Topic 5 – Restoration and Black Start

2024/25

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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 load continues to increase its share of distributed energy resources (DER).

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

- Grid-forming (GFM) technology, such as a battery energy storage system (BESS) is capable of hosting up to 10-times its MVA rating in grid-following technology (provided network impedance is sufficiently small such that it is has a negligible impact on system strength provision).
- The Dynamic performance and stability of a GFM BESS black starter is superior to that of a combination of synchronous condenser plus a grid-following (GFL) BESS, and potentially better than a synchronous generator, noting that fault-current limitations of a GFM BESS may still be problematic.
- Voltage and frequency protection settings of plant that are active in the system during system normal, are likely to still be acceptable during system restart scenarios. However, it is noted that changes to frequency control settings during restart may be of benefit by improving general system stability.

Using the above findings as a basis for this work, Stage 4 studies considered restarting a power system that comprises 100% IBR resources. Three major areas of investigation are based on offline EMT modelling and correspond to the first three milestones in the project plan. The project plan also includes one further area focusing on timeline and procurement needs of the NEM as it evolves to become IBR dominated, resulting in a fourth and final milestone. These research target areas and milestones are as follows:

- Milestone 1: Dynamic modelling of DER control systems and distributed energy source variations for a 100% IBR restart scenario.
  - An DER model developed by EPRI with dynamic representation of inner and outer inverter control loops is used. The work investigates any destabilising effects of DER (i.e., rooftop PV) on a restarting system when the restart source is comprised of a GFM BESS black-starter. Additionally, studies determine if the black-start source type (i.e., IBR vs. synchronous) has a material impact on the stability and performance of the DER itself, and what its tripping and susceptibility mechanisms are likely to be.
  - Target areas: Understanding the impact of distributed energy resources behaviour during system restart.
- Milestone 2: Evaluation of alterations to GFL IBR operational, and any high-level, operator-accessible, settings to enhance stability during 100% IBR system restoration, extending to hybrid (IBR and synchronous) plant.
  - This considers the problem of how existing IBR plant in the NEM can aid in the restart process without modification to deep controller settings affecting stability (e.g., PI controller gains), despite such plant not being specifically designed to operate in a restart scenario. It considers "on the day" operational strategies that could be employed by system operators to maximise success.
  - Target areas: Maximising the contribution of grid following inverters during system restoration through modifications to GFL-plant only.
- Milestone 3: Evaluation of IBR black start sources on network protection relay functionality.
  - Studies to be completed are to consider if there is any undesired performance of network protection relays when the system restart source is provided by an IBR resource, as opposed to a traditional synchronous machine source. Maloperation of network relays could have a variety of consequences for a fragile restarting system, hence their failure mechanisms should be understood.
  - Target areas: Understanding the impact of network control and protection settings on IBR system restart; Integrating protective relay response into power system restart modelling and simulation tools
- Milestone 4: Development of an analytical screening tool to estimate the amount of GFM IBR restart sources required in a rapidly decarbonising system. Based on the published retirement dates of key restart-capable

thermal generators across the NEM, previous research insights into GFM BESS restart capability, and previous system restart analysis experience, a tool is to be developed to estimate the quantity of IBR-based SRAS required to be procured as a replacement as the system evolves. Consideration on how the changes in network topology will affect restart capability be discussed and areas of further research identified.

  - Target areas: Estimation of time frame over which retirements of conventional plant are likely to make IBR system restart necessary and/or comparable in cost to convention restart options.

The above work is both aligned with the original System Restoration roadmap and the target areas called upon for the 2024-25 year.

