# GPST Blackouts and System Restoration Research

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# 1 Introduction

This report is prepared as part of Global Power System Transformation (GPST) research topic 5 entitled *Restoration & Black Start – Creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations.* Aurecon has been contracted by CSIRO to *develop a research plan for creating new procedures for black starting and restoring a power system with high or 100% inverter-based resources (IBRs) penetrations. This topic is not only about black starting a single IBR plant, but rather the careful sequencing of restoring the entire system while simultaneously ensuring stability, security, proper protection, etc. This research topic focuses on developing 1) grid code specifications for IBRs to be able to black start, and 2) methods and procedures and analysis techniques to black start and restore a power system with various penetrations of IBRs, up to 100%. The challenges include increased complexity of system restoration due to 1) imperfect information of instantaneous capability of variable renewables, 2) protection concerns due to lower and different fault current behaviours of IBRs, and 3) changed load due to potentially high penetrations of different types of distributed energy resources (DERs).*

# 2 Background

## 2.1 Definition of black start source

The following is generally sought from a black start generator:

- Have facilities to ensure that all generating units within the black start source can be safely shutdown without the need for external supplies, and can be maintained in a state of readiness for subsequent start-ups.

- Start-up independent of external supplies and without drawing power from the network.

- Energise parts of the transmission and distribution networks.

- Accept instantaneous loading of demand blocks.

- Provide steady-state and dynamic frequency and voltage control during the restoration process and its early stages.

- Operate stably with its auxiliary supplies, at low loading levels or with other network loads in a power island.

- Provide steady-state and dynamic voltage control. For early stages of restoration this may include providing all the reactive power needed for energising transmission lines, transformers and starting loads (such as auxiliary motors of other non-black start generators).

- Maintain a level of supply for a minimum time as agreed with the system operator.

- Has high availability, typically at least 90%.

- Provides redundancy of main and auxiliary equipment without any single point of failures

## 2.2 The importance of system restoration

In National Electricity Market (NEM), System Restart Ancillary Services (SRAS) is procured by AEMO as a non-market ancillary service to mitigate the economic cost of a major supply disruption. Similar arrangements exist in the Wholesale Electricity Market (WEM). SRAS provides the capability to restart the power system if there is a major loss of supply with the most extreme consequence being the total blackout of a region.

Whilst significant loss of generation or loss of load has occurred several times in the NEM power system, the only known event resulting in the use of SRAS sources is that occurred on 28 September 2016 in South

Australia. It has been estimated that the event came at a total cost of approximately $367 million to South Australian businesses and affected approximately 800,000 customers[1].

While rare, the extent of the impact of these events is such that the procurement of a specific quantity and quality of black start sources is essential as it enables timely restoration of supply following a major supply disruption including a black system event. Furthermore, the frequency and severity of such events have been increasing in recent times partly due to the impact of climate change. The continued security of the power system, at the lowest cost to consumers, is possible only if sufficient black start sources are in place. Without such a capability there is no guarantee that the power system can fully recover even within days after a major supply disruption. Whilst enhancements in system resilience reduces the likelihood of a blackout, it cannot eliminate the risk of a blackout and its consequences. The provision of black start capability therefore remains an essential part of ensuring the overall system resilience during the energy transition.

Black start capability is provided by generators with the capability to start, or remain in service, without electricity being provided from the grid. These generators must then energise sections of the transmission and distribution networks, and restart other large generators. Not all synchronous generators have this capability considering the additional cost involved to achieve this, and the vast majority of currently installed IBRs do not have this capability.

The importance of this research topic stems from the fact that a black start capability cannot be procured by AEMO unless that service is offered by a generator, and a service cannot be offered if the capability has not been considered and assessed during the plant design. Understanding the power system restoration needs, with rapidly changing power systems and generation mix, would provide justification to the necessary modifications in the design of new IBRs yet to be connected. Retrofitting the capability after a few years will be significantly more expensive if possible at all. The same applies to network elements, such as protective relays.

