

# TURBINE GOVERNOR TESTING AND MODEL VALIDATION GUIDELINE

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This document has been created by Network Development – Systems Capability and will be reviewed from time to time.

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## Glossary

|                  |   |
|------------------|---|
| AEMO             | Australia Energy Market Operator  |
| AGC              | Automatic Generation Control  |
| CHP              | Combined Heat and Power   |
| CCP              | Combined Cycle Plant  |
| Data Sheets      | Generating System Design and Settings Data Sheets   |
| Dead band        | The magnitude of the change in the steady state speed within which there is no resulting measurable change in the position of the governor controlled steam valves for steam turbine or the fuel valves for gas turbines or diesel engines. I.e. the insensitivity of the speed/load governing system expressed as a percentage of rated frequency. |
| Droop            | The percentage of speed or frequency change as a function of power or valve/gate position change  |
| FCAS             | Frequency Control Ancillary Services  |
| GT               | Gas Turbine   |
| HP               | High Pressure   |
| IP               | Intermediate Pressure   |
| IGV              | Inlet guide vanes   |
| HRSG             | Heat-Recovery Steam Generator   |
| LP               | Low Pressure  |
| Model Guidelines | AEMO Generating System Model Guidelines   |
| NSP              | Network Service Provider  |
| NER              | National Electricity Rules  |
| NEM              | National Electricity Market   |
| NEMDE            | National Electricity Market Dispatch Engine   |
| PSH              | Pumped Storage Hydro  |
| R2               | Registered data that consists of data validated after connection derived from on system testing   |
| SCADA            | Supervisory Control and Data Acquisition  |
| ST               | Steam Turbine   |
| TNSP             | Transmission Network Service Providers  |

# 1 Introduction

## 1.1 Purpose of document

This document has been developed to provide Generators with test guidelines suitable for demonstrating compliance with agreed performance standards, as well as deriving validated turbine-governor model data.

While this guideline provides an outline of the types of tests that may be conducted to validate turbine-governor models and demonstrate compliance with performance standards, it is the responsibility of the Generator to ensure that test plans are adequate to derive all the data appropriate for compliance assessment and modelling of various systems used in their installation.

The measurement quantities, proposed tests, and testing details described in this document are general. The relevant NSP and AEMO may request additional information during the commissioning planning phase and R2 testing process.

## 1.2 Legal and regulatory framework

Schedule S5.2.4(b) of the National Electricity Rules (the Rules) requires Generators to provide Network Service Providers (NSP) and AEMO with a range of data relating to their generating units, control systems and protection systems, sufficient to model the plant and assess its steady state and dynamic performance.

The Rules require AEMO to keep in place a *Generating System Design Data Sheet*, a *Generating System Setting Data Sheet* (Data Sheets) and *Generating System Model Guidelines* (Model Guidelines). These documents provide detail regarding the information and data that must be provided for each type of generation technology.

The data required is categorised by the stage of development of the installation, denoted as standard planning data (S), detailed planning data (D), and registered data (R1 and R2). The data is used for modelling generating systems (including generating plant, control and protection systems) in network analysis software that is used to assess and plan the security and performance of the electricity system.

With reference to governors, the data provided is also used by the NSPs and AEMO to assess the performance of turbine governors against the technical requirements of S5.2.5.11 and S5.2.5.14, in response to a connection application submitted under 5.3.4.

## 1.3 Related policies and procedures

This document is related to other policies, procedures and guidelines produced by AEMO and should be read in conjunction with the following:

- AEMO Generating Systems Model Guidelines [1]
- AEMO Commissioning Requirements for Generating Systems [2]
- Data and model requirements for generating systems less than 30 MW [3]

## 2 Guideline overview

With increased uptake of intermittent generation around the NEM, frequency control and stability is an increasingly significant aspect of power system operation and performance. Increased analysis of frequency control capability therefore drives a growing need for more detailed turbine-governor modelling.

While some non-synchronous generation technologies have the capability to provide frequency control capability, this guideline focuses on the turbine governor performance assessment and model validation testing methodologies associated with only synchronous generation technologies. The scope of this document is therefore limited to technologies including steam turbines, hydro turbines, gas turbines and reciprocating engine power plants. Future reviews of this guideline may expand to address the frequency control capabilities potentially provided by some renewable energy sources.

## 3 Turbine governor dynamic model requirements

All turbine governor models are required to meet the functional and accuracy requirements defined in AEMO's Generating System Model Guidelines [1]. Deviation beyond the model accuracy requirements may be permitted in specific circumstances as agreed between AEMO, the relevant NSP and the generator.

The model must accurately represent the performance of the generating unit for all possible operating conditions except for situations where the generator is offline, i.e: connection point circuit breaker is open<sup>1</sup>. It must therefore respond accurately when compared to the actual generating unit response when simulating a recorded network disturbance or test.

Governor models are employed in a variety of studies by AEMO and the NSPs, such as the reconstruction of major system incidents and frequency control assessments. Additionally the models may be utilised in specialised system studies such as system restart studies, system islanding assessments and other such analysis not explicitly covered under S5.2.4(b)(5).

On this basis, simulations using governor models can extend in duration to several minutes. As such, all phenomena with a dynamic response time of up to at least one minute that can have a material impact on the dynamic response of the generating unit, would need to be modelled<sup>2</sup>. This may include; boiler dynamics, fast valving in steam turbines, load rejection detection logic in gas and steam turbines, and any switching logic that may be invoked to alter FCAS response characteristics (variable gain, dead bands etc). While AGC response is also a phenomena experienced during this time frame, at present there is no requirement to model AGC response.

All turbine-governor limiters such as temperature limiters or power limiters are also required to be modelled and should be appropriately validated through testing. The models should be robust across the generators full range of operation, including islanded operation where this is relevant (black start stations for example).