2. Research completed

The research completed can be broken down into three categories:

1. Prerequisite model development
2. Operational strategies identified, based on model simulation, to increase stability during 100% IBR restart (Milestone 2)
3. The impact of DER on 100% IBR restart (Milestone 1, partially complete)

2.1 Prerequisite modelling

Considerable effort has been expended in developing a limited area EMT model that is reflective of a “realistic but not real” system, suitable for both exploring restart with 100% IBR arrangements and sharing with the broader research community. Such a limited area model represents approximately 300 km of primary restart path circuitry, covering transmission, sub-transmission and a representative distribution feeder. Up to 100 MW of generation and load is modelled, depending on the specific scenario. Further, it consists of:

- A suite of network transformer models that have parameters based on real transformer characteristics.
- A suite of geometric transmission and sub-transmission line models that are based on real tower arrangements and typical conductor types used in the NEM.
- Distribution feeder models containing DER models with inverter controllers, developed by EPRI.
- Surge arrester models based on manufacturer profiles.
- An open-cycle gas turbine synchronous generator model based on an amalgam of real plant profiles.
- A grid-forming BESS model developed by EPRI.
- A wind farm model developed by EPRI.
- A suite of integrations with models (non-releasable) of IBR provided by OEMs, including:
  - Solar, batteries and hybrids.
  - Grid forming and grid following.
- Online harmonic visualisation tools.

All non-confidential models are intended to be released at the conclusion of this research for further use and scrutiny by the research community.

2.2 Operational Strategies

Extensive studies were completed that looked at how the stability of a restarting 100% IBR system can be maximized by employing “on-the-day” strategies. Such strategies do not rely on retuning of complex internal control systems prior to the restart event, but instead supposes a scenario where a system operator has been forced to “make do” with a considerable existing GFL fleet that is not necessarily designed to operate stably during restart. Strategies included changes to restart sequences, changes to plant target setpoints that are both common and open to modification, and bypassing of plant componentry where easily implemented.

Several important findings were identified, including the following:

- Power Park Controllers (PPCs) are a major source of instability if their closed loop controllers (e.g. voltage, frequency) are not appropriately tuned for system restart. Stability may be restored if the PPC is placed into open-loop mode (bypassing any PPC closed loop control) and set to issue a fixed, constant active and reactive power command to each inverter as measured at each of the inverter terminals (e.g., active power set to 50% output, reactive power set to 0% output). This results in a constant output from the inverters and allows the generating system in aggregate to be insensitive to voltage and frequency fluctuations occurring within the broader power system (within nominal bounds). Although this makes maintaining voltage and frequency within bounds more challenging, requiring more coordination and communication between parties, it is preferable to an otherwise unstable system.
- It is not recommended to increase the aggressiveness of frequency droop in a black-start source (GFM BESS) in attempt to reduce variations and excursions in system frequency. . GFM frequency droop settings below approximately 3% [rated frequency to rated power] saw a much higher rate of instability manifest across several studies, particularly following a disturbance that resulted in a transient imbalance in active power. Instead, off-nominal frequency corrections may be better addressed by manually applying active power biases on the GFM black starter on-the-day, rather than attempting to utilise aggressive closed-loop control systems.
- The internal transfer of active power behind the point of connection of a hybrid plant (that is, the energy transfer between solar and BESS devices within the reticulation network) is an important quantity to monitor and control during system restart. Major disturbances to the grid (most notably, transformer energisations) can result in only a portion of the hybrid plant entering into fault ride-through mode, typically the inverters electrically closest to the connection point. Should there be a large *internal* power exchange with perhaps initially minimal export to or import from the grid, an unplanned disturbance may result in a large portion of the internal power exchange amount being forced out through the grid connections, causing a rapid frequency event in the broader system and subsequent system collapse. Hence, it is recommended to minimise internal power exchange within hybrid plant during restart attempts.
- Frequency variations outside the normal frequency band may be common and unavoidable during system restart, as load is energised or removed, or as generators without frequency correction devices (e.g. governors) are energised. Although many GFL IBR devices have excellent tolerance to frequency variation (i.e., ± several Hertz from nominal), this generally applies only *after* they have successfully synchronised to the system. Furthermore, not all plants in the system have the capability to stably operate with off-nominal frequencies. Prior to synchronisation, many GFL devices may have been set to expect a far tighter frequency tolerance to begin their connection process, in order to avoid potentially connecting during a frequency event during system normal. Such behaviour must be factored into the restart plan (and/or future technical performance requirements for IBR) and switching of generation and load arranged such that system frequency remains within the “wait-to-connect” band for the period required by the plant.

