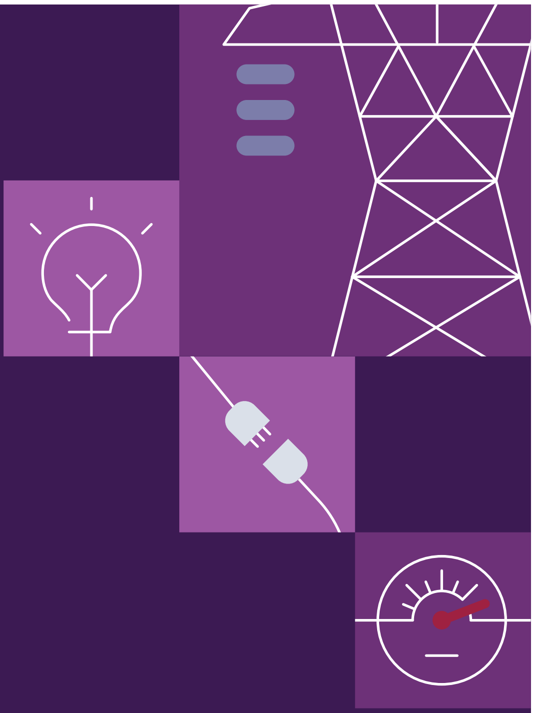

Amendments to the Power System Model Guidelines

Consultation paper – Standard consultation for the National Electricity Market

Published: 2 December 2022

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New South Wales | Queensland | South Australia | Victoria | Australian Capital Territory | Tasmania | Western Australia

Australian Energy Market Operator Ltd ABN 94 072 010 327

Explanatory statement and consultation notice

This consultation paper commences the first stage of the standard rules consultation procedure conducted by AEMO to update the Power System Model Guidelines, the Power System Design Data Sheet, and the Power System Setting Data Sheet (**proposal**) under National Electricity Rules (**NER**) S5.5.7. The standard rules consultation procedure is described in NER 8.9.2.

- Under NER S5.5.7, AEMO publishes the Power System Model Guidelines, the Power System Design Data Sheet, and the Power System Setting Data Sheet. These documents specify, in relation to power systems, control systems and plant technologies, the data and other requirements of participants under NER S5.5.7 and the rules listed in that clause.

The Power System Modelling Reference Group (PSMRG) has identified two critical issues that have recently emerged due to the changing nature of the National Electricity Market (NEM) that are not covered by these documents and that require amendment:

- The first issue is that the wording is specific to "generation" and there is no specification for modelling of loads. Traditionally, large industrial loads have been modelled by AEMO with simple mathematical models. However, AEMO and network service providers (NSPs) have now started receiving connection applications from very large, power-electronic interfaced loads, the two primary examples being data centres and hydrogen electrolysers. The large size of these loads and declining system strength means there could be material impact to power system security, and as such the existing approach will no longer be adequate to enable AEMO to accurately model these impacts. AEMO proposes to amend the documents so that they will also apply to loads. (Note this does not include modelling of distributed energy resources (DER), which is covered through a separate workstream at AEMO.)
- The second issue is that Electromagnetic Transient (EMT) simulations are becoming widely adopted due to the use of "real code" models – models of control systems that use the exact same code in simulation as in real operation. There is currently no standard in the documents for the provision of these models and there is therefore a risk of provided models becoming obsolete or otherwise incompatible with software used by AEMO. AEMO proposes to introduce a standard for compatibility and a requirement for accompanying documentation.

Several other minor updates have also been proposed in this document, to be discussed through consultation.

The detailed sections of this consultation paper include more information on the proposals and AEMO's reasons for making them.

Consultation notice

AEMO is now consulting on this proposal and invites written submissions from interested persons on the issues identified in this paper to **PSMGReview@aemo.com.au** by 5:00pm (Melbourne time) on **10 February 2023**.

Submissions may make alternative or additional proposals you consider may better meet the objectives of this consultation and the national electricity objective in section 7 of the National Electricity Law. Please include supporting reasons.

Please note the following important information about submissions:

- All submissions will be published on AEMO's website, other than confidential content.

- Please identify any parts of your submission that you wish to remain confidential, and explain why. AEMO may still publish that information if it does not consider it to be confidential, but will consult with you before doing so. Material identified as confidential may be given less weight in the decision-making process than material that is published.
- Submissions received after the closing date and time will not be valid, and AEMO is not obliged to consider them. Any late submissions should explain the reason for lateness and the detriment to you if AEMO does not consider your submission.

Interested persons can request a meeting with AEMO to discuss any particularly complex, sensitive or confidential matters relating to the proposal. Please refer to NER 8.9.1(k). Meeting requests must be received by the end of the submission period and include reasons for the request. We will try to accommodate reasonable meeting requests but, where appropriate, we may hold joint meetings with other stakeholders or convene a meeting with a broader industry group. Subject to confidentiality restrictions, AEMO will publish a summary of matters discussed at stakeholder meetings.

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1. Stakeholder consultation process

As required by the National Electricity Rules (NER), AEMO is consulting on proposed changes to the Power System Model Guidelines, the Power System Design Data Sheet and the Power System Setting Data Sheet in accordance with NER S5.5.7 and the Rules Consultation Procedure in NER 8.9.2.

Note that this document uses terms defined in the NER, which are intended to have the same meanings. There is a glossary of terms used in this consultation paper at Appendix A.

AEMO's indicative process and timeline for this consultation are outlined below. Future dates may be adjusted and additional steps may be included if necessary, as the consultation progresses.

Table 1 Consultation process indicative timeframe

Deliverable	Indicative date
Consultation paper published	2 December 2022
Submissions due on consultation paper	10 February 2022
Draft Report published	14 April 2023
Submissions due on Draft Report	19 May 2023
Final Report published	16 June 2023

AEMO has and will continue to work with internal subject matter experts, transmission network service providers (TNSPs), distribution network service providers (DNSPs), and regulatory bodies including the Australian Energy Market Commission (AEMC), through the PSMRG to receive input on the amendments to the Power System Model Guidelines, the Power System Design Data Sheet and the Power System Setting Data Sheet including input relevant to the preparation of this consultation paper.

2. Background

2.1. NER requirements

Under NER S5.5.7(a), AEMO must develop, publish, and maintain the Power System Model Guidelines (**Guidelines**), and the Power System Design Data Sheet and Power System Setting Data Sheet (referred to collectively as the **Data Sheets**).

These documents specify, for power system, control system and plant technologies, AEMO's requirements for mathematical models of such technologies. These models must be provided by Generators, NSPs, Customers, market network service providers (MNSPs), prospective Network Support and Control Ancillary Services (NSCAS) tenderers, and prospective System Restart Ancillary Services (SRAS) providers to AEMO and NSPs in specified circumstances.

The circumstances under which these models must be provided are outlined in NER 3.11.5(b)(5), 3.11.9(g), 4.3.4(o), 5.2.3(j), 5.2.3(k), 5.2.3A(a), 5.2.3A(b), 5.2.4(c), 5.2.4(d), 5.2.5(d), 5.2.5(e), 5.3.9(b)(2), S5.2.4, S5.3.1, S5.3a.1 and S5.5.

The Guidelines and Data Sheets are required to be published and maintained under the rules consultation procedures in NER 8.9. As such any material modification requires two rounds of consultation with industry and interested parties.

2.2. The national electricity objective

Within the specific requirements of the NER applicable to this proposal, AEMO will seek to make a determination that is consistent with the national electricity objective (NEO) and, where considering options, to select the one best aligned with the NEO.