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<sup>1</sup> Under such circumstances, it is acknowledged that some governor control settings may differ compared to those applied when synchronised to the power system.

<sup>2</sup> This is on the basis that the frequency apex (maximum deviation) for a contingency event will normally occur within approximately 10 seconds, followed by a period of frequency stabilisation and recovery. Given other modelling uncertainties, it is accepted that simulation accuracy beyond 60 seconds may begin to diverge from reality to some degree.

## 4 Performance testing

The performance of turbine governors is relevant to the following NER technical clauses:

- S5.2.5.11 Frequency control.
- S5.2.5.14 Active power control.

For altered generating systems, it is acknowledged that 5.3.9(d) imposes a requirement for governor control systems to be assessed against S5.2.5.7, S5.2.5.11 and S5.2.5.14. Unless AEMO and the NSP otherwise agree, governor performance shall be assessed only against S5.2.5.11 and S5.2.5.14.

The general principles that apply to the **performance testing** described in this guideline are as follows:

- Measurements should be taken using independent high speed monitoring equipment. Where this is not practicable, SCADA systems or internal data loggers<sup>3</sup> (provided the speed of response is appropriate for the time constants to be validated) may be utilised as agreed prior with AEMO and the NSP.
- The governor’s tested performance should be assessed against the success/acceptance criteria defined for each technical clause as per Table 1 below.
- Testing should be conducted over a range of outputs up to the generating units registered maximum output. In cases where the achievable maximum output is limited by ambient temperature, lake levels or other environmental variables, the generating unit should be tested at its highest possible output, with subsequent modelling results used to confirm compliance at registered maximum output.
- Performance tests should be undertaken when system frequency is as stable as possible. Tests that are completed during network frequency disturbances must be repeated when the system frequency is more stable. Tests that are affected by background system frequency deviations may still be used for model validation exercises as discussed in Section 5.

| NER clause     | S5.2.5.11 Frequency control   |
|----------------|---|
| Proposed tests | <p>a) Demonstration of stable frequency control under normal operating conditions through application of frequency steps sufficient to decrease or increase generator output by an amount in accordance with the generators performance standards requirement.</p> <p>b) Demonstration of stable frequency control at turbine limits through application of frequency steps sufficient to activate any applicable limiters.</p> <p>Magnitude of frequency step<sup>4</sup> applied should be appropriately derived taking into account the governor dead band and droop as expressed in the equation below.</p> $\Delta P \text{ or } \Delta \text{Valve/Gate Position} = \frac{\text{Bias}}{\text{Droop}} \times P_{\text{MAX}}$ |

<sup>3</sup> For internal data loggers it may be necessary to validate the performance of the power transducer, as its response may need to be taken into account when comparing measured and simulated plant performance, i.e.: what is measured is not necessarily how the machine has physically responded.

<sup>4</sup> A step change input signal must be applied as a step and not as a ramp. If additional logic is activated when the governor is under test to limit the rate or magnitude of the step test applied, these must be disabled.

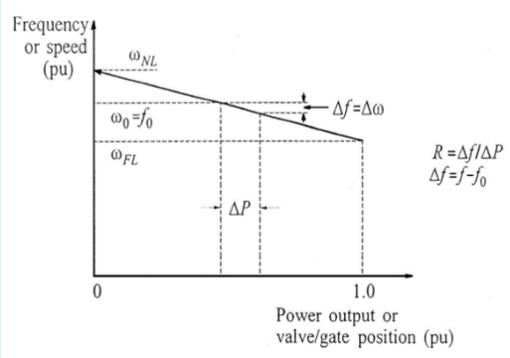
|                             |  |
|-----------------------------|--|
|                             | <p>Where the bias is with respect to nominal frequency (50Hz) and the droop is the percentage of speed or frequency change as a function of power or valve/gate position change as shown below.</p>  <p style="text-align: center;">Figure 1: Speed droop (P. Kundur 2013 [10])</p>  |
| <p>Acceptance criterion</p> | <ul style="list-style-type: none"> <li>a) Under normal operating conditions, the generator achieves required active power change, with any observed oscillatory response being adequately damped<sup>5</sup>.</li> <li>b) Following activation of the limiter, generator output is limited in accordance with the limiter settings and any observed oscillatory response is adequately damped.</li> </ul>  |
| <b>NER CLAUSE</b>           | <b>S5.2.5.14 ACTIVE POWER CONTROL</b>  |
| <p>Proposed tests</p>       | <ul style="list-style-type: none"> <li>a) Generator operated at constant output for a period of at least 10 minutes to demonstrate capability to maintain active power output in accordance with dispatch instruction.</li> <li>b) Positive and negative step or ramp changes applied to the active power reference, with each change held for at least one dispatch interval. The applied changes should emulate the generating units response to a change in dispatch instruction as issued by AEMO. The intent of this test is to verify the response of the generating unit to variations in NEMDE dispatch target, hence the type of test signal (ramp or step) and the point of signal injection, should be designed to achieve this objective.</li> </ul> |
| <p>Acceptance criterion</p> | <ul style="list-style-type: none"> <li>a) Generator achieves and maintains active power and, if required, is able to ramp linearly from one level to another with any observed oscillatory response being adequately damped.</li> </ul>  |

Table 1: Governor Performance Testing

<sup>5</sup> As defined in the National Electricity Rules Chapter 10 (Glossary)

## 5 Model validation testing

A number of standard library models for simulation of turbine governors in dynamic simulations are available in Siemens PTI PSS/E software. Examples include generic IEEE models as well as generalised manufacturer models such as GE (GGOV1) and Woodward (WEHGOV). Additional standard models are listed in Appendix 2.

