POWER SYSTEM ANALYSIS TOOLS – FUTURE REQUIREMENTS

August 2024

Version 1.1 Final

A review of requirements to support future connection studies and operational activities.

A report for the AEMO

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Version control

Version	Release date	Changes
0.2	20240414	First draft
0.3	20240417	First round comments incorporated
0.4	20240417	Clean copy draft for review
0.5	20240606	Neutral template, Incorporating internal review comments
0.6	20240618	Incorporated feedback, editorials
0.7	20240627	Revised executive summary, added co-simulation discussion
1.0	20240627	Final Draft – highlights public exclusions
1.1	20240827	Final – includes comments and edits

Executive summary

This report presents a strategy for AEMO's power system analysis tools and the infrastructure supporting these tools. The report is the culmination of a review of the status of the analysis tools and systems. The review included a consultation process that considered how some international power system operators are proposing to analyse their power systems with an increasing level of inverter-based resources (IBRs). Feedback from original equipment manufacturers, who produce the models used in analysis of the power system, and other stakeholders affected by the AEMO strategy on analysis tools and systems, contributed to the strategy and report.

Background

AEMO analyses the power system for several reasons, including:

- Operational purposes, which support AEMO's obligation to operate the power system securely.
- Planning purposes, which support the design and development of the power system, including the important connections process for participants wishing to connect to the grid.

In AEMO the System Design Department undertake the planning and development roles, including connections.

Operations and System Design analyse the same power systems. It makes sense that they use the same tools and systems for this purpose. Strategies and changes therefore need to simultaneously consider both Operational and System Design requirements.

The introduction of many IBRs has changed the analytical requirements for the power system. Well-developed tools and systems existed for the previous synchronous machine dominated power system. However, higher resolution tools are now required to assess the faster acting IBRs. Further, the large number of projects seeking to connect to the grid is creating a significant workload, particularly when using the slower, but more accurate, tools.

The existing processes within AEMO are delivering project approvals with an acceptable level of confidence that each project complies with the technical requirements in the National Electricity Rules and that the power system can be operated securely with the project connected. However, the processes are time-consuming, and some models are confidential, limiting the ability of project investors to fully assess the performance of their proposed plant.

AEMO uses the same tools for multiple purposes and the review cannot consider the connection processes in isolation. This review and strategy thus consider the wider applications within both Operations and System Design.

What this review is about?

This review develops a future strategy for AEMO's power system models and analysis tools with the objective of making the technical assessment of new connection applications faster and less risky, while also meeting other developmental and operational requirements within AEMO.

Making the power system analysis systems more efficient will assist AEMO process the projected number of new projects required to meet market demand and the statutory renewable energy targets for 2030 and 2050.

Primary objectives of the strategy are to:

- Improve the efficiency of power system analysis studies.
- Support the quicker assessment of inverter-based resources (IBRs)
- Provide confidence that AEMO can continue to operate the power system securely.

Other objectives include:

- Improved management of data and models that are used in power system analysis.
- Consideration of how additional analysis functionality, identified as gaps in earlier AEMO reports, can best be provided.

The strategy affects the technical assessment, which is only one component of the connections process. AEMO's role in the assessment is part of a wider process, with the technical assessment currently managed by the Network Service Providers. However, AEMO works collaboratively with the Network Service Providers and plays a key role in maintaining data and models are provided for use in the connection process assessments.

Scope of the strategy

The intention of the strategy for AEMO's power system analysis tools is to describe fit for service tools and systems that will allow a materially faster technical assessment of the power system, specifically for the connections processes but, importantly, also for operational applications. The review covers the following tools:

- Electromagnetic transient (EMT)
- Root Mean Square (RMS)
- Frequency Domain (FD)
- Steady sate (load flow)

The review and strategy exclude the AEMO Energy Management System (EMS), which is the real-time operational tool used for analysing the power system. The EMS is a specialised tool working with field data (SCADA) and integrated tools designed to give operators situational awareness and information to support decisions made in operational timeframes. As such, it is beyond the scope of this review, which is focussed on off-line tools. This report has assumed that the EMS will remain substantially as it is for the foreseeable future and avoid impacts on EMS functionality.

The outlook period for the review is two to five years. This reflects the projected high workload to connect many IBR installations to meet the renewable energy targets up to 2050.

Power quality tools are not considered as this is primarily a network service provider (NSP) accountability.

Where this strategy fits within AEMO processes

Within AEMO there are several forward-looking initiatives related to modelling, analysis tools and data management strategies, including:

- The Future Power System Modelling strategy within System Design department
- The Future State Architecture (FSA) for information technology systems
- The Operational Technology Roadmap (OTR) within the Operations department

This review and strategy fits with the Future Power System Modelling Strategy but attempts to consider organisation-wide requirements rather than isolated departmental requirements.

Impact on the process to connect new equipment to the power system.

Any changes to the connections process arising from the strategy will only be applied if it can be clearly demonstrated that they will result in a faster assessment. This can be either through quicker analysis, the avoidance of re-work, or the reduction in delays by de-risking the process.

Changes, when implemented, will also take account of ongoing connections assessments, and minimise the impact on approvals during any implementation stage.

Consultation process

The review included consultations within AEMO and with a sample of external stakeholders, including:

- Original equipment manufacturers (OEMs), who develop the models used in AEMO's analysis tools.
- A selection of international power system operators (PSOs) and transmission system operators (TSOs), who are facing similar issues with many new inverter-based resources (IBRs) seeking to connect to their power systems.
- Selected Australian developers (participants) with experience in completing the connection process and in implementing several IBR generation or storage projects in the NEM.
- Three transmission network service providers (TNSPs)

The review also included discussions with other entities in the NEM or overseas that have specialised knowledge of analysis tools or have relevant functions within the NEM. There is also much material available in industry journals discussing issues related to the integration of IBRs and analytical methods to improve stability and reliability outcomes.

Recommendations and findings

In the process of developing the power system analysis tools strategy, the review of the existing arrangements has led to some short and longer-term findings and recommendations. Although this report deals with a strategic plan with longer term outcomes, it makes two recommendations that may have a positive impact on the speed of the connections process. These short-term recommendations should thus be implemented as soon as possible. There are also recommendations relating to AEMO's data and model management systems with a longer timeframe. The recommendations are summarised in the following table.

TABLE 1: SUMMARY OF STRATEGIC RECOMMENDATIONS

#	Recommendation	Type
1	AEMO should develop a process for the early assessment of dynamic models created by Original Equipment Manufacturers (OEMs) with the objective of detecting and addressing issues that are inconsistent with requirements detailed in AEMO's Power System Model Guidelines.	Short-term for implementation as soon as possible – model quality improvement
2	AEMO should investigate how frequency domain (FD) tools can be deployed as soon as possible to improve controller tuning and mitigate the risk of	Short-term for implementation as soon as possible – controller design

#	Recommendation	Type
	controller interactions. This investigation includes proof of concept study examining the feasibility of using impedance scanning tools.	
3	AEMO should consider and adopt a set of strategic principles (see section 8.6.1) that it will apply in the future deployment of power system analysis tools, with a view to maximising flexibility to quickly adopt the best available tools and avoid being locked into a single vendor.	Strategic – guiding principles
4	AEMO should review the infrastructure supporting the modelling tools against the strategic criteria with a view to establishing a time-based data repository that meets the functionality requirements of Operations and System Design This can be achieved through procurement of an off-the-shelf solution or further development of AMP.	Strategic – data repository development
5	AEMO should investigate through engagement with tool vendors, including existing vendors, how enhancements that align with the strategic principles can be delivered for existing and new tools.	Strategic – new functionality
6	AEMO should select tools and systems that best allow it to meet its mission critical objectives, particularly power system security, and then rely on tools and protocols to provide efficient information exchange with an increasing number of Network Service Providers and participants who may use different tools.	Strategic – portability of data

Discussion and rationale for the recommendations

The following sections provide further detail on the recommendations and the rationale supporting them. A high-level indication of the benefits is also provided.

Short-term recommendations

The report makes two short-term recommendations.

Early review and approval of OEM models for inverter-based resources.

The quality of OEM models is fundamental to the validity of simulation studies that AEMO conducts for both planning / connection purposes and for operational purposes. AEMO has published Power System Model Guidelines [1] and dynamic model adequacy tests (DMAT) [2], making for a comprehensive assessment of OEM models. However, AEMO currently only sees the models well into the connection process and has no formal basis for engaging with OEMs ahead of a connection assessment.

The AEMO model requirements are detailed and complex. At present models are assessed and tested for each project using site specific settings. There is duplication of effort as each developer assesses the model from scratch and finds the same problems and resolves them with whichever TNSP is running the connection process. There are potential delays in resolving issues and a high risk of duplication of effort for all the OEM clients.

An early assessment of OEM models with the objective of identifying obvious short-comings and addressing these issues before prospective proponents start using the model. This has the potential to reduce the time taken to analyse connections and avoid rework and the current situation where multiple parties solve the same problems.

Recommendation 1. AEMO should develop a process for the early assessment of dynamic models created by Original Equipment Manufacturers (OEMs) with the objective of detecting and addressing issues that are inconsistent with requirements detailed in AEMO's Power System Model Guidelines. The benefits of this process are expected to include:

a. Reducing the risk of delays if problems are only uncovered during the connection assessment process.

b. Providing developers with some level of confidence in the OEM model

c. Reducing risks of project delays for developers and OEM

d. Reducing duplication of effort across projects if each project must separately identify and rectify the same issues.

Adoption of frequency domain methods for setting controllers to enhance stability.

Internationally, the industry is investigating oscillations observed in the sub-synchronous band (roughly 5-35 Hz) that are related to IBR installations (for example, as listed in [3]). The problem is significantly more severe in areas of low system strength. These oscillations are a relatively new phenomenon and arise because IBRs have control systems that can respond significantly faster than synchronous machines. The oscillations are interactions between IBR plant and typically appear as more IBRs are installed in weak parts of the power system.

The proposed solution to mitigate these oscillations is not new but requires some new approaches. Frequency Domain (FD) analysis has been used for many years to design power system stabilisers for synchronous machines, which had similar oscillatory issues when first fitted with fast acting excitation systems. These were addressed using frequency domain analysis and application of power system stabilisers (PSSs). Similar analytical approaches are proposed to guide controller design for IBRs so that they avoid the conditions that drive the observed oscillations. This would deliver stable IBR operation for the conditions expected at the point of connection. Large signal simulation is still required to account for non-linearities and limiter operation.

There are two main ways of working in the frequency domain for purposes of IBR controller design:

- State-space analysis, which is a theoretically robust approach and was used previously for synchronous machine controllers.
- Impedance scans, which is a new application of an existing approach and has some upsides and downsides when compared to the state-space approach.

Both approaches allow engineers to design control system settings that will give stable performance for the nominated conditions at their point of connection. The analysis should identify potential stability concerns and direct study effort to addressing these operating conditions where stability is most challenging.

There is extensive and successful experience with the application of state-space methods in the NEM. The current challenges with the state-space solution are the availability of models, confidentiality issues for models and, importantly, the time taken to obtain all the necessary models. There is a high confidence that state-space solutions will work as expected in directing controller design.

The impedance scan process, which is a relative newcomer to inverter controller design strategies, has benefits in that it is based on existing EMT models and can provide data in a manner that is sufficiently aggregated as to minimise confidentiality risks. The consultation process indicated many organisations are investigating this approach, particularly where large power systems make the state-space modelling approach more difficult. In a trial, the method was able to identify the underlying reasons of the West Murray oscillations [3]. There is thus a high confidence that the approach works.

The urgent outcome is to get some form of FD tool into the controller setting process to avoid stability issues and speed up the connections process. This means providing data and models to participants so that they can undertake the analysis.

This review recommends a proof-of-concept study to examine how frequency domain methods and tools can be deployed as soon as possible to improve controller tuning and mitigate the risk of controller interactions of the type seen in the West Murray.

Recommendation 2. AEMO should investigate how frequency domain (FD) tools can be deployed as soon as possible to improve controller tuning and mitigate the risk of controller interactions. This investigation includes a proof-of-concept study examining the feasibility of using impedance scanning tools. The benefits and outcomes of this investigation and proof of concept study include:

a. Significantly reducing the risk of IBR-based stability issues related to sub-synchronous oscillations.

b. Significantly reducing the number of wide-area and other EMT studies currently focussed on detecting these oscillations.

c. Potentially enabling the impedance scan method to be deployed within six months.

d. Providing a means of sharing system data in a form that does not include identifiable characteristics of specific equipment or require confidential models.

e. Providing the capability to collectively re-set IBR control parameters in the event this is required following a significant change in the power system (e.g., a new transmission investment or a power station retirement)

Longer term strategic recommendations

The longer-term recommendations form the strategy for AEMO's future tools and data support systems. The AEMO strategic requirements must consider:

- AEMO's role of system operator
- The accountability for power system security,
- The coordination and linkages with the EMS.

