Generator and Load Model Guidelines and Change Management Requirements

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PowerWater

Contents

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For development of this document Power and Water also considered the information in the publication, "Power System model Guidelines" dated July 2018 published by the Australian Energy Market Operator (AEMO).

1 Introduction

1.1 Purpose

The *Generator and Load Model Guidelines* clarify Power and Water's approach to developing and maintaining accurate computer models, and *User* requirements for the provision of computer models and associated information for new connections or modifications to existing facilities. For modifications, please refer to Generator Modelling Change Management Requirements described in Section 10. In particular, the objectives of the Generator and Load Model Guidelines are to:

1. Describe *Users* requirements for provision of computer models for facilities connected or proposed to connect to Power and Water's Regulated Networks, including:
   - Model functional requirements.
   - Model acceptance test and model performance requirements.
   - Model documentation and *user* manual requirements.
   - Model validation, registered data and model accuracy requirements.
2. Provide details of Power and Water's methodology for assessing compliance with the above requirements to assist *Users* with providing the required models and associated model information.

The Network Technical Code and Network Planning Criteria (NTC) requires that Power and Water ensure that computer modelling data used for planning, design and operational purposes is complete and accurate. This is fundamental to the safe and reliable operation of the power system within its specified limits.

This document does not discuss other requirements for data to be submitted to Power and Water as part of an access application or request by a *User* to modify its existing equipment. Its focus is on the computer model representation of the customer facility and the data, parameters, diagrams and schematics required to substantiate that computer model.

The requirements for the provision of models are expressed as obligation on *Users* with respect to connected plant and equipment. Parties applying to connect new loads and generators (Applicants) also need to supply computer models to facilitate the assessment of their access application. The computer models provided by Applicants and *Users* must satisfy the requirements specified in these guidelines.

1.2 Definitions

This table defines key terms used in this document (these are formatted in italics). Where an italicised term is not listed in this table, its meaning is consistent with that defined in the *NTC* and/or *NT NER*.

TERM	DEFINITION
Access application	Refers to either a Transmission Generator Access Application form or Transmission Load Access Application form.
Applicant	A party that has applied to connect a new load or generators
AEMO	Australian Energy Market Operator
Design report	A report describing the methodology and studies undertaken to tune model performance to meet Network *Technical Code* and Network Planning Criteria requirements at the nominated connection point to the Power and Water's Regulated Networks.
EMT	Electromagnetic transient.

TERM	DEFINITION
FCAS	Frequency Control Ancillary Service
Generator and Load Model Guidelines	This document.
GPS	Generator Performance Standard - Set of standards agreed between the generator and the network operator following the procedures in clause 3.3.5 of the NTC.
Model assessment	An assessment of a *User*'s computer model, documented in a Works Planning Report (WPR).
Model development report	A report describing the model development, usually with reference to control system block diagrams and/or models in other software packages.
NT NER	Northern Territory National Electricity Rules
Power and Water's Regulated Networks	Darwin-Katherine Alice Springs Tenant Creek
pu	Per-unit
SMIB	Single Machine and Infinite Bus (simplified network model)
R2 data, model validation and performance report	A report providing details of the tests conducted, assessed performance, model validation results, and registered (R2) data including final models and control system settings.
RMS	Root mean square
RUG	Releasable *user* guides
NTC	Network Technical Code and Network Technical Planning Criteria Version 4 dated 30th March, 2020.
Technical data assessment	An assessment of *Users* access application, documented in a WPR.
User	The Network Technical Code and Network Planning Criteria Attachment 1 Glossary of Terms defines a *User* as follows: "A person, whether a Network *User* or a Generator *User*, who has been granted access to the electricity network by the Network Operator in order to transport electrical energy to or from a particular point."
User manual	A document describing the setup and operation of a computer model.

TERM	DEFINITION
WPR	Works Planning Report: a consolidated report documenting the outcome of studies undertaken at various stages of the connection process, including a computer *model assessment*.

1.3 Application of the Generator and Load Model Guidelines

The *Generator and Load Model Guidelines* apply to all *generating systems*[1] (including inverter and converter coupled generating units), dynamic reactive control devices and loads, and to both new connections and modifications to existing facilities (including settings and configuration changes).

The NTC clauses below should be reviewed to assist with understanding the need for computer modelling information and the obligations of Power and Water and *Users* for provision and maintenance of accurate computer models.

1.3.1 Generating Systems

A computer model is required for all generating systems which meet the criteria specified in clause 3.3.1(b) of the NTC. Generally those generating systems will have a rating of 2 MW or more. The provision and use of generator models is further articulated in the following clauses in the NTC*:*

CLAUSE	SUBJECT
3.3.4	Provision of Information
3.3.5	Technical Requirements
5.4	Tests to Demonstrate Generator Compliance
5.5	Power System Tests

All generators must also provide the information specified in clause 11.2 of the NTC.

1.3.2 Small generating systems and small inverter energy systems

The NTC defines a *small generating system* as a generating unit or group of generating units with:

1. aggregate rated capacity of no more than 2 MW or 10% of the minimum demand of an isolated network whichever is lesser;
2. connected to the 22 kV, 11 kV or low voltage networks; and
3. not subject to dispatch by the System Operator.

The NTC defines a *small inverter energy system* as a *generating unit* which uses an inverter that changes its direct-current power to alternating current power acceptable for power system connection. The nominal network voltages and maximum energy system capacities for which these requirements apply are:

- 230 V single phase 10 kVA; and
- 400 V three phase 30 kVA.

Power and Water will assess the need for computer models for small generating systems and small inverter energy systems to perform dynamic simulation studies. If deemed to be required, the same model requirements as for generating systems > 2MW may apply.

Information to be provided by *Users* with small generators / small inverters are provided in the following clauses of the NTC.

[1] A *generating system* comprises one or more *generating units*

CLAUSE	SUBJECT
11.4	Information to be provided by *Users with small generators*
11.5	Information to be provided by *Users with small inverter energy systems*

1.3.3 Loads

For *load* connections Power and Water will assess the *load* characteristics (including *load* size, motor composition, harmonic emissions etc.), *connection point*, and capability of the local *transmission* or *distribution system* in the vicinity of the *connection point* to determine the extent of modelling information required. Power and Water may also request a computer model, although typically this would only be required for large *load* connections or those connections in weaker parts of Power and Water's *Regulated Networks.*

As indicated in section 1.7.6 of the *Technical code* each *User* with a *load* shall ensure that all *facilities* which are owned, operated or controlled by it and are associated with a *connection point* at all times comply with applicable requirements and conditions of *connection* for *load*s as set out in clauses 3.2 and 3.6.

1.4 Confidentiality

Information provided to Power and Water may be released to third parties in accordance with clause 3.3.4(e) of the NTC.

"Data provided by a Generator under clause 3.3.4 may be shared by the Network Operator with other Generators, for the purposes of this code, subject to the restrictions set out in the remainder of clause 3.3.4"

2 Model Requirements

As part of a new or amended access application Power and Water requires certain data and documentation to be provided with a computer model. This section provides details of Power and Water and NTC requirements for provision of this information. For existing *Users* seeking to modify their equipment where an access application is not required, these guidelines for model provision still apply.

When developing a computer model there are general requirements that apply to all models, irrespective of the type of facility, as well as specific requirements that are applicable depending on whether the facility is a generating system, load or other type of equipment, such as a dynamic reactive device (STATCOM, SVC, etc.).

2.1 General requirements

The following general model requirements apply:

1. The model and its associated data and parameters must be consistent with the information provided as part of an *access* application, or otherwise the *Users* request for modification to an existing facility. This should include, but is not limited to:
   - Consistency with Single Line Diagram (SLD) layouts and other schematics provided to Power and Water.
   - Consistency with relevant network data provided including all network impedances and ratings, voltage levels, transformer specifics (location, rating, vector groups, winding configuration, tap changer specifics etc), auxiliary loads and reactive devices etc.
   - Consistency with generating system or load specifics provided such as maximum capability and loading, active and reactive power ranges, generator reactance's etc. Loads, including generator auxiliary loads, must be modelled such that the load power factor is representative of the facilities actual performance under typical operating conditions.
2. In general, overhead transmission lines should be modelled using geometric tower models and conductor data.
3. The model must be suitable for balanced and unbalanced power flow studies, and for calculation of balanced and unbalanced short-circuit currents using 'Complete' and 'IEC' methods.

In summary, adequate load flow models must represent the plant steady state condition for the full operating envelop. Where applicable the load flow models of plant must include the information listed in Table 1An overview of the additional modelling information required for generation and loads is provided in Sections Generating system model requirements2.1.1 and 2.1.4. Section 2.2 describes the power system modelling software used by Power and Water. Models provided by *Users* must be compatible with the specified software.

