Economic Regulation Authority

Limit Advice and Constraint Equation Effectiveness Review

Draft Report

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Ampere Labs

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Revision History

Revision No	Date	Author	Reviewer	Revision Description
1.0	04/07/2025	J. Bryant	J. Susanto	Draft report
1.1	16/07/2025	J. Bryant	J. Susanto	Revised with ERA comments

Executive Summary

This report provides an engineering assessment concerning the development of Limit Advice and Constraint Equations (LACEs) and the mitigation of over-conservative and insecure outcomes as part of the Economic Regulation Authority's inaugural review of LACEs in Western Australia's South West Interconnected System (SWIS).

The assessment follows a prior body of work that included an inter-jurisdictional review, which identified some best practices employed across the world (e.g., Australia, Ireland, the United States, and New Zealand) concerning LACE activities, and the subsequent formulation of a framework for reviewing the effectiveness of SWIS LACEs. Hence, the report builds on this previous work and complements the ERA's process-focused review.

The implementation of a new Wholesale Electricity Market (WEM) in October 2023, which included the co-optimisation of energy and essential system services markets and a shift from unconstrained to constrained network access, has triggered substantial change across the SWIS. Additionally, the transition from relying on predominantly manual systems and processes for dispatching generators to security-constrained economic dispatch introduced further changes. Hence, this engineering assessment represents a suitable time to review the current processes and procedures associated with LACE activities.

One key finding of this review has been that Western Power and the Australian Energy Market Operator (AEMO), who are responsible for the development and maintenance of SWIS LA and CEs, respectively, have been diligently working over the past few years to revise many existing processes or create entirely new ones to reflect the contemporary market and operating environment.

There has been a natural evolution and maturation of LACE processes stemming from the new WEM environment

The new WEM has catalysed the evolution and maturation of LACE procedures and processes across Western Power and AEMO. While both organisations have undoubtedly been on a learning journey since market start, in their current state, the underlying LACE processes are relatively mature. As part of this review, subject matter experts (SMEs) across both organisations have articulated the processes well, suggesting the processes have been embedded adequately into workflows.

Standard technical approaches are used in LACE development

Western Power and AEMO adopt industry standard methods for the calculation of limits and formulation of constraint equations. As part of this review, we did not identify the use of any technical practices that were non-standard or experimental.

Robust and internally transparent processes underpin LACE development and maintenance activities

Automated calculations (where appropriate) employing standard methodologies are used across Western Power and AEMO for LACE development and maintenance activities to deliver repeatability and standardisation. SME review and approval occur at logical junctures, in conjunction with the provision of inter-organisational feedback. This helps provide a robust and internally transparent end-to-end process for LACE development and maintenance processes. Real-time system security monitoring serves as a backup measure while also delivering feedback that constraints imposed by the dispatch engine are functioning correctly.

Over-conservative and insecure outcomes are mitigated through frequent review of constraint sets and binding constraints, alongside control room and other internal feedback

The system normal constraint set, as well as outage constraint sets, are routinely reviewed to ensure that constraints are valid and represent the current network state. Regular reviews of binding constraints are performed as part of business-as-usual activities, which help to identify issues, trigger investigations, and drive changes that can lead to performance improvements. Validating the theoretical performance of newly developed or altered constraint equations to ensure they align with empirical data before deployment further adds to the process's robustness. Meanwhile, power system security monitoring tools inherently identify insecure outcomes. Stakeholder feedback from the control room to the AEMO teams responsible for LACE aspects helps to "close the loop", providing knowledge transfer that improves the performance of constraints. Meanwhile, the review of all AEMO control room operator interventions and security incidents helps drive continuous improvement activities, including the development of new control room instructions and the review of LACEs (where appropriate), further improving the existing processes.

Dynamic line ratings poised to help increase future network utilisation

The introduction of dynamic line ratings across the SWIS in the future has the potential to increase network utilisation and thus economic efficiency. The review has identified the establishment of a clear and progressive implementation pathway for digital dynamic line ratings, which is predicated upon the use of increasingly more sophisticated real-time data across a growing number of transmission lines. However, the introduction of dynamic line ratings will potentially trigger significant overhauls in Western Power's existing database structure and management, the operational technology it uses, and its communication mechanisms with AEMO for LACE activities. Hence, the re-evolution of some processes may need to be considered by future LACE reviews.

Table of Contents

Figures

Tables

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 (LACEs) in the Wholesale Electricity Market (WEM) as per clause 2.27C of the Electricity System and Market Rules.

The inaugural review follows the development of an inter-jurisdictional review in 2025, which helped identify some best practices from around the world (e.g., Australia, Ireland, the USA, and New Zealand) concerning LACE activities, and the subsequent formulation of a framework for reviewing the effectiveness of WEM LACEs.

The scope of this engagement is to undertake an engineering assessment for the following parts of the LACE effectiveness review according to the ERA's review framework:

- Development of limits and constraint equations
- Over-conservative outcomes
- Insecure outcomes

This report presents the outcomes of the LACE effectiveness review within Ampere Labs' scope of work.

1.2 Glossary

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

Table 1: Glossary of terms.

Term	Meaning
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
BAU	Business as Usual
EMS	Energy Management System
ERA	Economic Regulation Authority
ESMR	Electricity Market and System Rules
FCESS	Frequency Co-optimised Essential System Services

Term	Meaning
LACE	Limit Advice and Constraint Equation
LHS	Left-Hand Side
MT PASA	Medium Term Projected Assessment of System Adequacy
NEM	National Electricity Market
OM	Operating Margin
RCM	Reserve Capacity Mechanism
RHS	Right-Hand Side
RoCoF	Rate of Change of Frequency
RTO	Real-Time Operations
SCADA	Supervisory Control and Data Acquisition
SCED	Security-Constrained Economic Dispatch
SME	Subject Matter Expert
SWIS	South West Interconnected System
TNSP	Transmission Network Service Provider
WEM	Wholesale Electricity Market
WEMDE	Wholesale Electricity Market Dispatch Engine

1.3 Organisational structures and roles

Table 2 lists the relevant teams within the Australian Energy Market Operator (AEMO) and Western Power that are responsible for LACEs.

Table 2: Relevant AEMO and Western Power teams.

Organisation	Team	Role in the context of the LACE review
AEMO	Congestion Modelling	Develop and maintain all constraint equations and sets, including real-time, pre-dispatch, MT PASA and RCM constraints.
	Grid Systems Modelling	Maintain and update the AEMO Energy Management System (EMS), including ensuring that the limits are up to date.