## 2.3 Increasing need for system restoration

Several factors are contributing to an increasing need for system restoration in Australia and worldwide:

- Aging generation assets, in particular coal fired power stations and increasing experiences of their forced outage events.
- Aging network assets, and increasing experiences of their forced outages.
- A combination of the above two failures at the same time.
- Increasing impact of global warming and its manifestation into more extreme weather events impacting power system infrastructures more severely than before.
- Increasing occurrences of cyber-attacks on wide-area power system infrastructures.
- Increasing use of sophisticated computational and artificial intelligence algorithms for demand and generation control largely substituting the need for onsite operators, and increased possibility of electrical system failures due to IT system failures.

## 2.4 Restoration vs resilience

Power system restoration and resilience are essentially the two sides of the same coin whereby resilience refers to pre-arranged remediation measures that can be included in the power system design to break the causation chain and stabilise the system for the same electrical or weather related event that would otherwise result in a full or partial blackout. The focus is on operating conditions where the initial state of the power system is secure or at least satisfactory, with most if not all demand is supplied uninterrupted.

On the other hand, system restoration focuses on a power system that requires restoration regardless of the cause or the likelihood of a blackout. Under this scenario very little if any loads or generators remains connected to the power system.

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[1] AEMO, Integrated final black system incident report, March 2017, p. 5.

Improving system resilience will undoubtedly reduce the risk of a blackout and the need for system restoration. However, the activities required to prepare and execute a successful system restoration will not change regardless of the extent of measures included to improve the system resilience.

For this reason, it is recommended to segregate system resilience and system restoration, and investigate each on its merit. This research topic will not therefore discuss system resilience.

# 3    The impact of changing power system and generation mix

This Section discusses the impact of changing power system and generation mix on system restoration, and highlights the main gaps in existing industry practices, as well as research and development activities.

## 3.1    Reduced number of online synchronous generators

Synchronous generators have been traditionally used for two key objectives during system restoration:

- Black start capability

- Restoration support (non-black start)

Synchronous generators with a capability to supply their own auxiliaries and therefore restart without external supply, can in turn restart other power plants that do not have these capabilities by providing supply to other plant's auxiliaries.

Restoration support sources have also been traditionally provided by synchronous generators. They would assist further network energisation, generator restart and load pickup which cannot be supported by black starters alone. A key distinction from black start sources is that they do not need to be able to start-up or continue operating without drawing power for the network.

Most often it occurs that black start sources are relatively smaller generators compared to the larger non-black start thermal plant which are generally more critical for restoration support including load restoration.

Increased uptake of IBR coincident with a reduction in the number of online synchronous generators would pose the following challenges:

- A reduction in the number of traditional black start generators, and resultant impact on the diversity and capability of the options.

- A reduction in the number of baseload non-black start synchronous generators with multiple effects:

  – When offline these units can take up to five times longer to restart compared to a restart when they were online before the blackout.

  – Reduced load restoration capability as often most of the demand is supplied by these baseload units.

  – Reduced network support capability as many of these non-black start units provide positive contribution to the voltage and frequency control, and system strength and inertia support in addition to the MW generation.

## 3.2    Increased uptake of intermittent utility-scale IBR

Synchronous machines, comprising synchronous generators and condensers, have the advantage of creating their own voltage source and do not generally require a particular number of other synchronous machines or a particular fault level to operate stably. This is valid regardless of whether the synchronous machine has the black start capability.

Most IBRs such as solar photovoltaic (PV), wind, and batter energy storage systems (BESS) operate as grid-following inverters. With this control philosophy, a phase-locked-loop (PLL) or similar control system monitors the terminal voltage and automatically adapts inverter switching to ensure output power remains in synchronism with the grid. Unlike the synchronous machines, grid-following inverters need a sufficient number

of nearby synchronous machines to operate stably. This requirement is often expressed as the minimum short circuit ratio (SCR) at which the inverter remains stable. This is used as a simplified proxy of system strength. The inverter would not likely remain stable if the SCR available at the network drops below the minimum SCR at which at the inverter is designed for with original control system parameters. For this reason, grid-following inverters are not frequently used during early stages of system restoration until more synchronous generators or condensers are brought online or the black start island has been synchronized to a larger grid.

Also note that the strength of the power system and the number of nearby synchronous machines and interconnecting lines is not the only factor that determines stability. Design and tuning of control systems deployed in IBR have an equally important role to play. This will become especially important during system restoration where currently there is not sufficient information on what changes would potentially need to be made to their control systems to make them more robust during restoration conditions.