Table 1: Load flow model inclusion

PLANT ELEMENT	INCLUDING
Generating units[A], reactive support plant	MVA base
	Source impedance, including sub transient / transient impedance, negative and zero sequence impedance [C]
	Active and reactive power profile [B]
	Voltage control scheme
	MVA base and ratings
	Winding vector group

PLANT ELEMENT	INCLUDING
Plant transformers [A] (including step-up, intermediate and connection point)	All winding voltages
	Winding impedances, including positive, and zero sequence [C]
	Grounding arrangements and impedances
	Connection code
	Magnetising impedances
	Tap location, number and voltage range
	Voltage control scheme
Reticulation Network [A]	Positive and zero sequence impedance [C]
Shunt components	Switched shunts
	Fixed shunts
	Switched shunt voltage control scheme
Loads	Active and reactive power levels, in most appropriate format (power / impedance / current) Where required explicitly modelled motors and composite load models

A. For plant consisting of several distributed generating units, aggregation principles outlined in Section 2.6**.** must be used.
B. Consistent with the plant's performance.
C. Sequence impedance data required to support short circuit studies

2.1.1 Generating system model requirements

Pursuant to clause 3.3.4 of the NTC, the following requirements apply.

2.1.1.1 Model configuration requirements

The generator active and reactive power ranges must be defined in the model according to the generator capability, consistent with the requirements of clause 3.3.5.1 of the NTC.

For a synchronous generator, the following control system models would typically be included[2]:

- Synchronous machine modelled with exact parameters.[3]
- Excitation system, load drop compensation and exciter.
- Turbine-governor including speed droop and power control loops, turbine, boiler dynamics, temperature and power control/limiting functions, and other relevant control mode and protection functions.
- Power system stabiliser (PSS) including synthesised speed.

[2] Controller models such as AVR, PSS, OEL and UEL for synchronous generators should be modelled as unique DSL models and not combined into a single DSL model unless agreed with Power and Water.
[3]PowerFactory uses 'Exact' parameters as opposed to other software, which may use 'Classical' parameters (for further details, refer to P. Kundur 'Power System Stability and Control').

- Under-excitation limiter (UEL).
- Over-excitation limiter (OEL).
- Other limiters, such as stator current limiter, volts per hertz limiter, over-fluxing limiter.
- Power station controller.
- Other control and protection systems, including loss of excitation protection and pole-slip protection relays.

For a non-synchronous generator, the following control systems would typically be included:

- Generator model(s).
- Reticulation network including other relevant equipment such as static or dynamic reactive equipment, and harmonic filters.
- Farm-level control system with measurement points/control points (including Phase Locked Loops) appropriately configured.
- Other control and protection systems.

2.1.1.2 Other model requirements

For synchronous generators, there is no specific requirement for the provision of distinct models for sub-synchronous resonance studies. Sub-synchronous resonance studies will be based on transient stability models and the mechanical shaft model which is provided with the *user manual* and *access application*.

For non-synchronous generators, harmonic current and flicker emissions must be included in the model.

Power and Water will determine the need for protection relay models.

2.1.2 Static load and motor model requirements

Pursuant to clause 3.6 of the NTC, the following requirements apply for static load and motor models. These requirements are intended as a guide and should be agreed with Power and Water prior to model preparation.

2.1.2.1 Model configuration requirements

For *loads* where a computer model is assessed by Power and Water as being required the following provisions apply.

In general motors directly connected to 11 kV or higher and greater than 1 MW should be modelled explicitly. Smaller motors and those not directly connected to 11 kV or higher may be represented by lumped equivalents, however the approach taken should be clearly identified in the supporting documentation and the provided computer model.

If required the modelling information provided for the load should provide both a detailed representation of the load and information that can be aggregated with the other load information in Power and Water*'s Regulated network* computer model.

Where various *loads* are represented as a single lumped (static) *load*, they must be modelled with complex load parameters based on the constituent loads (VSD's, induction machines and other loads), and with suitable voltage and frequency dependent parameters.

Simplification of *load* model representation should be consistent with the requirements of AS 3851 and good electricity industry practice to ensure that *equipment* fault level contributions are appropriately represented.

2.1.2.2 Modelling motor starting

Explicitly modelled motors connected at 11 kV or more must have starting method parameters defined in the model (e.g. direct online, soft-starter). These requirements are intended as a guide and should be agreed with Power and Water prior to model preparation. They may need to be varied for large motors connected at voltages below 11 kV.

2.1.2.3 Other model requirements

Where Large Motors connect at 11 kV or higher are supplied by variable speed drives or utilise power electronic converters for slip energy recovery, the harmonic emissions must be assigned in the part of the model relevant for network power quality analysis (via harmonic load flow), across the range of partial load set-point to full load, as may apply in normal operation..

Explicitly modelled motors connected at 11 kV or more must have mechanical characteristics of the drive load (torque-speed characteristic) and total mechanical inertia parameters modelled.

Load shedding facilities, including under- and over-voltage and under- and over-frequency relays should be described and modelled.

Any other special protection schemes or requirements should be described.

Power and Water will determine the need for an EMT model to assess the impact of the load, generating unit or generating system on other *Users*.

2.2 Software

Power and Water requires the ability to study the power system using both phasor domain or Root Mean Square (RMS) analysis techniques and Electromagnetic Transient (EMT) techniques. While RMS techniques are suitable for steady state analysis and studying various aspects of power system dynamic behaviour, it is increasingly important to use EMT simulations to understand the dynamic behaviour of inverter connected generation such as solar farms.

Generators are required to provide both EMT and RMS models for their generating systems.

Loads will generally be required to provide sufficient information to allow their plant and equipment to be represented appropriately in an integrated RMS model for Power and Water's regulated network. Larger loads may be required to provide additional modelling information as outlined in Section2.1.4. Power and Water will determine the need for an EMT model to assess the impact of the load on other *Users*.

2.2.1 RMS model format

Power and Water has adopted DIgSILENT PowerFactory as the preferred software for RMS power system analysis. As models can be provided to other *Users*, a *User* supplying a RMS computer model may elect to provide a version of the model in an encrypted DIgSILENT PowerFactory format suitable for use in the version of software currently used by Power and Water[4] and suitable for integration with the Power and Water's Regulated Network computer model. The encrypted version would be provided to other *Users* by Power and Water when necessary to meet the model provision requirements in the NTC.

In addition, Generators must provide to Power and Water a native unencrypted version of the RMS computer model along with the set of functional block diagrams including all functions between feedback signals and generating system output. Power and Water recognise that Original Equipment Manufacturers (OEMs) can be reluctant to provide unencrypted models due to concerns over confidentiality and the protection of intellectual property. Addressing such issues may require specific agreements regarding the use of unencrypted models to be executed with OEMs. Power and Water is willing to work with Generators and OEMs to establish required agreements.

Requiring DIgSILENT RMS models is consistent with clause 3.3.4 of the NTC which requires that *User* supplied models be in a form which is compatible with the power system software used by the Network Operator.

RMS models must not have dependencies on additional external software.

2.2.2 EMT model format

Power and Water has adopted DIgSILENT PowerFactory as the preferred software for EMT power system analysis. All *Users* providing EMT models will be required to provide models compatible with DIgSILENT PowerFactory meeting the requirements specified in these guidelines.

EMT models must not have dependencies on additional external commercial software.

2.2.3 EMT Model black-boxing, compilation or encryption

As EMT models can be provided to other *Users*, model owners may wish to black-box, compile or otherwise encrypt portions of an EMT model that are commercially sensitive, or where additional intellectual property protection is desired. Black-boxing allows EMT models to be created which embed (and encrypt) the hardware code used in the actual generating equipment into an EMT model while protecting vendor intellectual property.

Provided the requirements in these Guidelines as to the model's utility are met, and a legitimate *user* of the model is not hampered in their ability to carry out legitimate studies using the model, black-boxing is acceptable. Model owners remain responsible for the adequacy of the black-boxing, compilation or other encryption of their model.

2.3 *RMS* and *EMT* dynamic model requirements

Applicants have the following system strength obligations:

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[4]Contact Power and Water to confirm the version of Power system analysis software currently in use.

2.3.1 General dynamic model requirements

Dynamic models provided under clause 3.3.4 of the Technical code must define the site-specific electromechanical and control system performance of components comprising plant under Steady State, set-point change and Disturbance conditions for all levels of system strength and energy source availability that the plant is rated to operate.

That *plant* includes:

- the *generating unit* or any other primary or relevant secondary plant within the *generating system* that may affect the overall interaction (active power, reactive power or voltage) of the *generating system* with the power system (e.g. reactive power compensating plant); and
- any dynamic reactive power or voltage compensation plant within the network that can have an impact on transient and voltage stability.

Parameters of dynamic models developed for new and modified generation connections (including any supervisory control) should be refined through extensive connection studies. Plant model and parameters must be assessed through the Power and Water due diligence process to be qualified as R1 data.

RMS and *EMT* models and parameters submitted to Power and Water must conform to the following general requirements before being considered for assessment.

2.3.1.1 Model compatibility and stability

Models must:

- be accompanied by a Releasable *User* Guide (RUG) meeting the requirements specified in Section 4.2;
- be compatible with the power system software simulation products specified by Power and Water;
- work for a range of dynamic simulation solution parameters rather than for specific settings only;
- be numerically stable for the full operating range including a wide range of grid SCR and grid and fault X/R ratio;
- have any model validity limitations due to system impedance or strength clearly defined within the *RUG*;
- be numerically stable up to a simulation time of up to five minutes (have voltage, frequency, active power and reactive power remaining constant for dynamic simulation runs with no Disturbance);
- not show characteristics that are not present in the actual plant response; and
- must represent the actual operation of the plant without manual intervention.