Organisation	Team	Role in the context of the LACE review
	Operations Planning	Assess and approve generator and network asset outages, including checking that appropriate constraint equations and sets are in place for the relevant outage conditions.
	Real-Time Market Monitoring	Support real-time operations with market monitoring and reporting, including discretionary constraint reports.
	Real-Time Operations	Invoke and revoke constraints in real-time, including discretionary constraints.
Western Power	Asset Performance	Calculate, maintain and update network asset limits in corporate databases.
	Engineering and Design	Update transmission protection equipment system limits.
	Grid Transformation	Plan the transmission network to alleviate network limitations. Develop and maintain non-thermal and RCM Limit Advice (for System Normal and future planned network conditions).
	Network Maintenance, Planning and Delivery	Manage the execution of network projects and provide notices that new asset limits should be applied.
	Network Operations	Maintain and update asset limits in operational systems. Develop and maintain non-thermal Limit Advice (for outage scenarios). Rerate limits in real-time operations.

2 Limits, Constraints, and Dispatch

2.1 What are power system limits?

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

- **Thermal limit**: Transmission equipment limits are governed by an element's physical properties. Electricity flowing 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.
- **Non-thermal limit**: Other power system limits exist that are unrelated to equipment thermal characteristics. Voltage and stability limits are two (2) examples of such critical limits, viz.:
    - **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. Moreover, power system apparatus like generators and inverters are designed to operate within defined tolerances and may disconnect from the grid or augment their operation when exposed to voltages outside these bounds, impacting power system security. 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 over 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.

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

All limits must be considered together to determine a line's (or other element's) actual power transfer limit.[3] The device with the smallest capacity determines the maximum transmittable current for branches with interconnected elements (e.g., a line and a transformer).[4]

Hence, limits relate to various temporal factors like:

- **Weather**[5]: 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.
- **Power system topology**[6]: Temporal variations in renewable energy, like solar, can locally influence a network's voltage profile owing to fluctuations in power production.[4]
- **Transmission element technology types**[7]: 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.[8]

Collectively, these various limit types 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 and through power system studies employing state-of-the-art simulation software like DIgSILENT PowerFactory, PSS/E, and PSCAD.

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.

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

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

[5] For example, inherent seasonal variations.

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

[7] 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.

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

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 and semi-scheduled generator dispatch. 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.[9]

Figure 1 provides an illustrative constraint equation example comprising the LHS, operator, and RHS components.[9] 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 a group of transmission elements whose power transfer is controlled. Hence, they are found on a constraint equation's RHS. A *contingent element* is a part of the transmission system assumed to have experienced an unplanned outage.[10] 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.[11]

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

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

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

Constraint sets, containing one or more constraint equations, are typically developed to facilitate efficient implementation by allowing groups of constraints to be enabled or disabled for different operating conditions or system topologies.[12]

2.3 Security-constrained economic dispatch

The constraints, in conjunction with bids and offers from market participants, form inputs to the security-constrained economic dispatch (SCED) process operating within the WEM. SCED represents a mathematical optimisation process that seeks to produce the most economical generation dispatch schedule while satisfying the system's constraints. The constraints ensure the power system's limits are respected, influencing the dispatch calculated by the dispatch engine to ensure the system remains secure across a given time horizon.

[12] AEMO, "Wholesale Electricity Market Procedure: Constraint Formulation," accessed online, 2022.

3 Development and Maintenance of Limit Advice and Constraint Equations

This section assesses the development and maintenance of thermal (including RCM) and non-thermal LACEs. We assess whether the application of standard calculation methods underpins the existing processes relating to LACEs. Moreover, the feedback mechanisms that exist between AEMO and Western Power are also reviewed.

3.1 Summary of best practices and their application in the SWIS

The inter-jurisdictional review[13] highlighted some key best practices relating to LACE development and maintenance. These best practices are listed below and linked to activities that we identified as being implemented in the SWIS' LACE activities.

Robust and transparent processes: The Western Power and AEMO LACE development and maintenance activities utilise, where appropriate, automated calculations that deliver repeatability and standardisation in conjunction with checks, validation, and approval by subject matter experts (SMEs) at logical junctures. Standard calculation methods are thus used throughout the end-to-end process. The public-facing Western Power and AEMO documents for developing LACEs provide outward transparency. The fundamental concepts and equations contained in such documents are encoded in many of the automated calculation processes. From a technical perspective, these key points help deliver robust and transparent processes.

Stakeholder feedback: The Western Power and AEMO processes assessed as part of this review utilised internal stakeholder feedback at logical junctures. This includes, where necessary, collaboration with internal stakeholders across different teams. There was also evidence of adequate communication between Western Power and AEMO across the LACE development and maintenance process, including for reviewing submitted data.

Real-time system security monitoring: Real-time system security monitoring helps as a backup measure, ensuring constraints imposed by dispatch engines are functioning correctly.

[13] For completeness, the inter-jurisdictional review report has been published in conjunction with this report. However, we reference the inter-jurisdictional review's findings throughout this document.

3.2 Application of standard methods

Having identified the overarching processes underpinning the development and maintenance of LACEs, this section assesses from a technical perspective whether both organisations apply standard methods across their workflows following good electricity industry practice.

3.2.1 Thermal limits

The first part of this review examines the determination of thermal limits for transmission lines and substations, power transformers, and their application across real-time power system security monitoring applications. We also consider the Reserve Capacity Mechanism (RCM) limits as a subset of thermal limits.

Transmission lines and substations

Western Power utilises a ratings philosophy for lines and transformers based on standard methods. A systematic methodology underpins the determination of transmission line circuit ratings, accounting for factors like conductor type, number of bundles, and clearance temperature obtained from the design 'as-constructed' information. Various line restrictions include thermal conductor limits, equipment ratings, telemetry high reasonability limits, and protection relay limits and settings. Circuit ratings implemented by Western Power are based on the circuit's lowest rated component when assessing each of these restrictions. In addition to the design information, the calculations also account for environmental factors such as solar radiation, emissivity, and wind speed that can influence thermal ratings.

The documents assessed as part of this review demonstrated that static thermal ratings used across the summer and winter seasons for overhead lines and transmission substations are calculated using various parameters. Examples include:

- **Continuous and cyclic cable ratings**
  - Primary plant nameplate ratings
  - Terminal and palm connections
  - Installation and construction details
- **Overhead substation conductors and transmission lines**
  - Geographical location
  - Line design
  - Conductor type parameters

- **Underground cables**
  - Cable design parameters and cable layout
  - Installation conditions
  - Soil parameters and soil thermal resistivity values

These factors align with the introductory points presented in Section 2.1. Since weather-related phenomena and the physical characteristics of the apparatus significantly shape a plant's thermal rating, the use of such parameters in the design process is standard. Many of the key assumptions or design parameters used as inputs to the calculations appear to be based on Australian or international standards/guidelines (where possible/applicable), or standard data (e.g., meteorological). For example, four (4) temperature zones across Western Australia corresponding to distinct summer ambient temperatures (38°C-44°C) are applied in the calculation of transmission line ratings. Likewise, conductor[14] temperatures applied in the rating of outdoor substation conductors are based on AS 2395.