While these requirements are of primary concern, the system planning and design functions are critical to the ongoing development of the power system. They include:

- Managing the connection process for new investments
- Providing data and models to allow market participants to assess their compliance with the technical standards in the National Electricity Rules.
- Providing market information on opportunities and potential development scenarios through documents such as the Electricity Statement of Opportunities and the Integrated System Plan.

AEMO systems were originally set up for RMS analysis in a power system dominated by synchronous machines. The new requirements for higher resolution, higher bandwidth analysis are creating needs to modify and adapt existing systems to accommodate EMT models, data, and processes. The following observations are pertinent:

- The existing analysis tools are by separate vendors, and each has its own data input and output formats, with very little inbuilt interoperability.
- The existing data platforms like AEMO Modelling Platform (AMP, used to be known as OPDMS) are based on network and operational data sourced from the EMS.
- The link between the EMS and AMP is highly valued as it allows study cases to be built up for specific operating conditions. A new initiative is to enable EMT cases to be automatically constructed from the EMS operating condition, which is valuable for operations analysis.
- AMP has been modified to include future network data and other data for applications such as network pricing.
- The current connections process is delivering a high level of confidence that new connections are compliant with technical requirements and can be operated stably in the power system.

The existing systems and processes may not be the most efficient way to analyse the power system in the future and there is scope to consolidate and refine both the tools and the supporting systems. The following recommendations define a strategy, which if implemented, would improve the efficiency and accuracy of AEMO's power system analysis.

Developing a set of strategic principles

A set of strategic principles, agreed by both Operations and System Design, should guide the consolidation of analysis tools and support systems. The following are examples of principles that should be adopted.

Recommendation 3. AEMO should consider and adopt a set of strategic principles that it will apply in the future deployment of power system analysis tools. This will maximise flexibility and enable AEMO to quickly deploy the best available tools. The strategic principles could include in approximate priority order:

a. AEMO's data repositories should represent the single source of truth for all AEMO applications.

b. Operational considerations have a high priority and Operations data, and model requirements must be met.

c. Interoperability is a critical requirement. Any new tools should either already have interoperability with AEMO's existing tools or the vendor should have a demonstrable strategy to deliver interoperability in the near future.

d. Encryption of models that contain OEM intellectual property is highly desirable so models can be provided to proponents and participants.

e. Data in repositories should be of the highest resolution likely to be required for any AEMO analysis, including likely future requirements.

f. Data management systems should conform to portability protocols and have the ability to adapt as these protocols are improved over time. The objective of the portability is to permit participants to analyse the performance of their equipment when connected to the power system.

g. AEMO's data repositories should not be restricted in modelling extent because of ownership boundaries (for example TNSP – DNSP – REZ NSP[1]) and should have the capability of importing data and configuring study cases across boundaries.

A comprehensive data repository is recommended.

The existing AEMO Modelling Platform was designed for use with RMS analysis tools. The adoption of EMT tools, with more modelling detail, is increasing demands in terms of both the volume and resolution of the data.

Recommendation 4. AEMO should review the infrastructure supporting the modelling tools against the strategic criteria and establish a time-based data repository that meets the functionality requirements of Operations and System Design. This can be achieved through procurement of an off-the-shelf solution or further development of AMP. The benefits of a common data repository include:

a. A single source of the truth, reducing risk of errors and maintenance effort.

b. Faster configuration of study cases

c. Change management to control data quality and reduce risk of errors.

d. Better interoperability between different tools

e. Ability to generate study cases for the existing and future power systems.

Interoperability and extended analytical functionality.

There is also an opportunity to improve the interoperability of tools if the data repository is set up with the ability to develop study cases and prepare, from the study case, data input requirements for each tool. This would make it possible to analyse the same study case in multiple tools, facilitating benchmarking and permitting engineers to select the most appropriate study tool for their analysis. In the absence of inbuilt interoperability, this common database approach at least allows multiple tools to analyse the same case.

AEMO previously identified gaps in the functionality available from its existing tools, particularly relating to analysis of unbalanced conditions and interfacing with other tools like dispatch simulators.

Recommendation 5. AEMO should investigate through engagement with tool vendors, including existing vendors, how enhancements that align with the strategic principles can be delivered for:

[1] TNSP – Transmission Network Service Provider; DNSP – Distribution Network Service Provide; REZ- Renewable Energy Zone

a. Co-simulation between EMT and RMS tools – potentially improving study efficiency and reducing further the requirement for wide-area studies covering the whole NEM.

b. Three-phase representation in the steady state and RMS domains to permit simulation of unbalanced faults and reflecting IBR capability to respond on individual phases.

c. Three-phase load flow capability to enable better simulation of unbalanced network or loading conditions and calculate negative phase sequence voltages.

d. Continuation load flow capabilities to enable medium to long duration studies (days to years) taking as inputs the outcomes of, for example, dispatch simulation tools, solar irradiation, or wind records.

Efficient sharing of data using portability protocols

AEMO is the natural custodian of system wide data and models. However, network service providers and participants require some or all this data to allow them to analyse their impacts on the power system. The trend is for an increasing number of participants requiring analytical data and models, driven partly by the establishment or renewable energy zones (REZs), which may have their own network service providers, and an increasing need to analyse across network ownership boundaries.

Recommendation 6. AEMO should select tools and systems that best allow it to meet its mission critical objectives, particularly power system security, and then rely on portability protocols to provide efficient information exchange with an increasing number of Network Service Providers and participants, many of whom may use different tools. The benefits from this include:

a. Fit for purpose tools within AEMO providing best support for both Operations and System Design.

b. Data exchange capability with participant tools that may have different objectives (e.g., distribution systems).

c. Ease of developing study cases across asset owner boundaries, such as TNSP-DNSP or TNSP-REZ NSP.

Summary

This report on the review and strategy development process has proposed two measures that could materially decrease the time take for the technical assessment phase of the connection process:

- Early assessment of OEM models, and
- Use of frequency domain tools to set IBR controllers.

The longer-term strategic measures relate to delivering fit for purpose tools and data systems within AEMO that meet both Operations and System Design objectives. These measures are informed by the consultation process and consideration of how other power system administrators are approaching increasing IBR installations.

Issues such as interoperability and portability are expected to be more prominent with the addition of new tools and data requirements. Vendors are expected to improve their offerings in these areas.

Data and model management are key areas for development and improvement. There are already initiatives within AEMO looking at power system data and modelling management strategies. Until common information models develop sufficiently to give wider portability and interoperability, a common repository with the ability to generate study cases for each of AEMO's tools will provide the most realistic options to improve interoperability.

There are some analysis function gaps that should be addressed, related to the analysis of unbalanced conditions in both steady state and RMS domains. This requires three phase RMS capabilities. Interfacing efficiently with market dispatch simulator tools is also desirable and signals the need for continuation load flow capabilities. These requirements trigger a need for additional or improved analysis tools.

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1 What this report is about

This report assesses AEMO's power system analysis requirements into the future and makes recommendations about the tools' functionality, interoperability, and the ability to meet both the developmental and operational needs. The objectives are categorised to primary and secondary based on their severity.

Primary objectives are to improve the:

- Efficiency of power system analysis studies
- Capabilities in the assessment of inverter-based resources (IBRs)
- Confidence that AEMO can securely operate the power system.

Secondary objectives include:

- Consideration of how additional power system analysis functionality, identified in earlier reports, can best be provided.
- Improved management of data and models that are used to operate the power system and analyse its performance.
- Reduction of entry barriers for OEM's seeking to enter the Australian National Electricity Market

1.1 Where this strategy fits within AEMO processes

This report is strategic in nature with an outlook of two to five years, although it makes some shorter-term recommendations where appropriate. Some of the observations and findings in this report are already under consideration in some form. There are several forward-looking initiatives related to modelling, analysis tools and data management strategies, including:

- The Future Power System Modelling strategy within System Design department
- The Future State Architecture (FSA) for information technology systems
- The Operational Technology Roadmap (OTR) within the Operations department

This review and strategy fits with the Future Power System Modelling Strategy but considers organisation-wide requirements rather than isolated departmental requirements.

This report attempts to identify a strategic framework that can encompass the current initiatives and set objectives for longer term development of AEMO's power system analysis facilities.

2 Background and motivation

Planning and operational decisions are made based on modelling and simulation of the power system. Fit for purpose tools are needed to analyse both the current and future power systems. AEMO has a planning and development role – System Design – and the operational accountability for the Australian National Electricity Market (NEM).

There is a single power system, and it is logical that both the system design and operational functions have consistency with respect to:

- The models used to represent the power system and equipment.
- The analysis tools deployed.
- The data used in the analysis.
- The infrastructure used to support power system analysis.

System Design have obligations to process new connection applications and the projected volume of these applications is set to rise and stay high for the foreseeable future. Their needs are for adequate tools to assess performance of new connections and network investments in a reasonable timeframe and to a level that demonstrates acceptable performance and compliance with the technical standards in the National Electricity Rules (NER).

The objective of the System Design connection assessments should be to deliver new facilities that can be operated securely in the power system. Ideally, Operations should have no need to put in place any special operating arrangements to manage new facilities for credible contingencies. Further, systems required to manage non-credible contingencies should be practical from an operational perspective.

In summary, both Operations and System Design have increasingly onerous tasks in delivering AEMO's mission critical objective of power system security. Tools and management systems are required that:

- Support fast, accurate and fit for service power system analysis for both groups.
- Are consistent across the company to minimise risks of errors and enhance staff competence for multiple roles.
- Are designed for the type of power system AEMO expects to be managing in the future.

2.1 Scope of the strategy

The intention of the strategy for AEMO's power system analysis tools is to describe fit for service tools and systems that will allow a materially faster technical assessment of the power system, specifically for the connections processes but, importantly, also for operational applications. The review covers the following tools:

- Electromagnetic transient (EMT)
- Root Mean Square (RMS)
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- Steady sate (load flow)

The review and strategy exclude the AEMO Energy Management System (EMS), which is the real-time operational tool used for analysing the power system. The EMS is a specialised tool working with field data (SCADA) and integrated tools designed to give operators situational awareness and information to support decisions made in operational timeframes. As such, it is beyond the scope of this review, which is focussed on off-line tools. This report has assumed that the EMS will remain substantially as it is for the foreseeable future and avoid impacts on EMS functionality.

The outlook period for the review is two to five years. This reflects the projected high workload to connect many IBR installations to meet the renewable energy targets up to 2050.

Power quality tools are not considered as this is primarily a network service provider (NSP) accountability.

This review examines:

- Existing power system analysis facilities (other than the EMS)
- Gaps already identified in other reviews
- Planned enhancements of existing tools
- Impacts on internal and external stakeholders of any changes to existing tools and systems.

The review included a consultation process that covered selected domestic and international stakeholders.

In addition, it makes recommendations on what changes may be required to give AEMO – both Operations and System Design– appropriate facilities for the analysis of the expected future power system.

Recommendations are for near term improvements as well as longer term (>2years) strategic initiatives. The tools and systems are discussed in terms of functional requirements rather than vendor-based tools as it is unlikely that any single vendor will meet all the requirements.

3 What has changed?

In the energy transition, many ageing fossil plants will retire, with AEMO expecting most coal-fired power stations to close within 15 years [4]. Participants are building many IBR generating and storage systems to replace the retiring power stations. This is changing the character of the power system from one dominated by synchronous generation to one that will have many IBR generators, loads[2] and storage systems.

The tools and facilities used to analyse the future power system must be fit for purpose. The following sections identify some changes that affect modelling tools and systems.

3.1 RMS tools used to be adequate for most power system simulation studies.

Ten years ago, AEMO had effective tools, processes, and systems in place to analyse and operate the power system with the predominant technologies deployed at that time. RMS tools were competent for most studies except for 'special' technologies like HVDC, where EMT studies were used to examine sub-cycle (occurring in less than 10-20ms) effects of converter stations. Even so, these studies were quite localised and did not represent much of the power systems at either end of the HVDC links.

3.2 IBRs require more detailed analysis as they have the potential to interact.

The introduction of IBRs creates similar analytical requirements to that of HVDC simulation except there are many more IBRs and they have a demonstrated potential to interact with one another, sometimes at frequencies that are beyond the capability of RMS tools. Because of the number of IBRs and their concentration in areas with good quality resources (sun, wind), it is no longer possible to only represent local points of connection and much larger parts of the power system must be simulated.

[2] Many loads have converter front ends. Examples include hydrogen electrolysers and large variable speed drives. The technology is the same as inverter-based generators and the same system strength issues apply.

3.3 Higher resolution tools are required to analyse IBRs.

As with HVDC system historically, IBRs have fast acting control systems and responses that are too fast to be simulated using RMS tools. This drives the need for the wider application of EMT tools, along with the increased data and model precision that this entails. AEMO has developed EMT wide area models to support this requirement.

The potential for higher frequency phenomena in what was previously regarded as the harmonic range indicates a need for higher resolution data that is valid at these frequencies [5].