2.3.1.2 Model composition and operating range

Models must:

- be a model of the specific *plant* being considered;
- include any relevant non-linearities, such as limits, arithmetic or mathematical functions, deadbands or saturation, etc.
- represent the *generating system* and reactive compensation plant performance for all possible steady state output and system strength levels where the plant would be in operation;
- represent *plant* response for set-point changes including active power, reactive power, power factor, voltage and frequency, including associated ramp rates.
- represent the *generating system* and reactive compensation plant performance for all possible values of energy source variation where the *generating unit* or *generating system* would be in operation;
- provide the ability to vary the energy source strength throughout the simulation study for *generating units* with an inherently variable power source;
- represent all plant within the *generating system*, including *generating units*, governors, park controllers, tap-changing transformers, and reactive power compensating plant;
- Relevant protection relays must be included in the model, explicitly where practically possible.
- represent delays between plant elements (e.g. SCADA, PLC and park controller communication delays) that have an impact on the performance of the plant;
- include adequate modelling of the mechanical components of the plant, to the extent that such mechanical components have a significant effect on the stability of the plant and its response to power system disturbances;

- include models of generating unit energy storage components that would be affected by Disturbances;
- represent plant response to any runback scheme or special protection scheme in which the plant participates in;
- represent plant performance accurately within the normal dispatch range between minimum and maximum active power output, but must also be able to be initialised at any active power dispatch down to 0 MW; and
- initialise correctly (for example, for *RMS* models from load flow) if dispatched to a power level lower than that available from the fuel source.

Linearised models that are accurate only for a single operating point are not acceptable[5].

2.3.1.3 Model multiple operating modes and control functions

A model must:

- represent all modes of operation that the physical plant is capable of operating in. For example, if applicable to the physical plant, the model must be able to represent:
  – generation, synchronous condenser and pump modes for relevant hydro-electric generation technologies, e.g. pumped storage;
  – voltage control, power factor control and reactive power control modes; and
  – activation /deactivation of frequency control and fast frequency response features.

  All automatic changes to operating modes that occur in reality should happen automatically within the model. Where automatic mode switchover cannot occur, operating mode changes must be based on configuration file or variable changes. It is not acceptable to require a separate model for each operating mode.
- represent the simultaneous control functions that are active within the physical plant without the need to change model setup, variables or configuration parameters. For example, a model must be able to represent both active power control and frequency control functions operating simultaneously.

2.3.2 *RMS* model specific representation

Use of DIgSILENT Simulation Language (DSL) expressions to represent functions that could otherwise be represented by standard PowerFactory library macro block definitions should be avoided to the extent practicable.

Inclusion of multiple (unique) equipment control functions within a single macro block definition should be avoided.

The number of lines of code within a single macro block definition - excluding parameter definitions, initial conditions and comments – should generally not exceed 30. The intent of this requirement is to provide guidance to the model developer and to improve macro code readability and model usability (it is not intended to result in increased complexity of macro equations or detract from macro code readability).

The model may include non-convergence warnings for some simulation events, however this may indicate issues with the dynamic model, have an adverse impact on simulation performance and/or cause the simulation to collapse. Care should be taken and unnecessary warnings avoided when developing the model.

For protection events (e.g. activation of Low Voltage Ride Through (LVRT) etc.) the simulation events, including initial detection, operation, and time-out, should be reported to the PowerFactory output window during the simulation.

Models must be tested for integration compatibility in Power and Water network. Experience has shown that single machine infinite bus (SMIB) simulations do not always reveal new models' adverse interactions with other models in the system.

2.3.2.1 *RMS* model initiation

When the dynamic model is opened and executed with the PowerFactory software version used by Power and Water,[6] it must automatically initialise its parameters from load flow simulations without warnings or errors, must not result in initialisation or run time warnings or errors, and there must not be any interactions or conflicts with other models.

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[5] Power and Water understands that this may be difficult to achieve for some plant with complex thermal componentry. Where the required accuracy cannot be met, Power and Water will consider the case separately.
[6] Contact Power and Water to confirm the version of DIgSILENT PowerFactory currently in use.

When the preconfigured system conditions are beyond plant operational limits or otherwise not consistent with valid operating conditions for the plant, the model must warn the *user* by way of a message to the PowerFactory output window during the simulation.

Dynamic model initialisation must be invariant to simulation start time (i.e. not require the simulation to be initialised at a particular time).

Where parameters need not be recalculated at each time step, the DSL commands selfix(), limfix() and outfix() must be used instead of select(), limits() and output() so that they are only calculated at initialisation.

2.3.2.2 RMS model configuration requirements

The control mode and droop settings in the *RMS* model must be configured according to the usual operation, and configured for both steady-state and dynamic simulations.

The *RMS* model must include all functional controllers and ancillary *equipment* that materially affect the performance of the *equipment* over the typical timeframes of a dynamic simulation (up to several minutes), and accurately represent the performance for all possible conditions where the *equipment* would be in operation.

In PowerFactory, each controller is linked to a "slot". To enable the complete dynamic model to be removed from service without the need to remove each of the controllers from service, the "Main Slot" checkbox should be selected for the slot which relates to the generator element (e.g. the synchronous machine).

The dynamic model must resemble the physical design of the *equipment* and controllers to allow Power and Water to assess the suitability of proposed settings.

The dynamic model must support both balanced and unbalanced time domain simulations and the response of each of the phases must be observable.

Where the equipment has the capability to respond per phase, a full three-phase model must be provided.

Dynamic model parameters should have parameter names, descriptions and units defined in the DIgSILENT Simulation Language (DSL) models, for example "Kp Proportional gain [*pu*]".

The PowerFactory DSL model must compile to C code without warnings or errors.

2.3.2.3 RMS model integration time step

The dynamic model must support time domain simulations with a minimum integration step size of 0.002s.

The model must not include algorithms that require use of a particular integration step size (for example the model should not fail to solve, or the response be materially different for an integration step size of 0.001s).

Time constants below 5ms should only be included if their inclusion is critical to the performance of the dynamic model and are required to meet the accuracy requirements (see Section 5.2).

Internal integration algorithms should only be included if their inclusion is critical to meeting the accuracy requirements, and should not materially detract from model simulation speed performance.

2.3.3 *EMT* model specific requirements

The following are requirements for *EMT* dynamic models supplied to Power and Water. *EMT* models must:

- have a bandwidth of at least DC to 10 kHz and settle to the correct final value for the applicable power system conditions and applied Disturbance(s);
- be based on plant design data and rigorously tested against factory acceptance tests for the corresponding version of plant;
- include detailed representation of all inner and outer control loops for the plant[7];
- represent all electrical, mechanical and control features pertinent to the type of study being done;
- have the full representation of switching algorithms of power electronic converters for power system harmonic studies;
- have all pertinent protection systems modelled in detail for power system transient and voltage stability analysis, including balanced and unbalanced fault conditions, frequency and voltage Disturbances, and multiple fault conditions and can disable the protection systems if required;

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7 The model cannot use the same approximations classically used in transient stability modelling, and should fully represent all fast inner controls, as implemented in the real equipment. It is possible to create models which embed (and encrypt) the actual hardware code into an EMT component. This is the recommended type of model.

- be configured to match expected site-specific equipment settings;
- allow plant capacity to be scaled;
- transient stability *EMT*-type models must operate with a time-step greater than or equal to 1 microsecond, ideally consistent with the switching frequency of the plant;
- for *EMT*-type models used for harmonic analysis or real-time *EMT* simulations, time-steps must be such that they allow for an accurate representation of the switching algorithm of semiconducting devices;
- allow model re-entry to facilitate integration into larger system studies;
- support multiple-run features to facilitate iterative studies;
- allow multiple instances of the model within the same simulation;
- be capable of self-initialisation, with initialisation to *user* defined terminal conditions within three seconds of simulation time;
- warn the *user* by way of a message to the progress output device when the system conditions are beyond plant operational limits or otherwise not consistent with valid operating conditions for the plant; and
- clearly identify the manufacturer's *EMT* model release version and the applicable corresponding hardware firmware version.

2.3.3.1 Multiple voltage disturbances

The *EMT* model provided must account for the most restrictive[8] electrical, mechanical, or thermal protection of the plant with respect to multiple voltage disturbances in quick succession, and calculate dynamically and accumulatively the impact of multiple voltage Disturbances, including but not limited to the following factors:

- heat dissipation across the dynamic braking resistors (if applicable);
- capability of auxiliary supplies, e.g. uninterrupted power supply (UPS);
- torsional stress protection on shaft drive train and prime mover (if applicable)[9];
- protection associated with thermal design limits of the integral assembly of the plant; and
- any other relevant electrical, mechanical or thermal protection.