From an engineering perspective, the calculations appear to be standard. They employ tried and tested methods that have been applied for decades.

The calculation of transmission line ratings is automated through in-built algorithms that encode pertinent formulae within the Western Power asset management system. For example, formulae from AS 62271.301:2022 *High-Voltage Switchgear and Controlgear* are encoded for calculations of ratings concerning metropolitan substations, lines, and connectors. The algorithms also integrate office studies for power transformers and underground cables, as well as laboratory temperature rise tests used as inputs to indoor switchgear equipment ratings.

Automating the calculation process ensures the overall ratings determination process is robust and consistent with relevant standards. The calculations are thus consistently applied, repeatable, and use the same parameters. These factors align with some of the best practices identified via the inter-jurisdictional review.

Power transformers

From the documentation reviewed, Western Power transformer ratings are dependent on factors like load profile, ambient temperature, and cooling mode. Meanwhile, internal components' limiting features are predicated upon nameplate ratings, manufacturer's recommendations, and calculations.

AS/NZS 60076.7:2013 (Loading guide for oil-immersed power transformers) underpins the calculations associated with transformer rating studies for assessing the risk level and

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[14] Note that the term *transmission line* refers to the entire transmission line system that includes the tower structures, conductors, insulators, etc, while the term *conductor* refers to the individual wire or cable.

accelerated ageing associated with loading levels greater than nameplate ratings and ambient temperatures greater than design ambient temperatures. Python- and Excel-based calculation tools have been developed to facilitate these calculations. The Excel-based tool is only used in specific circumstances, such as when:

- Loading or temperature data is absent, of poor quality, or corrupted from the database
- Short time emergency rating calculations are required
- Verifying results from the Python-based tool

Written instructions for using both tools have been developed that adequately document their use. Again, from an engineering perspective, the calculation processes are underpinned by relevant standards and thus employ tried and tested methods.

Application of limits within the Energy Management System via SCADA

Western Power utilises distinct databases for storing the transmission line thermal conductor ratings as well as the protection settings/limits related to the transmission and distribution networks. These databases connect to a "master" database for managing the various limits.[15] Subsystems within the Energy Management System (EMS) responsible for SCADA and managing transmission security form a closed feedback loop to ensure limits are up to date.

Line and transformer current flow is continuously measured in real-time and compared against two (2) pre-determined limits. The first limit is a warning, and the second limit is calculated via a set of rules relating to thermal conductor restrictions, equipment ratings, telemetry high reasonability limits, and protection relay limitations/ratings/settings. The first limit is set below the second with a sufficient margin. When current values exceed these limits in real-time, a SCADA system alarm automatically sounds.

The EMS application responsible for facilitating transmission security management provides various tools like state estimation, load flow analysis, and contingency analysis functionality to assist real-time controllers and planners. The real-time state estimator monitors the plant for overloads and reports any violations. The ratings for transmission lines and transformers are obtained from the "master" database, and the component limiting rating is derived from the transformer's or transmission line's circuit. The use of real-time system security monitoring is one of the best practices identified in the inter-jurisdictional review and aligns with good electricity industry practice.

[15] Specifically, for deriving the limiting element of a circuit.

Reserve Capacity Mechanism limits

Our discussions with Western Power SMEs regarding the determination of RCM limits demonstrated good alignment with the WEM Procedure. The key RCM limit steps articulated to us during the review included:

- **Estimating the future SWIS configuration** by accounting for factors like the retirement of network assets, facility retirements and the inclusion of new facilities, and new network augmentations.
- **Estimating the proportion of network demand** at each zone substation across the network by looking at historical data, trends, and anticipated future developments.
- **Determining the RCM thermal limits** by employing the same process as specified for the operational thermal ratings, but using different input assumptions concerning the ambient temperature and solar irradiance. The assumed ambient temperature for the RCM calculation is 41°C across the whole SWIS,[16] which aligns with the WEM Procedure. Moreover, the assumed solar irradiance used for the RCM calculation is also distinct, reflecting the time of day that peak demand occurs. Thus, from an engineering perspective, the assumptions appear sensible.
- **Provision of RCM Limit Advice to AEMO** underpinned by the information developed in the previous steps.

Western Power publishes much of the RCM data (e.g., connections, peak demand and block loads, and the PowerFactory model) publicly, which helps provide transparency and aligns with one of the best practices identified from the inter-jurisdictional review.

3.2.2 Non-thermal limits

The next part of the review concerns the development of non-thermal limits, which consider issues like voltage stability and transient stability. Our review has found that Western Power employs standard determination methods for the identification of critically stable cases as part of its limit equation development. A 95% confidence level is used for its limit equations (percentage of critical cases that are covered by a limit equation). This method is applied by other Transmission Network Service Providers in the National Electricity Market (NEM). Such confidence levels correspond to limit equations' predictions having less restrictive limits for 95% of critical cases, with 5% having more restrictive limits. It is our view that this generally aligns with industry standards in Australia and is in keeping with the risk tolerance needed for operating a power system.

[16] Recall that the calculation of operational thermal limits uses four (4) temperature zones.

The high-level determination process follows a logical order that aligns well with good electricity industry practice. The key steps are as follows:

- **Initial assessment:** Involves establishing a set of credible system scenarios under different conditions (e.g., system normal and abnormal conditions). System studies are then performed to identify if there are any violations of the Technical Rules.
- **Creation of network operating cases:** Involves considering the relevant variables for analysis and developing credible scenarios via randomised values. This is achieved by developing many load flow study cases to cover a range of load and generation operating conditions.
- **Transfer limit analyses:** Involves scaling load via an iterative process to identify the power transfer limit for each study case under system normal and contingent conditions. The limit corresponds to the power transfer across an element (or group of elements) that produces a marginally stable response.
- **Development of non-thermal limit equations:** Involves applying regression analysis on the studies' results to determine contribution factors (i.e., coefficients) for each relevant variable in each limit. The variables and their associated coefficient collectively form the limit equation.
- **Provision of non-thermal limit equations to AEMO:** Following internal checks and approvals, the resulting Limit Advice is produced and sent to AEMO for their review and use.