A further impact of changing generation mix is that a synchronous machine provides approximately two-three times higher fault current contribution compared to an IBR. The reason for this difference is that the contribution of synchronous machine is inherent and non-limited whereas an IBR is designed to limit the fault current to protect the semiconducting switching devices used in the inverters. IBR can be designed to provide higher fault currents and there are practical examples of some IBR providing more than 2 pu fault current. However, this comes at a cost and as such it is not a common practice in particular for grid-following inverters.

Existing system restart pathways have been developed to expedite access to large non-black start synchronous generators. Long distances between areas of IBR concentration and major synchronous generators and load centres means that IBRs are not often picked-up at early stages of system restoration even if there was a desire to do so. However, transitioning to a power system with significantly less or no synchronous generators, would challenge this approach.

## 3.3 Increased penetration of distributed energy resources and inverter-based loads

Many inverter-based DER cannot be readily controlled.  Smaller installations, such as many rooftop solar photovoltaic systems, are not interconnected with local utility dispatch systems for dispatch to avoid the cost of communication system connection.

Non-controllable IBR have been connected over many years, and as such exhibit very different level of network support. Indeed, many of the legacy DER, in particular kW range installations connected to the LV or MV level, have been designed with practically no voltage or frequency control capability. Introduction of relevant standards in recent years has meant that more modern DER are designed to provide some level of voltage and frequency control.

DER can cause two significant challenges during load pick-up including both during very early stages (cold load pick-up) and subsequently as more loads are picked up.

- Reducing the load required for stable operation of large synchronous generators, especially coal fired stations. At the worst case if DER offsets significant load, synchronous generators would need to be turned off to match the net load conditions.

- De-stabilising impact of non-controllable DER on synchronous generators during cold load pick-up such that a synchronous generator could suddenly pick up a much larger DER size than the load connected to the same feeder.

These mean that with significant penetration of distributed PV (DPV), certain restoration pathways may not be possible, and restart may eventually become impossible during daylight hours unless mitigation measures are implemented. In the absence of detailed analysis and option development, currently the only option considered is to avoid energisation of feeders with high DPV connections. This could severely impact system restoration with a forecast of significantly higher uptake of DPV in every region, resulting in the need for significant alteration of some restoration pathways. This would, in turn, require several more restoration pathways for system operators compared to those currently in place to be used depending on the time/season at which a blackout would occur, making it more difficult for operator training and implementation.

A further challenge is the proliferation of inverter-based loads often along with the inverter-based DER, sharing similar challenges with regard to modelling and performance assessment. Even for restarting more

conventional loads such as fans and pumps of large power stations, the approaches adopted to date may not be valid moving forward. This primarily stems from a reduction in network's available fault level when restarting in an IBR dominated power system. The time required for the motor to reach a steady-state could be significantly longer when the source is current limited because of the reduced current and the resulting further voltage depression during direct on-line (DOL) motor starting. This could adversely interact with motor protection systems. Theoretically, this time can be reduced if several IBRs simultaneously attempt the motor load pick-up, providing a comparable level of fault current to that of a synchronous generator. Alternately, IBR with a deliberate design for provision of additional fault currents can be used, however, this comes at a cost (also see Section 6.1).

# 4 Methodology

This section discusses the input data used, assumptions applied, and identified limitations and exclusions where the key objective is to identify the future needs and shortfalls associated with black starting the system and conducting an end-to-end system restoration.

## 4.1 Input data used

- CIGRE Technical Brochures and papers.
- Relevant EPRI, IEEE and NREL reports and papers.
- AEMO reports.
- ARENA website.
- Public domain information obtained from search engines.
- Ongoing discussions with international system operators as part of CIGRE WG C2.26
- One-on-one conversations with the following industrial and academic organisations
  - AEMO
  - AGL
  - ARENA
  - Monash University
  - Powerlink Queensland
  - Siemens
  - SMA

## 4.2 Assumptions

- An instantaneous IBR penetration level of at least 50% and up to 100% is assumed (consistent with other international works, an IBR penetration level of at least 50% is considered as high IBR share. Lower penetration levels would result in small changes to today's practices not to the point of warranting extensive research).
- System demand and network and generation developments (including retirements) up to 2026 are considered. This is because:
  - Reasonable certainty of power system developments, including generation changes.
  - Allowing sufficient time for new technologies/control strategies to be developed, tested and introduced to the market by original equipment manufacturers (OEMs).
  - No paradigm shift in available technologies is envisaged. This makes it possible to discuss about the opportunities and limitations with more certainty.