Note that these requirements apply only to *EMT* models as the simplifications of *RMS* plant models may result in inaccurate activation of fault ride-through mechanisms for unbalanced faults.

2.3.4 Additional requirements for frequency stability studies

For *frequency* stability studies, models must also:

- provide an accurate response of the plant to changes in network frequency, and active power generated to the network~~;~~
- take into account both central controllers and distributed plant if an aggregated service is used to provide *FCAS*;
- be an accurate representation of the maximum rate of change of frequencies that the plant is capable of operating with;
- be accurate for the full range of *network frequency* in which the *plant* can operate as specified in its performance standard for maintaining continuous uninterrupted operation following a frequency disturbance;
- represent the frequency and speed filtering applied in the governor system controller and/or time delays in control variable measurement transducers;
- represent any controller settable control variable position limits, ramp rate limits or deadbands;
- include any mechanical actuator limits e.g. fuel valve open/close rate of change limits, pitch limits, open/close position limits, exhaust temperature limits, internal turbine limits, active power limits or other physical limits within the control system that cause a limit on power output and/or fuel flow;

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8 It is the Applicant's responsibility to determine which protection element(s) will be the most limiting factor for multiple fault ride-through.

9 This is a relatively uncommon protection relay – the Generator must determine whether the exclusion of this relay from the model has a material impact on model accuracy.

- include fuel valves and fuel valve actuators that have control dynamics in addition to the control system, where these can affect the stability of the governing system or have an appreciable effect of the accuracy of the model must be included in the model;
- include non-linear fuel flow to valve position and/or non-linear fuel flow to power characteristics, where an efficiency characteristic has an appreciable effect of the accuracy of the model;
- include large Disturbance controls, such as intercept valve control on steam turbines, load rejection detection, acceleration control, power load unbalance detection and pre-emptive overspeed detection;
- include external (to the governor/power control system) control action (e.g. from Generator SCADA system), to regulate the power set-point during frequency Disturbances when enabled and not enabled for *FCAS*;
- include control mode changes or control gain changes that may be triggered from network Disturbances (for example, in the case of islanding situations where the network frequency may vary within the normal contingency bands, or where special logic is used to boost *FCAS* capability);
- represent any automated deployment of *FCAS* (specifically fast raise/lower and slow raise/lower service) where this is provided in addition to (or when generation has been dispatched for a specified *FCAS* amount) or by normal governor action with additional algorithms or controls. Where other control logic is used (e.g. SCADA/AGC) to deploy the *FCAS* by direct control of the power set-point during a frequency Disturbance this must also be included in the model; and
- represent the fuel delivery system dynamics where this has a material influence on the power output during and after a frequency Disturbance and within a timeframe up to five minutes from the initiating Disturbance, or where the fuel delivery system is common to multiple generating units or derived from the generation in other units within a plant such that changes in active power generation on one generating unit can cause a change on another generating unit. Some examples of these are:
  – combined cycle plant where a heat recovery system from gas turbines is used to generate steam for a steam generating unit; and
  – gas turbines where the turbine mechanical power decreases with frequency.

2.3.5 Assessable variables

Where applicable, all models must allow alteration to the following:

- all applicable set-points within all *plant* including (must be adjustable before and during a simulation run):
  – Active power
  – Reactive power
  – Voltage
  – Power factor
  – Frequency

  for a *generating system* this requires access to all applicable set-points;
- deadband, droop, delays (including communication delays) and slow[10] outer loop controls for any applicable control system such as frequency and voltage control;
- ramp rates for changes in active power;
- voltage and frequency protection settings, such as over/under voltage protection and over/under frequency protection;
- fault ride-through activation and deactivation thresholds, including any multiple-fault ride-through limits and hysteresis levels;
- active and reactive current injection/absorption settings during a fault;
- number of in-service generating units and reactive support plant, adjustable before and during a simulation run; and
- energy source input (e.g. wind speed or irradiance), adjustable before and during a simulation run without causing any adverse impact on initialisation or dynamic performance.

[10] Adequate for simulating actions of on-load tap changing *transformers*, static reactive *plant* switching, and 60 seconds Contingency *FCAS*.

Additional alterable variables may be required by Power and Water to undertake full stability impact assessment as described in the *system strength impact assessment guidelines*. For example, proportional and integral gains for inner/outer current/*voltage* control loops (including PLL, *voltage* control, and any other control loops which can have a system strength impact). These variables can be adjusted by means of applying a real number multiplier if the actual values of these gains are preferred to remain black-boxed.

2.3.6 Model outputs

Table 2 outlines the output quantities required to demonstrate model performance.

Table 2 Required model output quantities

PLANT TYPE	PLANT INTERNAL QUANTITIES	PLANT TERMINAL MEASURED QUANTITIES
Synchronous machine	Field current[A] Field voltage Limiter outputs[B] Mechanical power or torque Rotor angle PSS output[G] Unit speed AVR output[C] Exciter output Valve position[G] Guide vane/needle positions[G] Governor control output[G] Set-point for active power[G] Set-point for voltage External protection relay(s) status[H]	Active power Total current[E] Frequency Reactive power Voltage magnitude[E] Voltage phase angle
Photovoltaic (generating unit)	DC link voltage and current Error/status codes[D] Active and reactive currents Quantity determining FRT activation Set-point for active power Set-point for reactive power, voltage or power factor	
Battery (generating unit)	DC link voltage and current Energy storage level Error/status codes[D] Active and reactive currents Quantity determining FRT activation Set-point for active power Set-point for reactive power, voltage or power factor	
Wind (Generating unit)	DC link voltage and current Error/status codes[D] Generator rotor speed Active and reactive currents Mechanical torque or power Pitch angle Quantity determining FRT activation Set-point for active power Set-point for reactive power, voltage or power factor	

PLANT TYPE	PLANT INTERNAL QUANTITIES	PLANT TERMINAL MEASURED QUANTITIES
HVDC Link and Frequency Converters	DC link voltage and current Firing angle (for LCC HVDC and frequency converters using similar power electronics) Switch / valve currents[A] Error/status codes[D] Active and reactive currents Quantity determining activation of blocking models Set-point for active power Set-point for reactive power, voltage or power factor External protection relay(s) status[H] Frequency Set Points (for devices controlling frequency)	
Reactive compensation plant (SVCs, STATCOMs, etc.)	DC link voltage and current Shunt control status/set-points External plant set-point outputs Error/ status code[D] Active and reactive currents Quantity determining activation of blocking modes[I] Set-point for reactive power, voltage or power factor External protection relay(s) status[H]	
Centralised controllers (park and hybrid controllers)	Error/status codes[D] Quantity determining FRT activation Set-point for active power[F] Set-point for reactive power, voltage or power factor[F] External protection relay(s) status[H]	

A. In EMT models only.
B. Relevant limiter outputs, such as over-excitation limiter, under-excitation limiter, V/Hz limiter etc.
C. Including outputs of any compensation components.
D. Only those error/status codes which translate into a distinct electrical system response at the LV terminals of the plant. For example, normal, fault, stop, LVRT or HVRT activation, unstable mode identification etc.
E. Both waveform and RMS values for EMT models.
F. As sent to generating units within the generating system.
G. Not applicable for synchronous condensers.
H. External discrete protection relays relevant to the plant. For example, for transient stability studies; this may include over- and under-voltage, over- and under-frequency, RoCoF and reverse-power protection. For black-start studies, this may be extended to include negative sequence, out-of-step, over-fluxing, loss-of-excitation and generator and unit-transformer differential protection.
I. Include within models the blocking response below certain voltage levels or other conditions.

2.3.7 Integration compatibility

A model submitted to Power and Water for any power system element must operate as part of a full power system model alongside models of many other power system elements. This will inevitably include elements of the same type as the one in question, using either the same or a different release version of the same model code, submitted by the same or another *User*.

It is, therefore, imperative that the model is capable of coexisting and operating correctly alongside other independent instances of the same model, either of the same version or with a different version number. This requires attention as a minimum to the following:

- naming and referencing models, functions and libraries based on a version number, such that two different versions of a model of the same *plant* can run within the same simulation environment without interference;
- creating models to work for a range of time steps and dynamic simulation parameters, rather than for specific settings only; and
- models should, to the maximum extent practical, make use of the mechanisms provided within the host software platform to encapsulate separate model instances.

Models that prove problematic to integrate into larger cases will need to be rectified before Power and Water is able to accept the model for further assessment. Power and Water will work with the Applicant to identify the issues.

2.4 Small signal model requirements

The model must be capable of being represented in eigenvalue studies using both the QR method and Arnoldi method without modification.[11]

2.5 Power quality data requirements

The following sets of data must be included in the *RMS* software model:

- frequency-dependent Norton equivalences of each type of generating unit;
- harmonic current injection profiles (for each harmonic order) at each generating unit, including:
  - harmonic current magnitude, e.g. in Amperes, or in percentage of fundamental current;
  - harmonic current phase angle (if available);
- adequate model of collector grid[12];
- generating unit transformer models and generating system transformer models[13]; and
- data for harmonic filters (if present) must be provided, including connection point(s) of the filters, filter layout (e.g. single-tuned, double-tuned), qualify factor and electrical parameters.