As part of this review, Western Power provided two (2) examples of this process being applied to two (2) distinct SWIS areas to address short-term voltage stability network issues. The resulting written study reports identified:

- The pertinent network areas
- The cutset used for developing the limit equations
- The system performance as it relates to the Technical Rules (i.e., issue/non-conformance identification)
- The considered network operating cases and credible contingencies
- The resulting non-compliant scenarios
- The application of regression analysis
- The associated non-thermal limit equations

The reports align with the written procedure that details the standard determination methods as they relate to developing non-thermal limit equations and associated Limit Advice. From an engineering perspective, the methodology is sensible and aligns well with industry standards.

3.2.3 Constraint equations

Having received and reviewed Western Power's Limit Advice, AEMO subsequently develops constraint equations to keep the power system secure. Our review has found that AEMO employs standard methods for developing SWIS constraint equations by calculating the following pertinent parameters:

- **Sensitivity factors:** The effect an extra 1 MW produced by a given facility has on a monitored line's flow.
- **Redistribution factors:** The amount of flow redistributed from a contingent element to a monitored line.
- **Load coefficients:** The effect of load.

The resulting coefficients are used to create constraint equations that are implemented in the WEM dispatch engine (WEMDE). The coefficients and constraints are calculated and developed using various inputs, viz.

- A PowerFactory network model (provided by Western Power)
- The line and transformer ratings (provided by Western Power)
- Historical PI data[17]
- Facility registration data
- Special protection schemes[18]
- The constraints list
- Non-thermal Limit Advice assessment reports

The method follows the process outlined in the *WEM Procedure: Constraint Formulation*, which aligns with industry practice. Much of the workflow involved in developing coefficients for the constraint equations has been automated via Python scripting, which again helps deliver a robust process that is repeatable and efficient. The latter point is particularly important given the large volume of constraints that are developed by AEMO as part of their core workflows.

AEMO's internal wikis for developing constraint equations were perused as part of this review, including archived and current versions. The documents clearly illustrated the process's maturation, which is evident from the development of internal tools for activities such as reviewing and developing a better understanding of binding constraints, and performing weekly checks for outages and associated constraints. It is noted that some wiki sections are still in progress, and it is thus recommended that future reviews examine the continual, incremental build-out of this information source.

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[17] Actual power system time-series measurement data that has been collected and stored for post facto use.

[18] Condition-triggered, automated control schemes designed to maintain wide-area system stability.

3.3 Inter- and intra-organisational processes, feedback, and information flows

Having examined the application of standard methods to the development of LACEs, we now assess whether the information flow between different areas involved in the development of limits is being managed effectively and how feedback is treated from inter-organisational (between Western Power and AEMO) and intra-organisational (between the relevant teams in each organisation) perspectives.

3.3.1 Thermal limits

Various intra-organisational Western Power teams work together across the suite of design steps necessary to produce Limit Advice. The review identified clear delineations between these teams, whose roles are, viz.[19]

- **Grid Transformation:** Identify and plan required network reinforcements, including the uprating and decommissioning of assets
- **Engineering & Design:** Create and update protection limits in corporate databases
- **Network Maintenance, Planning, & Delivery:** Provide evidence that new or upgraded transmission infrastructure projects have completed construction and/or commissioning and provide notice of limits applied
- **Asset Performance:** Create and update asset limits in corporate databases
- **Network Operations:** Create and update limits in operational systems and send Limit Advice to AEMO

Through assessment of the written documentation provided by Western Power alongside discussions with subject matter experts (SMEs) from some of these functions, the underlying process appears to be working effectively and as intended. Evidence included explanations surrounding the deployment of “In Service Notifications” via email, which acts as a trigger for the modelling of thermal limits and ratings following ad hoc asset ratings changes or the construction and commissioning of a transmission line or plant.

Once the modelling/calculations of the relevant thermal limits have been completed, the corresponding databases[20] are updated, thus updating the business systems. The “master”

[19] Refer to Section 1.3 for more detailed Western Power and AEMO organisational structures as they relate to LACE functions.

[20] Recall that protection settings/limits and transmission line thermal conductor ratings are stored in separate (distinct) databases. A third “master” database ingests information from these databases to allow for management of limits and the creation of thermal limit advice.

database imports the data from these databases. At this point, engineers review the data according to the underlying calculation philosophy to ensure the data is correct; any issues are identified and flagged with the responsible internal stakeholders for alteration and re-importation. A DELTA spreadsheet[21] is automatically developed from the information stored in the "master" database, checked for correctness, and sent to AEMO via the AEMO portal. AEMO planning engineers review the submitted file and provide feedback. Western Power subsequently updates the SCADA system accordingly.

The reviewed documentation stipulates the actions required to notify AEMO of limit changes for the various types of limits (and their timing). Evidence was provided as part of this review demonstrating the interaction between Western Power and AEMO. Likewise, the internal interactions associated with updating the SCADA system's limits were shown to be clear.

The human checkpoints throughout this process appear to occur at logical junctures. The additional complexity of power transformers was articulated through discussions with Western Power SMEs owing to the various rating types that exist (e.g., short- and long-time emergency ratings). Following the use of the Python and/or Excel-based calculation tools for the development of ratings, a senior SME checks the calculation results for correctness before the ratings make their way to the asset management system. Thus, multiple peer review checkpoints exist (as required, depending on the asset) to approve the calculated data. These points, combined with the written documentation detailing the use of the business systems, create a robust process that aligns with some of the best practices identified in the inter-jurisdictional review.

3.3.2 Non-thermal limits

Like thermal limits, the development of non-thermal limit equations also leads to a review and approval checkpoint after the study, before the limit advice is sent to AEMO for review. Senior SMEs cross-check and approve the resulting Limit Advice development report. These checks and approvals again occur at a logical juncture in the process, i.e., after the study, once the written report has been produced, but before the formal submission to AEMO. The two (2) written reports for non-thermal Limit Advice development provided by Western Power for this review were well structured, clear in their reasoning and assumptions, and had a record of internal review and approval.

The process demonstrates robustness by using clear, detailed written procedures that provide a sufficient level of standardisation.

[21] The file shows changes between the newly calculated ratings/limits and the current ones.

3.3.3 Constraint equations

AEMO has automated many of the calculations involved in developing coefficients for constraint equations through Python scripting. The scripts encode the fundamental equations specified in the *WEM Procedure*: *Constraint Formulation* document. AEMO SMEs clearly articulated a robust check and approval process for new constraints that are developed (before being implemented in WEMDE).

The coefficients are generally validated using real-time or historical empirical data. One method discussed relates to estimating line flows using the coefficients and facility dispatch terms, then comparing the estimated line flow to the real-time or historical data as a means of confirming that the calculated coefficients are reasonable. Another method involves taking this a step further by assessing calculated coefficients over a year's worth of generation dispatch data and comparing the resulting values to the actual line flows. Statistical analysis then follows to identify anomalous results and changes that could drive improved performance. For certain situations, like outages, Study Network Analysis (STNET) can also be used to duplicate studies undertaken by planners by using their saved cases. In these scenarios, checking that empirical results match theoretical results aligns with good electricity industry practice. It would also generally be seen as the gold standard for validating constraint equations before their deployment.