- It is consistent with the shortest timeframe for power system planning in Australia's NEM, i.e. five years.

- A black out event is assumed that resulting in the use of black start generators. This means that load shedding events where system stability can be maintained are not considered.

- Distributed energy resources are assumed to predominately comprise non-registered generators.

## 4.3 Limitations

- Small-scale testing of the capabilities and limitations of grid-forming and grid-following models can only be attempted if the necessary models are provided to Aurecon by AEMO. This will be done on one representative make for each of the grid-forming and grid-following inverters.

## 4.4 Exclusions

- The following DER technologies have not been considered:
  - Synchronous distributed energy resources
  - Electric vehicles

- No network-level PSCAD studies will be attempted.

- The performance of emerging non-IBR renewable technologies, e.g. synchronous machines such as fixed-speed pumped hydro and solar thermal, will not be considered specifically.

- A restoration plan for an actual part of Australian power system will not be developed.

- This draft report has not considered the Northern Territory power system and its potentially unique restoration needs specifically.

# 5 Plan Development

## 5.1 Current Solutions

### 5.1.1 Background

This section provides a list of solutions adopted worldwide to achieve one of the following objectives:

- IBR initiating a black start
- IBR assisting in system restoration
- Addressing the adverse impact of inverter-based DER

All three areas have significant relevance to Australia.

### 5.1.2 Examples of IBR initiating a black start

**BESS as a cranking generator**

Emergency backup systems for black-start generators without inherent built-in capability has been traditionally provided by small diesel generators, or a smaller fossil fuel-powered turbine compared to the much larger units interfacing with the transmission and distribution grids. As such these smaller units are not directly connected to the transmission and distribution grids to provide black start capability. If BESS are used to provide the same ''cranking'' capability, they can be sized accordingly requiring a fraction of MW/MWh size of much larger grid-scale BESS projects. This would be a particular advantage for grid-

forming BESS if they are used as a cranking generator rather than as the main black starter. This is because most commercial BESS projects are based on lithium ion with its known MWh limitations, limiting their capability to provide black-start services for extended period. The following applications currently exists worldwide where a BESS is used as a cranking generator to provide the black start capability for a synchronous generator.

– The first known application is the use of a 33 MW / 20 MWh BESS to restart a 44 MW combined cycle natural gas turbine in 2017. The BESS is located at El Centro Generating Station in Imperial Valley, California.

– More recently, in mid-2020 FlexGen, a US system integrator, deployed a 12 MW / 5.4 MWh BESS to black start one of the two 77 MW gas turbine generators including a 112 MW step-up transformer for a utility in Indiana.

– A 7 MW / 5.48 MWh BESS will be installed at the 720 MW Marsh Landing Generating Station, comprising four gas turbine generators. The black start capability provided by the BESS can support up to three attempts to restart two of the Marsh Landing gas turbine units within one hour, and scheduled for operation by Q2 2021.

■ It is noted that the ratio of BESS MVA to the MVA size of the synchronous generator to be restarted by the BESS has been decreasing significantly since the first application.

## BESS as a direct black starter

– Roy Hill Iron Ore mining operations situated +1,300 kilometres (km) north of Perth, Western Australia, and supplied by Alinta Newman power plant through a very long 220 kV transmission line. Four sets of gas turbines are already installed and running on this plant, providing the required power to the mine. A 32 MW / 8 MWh BESS is used for energising the very long capacitive line, and black starting the mine. The grid forming BESS is designed to energise a 100 MVA transformer via soft starting and a capacitive 120 km of 220 kV transmission line. The inverters are designed with 2 pu overload capability for 2 s meaning that they can collectively provide 64 Mvar of reactive power which is more than enough to meet the 18 Mvar cable charging of the 220 kV line.