3.4 IBRs are often connected in weak parts of the power system.

In contrast to the larger conventional power stations, which were strongly connected to their load centres, IBR developers face strong locational signals to invest in more remote parts of the power system where land is lower cost and development approvals face fewer complications. In these more remote parts of the power system, IBRs have greater risks of interacting with other equipment (usually other IBRs) and may exhibit lightly damped oscillations, which may affect power system security.

3.5 Technology is developing solutions for the future.

Technology is responding by developing newer control features so that IBRs are better able to operate securely in weak parts of the power system. Other approaches address the system weakness by increasing the fault level using devices such as synchronous condensers and, potentially, grid forming inverters.

There is potential for further innovation in technologies such as HVDC and energy storage facilities, that may require higher resolution analysis to assess aspects of their performance on the power system.

3.6 Frequency domain tools need to be revitalised.

Frequency domain tools are very helpful in designing stable control systems. Frequency domain tools, specifically state-space tools, were successfully used to design power system stabilisers for synchronous machines. In the main, these studies could be localised around the generator of interest.

For various reasons, frequency domain analysis has not been widely applied to IBR controller settings. However, since the appearance of sub-synchronous oscillations in many locations, both in Australia and overseas, there is a renewed interest in frequency domain analysis, including new impedance scan methods.

Frequency domain tools are an aid to setting controllers and they do not replace the need for time domain simulation, which is required to examine the effects of non-linearities and conditional actions, such as limiters.

A significant difference with IBR frequency domain analysis compared with that used for synchronous machine analysis, is the need to represent larger parts of the power system so that interactions between the various co-located IBRs can be assessed.

4 The review process included stakeholder consultation.

The problems faced by AEMO in the NEM energy transition are not unique. Understanding how others view these issues and how they are proposing to address them is valuable. It is also important to understand the position of suppliers and investors as barriers to entry or imposition of unreasonable requirements will ultimately result in higher costs and then high energy prices.

4.1 External consultations

The groups consulted external to AEMO include *selected*:

- Original equipment manufacturers (OEMs), who are the providers of the RMS and EMT simulation models.
- Power system administrators – variously power system operators (PSOs) and transmission system operators (TSOs)
- Transmission network service providers (TNSPs), who administers aspects of the connection and negotiation process and conduct critical EMT studies to assess system strength for each connection in their state.
- System planners, with accountability to develop regional plans for parts of the power system.
- Investors with several existing and developing projects in the NEM/WEM

4.2 Discussions within AEMO

Within AEMO, there are two primary 'consumers' of modelling services – Operations and System Design. Although their objectives differ, the reliance on modelling of the power system is common and many of the tools are also common. The review included discussions with stakeholders in both groups and tries to find common ground and efficiencies in their respective analytical needs and support systems.

Neither the internal nor the external consultations were exhaustive, but they are considered sufficient to get the overview necessary for the development of a strategic position. From a tactical perspective, the various current initiatives are still likely to be required as business must continue. However, having a strategic position will help align initiatives and reduce rework and duplication in the two-to-five-year outlook.

5 Key observations from external consultations

This section presents the main observations and findings from the consultation with international and domestic stakeholders on the topics of modelling, analysis tools and data management. The breakdown of organisations consulted is given in Table 2.

TABLE 2: SUMMARY OF CONSULTED PARTIES

Classification	How many?	Location
Transmission System Operators / Power System Operators	Five	Three EU, UK, NZ
Original Equipment Manufacturer (OEM)	Four	EU, China
TNSP	Three	AU
Developers – Wind, solar, REZ	Three	AU
Planners, researchers	Two	AU, US

5.1 Need for EMT analysis to assess inverter-based resources.

There is uniform acceptance of the need to use wider bandwidth analysis tools to simulate power systems with substantial installed capacity of inverter-based resources. IBRs have power electronic and control elements that can respond significantly faster than synchronous machines and traditional analysis and simulation tools' simulation timesteps are not small enough to represent these dynamic behaviours or intra-cycle responses.

The need for wider bandwidth tools like EMT is considered essential in cases where the IBRs are installed in low system strength locations because of stability concerns and potential interactions between controllers.

However, once the initial assessment and setting of the IBR control systems is completed, general analysis can still be undertaken using the more traditional analysis based on phasors (RMS), particularly for equipment that is remote from the area of interest. Co-simulation would provide the ability to assess parts of the power system in greater detail, while modelling the rest of the power system in RMS.

The TSOs/PSOs indicated that analysis is still conducted using RMS tools but there is a recognition of the need to use EMT tools as IBR deployments increase in the various energy transitions. For planning studies, where control systems and plant characteristics are generic, there seems less motivation of using high resolution tools like EMT and RMS is preferred. However, most power system administrators are increasing their capabilities in EMT and building models and systems to support more widespread use of EMT tools.

Finding: It is not practical to restrict all connection analysis to RMS tools. EMT analysis is essential to assess at least some IBR performance during the connection process because of their fast-acting control systems and ability to respond within a power frequency cycle.

5.2 Frequency domain analysis

Frequency domain analysis, while extensively used previously for control system analysis, is now not as widely used by the consulted TSOs and PSOs. There is limited application within some TSOs that use applications, which support small signal analysis based on RMS models (i.e., dedicated small signal models are not required). However, the focus on frequency domain tools is changing as the higher bandwidth of IBRs increases the risk of sub-synchronous oscillations.

Consultation responses reflect there is now a growing and positive development effort into frequency domain analysis tools and processes among the consulted OEMs, Developers and TSO/PSO groups.

Respondents were interested in AEMO requests for small signal models. Some OEMs are providing, or considering providing, state-space models for frequency domain assessment.

However, several OEMs and TSO/PSOs indicated they were investigating *impedance scan* techniques because:

- OEMs have reported significant concerns providing detailed state space models if the risk to their IP is at an unacceptable level. This applies to detailed block diagrams and unencrypted models. Encrypted linearised state space models are expected to be acceptable to OEMs.
- The data used in the impedance scan method comprises of impedance information as a function of frequency and has no discernible IP content.
- The impedance scan methods are relatively fast to implement if existing EMT models are available and suitable EMT tools are developed [6].
- The impedance-based methods allow familiar controller design concepts to be used including:

    - Setting controls to give specified minimum gain and phase margins.
    - Tools such as Nyquist and Bode plots to visualise stability outcomes.
- There is an increasing body of literature [7] [3] [8] [9] [10] [11] and work reported by the respondents describing the theory and application of the technique, including demonstrations of case studies with successful outcomes.

The application of frequency domain analysis using impedance scans is still in a development phase, but most respondents report ongoing research activity within their organisations and some respondents indicate the techniques are already in use.

Finding: Frequency domain analysis is of great value in setting controllers and many respondents report active investigation, development, or trialling of tools.

Finding: The consulted OEMs have a strong preference for the impedance scan method because it avoids IP issues associated with the provision of state space models and can be implemented using existing EMT models and tools.

5.3 Verification of OEM models by AEMO

Most respondents supported the concept of OEM model certification, also referred to as whitelisting or verification. The expectation is clearly that if this is put in place, it must reduce the effort or time for the OEM's clients to obtain connection approval.

The main questions around such a process included:

- Who would do the verification? In Europe, third party certifiers test equipment for a significant fee. In Australia, respondents felt AEMO was the most appropriate body, as the end user, to do the verification.
- How would verification shorten the connection process? The suggestion was made that at least half of the existing DMAT could be dealt with in the OEM model verification process which could demonstrate compliance with some aspects of the NER performance standards. This may allow some of the model validation tests to be avoided or abbreviated.
- How would firmware updates be dealt with? Would they need a full verification study or tests to examine the new or changed functionality?
- Apart from the inverter and PPC (Power Park Controller), the generating system model includes the inverter transformers, collector system, main transformer, and other plant items that are different for each installation. How can verification work if this is the definition of a model?

Nevertheless, respondents supported the principle of some independent model assessment early in the connection process to avoid the same problems being solved again and again as each project attempted the DMAT. The assessment could also demonstrate compliance with any specific requirements in schedule 5.2 that can be assessed at the inverter terminals. The process may also include consideration of OEM factory tests that may be used to support model validity.

Finding: AEMO's verification of OEM models, in a process still not yet defined, may reduce OEM and investor risks, avoid repetition of problem resolution by each project, and reduce the extent of EMT analysis for each project. There is already an initiative under the connections reform initiative (CRI) reviewing data and modelling and, specifically, OEM model appraisal.

5.4 Data, model, and case management systems

Respondents reported varying degrees of data management, with most TSOs managing, as AEMO does, the master power system model. Several respondents have comprehensive data systems synchronised with asset databases and even the EMS. These systems are closest to the ideal ‘single source of truth’ concept.

Both proprietary and bespoke data management systems were reported.

Data management systems appeared to be the primary source of interoperability, sometimes with surprising workarounds of converting to a third format before converting again to the target format.

Interoperability is clearly an issue for some respondents, particularly where systems were originally set up for RMS tools and now there is a need to add EMT models and tools. Some TSOs reported that a few vendors were developing tools to convert data from other applications but differences in dynamic models and lower resolution RMS models (for example, ‘pi’ models of transmission lines) make these tools of limited value.

Some respondents reported that case management facilities with EMT tools were generally missing, which made project tracking and archiving difficult compared with their RMS tool infrastructure.

There are initiatives in Europe to develop common data exchange protocols to accommodate the different international system operators and their analytical tools (e.g., CGMES [12]). Third party developers are promoting modelling systems that can be interpreted by any compliant software platform (e.g., Modelica [13]). However, respondents, and importantly the OEMs, reported little interest in these initiatives and indicated that they had to provide whatever model formats a client requested. The OEMs did recognise the benefits of a common platform but clearly do not see anything becoming available in the immediate future.

Finding: Several TSOs / PSOs have well designed data management systems that reflect a single source of the truth, with synchronised links back to asset data and operational systems.

Finding: Data management systems that cover all applications (e.g., RMS, EMT, frequency domain) are available but imperfect due to formats specified by different vendors. Bespoke tools generally need modification to accommodate new models and data associated with the EMT tools.

Finding: Common model formats across tool vendors are agreed as desirable. These are well established for load flow data (e.g., CIM) but there do not appear to be any widely accepted protocols yet for dynamic models (RMS, EMT) that could be adopted in the short term. Longer term, it is likely that some of these protocols will be developed and adopted.

5.5 Reduction in competition between OEMs and EPCs

Several respondents hold the opinion that the modelling, analysis, and assessment requirements in the NEM are the most strenuous internationally.

One developer cited modelling requirements as a reason why some OEMs prefer not to enter the market. They evaluate the risks as unacceptable to them. The reality of these risks and their outcomes were substantiated by the publicised failures or market exits of some large industry organisations in Australia after losses.

Other evidence of reduced competition that was put forward included:

- Dominance of the BESS grid-forming market by one OEM
- Refusal of EPCs to quote on projects without exclusivity.

- An instance where a developer was unable to wrap a project (i.e., single source) because the OEM, while happy to supply the bulk of the equipment, was not prepared to offer an inverter because of risks associated with modelling.

The assertion was made that the reduced competition is leading to higher prices.

Respondents saw initiatives, such as the verification of models, as mitigations of the risks and potentially a mechanism to reduce barriers for new entrant OEMs or EPCs.

Finding: There is some evidence of a reduction in competition for plant OEMs and EPCs, which may be related to risks associated with the rigorous modelling and assessment requirements in the NEM. Initiatives that reduce these risks, such as OEM model verification, may therefore reduce some barriers for new entrants.

5.6 Co-simulation using both EMT and RMS techniques.

None of the consulted TSOs are currently using co-simulation but there is an awareness of the value such capabilities offer. Co-simulation was mentioned for both PSSE-PSCAD and PowerFactory (internal RMS and EMT tools).

Co-simulation is seen as a way of representing the higher bandwidth responses of IBRs without having to simulate the entire power system using EMT models. The benefits of co-simulation are:

- Ability to focus the detailed analysis around the area of interest, while using RMS models for the rest of the power system
- Faster simulation because only part of the power system is analysed in high resolution.
- Better representation of remote impacts, such as inter-area electromagnetic modes of analysis, which are lost if equivalencing is used.

Finding: Co-simulation is a tool of interest to some respondents undertaking connection or system studies but there are limited tools with sufficient flexibility to make this a short-term option.

5.7 Improved modelling of distribution networks is important in some locations.

One respondent highlighted emerging issues across the transmission / distribution interface, where models are terminated based on ownership rather than for some technical reason. Some of the specific issues raised by the respondents are summarised below:

- Significant changes in transmission flows may affect the distribution networks, especially where there are sub-transmission ties. Transmission studies may therefore need to represent at least some of the distribution network model.
- Transmission studies in proximity to strong distribution networks may benefit from representing parts of the distribution network where, for example, reactive devices may support the transmission network.
- In some REZ developments, the extent of IBR developments, including energy storage devices, may be significant in the distribution network. Assessment of these projects may benefit from better representation of both the transmission and distribution networks.

The discussion around this point centred on interoperability of the DNSP and TNSP tools to facilitate more detailed modelling of the interface without having to represent unnecessarily large parts of either system in the respective network models.