2.3 The impact of DER

Studies have been conducted within this Stage 4, investigating the impact of DER (i.e., rooftop solar within the distribution system) on a system that is being restored by 100% IBR resources. Importantly and unlike previous work, the DER models used in this work have generic representations of fast inner- and slower outer-control loops, allowing a more in-depth exploration of stability phenomena. This has been considered from several angles:

- The impact of a 100% IBR restarting system on DER’s ability to perform acceptably.
  - An inverter-based restarting system has different properties (e.g., reduced fault current) compared to a synchronous machine-based system restart which means that DER devices may respond differently to disturbance events.
- The impact of DER on the ability of a 100% IBR restarting system to perform acceptably.
  - Exploring the reasonable hypothesis that a BESS is more readily able to accommodate the uncontrolled export of power from DER devices than a synchronous machine, including the impact of uncontrolled energy source variations (e.g., cloud cover) on stability under restart conditions.
  - Whether DER remains stable in a restarting system with a very high share of inverter-based resources.

While the research on this topic is continuing, the work to date has led to the following conclusions:

- On the basis of all studies completed, a GFM BESS black-start device can readily accommodate the uncontrolled export of power expected from DER. This includes for sudden DER reconnection, disconnection, and variations of the DER energy source. Provided that sufficient (power variation) headroom remains available from the inverter and the state of charge allows it, the ability of the GFM BESS to return the system to balance appears to be superior to that of a synchronous machine.
- During transformer energisations in a restarting system, DER may be more prone to tripping offline when a GFM BESS restart source, rather than a synchronous machine restart source, is used. This is because the profile across time of the system voltage recovery is slower for the GFM BESS restart source studied, while it attempts to energise a large transformer. This relatively delayed return to nominal voltage operating bands increases the likelihood of mass DER tripping on undervoltage protection for large voltage drops.

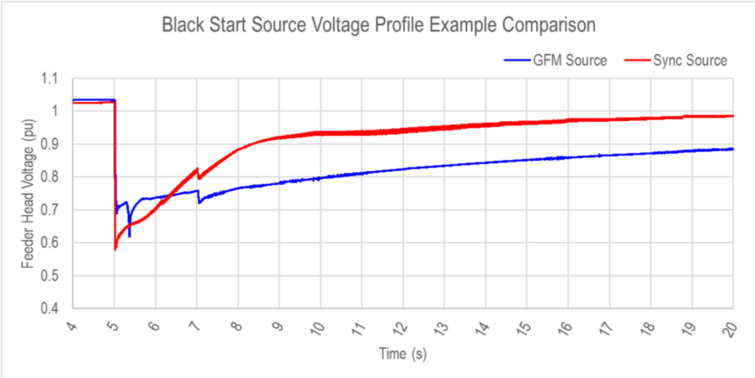

Figure 1 Following transformer energisation, voltages return to nominal bands (0.9-1.1) faster with a synchronous black starter

3. Outstanding activities

The following activities remain in this Stage 4 project:

- Milestone 1:
  - Completion of DER studies (approximately 20% studies remaining).
- Milestone 3:
  - Parameterisation of network protection relay models specific to the limited area network components which they will protect (i.e., matching the protection relay settings to the physical characteristics of the network line and transformers).
  - Studies of network protection relay operation in a 100% IBR dominated scenario, including multiple energisations of transformers in series.
- Milestone 4:
  - Development of a high-level procurement timeline tool, identifying approximate amounts of IBR-based black starters that need to be procured as thermal plants retire.
- A set of releasable models for the research community.
- A draft and final report for publication.

Progress of outstanding activities will continue to be regularly reported upon through monthly meetings with the CSIRO and broader G-PST entities.