The NEO is expressed in section 7 of the National Electricity Law as:

> *to promote efficient investment in, and efficient operation and use of, electricity services for the long term interests of consumers of electricity with respect to:*
>
> *(a) price, quality, safety, reliability and security of supply of electricity; and*
>
> *(b) the reliability, safety and security of the national electricity system.*

2.3. Context for this consultation

2.3.1. Need for power system models

The Guidelines and Data Sheets specify the requirements for mathematical models of plant and equipment connected or proposed to be connected to the power system. Power system models enable AEMO and NSPs to undertake power system analysis in order to fulfil a number of obligations under the NER, most critically AEMO's responsibilities to maintain power system security and AEMO's and NSPs' responsibilities to facilitate new connections to the national grid.

Power system models are used for many purposes, from the assessment of the suitability of proposed plant and capability to achieve its performance standards, to the ongoing management of power system security in near-term and operational timeframes.

There are many modes of failure for a large power system such as the NEM, and as such each individual piece of plant cannot be considered independently. To study the interdependencies of every power system component requires mathematical models for each piece of plant suitable for using in computer software simulations. Simulations are a very powerful tool used by AEMO and NSPs to assess the security of the power system by performing what-if scenarios on a digital reproduction of the NEM and defining operating limits for the physical system.

The format, accuracy and level of detail required of these models depends on the failure mode or phenomena being studied. For example, during system black conditions the network is highly susceptible to non-linear phenomena and assessing system restart paths needs highly specific and detailed models and information[1]. By foregoing detailed models or using only basic approximations, modes of failure are masked from the simulation – modes of failure which, if they occurred in real life, could risk the security and reliability of the power system, cause damage to physical plant, and risk safety to human life in the vicinity of any electrical devices.

On the other hand, AEMO and NSPs using accurate and up-to-date models can benefit participants and consumers. This is because the operating envelope of the power system is highly complex. Power system simulations allow AEMO and NSPs to define power system limits mathematically and then use advanced methods to optimise usage of the power system. For example, by having accurate information about generator reactive power capability, AEMO can formulate voltage stability limits that allow market benefit to participants and consumers that would not have been realised had the information not been provided.

2.3.2. The changing nature of power system phenomena

As the power system develops and evolves, so do the modes of failure. In the last several years, AEMO and NSPs have observed new phenomena (such as sub-synchronous control interactions) that have not been seen previously in the NEM and have little or no basis in historical power system literature.

The energy transition towards renewable sources is the prime reason for this, but it is not due to the fuel source, or even the intermittency, of the generation. Rather it is the technology that interfaces this plant with the power system that is driving the new phenomena.

Traditional large-scale sources of energy were historically based on a single technology, that of a synchronous machine. All traditional generation including coal, gas, and even hydro utilised synchronous generators to interface to the grid. The way this plant interacted with the power system was widely understood and was typically defined by the laws of physics through electro-mechanical coupling. As such, power systems were designed to facilitate this technology and modes of failure were widely understood.

However, in the last 10 years there has been a surge in the integration of large-scale renewable plant to the grid. Such plant includes wind turbines, solar photovoltaics and battery storage systems and cannot be interfaced to the grid through the use of a synchronous machine and are therefore known as asynchronous generators. There are many technologies available to interface these renewable resources to the grid and new technologies are constantly being developed. However, for the most part, asynchronous generators are connected to the grid through a power electronics interface. This interface uses power electronic switches to transfer the energy from the renewable resource (typically direct current (DC)) to the alternating current (AC) power system.

The way that asynchronous generators interact with the grid is significantly different from synchronous machines. The first major difference is that power electronic interfaces have no electro-mechanical coupling between the energy source and the grid, and as such concepts such as inertia and fault

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[1] Such information includes magnetic saturation characteristics of iron-core transformers, geo-spatial arrangement of transmission line towers, replication of generator prime-mover systems, protection systems and more.

current (which were inherently provided by synchronous machines) are minimal or absent from asynchronous generators. This is detrimental to the power system, as inertia and fault current improve the stability of the system and act as stabilising services to help recovery after a disturbance.

The second is that instead of being coupled to the grid through the laws of physics as synchronous machines are, the coupling is performed by control systems implemented as computer software. As a result, many new phenomena observed in the power system are the direct result of how the control systems have been programmed.

2.3.3. The changing nature of power system load

While over the last several years changes on the generation side have been dramatic, changes to technology of devices that consume energy, or power system loads – have been slower. Although there have been observed changes to consumer technology such as variable speed drives replacing induction machines as a technology in air-conditioning, refrigeration and many other consumer goods, and the rise of rooftop photovoltaics (PV), there have only been minor changes to methods for modelling and analysing the impact of loads in power systems. This is due to the difficulty of modelling aggregate customer load response on the transmission system.

This however has started to shift in the last year as interest in connections of very large, power electronic interfaced power system loads has risen. Two recent examples seen by AEMO and NSPs are hydrogen electrolysers (hydrolysers), and very large scale data-centres. Both technologies are typically interfaced by power electronic converters, and thus many of the same modes of instability introduced by asynchronous generators can also apply to these loads.

Whilst some large loads are obliged to provide modelling data to AEMO and NSPs under NER 5.2.4(c), 5.2.4(d), and S5.3.1(a1), no detail is provided regarding the requirements for models of large loads in the Guidelines, with the Guidelines frequently using the wording “Generating System” which does not apply to loads. Therefore, it is considered necessary to update the Guidelines to include specific modelling requirements for large power system loads.

Note the Guidelines and thus this consultation are specific to model requirements, **NOT** performance requirements. Performance requirements and Connection Agreements for customers will not be discussed or considered in this consultation.

2.3.4. The importance of maintaining models into the future

As has been demonstrated in the previous sections, detailed and accurate power system models are critical for ensuring power system security and to produce the optimal benefit to participants and consumers. However, as plant is typically in operation for potentially decades after commissioning, so too the power system models must also remain up-to-date and usable by AEMO and NSPs over that lifespan.

This is a significant challenge as computer software and hardware change, simulation software packages are updated and changed, and new tools are utilised or replace older software, while models received by AEMO and NSPs are specific to a single simulation tool and cannot be easily migrated to other tools, including newer versions of the same product.

For example, the software package PSCAD™ is used by AEMO for simulation of Electromagnetic Transient (EMT) models. AEMO recently undertook a program of work to migrate all existing models developed for PSCAD version V4 to the current version, V5. This was required because several software dependencies used by V4 became obsolete and were no longer obtainable. Converting all models to V5 was a labour-intensive process due to the models being highly coupled to PSCAD V4, and significant testing had to be undertaken to ensure the performance of the models was identical between V4 and V5. Migrating these models to a different simulation tool or software platform altogether (for example, and purely hypothetically, if PSCAD was made obsolete) would be even more challenging and in some cases, due to the high level of dependency on PSCAD, could prove impractical.

As AEMO cannot predict changes in software over the period in which plant is operational, and also taking into consideration that original equipment manufacturers may not exist for the life of the asset, some method for ensuring models remain usable and compatible for the life of the plant is required. AEMO and the NSPs propose to update the Guidelines to define a standard for how models are structured within the simulation tool that will promote ongoing compatibility.

Note this mostly applies to EMT models, as Root Mean Square (RMS) models are already required to be provided as source code which can be easily recompiled for different software tools. There are currently ongoing industry initiatives to consolidate the needs and requirements for AEMO and NSPs on this matter.

2.3.5. Other matters

AEMO has consulted internally and with NSPs and has identified several other minor changes to the Guidelines that are considered to be of benefit. These changes are detailed in Section 3.3.

3. Proposed updates to the Guidelines

3.1. Modelling requirements for large power system loads

Due to the complexity of modelling power system load, power system simulations have traditionally used very simple mathematical equations to account for the dynamic response of loads. This is because while each individual load component down to the household level is a complex, dynamic system, and the exact composition of types of loads is difficult to estimate, the overall aggregated response of load at the transmission level can be approximated using simple assumptions.