While such models are advancements to common legacy models that were previously used, experience has shown that they are often a simplification of reality, resulting in simulated responses that may not meet the accuracy requirements of the Model Guidelines.

Model validation testing, also commonly referred to as R2 testing, entails the derivation and/or validation of generating system modelling data through physical testing of actual plant and equipment. It includes a range of tests and measurements to derive modelling data that ensures the simulated plant response matches the performance and behaviour of the actual generating system.

While it is a requirement for R2 parameters denoted as 'R2' in the Data Sheets to be directly derived from such tests, this may not be practicable in all situations. In such cases, it is considered adequate that model parameters be derived from curve fitting (parameter optimization) or confirmed through overlays of simulated and measured plant performance.

In accordance with S5.2.4(d), a generator is required to provide to AEMO information that updates data provided under S5.2.4(b) of the Rules and provide information to the NSP that updates data provided under NER S5.2.4(b)(5). The updated information is required:

- within 3 months after commissioning tests or other tests undertaken in accordance with clause 5.7.3 are completed;
- when the Generator becomes aware that the information is incomplete, inaccurate or out of date; or
- on request by AEMO or the relevant NSP, where AEMO or the relevant NSP considers that the information is incomplete, inaccurate or out of date.

The required data is denoted as 'R2' in the Data Sheets and includes the control system's functional block diagram parameters.

The general principles that apply to the **model validation testing** described in this guideline include:

- Measurements should be taken using independent high speed monitoring equipment. Where this is not practicable, SCADA systems or internal data loggers<sup>6</sup> may be utilised for testing, provided the speed of response is appropriate for the time constants to be validated. This should be agreed prior to the commencement of testing with AEMO and the NSP.
- The governor model's functional block diagram should be included in the proposed test procedures. Any measurement quantities to be recorded that directly relate to states and outputs in the block diagram should be identified in the block diagram, or referenced to the corresponding signal in the block diagram. Examples are provided in Appendix 1.

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<sup>6</sup> For internal data loggers, it may be necessary to validate the performance of the power transducer as its response may need to be taken into account when comparing measured and simulated plant performance, i.e.: what is measured is not necessarily how the machine has physically responded.

- All model validation testing should be performed over a broad range of operating conditions from minimum to maximum unit output.
- For existing governors, AEMO or the relevant NSP, may consider appropriate the use of results from on-line disturbance monitoring to review performance and validate existing models.

## 6 Steam turbine model validation

The type of governor, the steam turbine configuration and available turbine control modes will determine the level of modelling detail and testing required to ensure compliance with the generating system model accuracy requirements.

Characteristics of the various steam turbine configurations will also have an impact on the governing response of the generating unit. This should be captured within the model topology and subsequently validated. Examples of turbines types and characteristics to consider include:

- Re-Heat Turbines – Turbine re-heat contributes to the time delays experienced between valve movement and change in turbine power output. The time constant for re-heat being in the order of 5-10 seconds has a significant effect on the response of the governor and should therefore be considered in the model.
- Extraction Turbines – Steam extraction at the extraction stage(s) affects the turbine power output and may need to be considered in the model.
- Back-Pressure Turbines – For steam turbines used in co-generation applications, the sensitivity of the turbine power output to the demands of coincident processes may impact upon the governing response. It may therefore need to be considered in the model.
- Turbine Control Action – Steam turbines can employ various controls that affect governing response. An example of this is “coordinated control” which would require some boiler dynamics to be considered in the model.

### 6.1 Measurement quantities

The quantities to be measured will largely depend on the type of turbine and the level of modelling required to capture relevant performance characteristics. As a guide, measurements would typically include:

- The test signal applied.
- Governor speed/load reference signal/s.
- Active power output of generating unit/s as measured at terminals.
- Steam flow to the turbine sections.
- Control valve set points and actual value signals (actual position). For partial arc operation, the set point and position of each control valve should be recorded, as well as the main governor output signal used to schedule the individual valves.
- Main steam pressure (chest and boiler separately wherever possible).
- Turbine speed/s (all shafts in cross compound turbine configurations).

### 6.2 Model validation tests

Tests to validate various parameters of the turbine governor model will depend on the type of turbine, type of governor and complexity of model to be validated. Tests should generally include the tests detailed in Table 2 which seek to validate various aspects of what would normally be expected in a typical block diagram, as well as parameters denoted as R2 in the Data Sheets.

In Table 2, parameters that can be determined/validated from direct measurement are denoted as “non-tuneable” while those that are may be confirmed through curve fitting or similar non-exact methods are denoted as “tuneable”.

Table 2: Steam turbine model validation tests

| MODEL ELEMENTS                               | PROPOSED TESTS  | APPLICABLE MODEL PARAMETERS <sup>7</sup>  | PARAMETER TYPE |
|--|---|---|----------------|
| Deadband                                     | Application of positive and negative frequency steps of both equal and greater magnitude than the governor's deadband. Tests should result in an in active power output change for only steps of a greater magnitude than the deadband.   | Functional block diagram parameters   | Non-tuneable   |
| Governing droop                              | <p>Verification of speed droop through application of frequency steps. The resultant change in steady state active power should equal the expected change based on the equation below.</p> $\Delta P = \frac{Bias}{Droop} \times P_{MAX}$ <p>If the speed droop acts on valve reference rather than active power, <i>P</i> should be replaced with valve reference in the above equation.</p> | Functional block diagram parameters   | Non-tuneable   |
| Governor gain (s)                            | Proportional gain constant of the governor controls measured from input signal and corresponding valve position. If other gains such as derivative or integral gain are present, these should be similarly validated. To be determined via application of test signals to frequency and load reference inputs (as appropriate).   | Functional block diagram parameters   | Tuneable       |
| Turbine steady state characteristics         | Steady state measurements of steam flow, pressure and temperature at the various turbine sections should be used to determine the thermodynamic properties of the turbines. Derived power fractions should then be validated against manufacturer provided data.  | FVHP, FHP, FIP, FLP, FLP1, FLP2   | Non-tuneable   |
| Governor and turbine dynamic characteristics | Verification of governor and turbine dynamic characteristics through application of a range of frequency steps across the operating range of the turbine. Model parameters relating to dynamic performance characteristics such as boiler effects (where represented) should also be validated by comparing the relevant recorded signals with that of the model.                             | <p>Sustained / non-sustained (transient) response to frequency change</p> <p>Governor control system time constant(s)</p> | Tuneable       |