2.6 Aggregation

For some detailed *load* models and for *generating systems* comprising a large number of *generating units*, there may be a requirement for the model to be aggregated. The methodology for aggregating *generating units*, *loads*, other *generating equipment* and the reticulation system are given below. In developing an aggregate model studies should be undertaken that illustrate the alignment of time-domain simulation overlays for voltage, active power and reactive power for the nearest and farthest generating unit and the aggregated generating unit, for:

- zero impedance balanced three-phase to earth and zero impedance two-phase to earth faults at the *connection point*; and
- voltage, reactive power, power factor and active power step response.

For *generating systems*, the aggregation should not prevent access to generator terminal quantities.

2.6.1 Scaling principles for derivation of multiple unit aggregates

The following general principles are assumed as the default for producing aggregates of N identical units, where each unit is assumed to consist of a ‘plant’ at low voltage (LV) in cascade with a unit transformer stepping up to medium voltage (MV).

The calculation methodology for equivalent MV ‘collector system’ which connects the individual generating units should be clearly indicated in the *RUG* with receptive references.

Where the modelling of power system plant requires an aggregation method that varies from these principles, this must be clearly documented in the *RUG*. Alternative aggregation methods include the provision of a separate aggregate model not directly derived from the individual unit model. Evidence must be submitted to Power and Water for the suitability of the aggregation method relative to the simple application of the scaling principles below. Power

11 Damping performance is assessed against the requirements of Technical Code clause 16.1.6.

12 Collector conductor models may need to consider skin and conductor proximity effects

13 Positive, negative and zero sequence impedance of these transformer models must be provided, including any earthing arrangement and transformer vector groups

and Water assess this evidence, and may accept the different method, or determine that the scaling principles will apply if the evidence submitted is weak.

The aggregate *generating unit* is represented in the model in an analogous fashion (size aside) to a single *generating unit*. It has the same associated dynamic model and appears similar to a *generating unit* in the *network* model in cascade with an equivalent unit *transformer*.

The LV and MV voltage levels are the same for the aggregate as for the individual *generating units*.

The MVA rating of the aggregate *plant* is N times the MVA rating for an individual *generating unit*. (This rating is called Machine MVA in the Power Factory model.)

The *active power* and *reactive power* of the aggregate are the sums of the individual *generating unit* powers. For modelling purposes, there is an underlying methodological assumption that each *generating unit* has identical power outputs, although these will vary from unit to unit.

Any other 'size quantities' specified in SI units, or in per-unit on a fixed system MVA base, are multiplied by N in the aggregate. Examples of size quantities are rated current in Amperes, rated torque in Newton-metres, and inertia constant in Joules or VA-seconds (but not speed or voltage). Where, on the other hand, the model specifies these quantities in a per-unit system on the generating unit MVA base, their numerical values are identical.

The MVA rating of the aggregate generating unit transformer is N times the MVA rating of each generating unit transformer.

Any internal series impedances of the aggregate generating unit, generating unit transformer and any intervening LV cables, when specified in ohms or in per-unit on a fixed system MVA base, have values 1/N times their values for each corresponding generating unit. Where, on the other hand, the model specifies these quantities in per-unit on the unit MVA base, their numerical values are identical.

Any internal shunt admittances of the aggregate generating unit, generating unit transformer and LV cables, when specified in Siemens or in per-unit on a fixed system MVA base, have values N times their values for each corresponding generating unit. Where, on the other hand, the model specifies these quantities in per-unit on the unit MVA base, their numerical values are identical.

Implicit in these scaling principles is a requirement that the underlying model of the unit is also capable of representing the aggregate of N units when configured with the larger MVA rating. If appropriate, the model may be coded to indicate the level of aggregation explicitly in the model configuration (for example, by including either each unit size or the number N of identical units as a configuration parameter). However, any necessary change to model configuration or settings beyond those stated above when switching between an individual unit and aggregate representation, or between aggregate representations with different numbers of units, must be clearly documented in the *RUG*.

2.6.2 Representation of the collector systems in aggregate models

Special attention must be given to the aggregated representation of the MV 'collector system' that connects the MV terminals of the generating unit transformers and (usually) conveys the aggregate generated or consumed power to an MV collector bus at the relevant substation.

In the simplest case, all identical *generating units* are combined into a single aggregate, and the model specifies a single equivalent collector impedance connected between the MV collector bus and the MV terminal of the aggregate equivalent *generating unit transformer*. In this case, the recommended procedure for calculating the equivalent collector impedance is given in National Renewable Energy Laboratory (NREL) report NREL/CP-500-42886, "Method of Equivalencing for a Large Wind Power Plant with Multiple Turbine Representation"[14].

14 For reference, see Kosterov et. al., Method of Equivalencing for a Large Wind Power Plant with Multiple Turbine Representation, NREL, 2009.

3 Pre-Connection Model Assessment

In the pre-connection model assessment, *User* must perform a thorough investigation of the suitability of *RMS* and *EMT* computer model in a *SMIB* model and verify the *Generator* capability to meet the proposed performance standard. The *RMS* studies must cover all the relevant clauses indicated in Table 3 while appropriate subset of clauses should be covered for the *EMT* studies.

Before commencing a *model assessment* the *User* should seek details of the characteristics of Power and Water's *Regulated Networks* at the nominated *connection point* and tune the model to best meet the performance requirements of the NTC. The report prepared to document the tuning methodology is generally referred to as a *design report* (see section 3.1). The *User* must provide a complete model assessment report which includes the tuning methodology and the study assessment to meet the proposed access standard.

Power and Water undertakes a due diligence assessment (*model assessment*) of the *User* supplied computer model to assess its performance against the requirements of the NTC.

If these studies identify the *facility* is not meeting the requirements in the NTC then the issue may not be a shortcoming of the computer model itself. In some cases NTC compliance requires network augmentation and/or additional equipment installed within the *facility* to be compliant.

Table 3 NTC clauses typically assessed in a model assessment report

CLAUSE	DESCRIPTION	TYPICAL ASSESSMENT METHOD
N/A	Model parameter, setting and initialization check	• Confirm the RMS and EMT models are accurately modelled up to the connection point as per the Single Line Diagram (SLD) of the connection and all other data is consistent with the respective RUGs. • Verify the transformer impedances are as per Factory Acceptance Test (FAT) reports if available, network reticulation, earthing capacitor bank / filters and aligned with the respective references. • Demonstrate that model initialises in SMIB model at maximum and minimum fault level scenarios without warnings or errors generated in the PowerFactory output window (option 'Validate Initial Conditions' must be selected in the Initialisation options). • Demonstrate that the EMT models are initialized within 3 s and run for 30s to without any oscillations. • Demonstrate that, for each mode of operation, and at minimum, half and full output at maximum leading and lagging power factor, the model initialises and runs for a 10 second dynamic simulation without material fluctuation or drifting in terminal and connection point quantities.
3.3.8	Maximum Fault Currents	• Assess maximum three-phase, two-phase, 2-phase to ground and single phase-ground fault current contribution at the connection point.
3.3.5.1	Reactive power capability	• Plot reactive capability for individual generating units, and reactive capability at the connection point. • Confirm that limiter settings and protection settings align with reactive capability.
3.3.5.3	Generating Unit Response to Frequency Disturbance	• Ramp the equivalent external grid from nominal to maximum operating frequency and nominal to minimum operating frequency at 4 Hz/s, at unity and leading power factor for maximum and minimum source impedance at the connection point. • Verify the generator capability to withstand the given frequencies as per Technical code clause 3.3.5.3.

CLAUSE	DESCRIPTION	TYPICAL ASSESSMENT METHOD
3.3.5.4	Generating System Response to Voltage Disturbances	• Apply voltage disturbances at the connection point as given in 3.3.5.4 and verify the generating system protection system capability to maintain the agreed limits. • The above studies will be repeated for minimum and maximum source impedance cases for maximum active power at unity, maximum lagging and leading power factor as agreed in clause 3.3.5.1. As per 3.3.5.4 it is important that the generator should maintain Continuous uninterrupted Operation (CUO) within 90% and 110%.
3.3.3.5	Generating system response to disturbances following contingency event	• Assess transient stability for solid three-phase fault at the connection point for the maximum permitted fault clearance time (see NTC Figure 5 and 6). • Assess the generator capability for 3 phase voltage disturbances for 25%, 50% and 80% retained voltage profiles at the point of connection. • For variable generation technologies with low voltage ride through (LVRT) function, apply a voltage disturbance closer to the LVRT limit and verify the correct operation. • Conduct number of unbalance fault studies. • Assess continuous uninterrupted operation for series of disturbances within 5 minutes period as described in clause 3.3.5.5.(d). • Assess the capacitive and inductive reactive current capability during the disturbance. • Assess the reactive current rise time and settling time for asynchronous generators. • Assess the 95% of active power recovery time after fault clearance. • Overlay transient overvoltage curve from NTC figure 18 in section 17.1.1 with voltage response for solid three-phase fault and solid two-phase fault at the connection point and verify the generator is within the specified limits. • Assess post-fault voltage recovery. In the simulation plots, identify when limiters operate, and identify at what time the voltage recovers to 0.8 pu and 0.9 pu. • For synchronous machines, assess the Critical Fault Clearing Time (CFCT) at maximum active power, maximum leading power factor in the maximum source impedance case.
3.3.5.7	Partial load reduction	• Assess continuous uninterrupted operation for load rejection studies as described in the clause 3.3.5.7.
3.3.5.11	Frequency Control	• Verify the dead band and droop settings. • Assess the generator capability to decrease the power for frequency increase beyond the dead band. • Subject to energy source availability, assess the generator capability to increase the power for decrease in frequency beyond the dead band.
3.3.5.13	Voltage and Reactive Power Control	• Assess voltage step response settling time at minimum, half and maximum active power output, at unity, maximum lagging and maximum leading power factor, for the minimum and maximum source impedance cases by applying 5 % voltage steps. • Assess limiter settling time by applying appropriate steps.