Finding: In parts of the network, analysis may require better representation of the TNSP / DNSP interface. This is expected to be more important where there are sub-transmission ties or significant IBR developments in the DNSP power system.

5.8 System planning utilises dispatch simulation tools.

System planning, which considers scenarios for the future development of the entire power system including generation, demand, and transmission network, uses dispatch simulation tools to determine how generation might enter and operate in the market. Dispatch simulation tools are valuable in determining economic outcomes in the power system. The tools use a simplified DC model of the power system, sometimes using only a few nodes or even one node to represent a region. Constraints are reformulated to fit the reduced model, but the dispatch outcomes do not consider flows on individual network assets.

In some cases, particularly for extreme or outage conditions, it is desirable to test the dispatch outcomes in a full AC load flow study. These studies can also look at how the assets are affected during credible contingencies.

The desired capability is to:

- Export the dispatch and demand conditions to a contemporaneous load flow and solve to check asset ratings and voltages (for normal and outage conditions)
- Repeat the above for multiple dispatch intervals (say, all dispatch intervals in one year) to build up statistical flow and voltage information.

For the second dot point, a continuation load flow functionality is indicated as a year's worth of five-minute dispatch intervals is 8760hours/year*12 dispatch intervals per hour, giving 104120 studies.

Finding: An interface between dispatch simulation tools and AC load flow cases is required to confirm feasible dispatch outcomes and examine performance over long periods of time.

5.9 TNSP and AEMO interactions

While it is not strictly related to modelling or tools, developers referred to the differences between the connection and commissioning processes developed by TNSPs and suggested a more uniform approach across the NEM.

Reported issues include:

- Solving the same problems with different TNSPs
- Differences in process and requirements between individuals within the same organisation
- Several projects having to solve the same problem because there is insufficient sharing of corporate knowledge across TNSP and AEMO.

Finding: Ongoing engagement with the TNSPs as part of the streamlined connection process (SCP) initiative should focus on formalising the connection processes and making the process recognisably consistent across all TNSPs

5.10 Commissioning, testing and model validation.

Some respondents reported that the commissioning process was a potential source of efficiency gains. In particular, the number of hold points and tests was considered excessive.

Two initiatives were proposed:

- Use of hardware in loop (HIL) testing to confirm model validity and the applied equipment settings. This would give a significant improvement in confidence that the plants were 'safe', and the number of hold points and tests could be reduced as a result.
- Adoption of fault throwing (i.e., actually applying a fault intentionally) as a primary test method used to confirm fault ride through of modelled plant and auxiliary plant (which is typically not modelled). The assertion is that FRT is one of the most important IBR control functions and use of actual faults would test functionality, particularly of auxiliary equipment, that is not currently tested during commissioning.

Other suggestions from respondents included:

- Reduce the number of routine step tests done at each hold point and focus on those areas where problems are more likely to occur.
- Do not repeat OEM factory tests if they show the required performance.
- Avoid unnecessary testing and associated analysis at operating points where performance is clearly stable and focus on operating conditions where performance is challenging.

Finding: Hardware-in-loop testing may have some benefits in confirming that plant is correctly set up and performance aligns with simulation studies. Successful HIL should reduce the risk of unexpected performance on commencement of on-line testing but will have less value for plant setting or design.

5.11 Establishing a funded OEM consultative body

One of the developers suggested a paid OEM advisory group to deal with emerging modelling and performance issues. The group's functions would include:

- Advise on performance issues.
- Adaptation of plant to meet required performance (on an OEM-by-OEM basis)

The funding could be justified on the basis that industry costs would reduce materially. Qualification for the panel would include successfully passing an AEMO model certification process.

This suggestion is reported but would clearly need greater justification and consideration of anti-competitive practices.

It is understood that there are already formal engagements between AEMO and OEMs and that such a consultative body already exists, perhaps with a lesser scope of activity.

5.12 Summary of consultation findings for external stakeholders

TABLE 3: SUMMARY OF FINDINGS DERIVED FROM CONSULTATION WITH STAKEHOLDERS

#	Finding	Section
1	It is not practical to restrict all connection analysis to RMS tools. EMT analysis is essential to assess at least some IBR performance during the connection process because of the IBR fast-acting control systems and ability to respond within a power frequency cycle.	5.1
2	Frequency domain analysis is of great value in setting controllers and many respondents report active investigation, development, or trialling of tools.	5.2
3	The consulted OEMs have a strong preference for the impedance scan FD method because it avoids IP issues associated with the provision of state space models and can be implemented using existing EMT models and tools.	5.2
4	AEMO's verification of OEM models, in a process still not yet defined, may reduce OEM and investor risks, avoid repetition of problem resolution by each project, and reducing the extent of EMT analysis for each project.	5.3
5	Some TSOs / PSOs have well designed data management systems that reflect a single source of the truth, with synchronised links back to asset data and operational systems.	5.4
6	Data management systems that cover all applications (e.g., RMS, EMT, frequency domain) are available but imperfect due to formats specified by different vendors. Bespoke tools generally need modification to accommodate new models and data associated with the EMT tools.	5.4
7	Common model formats across tool vendors are agreed as desirable. These are well established for load flow data (e.g., CIM) but there do not appear to be any widely accepted protocols yet for dynamic models (RMS, EMT) that could be adopted in the short term. Longer term, it is likely that some of these protocols will be developed and adopted.	5.4
8	There is some evidence of a reduction in competition for plant OEMs and EPCs, which may be related to risks associated with the rigorous modelling and assessment requirements in the NEM. Initiatives that reduce these risks, such as OEM model verification, may therefore reduce some barriers for new entrants.	5.5
9	Co-simulation is a tool of interest to some respondents undertaking connection or system studies but there are limited tools with sufficient flexibility to make this a short-term option.	5.6
10	In parts of the network, analysis may require better representation of the TNSP / DNSP interface. This is expected to be more important where there are sub-transmission ties or significant IBR developments in the BNSP system.	5.7

#	Finding	Section
11	An interface between dispatch simulation tools and AC load flow cases is required to confirm feasible dispatch outcomes and examine performance over long periods of time.	5.8
12	Hardware-in-loop testing may have some benefits in confirming that plant is correctly set up and performance aligns with simulation studies. Successful HIL should reduce the risk of unexpected performance on commencement of on-line testing but will have less value for plant setting or design.	5.10

6 Consultations within AEMO

6.1 Background relating to analytical tools and processes.

AEMO is successfully managing the integration of IBRs using existing tools and infrastructure, albeit with some workarounds and inefficiencies.

The AEMO modelling platform (AMP) and its link to the energy management system (EMS) are central to the development of study cases from snapshots. AMP is being upgraded to extend its capabilities to support EMT case generation and future network and generation developments.

Other initiatives are active in improving and introducing new analysis tools and investigating ways of streamlining the connection assessment processes to reduce the overall time to get new projects connected or existing projects upgraded. Internal reviews have identified some specific analysis capability gaps and some issues with data management.

AEMO interacts extensively with the international community to establish current and best practices. In many aspects, consultation respondents indicate that they see AEMO as being a leader in IBR analysis, assessment, and integration. This is particularly the case with the application of EMT tools in wide-area modelling and the rigorous assessment of compliance with technical standards. For many larger power systems – China, North America, Europe – the option of EMT modelling of the entire system is likely not available with current technologies but the lessons from Australia’s approach are nevertheless valuable.

However, there are now strong drivers to consolidate all the knowledge, processes and models and consider the best way to manage analysis in the future, which is expected to have an increasing demand on high accuracy data and simulation. The objectives for future requirements identified within AEMO include:

- Improving model quality and usability
- Reducing duplication of effort across Operations and System Design
- Reducing AEMO risks – operational, reputational, data accuracy
- Ensuring fit for purpose modelling into the future

Supplementing and supporting the above objectives are requirements for:

- Significantly speeding up the connection assessment processes.

- Establishing appropriate data infrastructure to support existing systems and tools, including:
    - EMS power system model.
    - EMT, RMS and frequency domain tools.
    - Models and setting management for all tools.
- Improving interoperability between tools as far as is feasible.

The following sections identify some known issues and gaps with the current tools and facilities.

6.2 The wide-area EMT model adds complexity.

The WAM for EMT studies is of great interest internationally because of its size and number of detailed dynamic models that are represented.

WA studies, with the four mainland states represented, have been used extensively to assess the performance of IBRs that are connecting to the power system and to undertake system strength assessments.

There are some challenges with the WA model:

- It is complicated and time-consuming to set up a study case and include all committed plant. There are two classes of WA model:
    - The existing system – as mainly used by Operations.
    - The 'future' system – including committed developments.
- The resolution and extent of the network data is set by the EMS data model.
- The NEM-WA model represents one system condition and is used for assessing IBR response to faults. Varying power flow conditions are secondary for this application.
- The EMT solution is not always robust and making significant changes to flows (for example, on interconnectors) can result in solution problems. Constraints are not modelled and can be violated. Non-convergence indicates further analysis is required.
- The EMT models are not encrypted and are confidential to AEMO and the TNSPs, restricting the ability of proponents to obtain the WAM and undertake their own studies.
- The 'connections simulation tool' (CST) makes the NEM WA model available in a sophisticated way, maintaining model confidentiality but with a consequence of restricting information on simulation results in the network, other than at the point of connection. Some information is supplied but at specific nodes.

However, even with these challenges, the NEM WA model has proven its worth by demonstrating issues with fault ride-through performance and revealing sub-synchronous oscillations. The WAM thus remains important to Operations in their management of power system security and System Design in testing for these types of phenomena.

An initiative to automatically generate NEM WA study cases from AMP has prospects of reducing the set-up times for snapshots and making an increasing range of cases available. The appending of committed generators is still required for the 'future' system case but the ability to generate snapshots is expected to be of direct and immediate benefit for operational assessment of power system security.

The TNSPs, as system strength providers (SSPs), must assess system strength in their states using EMT WA models. They are thus a customer for the WA models developed and maintained by AEMO, even though they indicate that they abbreviate the model to reflect their networks and requirements.

Potential future developments in RMS- EMT co-simulation tools will also rely on there being a NEM WA EMT model, even though only part of it will be utilised in any given co-simulation.

Finding: AEMO will need to maintain a current NEM power system WA model for EMT studies to support a range of assessments and the model will need to have two forms:

- Existing system for operations used to support security assessments.
- Existing system plus committed projects ('future' system), for System Design purposes.

6.3 Model development and configuration using AMP.

The AMP tool, which derives its network data from the EMS, is the primary study case configuration tool in AEMO. AMP produces half-hourly power flow snapshots of the existing power system and has enhancements that include:

- Marginal loss factor model extensions to represent metering points.
- Future developments (committed generation, network).
- Mapping of the EMS node-breaker model to a bus-branch model with defined bus numbers.

6.3.1 The network model is calculated by the TNSPs.

The network model is essentially taken from the EMS, which includes an internal positive sequence load flow tool. The source data in the EMS is provided by the TNSPs from their asset databases. The TNSPs calculate the sequence impedances based on the geometric layout of the lines/cables using their assumptions and formulae. The resulting impedance models are 'pi equivalents' and do not fully represent unbalances due to asymmetries.

This is shown in Figure 1 where the data path is from the TNSPs to the EMS.

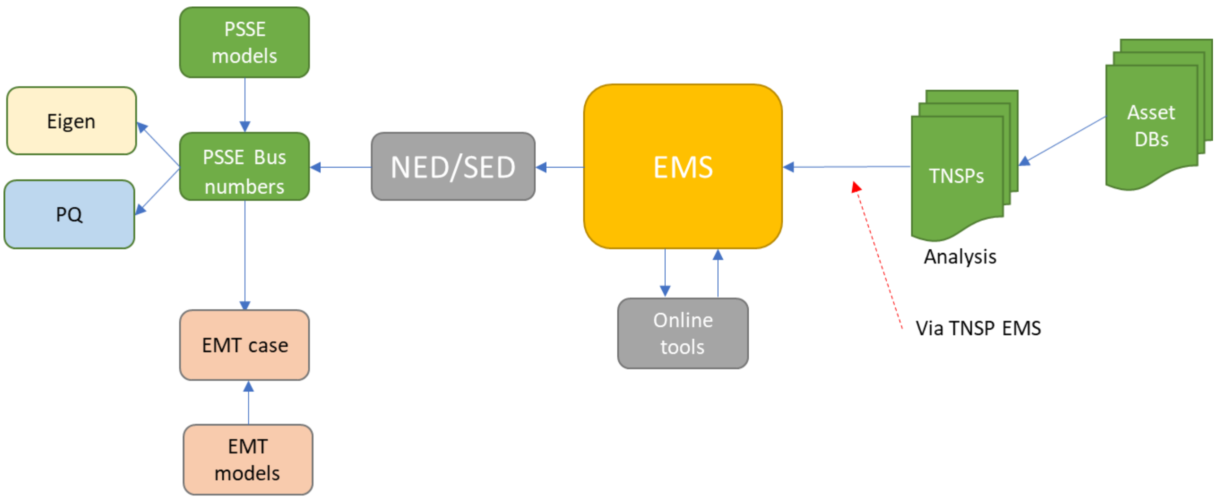

FIGURE 1: EXISTING NETWORK DATA PATHS FROM THE TNSPS VIA THE AEMO EMS, WHERE NED AND SED FILES ARE EXPORTED TO AMP

NED refers to a proprietary format for network data for the model represented in the EMS. Similarly, SED is a related format of state estimator data. Together, the NED and SED information defines an operating condition that can be solved in a load flow application.

