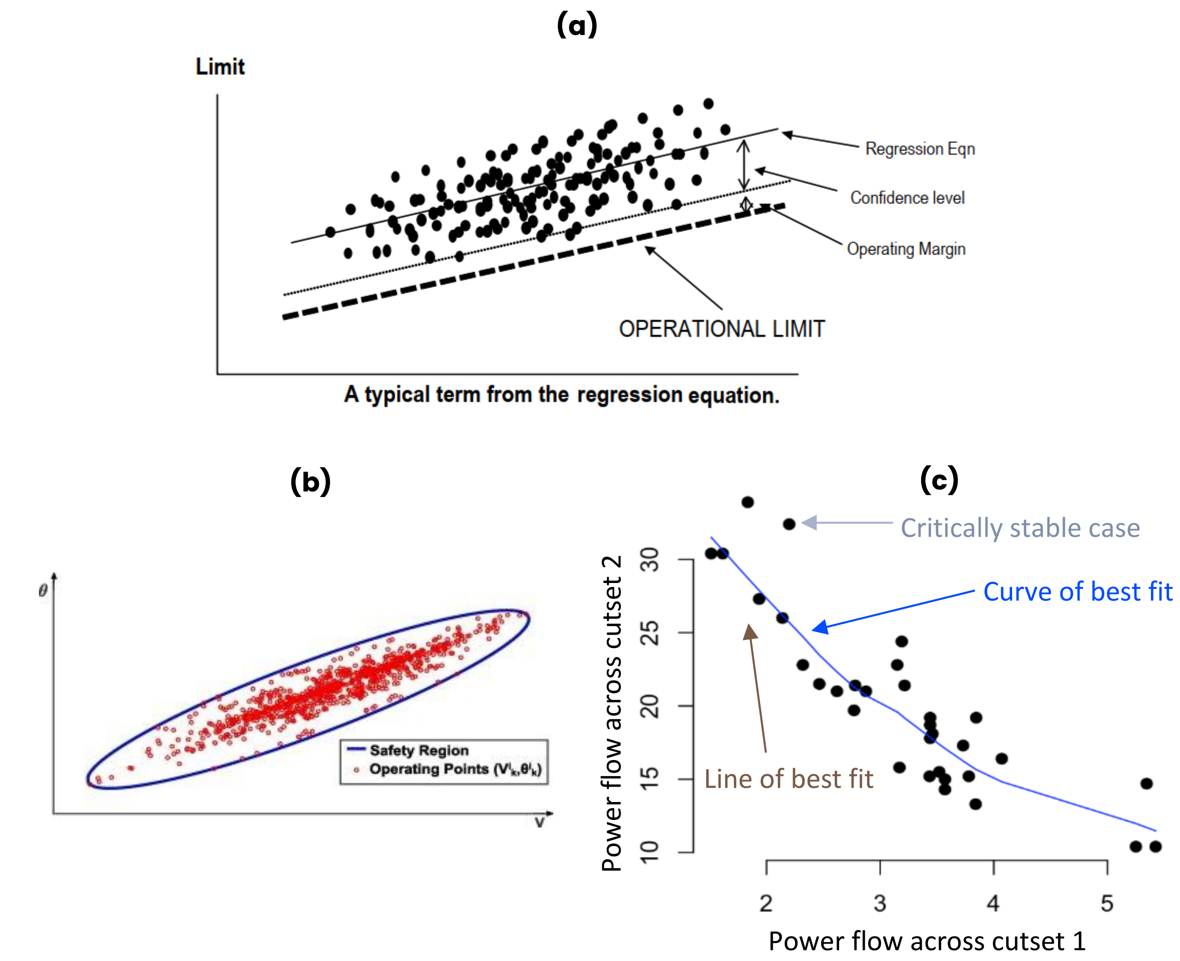


A2.1.3 Linear limit equations – The best linear fit from a set of critically stable cases

Non-thermal limits are not statistical, i.e., critically stable cases are not random variables and do not have standard statistical properties. However, non-thermal limit equations are created through curve fitting approaches that use the language of statistics, e.g., linear regression and a 95% confidence level.

In principle, non-linear curves can be used to fit points and set limits, as shown Figure 17b[122] and Figure 17c. However, the dispatch engine can only accept linear constraints, so a linearised curve fitting approach (i.e., linear regression) is used—refer to Figure 17a.[69] Also note that regression equations are multi-dimensional, so the linear equations are hyperplanes (while only 2-dimensional limits are shown here).

Figure 17: Examples of lines of best fit operational limits. (a) NEMDE constraint formulation. (b) System safety region. (c) Curve of best fit for power flows of cutsets.



[122] Ferreira et al., "Optimal power flow with security operation region," *Int. J. Elect.l Power Energy Syst.,* vol. 124, 2021.