3.1.1. Modelling of aggregate loads

The traditional power system load model is known as the ZIP model, comprising of constant impedance (Z) constant current (I) and constant power (P) components. The equation for the ZIP model is:

$$\frac{P}{P_0} = p_1 V^2 + p_2 V + p_3$$

$$\frac{Q}{Q_0} = q_1 V^2 + q_2 V + q_3$$

where V is the RMS voltage deviation, p_1, p_2, p_3 are the active power coefficients, and q_1, q_2, q_3 are the reactive power coefficients. This model gives a good approximation for aggregate load response to deviations in voltage and the coefficients can easily be determined from historical SCADA or fault recorder measurements.

An extension from the ZIP model is the IEEE load model, which allows for different exponents of voltage and also includes a dependency on frequency (known commonly as *load relief).* The IEEE model is:

$$\frac{P}{P_0} = (p_1 V^{n_{p1}} + p_2 V^{n_{p2}} + p_3 V^{n_{p3}}) \cdot \left(1 + k_p \frac{f}{f_0}\right)$$

$$\frac{Q}{Q_0} = (q_1 V^{n_{q1}} + p_2 V^{n_{q2}} + p_3 V^{n_{q3}}) \cdot \left(1 + k_q \frac{f}{f_0}\right)$$

where n_{p1}, n_{p2}, n_{p3} are voltage active power exponents, n_{q1}, n_{q2}, n_{q3} are reactive power exponents, k_p is the active power frequency coefficient (load relief), and k_q is the reactive power frequency coefficient. The IEEE load model can represent a wider range of power system loads including larger industrial loads. It also includes a frequency dependency typical of induction machines. Although determining the voltage coefficients is similar to the ZIP model, determining the frequency coefficient is more difficult and requires detailed analysis of high-speed fault recorder data.

AEMO chooses to use the IEEE model for most power system studies.

The following parameters have been derived over many years of analysis to represent general power system loads (all unlisted parameters are 0.0). Specific parameters have also been derived for significant individual loads such as large mines and industrial facilities.

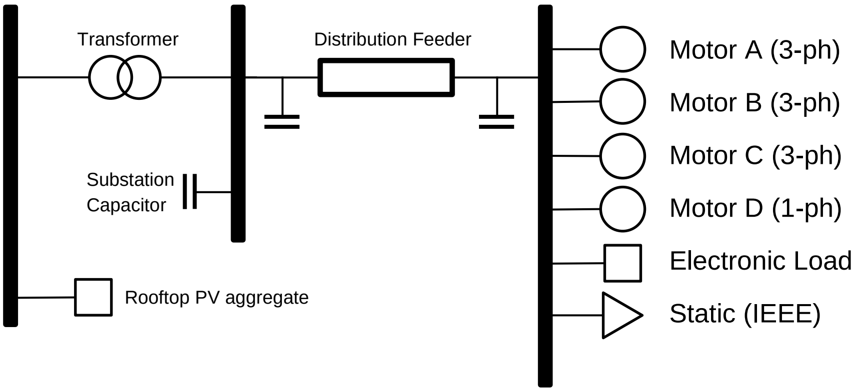
Table 2 IEEE load model parameters used in the NEM

Coefficient	Mainland	Tasmania
p_1	1.0	1.0
n_{p1}	1.0	1.42
k_p	0.5	0.25
q_1	1.0	1.0
n_{q1}	3.0	2.5
k_q	0.0	-1.7

Although the IEEE model is suitable for a wide variety of power system studies, there are instances where it is necessary to model the dynamics of load components. This is becoming more prevalent with the rise in distributed energy resources (DER) (in particular rooftop PV) which have complex dynamic responses to disturbances and in some cases could account for a large contingency.

For the last few years, AEMO has been developing the Composite and DER Load model, suitable for representing the aggregate response of DER, which has been benchmarked and tuned against real data. Figure 1 shows a diagram of the model.

Figure 1 Composite and DER Load model



The Composite and DER Load model allows for dynamics of PV, three independent 3-phase motor components, a single-phase motor component, an electronic load component, and a static component. It also allows for modelling of the distribution network and transformer. Each component has independent parameters and can be enabled or bypassed, allowing for a wide range of flexibility.

AEMO has performed extensive analysis of historical fault recorder and phasor measurement unit (PMU) data to determine the parameters of each component. Many of the parameters will also vary with time of day, time of year, and area of the network, and as such parameter sets have been developed to factor in these sensitivities.

3.1.2. Modelling of traditional large power system loads

In addition to the aggregate loads, there are also large individual power system devices that consume energy. These have traditionally included large industrial loads such as arc furnaces and smelters, railway traction systems, and large induction and synchronous motors as part of industrial processes, including generator auxiliary fans and pumps. From experience, these loads are not known to be the root cause of control instability. Power quality problems and issues relating to voltage recovery following faults, on the other hand, are usually the first issues to be manifested.

Harmonics and voltage unbalance are highly localised and therefore do not have a large impact in wider power system studies. As such, using typical IEEE static load models for large industrial plant has been seen as appropriate. For more detailed studies that can be impacted by phenomena such as harmonics, detailed models are typically requested and utilised. This is most common for system restart studies where detailed models of generator auxiliary fans and pumps are required.

However, as system strength and inertia in the power system decline, these assumptions about traditional large power system loads may no longer be appropriate. As such, more detailed models for these loads may be required in power system simulations.

Consultation questions

1. What is the threshold (if any) for deciding when to model a traditional large power system load in detail for power system simulations, be it megawatt-based, location-based or otherwise?
2. Is the IEEE or Composite and DER Load models suitable for these types of loads or is more detail required?

3.1.3. Modelling of inverter-based loads (IBL)

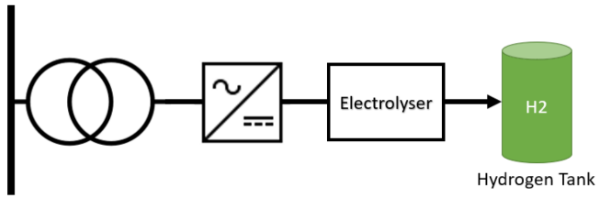
Over the last year, AEMO and NSPs have been receiving enquires and connection applications for large power system loads that are typically interfaced through power electronic converters (referred to as inverter-based loads (IBL) in the system strength rule changes[2] to take effect on 15 March 2023). The nature of the converter control systems and fault-ride-through characteristics mean that loads of these types above a sufficient size can have a material impact on power system stability.

These large IBLs have so far fallen in the following two categories.

Hydrogen electrolysers

A hydrogen electrolyser unit converts electrical energy into hydrogen through electrolysis and the stored hydrogen can be converted back into electricity using fuel cell technology.

Figure 2 Generalised hydrogen electrolyser load



There are four types of electrolysers, distinguished by the electrolyte, operating temperature, and charge carrier; alkaline electrolysers (ALK), polymer electrolyte membrane (PEM), solid oxide electrolysis cells (SOEC) and anion exchange membranes (AEM). Electrolysers are flexible in short timeframes and can handle load fluctuations. They are required to operate above a minimum load level however the electrolyser size, defined by the number of stacks at a single site, can be varied by switching off individual stacks to keep a lower minimum rating.

