Inertia in the NEM explained

March 2023

As Australia's National Electricity Market (NEM) transitions to lower levels of synchronous generation, one area attracting attention is the reduction in synchronous inertia levels on the power system. At the same time, inertial response capabilities from advanced inverter technologies are fast emerging.

This fact sheet seeks to clarify and distinguish key terms and explore inertia from the perspective of a transitioning power system. It represents AEMO's technical view on inertia in the NEM[1] at the time of publication.

Power system inertia

An *inertial response* is the immediate, inherent, electrical power exchange from a device on the power system in response to a frequency disturbance. *Power system inertia* is the aggregate equivalent inertia of all devices on the power system capable of providing an inertial response.

Power system inertia is commonly linked with the system's ability to manage the rate of change of frequency (RoCoF). All else being equal, a higher inertia system will exhibit a slower initial RoCoF following a frequency event, and vice versa.

In the NEM, power system inertia is currently only quantified as the aggregate synchronous inertia of synchronous machines on the generation side of the system. While there may be some level of load (or demand) side inertia, such as from large induction motors, the quantity of load side inertia in the NEM is currently not well understood, and its contribution to overall power system inertia remains under investigation.

Historically, a high inertia power system was largely synonymous with a power system abundant in all synchronous machine characteristics. As the system transitions away from synchronous resources, this association may no longer be valid.

As levels of inverter-based resources (IBR) increase in the NEM, the consideration of power system inertia needs to capture the collective effect of inertial responses (instantaneous active power exchanges) from all devices on the power system.

Synchronous inertial response

A *synchronous inertial response* is the electromechanical inertial response from stored kinetic energy in the rotating mass of a machine that is electro-magnetically coupled to the power system's voltage waveform at 50 hertz (Hz).

Synchronous generators – like coal, gas and hydro plants[2] – have large spinning turbines and rotors whose rotation is synchronised to the frequency of the power system. These components are heavy, typically weighing tens or hundreds of tonnes, and provide mechanical inertia. As the machine spins at high speeds, rotational kinetic energy is stored in its mass.

Other synchronous machines, such as synchronous condensers, are also capable of providing a synchronous inertial response.

The inertial response from synchronous machines comes from the kinetic energy stored in their large rotating components. The kinetic energy is exchanged with the power system as electrical energy following

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[1] The information presented in this fact sheet is focused on the NEM. While it includes generic technical explanations of inertia, its application to the South West Interconnected System (SWIS) in Western Australia would need to consider the specific system configuration of the SWIS and the existing market arrangements of the Wholesale Electricity Market (WEM).

[2] Note that some variable speed drive hydro units can be inverter-interfaced with the grid and therefore do not provide a synchronous inertial response.

disturbances that cause a change in the speed of the rotating machine. This electromechanical response is instantaneous and inherent to the physics of the rotating machine.

The rate of energy exchange is directly proportional to the rate of change of the machine’s rotational speed (which is electromagnetically coupled to the electrical frequency at the machine’s terminals) in a manner that resists the change. That is, the synchronous inertia of the machine resists the electromagnetic forces applied by the grid. From a power system perspective, the injection or absorption of electrical energy in the form of active power is observed as a synchronous inertial response from the machine.

Characterising synchronous inertia

A synchronous machine’s inertia is calculated as a function of the distribution of mass of the machine around its axis of rotation and its synchronous speed. This means a synchronous machine’s inertia is a consequence of its mechanical design, including the mass of its rotor, shaft, prime mover (turbine) and even any fuel travelling through the turbine.

Synchronous inertia is quantified in megawatt-seconds (MWs) or megajoules (MJ) of kinetic energy. An inertia constant of a synchronous machine is calculated as the ratio of kinetic energy stored at nominal speed to the generator’s size in megavolt-amperes (MVA), and quantified in seconds.

$$H = \frac{{}^{1}/_{2}J\omega^{2}}{S}$$

$H = Inertia\ constant\ in\ seconds$
$J = Moment\ of\ inertia\ in\ kgm^{2}\ of\ the\ rotating\ mass$
$\omega = nominal\ speed\ of\ rotation\ in\ rad/s$
$S = MVA\ rating\ of\ machine$

The inertia constant is a fixed value that describes how long the machine could inject energy at its rated electrical output, solely with its stored rotational kinetic energy when initially spinning at nominal speed. Inertia constants for synchronous machines are typically in the range of 2-8 seconds.

