Notes on Frequency Control
for the
Australian Energy Market Operator

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1 Terminology

AEMO	Australian Energy Market Operator
AGC frequency bias	Frequency bias gain incorporated in a system-level automatic generation control system.
DCS	The digital control system of a power plant
Frequency	The frequency of the fundamental voltage wave on the NEM; synonymous with Speed
NEM	The mainland eastern Australian bulk power system operated by the AEMO
Speed	The speed of a rotating generator, expressed as rotations per second or per unit, as appropriate
Unit frequency bias	Frequency bias gain incorporated in a unit load controller.
Unit load controller	A device or section of logic in a DCS that receives a power order (expressed as a setpoint) and manipulates the speed-load reference of a govenor.
Zone of insensitivity	The field of frequency variation over which a controller does not detect changes in its input signal

2 Summary

2.1 Background

This memorandum reviews issues arising in connection with variation of the frequency of the NEM mainland power system. The issues discussed here are of current concern and, more importantly, must be expected to grow in significance as electronic fraction of the generation fleet grows.

2.2 Scale of frequency variation in normal operation

The NEM frequency control system incorporates the tiered arrangement that is widely used in the control of bulk power generation and transmission sustems, but, contrary to widespread practice, allows power plants to effectively disable or suppress the actions of their primary control elements (governors) while system frequency varies over a very broad band. This frequency band coincides with the Normal Operating Frequency Band of the NEM, whose extent is +/-150mHz from 50Hz.

During normal operation, present practice in the NEM leaves the system frequency:

- ineffectively controlled, and at times uncontrolled, while it is within +/-150mHz of scheduled frequency

  and

- well controlled when it reaches the edges of the +/-150mHz band, but to a value offset 150mHz below or above the scheduled value

Australia is at the forefront of incorporating electronically coupled generation into its fleet and therefore must be prepared to encounter equipment characteristics and operational behavior that are outside the range of available practical experience. The experience that is available is shows that unanticipated behavior does occurr in complex real-world operating situations.

Accordingly, prudence asks for electronic equipment to be operated at frequencies that are well within the frequency band specifications given to equipment developers. This, in turn, asks that grid frequency be maintained within the narrowest practical band. Contrary to that request, the behavior of the NEM at present does not aim to stay well within the frequency bands in which electronic equipment is proven by experience to be secure; rather, the frequency of NEM continually challenges the edges of those bands.

2.3 Frequency variation in the wake of contingencies

Generator trips and consequent dips of frequency are inevitable in power system operations. Frequency dips have two characteristics:

- Their depth is affected by the size of the generation loss and the timing with which primary controls across the entire grid respond to reestablish the balance between load and generation.

- The rate at which frequency falls at the start of a frequency dip is dependent on the inertia of the system

Both of these characteristics are affected adversly as the electronic fraction of the generating fleet grows. Variation of frequency in normal operation increases the field that frequency dips range over, and thus erodes the margins of safety that are available between estimated consequences of contingencies and load shedding thresholds.

2.4 Control capabilities

The present unsatisfactory behavior of the NEM frequency is very likely not explained by deficiency in the design or tuning of the AGC system or by the absence of required primary control equipment at the power plants. Rather, it seems to be due to the ill advised application of power plant primary controls that could readily execute the required control actions if properly applied and adjusted.

2.5 Recommendations

The dead bands incorporated into turbine governors, and the associated zones of insensitivity of turbine control, should be required to be smaller than +/-15 millihertz.

Unit load controllers should incorporate frequency bias action, with the frequency bias factor carefully coordinated with governor or primary controller droop.

The obligation to provide primary control response to variations of frequency should be applied to the widest practical part of the generating fleet. The obligation should apply, to the extent that it is practical, to all generating resources including those that are coupled to the grid through electronic inverters.

2.6 Implementation of changes

The implementation of changes in the way the NEM controls grid frequency would be a large and complex undertaking. In particular, as changes are made, it will be necessary for as large a part of the generation fleet as possible, to participate. Attempts to make a trials by changing governor activity at a single plant would result in that plant executing large responses to ongoing frequency variations that it would have very little effect on; such a test would not give any useful indication of the extent to which effects would occur when multiple plants contribute effectively to primary frequency control.

3 Introduction

3.1 Background

This memorandum is the result of a review of the frequency behavior of the NEM mainland power system. Discussions were held on 24-28 June 2019 at AEMO offices in Sydney and at two power stations.

Discussions covered both specific technical points that can be addressed in terms of technical calculation and points of judgement that must be addressed in terms of accumulated operational experience. This memorandum summarizes considerations and a viewpoint that have been formed by the author as a result of the discussions.

3.2 Data, assumptions, and estimates

Quantitative data on frequency behavior of the mainland power system was assembled prior to and during the discussions and is used as factual information in this memorandum.

Qualitative information about power plant capital equipment (e.g. boilers, turbines, generators) and control systems (e.g. governors, boiler controls, DCS) was covered in terms of principles and general configurations, but detailed data were not obtained. The discussions at two power stations confirmed that the plant configurations, operating practices, and operators' concerns are consistent with those found in power plants worldwide. Accordingly the notes presented in this memorandum are based on a combination of particular assumptions regarding plants in the NEM and broad experience in power plants of varied type in power systems ranging from the very small to the very large.

The data accumulated in connection with these discussions were used to illustrate the character of the behavior of the NEM in particular operating situations. Data were not used for statistical purposes; statistical information has been presented and discussed elsewhere. [1]

3.3 Two threads of questions

The discussion addressed two related but separable threads of questions:

- Is the present (in 2019) frequency behavior NEM acceptable in terms of the reliability of electric power supply. Are frequency variations with the character now seen in the NEM detrimental to reliability of individual power plants, to the resiliance of the NEM grid as it responds to contingent disturbances, or to the ability to absorb large power contributions from incoming electronically coupled generating equipment.
- Is the present frequency behavior caused by technical characteristics of presently installed equipment, at the power plant or the grid level. Is it caused by operating practices at the power plant or the grid energy management level.

Both threads of questions were addressed in terms of the present generating and load fleets, and in terms or the expected effects of large increases in the fraction of the power production that will be by electronically coupled sources.

4 Issues for discussion

4.1 Tiers of control

In the great majority of power systems the control of frequency is implememented by a tiered arrangement of feedback control systems:

Primary Control The governors of turbine generators manipulate turbine control valves in response to changes of frequency. The responses of the many governors in the many power plants are coordinated through rules relating to governor settings, so that changes of frequency are arrested within and restricted to a narrow band. While is is essential that governors act to contain changes of frequency within a narrow band, it is neither necessary nor desirable for them to return frequency exactly to the desired value after a disturbance has occurred. Governors are *primary controls*.

Unit level secondary control The adjustment of the governor speed-load references is handled by unit load controllers that receive desired load signals from plant operators (via manual entry at a control console), or from a system-level automatic generation control system. Plant load controllers are *secondary controls* in that they require action by the primary controls that they supervise to influence the controlled variables.