<sup>7</sup> Model parameters symbols are as per the Data Sheets. Other model elements may need to be validated as part of the functional block diagram parameters.

|                           |   |                                     |          |
|---------------------------|---|-------------------------------------|----------|
| Switched logic functions  | Parameters relating to switched logic functions such as FCAS, fast valving and others should be validated through the application of frequency steps above and below the activation threshold of the switched function.   | Functional block diagram parameters | Tuneable |
| Standstill valve response | As appropriate, a range of step changes in valve reference should be performed with the generator shutdown to validate time constants and rate limits associated with the control and intercept valve(s) (where present). | Functional block diagram parameters | Tuneable |

## 7 Hydro turbine model validation

### 7.1 Conventional hydro turbines

Francis, Pelton and Kaplan turbines are the three most commonly used hydro turbine types installed in Australia, although others do exist, e.g.: “bulb” turbines. The various design characteristics of the plant and turbine that have an effect on the generating units governing response should be considered in the development of dynamic models, so as to ensure compliance with the generating system model accuracy requirements.

Examples of such characteristics for the various turbines include:

#### Francis turbines:

- Effects of head and tail water level variations.
- Nonlinearities between the guide vane position and water flow.
- Effects of turbine relief valves if present.

#### Pelton turbines:

- Effects of turbine deflectors and coordination with spear valve movement/position.

#### Kaplan turbines:

- Effects of head and tail water level variations.
- Effects of the nonlinearities between guide vane position, runner blade position, total available head and resultant output power.

#### Other considerations:

- Effects of travelling pressure wave phenomena would need to be considered in hydro plants having long penstocks and/or power tunnels.
- Effects of surge chambers on pressure relief.
- Effects of having a number of machines sharing a common penstock (whereby pressure disturbances are shared through a common manifold at some point in the pressurised water delivery system).

### 7.2 Pumped storage hydro plants

The Model Guidelines require that dynamic models be capable of representing the plant for all possible steady state output levels where the generator would be in operation.

Appropriate models are therefore required for pumped storage hydro (PSH) plants which are capable of representing the plant in either generating or pumping mode.

The models should include the turbine, pump and governor elements of a PSH plant, with the level of modelling detail dependent on the specifics of the unit. For example, advanced PSH plant such as ternary systems (that have the capability to undertake speed control while in pumping mode) would require a detailed governor model [13] to reflect this capability.

Other characteristics that should be considered include:

- Effects of speed variations that occur during transient conditions (and impacts this may have on pump head and flow rate).
- Nonlinearities between gate position and flow when in pumping mode.

### 7.3 Measurement quantities

The quantities measured will be largely dependent on the type of turbine and corresponding parameters to be validated in the model, but would normally include at least the following:

- The test signal applied.
- Load / speed reference signals.
- Active power output of generating unit as measured at terminals.
- Speed / frequency feedback signals.
- Guide vane / needle position (both referred to as ‘gate’ in Table 3 below).
- Deflector, runner blade, or relief valve positions (if present).
- Net head.
- Penstock pressure.

### 7.4 Model validation tests

Tests to validate various parameters of hydro turbine governor models will depend on the type of turbine, type of governor and corresponding governor model. Tests should generally include the tests detailed in Table 3 below which seek to validate various aspects of what would normally be expected in a typical block diagram, as well as parameters denoted as R2 in the Data Sheets.

In Table 3, parameters that can be determined/validated from direct measurement are denoted as “non-tuneable” while those that are confirmed through curve fitting or similar non-exact methods are denoted as “tuneable”.

Table 3: Hydro turbine model validation tests

| MODEL ELEMENTS                               | PROPOSED TESTS  | APPLICABLE MODEL PARAMETERS <sup>8</sup>                | PARAMETER TYPE |
|--|---|---|----------------|
| Rated mechanical power                       | Measurement of active power output at “as close” to the rated turbine conditions as possible. If operation near rated turbine head is not possible over the test period, the measured active power output should be compared to turbine manufacturer’s curves or translated to rated head assuming that turbine maximum active power varies with head to the power of 1.5.  | PM1   | Non-tuneable   |
| Power limits imposed by valve or gate travel | Measurement of active power output when operating at the maximum and where relevant minimum gate positions (the latter for the derivation of motoring characteristics).   | PTMAX<br>PTMIN  | Non-tuneable   |
| Governor gain(s)                             | Proportional, integral and derivative gain constants (or equivalent) of the governor controls measured from input signal and corresponding gate reference signal. To be determined via application of test signals to frequency and load reference inputs (as appropriate).   | Functional block diagram parameters                     | Tuneable       |
| Deadband                                     | Verification of deadband through application of positive and negative frequency steps of both equal and greater magnitude than the governor’s deadband. The test should result in a change in active power output for only steps of a greater magnitude.  | Functional block diagram parameters                     | Non-tuneable   |
| Governing droop                              | <p>Verification of speed droop through application of a range of frequency steps. The resultant change in steady state active power should equal the expected change based on the equation below.</p> $\Delta P = \frac{Bias}{Droop} \times P_{MAX}$ <p>If the speed droop acts on gate reference or other internal signal within the governor (rather than active power), <math>P</math> should be replaced with the corresponding reference signal in the above equation.</p> | Functional block diagram parameters                     | Non-tuneable   |
| Turbine steady state characteristics         | Measurement of gate position and active power output over the operating range of the turbine. The resulting relationship between gate position and active power output should be used to validate turbine constants and non-linearities within the model.   | TW,TG,TP,TR<br>Governor control system time constant(s) | Tuneable       |