In addition to these self-checks, a robust peer-review process was also articulated in AEMO's internal wiki and was demonstrated by AEMO SMEs. Code and constraint (JSON) files are stored in online (Git) repositories, and senior SMEs review and approve changes. The overall process is collaborative, and not only involves SMEs within the constraints team discussing each other's work, but also stakeholders from the planning team and the control room.

4 Over-Conservative Outcomes

This section assesses whether good electricity industry practices are employed to mitigate over-conservativeness in SWIS limits and constraint equations. We cover both thermal and non-thermal limits and constraints, as well as operating margins and RCM limits and constraints.

One primary finding of this review section, through numerous discussions with AEMO SMEs, relates to the evolution of AEMO's LACE processes and underlying philosophies since the new WEM's inception. While power system security remains paramount,[22] economic considerations have been elevated, with both factors now receiving close attention. For example, AEMO's Real-Time Market Monitoring team now supports Real-Time Operations with market monitoring and reporting, including the development of discretionary constraint reports. Our discussions with AEMO SMEs also demonstrated that there is an ongoing awareness of the economic considerations and potential economic impacts from day-to-day LACE activities.

Our discussions have also highlighted the transition from using predominantly manual systems and processes for dispatching generators, which can lead to market inefficiencies (particularly in the face of an increasingly complex system), to more automated LACE processes as part of SCED. Many processes are maturing well, and the SMEs we have spoken to throughout the review process have been able to clearly articulate what the current processes are and provide a rationale for why the processes are what they are.

4.1 Summary of best practices and their application in the SWIS

The inter-jurisdictional review highlighted some key best practices for mitigating over-conservativeness in limits and constraints. These best practices are listed below and linked to activities that we identified as being implemented in the SWIS' LACE activities.

Robust and transparent processes: Routine reviews of the NIL constraint set and those related to outages ensure that constraints are valid and represent the current network state, bolstering the process's robustness. All control room interventions are documented and reviewed, providing internal transparency, particularly concerning the performance of LACEs.

[22] The inter-jurisdictional review found that the nature of real-time operations departments across the world inherently prioritises maintaining system security and reliability, generally to the exclusion of economic factors.

Regular assessment of binding limits and constraints: Binding constraints are regularly reviewed as part of BAU activities. These reviews help identify issues, trigger investigations, and drive changes that can lead to performance improvements.

Stakeholder feedback: Internal communication between the control room and the constraints and planning teams ensures internal stakeholder feedback is regularly provided, helping deliver continuous improvement.

4.2 Western Power's processes for mitigating over-conservativeness

Through discussions with Western Power SMEs as part of this review, we have identified that most planned SWIS outages do not require non-thermal assessment. However, specific transmission network areas have been identified as being subject to non-thermal constraints. Western Power provides advice to AEMO for each planned outage, confirming that:

- Non-thermal limit equations are not required
- An existing non-thermal limit equation is sufficient to provide system security
- One or more new non-thermal limit equations are required.

The resulting advice is provided to AEMO via Western Power's planned outage management system (which connects to AEMO's outage management system) and the application tool responsible for managing Limit Advice.

At any given time, there may be multiple concurrent outages in a SWIS area. Thus, limit (and ultimately constraint) equations need to be carefully managed to ensure the system remains secure while still being as economically efficient as possible. In such cases, Western Power tracks the permutations associated with the various outage combinations that occur temporally. The same combination of outages at different times may then be subject to the same non-thermal Limit Advice. Previous advice can sometimes be reused for the same set of outages if network conditions are similar—power system analysis is employed (e.g., simulations) to ensure the behaviour is as expected. Generally, while one outage will provide a limiting constraint, all outages are assessed, and there may be reduced constraints on days with fewer outages.

Western Power SMEs articulated in discussions as part of this review that, when balancing concurrent outages, over-conservativeness is primarily mitigated by examining the use of existing equations, specifically system normal equations, which are thought to constrain market participants the least. Additionally, equations corresponding to the fewest outages are tried first (e.g., an equation with one prior contingency as opposed to two), with more restrictive equations then being used if necessary.

Given the volume of limit equations and Limit Advice that needs to be furnished on a day-by-day basis to enable works programs, we consider that these measures are sensible.

4.3 AEMO's processes for identifying over-conservative outcomes

Over-conservative outcomes correspond to situations where a constraint is binding despite the system being in a secure operating state. Hence, system security is achieved, but in an economically inefficient way. In such situations, the control room may not necessarily identify the economic inefficiency because there are no real-time violations, and the system is secure (hence, there may be no inherent reason to question the binding constraint).

Through discussions with AEMO SMEs, this review has identified that there are two (2) main types of processes in place for identifying over-conservative outcomes. The first process is **proactive** in nature, whereby outage constraint sets and certain aspects of the NIL constraint set[23] are reviewed weekly as part of business-as-usual (BAU) activities. Meanwhile, the NIL constraint set is comprehensively reviewed and rebuilt approximately every two (2) months. However, updates are generally made as a matter of good practice, with the usual key triggers being:

- Network reconfiguration
- New facilities
- The accreditation of a facility for Frequency Co-optimised Essential System Services (FCESS); and
- The introduction of special protection schemes.

This cadence accounts for the significant number of constraint equations that the NIL set comprises, and the review and approval processes required to confidently put the constraint equations into production.

The reviews ensure that the constraints are valid and representative of the current network state, thus preventing constraints from being active and binding when they should not. This validation process may also involve constraints being added or removed from constraint sets. Updates to constraint sets invoke notifications to the Real-Time Operations team via email, highlighting that a given set has been changed. The Real-Time Operations team then provides further review to ensure that the necessary constraint equations are contained within the set, and it is sufficient for their needs.

[23] The NIL constraint set corresponds to a collection of constraint equations that are active under system normal conditions.

The second process is **reactive** in nature and involves retrospective data analysis, reporting, and internal communication to continually deliver better-performing constraints. For example, the Real-Time Market Monitoring team collects information on various statistics, including binding constraints' frequency, which provides internal transparency and a better focus on where LACE performance improvements could deliver the most value. The Congestion Modelling team is also part of this retrospective process, checking and reviewing constraints to ensure they are working effectively and as intended.

In addition to these internal processes, AEMO delivers transparency by publishing various public-facing reports like the weekly *Constraint Outcomes Report*, the quarterly *WEM Relaxed Constraints* report, the *WEM Annual Congestion Report*, and the *RCM Congestion Report.* The reports are important for providing market participants with detailed information relating to the most binding constraints, the impact of these constraints, and any alleviation efforts that may have been attempted.