The influence of synchronous inertia on the power system

While synchronous inertia has always been a part of the power system, it is not an inherent power system requirement. Rather, synchronous inertia is an inherent characteristic of synchronous machines that provides a fundamental stabilising effect on the power system which will continue to be required as the system transitions. When there is an abundance of synchronous inertia, its presence forms a baseline on which other solutions can be robustly designed to meet power system requirements.

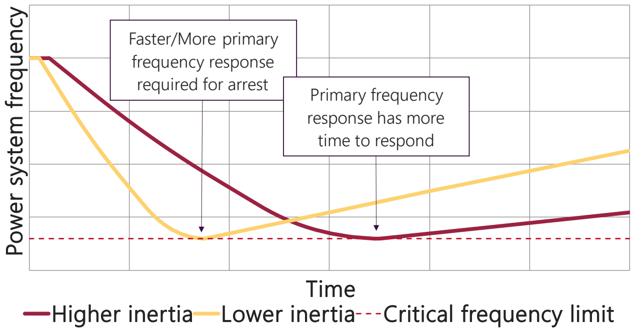
Relationship to frequency stability

Power system inertia is a core input to the design of NEM frequency control mechanisms, including frequency control ancillary services (FCAS) and various emergency frequency control schemes (EFCS).

A power system with high inertia, exhibiting a lower RoCoF, allows more time for frequency arrest mechanisms to act effectively.

Conversely, a low inertia power system could still sufficiently arrest a change in frequency with a faster and/or greater magnitude of primary frequency response.

In this regard, inertia is one option in a suite of mechanisms to meet frequency stability needs.



From a frequency control perspective, the ability to manage reducing levels of synchronous inertia through other frequency control mechanisms is technically well understood. The optimal mix of solutions is largely a question of economic efficiency.

Note, however, that by slowing down the RoCoF, high inertia systems will also require more energy to recover to nominal frequency.

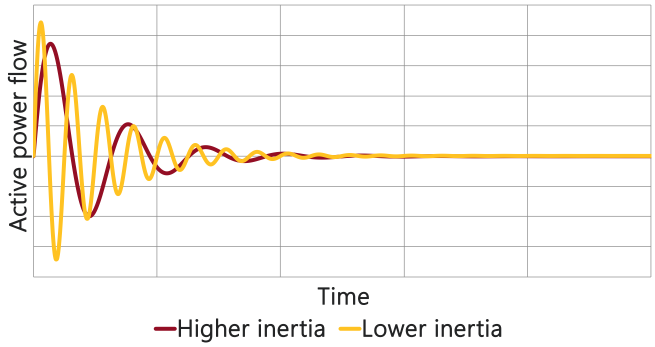
Locational factors

While it has historically been common to consider power system inertia as a global parameter at a system level, the exchange of active power involving multiple inertial responses is limited by available network capacity for power transfer. During a disturbance, if the distribution of power system inertia is concentrated in an area of the network with insufficient capacity to carry the resultant power flows out to the rest of the system, the impacts of exceeding transfer limits and other flow-on effects must be considered. This is particularly true for large, sparse networks such as the NEM. Consequently, it is critical to ensure a geographically diverse distribution of power system inertia across the NEM.

With any loss of transfer capacity for active power, for example resulting from a separation event, inertia that is not electrically connected[3] to the alternating current (AC) power system sub-network of interest has no effect on that sub-network. This means each sub-network in the power system needs to maintain a minimum level of power system inertia in case of total islanding.

Relationship to rotor angle stability

Inertia can influence power system characteristics that are not directly related to frequency and RoCoF. One such example is the impact of inertia on rotor angle stability, whereby clusters of synchronous machines on the power system may swing against each other following (small or large) disturbances.



All else being kept equal, a reduction in synchronous inertia levels will lead to faster power system dynamics. This could amplify and increase the frequency of oscillation of power exchanges over the connecting power lines, which could then increase damping requirements.