CLAUSE	DESCRIPTION	TYPICAL ASSESSMENT METHOD
		• For synchronous machines, apply 10 % impulse to assess excitation system ceiling voltage.
3.3.5.14 (D)	Ramping Rates	• Demonstrate the generating units ramp rate capability from minimum to maximum active power output and maximum to minimum active power output at a rate not slower than 5% of nameplate rating per minute.
3.3.5.15	Inertia and Contingency *FCAS*	• Assess the generating system inertia and Contingency FCAS capability as defined in Figure 9 of clause 3.3.5.15 of the NTC.
2.6.2	Dynamic Stability	• Assess damping ratio for small disturbances (voltage step changes) and large disturbances (faults) for minimum and maximum source impedance over the operating capability of the generating system. • Conduct eigenvalue study and present root-locus plot identifying local and, if relevant, inter-machine modes.
2.3.1, 16.2 & 16.3	Power Frequency Voltage levels	• Undertake suitable studies for load models based on type, size and location. This may include voltage step change studies and transient stability studies.
3.6.7	Power Factor Requirements	• Undertake calculations or simulations to assess power factor range at the connection point.

All simulation plots must, as a minimum, include terminal and Point of connection voltage, active power, reactive power, applied input signal (e.g. voltage reference step change, grid voltage step change) and other relevant signals (e.g. PSS output, SVC reactive power).

3.1 Model tuning

This section provides general information regarding the tuning methodology and requirements for synchronous generators. The methodology should be adapted based on plant functionality and technology type.

A *design report* must include at least the following:

- Open-loop gain margin and phase margin of the AVR and Generator. The gain margin and phase margin shall be compared with values that are considered good design practice of 6 dB and 40 degrees respectively.
- Unsynchronised step response settling time.
- The selection of PSS inputs, the nature of the speed measurement (if applicable), and justification for selection of washout filter settings and PSS output limits (generally 5 to 10 %).
- Details of system Pvr transfer functions (including system conditions and generator operating points) used to tune PSS.
- Root locus plots demonstrating selection of optimal PSS gain for maximum and minimum source impedance, operating points across the generators capability, and for relevant combinations of machines online (for example, 1, 2 and 4 machines online for a generating system comprising 4 machines).
- Demonstrate that damping is positive over the frequency range of 0.1 to 2.5 Hz (see clause 3.3.5.13(b, 2, (iii) of the NTC).
- Tabulate eigenvalue results (damping, damping ratio and frequency of oscillatory modes) and voltage step-response settling time results for:
  - Maximum and minimum source impedance, for relevant combinations of machines online; for
  - Operating points across the generating units capability without engaging limiters (typically at minimum, half and full active power output, at unity power factor and maximum leading and lagging power factor); and
  - Operating points across the generating units capability which do engage limiters (typically at minimum, half and full active power output, at maximum leading and lagging power factor).
- Assess large disturbance damping ratio in response to solid three-phase fault at the connection point.

Note that clause 2.6.2 and clause 3.3.5.13 of the NTC state damping ratio and settling time requirements.

Please contact Power and Water prior to commencement of model tuning to discuss and agree on control system configuration and tuning methodology.

3.2 Model acceptance tests

In cases where a *User* seeks to develop a *facility* with a particular technology type, but where a site and/or *connection point* has not yet been selected (e.g. as part of an Enquiry), the *User* may seek to have Power and Water provide an initial assessment of the computer model and associated information against the requirements of the NTC and the *Generator and Load Model Guidelines*.

This assessment would be conducted using an infinite bus model for a range of system strengths to emulate different connection locations. This assessment would therefore not assess electromechanical interactions with generators, which could later be assessed using the complete model of the Power and Water's *Regulated Networks* once the *connection point* is known.

4 Model Documentation Requirements

This section describes the requirements for model block diagrams and *user manual* documentation.

4.1 *RMS* model block diagrams

Block diagrams must be submitted alongside all *RMS* models. The following requirements apply to model block diagrams:

- The model block diagrams must illustrate all input and output signals including set-point signals on the model block diagrams and model frames, and clearly illustrate the interconnection of the various functional controllers.
- The model block diagrams must illustrate all derivative states including derivative state variable names consistent with the block diagrams.
- All required control and output signals should be available for dynamic (*RMS*) simulations and clearly illustrated on the model block diagrams. These signals would typically include, but are not limited to the following:
  - Active and reactive power.
  - Machine and exciter current and voltage.
  - Applicable set-points, including:
    a. Active power set-point.
    b. Frequency and/or speed reference set-point.
    c. Voltage set-point.
    d. Reactive power and/or power factor set-point.
    e. Where applicable, park controller, capacitor bank and SVC set-points, etc.
  - Other signals depending on the technology type.
- The model block diagrams must clearly illustrate whether limits are windup or non-windup,[15] and provide details as to which state variable is limited and the relationship between the limit value and state variable that is being affected by that limit. For example, for a lead-lag function, whether the state variable or the feedback to the 'integrator' within the equivalent lead-lag representation is limited.[16]
- The model block diagram documentation must include descriptions of any arithmetic or mathematical functions, such as protection events or voltage ride-through sequences.
- The model block diagrams must show all relevant non-linearities, such as limits, arithmetic or mathematical functions, events, dead bands and saturation.
- The model block diagrams and documentation must show all controller settings and settings ranges. Non-configurable settings should be identified on the block diagrams.
- The model block diagram documentation must identify any internal integration algorithms.
- The model block diagrams must identify the lookup table interpolation method (e.g. spline, linear).
- Settings shown on the model block diagrams must align with the computer model.
- Where a controller uses input measurements or control outputs, these must be appropriately configured and identified on the functional block diagrams.

4.2 Releasable *User* guide

A Releasable *User* Guide must be submitted to Power and Water with the computer model. As indicated in *NTC* 3.3.4 (c), two separate releasable *user* guides for *RMS* and *EMT* models should be provided. The Releasable *User* Guide must contain sufficient information to enable Power and Water to use the computer model to carry out power system studies for planning, design and operational purposes in accordance with clause 1.7.1 (b)(5) of the *NTC*. The *RUG* must be written such that any *User*, without any prior knowledge of the plant, would be able to successfully perform studies.

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[15] See Benedito et. al., A Circuit Approach for the Computer Modelling of Control Transfer Functions, PSCC, 2002.

[16] See Kundur, Power System Stability and Control, EPRI, 1994, page 360.

Releasable *User* Guide should not contain confidential information that cannot be released to third parties.

Information to be provided in the *user manual*, must include, but not limited to the following:

- Information that is necessary to allow modelling of the plant (in the case of generation, both each generating unit and generating system) for connection assessment and other power system studies.
- Information about how the model parameter values vary with the operating state or output level of the equipment or with the operating state or output level of any associated equipment (e.g. excitation system automatic and manual control, configuration of voltage and power factor control modes).
- Description, site specific values, ranges of all configuration parameters, control system settings, component trip/status codes used in the *RMS* and *EMT* models.
- Protection system settings and algorithms relevant to load flow or dynamic simulation studies (e.g. under- and over-voltage or frequency protection settings).
- Any special control or protection schemes that are relevant to load flow or dynamic simulation studies (e.g. runback schemes, low voltage ride-through schemes, active power reduction schemes).
- Information provided in accordance with clause 3.2.2 of the NTC only to the extent that the information is not a part of the model or the model parameters and that it is reasonably necessary to allow modelling of the generating unit, generating system, load or related equipment in power system studies.
- Connection point details including single line diagrams, its parameters and values, location, associated network augmentations or modifications (if applicable) and other relevant connection information, sufficient to identify where to connect the equipment in the Power and Water's *Regulated Networks* power system models.
- Instructions on the use and operation of the *RMS* and *EMT* models, including operational limitations, but not limited to:
  - Expected operational practice.
  - Specific software simulation setup such as integration algorithm, EMT or RMS simulation options, etc.
  - Special setup for any associated auxiliary equipment or reactive compensation equipment.
  - Details of modifications required to "scale-up" an aggregated generating system model and/or complex load model.
  - Special setup required to enable, disable and configure protection functions.
- For a *generating system, generating unit* or *load* incorporating any power electronic devices, a description of how that device should be included in the short-circuit fault calculation.
- Any other information the *User* considers relevant to the performance of the *equipment* for the model's intended use or to achieve the relevant accuracy requirements.