<sup>8</sup> Model parameter symbols are as per the Data Sheets. Other model elements may need to be validated as part of the functional block diagram parameters.

|  |   |  |          |
|--|---|--|----------|
| Governor and turbine dynamic characteristics | Verification of governor and turbine dynamic characteristics through application of a range of frequency steps across the operating range of the turbine. Model parameters relating to dynamic performance should be validated by comparing the relevant recorded signal with that of the model.  | Sustained / non-sustained (transient) response to frequency change<br><br>Governor control system time constant(s) | Tuneable |
| Standstill gate response                     | As appropriate, a range of step changes in gate reference should be performed with the generator shutdown to validate time constants and rate limits associated with gate travel. It should be noted that the lack of applied water pressure on some mechanical components, e.g.: needles in spear valve, can affect measurements and this should be considered when analysing results. | Functional block diagram parameters  | Tuneable |
| Limiter response                             | Parameters relating to limiters should be validated through the application of frequency steps such that the activation threshold for the limiter is crossed during the test. The initial operating level and step size should be set such that the dynamic response of the limiter can be clearly identified.  | Functional block diagram parameters  | Tuneable |
| Switched logic functions                     | Parameters relating to switched logic functions should be validated through the application of frequency steps above and below the activation threshold for the switched function.  | Functional block diagram parameters  | Tuneable |

## 8 Gas turbines and combined cycle plant model validation

### 8.1 Gas turbines

The level of modelling detail necessary to ensure compliance with accuracy requirements would typically depend on the type of gas turbine (GT) and the turbine controls which are relevant for the particular unit, i.e. presence of load control, temperature control and acceleration control loops, possibly in combination.

Other principal elements and characteristics of the various gas turbine types that may have an effect on the governor response and therefore may need to be considered in the development of a dynamic model include:

- Effects of shaft speed on maximum turbine output.
- Effects of ambient temperature and pressure conditions on maximum turbine output.
- Effects of exhaust temperature controllers.
- Effects of variable MW loading rate controls to prevent over-firing (over shoot of turbine temperature)
- Effects of inlet guide vanes (IGV) (where present) noting that dynamic models are to be robust over a wide range of operating conditions, not just at near maximum output.
- Capability of turbines to run on dual fuel types. Maximum output power and governor settings may be different when running on liquid fuel compared to gas.
- Effects of having several fuel injection points such as in the case of dual-stage combustor turbines which may impact on the turbine dynamic behaviour.
- Effects of having multiple gas turbines coupled to a single generator shaft (relevant to some aero derivative GT applications).

### 8.2 Combined cycle plant

The complexity of dynamic models required to simulate the performance of combined cycle plant (CCP) will depend on the plant configuration, i.e. single-shaft versus multi-shaft, and the level of model detail required to capture the key characteristics of the principal individual components i.e. the gas turbine, steam turbine and the heat-recovery steam generator (HRSG).

As a useful guide, Reference [5] provides information on the explicit modelling of the HRSG and steam turbine to ensure that the relationship between the power output of the GT and the steam turbine is represented accordingly.

The various effects and phenomena that should be considered in the development of a dynamic model for a CCGT unit include:

- Effects of the gas turbine temperature control on maximum GT output.
- Relationship between GT output and HRSG capability (to support different levels of ST operation)
- Appropriate representation of HRSG dynamics and the type of control used, i.e. sliding pressure or inlet-pressure control.
- Availability of auxiliary firing capability on HRSG.
- Appropriate representation of the steam turbine dynamics.

### 8.3 Measurement quantities

For gas turbines, the quantities measured will largely depend on the type of turbine and the model parameters to be validated, but would typically include as a minimum:

- The test signal applied.
- Electrical power output of gas turbine.
- Load reference(s) (MW set point).
- Speed / frequency feedback signal(s).
- Output signals from governor control loops: speed control, load control, temperature control, pressure control etc. (usually signals internal to the turbine control system).
- Gas turbine governor fuel valve demand signal (governor output signal).
- Gas turbine fuel valve actual position signal (valve feedback signal).
- Gas turbine fuel flow.
- Gas turbine guide vane opening.
- Gas turbine exhaust temperature.
- Gas turbine pressure ratio (or compressor discharge pressure).
- Ambient temperature and pressure<sup>9</sup>.

For combined cycle plant, the following additional signals should be considered:

- Steam turbine power output.
- Steam turbine governor reference signal.
- Steam turbine governor control valve demand and position signal.
- Boiler drum pressures(s).
- Superheater outlet steam temperature(s).
- Steam turbine throttle pressure (upstream of control valves).
- Steam flows to HP, IP, and LP turbines (or combinations of).

### 8.4 Model validation tests

Tests to validate the various parameters of a gas turbine governor model will depend on the type of turbine, type of governor and corresponding complexity of the model itself. Tests should generally include the tests outlined in Table 4 below.

In Table 4, parameters that can be determined/validated from direct measurement are denoted as “non-tuneable” while those that are confirmed through curve fitting or similar non-exact methods are denoted as “tuneable”.

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<sup>9</sup> SCADA data is anticipated to be sufficient as the time constant of these variables is sufficiently long.