System level secondary control The return of frequency to its desired value and the simultaneous allocation of power production among the generators is handled by system-level automatic generation control that responds to changes in frequency and real power production. Automatic Generation Control systems are secondary controls and cannot influence system frequency directly; they can influence the power system only by supervising and instructing the plant load controllers which, in turn, instruct the primary controls.

Primary controls are used to maintain control of frequency in the short term and secondary controls are used to direct the primary controls so that frequency is held at its intended value in the long term.

Basic principles of dynamics and automatic control require that primary controls act quickly in relation to the inherent characteristics of the things to be controlled, and that secondary controls act slowly in relation to the characteristics of the primary controls that they supervise.

4.2 Governors and dead bands

The function of the governor of a generating unit is to maintain generator power and turbine speed in the droop relationship shown in figure 4.1. The normal speed is the required speed of the grid (normally 50Hz). The speed-load reference is the command input to the governor. The plant operator or the automatic generation control system can influence the power output of a turbine-generator by adjusting the speed-load reference of its governor.

In a power system with many turbine-generators:

- Collective adjustments of governor speed-load references in the same direction and in equal amount cause the speed of the system and, therefore its frequency, to increase or decrease

- Differential adjustments of governor speed-load references in opposing directions or in differing amount cause the power produced by the many turbine-generators to vary in relation to one another

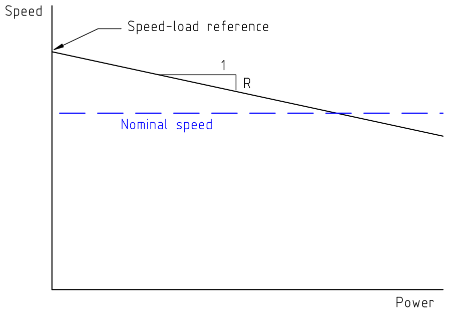

Figure 4.1: Droop relationship as implemented by an ideal governor

The speed and generator power signals 'seen' by governors are never constant and so governors that implement the droop characteristic of figure 4.1 exactly would never be still; they would move the turbine control valves constantly, by small amounts, in response to continual small variations of system demand.

Mechanical 'imperfections' in mechanical governors can cause them to exhibit a zone of insensitivity within which small variations of perceived turbine speed are ignored. These imperfections are often vizualized and represented in mathematical modeling by *dead bands*, as indicated by figure 4.2. In mechanical governors the effects of these mechanical imperfections can appear as dead bands in the locations shown by figures 4.2c and 4.2d. Zones of insensitivity due to mechanical imperfection are found, also, in the mechanical-hydraulic valve actuating parts of modern digital governors.

While dead bands of mechanical origin are undoubtedly present in essentially all governors [1], they can be so small in well maintained equipment that they are negligible and difficult to measure.

Constant activity of turbine control valves is resulting from governor action is widely perceived (or misperceived) as being undesirable. The desirability or undesirability of governor activity is discussed elsewhere in this report.

It is widespread practice to put programmed intentional dead band into modern digital governors to cause small zones of insensitivity. These deadbands do have the effect of 'quieting' the activity of turbine control valves and are widely seen as beneficial.

Intentional zones of insensitivity in governors are acknowledged in the grid codes of nations such as the UK, Singapore, Italy, as being necessary [2]or desirable. These acknowledgements of zones of insensitivity are consistent in requiring that they be small. Table 4.1 shows the maximum sizes permitted in several grid codes.

In contrast to these grid codes, the NEM rules are silent regarding governor dead band. Rather than specify governor characteristics, the NEM rules specify the performance objective

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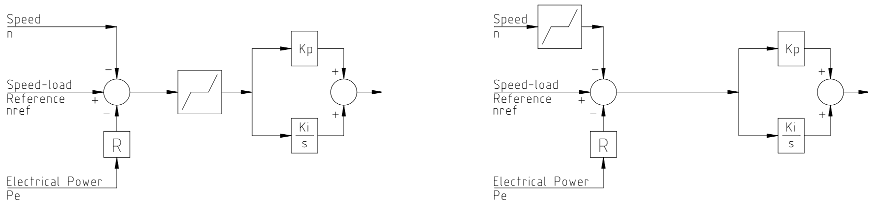
[1] Except purely electronic controllers of inverters, which are sometimes referred to as governors.
[2] or inevitable

Table 4.1: Allowable dead band extents

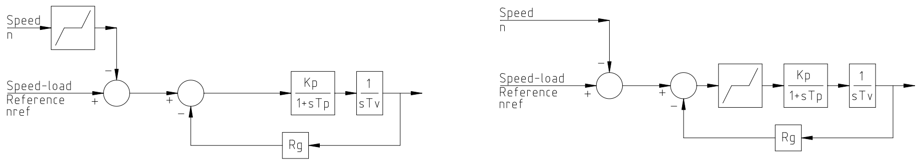
Power System	Dead Band dimension
Italy	10 mHz
Ireland	15 mHz
United Kingdom	15 mHz
Texas	17 mHz
Ontario	36 mHz
Malaysia	25 mHz

that system frequency is to remain within +/- 150 mHz of the desired value. (Temporary excursions beyond +/-150mHz are permitted in the wake of sudden disturbances.) This performance objective does not set a technical requirement for the primary control; it leaves it to the plants to adopt governor settings of their choice. In practice, plants in the NEM are choosing to set programmed deadbands over a range from +/-10mHz to +/-150 mHz.



(a) Programmed dead band in PI controller error

(b) Programmed dead band in PI controller speed signal



(c) Programmed dead band in P controller speed signal

(d) Mechanical imperfection dead band in valve actuator

Figure 4.2: Turbine governor dead band

4.3 Unit load controllers and frequency bias

While internal details vary from plant to plant (as do internal details of governors), the unit controller, the governor, and the relationships between them are as indicated by figure 4.3.

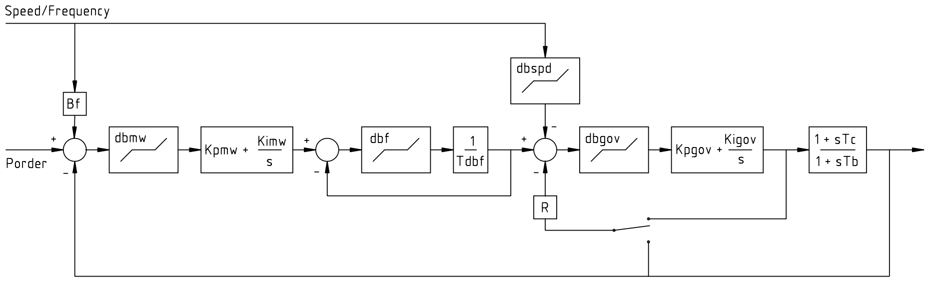


Figure 4.3: Configuration of simulation model of turbine governor and unit load controller

The control objective of the governor is described, in the absence of deadbands, by

$$Err = (N_{ref} - N_{meas}) - R\, P_{meas} \tag{1}$$

where

N_{ref}	is the governor speed-load reference setting
N_{meas}	is the measured actual turbine speed
P_{meas}	is the measured actual power output (or a measurable surrogate for power output)
R	is the governor droop setting

The control objective of the load controller is described, in the absence of deadbands, by

$$Err = (P_{ord} - P_{meas}) - B_f\, \Delta f \tag{2}$$

where

P_{ord}	is the is the desired power setting received from manual entry or from the system AGC
P_{meas}	is the measured actual generator power output
B_f	is the unit frequency bias setting of the unit load controller

The governor and the unit load controller act individually to drive their error signals to zero. When their settings are properly coordinated the governor responds to disturbances more quickly than the unit load controller.