From this perspective, PEM electrolysis offers the best flexibility for load changes, as the minimum load can be between 0-10% compared to 20-40% for ALK. The capability of cold start time in less than five

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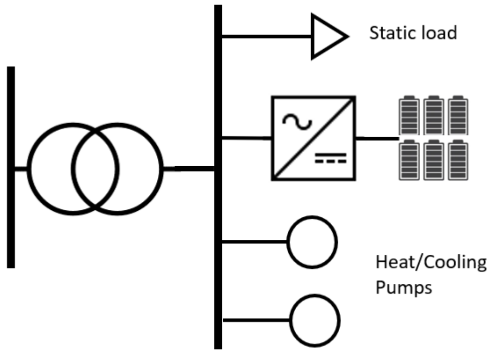
[2] https://www.aemc.gov.au/rule-changes/efficient-management-system-strength-power-system

minutes and shutdown time within a few seconds make PEM electrolysis an ideal candidate to provide network services such as demand side response.

Large data centres

The rated power of data centres can vary based on the data centre size, reaching potentially up to several hundred megawatts. The major portion of energy consumption is used to operate IT equipment including low voltage distribution, direct-current server racks, and air-conditioning and cooling systems.

Figure 3 Generalised data centre load



For high reliability data centres, an uninterruptible power supply (UPS) is at the core to ensure safe and reliable operation and prevent any damage to IT equipment. Alternatively, high processing capacity data centres (such as crypto-currency processing facilities) can vary the load substantially and quickly based on individual operating objectives. These facilities may have no or limited UPS systems but are not likely to interface to the grid through an inverter.

IT equipment comprises computing, storage devices, network switches, monitors and workstations which can be considered as static or electronic load. A cooling system typically comprises of fans, pumps and cooling towers driven by either induction motors or variable speed drives.

Data centre loads typically have additional protection systems and can trip if the voltage and/or frequency drifts outside of the normal operating range.

Consultation questions

3. Are there any other types of large loads that have not been considered here?
4. Is the Composite and DER Load model sufficient to model data centres in RMS and EMT domains?
5. What additional protection and control systems are expected to be required in the models?

3.1.4. Current interest in IBL

The following table lists indicative sizes in some NEM regions for these types of loads based on applications, inquiries, and government plans.

Table 3 Indicative large load sizes (MW)

Region	Indicative sizes (MW)	Type
Queensland	200-1,000	Hydrogen Electrolysis Plant[A]
Victoria	40-150	Data Centre[B]
South Australia	40-600	Data Centre and Hydrogen Electrolysis Plant[C]
Tasmania	100-1,000	Hydrogen Electrolysis Plant[D]

A. Based on inquiries and applications.
B. Based on inquiries.
C. Based on inquires and applications.
D. From the Tasmanian Renewable Hydrogen Action Plan, at https://recfit.tas.gov.au/__data/assets/pdf_file/0013/313042/Tasmanian_Renewable_Hydrogen_Action_Plan_web_27_March_2020.pdf.

3.1.5. References to loads in the NER

Section 2.3 of the Guidelines outlines the NER clauses under which large loads (typically registered as Customers) are required to provide models and other information. These are shown in Table 4.

Table 4 NER clauses referencing provision of models from *Customers*

Clause	Requirement	Timing
5.2.4(c)	(b) Where there is, in AEMO's reasonable opinion, a risk that a *Customer's plant* will: (1) adversely affect *network capability, power system security*, quality or reliability of *supply, inter-regional power transfer capability*; (2) adversely affect the use of a *network* by a *Network User*; or (3) have an *adverse system strength impact*.	Within: 20 business days of AEMO's notice of the impact described in sub-paragraph (1) or (2); or 15 business days of AEMO's notice of the impact described in sub-paragraph (3).
5.2.4(d)	If in *AEMO*'s reasonable opinion, information of the type described in clause S5.3.1(a1) is required to enable a *Network Service Provider* to conduct the assessment required by clause 5.3.4B.	Within 15 business days of AEMO's request to provide the relevant information.
S5.3.1(a1)	Before a *Network User connects* any new or additional equipment to a *network*.	With the application to connect submitted under clause 5.3.4 of the NER.

From the perspective of the NER, all Customers already must provide modelling information, and as such no rules change is required to request models for large IBL.

3.1.6. Loads in the *System Strength Impact Assessment Guidelines*

In the system strength rule changes to take effect on 15 March 2023, NER 4.6.6(a) will be updated to include reference to IBL:

- 4.6.6(a)(5) – prescribe, for the purposes of the definition of *inverter based load* in Chapter 10, the criteria for classification of a *load* as an *inverter based load.*

Chapter 10 will be amended to define *inverter based load*:

- A *load* that is supplied by power electronics, including inverters, and potentially susceptible to inverter control instability, and that is classified as an *inverter based load* applying criteria specified in the *system strength impact assessment guidelines*.

The System Strength Impact Assessment Guidelines will define the determinant for classifying *load* as an *inverter based load*. All IBR that fall under this category are required to provide vendor-specific EMT and RMS models.

Consultation questions

6. What level of detail is required for IBL in RMS and EMT domains?

3.1.7. References to loads in the current Guidelines

Historically, no load modelling information was provided to AEMO. Instead, using historical data, AEMO and NSPs have developed traditional static ZIP or IEEE models to reflect large industrial loads. However, there is very little mention of load modelling in the Guidelines.

Section 3.1 states that Network Users must provide:

- Completed Power System Design Data Sheets and Power System Setting Data Sheets;
- Site-specific RMS models of all plant that comply with these Guidelines, including:
  - Model block diagrams; and
  - Model source code;
- Site-specific EMT models of all plant that comply with these Guidelines;
- a RUG for both RMS and EMT models in the template specified in the Releasable User Guide Template; and
- R2 test report, and pre-commissioning model confirmation test report.

Section 4.1 provides load flow requirements for loads being the ZIP model discussed previously:

- Loads – Active and reactive power levels, in most appropriate format (power / impedance / current)

Section 4.3 details requirements for RMS and EMT stability models however makes no mention of loads. The wording is specifically stated as *generating system*, which does not apply to loads.

Section 4.4 details requirements for black start models, however does not contain a subsection for loads.

Section 4.7 details a model aggregation methodology for many cascaded low-voltage plant, however specifically uses the terminology *generating system.* This methodology would also apply to a large number of cascaded VSC-connected loads.

Section 5.1 details the Releasable User Guide. Wording in this section is agnostic to Generator, or Customer however footnote 40 references AEMO's "Guideline and Template for Preparation of a Releasable User Guide"[3]. This document is currently specific to Generators.

Section 7 details Confidentiality of Information and Models Provided. Table 6 details the types of model that AEMO is able to provide to a *Registered Participant* and makes no mention of Customer or loads.

Appendix C contains tables for each type of power system plant which components are required to be included based on the type of plant, studies being completed and tool being used. There is no subsection for loads.

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[3] The Guideline and Template for Preparation of a Releasable User Guide is a discretionary guideline prepared by AEMO to assist industry and improve consistency of Releasable User Guides provided for Generating Systems. It can be reviewed and updated at AEMO's discretion.

3.1.8. References to loads in the current data sheets

There are currently no references to loads in the data sheets.

3.1.9. Proposal

The following modifications to the Guidelines are proposed to define requirements for models received from loads.

- Update wording in Section 4.3 to remove references to g*enerating system;*
- Include two subsections, one for requirements specific to Generators, and one for requirements specific to loads;
  - In the loads subsection, define the criteria for when a load is required to be modelled in more detail than the IEEE or Composite and DER Load Model;
- Update Section 4.3.6 to include model outputs for IBL*;*
- Update Section 4.4 to include black start model requirements for loads;
- Update Section 4.7 to remove references to *Generating System* and include aggregation of identical IBL;
- Update section 6 to include accuracy and validation requirements for IBL;
- Update Section 7 including Table 6 to specifically mention IBL;
- In Appendix C add a new subsection between C4 and C5 for IBL*;* add a table with required components based on the plant, studies being completed and the tool being used.