There is a CIM-compatible tool at the data input stage of the EMS. This tool has some temporal capability in defining elements that are in service at a particular time. However, this is not accessible to the NED/SED transfers or in the AMP.

At present the NED file represents data suitable for power flows, with lines and cables typically represented as 'equivalent pi'. The internal EMS load flow assumes balanced operation and positive sequence quantities. For unbalanced faults, negative and zero sequence impedances are added. The network model in the EMS (and therefore the NED) is in node-breaker format, which represents substation and busbar detail. This is simplified to bus-branch format when exported to other applications (RMS, EMT) for analysis.

6.3.2 Dynamic models are stored in AMP.

AMP includes the dynamic models in EMT, RMS and small signal (MudPack) format. The small signal models are being revised and supplemented for IBRs to suit a new small signal application (SSAT).

6.3.3 AMP creates study cases for different applications.

Study case configuration is typically based on a snapshot and modified to reflect the required time by manually configuring committed projects and scaling loads.

The study cases are currently exported in RMS format for different applications, including:

- Standard snapshot cases for distribution to Participants (fee-based)
- A 'standard' RMS case that is then converted to EMT format. There is a current project to also export the same snapshots directly in EMT format.
- Automated study cases with dynamics for use in the dynamic security assessment (DSA) bespoke tool used to support real time operations.

The exported cases require significant effort to make them useful in System Design studies. Committed generators must be added and generation adjusted to accommodate these new generations sources. A project to automate this process is already under consideration.

The generation of snapshots has contributed significantly to the ease with which the power system can be analysed, and it is a feature that should be retained. Current initiatives to extend snapshot export in EMT format for operational purposes are constructive and helpful.

Significant manual processes are required to finalise study cases that include future developments. Developments to automate more of the cases creation process would be beneficial. These manual processes require support from senior engineering staff with expertise in models and how to integrate new models into the future oriented cases. By the time a project reaches commissioning stage, the integration must be complete and tested to be robust. Both Operations and System Design are beneficiaries of an efficient integration process for new models.

Finding: The AMP assists significantly with study case configuration but there are still many manual interventions required, particularly for future cases with committed developments.

Finding: The support for dynamic models is limited with multiple repositories and few data administration tools to provide, for example, change/issue tracking and version control.

Finding: The AMP serves both Operations and System Design but there are no centrally assigned resources to maintain data, dynamic models, and the configuration of study cases. Both Operations and System Design have groups with similar accountabilities to develop modelling and simulation facilities.

6.4 Analysis gaps in AEMO

There are two reported analysis needs that are not currently met:

- Simulation of unbalanced voltages arising from, for example, imperfect line transposition [3]
- Interfacing with dispatch simulation tools (as also raised by an external stakeholder in section 5.8).

Neither of these is theoretically difficult to do. These challenges are present due to the limited interoperability of the existing tools and the resolution of the data held by AEMO in AMP.

6.4.1 Simulation of unbalanced voltages on the transmission network

An ideal power system is balanced across the three phases. The assumption is usually made that this is the case and that, for example, all transmission line and cables are transposed to mitigate unbalance due to differences in mutual impedances between conductors. If this assumption is not true, the individual phase and mutual impedances may differ and produce imbalance in the three phase voltages. This imbalance may cause problems for end-use customers by, for example, creating additional losses in directly connected motors and generators. Standards limit the permissible negative phase sequence (NPS) voltage and TNSPs have obligations to have regard to these limits. This is a power quality issues and not a security issue – it is unlikely Operations will have an interest in this phenomenon unless the issues become critical in processes like system restart.

In Victoria there are some parts of the network where the levels of NPS can approach the limits specified in the Standard. Network constraints are implemented to maintain the NPS voltages below these limits.

[3] This is in relation to AEMO's Victorian planning responsibilities

The requirement is to simulate these steady state NPS voltages for a range of expected operating conditions and to have tools that can assess the impact of remedial actions, which may include, phase swapping on towers, transposition of conductors and application of unbalanced reactive equipment (dynamic or static).

A three-phase load flow application with high resolution transmission line / cable modelling can simulate the NPS voltages for unbalanced network elements and loads. Since the NPS voltages are also related to current flow through the unbalanced impedances, simulation of the range of daily and seasonal power flows will show the conditions under which the limits are approached. This will support development of constraints to maintain NPS levels within the required standards.

Three phase load flow tools exist, and the analysis is relatively straightforward. An issue is that AEMO may not have the high resolution of data required for transmission lines, cables and transformers that would support the analysis. Further, a continuation load flow that allows assessment of various loading conditions would also be desirable. One solution would be to utilise yet another tool with these capabilities, which may be feasible if a comprehensive data repository is developed as a single source of the truth.

***Finding**:* Assessment of steady state negative phase sequence voltages requires high resolution network data that can be analysed using a three-phase load flow tool with a continuation load flow facility.

6.4.2 Interfacing with dispatch simulation tools

This issue is described in more detail in section 5.8.

AEMO uses dispatch simulation tools extensively in the analysis supporting the Integrated System Plan [4].

Analysing the results from the dispatch simulation tools will require:

- Establishing a compatible AC-load flow case, with the same assumptions in relation to:
    - Generation plant in service
    - Demands and their locations.
    - New network developments
- A tool or facility to map each demand condition and the associated dispatch outcomes to the load flow case.
- Automated reporting of rating and voltage control violations
- A continuation load flow is desirable if multiple sequential cases are to be analysed.

The problem is largely around manipulation of data (demand, dispatch outcomes per dispatch interval) and automation of repeated calculations. Since generator dispatch outcomes can vary from minimum to maximum, reactive limits as a function of MW output and transformer tap information are also desirable for voltage reporting.

The gap could largely be filled by a load flow tool offering a continuation load flow facility.

7 Required characteristics of future tools

This section describes some characteristics of an ideal set of tools. It is unlikely that one vendor will provide a single tool that meets all these requirements but in a perfect world, these characteristics would facilitate efficient power system analysis.

7.1 Underlying assumptions about the tools and systems required for the future.

The context for defining these tool characteristics is the likely future requirements. The underlying assumptions for the foreseeable future include:

- The higher bandwidths of power electronic energy conversion systems, such as IBRs will necessitate ongoing use of higher precision tools, such as EMT.
- The data resolution[4] will need to increase to match these tools and future IBR, or equivalent, equipment.
- Forward planning will still use lower resolution tools like RMS but with enhancements and extended automation facilities.
- The analytical tools will need to consider unbalanced operating conditions and faults.
- Frequency domain tools will be essential to design control system settings that work harmoniously with other equipment and avoid stability issues.
- Interoperability and co-simulation will depend on data management infrastructure.
- Data volumes will increase.
- Data quality will need to be carefully managed to preserve integrity.
- Data exchange and portability, including dynamic models, will improve through protocols like CIM.
- Case development and case management, including archiving, will improve overall study efficiency.

7.2 There is an ongoing requirement for high resolution EMT analysis.

Power electronic converters will continue to dominate the analytical requirements as the energy transitions continues. The wider bandwidth of these converters will require ongoing application of higher resolution tools like EMT and wide area models to account for interactions with other IBRs.

Requirement: Future tool requirements should centre on making EMT analysis as efficient as possible with high degrees of automation in:

- Case configuration
    - Snapshot preparation
    - Inclusion of dynamic models
    - Inclusion of future developments

[4] Examples include network models using detailed frequency dependent models rather than Bergeron models based on pi-equivalents and representation of saturation effects in transformers.

- Configuring co-simulation cases with RMS tools

7.3 Network data resolution will need to increase to meet EMT requirements.

The network data in AMP is simplified (e.g., equivalent 'pi') and does not contain detailed information on transmission lines, cables, and transformers. In the future, it is expected that some studies will require a higher level of detail than is currently available from the TNSPs via the EMS. An example of where higher resolution data is likely to be required is HVDC technology and any operating conditions, whether HVDC or IBR induced, where higher frequency instabilities may occur. Further, interactions between the power system and fast-acting controllers, such as the current controller in a grid following converter, could lead to instabilities in the 100s to 1000s Hz range [5]. At these frequencies the equivalent pi models are inaccurate and higher resolution data is required.

Future technologies may also require higher levels of data accuracy. Direct provision of high-resolution network data will thus likely be required. This is illustrated in Figure 2.

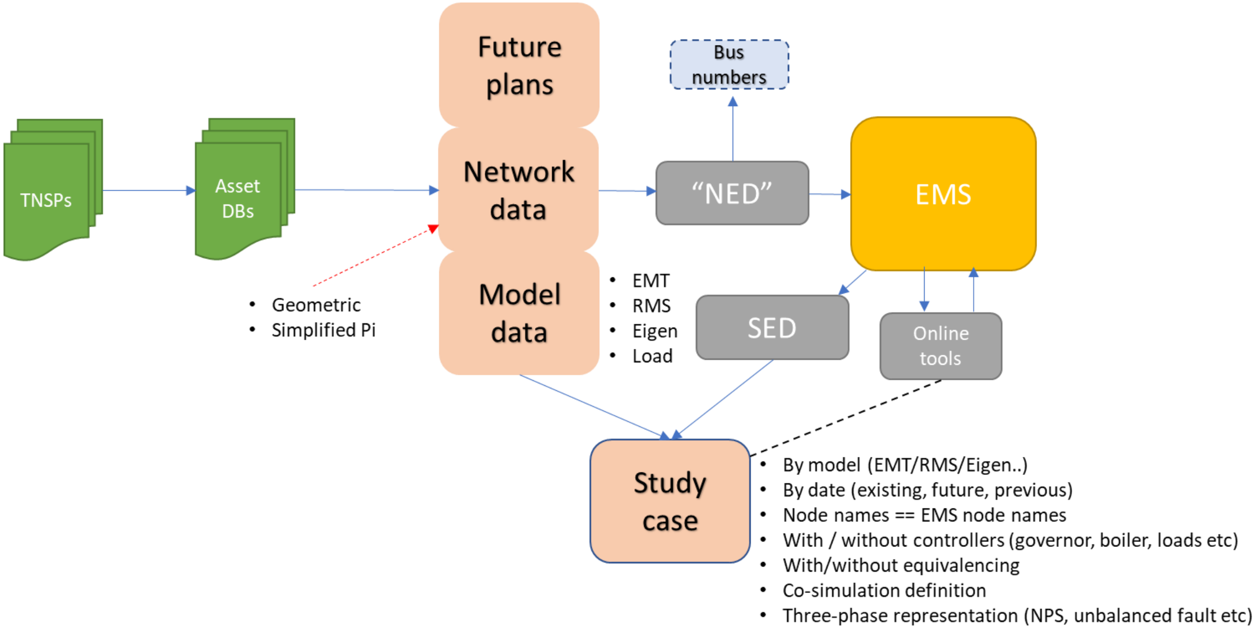

FIGURE 2: HIGH RESOLUTION NETWORK DATA PROVISION TO AEMO FROM THE TNSPS SHOWING REVISED SYNCHRONISATION WITH THE EMS

Figure 2 illustrates a possible data path for high resolution network data. Detailed network data is sourced directly from the NSPs and retained in the data repository in several different resolutions ranging from geometric to equivalent pi. Calculations of lower resolutions are made using AEMO assumptions and are consistent across entire NEM. The data repository (beige) includes all study data for all tools and a configuration feature allows production of study cases. The EMS could derive its data from this repository via a NED-like conversion. The EMS state estimator would export snapshots to the repository that could then be used in the formation of study cases.

The network model in the EMS is in node-breaker format, which contains more information than the 'standard' network model currently used in both RMS and EMT data files. The node-breaker format shows details of connections within substations and uniquely names all items of the plant.

It would make sense for AEMO to use a common network model across both Operations and System Design and to convert this in the event any data customers (including TNSPs, participants) want to use a more simplified form. Conversion is not challenging and is a feature of the existing AMP.

Requirement: Data in AEMO repositories should include the highest resolution of data that might be required for any analysis.

Requirement: The network model used in AEMO systems and analysis tools should conform with that in the EMS, taking the form of a node-breaker configuration and using the same node and equipment names as in the EMS.

