Australian Research in Power System Transformation

Topic 5 – System Restoration and Black Start

2025/26

Commonwealth Scientific and Industrial Research Organisation

19 December 2025

Contents

1. Introduction

Topic 5's remit considers the low probability but high impact scenario of a power system that has electrically collapsed and needs to be independently restarted and returned to a normal operating state. This is a challenging scenario to manage at the best of times with known technology but is becoming even more complex and uncertain as the generation mix shifts to becoming dominated by inverter-based resources (IBR) and large new (and often remote) renewable energy zones (REZs) begin to become more numerous.

Previous work completed by researchers undertaking Stage 3 and 4 developed an important baseline which this work builds upon. Most important for the Stage 5 focus areas currently underway, the previous researchers determined that:

- Grid-forming (GFM) technology, such as a battery energy storage system (BESS) can maintain dynamic stability for up to 10-times its MVA rating in grid-following technology during system restart.
- GFM technology is capable of energising large network transformers with less tendency for the spurious tripping of protection mechanisms compared to traditional synchronous machine technology.
- The use of BESS devices during system restart can accommodate uncontrolled variations in demand or generation within the restarting system more readily than traditional synchronous machine technology.

Using the above findings as a base for this work, Stage 5 studies centred around restarting a renewable energy zone (REZ). Two areas of investigation centred around offline EMT modelling to identify the steps required to use a REZ as a restart source for the broader network: (a) technical performance standards that must be maintained by IBR devices participating in system restart, and (b) the development of a practical test plan to allow GFM BESS as a viable system restart source to undertake real network testing ahead of procurement. Stage 5 milestones are as follows.

- Milestone 1: Realistic REZ model development, self-energisation and black-start studies.
  - Develop open, publicly shareable models of a complete REZ, including sub-component models of grid forming batteries, solar plant, wind farms, synchronous condensers, and network layouts, suitable for sharing with the broader research community. Perform studies on this model to determine required steps, strategies and timelines for a REZ to self-energise and reach its point of connection. Once energised at its point of connection, determine how far into the external network it can energise, and what services could be offered.
  - Target investigation areas: Determine how REZs can be best exploited as future System Restart Ancillary Service (SRAS) sources and how long (after loss of supply) is required for a typical REZ to complete the self-start stage and to become ready to energise the network, whether only a small nearby portion or beyond. Study possible REZ restart methods and requirements.
- Milestone 2: Hybrid plant configuration for energy exchange
  - Evaluate a "remote hybrid" concept for a REZ, whereby dispersed energy sources are connected to form a single viable SRAS source. Determine the most robust types of IBR to include, any control and coordination requirements between plant, and how much energy reserve a BESS must hold to accommodate this scenario.
  - Target investigation areas: Investigate the technical feasibility of using hybrid GFM BESS and IBRs as reliable SRAS sources. Broaden the scope of investigation to include modelling and performance of Inverter-Based Loads (IBLs), especially including performance in weak grid conditions.
- Milestone 3: IBR Technical Requirements for Restart
  - Develop proposed restart capability technical standards for IBR that consider: risks associated with islanding under low-inertia and low system strength conditions, operation in low system strength environments, GFM and protection control interaction and mitigation strategies, power quality and distortion requirements during restoration, and damping of weak-grid oscillations.
  - Target investigation areas: Evaluate the fundamental technical requirements for inverters for system restart, including grid forming capability, as a basis for developing technical requirements and standards.

- Milestone 4: Development of a GFM-BESS restart test plan template
  - Create a test plan template suitable for live network testing of GFM BESS restart sources, based on a combination of existing and proven test plan templates and advice from network service provider(s) to help protect the safety of network assets. Consider monitoring of equipment requirements, international best practice, and inter-organisational communication requirements.
  - Target investigation areas: Investigate and establish a GFM-BESS restart test plan for a real plant, to develop confidence in the capability of the device to restart a portion of the system.

The above work is both aligned with the original System Restoration roadmap and the target areas called upon for the 2025-26 year.