Practice regarding governor droop settings is remarkably uniform across the worldwide turbine fleet, (though, in contrast, no consensus has yet emerged regarding the droop settings of primary controllers of electronically coupled generating units).

Practice regarding settings of unit load controllers for turbine generating units is significantly less uniform than practice regarding governor droop. There is variation in choice of droop, of the frequency bias factor, B_f, and with regard to the timing of response[3]

When the unit controller bias factor, B_f is set to zero (or absent) the unit load controller acts to maintain constant output power and ignores frequency. The result is that the unit load

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[3] The timing of load controller response is determined mainly by the gain settings of its proportional-integral element.

controller allows the governor to respond initially to change of frequency, but countermands the initial response and returns power output to the scheduled value.

When the unit controller bias factor, B_f is greater than zero and advantageously coordinated with the governor droop, the unit load controller can be made to ’agree’ with and ’support’ the initial response of the governor so that it is maintained as long as frequency differs from scheduled value.

In the NEM system frequency bias in unit load controllers, if present, produces action at the generating units that is in the same sense as the intended action of the AGC system, and that is produced without the delays associated with round-trip exchange of data via the SCADA system. If present, it is beneficial to the control of system frequency and, if absent, leaves the unit load controllers to withdraw the regulating effort that primary controls have produced.

The time scale of their action is important with regard to the detrimental effects of unit load controllers without frequency bias. If unit load controllers act on a time scale that matches the timing of system Automatic Generation Control action, that is over tens of 4-second SCADA cycles, the AGC can recognize that initial governing response is being withdrawn and can compensate accordingly. If unit load controllers act too quickly for AGC to ’keep up’ with what they do, their effect on frequency is strongly detrimental.

5 Points regarding primary control

5.1 General

Discussion with AEMO and industry representatives raised concerns related to the administration and commerce of grid operation. This section is included to provide context around the observations, conclusions, and recommendations of this report.

5.2 Precision of frequency control

5.2.1 Security of electronic generating equipment

While legacy rotating generating units are known, from 100 years of operating experience, to be tolerant with regard to variation of frequency, this is not the case with the electronically coupled generation that is presently going into service. Overload margins of electronic inverters are much tighter than those of legacy equipment and tolerance of rapid changing of grid conditions is less generous

Australia is at the forefront of incorporating electronically coupled generation into its fleet and therefore must be prepared to encounter equipment characteristics and operational behavior that are outside the range of available practical experience. The experience that is available is showing that unanticipated behavior does occurr in complex real-world operating situations.

Accordingly, prudence asks for electronic equipment to be operated at frequencies that are well within the frequency band specifications given to equipment developers. This, in turn, asks that grid frequency be maintained within the narrowest practical band. Contrary to that request, the behavior of the NEM at present does not aim to stay well within the frequency bands in which electronic equipment is proven by experience to be secure; rather, the frequency of NEM continually challenges the edges of those bands.

5.2.2 Depth and timing of frequency dips

Generator trips and consequent dips of frequency are inevitable in power system operations. Frequency dips have two characteristics:

- Their depth is affected by the size of the generation loss and the timing with which primary controls across the entire grid respond to reestablish the balance between load and generation.
- The rate at which frequency falls at the start of a frequency dip is dependent on the inertia of the system

With regard to the first point, the introduction of generation (both conventional and electronic) that does not respond quickly to change of frequency adversely affects the depth of frequency dips while prompt response is beneficial.

With regard to the second point, increasing the electronic fraction of the fleet decreases system inertia which is detrimental to the rate of change of frequency. Further, (with recognition of the limited available experience) it must be assumed that electronic generation is a two edged sword with regard to rapid changing of frequency. While its operation is within its sphere of control, electronic generation can produce constructive response to changing freqency very quickly, to the great benefit of the power system. However, the ability of electronic generation to respond quickly to changing grid conditions is accompanied by the need to act quickly to protect itself. There is useful experience indicating that electronic generation can contribute constructively to frequency control when the security of its connection to the grid is sound, but much less experience regarding the security and resiliance of that connection.

5.2.3 Large scale frequency events

The evolution mentioned above will cause the frequency dips caused by trip of large blocks of power to both deeper and quicker. The nadirs of frequency dips will approach the first load shedding frequency (49Hz for the mainland system). Allowing frequency to be as low as 49.8Hz in normal operation reduces the available margin by 0.2Hz. For example, the trip of 560MW, today, causes frequency to dip by approximately 0.22Hz. If this dip starts from 50Hz, the nadir is at 49.78Hz and the margin to the first load shedding frequency is 0.78Hz. If the dip starts from 49.8Hz, the nadir is at 49.58Hz and both:

- the margin between the frequency nadir and the first load shedding frequency is significantly reduced
- frequency at the terminals of electronic generation is taken significantly closer to the edges of its proven secure operating envelope.

Both of these points are cause for concern at present, and the evolution of the NEM system towards a high level of electronic generation takes both in the direction of increasing concern.

5.3 Power plant points

5.3.1 Wear and tear on control valves

It is often claimed that allowing turbine governors to respond to small random variations of system frequency results in wear and tear with associated expense. It is also often claimed this wear and test reduces the reliability of the generating plant. Instances of excessive wear of control valves stems have certainly been recorded but, there is not a good accumulation of quantitative operating experience to indicate whether it is rare, common, or an ongoing acute problem.

5.3.2 Effect of governor action on efficiency

Another claimed basis for concern about primary control action is that it reduces power plant efficiency. As with wear and tear, there is not a useful accumulation of operational experience to support or contradict such claims.

5.3.3 Wear and tear on boiler, turbine, and hot gas path structures

It is undeniable that continual large scale maneuvering has a cumulative effect on the life of power plant capital equipment. There is good evidence, however, that such cumulative effects are in general proportion to the scale of temperature changes, and that continual small maneuvering can be well tolerated.

5.4 The scale of maneuvering for primary control

The reasonable interpretation of the various points noted above is that the extent of maneuvering for primary control of each individual turbine-generator unit should be as small as possible. The leads directly to the indication that the responsibility for primary control of power system frequency should be distributed, in proportion to size, as widely as is practical across the generating fleet. To the extent that it is practical, the assignment of primary control duty should be independent of the technologies of generating units.