7.4 RMS tools will continue to be valuable for many forms of analysis.

Planning studies and simulation of slower transients are still likely to utilise RMS tools because of their faster speed and lesser data requirements. RMS tools may have different characteristics relating to whether they can deal with unbalanced conditions and how they manage events. This may make the RMS tool better or less suited to system studies. However, once RMS models for IBR equipment are benchmarked with their detailed EMT models, their application would be valid for the assessment of compliance for some technical requirements and for slower transients such as:

- Transient stability
- Frequency and voltage control
- Protection (where phasor analysis is sufficient)
- Dynamics for future scenarios where generic models and assumed settings are used.

Requirement: RMS tools should be retained and, where possible, enhanced to provide better capabilities for analysing future scenarios, unbalanced operation, and continuation load flow.

7.5 Frequency domain tools are essential for coordinating controller settings.

Experience with lightly damped control system interactions highlights the need for formal tools and processes to test stability and damping and avoid oscillations due to low gain and phase margins. Historically, lightly damped, or unstable oscillations in synchronous machines with fast acting, high-gain excitations systems were solved using power system stabilisers (PSSs). The PSSs were set using FD tools and stability issues are now quite rare.

7.5.1 Using frequency domain tools to set control systems

At present the controller tuning process does not consider FD analysis and this may be a contributing factor to the control system interactions observed in many power systems across the world.

IBRs with their wider response bandwidths, should be set in the FD to provide stable performance with good gain and phase margins. It is less important which FD tools are used but the key outcome is that the controllers should be shown in the design stage to be stable for reasonable power system conditions.

7.5.2 Correctly set control systems reduce the need for as many EMT studies.

To check stability of IBR equipment, many EMT studies are run using a wide area model. This is necessary because oscillations will typically only arise under certain network conditions, usually where low fault levels exist at the point of connection.

Using FD tools to set controllers allows engineers to avoid these oscillations for all expected conditions at the point of connection. This has a significant benefit in reducing the requirement for as many EMT studies and, potentially, removing the need for participants to undertake any wide area EMT studies. EMT studies are still required to confirm system strength performance and these studies are run by TNSPs using regional EMT models. Further, AEMO needs to run due diligence studies for both system strength and overall performance and may elect to do this in a wide area or regional EMT study. From the perspective of EMT simulations, the participant may only need to undertake single machine infinite bus (SMIB) studies to verify performance, particularly under S5.2.5.5. This avoids issues with model confidentiality in the EMT domain.

7.5.3 A revised connection process may be feasible with fewer EMT studies.

Recognising that a process to examine and approve OEM models is likely to be the first step in a connection process, a revised process along the lines shown in Figure 3 may be possible.

In Figure 3, the controller settings are calculated ahead of any EMT analysis. With correctly set controllers, the risk of stability and oscillation issues are greatly reduced. Once set, the TNSP system strength assessment can occur, typically using a state based EMT model. Assessment of Schedule 5.2 performance standards and AEMO due diligence follow, all with reduced risk of iterations to revise control settings.

Discussions on this process identified that the sequence of having the TNSP system strength assessment ahead of the Schedule 5.2 assessment is not essential and the steps could be re-ordered if required.

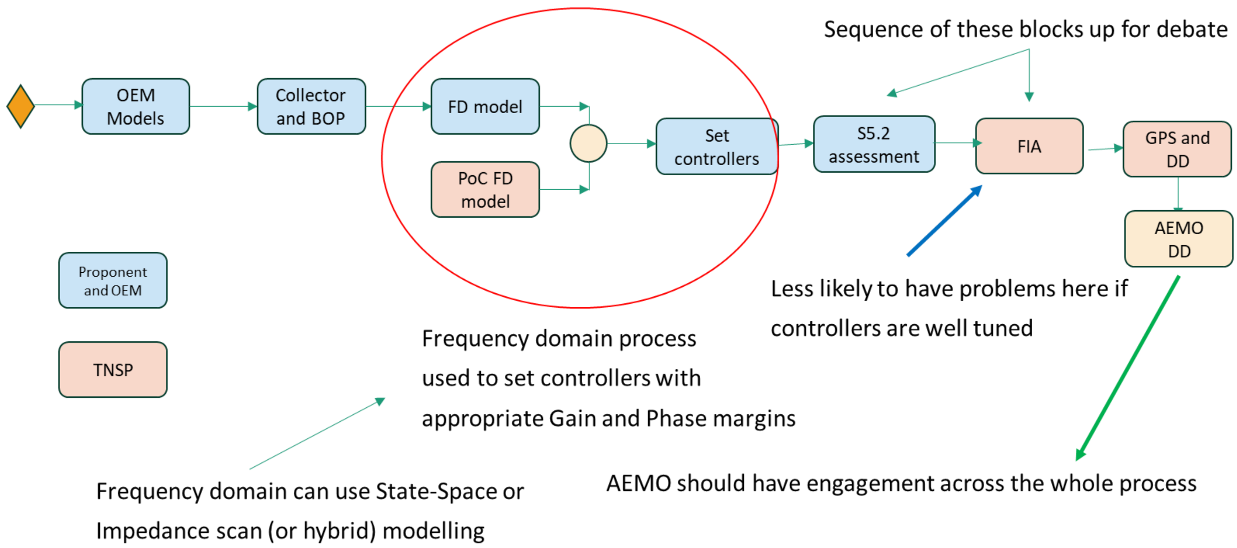

FIGURE 3: POTENTIAL CONNECTION ASSESSMENT PROCESS USING OEM TOOL APPROVAL AND FREQUENCY DOMAIN TOOLS TO SET CONTROL SYSTEMS

The key point in the process outlined in Figure 3 is that the need for the participant to carry out wide area studies is either obviated or significantly reduced. The FD tuning process will highlight which study configurations are most challenging and analysis effort can focus on the problematic operating conditions. Generally, SMIB analysis should be adequate for the Participant assessment of schedule 5.2 performance. The extent of EMT studies is something that could be explored in a proof-of-concept study, which is foreshadowed in this report.

7.5.4 IBR control settings are likely to change as system conditions change.

AEMO expects the power system to change materially over the transition with most coal-fired plants retiring over the next ten to twenty years [4]. There are also plans in the same document for significant transmission investments over the same period. The key point is that it is unlikely that control systems will remain on the same controller settings for all their service life. FD tools provide the ability to review and change controller settings in a systematic way to adapt to the changing power system conditions. It is highly probable that multiple controllers in a region or area may benefit from re-tuning when a substantial change occurs, such as retirement of a large synchronous generator. In such a case, the collective tuning process will coordinate all the settings to enhance the ability of the plant to operate stably and to avoid unstable interactions.

Requirement: Frequency domain tools should be used to set control systems in a way that has satisfactory gain and phase margins over their response bandwidth, mitigating the risk of control system interactions and oscillations.

7.6 Three-phase models for unbalanced analysis

Synchronous machines are inherently balanced devices. Analytical tools capitalised on this by assuming balanced conditions and simulating the power system using positive sequence voltages and impedances. IBRs can respond on individual phases and the assumption about balanced systems is no longer valid as the correct representation of individual phase voltages is now desirable when simulating unbalanced conditions.

Simulation of unbalanced conditions is required for:

- Unbalanced faults (that is everything except three phase faults)
- Un-transposed or partially transposed lines or other asymmetric devices giving rise to negative phase sequence voltages.
- Unbalanced loads, where individual phases have different loads, such as phase to phase traction loads.

EMT tools represent each phase, but some RMS tools represent the positive sequence only and use negative and zero sequence data for the purpose of calculating unbalanced fault currents. The voltages represented in the RMS study are always positive sequence only and do not align with actual or EMT simulated voltages and may result in incorrect simulation results.

7.6.1 Unbalanced faults in RMS tools

For unbalanced faults, a representation of each phase of the power system is required if the simulated voltages are to match those that will be observed in practice or in EMT simulations.

IBR equipment responds to individual phase voltages and the sequence impedance approach used by positive sequence RMS tools to simulate unbalanced faults do not give the individual phase voltages. This affects the IBR response as well as the ability to benchmark RMS results with EMT.

During unbalanced faults, the voltages on non-faulted phases may be affected by the negative phase sequence currents and produce temporary over-voltages. These can be simulated in a three phase RMS tool but not in a positive sequence RMS tool.

Ideally, RMS tools would also have three-phase representation equivalent to that in EMT tools. If the RMS tool does not have three phase representation, EMT simulation will be required for unbalanced faults.

Requirement: Individual phase representation should be provided in the RMS tools for simulating responses to unbalanced faults.

7.6.2 Un-transposed or asymmetric lines, cables, and loads

Steady state negative phase sequence arising from the configuration of lines and cables needs a detailed representation of the coupling between phases. This is typically obtained using geometric descriptions of the spacing in conductor bundles and between conductors. The unbalance is the calculated using the unsymmetrical mutual coupling between conductors.

The magnitude of negative phase sequence voltage (NPS) depends on the current through the conductors. A range of loading conditions must be examined in cases where the NPS voltage is at risk of exceeding limits in the relevant standard or the connection agreement.

Analysis using geometric line/cable models can also assess the benefits of mitigating actions such as conductor reconfiguration on towers or addition of unsymmetrical reactive compensation.

Requirement: Individual phase representation is required to calculate the NPS voltages cause by asymmetrical impedances in the network

Requirement: Individual phase modelling of network components is required to represent the asymmetric coupling between conductors.

Requirement: Continuation load flow analysis (or equivalent) is required to calculate NPS voltages for a range of loading conditions.

7.7 Using a common data set to improve interoperability.

With multiple vendors for the current suite of analysis tools, the interoperability could be enhanced. There is some interoperability between the RMS tool and the frequency domain tool and third-party developers are offering tools to improve RMS and EMT interoperability.

An ideal arrangement might be to have a common data system with all models, settings and network data and synchronised with the EMS for snapshots. All tools would source their input data from this common database, which would have tools to export data in the appropriate formats for each tool.

The ability to generate tool-specific input data files from the same study case or snapshot would effectively improve interoperability and avoid the need, as at present, to generate a case in one format and then perform a second conversion to generate the input files for another tool.

The AMP provides some of these features and could be enhanced to improve the functionality and specifically the interoperability between tools and models (e.g., common settings for RMS and EMS models to the extent this is possible). Alternatively, a purpose designed database may be required. Several vendors and research organisations [14] are developing data management systems with at least some of the required features.

7.7.1 EMS snapshots are highly valued.

The ability to generate an RMS study case from a snapshot taken from the EMS is a valuable feature of the current arrangements and its retention is a high priority.

Extending this feature to include the ability to generate an EMT study case is a current initiative. The benefits supporting this initiative are operational. Conceptually, significant benefits arise for:

- Incident analysis
- Operational planning for unusual operating configurations (for example, isolated sub-region or skeletal system)

The advantage that the EMT snapshots have over RMS is the ability to represent fast transients associated with, for example, fault ride through and the operation of fast control loops, such as PLLs or current controllers.

Requirement: It should be possible to export and benchmark the same snapshot to any of the tools. Alternatively, the application tools should access the database directly, removing the need for multiple study cases.

7.7.2 Adding data for future generation, dynamic loads and network projects

Although Operations and System Design both need to analyse the NEM power system, their focus is slightly different:

- Operations are focussed on the existing power system.
- System Design need to consider committed projects and developmental projects.

Operations are also interested in the future power system from a planning perspective, where system security requirements must be provisioned ahead of new assets being commissioned. However, this is a shorter look-ahead than, say, the Integrated System Plan, where committed projects may be five to twenty-plus years in the future.

Operations may also require access to historic snapshots for incident investigation or for developing trends.

There are also extended data sets in AMP for committed or future development on the power system, as well as the extensions to the EMS model to represent metering connection points for loss factor studies.

Requirement: A future data management system should be time based and enable the existing system as well as future or historic cases to be configured.

Requirement: Specialised cases, such as for marginal loss factors, should be available as required and for future and past conditions.

7.7.3 Managing dynamic model settings

The different dynamic models – RMS, EMT and FD – could either be in a common power system data repository or in a dedicated model database with links to the common repository. Alternatively, it may be possible in the future to have a fully specified model that is the basis of each of the model types listed, with only one set of controller settings.

A key aspect of a model database is managing settings and changes over time. It is very likely that most IBR will have at least one setting change in its service life. It is also possible that in the future model settings may change adaptively or diurnally to meet performance requirements for different operating conditions.

The functional requirements for managing settings could include:

- Settings files for:
  - Each relevant plant item (hardware)
    - Firmware version
    - Actual setting files as downloaded.
  - EMT, RMS and FD models

- Change management records and workflow showing:
  - Development of settings
  - Implementation on site
  - Testing
  - Downloaded setting files.

Requirement: The model database should be synchronised with the main data repository so that changing model settings only happens in one location and is synchronised with the input data files for simulation studies in all tools.

7.7.4 Case management and archiving facilities should be improved.

As the number of dynamic models increases and data volumes increase, formal processes to manage cases (or projects) in a way that is traceable and auditable will become important. On completion of the connection process, for example, a record should exist for all analysis, reports and important documents associated with the connecting plant. An archive should provide all the information an engineering analyst would need to understand what was done during a connection assessment five or ten years ago (or more).