2. Research completed

Previous AR-PST research stages identified through EMT modelling that:

1. System restoration from IBR resources is achievable, with grid-forming batteries being the most preferable option of the IBR suite of generators for a robust system restoration source (Stage 2 & 3, Aurecon).
2. Grid-forming technology either can be a primary restart source or can readily complement existing synchronous machine restart sources with minimal, or no, accommodations required (Stage 2, Aurecon).
3. Grid-forming batteries can host up to ten times their nameplate rating of grid-following devices (not accounting for network impedance) before dynamic stability issues become detrimental (Stage 3, Aurecon).
4. Power variations from DER along distribution feeders do not destabilize a restarting system if an appropriately tuned and optioned GFM BESS is used, however, DER penetration exceeding 80% of the BESS's nameplate rating can cause phase-locked loop (PLL) instabilities within the DER itself (Stage 4, Etik Energy).
5. Poorly configured or poorly tuned park power controllers (PPCs) are more likely to be a source of instability during system restart (compared to inverter PLL destabilisation), however this can be mitigated using direct power control (Stage 4, Etik Energy).
6. GFM IBR restart sources appear to have an ability to energise larger transformers without spuriously tripping transformer differential protection, owing to the IBR source's current-limited nature (Stage 4, Etik Energy).
7. Approximately 35 to 40% of a retiring synchronous generator's capacity (by MW) must be replaced with GFM IBRs to maintain the same network restoration capability (Stage 4, Etik Energy)

This Stage 5 work builds upon items 1, 2, 3, 5 and 6 above to extend analysis of how IBR can best play a role in system restart to the four milestone areas described in the introduction. To date, the following research has been completed:

1. Underpinning much of the work of Milestones 1 and 2, a detailed, publicly shareable EMT REZ model has been developed, suitable for future researchers to use for their own investigations. This model includes an extensive REZ network representation, including full geometric line model representations, internal network transformers and generator point of connection transformer models, and detailed switching arrangements (terminal station circuit breaker layout). Protection relay models are also included[1], customised for each asset under test, including transformer differential protection, line distance protection and generator voltage and frequency protection. A full suite of shareable IBR generator models has been developed or greatly refined, including VSM-mode GFM BESS models, droop-mode GFM BESS models, GFL solar farm models, type 3 and 4 wind turbines models, wind farm reticulation networks, and hybrid plant models (including park controllers). Extensive work has been undertaken to improve these models for deployment in a REZ and to include options for energy source variation. Synchronous condensers, with an associated variable speed drive for energisation, have also been developed, and a pumped hydro model (based on a DFIG configuration) is now ready for further studies.
2. Studies have been completed that investigate how a REZ can self-energise, what strategies may be required, and which pitfalls must be avoided. Studies of energisation of external (to the REZ) network have been completed, both for when the REZ comprises a single GFM BESS as the only source, and for when a suite of

[1] Protection relay models use the add-on Manitoba Hydro relay library, available with PSCAD.

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four or more primary energy source generators work together to form a coherent co-ordinated system restart source.

3. A comprehensive suite of energy consumption scenarios has been completed to determine how much energy is required to energise and to keep online each network element of a REZ. This includes high-voltage lines, large network transformers, and synchronous condensers energised through variable speed drives. These studies tackle the oft-quoted limitation of a BESS as a restart source in that it only has a finite amount of energy. This aspect is analysed by determining realistic amount of energy consumption of each component and thus a realistic runtime of a black-start BESS before its energy is exhausted.
4. Related to the above, the ‘remote-hybrid’ concept has been explored in detail. Here, a GFM BESS is the primary black starter, which goes on to energise a non-black start IBR-based primary energy production plant (such as a wind or solar farm) within the REZ that is purposely neither located close by, nor is under the same coordinated control scheme as the GFM BESS. Heavy variations in the output of the energy source were applied to represent the worst-case scenario of (for solar farms) scattered and fast-moving cloud cover and (for wind farms) inconsistent wind speed. The GFM BESS, notably, could readily accommodate such output variations without issue.
5. Beyond to the originally planned scope, this ‘remote hybrid’ concept was further expanded to consider synchronisation and coordination of multiple REZ islands. Operating effectively as two entirely independent REZs, multiple islands with heavy variations in the output of their primary energy sources were first analysed independently and then later brought together to identify any additional challenges in maintaining a stable system within normal operating envelopes given the large variation in uncontrolled and uncoordinated power generation.
6. Interviews with a network service provider have taken place to understand network asset owner concerns about the use of GFM BESS devices in providing a system restart service, and what safeguard mechanisms to minimise the chance of damage to network assets are required in network testing plans. Work is continuing on the development of a comprehensive GFM BESS test plan template that would be suitable as a basis for system restart testing (including energisation of network elements beyond the point of connection) in the Australian power system.