The processes for identifying over-conservative outcomes align with some of the best practices from the inter-jurisdictional review, particularly regarding robustness and transparency. Aside from the regular review of constraint sets, the interaction between the SMEs developing constraint equations and the Real Time Operations team further enhances the process's robustness to ensure the constraint sets and their associated equations are fit-for-purpose.

In our view, given that the WEM is dispatched with *N-1* security in mind, and there appears to be robust processes in place for identifying and mitigating over-conservativeness, the existing practices are quite reasonable as they relate to minimising over-conservative outcomes.

4.4 AEMO's application and review of discretionary constraints

Discretionary constraints are very simple constraint equations (from a technical perspective) that are created and invoked to maintain power system security, to cover situations where existing constraint equations do not exist. Examples of discretionary constraint applications identified during the review included:

- To address IT issues
- For instances where constraints did not include a relevant facility (has not happened yet, but discretionary constraints would be applied in such cases),
- As part of efforts to relieve congestion or maintain power system security.

Our discussions with AEMO SMEs as part of this review have uncovered a natural evolution in processes and practices since the start of the new WEM that seeks to deliver increased robustness and a better balance between power system security and economic efficiency. Some of the maturer processes currently in use include:

- **Frequent retrospective review of control room interventions:** Every intervention made by the Real-Time Operations team in the control room is reviewed retrospectively, and a report is produced by the Real-Time Market Monitoring Team analysing each situation and its outcomes. The analysis is performed not only through the lens of power system security but also economic efficiency. The findings are communicated to the Real-Time Operations team to help drive improvements.
- **Discretionary constraints turned into library constraints:** If required, discretionary constraints are formally developed into library constraints for posterity by the Congestion Modelling team. This involves reviewing why a constraint was needed, then building the constraint and adding it to the library for similar situations in the future.
- **A burgeoning library of instructions and procedures:** There is a growing number of control room instructions developed to document past learning and assist controllers in their day-to-day tasks. The process helps with standardising decision-making, clearly defining expectations for specific situations, and improving internal transparency. Overall, this point reinforces that the Real-Time Operations processes are maturing. It may be helpful for future reviews to assess the document library for Real-Time Operations to see how this process evolves.

The processes have helped significantly reduce the number of discretionary constraints being employed since the start of the new WEM. Generally, a hands-off approach is adopted for issues to minimise interventions—market advisories are sent first (if possible), then interventions are made if necessary. The approach provides the market with an opportunity to adjust (if possible) before interventions are made. Additionally, the constraints built by the Congestion Modelling team are formulated in a way that minimises the need for intervention. For example, network commit constraints that commit a facility to its minimum generation are built using the ">=" operator rather than a simple "=" operator to allow facilities to go above their minimum generation if they bid above that value.

4.5 Western Power's processes for reviewing Limit Margins

Discussions with Western Power as part of this review have uncovered that data collection on limit margins is still ongoing. Hence, a review of limit margins has not yet been conducted. The NEM approach is currently adopted and used as a baseline (refer to Section 3.2.2). Our view is that the application of such non-thermal limit margins reflects standard Australian industry practice and is sound, given the potential for uncertainties like modelling inaccuracies or measurement/dispatch errors that may occur in practice.

As part of this review, we examined an AEMO report that assessed Limit Advice provided by Western Power for a particular SWIS network area. The assessment used a subset of study cases to examine the performance of a small set of limit equations. The results demonstrated that while the limit equations tended to fall on the side of conservatism, they were not overly conservative, but rather in keeping with the risk appetite one would expect for operating a power system. However, it is recommended that future LACE reviews investigate the progress of Western Power's review of limit margins and whether any changes have eventuated because of the data review. A significantly larger volume of data will help identify key trends and whether any changes to current practices are required

4.6 AEMO's processes for reviewing Operating Margins

Binding constraints are regularly assessed as part of the BAU constraint reviews. AEMO SMEs articulated that operating margins can be changed from their default value owing to two (2) primary reasons: 1) large line losses, and 2) operating power factor.[24] All operating margins are set to 0.95 by default as part of the constraint development process. It is our view that this value is acceptable because it is an indicative power factor for a transmission system.

Generally, the operating margins of binding constraints are assessed on a case-by-case basis, and alterations are made as required during the review process (before approval). Changes in an operating margin are typically incremental and rely upon both engineering judgment and power system experience. The effects of a change in operating margin are tested through simulation. Then, following implementation, empirical evidence is gathered from observations in the power system data to confirm performance. From an engineering perspective, the application of incremental change is sensible, and the use of power system simulation studies in conjunction with a wait-and-see approach for empirical data aligns well with the organisation's risk tolerance.

An example was given during discussions with AEMO SMEs whereby oscillations on a large SWIS transmission line were rectified through incremental adjustment of an operating margin.[25] The operating margin was insufficient owing to significant line losses—increasing the margin to better account for these losses was shown to alleviate the oscillation issues during testing using data from the EMS platform. The changes were subsequently implemented, delivering the expected performance improvement.

[24] The ratio of active power (MW) to apparent power (MVA)—typically very high in transmission systems, e.g., >0.90.

[25] NB: In an offline simulation environment when trying to improve the performance of the relevant constraint equation.

4.7 Feedback loops between Western Power and AEMO

Errors in limits and constraint equations will generally be identified through the end-to-end process involved in developing constraint equations and deploying them in WEMDE, from empirical data, and through the regular review of constraint equations.

For example, the Western Power processes are unpinned by automated calculation methodologies in conjunction with human (SME) checks at logical junctures to identify any issues. AEMO also reviews the data it receives from Western Power (as required and subject to resource constraints). Feedback is then provided to Western Power, and discussions will clarify potential issues. Once the resulting constraint equations have been developed, they are also checked and approved by AEMO SMEs. Internal discussions between the constraints, planning, and control room teams will ensue if any issues are identified at this stage. Hence, the initial formulation process is robust enough to identify errors. Our discussions with AEMO SMEs have confirmed there are clear communication channels between Western Power and AEMO regarding issues that are identified.

One example provided as part of this review related to a binding constraint from an infrastructure-related bottleneck. Western Power upgraded a current transformer (CT) in the network area, which increased the limit along the whole section by a reasonable margin, alleviating impacts on market participants.

AEMO also has access to the Western Power control room instructions, facilitating knowledge sharing and transparency between the organisations.

5 Insecure Outcomes

This section assesses whether Western Power and AEMO's internal processes inherently avoid situations where limits and constraints are missing or not performing as expected, which can lead to insecure outcomes. We again cover both thermal and non-thermal limits and constraints, as well as operating margins and RCM limits and constraints.