**Figure 5-1Roy Hill Iron Ore Mining BESS black start schematic diagram (Courtesy of Hitachi ABB Power Grids)**
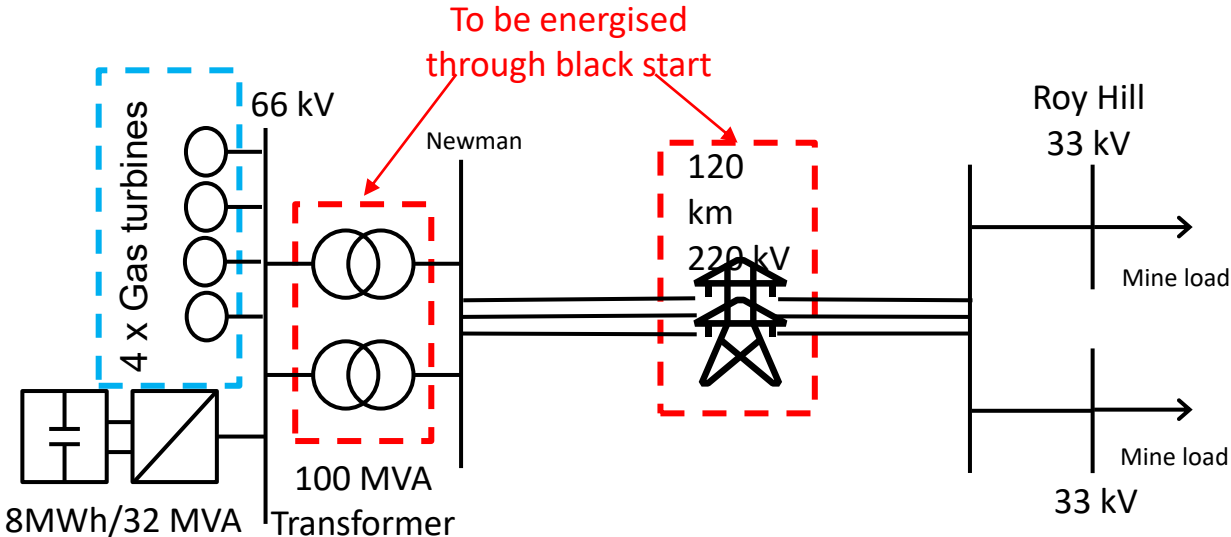


■ The 25 MW grid-forming Darlymple BESS in South Australia can black start the local 33 kV distribution network as shown below. This is achieved through a soft energisation of BESS coupling transformers (6 x 6 MVA) and one of the substation transformers (25 MVA) with the subsequent energisation of the two 33 kV distribution feeders.

**Figure 5-2 Darlymple BESS in SA schematic diagram (Courtesy of Hitachi ABB Power Grids)**
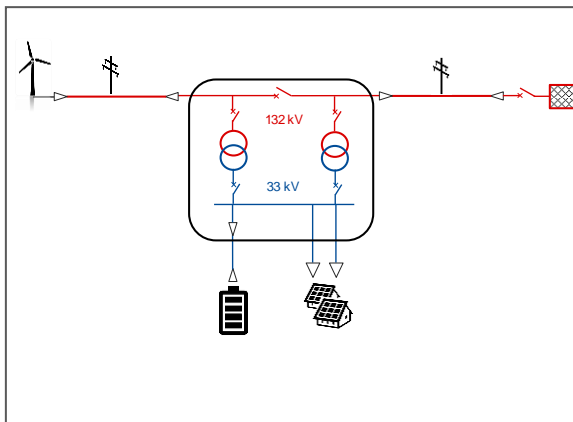


- The ability of a 4 MW grid-forming BESS to succesfully restart the network shown in Figure 5-3, and associated 4 MW of loads was demonstrated by physical testing. An end-to-end duration of eight minutes and a load step gradient of +/-37 kW/ms was reported. Grid-following BESS were used as loads.