From the work completed to date, the following key findings are available:

- Early stages of REZ re-energisation can suffer from passive network sub-synchronous resonances, due to the extremely weak and unmeshed nature of the network. Given the limited size of a REZ, passive impedance scans for all potential network element energisation combinations are feasible and strongly encouraged to identify and avoid potentially hazardous sub-synchronous resonances.
    - It was noted that the inclusion of harmonic filters (which are typically not energised during system restart, due to their injection of reactive current in an already lightly loaded network), may be beneficial to include in the switching plan, in order to alter low-frequency harmonic resonance profiles, provided there is sufficient reactive absorption headroom.
- So long as each plant has a typical (and stable) reactive power control scheme in place designed to maintain either (i) the terminal voltage (i.e., a PPC-less arrangement) or (ii) the point of connection voltage of each unit to within nominal bounds, the presence of one or more GFM BESS(s) was readily able to compensate even for excessive variations in active power arising from multiple primary energy producing assets simultaneously. Each of VSM and droop GFM control modes were able to absorb these active power variations, with acceptable variations in frequency, provided their limits on active power absorption and production were not breached. Additional complex, overarching dispatch, control and coordination schemes have not been required[2].
    - It was noted, however, that it would be beneficial for the GFM sources with droop mechanisms to have an active power offset/trim function to facilitate the correction of steady-state frequency errors. This is to ensure that GFL device “wait to connect” bands could be met (e.g., between 49.85 to 50.15 Hz), as identified in the previous Stage 4. This requirement could be understood as being similar to the frequency correction function that NEMDE provides. However, given the limited system scale and long

[2] This is not entirely unexpected, as aside from slow frequency corrections from NEMDE, the power system routinely reaches an equilibrium where voltage and frequency control mechanisms (typically droop) are in service at each plant. Whether it is an *optimal* equilibrium is a separate consideration, and likely unimportant during a system restart scenario.

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timeframes for which such a frequency setpoint offset should operate, this enhancement could be operationally implemented manually.

- Synchronous condensers undoubtedly provide system strength, inertia for better frequency control, and voltage control functions, to the REZ. However, from the studies conducted to date, so long as the GFM BESS has sufficient active and reactive power control headroom, synchronous condensers bring only minor improvements to system stability. If energy reserves are in short supply, it may be best to forego their energisation (a process which can take in excess of an hour depending on inertia constants and pony motor sizes) unless other circumstances require them to be online.
- For the asset owner who was providing input into the development of a GFM BESS test plan template, primary concerns were a lack of communication among, and lack of co-ordinated rehearsals by, the many parties involved in a system restart network test, and the lack of real-time high-speed monitoring on critical assets such as network transformers. These concerns are less technically complex than originally anticipated but are nevertheless just as valid, given the experience the network operator shared with the researchers. Hence, further development of the restart test plan template will focus strongly on the need for both interorganisational communication, and reliable real-time data feedback, to facilitate a successful and safe system test.

3. Outstanding activities

The following activities are yet to be completed, but are still on schedule for project conclusion:

- Further analysis of the voltage and frequency services that are able to be provided to the network external to the REZ.
- Development of switching timelines that are sufficient for a REZ to self-start and to be ready at the point of connection for further instructions.
- Determining the capability of the BESS to provide energy absorption services for nearby synchronous machines during restart.
- Development of a set of (recommended) technical requirements for IBR to participate in system restart.
- Production of a test plan template for a GFM BESS to undertake network testing in an Australian context.

4. Progress against the Roadmap

The Stage 5 work planned and completed aligns strongly with the original roadmap for Topic 5. Specifically, the following roadmap areas are being investigated through the above described work.

The treatment of inverter-based resources during system restoration (Item 1), with respect to:

- Grid-following inverters (Item 1-1), including interaction with low-order harmonic resonances and the impact of variable energy sources on greater system stability.
- Grid-forming inverters (Item 1-2), including interaction with low-order harmonic resonances, storage requirements for black start sources, interaction with protection relays, evaluation of different synchronisation techniques and physical testing of grid-forming IBR unit to confirm their capabilities and limitations.

The impact of network control and protection systems (Item 2), with respect to:

- The impact on protection systems (Item 2-2), including impedance-based protection, including distance protection.
- Assessing the need for protection modifications. (Item 2-3), including whether there is a need to block certain protection systems during system restoration.

Technical and regulatory requirements (Item 4), with respect to generator technical requirements and power system technical requirements.

End-to-end system restoration in power systems with high share of inverter-based resources (Item 5), with respect to bottom-up restoration (5-1), including the use of various storage technologies as stabilising loads and synchronising two or more IBR only power islands.

It is our view that the original roadmap in 2021 still remains highly relevant to the situation today.