4. Progress against the Roadmap

The Stage 4 work completed and planned aligns strongly against the original roadmap[1] for Topic 5. Specifically, the following roadmap areas (as described in Section 1) are being investigated through the above work:

- The treatment of inverter-based resources during system restoration, with respect to:
  - Grid-forming inverters (Milestone 1-3)
  - Grid-following inverters (Milestone 1-3)
  - Distributed energy resources (Milestone 1)
  - Comparison with synchronous machines (Milestone 1-3)
- Impact of network control and protection systems, with respect to:
  - The impact on protection systems (Milestone 3)
  - Assessing the need for modifications. (Milestone 3)
- End-to-end system restoration in power systems with high shares of IBRs (Milestone 2).

It is our view that the original roadmap in 2021 still remains highly relevant to the situation as it has evolved in reality, and it recommended that the roadmap is adhered to for the foreseeable future.

5. Research relevance to Australia

The work being completed in this Stage and Topic is directly related to the evolution of the Australian power system to an inverter-dominated paradigm and is now more important than ever. Notably, a recent Issues Paper published by the AEMC[2] points out that, amongst other concerns:

- Procurement options for system restart sources are dwindling and resulting in some periods where the system restart standard[3] cannot be met with traditional synchronous plant.
- Alternative options for primary restart and restart support services, such as the potential use of new and existing IBR, are urgently needed and the technical feasibility of such options must be evaluated as a matter of priority.
- There is concern that large amounts of DER and the dynamic performance of the distribution system will undermine the ability of the system to be restarted during daylight hours, and that such concerns should be investigated and if needed, solutions found.
- The operation of protection mechanisms may be affected by the changing properties of electricity which IBR plant deliver to the system. This should be tested and if found to be material, a solution found.

Given that much of the work being considered in Stage 4 directly investigates these live concerns of the AEMC and the Reliability Panel[4], it is clear that the work is pertinent to very real, very urgent issues in the Australian context. Specifically, the scenarios being considered are related to the above as follows:

- The investigation of high levels of distributed energy resources (e.g. solar PV) during 100% IBR restart.
  - This is a pressing issue currently in the NEM whereby there have been discussions about the potential for delaying system restart to non-daylight hours as to avoid the need to deal with the uncontrolled output of

[1] B. Badrzadeh, "GPST Blackouts and System Restoration Research", Aurecon, Melbourne, Victoria, Australia, 2021. Accessed 5/02/2025. [Online]. Available: **https://www.csiro.au/-/media/EF/Files/GPST-Roadmap/Topic-5-Blackouts-and-System-Restoration-Final-Report-with-alt-text-2.pdf**

[2] AEMC, "Issues Paper - Review of the System Restart Standard", AEMC, Sydney, New South Wales, Australia, 2024. Accessed 5/02/2025. [Online]. Available: **https://www.aemc.gov.au/sites/default/files/2024-12/Issues%20Paper%20-%20Review%20of%20the%20System%20Restart%20Standard.pdf**

[3] AEMC, "The System Restart Standard", AEMC, Sydney, New South Wales, Australia, 2021, Accessed 5/02/2025. [Online]. Available: **https://www.aemc.gov.au/sites/default/files/2021-01/SRS%20Review%20-%20System%20Restart%20Standard%20-%20FOR%20PUBLICATION_0.pdf**

[4] AEMC, "Reliability Panel", Australian Energy Market Commission, Accessed: 5/02/2025. [Online]. Available: **https://www.aemc.gov.au/about-us/reliability-panel**

DER on the system. The work in Milestone 1 has been considering a 100% IBR dominated system to investigate what steps, if any, should be taken to accommodate this precise situation.