4.3 Model development report

User must provide a *model development report* which details how the model was developed. It is expected that the model will be rigorously derived from design information. The report should include the guidance to allow bi-directional translation of parameters from controller to the model.

4.4 Other documentation

As applicable, other documentation should be provided such as follows:

- Equipment data sheets associated with the computer model.
- Protection settings and model tuning report (*design report*).
- For inverter connected generators, fault ride-through performance and validation reports.
- Other relevant documentation, such as model validation reports or type test reports.

5 Model Accuracy Requirements

5.1 Steady-state model accuracy requirements

The steady-state computer model accuracy requirements apply to both loads and generating systems, including dynamic reactive plant. The general requirements are as follows:

- The difference between the actual and simulated response of any measured quantity must not exceed 10%.
- The model must accurately represent the performance of the *load*, *generating unit* or *generating system* at its terminals (or *connection point* for aggregated model) and not show any characteristics not present in the actual *equipment* response.

5.2 Dynamic model accuracy requirements

5.2.1 Accuracy locations

Model accuracy must be demonstrated for all components within a plant that impact on power system dynamic performance.

Synchronous plant typically requires demonstration of model accuracy at each generating units' terminals.

Power electronic interfaced asynchronous technologies (such as wind and photovoltaic solar generating systems) may consist of several generating units, plant controllers, Reticulation Networks and dynamic reactive support devices such as STATCOMs and synchronous condensors. As such, demonstration of model accuracy must occur at:

- Connection point or high voltage terminals of plant transformers.
- Reticulation Network collector bus to which an individual item of dynamic plant is connected.
- Generating units (for each different type of generating unit, including batteries).
- Terminals of each type of dynamic reactive support device, such as STATCOMs and synchronous condensers (if applicable).
- Central park-level controllers, and any other overarching coordinated controllers.

5.2.2 Accuracy criteria[17]

For any control system models, the overall linear response over a frequency bandwidth of at least 0.1–5 Hz must be within the following tolerances:

- magnitude must be within 10% of the actual control system magnitude at any frequency; and
- phase must be within 5 degrees of the actual control system phase at any frequency.

For time domain responses that include non-linear responses or performance, as well as responses to switching or controlled sequence events (e.g. operation of fault ride-through schemes and converter mode changes), the key features of the response are within the following tolerances:

- rapid slopes in the actual plant response, compared with the simulated response must be within the less restrictive of:
  - ±10% of the change; and
  - from the start to the finish of the slope, a difference of less than 20 ms.
- for rapid events caused by control sequences (such as some fault ride-through control schemes) or switching events, the sizes of peaks and troughs (measured over the total change for that peak or trough) must be within 10% of the change;
- oscillations in active power, reactive power and voltage in the frequency range 0.1 to 5 Hz must have damping[18] and frequency of the oscillation within 10% of the actual response of the equipment. The phase of the oscillations (relative to the other quantities - e.g. active power versus reactive power) must be within

17 Accuracy requirements reflect those specified in the AEMO Power System Model Guidelines, 2018. Appendix E of the AEMO guidelines provides example illustrating how accuracy requirements may be assess from time domain responses

18 Measured as a rate of decay of the oscillation (e.g. halving time).

5 degrees in terms of the dominant oscillatory mode. This does not apply to rapid events under item (b), but does apply to any subsequent oscillations;

- the timing of the occurrence of the rapid slopes, events or the commencement of oscillation described in paragraphs (a) - (c) must be consistent with the *equipment* characteristic that initiates the response.[19]

Taking into account the *voltage* at the *connection point*, at any point during the simulation, the deviation of the equipment model response from the actual equipment response for active power and reactive power must not exceed 10% of the total change in that quantity. During periods of oscillatory behaviour, this criterion applies to:

- the first cycle of the oscillatory response after the transient period (i.e. if associated with a fault, then after clearance of the fault and the transient recovery from the fault); and
- after the first cycle of the oscillatory response, to the upper and lower bounds of the envelope of the oscillatory response.

The final *active power* or *reactive power* value at which the model settles is within the more restrictive of:

- the final value at which the actual equipment response would settle ±2% of the equipment's nameplate rating; or
- the final value at which the actual *equipment* response would settle ±10% of the total change in the final value of the quantity.

Where measurement results can be shown to have been affected by changes in supply source, this shall be taken into consideration when assessing this criterion, so long as sufficient evidence can be shown to demonstrate the cause of the input power change.

The model response must not show characteristics that are not present in the actual equipment response.

Assessment of compliance with these requirements can be conducted by a combination of visual inspection of results, results plots including accuracy tolerances, and mathematical calculations. Particularly for cases where the modelled response deviates from the simulated response there is a need to demonstrate the extent of that deviation and the impact on plant performance. Note that for convenience it is acceptable to apply accuracy tolerance bands to the simulated response rather than the measured response.

5.2.3 Balanced and unbalanced disturbances

Positive-sequence simulation models are expected to meet the model accuracy requirements specified in Section 5.2 for balanced Disturbances. For comparison of the response to different types of unbalanced faults a positive-sequence model can still be used if it can achieve the required accuracy requirements[20] When a positive-sequence model fails to meet the accuracy requirements by a material margin, the use of EMT-type or three-phase *RMS* simulation models is permissible provided that the simulation model chosen can demonstrate compliance with the model accuracy requirements.

5.2.4 Stable response for the entire intended operating range

The model initialisation and operating range should be consistent with the actual equipment design in regard to the following:

- The entire range of active power.
- The entire range of reactive power/power factor (including limits of reactive power generation and consumption).

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19 Switching events or rapid control actions initiated as a result of passing a threshold level in a measured quantity and any time delays in the design of the equipment should be straightforward to assess. The recommended fall back criteria for this requirement are:

a) the response must be explainable; and
b) any inconsistency in the response should lead to an investigation to establish a plausible reason for the inconsistency. A revision to the model should be considered in the latter circumstance.

20 When using positive-sequence type models for simulation of unbalanced Disturbances, the Applicant must provide information on any possible changes in the model parameters to simulate various types of faults.

5.2.5 Stable but different response when the response becomes limited

Models must demonstrate accurate and stable behaviour when the limits implemented within the plant control systems are reached. For example, activation of a synchronous plant under- or over-excitation limiter should not cause model instability, or produce the same response for a scenario where limiters have not been activated. Output of each limiter must be available for plotting to demonstrate that it acts for intended operating conditions, and do not falsely activate when the limit is not reached.

5.2.6 Unstable response when operated beyond its intended operating range

Where network conditions, energy source limitations, Disturbances etc. would cause the plant to become unstable, activate protection mechanisms, or otherwise cease operation, it is expected that the model would reflect the plant's response. Models should not be created such that they continue to operate stably outside of the plant's operating envelope[21].

5.2.7 No unexpected or uncharacteristic responses

The model must not show characteristics that are not present in the plant response, both in terms of the electrical response and modelling numerical artefacts.

21 Models that cease output when exposed to conditions outside the intended operating range are not considered inferior, however, the cessation of the model output must not result in instability or crashing of the underlying simulation tool.

6 R2 Model Validation and Performance

6.1 General

Clause 5.4 of the NTC identifies that data associated with the relevant *access application* must be validated and submitted to Power and Water following tests. The data to be validated includes, but is not limited to, the computer model, generator and control system parameters. The schedule of tests for performance verification and model validation for synchronous *generating units* is provided in Attachment 5 of the NTC, which also includes details of the measurement signals. Additional tests may be required to be conducted to validate the models if deemed necessary by Power and Water. Test requirements for non-synchronous *generating systems* and *load*s will be specified by Power and Water.

Clauses 5.1.1 and 5.1.2 of the NTC describe the obligations of both Power and Water and *Users* for the preparation of commissioning programs, test procedures, setup of test *equipment* and provision of test data. It should be noted that only approved settings-may be applied, and that control system settings or configuration may not be modified without prior approval from Power and Water as per clause 3.3.2 of the NTC.

6.2 Test witnessing

In accordance with clause 5.1.1 of the NTC, Power and Water has the right to witness performance testing. During test witnessing, Power and Water assesses whether:

- tests are conducted in accordance with the approved test procedure; and
- tests pose any risk to *power system security* or *stability*, safety or to other *Users*, in which case there may be a requirement to omit particular tests (for example, for a *synchronous generator*, omit some tests with the Power System Stabilizer out of service) or cease testing.

In lieu of attending site for test witnessing, Power and Water may request the *User* submit test results and plots with relevant performance analysis to Power and Water.[22] For commissioning tests there may be a requirement for results to be provided before Power and Water provides approval for *generating units* to be synchronised and before they can operate at progressively higher *active power* output levels. Following and such tests, in accordance with NTC Attachment 5, A5.2 and Schedule S3.2 the *User* must provide test results to Power and Water.