Table 4: Gas turbines and combined cycle plant model validation tests

| MODEL ELEMENTS                       | PROPOSED TESTS   | APPLICABLE MODEL PARAMETERS <sup>10</sup>                               | PARAMETER TYPE |
|--------------------------------------|--|---|----------------|
| Rated mechanical power               | Measurement of active power output at rated mechanical power. If ambient conditions prevent rated power from being achieved during the test period, the maximum measured active power output should be compared to turbine manufacturer's curves for the measured ambient conditions.  | PM1   | Non-tuneable   |
| Deadband                             | Verification of deadband through application of positive and negative frequency steps of both equal and greater magnitude than the governor's deadband. The test should result in a change in active power output for only steps of a greater magnitude.   | Functional block diagram parameters                                     | Non-tuneable   |
| Governing droop                      | <p>Verification of speed droop through application of a range of frequency steps. The resultant change in steady state active power should equal the expected change based on the equation below.</p> $\Delta P = \frac{Bias}{Droop} \times P_{MAX}$ <p>If the speed droop acts on valve reference rather than active power, <math>P</math> should be replaced with valve reference in the above equation.</p> | Functional block diagram parameters                                     | Non-tuneable   |
| Governor Gains                       | Proportional, integral and derivative gain constants (or equivalent) of the governor controls measured from input signal and corresponding valve reference signal. To be determined via application of test signals to frequency and load reference inputs (as appropriate).   | Functional block diagram parameters                                     | Tuneable       |
| Turbine steady state characteristics | Measurement of valve position(s), exhaust temperature and active power output over the operating range of the turbine. The basic relationship between valve position(s) and active power output should be used to validate turbine constants and non-linearities within the model.   | KFC, TFC, TFS, TC, TCD<br>Output power characteristic / torque function | Tuneable       |

<sup>10</sup> Model parameters symbols in the table are as denoted in the Data Sheets. Other model elements may need to be validated as part of the functional block diagram parameters.

|  |  |  |              |
|--|--|--|--------------|
| Governor and turbine dynamic characteristics | Verification of governor and turbine dynamic characteristics through application of a range of frequency steps across the operating range of the turbine. Model parameters relating to dynamic performance should be validated by comparing the relevant recorded signal with that of the model.   | Sustained/non-sustained (transient) response to frequency change<br><br>Governor control system time constant(s) | Tuneable     |
| Standstill valve response                    | As appropriate, a range of step changes in valve reference should be performed with the generator shutdown to validate time constants and rate limits associated with the gas turbine fuel valve(s).   | TVP, KVP, KVPF<br>VPMAX<br>VPMIN<br>VPMAXR<br>VPMAXL   | Tuneable     |
| Temperature control response                 | The response and parameters relating to the exhaust gas temperature limiter should be validated through the application of frequency steps such that the activation threshold for the limiter is crossed during the test. The initial operating level and step size should be set such that the dynamic response of the limiter can be clearly identified. | Functional block diagram parameters  | Non-tuneable |
| Other limiter response                       | Parameters relating to other limiters should be validated through the application of frequency steps such that the activation threshold for the limiter is crossed during the test. The initial operating level and step size should be set such that the dynamic response of the limiter can be clearly identified.                                       | Functional block diagram parameters  | Tuneable     |
| Switched logic functions                     | Parameters relating to switched logic functions should be validated through the application of frequency steps above and below the activation threshold for the switched function.   | Functional block diagram parameters  | Tuneable     |

## 9 Reciprocating engines

The modelling requirements for diesel and gas fired reciprocating engines are the same as outlined above for other generation types. It is necessary that the principal design characteristics of the plant that impact on the units governing capability be considered.

Characteristic which should be considered as part of developing an appropriately representative dynamic model include;

- Ability to operate on dual fuel and any changes in governor controls necessary to facilitate this.
- Effects of ambient temperature and pressure on maximum achievable power output.
- Part-load performance (efficiency) of the engine (throttle position to power output relationship). Models are required to be robust over the full range of operating conditions.
- Appropriate representation of engine dynamics to ensure correct representation of time delays (ignition dead time, fuel system delays etc.) experienced between throttle position movement and change in engine power output.
- Presence of turbocharging and the presence of turbo lag when increasing engine output following frequency transients.
- Appropriate representation of heat recovery dynamics for reciprocating engines used in combined heat and power (CHP) plants.
- Minimum power output limits (steady state and transient).

### 9.1 Measurement quantities

For reciprocating engines, the quantities measured will largely depend on the type of turbine and the model parameters to be validated, but would typically include as a minimum:

- The test signal applied.
- Governor speed / load reference.
- Generator electrical power output.
- Desired fuel valve (“fuel rack”) signal (being the governor output signal).
- Actual fuel valve position (feedback).
- Exhaust temperature.
- Engine / generator speed as well as turbocharger speed (if present).
- Fuel flow (if available as a measurement).
- Ambient temperature and pressure<sup>11</sup>.

### 9.2 Model validation tests

Tests to validate various model parameters of a reciprocating engine unit will depend on the type of engine, governor and the corresponding complexity of the governor model itself. Tests should generally include those shown in Table 5 below, with the definitions of “tuneable” and “non-tuneable” being as previously outlined.

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<sup>11</sup> SCADA data is anticipated to be sufficient as the time constant of these variables is sufficiently long.