5.5 Need for trials

The only reliable way to assess claims in favor of, or in opposition to, changes in practice regarding primary control might be to make field trials. Such trials would be a large undertaking because it would be necessary to have a significant fraction (one third or more) of the connected turbine-generator capacity have its governors set to act in a proposed manner. An attempt to make a trial by changing governor activity at a single plant would result in that plant executing large responses to ongoing frequency variations that it would have very little effect on; such a test would not give any useful indication of the extent to which effects would occur when multiple plants contribute effectively to primary frequency control.

6 The present situation of the NEM power system

6.1 Measurements of frequency

6.1.1 Frequency recording at SCADA rate

Figure 6.1 shows the frequency of the NEM measured at a single location over two days in May 2019, as seen by the AEMO energy management system. It shows frequency at a rate of one sample every 4 seconds; it is a reliable indication of frequency behavior on a time scale of tens of seconds but cannot reveal what is going on at a time scale of one-to-five seconds.

Figure 6.1a shows that deviations of frequency to the edges of the +/-150mHz band are not infrequent occurrences that can be associated with discrete events (such as trips of generating units) but, rather, that ’wandering’ across the full +/-150mHz range is continual. Figure 6.1b shows three one-hour spans expanded from figure 6.1a. It indicates that the variation of frequency contains both a random component and several rythmic components with periods between roughly one and ten minutes.

Figure 6.3 shows the variation of frequency recorded, 4 samples per second, in July 2005, July 2009, and May 2019. The change in character of the variation is clear.

6.1.2 High resolution frequency recording

Figure 6.2 shows the frequency as measured at locations in QLD, NSW, VIC, and SA as sampled at 50 samples/second by phasor measurement units. Figure 6.2b is a zoomed-in view of a portion of figure 6.2a; it shows that frequency is very nearly the same at the four locations and that it has a tendency to oscillate with a period of a few tens of seconds.

Figure 6.2c shows a further zoomed-in view of frequency at the four locations. This view shows variation of the local frequencies relative to one another and confirms the presence of the rotor angle motions that are inherent in the dynamic behavior of the electrical interconnection of synchronous machines. The rotor angle oscillations are stable and have periods that are consistent with those that would be calculated in dynamic simulations of the overall NEM electric system.

It is clear from figure 6.2 that the variation of frequency across the band of +/-150mHz is largely random (though there is a tendency to oscillate with a period of about 30 seconds) and that there is no significant interaction between relative rotor angle motion and the broad frequency variations. From this it can be concluded that the uncontrolled variation of frequency across the +/-150mHz band is not caused by, and could not be alleviated by, means that are often used [4]to stabilize relative rotor angle motions.

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[4] Such as "power system stabilizers", or electronic power flow control devices (FACTS), for example.

6.1.3 NEM practice

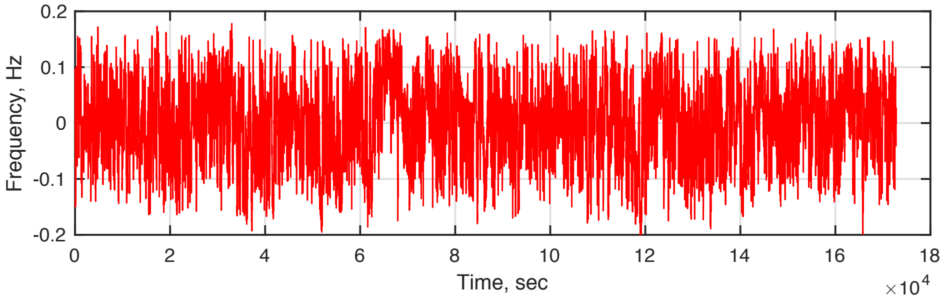
The NEM frequency control system incorporates the tiered arrangement outlined above but, contrary to widespread practice, allows power plants to effectively disable or suppress the actions of their primary control elements (governors) while system frequency varies over a very broad band. This frequency band coincides with the Normal Operating Frequency Band of the NEM, whose extent is +/-150mHz from 50Hz.

During normal operation, present practice in the NEM leaves the system frequency:

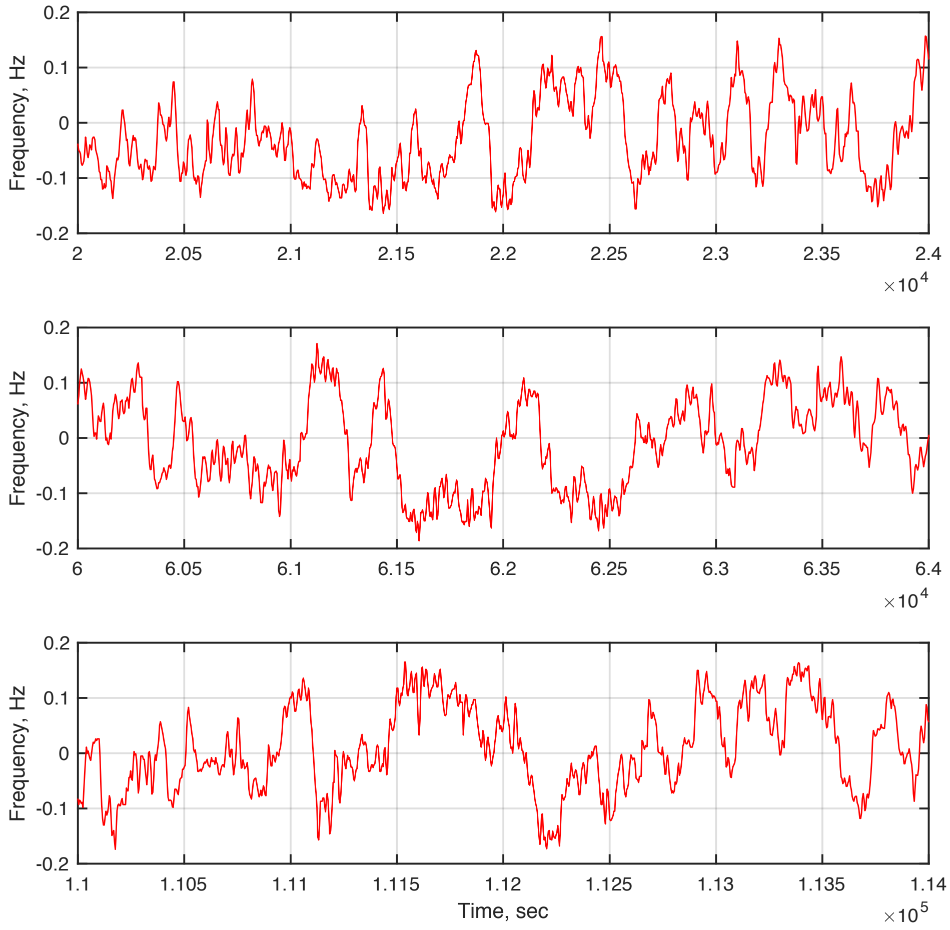
- ineffectively controlled and, at times uncontrolled while it is within +/-150mHz of scheduled frequency

  and

- well controlled when it reaches the edges of the +/-150mHz band, but to a value offset 150mHz below or above the scheduled value