5. Research relevance to Australia

The work being completed in this Stage and Topic is directly related to the continuing evolution of the Australian power system as it evolves to an inverter-dominated paradigm. Notably, the recent AEMC Issues Paper[3] and subsequent Review of the System Restart Standard[4] was precipitated by the rapid and prolific shift of generation sources to inverter-based resources across the power system. Specifically:

- Procurement options for traditional synchronous system restart sources are dwindling, resulting in periods of time where the system restart standard in some regions can not be met, unless non-synchronous options are considered.
- Scores of new IBR-dominant REZs are being built across the NEM without necessarily embedding a restart capability, nor being located nearby to traditional restart sources.

Furthermore, the situation is becoming severe enough that AEMO has recently developed a "Type 2" trial program[5], to prove the capability of IBR technologies to provide viable restart options with a focus on delivering real-world experimentation on the actual power system.

Recalling that the focus areas of this Stage 5 work are:

- Development of an open and shareable generic REZ EMT model such that technical elements relevant to restart can be assessed both by these researchers and the general research community,
- Evaluation of whether a REZ can offer a primary black start service to the NEM, including addressing the perennial issues, for BESS of limited energy reserve capacity, and for solar and wind resources of their highly variable nature,
- Defining critical technical standards that IBR must meet to participate in system restart, and
- Developing a practical test plan template, based on NSP advice, to allow real network testing of a restart from a GFM BESS as a primary source.

It is clear that the work being progressed in this stage is directly relevant to AEMC and AEMO initiatives to enable IBR devices to participate in restart, while respecting the concerns of network asset owners. The outputs of this work might be used as direct inputs to the AEMO Type 2 trials for IBR-based system restart (e.g., the GFM BESS test plan template may be used by participants to demonstrate their readiness to conduct live network restart testing).

Nevertheless, AEMO forecasts that gas-powered generation (GPG) will remain an important part of Australia's energy mix to support the transition from coal, providing firmed energy for the grid[6]. Therefore, in the system with no-coal scenario, GPGs along with IBRs would play a key role in system restoration. As traditional coal fired generation retire, and new GPGs are getting built, a certain amount of GPGs with restart capabilities would benefit system restoration.

6. Recommended research priorities

The output from multiple researchers across multiple years in this field has been consistent: EMT studies show that inverter-based plant is entirely capable of providing a system restart service, particularly where GFM BESS devices are used as the primary restart plant. Furthermore, these studies have shown that asset protection relay operation may remain viable, based on generic models. It is recommended that focus now shifts to enabling real-life trials of inverter-driven restart and better evaluating actual, physical protection relay responses to high IBR scenarios (due to the unavailability of manufacturer-specific EMT models). To that end, the following areas are recommended research priorities:

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[3] **https://www.aemc.gov.au/sites/default/files/2024-12/Issues%20Paper%20-%20Review%20of%20the%20System%20Restart%20Standard.pdf**
[4] **https://www.aemc.gov.au/market-reviews-advice/review-system-restart-standard-0**
[5] **https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/transition-planning/transitional-services---type-2-services/black-start-capability-from-ibr**
[6] **https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2025/2025-gas-infrastructure-options-report/final/2025-gas-infrastructure-options-report.pdf**?

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- Support the Type 2 trials likely to occur in the NEM by conducting exploratory operational studies on real network and plant data provided by NSPs, OEMs and AEMO.
- Testing of real network protection relays within a hardware-in-loop setup to confirm the conclusions made through the network protection relay investigations conducted in this Stage 4 period apply to common manufacturer-specific devices used in the NEM.
    - Where hardware-in-loop studies are conducted, an evaluation of the conclusions between offline EMT studies and HIL studies to confirm the validity of the tools used for analysis.

  Protection in low-fault-current restoration islands, exploration of what constitutes protection-quality fault current, and whether there are additional facets specific to system restoration.
- Assessing what system restoration involves in the presence of large inverter-based loads, such as data centres and electrolysers, and how their electrical behaviour may influence restoration outcomes.

  To assess the role of forecasted gas-fired generation capacity in supporting system restoration and to determine optimal locations and capacities for system restart sources in future coal-free scenarios across each region, considering both existing and projected gas-fired generation
- Optimal sizing and strategic locations of system restoration sources in future coal-free scenarios:

  Through system studies and analysis, identify strategic locations and both minimum and optimal sizing of system restoration sources in future coal-free scenarios across each region.

  Investigate possible opportunities of retro-fitting existing gas-fired generation fleet to enable system restart capability to support future coal-free scenarios across each region.

  Examine the role that future hydro and gas-fired generation, as projected by the ISP, can play in system restoration for future coal-free scenarios.

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