**Figure 5-3 Bordseholm BESS black start arrangement (Courtesy of SMA Solar Technology)**
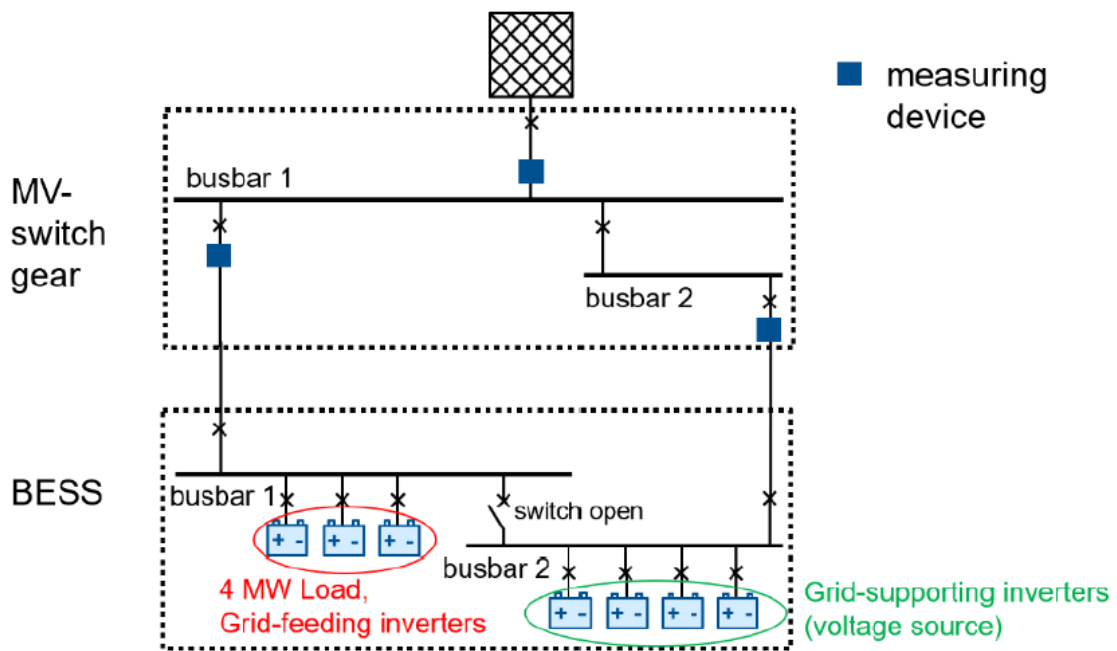


## Onshore wind farms

- The first known application of using onshore wind farms for system black start is the 69 MW Dersalloch wind farm in Scotland. It is noted that the wind farm was commissioned several years ago as grid-following wind turbines, but its control system software was upgraded to provide the black start capability based on the so-called virtual synchronous machines. No information exists on the extent to which the wind farm can energise network and generation assets outside its connection point.

- Recently RTE used a 12 MW / 24 MWh BESS to restart a 10 MW wind farm. This test differs from all other tests discussed so far as the BESS and wind farm are not located within the same connection point, and black starting the wind farm required energising parts of the network in between, and the need for

multi-party involvements. This particular aspect makes this test set-up more practical and relevant for bulk power system restoration by IBRs compared to the two Australian experiences discussed above. This information was provided by RTE to Aurecon, and is not currently documented in the public domain. Final report will provide further information on this test.

## Offshore wind farms

- In December 2020 the Kriegers Flak Combined Grid Solution (CGS) was developed and successfully tested to energise a Power Station in Germany via the offshore wind farms in Denmark. The CGS currently includes Baltic 1 and 2 offshore wind farms both connected to Germany's AC system. Later in 2021 the scheme will be augmented to include Kriegers Flak wind farm connected to Danish AC system.

## VSC HVDC links

Several point-to-point HVDC links have been developed with black start capability. Examples include:

- 1 GW NEMO Link between Belgium and UK
  - Successful energisation of 400 kV cable, 400/165 kV transformer and a microgrid within Belgium was demonstrated by live testing.
- 300 MW Hokkaido – Honshu link in Japan
  - Black start testing involved the VSC HVDC link, surrounding AC transmission network and a thermal power plant.
- 500 MW East – West Interconnector (EWIC) between UK and Ireland
  - The capability of the EWIC scheme to provide a black start service to start-up a remote 300 MW non-black start coal-fired generation unit was successfully tested using a field trial on the Irish grid during overall commissioning of the scheme.
- 700 MW Skagerrak 4 link between Denmark and Norway
  - The capability of HVDC link in supplying 90 MW of load in Norway from a supply in Denmark using Skagerrak 4 HVDC link was successful tested and demonstrated.

