The Future of Power System Inertia

Submission to the AEMO Renewable Integration Study

30 June 2020

1. Introduction

Lloyd's Register welcomes the opportunity to comment on AEMO's first stage Renewable Integration Study. It is our view that the RIS provides a valuable framework for consideration by the entire industry of system technical issues arising from the high penetration of renewable energy, with Australia's National Electricity Market at the forefront of global developments in this area. In particular it contributes to AEMO's ongoing Integrated System Plan process and underpins the contemplated move to a future 100% renewable electricity system.

While there is much that can be discussed as part of the ongoing engagement process, we confine our comments here to a key issue that we believe merits close technical focus. This is the need – alongside the mandate for primary frequency response (PFR) from non-mechanical plants such as inverters – to actively study, validate and make provision for the full participation of such plants in the frequency dynamics, control and stability of the power system. This includes recognising the potential, to the extent it can be quantified through simulations and validated performance, for 'grid forming' inverter technologies to assume the inertia-mediating function historically performed by synchronous generators and motors.

The subject matter in our submission is technical in nature, but aimed at clarifying some of the deeper issues underlying the concept of system inertia and short-term frequency stability. These issues, while necessarily technical, have much wider economic implications for the future of the NEM.

2. System Inertia in the RIS

Technology neutrality is a fundamental principle that has guided the development of technical requirements under the National Electricity Rules since the appearance of the first grid-scale wind farms in the NEM in the early 2000s. It is recognised that one generator should not be subject to more onerous obligations than another purely because it employs different or newer technology to deliver electricity to the system; such distinctions should be made only when justified by differences in objectively verifiable performance.

One of many vital non-market services that generators perform in any AC power system is the provision of 'inertia', to help manage the primary response to large frequency disturbances by limiting the rate of change of frequency (RoCoF). Absent sufficient provision of this service, power systems would be unable to withstand the effect of even a moderate imbalance between generation and load from a credible contingency event. Operators would then have to rely heavily on load shedding and other blunt instruments to manage such events, with severe consequences for all electricity consumers. Inertia accordingly qualifies as a 'mission critical' service in AC power systems.

However, inertia also stands out as one aspect of technical performance where technology discrimination of the kind described above is held to be warranted (although not without challenge). The stated position of the RIS on inertia is as follows (Appendix B, Section 3.2):

> *System inertia is provided by the aggregate rotating mass of all synchronous machines and motors that are directly coupled to the grid. Synchronous inertial response is the instantaneous transfer of energy from these machines to the grid in response to a change in grid frequency. The response is provided by the physical properties of the machine, and does not require control system interaction.*
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> *The response acts to limit the RoCoF. Under low RoCoF conditions, PFR has more time to respond than under high RoCoF conditions.*

This statement reflects the traditional, century-old understanding of system inertia as an essentially mechanical property that an AC power system inherits from its synchronous machines. So conceived it is objectively technology-specific: electronic inverters, as they have no moving parts, cannot possess inertia or contribute to the inertia of the system. Consistent with this position, the RIS frames the question of frequency stability under high renewable energy penetration (and further displacement of synchronous plants by electronic inverters) not as one of operating a system with more diverse sources of inertia, but as one of adapting to conditions of low inertia.

Also implicit in this position is the premise that a future '100 per cent renewable grid' on mainland Australia cannot be technically feasible without either a mandated technology mix incorporating large quantities of synchronous generation (from new hydro plants, for example), or else a substantial investment in new auxiliary plants such as synchronous condensers or flywheel storage. Either alternative is likely to reduce the economic efficiency of the electricity system compared to a hypothetical world in which system inertia were not a decisive consideration.

Before conceding that these are the only alternatives, subject-matter experts have a professional obligation to test the assumption that what we call 'inertia' in a power system is by nature mechanical, given the system itself is electrical.

Such a test in practical terms, it must be acknowledged, will likely rely on further innovations in inverter technology as offered to the market. 'Grid following' technology, as employed in the current market-leading inverters for solar and wind applications, has proven itself commercially in its primary objective of supplying renewable electricity to the grid while meeting the essential requirements for system security. However, it is not designed to emulate the inertia contribution of synchronous machines, and experience with 'synthetic inertia' provided as an incremental addition to this technology is mixed.

Could the alternative 'grid forming' or other inverter technologies in principle act as a non-mechanical source of system inertia, performing a role akin to that of synchronous machines? A return to first principles may point the way to a tentative answer.

3. Physical Basis of Inertia

In order to operate any extensive power system securely, automatic mechanisms must be in place to correct any discrepancy between energy generated and energy consumed. Such discrepancies in an electrical network can cause it to move dangerously far from equilibrium in a very short time – sometimes in less time than required for a coordinated control response to operate.