5.1 Summary of best practices and their application in the SWIS

The inter-jurisdictional review highlighted some key best practices for mitigating insecure outcomes resulting from missing or poorly performing limits and constraints. These best practices are listed below and linked to activities that we identified as being implemented in the SWIS' LACE activities.

Robust and transparent processes: Checks throughout the end-to-end process, including AEMO's validation of theoretical results to ensure they align with empirical data before constraint equation deployment, help deliver a robust process. Moreover, forward-looking studies help identify issues ahead of time. Internal reports developed by the Real-Time Market Monitoring team provide (internal) transparency regarding interventions and incidents, fostering knowledge sharing.

Regular assessment of binding constraints and interventions: Routinely reviewing constraint sets, binding constraints, and all control room interventions helps identify missing or poorly performing constraints.

Real-time system security monitoring: The use of real-time system security monitoring serves as a backup measure, while also providing feedback that constraints imposed by the dispatch engine are functioning correctly.

Stakeholder feedback: Violations in real-time result in feedback from AEMO Real-Time Operations to the planning and constraint teams. The internal stakeholder feedback ensures discretionary constraints are turned into library constraints, as required. It also "closes the loop" by delivering feedback to the constraints team on the performance of any constraints.

5.2 Western Power's processes for identifying and managing insecure outcomes

As part of the review, we discussed the identification and management of insecure outcomes with Western Power SMEs, particularly about the development of non-thermal Limit Advice. These discussions highlighted that non-thermal Limit Advice is developed according to the Technical Rules. The resulting limit equation development reports satisfy these phenomena. However, at times, power system phenomena may manifest that are outside the scope of the non-thermal limit equation development (or were not identified a priori). Hence, the Limit Advice will be developed retrospectively to automate the process to address the issue if it can be managed by WEMDE. Thus, in some situations, issue identification is made a posteriori. From an engineering perspective, power system simulations only capture a snapshot of behaviour for a given set of conditions, and their nature can inherently lead to blind spots based on the inputs and assumptions made. In our view, this justification is reasonable for certain situations. It may be helpful for future reviews to revisit this process to ascertain how it is maturing (e.g., the inputs and assumptions made to establish scenarios, the feedback between AEMO and Western Power following insecure outcomes).

One example discussed with Western Power SMEs at a very high level was limit equation 28, where sub-synchronous power system oscillations occurred that were not foreseen, and a limit equation was subsequently created to address the issue. This situation demonstrates the aforementioned process in action.

5.3 AEMO's processes for identifying insecure outcomes

Insecure outcomes correspond to situations where a constraint does not bind despite the system being in an insecure operating state. Generally, such outcomes may arise through constraints that are either **missing** (e.g., a risk was not identified and mitigated by a constraint) or **non-performing** (e.g., a constraint is present, but not performing as intended to mitigate the risk). In contrast to over-conservative outcomes, the control room has visibility of insecure outcomes since they lead to violations in real-time. Hence, the real-time system security monitoring tools provide a first line of defence in such cases by alerting the controllers to system issues manifesting from missing or poorly performing constraints. This identification mechanism aligns with one of the best practices from the inter-jurisdictional review, where real-time system security monitoring serves as a useful backup measure, ensuring constraints imposed by dispatch engines are working correctly. In our view, the use of such tools is the gold standard for identifying such outcomes.

Aside from the use of real-time system security monitoring tools, the processes underpinning the end-to-end development and implementation of constraint sets and associated constraint equations align with aspects of other best practices identified in the inter-jurisdictional review. Some of the key actions from the overall process that help bolster its robustness as it relates to accurately formulating limits and constraints to mitigate system security risks include:

- **Checks throughout the entire process pipeline:** Many checks are conducted by SMEs throughout the entire process. The AEMO Congestion Modelling team also ensures (as much as possible) that theoretical results align with empirical data before the deployment of constraint equations. The Real-Time Operations team is notified of changes to constraints, and they also conduct a review to ensure the constraint sets are appropriate.
- **Forward-looking studies:** AEMO's Real-Time Operations team conducts system studies the day and night before to identify any potential issues. These studies use e-Terra applications to undertake contingency analysis to investigate the effects of upcoming outages and look at the system under minimum and maximum generation scenarios. If an issue exists, then a constraint equation is sought.
- **Regular reviews of constraints and interventions:** As previously mentioned, the NIL constraint set and other constraint sets related to outages are routinely reviewed. All control room interventions are also reviewed, and a formal report is developed to help drive improvements through the dissemination of learnings and creation of control room instructions.

5.4 AEMO's processes for managing insecure outcomes

As part of the review, we also discussed with AEMO SMEs their processes for managing insecure outcomes. Generally, real-time violations correspond to constraint equations not working because a facility is not in service or because a constraint is not performing as intended. AEMO SMEs stated that while it is uncommon to see a non-performing constraint equation, when it does happen, it is generally because of a non-credible contingency.

In situations concerning insecure outcomes, Real-Time Operations intervene as required to ensure power system security and minimise the cost impact—they also communicate with the Operations Planning and Congestion Modelling teams regarding constraint equations' performance. The Congestion Modelling team is particularly important when a discretionary constraint needs to be turned into a library constraint. AEMO SMEs articulated that such constraints are formalised as a matter of good practice. These actions are captured in a control room procedure that has evolved for situations involving insecure outcomes as part of continuous improvement strategies that represent best practice.

The Real-Time Market Monitoring team also monitors and assesses situations where there is a market impact (or potential for a market impact) as part of retrospective analysis This aligns with AEMO's increased focus on economic efficiency, in addition to its primary concern of power system security. The insights developed by the team would undoubtedly help with aspects of LACE performance improvements. In our view, this process is helpful to drive continuous, incremental improvements.

5.5 Documentation and review of operational outcomes

As previously discussed, the Real-Time Market Monitoring team examines statistics like operator interventions, security violations, and power system incidents. Once the Real-Time Market Monitoring team has published the internal report for an intervention or incident, the principal engineers and managers in the Real-Time Operations team discuss the report's findings with the operators, and, if applicable, control room instructions will be developed to address any issues that may have been identified. This helps facilitate a process of continuous improvement and provides transparency internally regarding incidents that have happened and their outcomes.

As part of the review process, AEMO demonstrated a growing library of control room instructions, which aligned with their description regarding the evolution of control room processes and procedures. In our view, formalising key learnings and information from past experiences in the form of control room instructions is sensible. The process provides a good level of internal transparency, clearly sets expectations around how to deal with certain situations, and ensures each controller has access to the same information. It may be helpful for future reviews to examine how this burgeoning library of documentation is being managed and augmented.