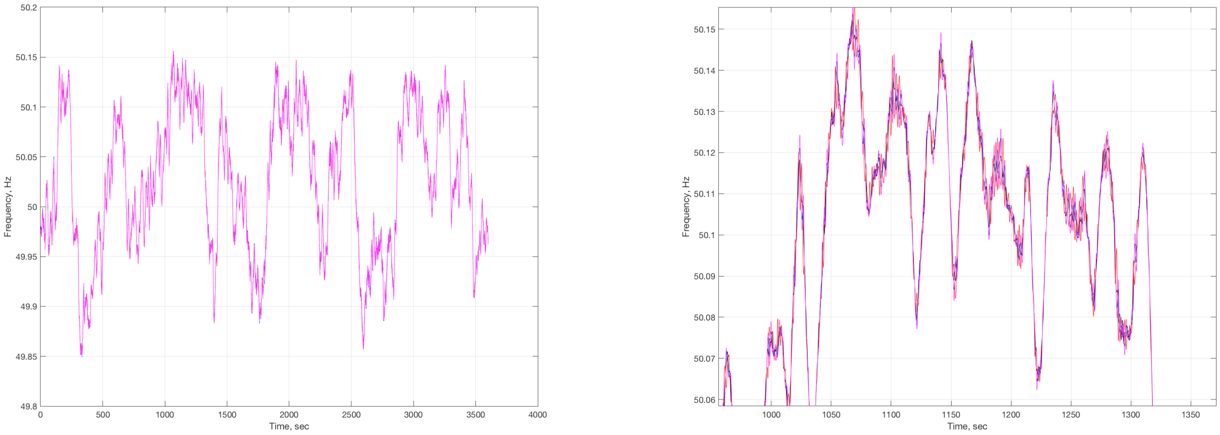


(a) 2 days



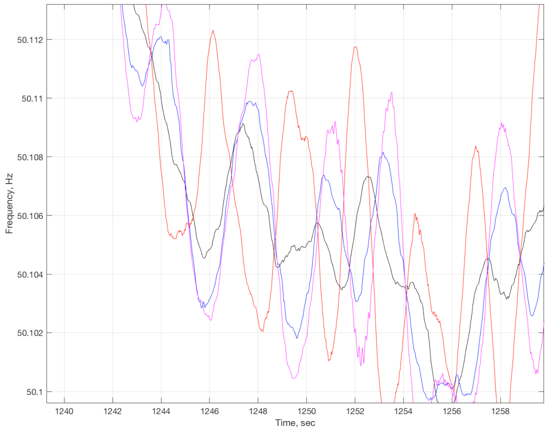
(b) 1 hour

Figure 6.1: Frequency as seen by AGC system
one sample every 4 second



(a) 1 hour

(b) 6 minutes



(c) 20 seconds

Figure 6.2: Frequency measured by PMU at four locations
50 samples per second

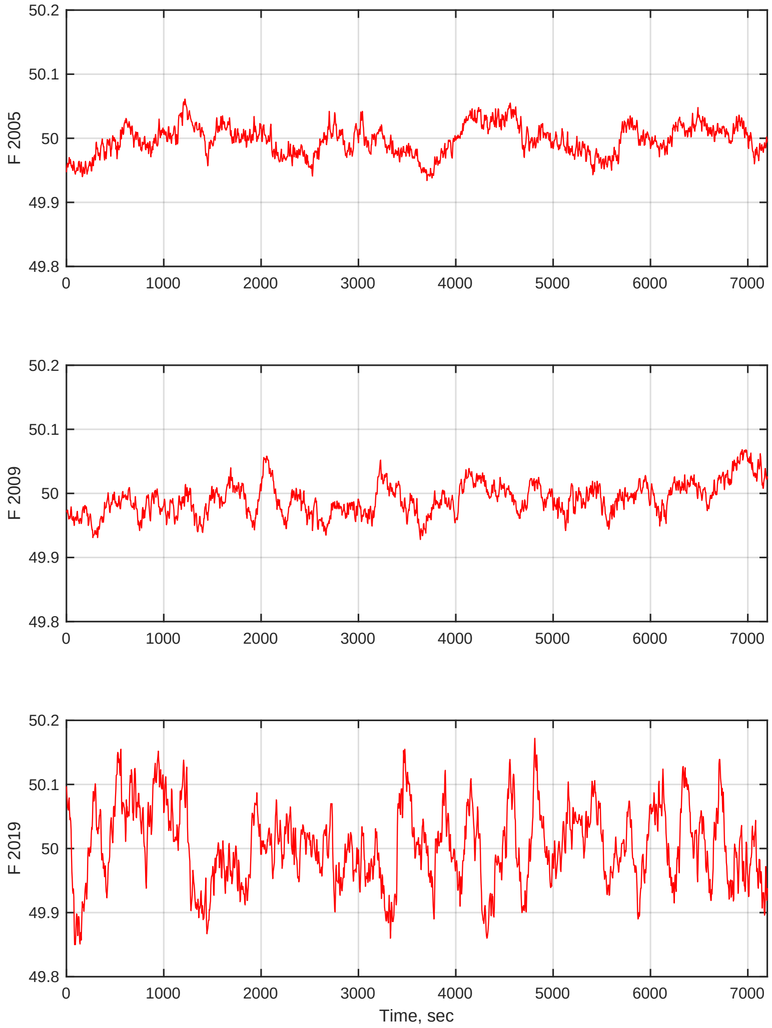


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Figure 6.3: Frequency recorded in 2005, 2009, and 2019

7 Use of simulation to consider frequency behavior

7.1 Simulations for illustration

The relationships between governor properties, the AGC system, the plant load controllers, and the behavior of the NEM frequency can be illustrated by using a very simple dynamic model. Simulations shown here were made with the small scale dynamic model described in appendix 1. This model is generic. It has been made up to reproduce the principal features of the NEM mainland power system with regard to frequency behavior. It has not been closely tuned to represent the behavior of the NEM system in detail.

Results obtained with this model and shown here are most useful when compared with one another to show the relative effects of changes to plant and system controls. Comparison of simulations with recorded real behavior of the NEM system must be used with careful recognition of the deliberately simplified nature of the model.

7.2 Base case

First consider the simulation shown in figure 7.1. This simulation shows the behavior of the frequencies at the nodes representing Northern Queensland, New South Wales, and South Australia. The conditions simulated are an idealized situation for reference, as follows:

- All generation is within maneuvering range and all governors are active
- All governors have a deadband corresponding to 15 mHz
- The total system electrical demand is a constant base value with a superimposed ’sizzle’ component equal to 0.2 percent of the base value
- All power plants have their unit load controllers in ’manual’ mode so that the speed-load references of all governors are held constant

The simulation result is as would be expected for the idealized situation. Frequency varies from 50Hz in a small random sizzle and the histogram of frequency deviations exhibits peaks corresponding to the edges of the 15mHz governor dead band.