The following modifications to the Data Sheets are proposed:

- Update the wording for Sections 6, 7, and 9 to be applicable to both generation and load
- Add two new entries under Section 9:
  - Hydrogen electrolyser
  - Composite and DER Load Model
- Add two new proposed plant examples:
  - Load (Converter Interface).
  - Load (Composite Load) (for non-IBL based plant).

The "AEMO Guideline and Template for Preparation of a Releasable User Guide" will also be updated to include IBL as part of this consultation.

Consultation questions

7. What are the black start simulation model requirements for large power system loads (if any)?
8. What level of R2 validation is appropriate for different types of load models?
9. What should the requirements for model provision in Section 7.4 be for IBL? Should it be identical to *Generator data?*

10. What components should be included in a new table in Appendix C for IBL? Are there any specific control systems, protection systems or other components that are specific for loads that will have material impact on power system simulations?
11. Are there any other issues relating to model requirements for large loads that AEMO has not considered?

3.2. EMT model compatibility

EMT simulation has become a common and essential tool in power system analysis of the NEM. It offers a highly accurate representation of the system being modelled, due to the use of differential equations and enables simulations of the network and associated plant as a full 3-phase sinusoidal system including frequency-dependant and non-linear elements.

Historically, EMT tools have been used for very small, localised and specific studies, such as analysing the effect of lightning surges on transmission lines, analysing the effect of inrush current and saturation on transformers, coordination of protection systems, filter tuning and harmonic analysis, and studying sub-synchronous resonance (SSR). The consequence of modelling the network in such a level of detail is that the computational burden is large, and as such simulations can take a long time to complete even with high performance computer hardware.

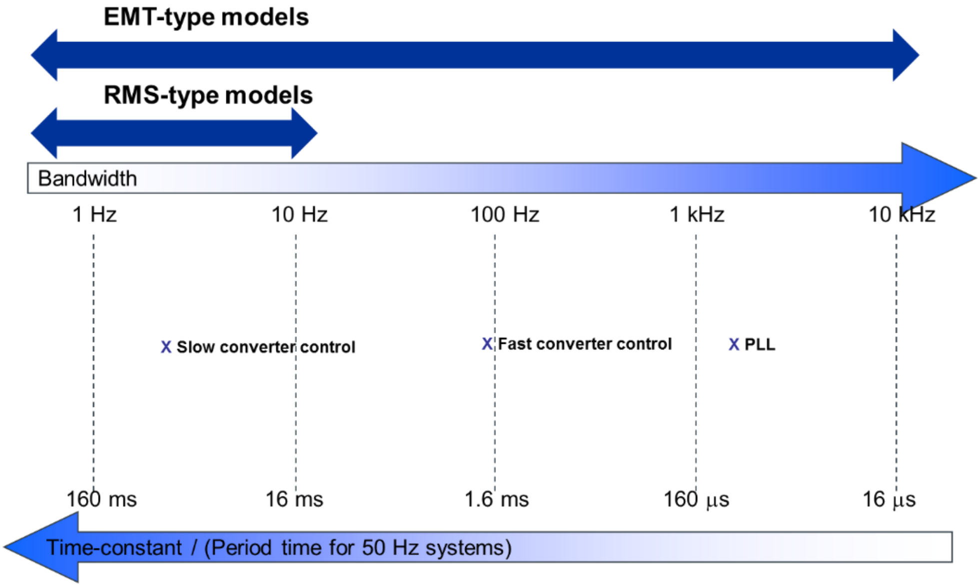
As the availability and affordability of computer hardware has increased, so too have the size and scope of EMT simulations. Larger areas of the network can be efficiently simulated and therefore the scope of EMT studies has widened to include studies more traditionally performed by RMS transient stability programs.

The use of traditional RMS tools has been challenged in recent years as IBR displace synchronous resources. While the dynamics of synchronous generators are widely understood and are governed by the laws of physics, the dynamics of IBR are determined by the control systems and the software specific to that individual plant.

RMS tools cannot adequately capture the full dynamic response of IBR due to the inherent simplifications and limited bandwidth of the RMS domain. Control systems that have been shown to be critical to stability in weak systems such as fast converter control and the phase-locked-loop (PLL) are either ignored or simplified in the RMS domain.

EMT simulations have no inherent simplifications and operate at a much larger bandwidth and therefore can adequately capture the full dynamic response of IBR.

Figure 4 Typical bandwidth ranges for RMS and EMT models



A benefit of utilising an EMT tool with no assumptions or simplifications is that models are often provided as “real-code”. This means that instead of recreating the plant control systems in an EMT environment, the actual code used to implement the control systems is packaged and used in the simulation. This is critical due to the high coupling between the power system dynamics and the software in IBR, meaning factors such as the way the code has been implemented, software bugs, and other features can all factor directly into performance of the plant.

AEMO has been requesting detailed, site-specific EMT models for many years now and provision of these models are now a requirement for connection of generators. These models have now become critical in AEMO and NSPs operations for maintaining power system security. As the life of the plant that is being modelled will typically last decades, so too must the EMT model be up-to-date and usable.

The method for implementing an EMT model of an IBR will vary depending on the simulation package being used. AEMO currently uses the commercially available tool PSCAD version 5 for performing EMT simulations. Several common methods for EMT model development are discussed below. These are specific to AEMO’s preferred EMT package PSCAD, however could also apply to other EMT tools.

Fully open model with no custom components

PSCAD has an extensive inbuilt library of control, maths and simulation blocks. This means that virtually any control system can be built using fundamental components. By only using these standard blocks and keeping the model open (no blackboxing), compatibility between releases of PSCAD is ensured regardless of compilers or operating systems. In addition, as each fundamental block is simple in function, translating to a different software package is straightforward, and many alternative EMT platforms already support import from PSCAD.

One disadvantage of this method is that the model developer will need to translate their entire model into PSCAD components which, depending on the complexity of the model, can be a time-consuming process. In addition, while the PSCAD library is extensive, there may be certain functions or logic that cannot be replicated without custom code. Another disadvantage is that by the model being open, intellectual property is more exposed.

This method is preferred by AEMO for synchronous machine models and control systems, because they commonly incorporate physical processes with control as part of the model such as control valves and excitation circuits. In addition, synchronous generator control theory is widely known, and as such implementation of protection and control is typically less sensitive than it is for IBR[4].

Blackboxed PSCAD model

PSCAD has an inbuilt blackbox functionality. With a few clicks, a model developer can replace the open model made up of inbuilt PSCAD library components with a compiled module. This module typically consists of a static library file (.obj or .lib) which is linked to the PSCAD simulation executable. This function is utilised by model developers to help protect intellectual property by obfuscating the control systems into non-human-readable machine code.

The first challenge with this method is that the static library file is generated using a specific toolchain (Fortran Compiler, Visual Studio), and therefore is only compatible if the same versions are used to generate the PSCAD simulation executable. The components of this toolchain are continuously updated, and older versions become obsolete.

The second challenge with this method is that the static library file contains references to intrinsic functions and variables as part of the PSCAD/EMTDC simulation. Therefore, it is impossible to transfer this type of model to a different software platform, and any major changes to the underlying PSCAD/EMTDC code in a future version could be incompatible with the model.

PSCAD model with external static library

As mentioned previously, it is often convenient and desirable for a model developer to use the exact same code for the EMT simulation as in the physical plant. To facilitate this, the code is compiled into a static library which is completely independent of PSCAD/EMTDC. An interface module is then developed to link the static library file and the PSCAD simulation, typically facilitated using the "iso_c_binding" Intel Visual Fortran module.