For this reason, system security relies on the existence of one or more electrical variables that, as a consequence of the underlying physics of the system, can be relied on to monitor the balance between generation and demand from one time instant to another. Changes in these variables then trigger automatic changes in generation through either inherent dynamics or very fast-acting local control.

In a DC system, voltage performs this role of balance monitoring. Brute physics in the form of Ohm's law decrees that energy in the system always flows from points at higher voltage to points at lower voltage. An excess of generation then causes voltages to rise, and a shortfall in generation causes voltage to fall. Fast-acting controls responding to voltage provide the automatic response that restores balance, usually assisted by load damping from constant-impedance and constant-current components of demand.

In an AC system, voltage magnitudes can rise and fall independently of energy transfer, being tightly linked to reactive as well as active power. Instead, it is the phase angle displacements of sinusoidal voltages that couple to active power flow via Ohm’s law (in its AC form). The greater the active power transfer between two busbars, the larger the phase lag in voltage at the destination bus relative to the source bus.

If a discrepancy arises between the sources and sinks of the overall power transfer in the system, and this causes the phase angle displacements of successive bus voltages to advance or retard simultaneously, this will be detected as a perturbation to the system frequency. This leads one to conjecture that frequency in an AC system takes on the same monitoring role that voltage does in a DC system, even before any reference is made to synchronous machines.

Of course in real AC systems to date, the sources of power transfer are predominantly synchronous machines, in each of which the frequency of the voltage at the grid terminal is electromagnetically coupled to the speed of a rotating mass. The (mechanical) rotor equation of motion regulates the short-term increase or decrease in rotor speed in response to changes in the power loading impressed on the machine, as a result of changes in voltage phase angle displacements throughout the network. The regulating effect manifests as ‘synchronising power’ (or torque) again as a consequence of Ohm’s law, as (for example) acceleration of the rotor induced by a load rejection opens up the gap between the phase displacement of the EMF induced from the rotor flux, and that of the voltage at the grid terminal. This synchronising power acts on the network to further advance or retard voltage phase angles in step with the movement in the rotor angle, thus tending to equalise the system frequency with the machine’s rotor speed.

When the power system can be characterised in this way as an ensemble of synchronous machines linked by a passive electrical network, passive loads and motor loads, these considerations lead to the familiar swing equation

$$2H\frac{d^2\bar{\delta}}{dt^2} + D\frac{d\bar{\delta}}{dt} = P_0 - P(\bar{\delta})$$

for the short-term dynamics of a ‘gauge angle’ $\bar{\delta}$ that represents the common-mode component of all voltage phase angle displacements and machine EMF angles in the system as they move coherently under stable operation. The angle $\bar{\delta}$ is constant in the steady state at nominal frequency and its rate of change $\Delta\omega = d\bar{\delta}/dt$ is the system frequency deviation from nominal. The movement of $\bar{\delta}$ in response to short-term mismatches between input power P_0 and network consumed power $P(\bar{\delta})$ is regulated by the terms on the left, governed by the inertia H – the sum of individual machine contributions – and the load frequency damping D.

The important point to be made is that while the above reproduces the form of a mechanical equation, it actually describes the evolution of an electrical variable. It is conventionally derived by aggregating the behaviour of mechanical subsystems, but one must beware the fallacy of composition here – evocative as it is to describe large AC power systems as “the biggest machines on Earth”, a system does not become a machine simply because it contains machines as subsystems. Inertia and damping in this equation are analogues (much as voltage is an analogue of pressure) rather than mechanical properties in their own right. It is commonly recognised that the damping term $D\,d\bar{\delta}/dt$ is not necessarily mechanical in origin – load power may rise and fall instantaneously in proportion to frequency for entirely non-mechanical reasons – and likewise the same will in principle be true of the 'inertia' term itself.

4. Inverter Technology

In the above discussion, it should also be observed that the "instantaneous transfer of energy" that synchronising power represents is not, strictly speaking, mechanical in origin: it is rather the result of the complex Ohm's law reaction to a changing difference in phase angle between a source voltage (the rotor induced EMF) and a network voltage (the stator terminal). The energy transfer is thus amenable to a purely electrical description: what is contributed by the mechanics is the limitation on the rate at which the source voltage phase angle moves. A hypothetical electrical device that maintained a similar source voltage, limited the movement of its phase angle, and achieved the same instantaneous energy transfer in response to changes in the angle difference between source and the terminal voltage, would from an electrical point of view be providing the same inertial response as a synchronous machine, whether or not the source is maintained and regulated mechanically.

As is well known, an electronic inverter is a controllable AC voltage source whose fundamental-frequency component has an amplitude and phase displacement determined (respectively) by a programmable modulation index m (essentially a switch duty ratio) and a modulation angle θ. Changes to these parameters take effect in a sub-millisecond time frame, determined by the switching frequency. However, the effect of leaving them fixed is that the inverter behaves as a fixed voltage source behind the impedance contributed by the *LC* or *LCL* harmonic filter on the AC side.