7.3 Base case with load ramping but no secondary control action

Now consider that the system conditions are the same as in the base case, except that the total system demand is increasing at a steady moderate rate. Figure 7.2 shows the simulation result. The generator real power outputs increase to cover the demand but, because the governor speed-load references are not adjusted, system frequency drifts downward in accordance with the governor droop setting (4 percent). The magnitide of the sizzle of system frequency is unchanged from the previous case. The center of the frequency distribution (figure 7.2b) is shifted slightly below 50Hz but its edges are are well within the +/- 150mHz normal operating frequency band.

7.4 Base case with load ramping and Automatic Generation Control

The simulation shown in figure 7.3 considers the same situation as that of figure7.2 but has secondary controls turned on. The AGC has adjusted the governor speed-load references to hold frequency very close to 50Hz; the distribution of frequency variation is essentially the same in the two prior simulation cases.

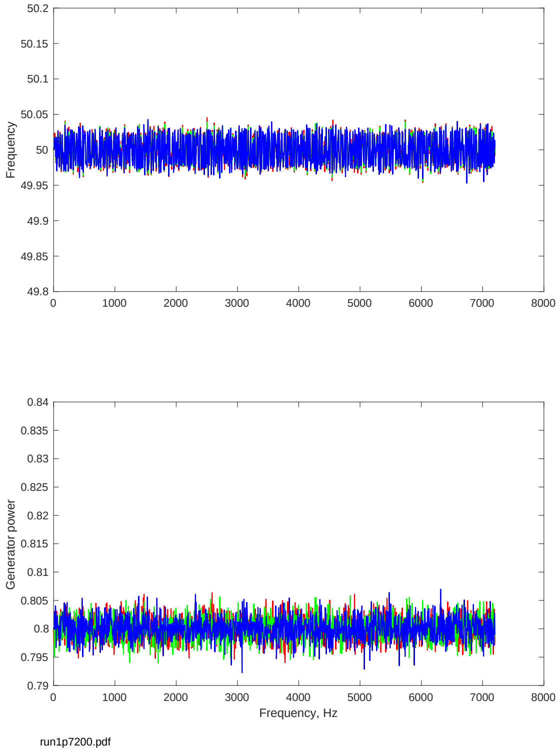
7.5 Case with load ramping and AGC, but with 150mHz governor dead band

The preceding three cases are *not* representative of the behavior of the NEM system because they simulate governors with a dead band of 15 mHz. The 15mHz deadband is representative of 'worldwide' practice, but not of generating plants in NEM. Figure 7.4 shows the effect of increasing the zone of insensitivity of turbine-generator governors from 15mHz to 150mHz, which corresponds to practice that is common in NEM.

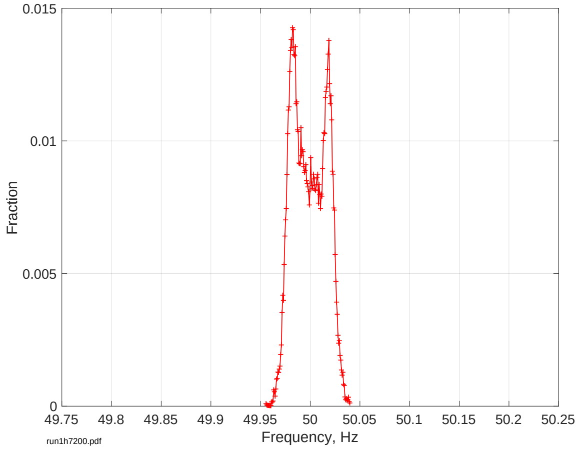
The simulation is the same as that shown in figure 7.3 except that the dead band of the all governors has been changed to 150mHz. Frequency now wanders in a manner that has the same general character as seen in recordings of real frequency; it wanders uncontrolled and essentially at random within a band whose edges are very close to plus and minus 150mHz. Control is achieved only as the speed input to the governors reaches the edges of the dead bands.

7.6 Case with constant load but 150mHz dead band

A last simulation case is shown in figure 7.5. This simulation is the same as the first run shown in figure 7.1 except that the governors have dead bands of 150mHz. The distribution of frequency deviation (figure 7.5a) is substantially flat between 48.85Hz and 50.15Hz; this confirms that the variation of frequency between these extremes is essentially uncontrolled and random.