This method has similar challenges as those stated for the previous method (Blackboxed PSCAD model), because the static library files will be highly dependent on the specific toolchain versions used to create it. In addition, while the interface module can be provided as uncompiled Fortran code without revealing confidential information, it is commonly provided as a static library file which will contain references to PSCAD/EMTDC functions and variables, and therefore compatibility with future versions is not assured.

PSCAD model with external dynamic link library (DLL)

This method is the same as the previous method (PSCAD model with external static library), but instead of compiling the real code into a static library, it is compiled into a dynamic link library (DLL). DLLs are loaded into memory at run-time, not during compilation of the simulation executable, which means they are completely independent of the toolchain used to generate it.

There are two methods to interface with a DLL: implicit linking and explicit linking. Implicit linking uses an interface module similar to the external static library method, and as such shares the same disadvantages. Explicit linking loads the DLL at runtime using the Windows API functions "LoadLibrary" and "GetProcAddress". As long as the name of the function being imported from the DLL and the data

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[4] Despite the less sensitive nature, synchronous generator control models are still afforded the same confidentiality protection by AEMO and NSPs.

types of the inputs and outputs are known, it does not matter what software is calling the code, be it PSCAD/EMTDC or otherwise.

3.2.1. Analysis of methods

From the above methods, the most desirable one for ongoing model compatibility is the external dynamic link library (DLL) method. Because the DLL is self-contained, it has no dependencies on compilers, linkers or external static libraries; it has no references to intrinsic PSCAD / EMTDC variables and functions and can be run from any software that implements the “LoadLibrary” and “GetProcAddress” functions. In addition, intellectual property is protected, as all control system code is obfuscated as machine code inside the DLL.

That said, while the DLL component is desirable, it still requires a method to interface with the simulation. Models using DLLs received by AEMO have used many different interface methods, both implicit and explicit linking. Not all these interfaces are fully compatible between different versions of PSCAD.

Consultation questions

12. Are there any other methods that could guarantee that models remain usable for the life of the plant despite changes to simulation tools, versions, or compiler toolchains that AEMO has not considered here?

3.2.2. Proposal

To ensure all these models remain compatible in future versions of PSCAD and potentially usable in different software packages, AEMO recommends a standard for DLL format and interface is developed for inclusion in the Guidelines. The original equipment manufacturer (OEM) would provide a DLL that is compatible with an open-source interface developed by AEMO and NSPs as part of this consultation.

This standard would cover the following topics:

- The current version of PSCAD (and other simulation tools) that AEMO uses.
- Requirement for restricting the use of the PSCAD inbuilt “blackboxing” feature and ensuring all electrical components[5] are from the standard library.
- DLL format and entry points.
- A standard PSCAD explicit linking routine developed by AEMO which the DLL is required to be compatible with.
- Required additional model documentation to ensure future compatibility.

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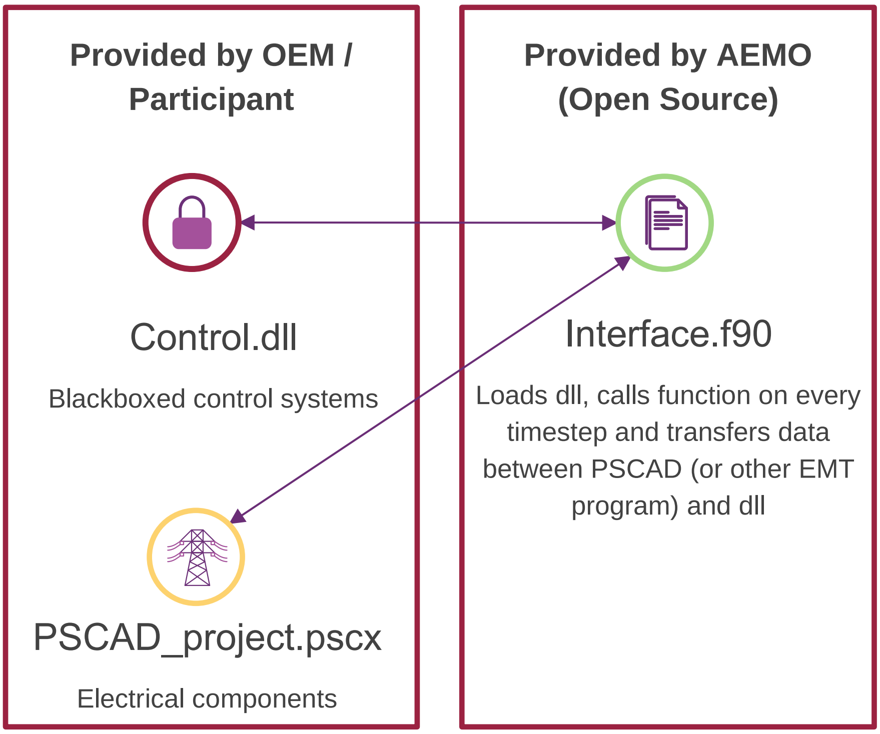
[5] Electrical components mean blocks that interface with the PSCAD / EMTDC electrical network solution. For example but not limited to, synchronous machines, induction machines, power electronic switches, DC energy sources such as battery cells and PV panels, passive network elements such as filters and transformers, metering devices.

Figure 5 Example DLL Interface



A mock-up PSCAD model and explicit linking routine is detailed in Appendix B. This is an example only to promote discussion.

Consultation questions

13. Would there be any issues with developing a DLL to conform with a standardised explicit linking routine?

3.3. Other matters

Several minor changes have been identified by the PSMRG which are detailed below.

3.3.1. Inclusion of remedial action schemes in the Guidelines

On 18 July 2022, AEMO initiated a consultation on the Remedial Action Scheme (RAS) Guidelines. The draft RAS Guidelines outline the criteria for provision of RAS modelling information and the level of detail to be provided.

There is no direct reference to RAS modelling in the Power System Model Guidelines and as such it is proposed to include a new section in Appendix C of the Guidelines to include level of detail required for RAS models.

3.3.2. Inclusion of integrated energy storage systems in the Guidelines

On 2 December 2021, the AEMC made the Final Rule on Integrating Energy Storage Systems (IESS) into the NEM. The majority of these rules will take effect on 3 June 2024.

The IESS Rule makes significant changes toward a technology agnostic two-way market model for the NEM. These changes help to prepare the NEM for the future steps being envisioned through the Energy Security Board's (ESB's) Post-2025 Market Design initiative.

Under the IESS Rule, an *Integrated Resource Provider* (IRP) may be required to provide AEMO and the relevant *Network Service Provider* with modelling information under NER 5.2.5A(d), 5.2.5A(e) and 5.3.9(b)(2A) (as amended).

Accordingly, the following amendments are proposed:

- Section 2 of the Guidelines to include the circumstances in which the IRP may be required to provide the relevant modelling information.
- The references in the Guidelines to *generating plant* to be changed to:
    - *generating system* or *integrated resource system*;
    - *generating unit* or *bidirectional unit*; or
    - any such other terms as may be appropriate under the IESS Rule.
- The Releasable User Guide Template to use the terminology which is consistent with the IESS Rule.
- The Data Sheets to use the terminology which is consistent with the IESS Rule.

3.3.3. Updates to loadflow model requirements

Two changes have been proposed regarding loadflow modelling:

- The first is to include a requirement for provision of generator capability curve data in a usable format. Capability curves are required to be provided as images in the Data Sheets, however this cannot be easily translated into a form compatible with loadflow programs. It is proposed that capability curve data be required to be provided in PSS®E .gcp format.