Requirement: The model database should be included in, or be linked to, a repository and archive for each connection assessment. The outcome is that historic study files can be used to confirm previous analysis, if required.

7.7.5 Data portability is expected to improve and will become more important.

Data exchange protocols are used on interconnected power systems with multiple asset owners, including CGMES [12] and CIM [15], mostly in Europe. Other initiatives are examining common modelling languages that could provide portability of dynamic models across different vendors' platforms.

Data exchange with other NSPs, particularly DNSPs where the modelling extent may be restricted to the bulk supply point transformer, may need consideration as more generating systems – wind, solar, batteries – are connected and can be aggregated to provide services to the NEM.

The establishment of REZs, with their networks developed and operated by new NSPs, similarly drives consideration of modelling extent that should not consider or be restricted by asset ownership boundaries.

The issue of material inter-network impacts – MINI – was considered in the past for transmission investments. However, investment in generation now occurs practically anywhere in the power system including at locations close to asset ownership boundaries. Analysis must consider the potential impacts anywhere in the power system and this may lead to developments in one network created impacts in another network.

Seamless exchanges of data between TNSPs, NSPs, and DNSPs will be required for efficient assessment of performance and management of security. Exchange of data between parties is facilitated if portability protocols are adopted. In terms of process, existing guidelines on inter-network impacts should be updated to reflect system strength impacts and processes revised to ensure that no extra costs are incurred because of asset ownership in the vicinity of the connection point.

Requirement: The model database should conform to the extent possible with commonly agreed and compatible data exchange formats such as CIM and CGMES to facilitate development, operation, and aggregation of distribution IBRs.

Requirement: The model database should be capable of exporting data for regions or sub-regions that are not restricted in any way by asset ownership boundaries to facilitate assessments with material inter network impacts.

7.8 Co-simulation delivers the best of both the EMT and RMS worlds.

Co-simulation allows part of the network to be simulated in EMT and rest to be simulated in RMS, providing potentially faster simulation times, and allowing representation of system-wide phenomena, such as inter-area electromechanical modes and frequency effects. Some information is lost in the parts of the network modelled using RMS, but this is generally a second order effect is the sub-region modelled in EMT is selected appropriately.

An alternative to co-simulation is where a sub-region of the power system is analysed in EMT and the connections to this sub-region are modelled using equivalences for the rest of the power system. The use of sub-regions and equivalences, and even sub-regions with co-simulation, may be appropriate for some analysis, but some information is lost in the equivalencing process and engineering judgement is required as to whether this is significant.

It is understood that there are various initiatives under development by third parties (i.e., not the vendors of the RMS or EMT tools) to develop co-simulation options. AEMO is currently considering such a co-simulation option.

Within AEMO, the Victorian Planner is trialling a co-simulation tool in proof of concept for the Victorian networks. This approach is modelling a selected part of the network in EMT, based on an RMS study case. The selected part of the network is interfaced with the RMS study case and appropriate EMT models are imported from local datasets. The results are considered for modelling boundary conditions as a Thevenin sources, which is an approximate approach, or proper co-simulation, which is more accurate. Bespoke data files are used for high resolution network data and the EMT models. Future roll-out of the approach should consider using common data repositories.

Requirement: Co-simulation facilities allowing configuration of joint EMT and RMS study cases should be provided to deliver analysis and time efficiencies over modelling of the entire power system in EMT.

7.9 Summary of future requirements and desired outcomes

The requirements in the preceding sections are summarised in Table 4.

TABLE 4: SUMMARY OF FUTURE MODEL AND TOOL REQUIREMENTS AND DESIRED OUTCOMES

#	Requirement	Rationale	Outcome
1	Tools to support EMT case configuration	Ongoing requirement for EMT analysis Efficient case generation will save significant set-up time	EMT cases support other functions: System strength analysis Impedance scan Co-simulation
2	AEMO data base should include highest resolution data	Future analysis likely to require better data,	High resolution network data should be available within AEMO.

#	Requirement	Rationale	Outcome
		especially for high frequency phenomena. Some existing gaps with unbalance analysis in steady state	Select resolution of models and data to suit application
3	EMS network topology	All AEMO departments should be analysing same system model. Node-breaker configuration gives greater detail of connectivity	Common node and asset names across all tools Simplified data storage and conversion
4	RMS tools and models should be retained and enhanced	Use for slower transients, limit calculations, frequency analysis. Faster than WA EMT studies and easier to reconfigure.	Efficient assessment of full power system using best suited tool
5	Frequency domain analysis tools should be available	Use to set control systems. Use to determine oscillatory limits	Stable controllers, no inter-controller oscillations Power system security confidence
6	Three phase analysis in RMS	Need to better benchmark with EMT. IBR equipment has individual phase control and may otherwise not work as expected for unbalanced fault	More accurate phase voltages in simulation More accurate IBR responses for unbalanced conditions
7	Three phase load flow	Calculate negative phase sequence voltages in steady state. Represent unbalanced networks and loads using more accurate network models	Compliance studies for NPS levels Ability to design mitigation options. Assess impact of unbalanced loads
8	Continuation load flow	Calculate flow duration curves. Test for rating violations not seen in Dispatch simulation tools	Confirm dispatch simulation outcomes. Simulate variability using irradiation, wind, hydro data. Test NPS remedial measures
9	Export study cases and snapshots to any tool	Benchmarking between tools Improve interoperability	Efficiency in case development

#	Requirement	Rationale	Outcome
10	Database should be time-based	Case configuration for past, present future Investigations of incidents Trend analysis	Facilitate audit studies for incidents. Confirm timing of development options
11	Specialised case generation	MLF studies using future committed developments.	Efficiencies and auditability
12	Synchronised model database	Changing model parameters only required in one location. Workflow for change management	Data error mitigation Confidence in as-built settings Settings audits
13	Case management and archive	Records of assessments, including study cases	Auditable records Long term review of decisions made
14	Data and model portability	CIM, CGMES compatibility Data exchange between NSPs, AEMO and Planners	Supports study case configuration at interface of network owners (e.g., TNSP/DNSP) Supports other tools and vendors (future)
15	Assessments across asset ownership boundaries TNSP, DNSP, REZ NSP	Analysis of inter-network impacts must be efficient. Ability to export/import relevant section of network using CIM protocols	Should be no additional costs due to asset ownership. Efficient construction of study cases
16	Co-simulation	Reduction in simulation time Less need for equivalencing	More accurate than equivalencing. Time savings over EMT WA studies

8 A strategy for the future

The energy transition is likely to see a continued reliance on power electronic generating systems and converter-based loads. Technology may change but it is reasonable to assume that the fast-acting controllers of power electronic equipment will require high resolution analysis tools. This section discusses the likely development in analysis tools and the strategy that AEMO should follow as it responds to the changing technology and analytical needs.

8.1 EMT analysis tools will develop and improve.

The consultation outcomes confirm that most respondents are moving towards some form of EMT analysis to support IBRs. This demand is likely to drive vendors to offer new and modern tools for EMT analysis that will likely address some of the key issues currently experienced, including:

- Greater interoperability with RMS tools, including co-simulation.
- Ability to quickly initialise to defined operating conditions (e.g., snapshots, dispatch simulator outputs)
- Portability of dynamic models to reduce dependency on specific vendors.
- Faster simulation times
- Encryption of models to protect OEMs' intellectual property.
- Improved case management and archiving
- Modernised algorithms and use of languages that do not require specialised compilers.

There is also the prospect of new algorithms that adapt the step size of the simulation according to the active dynamics. Potentially this could remove the distinction of EMT/RMS and result in one application that is able to deliver a much wider range of dynamics within a single application. Existing issues such as model IP and the requirement to encrypt models may remain but the idea is for a unified application for a wide range of phenomena. This is expected to be a longer range outcome.

8.2 RMS analysis tools will still have widespread application.

RMS tools using improved designs and implementation will continue to have application for slower dynamics such as angle stability, frequency control, and transmission capabilities. As with EMT tools, it is likely that there will be further development of RMS tools including:

- Easy to configure co-simulation with EMT tools.
- Three phase representation that correctly models unbalanced operating conditions, loads and faults.
- Encryption facilities to protect IP.
- Portability of dynamic models to reduce dependence on particular tools (DNSP, REZ NSP may use other tools)
- Ability to equivalence parts of the network to facilitate analysis across transmission-distribution interfaces.
- Improved standard models for slower-acting plant like governors and boilers.
- Greater automation of reporting of results and 'reasonableness' checking
- Independence from specialised compilers
- Ability to represent a node-breaker representation of the power system will provide greater alignment with operational systems.
- Standardised naming conventions and less emphasis on historic dependencies on bus numbers

- Continuation load flow tools to support generation of flow duration data and simulation of variable resources (wind, sun, variable hydro)

8.3 Frequency domain tools will be used much more widely.

The observed problems related to inter-control system oscillations are likely to drive greater interest in frequency domain tools, which can be used to set control systems to deliver stable operation and have reduced risk of interactions with other equipment. As with EMT tools, the increased demand for competent FD tools is expected to encourage vendors to deliver tools with greater ease of use and, potentially, the ability to linearise existing RMS or EMT models for small signal assessment. The further development of FD tools could include:

- Greater interoperability with EMS and RMS tools allowing quick analysis of a given study case.
- Automated derivation of small signal models from EMT or RMS models
- Compatibility with other FD tools and approaches, such as impedance scanning techniques.
- Portability of models and study cases to allow efficient exchanges with other stakeholders that may not use the same tool.
- Control design tools such as Nyquist and Bode to allow efficient calculation of control settings with good stability outcomes (e.g., good gain and phase margins).
- Encryption of any OEM models to protect IP.
- Representation of transmission line propagation times[5].

8.4 Other related tools to deal with assessment of power quality and protection.

Although not discussed in this review, power quality and protection assessment require analysis of the power system and it is logical that tools should be aligned with those used for planning, operational and security purposes. The power quality (PQ) and protection tools are expected to:

- Utilise the same data sources as the EMT, RMS and FD tools.
- Comply with, and have tools to assess performance in accordance with, relevant standards.
- Have a high degree of interoperability with other tools.
- Adopt portability protocols to facilitate efficient sharing of data and outcomes with stakeholders.

8.5 Data and modelling infrastructure

The addition of EMT tools for general application in power system analysis creates a new dimension of data that must be managed, including:

- Dynamic models of IBRs, which are likely to have some confidentiality requirements.
- Higher resolution network data, including for lines, cables, transformers etc.

[5] Transmission line propagation times are suggested as relevant in assessing dynamics of IBRs, see [26]

The data and modelling infrastructure also must support a suite of tools (including at least EMT, RMS, FD), always providing consistency and interoperability.

8.5.1 Data repository functionality

The current diversity of tools, vendors and data formats is expected to encourage the development of better data and model management infrastructure. Organisations such as EPRI, North American Electricity Reliability Council, and others (North America) and ENTSO-E (Europe) are developing standards for data management that specify what data is held and how it can be shared between the various stakeholders that need to analyse their respective power systems. A key aspect of these standards (more so in Europe) is the portability of data, including dynamic models, which caters for multiple owners and administrators in their interconnected power system. It is therefore expected that data and modelling infrastructure systems will develop with, at least:

- Single source of truth designs, with all data in one linked repository
- Linkage to the operational energy management system (EMS) to allow analysis of snapshots and historical incidents with minimal manual intervention.
- Compliance with portability protocols such as CIM, CGMES and other that are likely to emerge.
- Time dependence, where power system model component has a start and end date, and case configuration is according to date.
- Configuration tools to facilitate setting up of cases and snapshots.
- Comprehensive data administration tools, including:
    - Change management
    - Version control
    - Reasonableness checking
- Data resolution appropriate for the tools being used:
    - High resolution for EMT and power quality tools
    - Simplified models for steady state and RMS
- Setting management for controllers providing
    - Single entry for each setting
    - Version control for firmware and on-site settings

8.5.2 Data portability

Access to comprehensive power system data is necessary to support the assessment of technical compliance and potential impacts on power system security.

The ability to efficiently exchange data with network service providers and developers is necessary to support the connections process and assessments of performance across network ownership boundaries. There is a diversity of analysis tools across network owners, particularly for the distribution sector.

Data portability is a key feature of power system with multiple stakeholders and protocols like CIM [15] are widely used. Further protocols are being developed for dynamic model portability [12] [13] [16]. The data exchange protocols are not yet fully developed and are subject to ongoing improvement and extension. However, adoption of current protocols and a provision for improved or extended protocols is desirable and of increased importance as the number of NSPs is increasing (REZs) and investments are implemented in the distribution networks with the potential to impact the transmission system and vice versa. Any redevelopment of existing data repositories or acquisition of a new data repository should align with data portability protocols to facilitate efficient exchange of data between parties that need to analyse the power system.

8.6 Strategic requirements for AEMO's future power system analysis tools

AEMO's strategic approach to power system modelling should recognise the development trends in both tools and data management infrastructure. The following section summarises an overall strategy.