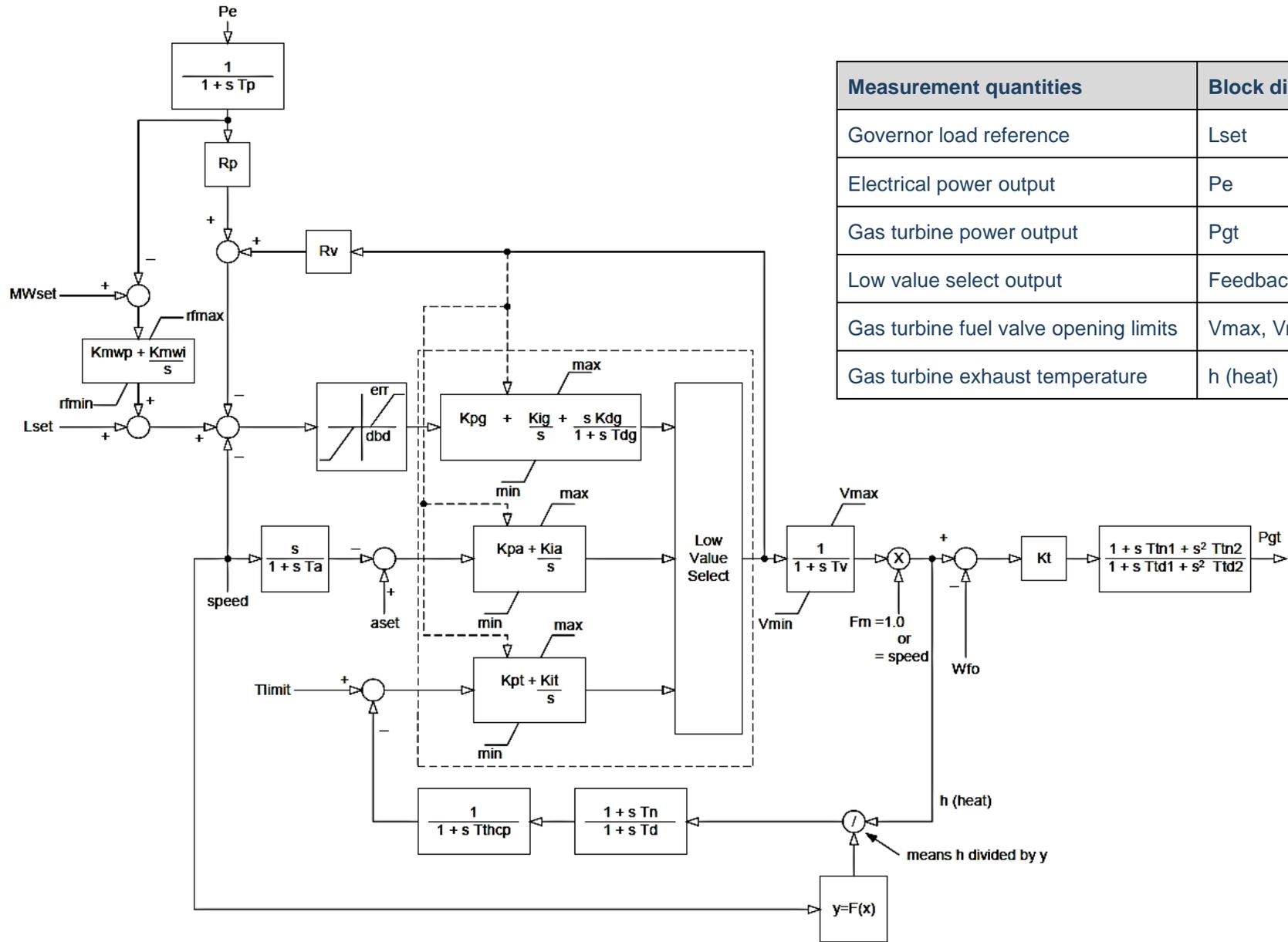
Table 5: Reciprocating engine model validation tests

| MODEL ELEMENTS                              | PROPOSED TESTS   | APPLICABLE MODEL PARAMETERS <sup>12</sup> | PARAMETER TYPE |
|---|--|---|----------------|
| Rated mechanical power                      | Measurement of active power output at rated mechanical power. If ambient conditions prevent rated power from being reached during the test period, the maximum measured active power output should be compared to turbine manufacturer's curves for the measured ambient conditions.   | PM1                                       | Non-tuneable   |
| Governing droop                             | <p>Verification of speed droop through application of a range of frequency steps. The resultant active power change should equal the expected changed based on the equation below.</p> $\Delta P = \frac{Bias}{Droop} \times P_{MAX}$ <p>If the speed droop acts on fuel valve (throttle) reference rather than active power, <math>P</math> should be replaced with fuel valve reference in the above equation.</p> | Functional block diagram parameters       | Non-tuneable   |
| Governor Gains                              | Proportional, integral and derivative gain constants (or equivalent) of the governor controls measured from input signal and corresponding fuel valve reference. To be determined via application of test signals to frequency and load reference inputs (as appropriate).   | Functional block diagram parameters       | Tuneable       |
| Engine steady state characteristics         | Measurement of fuel valve position, turbo speed, exhaust temperature and power output over the operating range of the engine. The basic relationship between fuel valve position and power output should be used to validate constants and non-linearities within the model.   | TD<br>Output power characteristic         | Tuneable       |
| Governor and engine dynamic characteristics | Verification of governor and engine dynamic characteristics through application of a range of frequency steps across the operating range of the engine. Model parameters relating to dynamic performance should be validated by comparing the relevant recorded signal with that of the model.   | Functional block diagram parameters       | Tuneable       |