Relationship to other power system phenomena

Due to its historical abundance, the criticality of synchronous inertia alone on all power system stability phenomena (particularly over very short timescales) has not yet been studied in detail. This will only become relevant if future forecasts indicate synchronous inertia in the NEM will fall to significantly lower levels, at which a very high RoCoF over a small number of cycles could result in adverse outcomes at timesteps typically not considered for frequency control.

Studying this question is further complicated by the inherent linkage between a machine's mechanical properties and its electrical design, meaning it is often unrealistic to assume all else is kept equal when studying the impacts of reduction in synchronous inertia on power system stability. This means the impacts of synchronous inertia on general power system security cannot be easily unbundled from, or considered independently to, impacts of other synchronous machine characteristics.

Given these inter-relationships across synchronous machine characteristics and system phenomena, AEMO considers it would be prudent to maintain (where efficient) substantial levels of synchronous inertia for general power system resilience, particularly to assist in managing risk as the power system transitions.

Synthetic inertial response

A *synthetic inertial response* is the emulated inertial response from an inverter-based resource that is inherently initiated in response to a power system disturbance, and sufficiently fast and large enough to help manage RoCoF.

Inverter-based resources are interfaced with the power system through power electronic devices. They

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[3] As active power across DC interconnectors are controlled, inertial responses across DC connected systems is only possible if the converters of the DC interconnectors are designed to provide synthetic inertial response.

typically do not have spinning masses that are electro-magnetically coupled with the power system[4], so IBR generally do not supply synchronous inertia to the power system. However, it is possible for some IBR to provide an emulated inertial response to the power system through appropriate design of their inverter controls.

While there is not presently a consensus on the definition of synthetic inertia, for a complete replacement of synchronous inertia, AEMO proposes that a synthetic inertial response must be inherently initiated, and sufficiently fast and large enough to help manage RoCoF. This may not necessitate the response to be directly proportional to RoCoF, although this currently appears to be the most common form of implementation.

It is important to distinguish synthetic inertial response from other forms of very fast frequency response which may require external measurements of frequency to initiate an active power response.

Characterising synthetic inertial responses

As with most inverter-based responses, a synthetic inertial response requires an energy buffer and power headroom/footroom to facilitate a fast exchange of energy with the grid following a disturbance. Examples may include the stored chemical energy in a battery, the kinetic energy contained in spinning wind turbine blades, or operational headroom maintained by curtailing the output of a solar plant.

Inverters are normally current limited at significantly lower overcurrent levels than synchronous machines are capable of. This can limit an inverter's synthetic inertial response, especially when the inverter is operating near its rated capacity, resulting in different levels of inertial contribution capability at different operating points.

The contribution of a synthetic inertial response is also critically sensitive to its control system design. The "inertia constant" parameter of synthetic inertial response providers may be implemented differently, and potentially dynamically, across different control algorithms. This means there is not necessarily a fixed "inertia constant" for synthetic inertial response sources that is directly comparable to the inertia constant of a synchronous machine.

Therefore, while synthetic inertial responses could theoretically replace synchronous inertia for the purposes of RoCoF management, there is currently no standardised approach to quantifying a synthetic inertial response.

Furthermore, there is limited understanding of the impacts on other power system phenomena as synthetic inertial response is used to replace synchronous inertia.

Future power system inertia

As the power system transition progresses, AEMO expects the NEM's future RoCoF control needs can be met by a combination of synchronous inertia and synthetic inertial response on the power system.

Each type of inertial response will coincide with other characteristics of the devices delivering the response. This will in turn have implications for other power system phenomena that need to be understood as new sources of both synchronous and synthetic inertial response are introduced into the system.

The importance of understanding those implications only becomes paramount if the NEM is projected to reach critically low or sparsely located levels of synchronous inertia. In that case, a combination of desktop studies and operational experience would be needed to prudently transition into this uncharted territory.

However, as noted earlier, AEMO believes it would be prudent to maintain (where efficient) substantial levels of synchronous inertia for general power system resilience, such that this approach would not be necessary.

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[4] While wind turbines have large rotating parts, many modern wind farms are fully inverter-interfaced and therefore do not inherently provide synchronous inertia to the power system. This is similar to variable speed drive hydro units that are inverter-interfaced to the grid.