8.6.1 Principles to deliver strategic improvements in modelling tools and infrastructure.

Any changes or development should consider the following principles:

- Data repositories should represent the single source of truth for all AEMO applications.
- Operational considerations have a high priority and data, and model requirements must be met.
- Interoperability, in the sense of being able to use common data repositories, is a critical requirement. Any new tools should either already have interoperability or the vendor should have a demonstrable strategy to deliver interoperability soon.
- Encryption of models that contain OEM intellectual property is highly desirable.
- Data resolution in repositories should be of the highest resolution likely to be required.
- Data management systems should conform to portability protocols and can adapt as these protocols are improved over time.
- Bespoke data formats for input or output data are highly undesirable in the longer term and should be avoided.

8.6.2 EMT tools

AEMO is currently utilising the EMT most widely adopted by OEMs and other power system administrators. However, the significant trend to EMT tools is very likely to deliver options for improved tools and systems, particularly with respect to interoperability and co-simulation.

A watching brief is recommended and possibly engagement with the current vendor to address and improve alignment with the strategic principles in section 8.6.1. Engagement with other mainstream power system analysis tool vendors will also provide insights as to other options that may be available. It is likely that further EMT tool options will become available as the power system engineering community increases the focus on these tools.

8.6.3 RMS tools

AEMO is using an internationally benchmarked RMS tool. However, interoperability is low, and the tool is based on positive sequence, balanced algorithms, rather than three phase systems that can analyse unbalanced conditions more accurately.

It is recommended that AEMO engage with the current vendor to seek better alignment with the principles in section 8.6.1. Further engagement with alternative vendors is recommended to assess tools that conform more closely with expected RMS capabilities, as described in section 8.2.

8.6.4 Frequency domain tools

AEMO is establishing new tools for FD analysis, following obsolescence of the previous tool (Mudpack). There is some interoperability but the developments of section 8.3 should be discussed with the vendor to improve alignment with the other AEMO tools.

As with EMT, it is expected that other tools and vendor offerings will be developed given the increasing need for frequency domain analysis. Techniques such as impedance scanning may also have new tool offerings, and these should be considered and evaluated against the principles in section 8.6.1.

8.6.5 Data and modelling infrastructure

The AEMO Modelling Platform has evolved over the past 20+ years and is still the basis for power system data and configuration of study cases. The original design specification was to support RMS analysis. AMP is now being upgraded to support EMT snapshots. The source of network data for AMP is the EMS and this data may not be appropriate for higher resolution analysis expected in the future. AMP will support improved interoperability between tools but may have limited value in case configuration that is common across all tools.

AEMO should consider further development of AMP to better align with the principles of section 8.6.1 and the functionality discussed in 8.5. Developing a new bespoke data management systems is unlikely to be cost effective and engagement with vendors offering standardised data systems specifically for power systems is encouraged.

8.7 Summary of AEMO modelling strategy for the next five years

Table 5 summarises the strategic requirements for tools and data systems.

TABLE 5: SUMMARY OF STRATEGIC REQUIREMENTS FOR POWER SYSTEM ANALYSIS TOOLS AND SYSTEMS

Topic	Strategy	Comment
EMT tools	• Watching brief on new developments in EMT tools • Develop co-simulation capability. • Add encryption to allow wider distribution of models. • Support inter-operability options. • Develop portability options	Vendors are expected to deliver upgraded EMT tools that align more closely to strategic principles. Portability of dynamic models is key to enable data sharing and choice of alternative vendors or tools.
RMS tools	• Provide unbalanced analysis (three phase analysis) • Provide continuation load flow functions. • Support inter-operability options. • Develop portability options	Ability to analyse unbalanced conditions. Portability of dynamic models to enable use of alternative tools. Alternative is using an additional tool to support the required functions.
Frequency domain tools	• Improve interoperability. • Investigate impedance scanning options.	Both state space and impedance scan options could significantly reduce risk of oscillations. A corresponding

Topic	Strategy	Comment
	• Finalise rollout of state-space tool • Develop portability and model automation	reduction in the requirement for wide-area EMT analysis is then likely.
Data and modelling infrastructure	• Provide single source of data truth. • Comply with data portability protocols (e.g., CIM, CGMES) • Develop a time-based configuration tool – each case applies at a point in time: existing, future, or past. • Redevelop data paths for highest resolution network data. • Provide data administration tools (e.g., version and change controls) • Provide configuration functions for each tool for common snapshot or built case.	Key requirement is to avoid multiple data repositories and duplicated data structures. Provide compliance with data portability protocols to facilitate data and model sharing.
Other tools – power quality, protection modelling	• Provide interoperability. • Utilise common data repository. • Provide portability of data • Avoid bespoke data formats	Power Quality and Protection tools apply more to AEMO's planning functions. Tools should comply with strategic principles relating to portability and interoperability.

9 Conclusions and recommendations

9.1 General conclusions

AEMO is currently analysing the power system using fit for purpose EMT and RMS tools but with low interoperability and many manual processes. Some studies use higher resolution tools than necessary, partly due to limitations in the tools and partly due to the current lack of functioning frequency domain analysis tools.

Consultations and a literature survey show great interest in frequency domain tools that are expected to be fundamental in the design of controller settings that deliver stable performance and avoid sub-synchronous oscillations. These oscillations have been observed in many power systems (China, Australia, Hawaii, UK, Texas, Scotland as per [3]). The early adoption of frequency domain tools should reduce the number of wide-area EMT studies required and mitigate the risks of sub-synchronous oscillations occurring. This should provide material benefits by reducing the need for many time domain stability investigations and the consequential delays when issues are uncovered later in the connections process. Initiatives are already in place to deliver a state-space frequency domain tool (SSAT) and there may be benefits in exploring other options, such as impedance scans, that could complement this tool.

The quality of OEM dynamic models is critical in the assessment of IBR plant performance. Although AEMO publishes the Power System Model Guidelines, the models are only assessed after the individual connection applications are submitted. Early assessment of OEM models, possibly funded by OEMs, offers significant potential for mitigation of delays during the connection assessment and commissioning processes by identifying and rectifying problems even before connection application studies commence.

The data systems supporting AEMO's power system analysis tools have evolved since the start of the NEM and require consolidation to include the new dimensions of data and models required for EMT analysis. The existing data systems are linked to the energy management system (EMS) and offer the ability to analyse operational snapshots, which are exported as RMS study cases. Extensions are required (and are being implemented) to produce EMT snapshots.

AEMO will benefit from having a consolidated central data repository, which is a single source of truth for all analysis (Operations and System Design). This repository should be time-based, allowing existing, future, and past power system conditions to be configured in study cases. The data repository might be achieved by developing the existing AEMO Modelling Platform (AMP) or, potentially, procurement of an off the shelf, purpose designed system.

The development of a comprehensive data base is a high priority and is central to achieving outcomes such as interoperability, faster preparation of study cases and the ability to undertake more accurate studies using high resolution data when appropriate.

The ability to configure study cases in a central data repository would improve the interoperability between analysis tools, thus increasing overall study efficiency and the ability to benchmark performance across all AEMO tools.

AEMO shares data with NSPs and participants. Efficiency of this process, including the ability to incorporate committed projects in data files, will deliver time savings for new connections. Compliance with data sharing protocols like CIM (common information model), CGMES (common grid model exchange specification) will shorten study case preparation times and reduce the dependency on specific tools and vendors. This will also enable all parties – AEMO, TNSPs and participants – to select their preferred tools for their specific requirements. With the power system security obligation, AEMO needs to consider and manage its own requirements as a priority and then work out data and information exchange protocols that meet the requirements of others.

A set of strategic principles was developed to guide future development of power system analysis tools and systems with specific guidance given for the primary tools and data management infrastructure.

9.2 Recommendations

There are two short-term recommendations and four longer-term recommendations related to data management and tools.

9.2.1 Short term recommendations

Recommendation 1. AEMO should develop a process to assess dynamic models created by Original Equipment Manufacturers (OEMs) with the objective of detecting and addressing issues that are inconsistent with requirements detailed in AEMO’s Power System Model Guidelines. The benefits of this process are expected to include:

a. Reducing the risk of delays if problems are only uncovered during the connection assessment process.

b. Providing developers with some level of confidence in the OEM model

c. Reducing risks of project delays for developers and OEM

d. Reducing duplication of effort across projects if each project must separately identify and rectify the same issues.

Recommendation 2. AEMO should investigate how frequency domain (FD) tools can be deployed as soon as possible to improve controller tuning and mitigate the risk of controller interactions. This investigation includes a proof-of-concept study examining the feasibility of using impedance scanning tools. The benefits and outcomes of this investigation and proof of concept study include:

a. Significantly reducing the risk of IBR-based stability issues related to sub-synchronous oscillations.

b. Significantly reducing the number of wide-area and other EMT studies currently focussed on detecting these oscillations.

c. Potentially enabling the impedance scan method to be deployed within six months.

d. Providing a means of sharing system data in a form that does not include identifiable characteristics of specific equipment or require confidential models.

e. Providing the capability to collectively re-set IBR control parameters in the event this is required following a significant change in the power system (e.g., a new transmission investment or a power station retirement)

9.2.2 Longer term recommendations

Recommendation 3. AEMO should consider and adopt a set of strategic principles that it will apply in the future deployment of power system analysis tools. This will maximise flexibility and enable AEMO to quickly deploy the best available tools[6]. The strategic principles could include in approximate priority order:

a. AEMO's data repositories should represent the single source of truth for all AEMO applications.

b. Operational considerations have a high priority and Operations data, and model requirements must be met.

c. Interoperability is a critical requirement. Any new tools should either already have interoperability with AEMO's existing tools or the vendor should have a demonstrable strategy to deliver interoperability in the near future.

d. Encryption of models that contain OEM intellectual property is highly desirable so models can be provided to proponents and participants.

[6] Power system analysis tools have differences that can affect accuracy, including integration methods, equipment models and event handling. Improved accuracy is expected to be a driver for investment in new/different tools as analytical challenges increase.

e. Data in repositories should be of the highest resolution likely to be required for any AEMO analysis, including likely future requirements.

f. Data management systems should conform to portability protocols and have the ability to adapt as these protocols are improved over time. The objective of the portability is to permit participants to analyse the performance of their equipment when connected to the power system.

g. AEMO's data repositories should not be restricted in modelling extent because of ownership boundaries (for example TNSP – DNSP – REZ NSP[7]) and should have the capability of importing data and configuring study cases across boundaries.

Recommendation 4. AEMO should review the infrastructure supporting the modelling tools against the strategic criteria and establish a time-based data repository that meets the functionality requirements of Operations and System Design. This can be achieved through procurement of an off-the-shelf solution or further development of AMP. The benefits of a common data repository include:

a. A single source of the truth, reducing risk of errors and maintenance effort.

b. Faster configuration of study cases

c. Change management to control data quality and reduce risk of errors.

d. Better interoperability between different tools

e. Ability to generate study cases for the existing and future power systems.

Recommendation 5. AEMO should investigate through engagement with tool vendors, including existing vendors, how enhancements that align with the strategic principles can be delivered for:

a. Co-simulation between EMT and RMS tools – potentially improving study efficiency and reducing further the requirement for wide-area studies covering the whole NEM.

b. Three-phase representation in the steady state and RMS domains to permit simulation of unbalanced faults and reflecting IBR capability to respond on individual phases.

c. Three-phase load flow capability to enable better simulation of unbalanced network or loading conditions and calculate negative phase sequence voltages.

d. Continuation load flow capabilities to enable medium to long duration studies (days to years) taking as inputs the outcomes of, for example, dispatch simulation tools, solar irradiation, or wind records.

Recommendation 6. AEMO should select tools and systems that best allow it to meet its mission critical objectives, particularly power system security, and then rely on portability protocols to provide efficient information exchange with an increasing number of Network Service Providers and participants, many of whom may use different tools. The benefits from this include:

d. Fit for purpose tools within AEMO providing best support for both Operations and System Design.

[7] TNSP – Transmission Network Service Provider; DNSP – Distribution Network Service Provide; REZ- Renewable Energy Zone

e. Data exchange capability with participant tools that may have different objectives (e.g., distribution systems).

a. Ease of developing study cases across asset owner boundaries, such as TNSP-DNSP or TNSP-REZ NSP.

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Glossary

Abbreviation	Meaning
AMP	AEMO Modelling Platform
BOP	Balance of Plant
CGMES	Common Grid Model Exchange Standard.
CIM	Common Information Model
DD	Due Diligence
DMAT	Dynamic Model Acceptance Test
EPC	Engineering Procurement and Commissioning
ENTSO-E	European Network of Transmission System Operators for Electricity
EMS	Energy Management System
EMT	Electromagnetic transient time domain
FD	Frequency Domain
IBR	Inverter Based Resource (Generator or load or storage system)
NER	National Electricity Rules
NEM	Australian National Electricity Market
NPS	Negative phase sequence
OEM	Original Equipment Manufacturer
PSO	Power System Operator
RMS	Root Mean Square time domain
TNSP	Transmission Network Service Provider
TSO	Transmission System Operator