- The second is to remove references to 3-winding transformers being represented as 2-winding equivalents. This equivalence is not perfect and has been known to mask voltage unbalance issues on two low voltage (LV) windings of the transformer and cause issues with transformer voltage regulation. Modern loadflow, RMS and EMT tools all natively support 3-winding transformer models so there is no reason to convert the 3-winding data into an equivalent 2-winding transformer.

3.3.4. Requirements for legacy plant models

The Clean Energy Council and the PSMRG raised the issue of legacy assets (most commonly wind farms) that were connected to the NEM prior to the current modelling expectations, and as such have limited or no EMT models available. This may result in challenges when there are performance issues identified in that area of the network, or if the owner wishes to connect additional plant behind the connection point (such as a solar farm or battery system). In the case of the latter, a full EMT model including the legacy part of the plant is required to be provided under NER 5.3.9(b)(2).

While it is possible to engage the OEM to provide or develop a model of the legacy plant, this can be challenging and costly.

Another proposal has been to use generic models tuned to the legacy plant using real-time data. However, experience among PSMRG members has shown that development of tuned generic models can be complex and inaccurate, showing unexpected behaviour in wide-area studies.

Four key control loops of IBR plant were identified: active power control, reactive power/voltage control, frequency control, and fault-ride-through characteristic. It was proposed that the reactive power/voltage control and fault-ride-through characteristic were the most critical and should be appropriately represented in PSCAD for legacy models.

It is proposed to add an additional section to the Guidelines outlining requirements for modelling of existing legacy plant where there is no or limited EMT modelling information. This section would outline the criteria for submission of a legacy model under this section and the implementation and accuracy requirements.

3.3.5. Small signal modelling

Due to the unique network configuration of the NEM, small signal stability analysis has been critical to understand the behaviour of inter and intra area modes of oscillations. Traditionally only electromechanical modes of oscillations have been studied using this method, and only synchronous machines and static-var-compensators (SVCs) have been included for such analysis. The models have been constructed by AEMO and TNSPs from the detailed model block diagrams provided by plant owners or OEMs. The PSMRG have officially adopted the DSATools™ “Small-Signal-Analysis-Tool” (SSAT) software developed by Powertech Labs to be used by AEMO and NSPs for performing small signal studies.

The increasing penetration of IBR is affecting the generation dispatch and changing the nature of existing electromechanical modes of oscillations. It also introduces new forms of oscillations as experienced in the West Murray Zone and North Queensland. Detailed modelling of IBR in the small signal domain is critical to understand the technical envelope of the NEM and therefore maintaining power system security.

The accuracy and performance of small signal models is dependent on the level of detail included in the block diagrams received from OEMs. AEMO and NSPs have identified that block diagrams received to date of IBR do not include enough details at the inverter level (such as lack of inclusion of PLL and fast current control loops) and/or are in a format that is unsuitable for development of small signal models, making it impossible for AEMO or NSPs to study the plant in the small signal domain.

One reason detailed block diagrams have not typically been provided by OEMs is due to concerns around exposure of the intellectual property contained within the control systems which is detailed in the diagrams. This is despite strict confidentially obligations around use and storage of this information placed on AEMO and NSPs. To address this, some small signal stability programs including SSAT allow control systems to be blackboxed, similar to EMT tools. The OEM would develop a subroutine which will take as input the initial conditions (properties such as terminal voltage, current, setpoints, irradiance, windspeed and others), and would output the linearised control system matrices based on those initial conditions. This subroutine would be compiled into a DLL, thus obfuscating the control systems as non-human readable machine code, similar to how EMT models are provided to AEMO and NSPs.

It is proposed to reinforce the need for accurate and detailed block diagrams in a format suitable for development of a linearised small signal model. This would include removing any reference to “RMS” to ensure inclusion of components such as the PLL and fast current control that are typically approximated or not included in the RMS domain.

If due to confidentiality concerns or otherwise, detailed block diagrams cannot be provided by the OEMs, it is proposed to allow a DLL be provided that calculates the system matrices based on initial conditions compatible with SSAT. The format of this subroutine and assumptions around linearisation would be specified by AEMO and the NSPs.

It should be noted that this is NOT an additional requirement as Sections 4.5 and 5.3 of the Guidelines already allow AEMO and NSPs to request required information to assess small signal stability of the plant and the power system.

3.3.6. Other Changes

There may be additional changes not listed in this document, such as provision of models of network assets by NSPs, clarifying acceptance of model formats or any other issues that arise through the consultation process or through further discussions between AEMO and the NSPs. Any additional changes identified will be listed in the draft report to be published on 14 April 2023.

Consultation questions

14. Are there any issues with the proposals made under “Other matters”?
15. Are there any additional required modifications to the Guidelines that AEMO has not considered here?

Appendix A. Glossary

Term or acronym	Meaning
AC	alternating current
AEM	Anion exchange membrane (electrolyser)
AEMC	Australian Energy Market Commission
ALK	Alkaline (electrolyser)
DC	direct current
DER	distributed energy resources
DLL	dynamic link library
DNSP	distribution network service provider
EMT	Electromagnetic Transient (simulation / model)
EMTDC	Electromagnetic Transients with DC
ESB	Energy Security Board
IBL	inverter based load
IBR	inverter based resources
IESS	Integrated Energy Storage System
IRP	Integrated Resource Participant
IRS	Integrated Resource System
LV	low voltage
MNSP	market network service provider
NEM	National Electricity Market
NEO	national electricity objective
NER	National Electricity Rules
NSCAS	Network Service and Control Ancillary Services
NSP	network service provider
OEM	original equipment manufacturer
PEM	Polymer electrolyte membrane (electrolyser)
PLL	Phase-locked-loop
PMU	phasor measurement unit
PSMG	Power System Model Guidelines
PSMRG	Power System Modelling Reference Group
PV	photovoltaics
RAS	remedial action scheme
RMS	Root Mean Square (simulation / model)
SOECs	Solid oxide electrolysis cell (electrolyser)
SRAS	System Restart Ancillary Services
SSR	sub-synchronous resonance
SVC	Static Var Compensator
TNSP	transmission network service provider
UPS	uninterruptible power supply
ZIP	Constant impedance (Z), current (I), power (P) load model