- How to best accommodate the considerable existing fleet of IBRs in the NEM without the need to re-open technical negotiations with plant owners, maximising the chances of a successful system restart.
  - Australia already has a substantial fleet of IBR, that due to its connection locations and long remaining lifespan, will almost certainly need to contribute to restart paths as more of Australia's restart-capable synchronous machines retire. However, these existing IBR devices have not been specifically tuned to cope with a system restart scenario, and re-opening negotiations to tune these devices for a low-probability, high-impact scenario may be a very unappealing prospect for plant owners. Hence, the work in Milestone 2 has investigated how such existing IBR can be accommodated within a restart process on a no-regrets, best-effort basis, without the need to re-open negotiations, by determining which (relatively less burdensome) *operational* changes can maximise plant stability during restart. However, it is important to note that as this approach may ultimately have limited success., Such work is not a replacement for investigating more comprehensive Australian restart scenarios with specific inverter installed designs and settings.
- Addressing the concerns of Australian network operators that protection relays may no longer be fit for purpose once substantial numbers of synchronous machines retire from the system.
  - Given the current limitations of existing IBR technology, fault current magnitudes and quality are presently believed to be strongly dependent upon the presence of online synchronous machines, which are a dwindling resource in Australia. As the dependable operation of certain protection relays in the network relies on several system characteristics (e.g., high fault current magnitude, unbalanced current provision) always remaining present in the power system, this may no longer be valid as the Australian generation fleet shifts from synchronous-dominant to IBR-dominant. Milestone 3 work will investigate how such protection relays may operate with such a different, IBR-dominant, set of generators comprising a restarting system in the Australian context.
- Understanding approximately when, over the evolution of the power system, the procurement of IBR-based system restart sources will become a necessity.
  - The retirement of restart-capable thermal plant across the NEM is occurring rapidly, hence the need to procure IBR restart sources will become a necessity. Milestone 4 work will look to establish a high-level methodology, and calculation tool, to estimate when and how much IBR restart sources will need to be procured as the NEM evolves.

The models being developed to investigate these issues have similar topologies to those expected to be present in the NEM during restart. The limited-area, detailed model developed for Stage 4 has realistic, though not real, topologies, using configurations and network asset types that are typical of, and often used in, some NEM jurisdictions. This has largely been based on the practical experience of the researchers, who have worked on developing operational system restart scenarios in the NEM.

Finally, excluding any confidential or sensitive data used, the EMT models developed will be released to CSIRO to share with the research community, to be scrutinised, change, grow, or otherwise used as appropriate.

6. Recommendation on research priorities

Based on 2021 roadmap, as well as the studies described here and discussions with the broader G-PST team to date, the following research priorities in Topic 5, System Restart, are recommended.

- Studies into potential methods and requirements for Renewable Energy Zones to restart both plant within the zone and a portion of the nearby network beyond its point of connection.
  - Including the particularly vexing issue of energisation of large, network-owned, transformers (>1 GVA) from inverter-based resources.
- Evaluate the capability of an expanded set of technologies to assist in a system restart, such as pumped hydro devices and modern HVDC links, in addition to evaluating their other possible interactions with GFM IBR restart sources.

- Consider how new network topology changes, that are expected over the next 10 years, may aid or hinder the restart process (e.g., increased meshing of the network versus a propensity to connect new generation centres using higher-voltage, and series-compensated, circuits).
- Extend DER studies to consider the representation of other consumer energy resources (CER) such as residential BESS, EV charging, and heat-pumps. Explore whether conclusions to date regarding DER performance differ significantly or whether materially different distribution system performance is expected, for this expanded set of equipment.
  - Investigate what changes to design principles or technical standards could better enable CER to participate more effectively in system restart.
- 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.
  - Initially through simulation using Hardware-In-Loop (HIL) / real-time simulation facilities.
  - Ultimately, through testing of a real, full scale-scale, in-NEM, facility deemed appropriate (noting that such testing is operationally challenging and requires coordination across many parties, and will likely be a multi-year programme).
- Testing of real network protection relays within a hardware-in-loop setup to confirm that the conclusions made through the investigations into network protection relays conducted in this Stage 4 period through simulation also apply to common, manufacturer-specific, devices used in the NEM.
- Where hardware-in-loop studies are conducted, an comparison of the results between offline EMT studies and HIL studies to confirm the validity of the tools used for analysis.
- Investigation on the extent to which network support equipment, such as SVCs, STATCOMs, and series compensated devices, needs to be altered to better support power system operation during 100% IBR restart, and whether certain limited capability equipment (such as SVCs) will remain appropriate for network voltage support in the medium- to long-term.