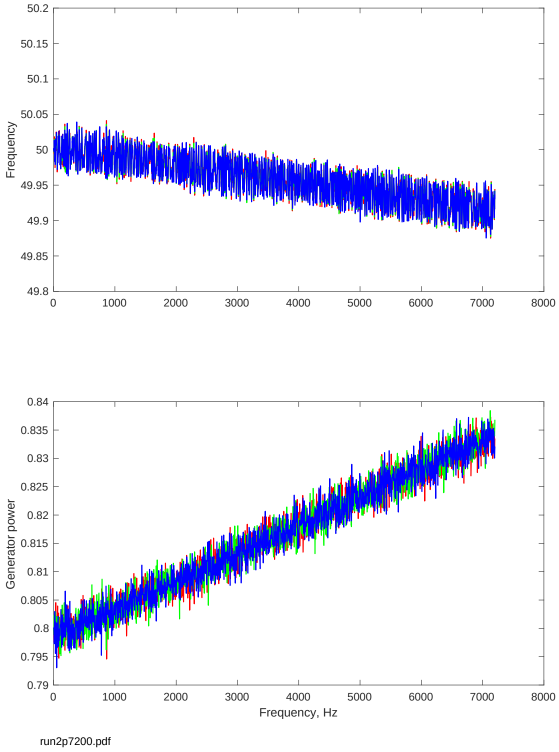


(a) Frequency and electric power

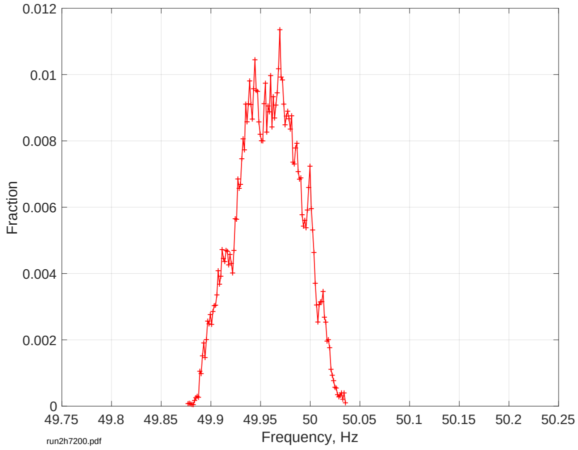


(b) Frequency distribution

Figure 7.1: Simulated Frequency - simulation run 1 - Base case

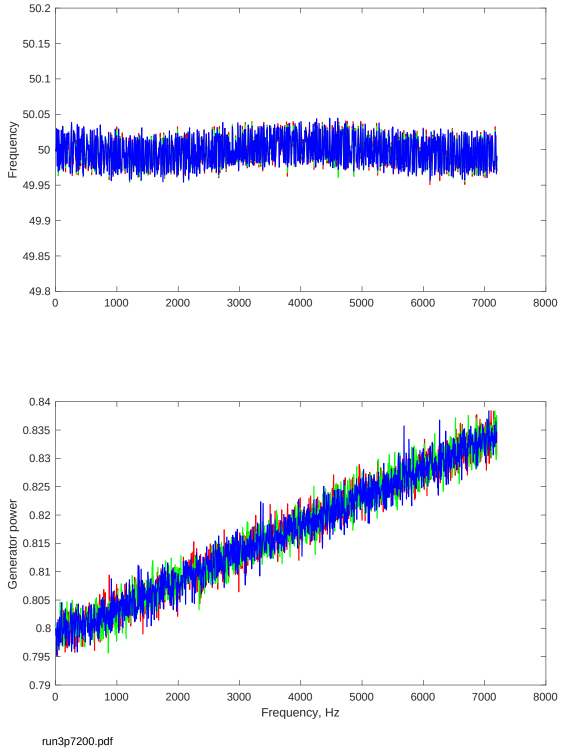


(a) Frequency and electric power

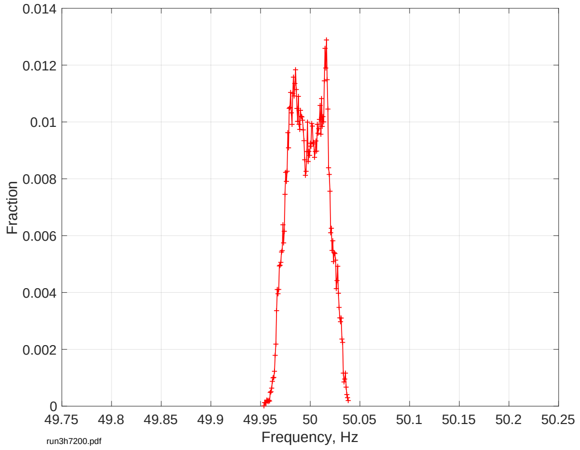


(b) Frequency distribution

Figure 7.2: Simulated Frequency - simulation run 2 - Base case with load ramp

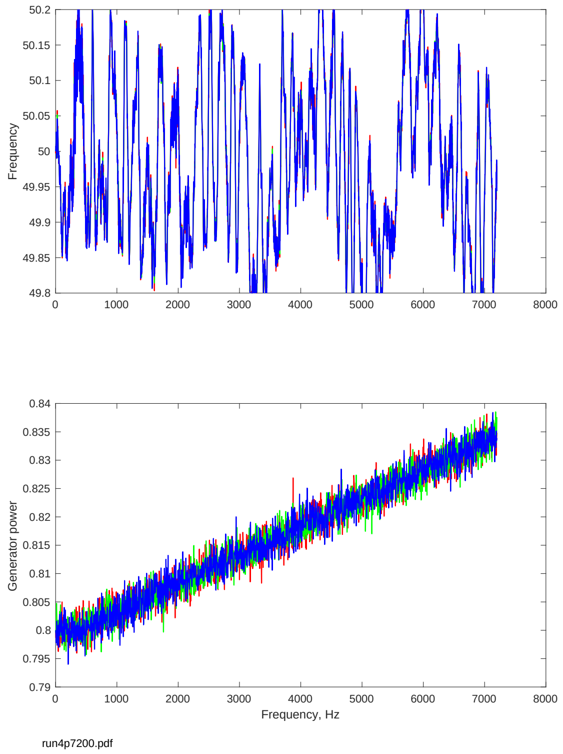


(a) Frequency and electric power

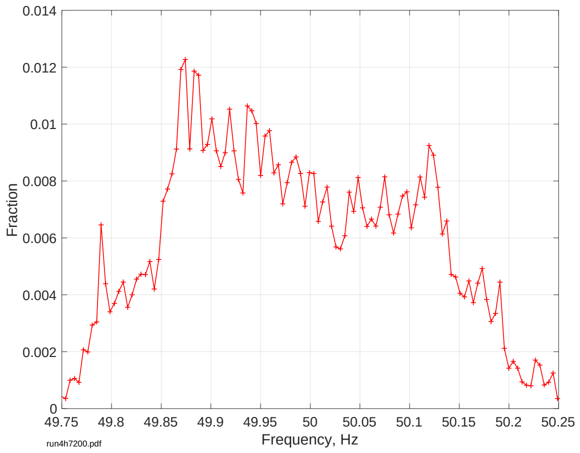


(b) Frequency distribution

Figure 7.3: Simulated Frequency - simulation run 3 - Base case with load ramp and AGC

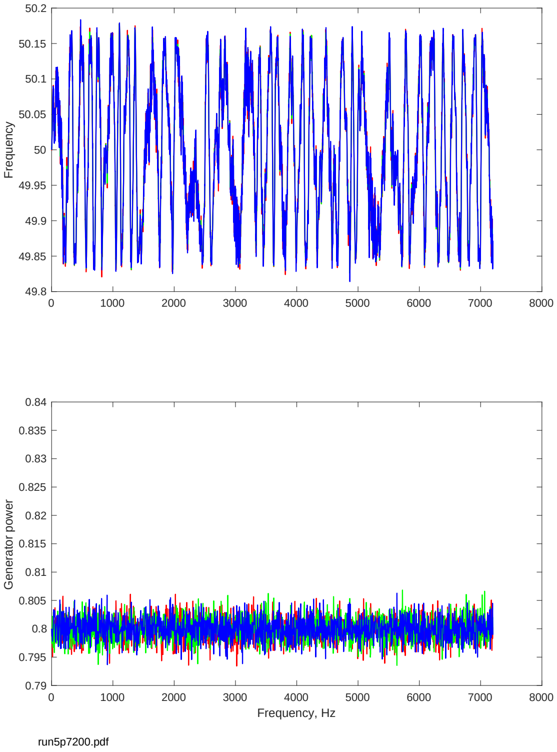


(a) Frequency and electric power

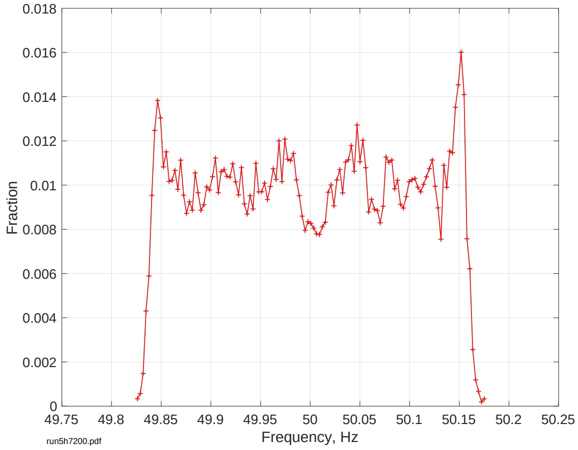


(b) Frequency distribution

Figure 7.4: Simulated Frequency - simulation run 4 - As case 3 but with 150mHz dead band



(a) Frequency and electric power



(b) Frequency distribution

Figure 7.5: Simulated Frequency - simulation run 5 - As case 1 but with 150mHz dead band

8 Observations and Conclusions

8.1 Controls in the NEM

The NEM is presently operating with very limited primary control capability, and very possibly at times with no effective control of frequency. The limited primary control action leaves the secondary control system trying to manage the behavior of a power system that it does not have effective control of.