6 Anticipated LACE Developments

One of the key future developments highlighted through the LACE review concerns Western Power's implementation of dynamic line ratings. As presented in Section 2.1, dynamic line ratings take the concept of a rating a step further by varying transmission line capacity in real-time using weather and operational conditions. Hence, this technology presents an opportunity for Western Power to increase network utilisation in parts of the SWIS, and thus economic efficiency.

Our discussions with Western Power SMEs demonstrated a clear and progressive pathway to implementing digital dynamic line ratings using increasingly more sophisticated real-time data across a growing number of transmission lines. A mix of direct and indirect[26] dynamic line ratings is proposed to be used. Since the use of direct measurements is impractical across the whole system, Western Power SMEs suggested that the technology would be applied in various circumstances, which include, but are not necessarily limited to:

- The most constraining lines (where accurate measurements provide the most impact)
- In areas that lack good weather data
- In cases where single lines connect a market participant to the grid and the participant requests and pays for the direct measurement technology on that line.

The introduction of such technology will potentially trigger a significant overhaul in Western Power's existing database structure and management, the operational technology that the organisation applies, and the communication mechanisms currently in place between Western Power and AEMO for LACE activities. Hence, there is potential for the re-evolution of some LACE processes, which future reviews may need to consider.

[26] Direct dynamic line ratings use sensors connected directly to conductors to measure physical conditions, which helps produce a rating. In contrast, indirect line ratings use information from sources such as weather stations and forecasting models. Hence, while direct methods are more accurate, they are also more costly to implement owing to the use of the sensors.

A1 Summary of Reviewed Documentation

This appendix summarises the documentation provided by Western Power and AEMO throughout the review process. These documents have underpinned the effectiveness review in addition to meetings with key personnel from both organisations involved in (in-scope) LACE activities.

Table 3: Reviewed Western Power documentation.

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
WP Organisational structure	X			
WEM Procedure - Limit Advice Development (public)	X			
WEM Procedure Limit Advice Development - ERA questions - WP response Dec 2024	X			
Western Power ERA Limit Advice – initial presentation	X			
ERA Limit Advice Review – high-level summary		X		
SALM Operational Limits Rating Philosophy		X		
G332 Operating Limits and Ratings Guideline		X		
G408 AEMO Grid Modelling Guideline		X		
SALM Work Process Document		X		
SOLE Role - Thermal limits workflow		X		
Guide for Maintaining and Managing Transmission Asset Thermal Ratings and Limits in WP Asset Management Systems		X		
Procedure for Calculation of Transformer Ratings		X		
Transmission Thermal Ratings Methodology		X		
WP Thermal Limits Process – presentation to ERA - June 2025 – and Western Power responses to follow up queries		X		
Transmission Asset Ratings Process for Ad-Hoc Rating Requests – flow chart		X		
Transformer Rating Study - PyRate Instructions		X		
Transformer Rating (TORP) Study Guide & Instruction		X		

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
Thermal Ratings and Limits Work Triggers		X		
Temperature Zones for Line Ratings		X		
Western Power Thermal Limit Advice 2025-03-24 – sample Excel workbook		X		
AEMO Confidence Levels, Offsets and Operating Margins (public)	X		X	
G356 Operation of Transformers and Transmission lines		X	X	
Limit Equation Development for SWIS		X	X	
Limit advice #1 development - EGF under N-0 or with a prior outage of MU-NT91 - Internal Report			X	
Non-thermal Limit Advice development - North Region under N-0 or with a prior outage of MU-NT 91 - Internal Report			X	
Non-thermal limit equation process in connection study			X	
Non-Thermal Limit Equation calculation - process			X	
Non-Thermal Limit Assessment - process			X	
Non-Thermal System Normal Limit Equation Advice Process – presentation to ERA - June2025 – and Western Power responses to follow up queries			X	
WP Non-Thermal Limit Equation Register – sample Excel workbook			X	
Guide to using Transformer Loading Calculations as per AS60076X			X	
Non-Thermal Planned Outages – Presentation to ERA - June 2025 – and Western Power responses to follow up queries			X	
G 488 Planned Outage Non-Thermal Limit Assessment Process			X	
Assessment of outage for Limit Advice LAMA (multiple numbers) – template example			X	

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
Assessment of outage for Limit Advice LAMA # 801 – template example			X	
Assessment of outage for Limit Advice LAMA # 1622 – template example			X	
LAMA design requirements			X	
Non-thermal Limit Advice for outages – model assessment sample			X	
Response to ERA queries planned outage non-thermal limits – July 2025			X	
Limit advice RCM presentation – July 2025				X
Asset Management Configuration Change Request for Addition of RCM Ratings Nameplate Attributes (@41DegC)				X
Reserve Capacity Management Limit Advice Process				X
Work Instruction – RCM Limit Advice – GT – Estimate SWIS Configuration Peak Demand				X

Table 4: Reviewed AEMO documentation.

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
WEM Procedure: Constraint Formulation (public)		X	X	
WEM Procedure: Limit Advice Requirements (public)		X	X	
WEM Procedure: RCM Constraint Formulation (public)				X
WEM Procedure: RCM Limit Advice Requirements – draft for consultation (public)				X
AEMO Confidence Levels, Offsets and Operating Margins (public)	X	X	X	
AEMO Congestion Information Resource (public website)	X			
AEMO Limit Advice review guideline			X	

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
AEMO response to ERA on document review queries and constraints sample– July 2025	X	X	X	X
AEMO response to ERA follow up queries on non-thermal limit advice – July 2025			X	
AEMO Limit Advice 3 Assessment Report v1.1			X	
Congestion modelling – flow chart	X			
Congestion modelling – Limit Advice non-thermal – flow chart			X	
Congestion modelling – Limit Advice thermal – flow chart		X		
Congestion modelling – Constraint formulation – flow chart	X			
Congestion modelling – CIR Management – flow chart	X			
Congestion modelling – Developing and updating constraints lists – flow chart	X			
Outage Management – Network – flow chart	X			
OMS screenshot sample	X			
Real-Time Operations Confluence – sample on ROCOF shortfall intervention and Control Room Instructions	X			
Real-Time Operations Confluence – sample on a thermal limit issue management and Control Room Instructions		X		
Constraint builder governance samples (multiple samples)	X			
Constraint management system sample	X			
Outage Management – Generator – flow chart	X			
Network Augmentation – flow chart	X			
WEM Annual congestion report 2023-24 (public)	X			
Internal Wiki – Archived Material		X	X	
Internal Wiki – Current Material		X	X	
Internal Wiki – RCM Material				X

Document name	Other / Overall	Effectiveness Review Scope		
		Thermal	Non-thermal	RCM
WEM RCM Congestion report 2024 (public)				X
Formulating RCM Constraint Equations (RCMCE) (NAQ)				X