All test results and associated relevant information including final transfer function block diagrams and settings of automatic *voltage* regulator, *power system* stabiliser, under excitation limiter and over excitation limiter must be forwarded to the Power and Water within 10 *business days* after the completion of the test or test series. Power and Water may also request specific test result information for loads which require a computer model.

6.3 R2 data, model validation and performance report

As stated in Attachment 3 of the NTC, data is coded into categories, according to the accuracy of the information available. Throughout the process of a new *connection application* or modification to an existing *facility*, data accuracy is refined over time until it is validated during commissioning tests and R2 validation tests.

Following completion of tests an *R2 data, model validation and performance report* must be submitted to Power and Water for approval within 3 months' time or as otherwise agreed between Power and Water and the *User*. The *R2 data, model validation and performance report* must include the following:

- Details of the tests undertaken.
- Details of any discrepancies between the tests conducted and the agreed test procedures.
- Results, measurements, analysis techniques used and any relevant information to assist Power and Water with performing a due diligence assessment.
- Specific assessments of the performance against relevant clauses of the NTC[23] should be documented, and illustrated on results plots. The performance should also be tabulated in a registered performance spreadsheet in the format defined in Table 4.

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[22]These results must ultimately be included in the *R2 data, model validation and performance report* (see Section 6.3**.**)

[23] If there are differences in R1 and R2 parameters, there may be a requirement to demonstrate the impact of these differences on the technical performance.

- Model validation assessment with respect to the requirements outlined in this document, including overlays of measured and simulated responses with accuracy bands.
- Final model and model documentation (computer model, block diagrams and settings, updated *user* manual, etc.).
- Updated access application with registered (R2) data. For upgrades or modifications this should be the updated R2 data relevant to the upgrade. Consistent with these Guidelines, parameters to be derived from on-site tests are as follows:
  - Parameters designated as "R2" in the NTC Attachment relevant to the facility.
  - Parameters, other than those designated as "R2" in the NTC that contribute most significantly to the accuracy of the model for fault, voltage and frequency disturbances in the power system, must be derived from on-site tests, where possible. Where parameters are not designated as "R2" in the NTC, there remains the requirement to validate the value of these parameters (in aggregate) through the validation of the overall performance of the system, device, unit or controller to which they pertain.
- If there is a network disturbance occurred during the period of testing, as part of the compliance program, applicant must submit the overlays of the actual disturbance data against the simulated disturbance data.

Table 4 Performance standard table format

CLAUSE	SUB-CLAUSE	CLAUSE DESCRIPTION	COMPLIANT (YES/NO/EXEMPT)	DETAILED DESCRIPTION OF PERFORMANCE INCLUDING REFERENCES	POWER AND WATER REMARKS
Clause and relevant NTC version	Sub-clause	Clause description	If exempt, include relevant supporting information	Details of simulated or validated performance and specific references.	-

6.4 Review of test reports

After receiving complete test reports and associated supporting information, Power and Water will advise one of the following outcomes:

- Acceptance of the test report, associated data, parameters, model(s) and performance assessment.
- Request for further information, further testing and/or model changes.

If an *R2 data, model validation and performance report* is not accepted, Power and Water will inform the *User* of the reason(s) and work collaboratively with the *User* to expedite resolution of any issues preventing acceptance of the test report. Sufficient evidence has to be provided by Power and Water if it requires the *User* to carry out additional tests. Power and Water and the *User* must co-operate to reach agreement on the scope to address any deficiencies within a reasonable period.

6.5 Post connection model validation

Congruence between plant and model dynamic responses for some aspects may be difficult to demonstrate until a network Disturbance occurs. It is, therefore, necessary that the Applicant develops a continuous monitoring program to demonstrate model accuracy for all major items comprising the plant (i.e. both at a generating system and generating unit level). The Applicant must submit the model overlays to the Power and Water for analysis and model verification as soon as possible following such a Disturbance.

6.6 Non-conformance with model accuracy requirements

Power and Water may accept the *R2 data, model validation and performance report* as an accurate reflection of the *facility*. This does not necessarily mean the *facility* is compliant with the NTC. Should the final performance not comply with the requirements of the NTC there is a requirement for this to be addressed. Options may include the following:

- Changes to installed plant (settings, configuration, or additional plant requirements).

- By applying the process in clause 12 of the NTC, the *User* may apply for a derogation to vary the performance requirements captured in its performance standard. The *User* must submit that application in a form reasonably required by the Network Operator and following the process specified in clauses 12.1 (d) and (e) of the NTC.
- Power and Water may direct the *User* to operate at a particular output or in a particular mode of operation until the matter is resolved. Clause 5.6.2(c) of the NTC states:
  - "… the Network Operator may direct the relevant User to operate the relevant generating unit at a particular generated output or in a particular mode until the relevant User submits evidence reasonably satisfactory to the Network Operator that the generating unit is complying with the relevant technical requirement. A Direction under this clause 5.6.2 (c) shall be recorded by the Network Operator".

It should also be noted that NTC clause 5.6.1 describes *Users* obligations to undertake testing if a requesting party believes that equipment owned or operated by, or on behalf of, another party may not comply with the *Access Code*, the NTC or the *connection agreement*.

6.7 Registered data and performance standards

The generators registered data and performance standards consist of the following artefacts:

- Test report(s) including:
  - R2 data, model validation and performance report (with R2 data and performance standards attachments).
  - Model tuning report (design report).
  - Various study reports conducted by Power and Water on behalf of the proponent to assess performance of the facility with respect to the NTC and the relevant connection agreement. This must include any due diligence studies conducted by Power and Water following receipt of the R2 data, model validation and performance report.
- Final computer model and block diagrams.
- Approved exemptions from the requirements of the relevant version of the NTC.
- Any special conditions specified in the *connection agreement*.

There is a requirement for *Users* to demonstrate ongoing compliance with the NTC in accordance with an agreed compliance monitoring program (Please refer *Technical code* clause 5.4 (d)).

7 Generator Modelling Change

While each submitted model must be a faithful representation of the plant at the time of submission, it is natural to expect that updates to the model will be issued from time to time by the supplier or other party responsible for the model.

It is especially important that alterations to the plant or its control firmware that alter the plant's dynamic performance are correctly reflected in an updated simulation model. It is also possible for several reasons for model updates to be proposed without any change to the plant.

8 Management Requirements

8.1 Changes to generator models during connection process

Following the R1-model provision from the *user* during the connection process, Power and Water is required to be notified if there are any material change in the model submitted by the *User*. The change includes but not limited to the following:

- Updates to improve computational or numerical performance of the model code.
- Updates to incorporate additional functionality provided with newer versions of the same equipment, or to allow greater flexibility in configuration.
- Updates to broaden the scope of the model code to represent multiple equipment types within the one family, by varying the configuration parameters.
- Updates to correct ‘bugs’ or unanticipated performance issues, particularly to reflect novel ‘use cases’ arising during long term operation.

In general, an update to a model held by Power and Water for specific power system plant, in the absence of any alteration to the plant itself, will be considered only where it is relevant to the performance of that element in ongoing dynamic assessments (including the performance of the simulation software itself). Where the update is relevant only to accommodating future plant using the same model, it is generally expected that the existing plant will continue to use the ‘old’ model, which will continue to perform adequately after new plant are introduced using the updated model version.

The updated model’s acceptance by Power and Water will be subject to additional dynamic studies conducted by Power and Water at the *User*’s expense.

8.2 Changes to generator models due to the *User* proposing to alter a commissioned operational generating system

The process to manage the potential change to model due to *User* proposing to alter generating system is described in *NT NER* 5.3.9. This document (Generator and Load Modelling Guideline) applies in regards to modelling change associated to the proposed modification/alteration of a generating system.

8.2.1 Updates to account for changes in the plant including parameter changes

Updates to plant firmware or settings that alters dynamic performance or protection operation must be captured in a revised dynamic model(s) to be submitted to Power and Water. The revised dynamic model(s) must be accompanied by a report that shows the revised model(s) and its settings meets all accuracy requirements to ‘R1[24]’ level, prior to acceptance of performance standards for the altered plant. This will be followed by on-system tests as part of plant commissioning, including tests to validate the revised dynamic model(s) to R2 level.

The updated model’s acceptance Power and Water will be subject to additional dynamic model acceptance testing conducted by Power and Water at the Applicant’s expense.

8.2.2 Updates to account for later versions of simulation tools

It may be necessary for Power and Water to move to later versions of *RMS* and *EMT* simulation tools. Ideally, later versions of these simulation tools will be backwards-compatible with existing models.

However, if Power and Water deem it necessary that a later version of a simulation tool is required to undertake studies, and an Applicant’s existing model no longer functions correctly in the later version of the simulation tool, an update to the Applicant’s model is required to provide compatibility with the later version of simulation tool. This model update is required from the Applicant without cost to Power and Water. These updates may be required at any point in the life of the plant.

[24] R1 means pre connection.

9 Document history

DATE OF ISSUE	VERSION	PREPARED BY	DESCRIPTION OF CHANGES
31/07/2020	Draft v1.0	D Bones	Draft for consultation
9/10/2020	Final v1.1	D Bones	Incorporates revisions following consultation