Appendix B. EMT model DLL interface mock-up

Figure 6 PSCAD model with standardised DLL interface block

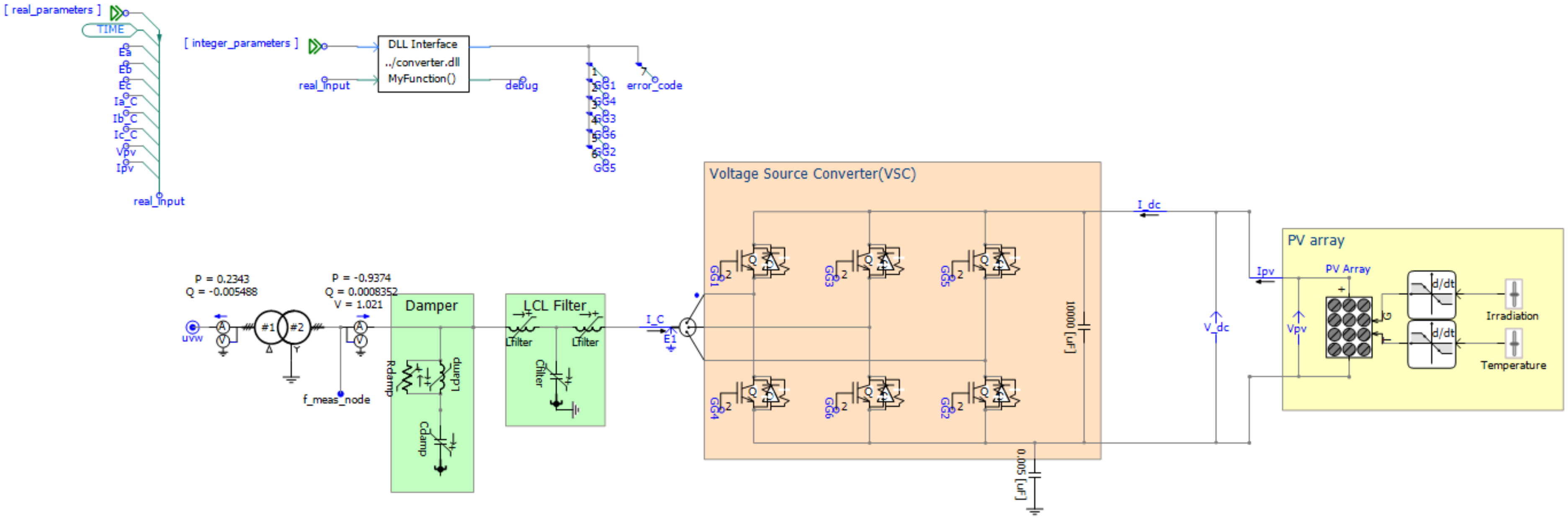
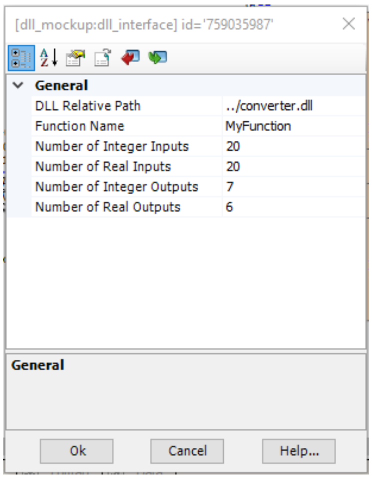


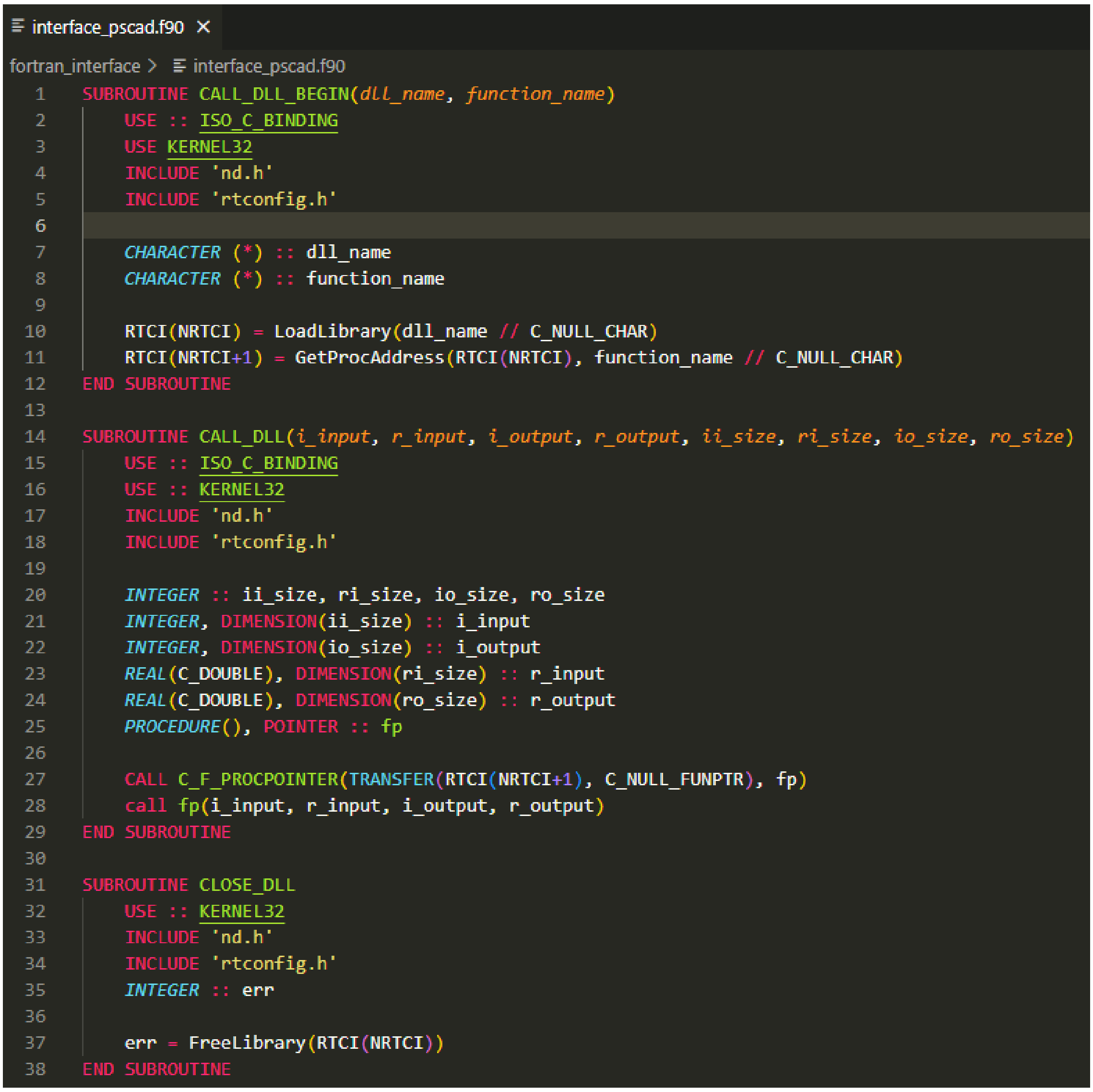
Figure 7 Interface block parameters



General

DLL Relative Path	../converter.dll
Function Name	MyFunction
Number of Integer Inputs	20
Number of Real Inputs	20
Number of Integer Outputs	7
Number of Real Outputs	6

Figure 8 PSCAD Fortran to DLL interface



```fortran
SUBROUTINE CALL_DLL_BEGIN(dll_name, function_name)
    USE :: ISO_C_BINDING
    USE KERNEL32
    INCLUDE 'nd.h'
    INCLUDE 'rtconfig.h'

    CHARACTER (*) :: dll_name
    CHARACTER (*) :: function_name

    RTCI(NRTCI) = LoadLibrary(dll_name // C_NULL_CHAR)
    RTCI(NRTCI+1) = GetProcAddress(RTCI(NRTCI), function_name // C_NULL_CHAR)
END SUBROUTINE

SUBROUTINE CALL_DLL(i_input, r_input, i_output, r_output, ii_size, ri_size, io_size, ro_size)
    USE :: ISO_C_BINDING
    USE :: KERNEL32
    INCLUDE 'nd.h'
    INCLUDE 'rtconfig.h'

    INTEGER :: ii_size, ri_size, io_size, ro_size
    INTEGER, DIMENSION(ii_size) :: i_input
    INTEGER, DIMENSION(io_size) :: i_output
    REAL(C_DOUBLE), DIMENSION(ri_size) :: r_input
    REAL(C_DOUBLE), DIMENSION(ro_size) :: r_output
    PROCEDURE(), POINTER :: fp

    CALL C_F_PROCPOINTER(TRANSFER(RTCI(NRTCI+1), C_NULL_FUNPTR), fp)
    call fp(i_input, r_input, i_output, r_output)
END SUBROUTINE

SUBROUTINE CLOSE_DLL
    USE :: KERNEL32
    INCLUDE 'nd.h'
    INCLUDE 'rtconfig.h'
    INTEGER :: err

    err = FreeLibrary(RTCI(NRTCI))
END SUBROUTINE
```