8.2 Overall frequency control

The frequency of the NEM power system is not effectively controlled when it is between limits of essentially 49.85Hz and 50.15Hz. Effective control is gained only as the deviation of frequency from the intended value exceeds +/-150 mHz. The band in which frequency control is ineffective (+/-150 mHz) is a result of the fact that NEM rules do not require generators to contribute regulating action to the grid while frequency is within the Normal Operating Frequency Band.

When frequency goes beyond the +/-150mHz band the primary controls in the power plants leave their zones of insensitivity and begin to exert control over turbine power and speed/frequency. With the primary controls active, the link between the AGC system and frequency is reestablished; frequency is controlled effectively but to a value that is either above the desired value, or below it, by slightly more than 150mHz.

8.3 Power plant controls

The primary controls of the power system are located in generating plants. These primary controls are essential for predictable and secure operation of the power system and must be used in accordance with standards that are accepted by *both* generating plant and power system interests.

These groups have inherently different views in regard to the action of the primary controls of turbines.

- Power plant interests regard activity of the primary controls as a cause of wear and tear and hence as undesirably effecting reliability and operating costs of the plant
- Transmission grid interests regard insensitivity of the primary controls as a threat to their ability to maintain control of the collective system and therefore as a threat to the reliability and operating costs of the overall power system
- Both power plant and electricity market interests have concerns that small continual variations of power output have a negative impact on thermal efficiency and fuel consumption

8.4 Reasons that primary control in NEM is inadequate

Observation of the character of frequency variation, as measured at both low and high sampling rate, leads to the conclusion that the NEM is operating with insufficient governing capability. This may be perceived to be in contradiction to the presence of governors on essentially all turbines and to the belief that, by starting to act when speed deviations reach 150mHz, they are contributing constructively to primary control action. The fact is that, while the plants can be in control modes that nominally have the governor in command of turbine power, their governors can be ineffective.

There are two main reasons for this:

- While speed is within the governor dead band (which is wide) the governor, while it is nominally in command, is not aware of a need to act.
- A governor can be active (without or with deadbands) but can have its activity countermanded by the actions of the unit load controller.

8.5 Relative roles of governing and AGC

The present unsatisfactory behavior of the NEM frequency is very likely not explaned by deficiency in the design or tuning of the AGC system or by the absence of required primary control equipment at the power plants. Rather, it seems to be due to the ill advised application of power plant primary controls that could readily execute the required control actions if properly applied and adjusted.

8.6 Inertia

The deterioration of frequency behavior in normal operation (absent large contingent disturbances) cannot be attributed to the reduction of system inertia that is occurring as electronic generation becomes a greater part of the fleet. Reduction of inertia does affect the frequency dips caused by contingencies and this will evolve in the adverse direction

9 Recommendations

9.1 Amplitude of governor dead bands

Governor deadbands should be such that the zone of insensitivity of each generating unit is less than 15mHz.

9.2 Size of governor dead bands

In the interest of equitable participation in primary control among generating units, governor deadbands and governor droop settings should be as uniform as practical. Variations in droop and dead band settings should be discouraged.

9.3 Dead bands in generating unit load controllers

Dead bands that may be present in the power plant controls that supervise the turbine governor should be such that the zone of insensitivity of each generating unit is less than 15mHz.

9.4 The role of unit load controllers

Unit load controllers without frequency bias should be used to determine the real power output of generating units only when their real power setpoints are specified by the NEM real time energy management or AGC system. Unit controllers without frequency bias should not be used to hold generator power to a constant value unless such operation is known to the AEMO and properly factored into the NEMDE dispatch of real power.

9.5 Use of frequency bias in power plant load controllers

Unit load controllers should include frequency bias of the general type indicated by figure 4.3. This form of frequency bias prevents unit load controllers from withdrawing primary response in the wake of frequency disturbances. With frequency bias in effect, the real power setpoint presented to the unit load controller should be interpreted as the power that the generator is required to produce *when frequency is at its desired value*, with acknowledgement that the power actually produced will exceed the setpoint value when frequency is low, and vice versa.

9.6 Elimination of trading penalties on frequency regulating action

The NEM market rules should be modified to, at minimum, remove the penalty (and perhaps even the perception of a penalty) incurred by generators that contribute to the control of frequency by their governor action. [5]

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[5] It can be noted that control of frequency is essential for the power system to operate reliably, while the production of energy at minimum cost is not. The power system can operate quite satisfactorily if its production costs rise above lowest possible level, but it cannot operate at all if it cannot control its frequency.

10 References

1 "Frequency in the Normal Operating Frequency Band - Update Report", DigSilent, 3518.01 ETR 1 Version 2.1, 4 June 2019

2 "Power and Frequency Control as it Relates to Wind-Powered Generation", J. Undrill, Lawrence Berkeley National Laboratory, LBNL-4143E, 2010

3 "Primary Frequency Response and Control of Power System Frequency", J. Undrill, Lawrence Berkeley National Laboratory, LBNL-2001105, 2018

The power system model

A Seven node system model

The synchronous power system is modeled as seven rotating masses at seven ’nodes’ as shown in figure A.1. Each rotating mass represents the collective inertial mass of a set of generators whose internal electrical connections are assumed to be strong in relation to the connections to generators at the neighboring nodes. The power flows between nodes are taken to be proportional to the angular displacements between the rotors at the nodes. The angles vary in accordance with the standard Newtonian dynamics of the generator rotors. The turbines are represented by the simple ’lead-lag’ model shown in figure 4.3.

The model, as used for this memorandum, is illustrative; the inertia constants of the machines at the nodes and the stiffness factors of the inter-node ties were assigned representative typical values.

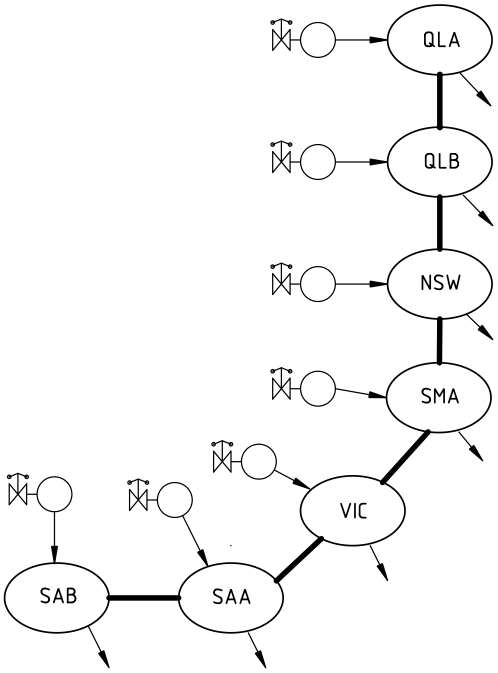

Figure A.1: Power system model consisting of 7 nodes of coherent synchronous generation