The conventional 'grid following' or 'current source' mode of control for inverters adjusts the m and θ (or equivalent) parameters on a rapid timescale, so that the output current of the inverter follows commands for the components I_p and I_q in a synchronous rotating reference frame. Provided the reference frame remains aligned with the grid terminal voltage, these components correspond respectively (when scaled by voltage magnitude) to the active power output P and reactive power output Q. Additional closed-loop controls are used to increase the robustness of this strategy, which is capable of controlling power and voltage with response times typically around 1 to 2 seconds.

This mode of control operates inverters worldwide providing a highly flexible and cost-effective grid interface for wind, solar and storage applications. Most such inverters offered to the market now also provide PFR capability, and some include controls that respond directly to RoCoF. However, at a fundamental level this technology relies on working as a subsidiary device on an established grid. This reflects the origin of the grid following control in industrial motor drive applications, where the presence of the external grid is assumed. In particular, grid following inverters depend on a phase-locked loop (PLL) to maintain the necessary frame alignment with the terminal voltage, meaning it is only with great difficulty they can provide an instantaneous response to a changing phase angle displacement, as implied by the concept of synchronising power.

Other modes of inverter control are possible, including methods that give a more prominent role to the control parameters m and θ. These are analogous to the magnitude and phase of the EMF source for a synchronous machine, and can indeed be controlled to emulate machine behaviour (or a variant thereof), with a virtual 'excitation system' controlling m, and a virtual equation of motion controlling θ. Importantly, in this 'grid forming' mode of control these parameters evolve on slower timescales, in contrast to the rapid m–θ variations typical in grid following control.

When an inverter controlled in this manner encounters a shift in its terminal voltage phase angle (typically in response to a power imbalance within the network), the short-term response is an instantaneous transfer of energy as for a synchronous machine, albeit the energy is not transferred from a rotating mass in this case but from a stiff DC bus. It nonetheless still has the effect of advancing or retarding voltage angles within the network, so as to bring the wider movement in angles into alignment with the movement of its own modulation angle θ. This angle movement in turn may be limited by design, including in accordance with a specific desired value of 'inertia'.

There are limitations to this grid forming control, just as there are limitations to the synchronising tendency of machines. In the case of machines, a too-wide discrepancy between network and rotor phase angles leads to a loss of control and the need to trip to prevent damage from pole slipping. A grid forming inverter could in principle use a subsidiary PLL to impose a hard limit on the allowable angle difference between its own source and the grid voltage to maintain stability. However, the more stringent limitation for any inverter is on the magnitude of current flow possible. Under fault conditions or extreme grid frequency disturbances, synchronous machines may produce short-term currents up to an order of magnitude larger than their continuous current rating, limited only by short-term thermal considerations. Semiconductor devices in inverters, on the other hand, cannot withstand short-term currents above the device rating without damage. Devices in grid-scale inverters are typically sized some 30% above the level mandated by the nominal power rating, in order to provide reactive power capability. Grid forming inverters may require larger devices still in order to provide sufficient synchronising power capability. The economics of these sizing decisions and the nature of the corresponding limitations will be a matter for future market design and regulatory frameworks, and could warrant consideration in later stages of the RIS.

Inverters with grid forming modes of control are currently offered commercially, mainly for battery storage applications, albeit with low market share at present. Within the NEM, the 30MW ESCRI storage project at Dalrymple in South Australia utilises grid-forming technology to operate as an island with the Wattle Point Wind Farm. When operating in this island configuration it provides a working example of a 100% renewable energy grid controlling frequency with little or no inertia contribution from synchronous machines.

5. Conclusion

Lloyd's Register agrees with AEMO's staged approach to frequency management under high penetrations of renewable energy, as developed in the RIS. Our recommendation is the broadening of this approach to consider not only the adaptation of the NEM system to conditions of low system inertia, but also to operation with more varied sources of inertia, including non-mechanical sources.

Our submission has outlined a technical case that system inertia, as a practical service that limits the short-term RoCoF for frequency disturbances, should not be regarded as fundamentally a mechanical concept but rather as an analogue to a mechanical concept. In the future power system, inverters and other electrical technology have the potential to offer a comparable service. AEMO is well placed to study this potential as part of its staged approach to managing frequency stability in an evolving NEM.

6. References

1) AEMO. *Renewable Integration Study: Stage 1 report*, April 2020.
2) AEMO. *Renewable Integration Study Stage 1 Appendix B: Frequency control*, March 2020.
3) AEMO. *Draft 2020 Integrated System Plan*, 12 December 2019.