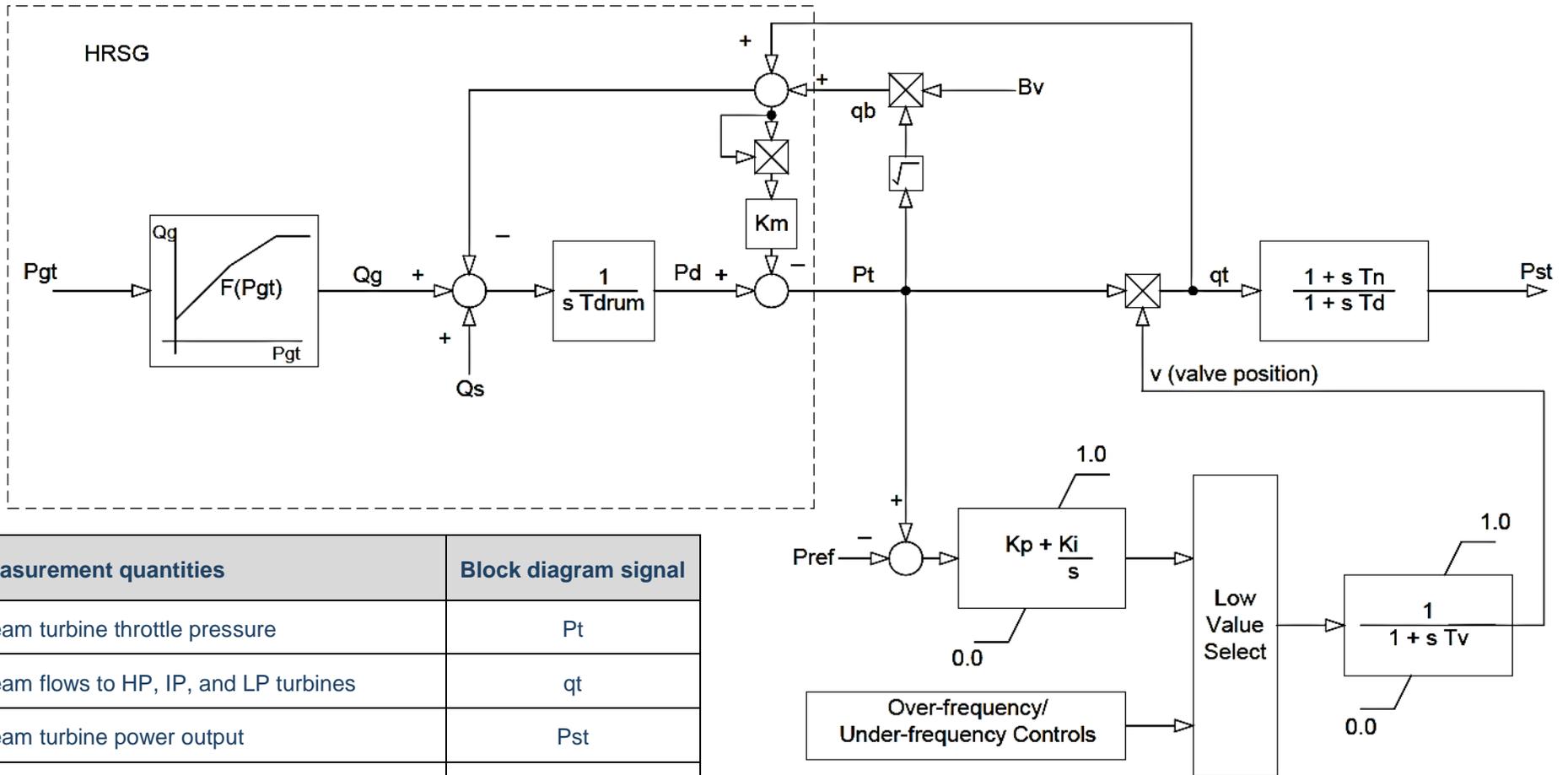
<sup>12</sup> Model parameters symbols in the table are as denoted in the Data Sheets. Other model elements may need to be validated as part of the functional block diagram parameters.

|                                  |  |  |                 |
|----------------------------------|--|--|-----------------|
| <p>Limiter response</p>          | <p>Parameters relating to any applicable limiters should be validated through the application of frequency steps such that the activation threshold for the limiter is crossed during the test. The initial operating level and step size should be set such that the dynamic response of the limiter can be clearly identified.</p> | <p>Functional block diagram parameters</p>   | <p>Tuneable</p> |
| <p>Standstill valve response</p> | <p>As appropriate, a range of step changes in valve reference should be performed with the generator shutdown to validate time constants and rate limits associated with the fuel valve(s).</p>  | <p>ACMAX<br/>ACMIN<br/>ACMAXR<br/>ACMAXL</p> | <p>Tuneable</p> |
| <p>Switched logic functions</p>  | <p>Any parameters relating to switched logic functions should be validated through the application of frequency steps above and below the activation threshold for the switched function.</p>  | <p>Functional block diagram parameters</p>   | <p>Tuneable</p> |

## Appendix 1 - Example model block diagram (for CCGT)



| Measurement quantities                | Block diagram signal |
|---------------------------------------|----------------------|
| Governor load reference               | Lset                 |
| Electrical power output               | Pe                   |
| Gas turbine power output              | Pgt                  |
| Low value select output               | Feedback to Rv       |
| Gas turbine fuel valve opening limits | Vmax, Vmin           |
| Gas turbine exhaust temperature       | h (heat)             |



| Measurement quantities                        | Block diagram signal |
|---|----------------------|
| Steam turbine throttle pressure               | Pt                   |
| Steam flows to HP, IP, and LP turbines        | qt                   |
| Steam turbine power output                    | Pst                  |
| Steam turbine governor reference signal       | Pref                 |
| Boiler drum pressures                         | Pd                   |
| Steam turbine governor control valve position | v (valve position)   |

## Appendix 2 – Example governor models

Steam turbine dynamic models:

- IEEEG1
- TGOV3
- TGOV4
- TGOV5

Hydro turbine dynamic models:

- WEHGOV
- HYGOV
- HYGOVT
- HYGOVM

Gas turbine dynamic models:

- GGOV1

Combined cycle turbine dynamic models (CIGRE models):

- UCBGT
- UHRSG
- UCCPSS

Reciprocating engine dynamic models:

- DEGOV1

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