### 5.1.3 Examples of IBR assisting system restoration

Limited experiences exist on the use of IBRs to assist system restoration rather than initiating it. One known application is the Linth–Limmern Power Stations which comprises four, 250 MW variable-speed pumped hydro machines (similar to those planned for Snowy 2.0). Whilst not black start capable, once energised by nearby fixed-speed hydro units based on conventional synchronous machines, these variable-speed units provide the advantages of improved frequency control with increased efficiency, and dual mode operation as a generator or a load. The latter is very useful under light load conditions where sufficient load may not exist to allow stable operation of large synchronous generators.

### 5.1.4 Examples of solutions for addressing the impact of inverter-based DER during system restoration

The Australian standard AS4777.2: 2020 has included enhanced fault ride-through requirements for DER and in particular DPV. This will assist in mitigating concerns associated with the impact of a single credible contingency in an IBR dominated power island with high share of DPV. However, the potential susceptibility of DPV to operation under low system strength and inertia conditions is not currently considered.

Furthermore, AEMO has been carrying out studies with particular focus on South Australian power system to answer the following questions:

- Appropriate disconnection and reconnection settings to avoid system stability issues during restoration.

■ Impact on cold load pick-up, and the potential consequent impact on restart path and the sequence of switching in metropolitan areas.

## 5.2 Industry Activities

The following is a summary of various activities associated with the impact of rapidly changing power system and generation mix from an Australian perspective.

■ CIGRE WG C2.26, *power system restoration accounting for rapidly changing power system and generation mix,* is one of the major working groups worldwide investigating similar issues to the scope of this research. This working group is convened by an Australian representative, and comprises three additional Australian members.

■ In 2020 AEMC determined new rules facilitating better utilisation of IBR during system restoration, even if not black start capable, under the category of restoration support services. Subsequently AEMO revised its SRAS Guidelines providing more clarity on treatment of restoration support services. Despite this, it does not appear that any IBR has been formally procured to provide restoration support services. Furthermore, the use of IBRs during system restoration is very limited in system restart plans.

■ As discussed in Section 5.1, there are several microgrid projects across Australia where grid-forming inverters provide black-start capability in off-grid or fringe-of-grid applications. This trend is expected to continue in the coming years.

■ Of several proposed applications of grid-forming inverters on the backbone of NEM power system, there is currently no known application with the key value proposition of black-start capability. Furthermore, there is no known black start capable IBR with confirmed ARENA funding. Aurecon is not also aware of any such projects in the WEM.

■ Several open-cycle gas turbines across the NEM have considered the installation of relatively small, i.e. less than 10 MW, BESS to provide the gas turbine with the black-start capability such that it can be considered as a SRAS source by AEMO. We understand that none have been materialised to date.

■ The *Australian National Energy Simulator*, a joint initiative between AEMO and CSIRO, will act as an enabler for better understanding of the positive and negative impacts of IBRs during system restoration, allowing a more systematic utilisation of these technologies.

■ AEMO and South Australian Power Network (SAPN) have been investigating strategies to better understand the materiality of DER impact on successful system restoration, and to determine the necessary mitigation strategies.

## 5.3 Key Research Questions

Below are the four original research questions provided by CSIRO:

■ How do system operators black start a system with very few (or no) synchronous machines?

■ What additional tools, methods or equipment is needed to support system restoration with a 100% IBR grid?

■ How will control rooms monitor the network to know if they have sufficient grid formation, inertia, system strength during the system restoration process?

■ In the context of the evolving risk profile of the power system, what principles should guide industry objectives in relation to the cost and timeframes associated with system restoration?

Aurecon concurs with these questions and have made the following modifications along with the proposed priorities.

a) How network planners and system operators plan and execute system restoration with very few (or no) synchronous machines?

   i) Is end-to-end system restoration possible with no synchronous machines at all? If not what prompts the need for synchronous machines?

ii) What is the minimum required ratio of grid-forming to grid-following inverters, for a system with no synchronous generation as well as a system with a set number of synchronous machines?

iii) For the same IBR technology, e.g. grid-forming, are there power system dynamic performance differences between different IBR types, e.g. BESS, solar, wind, and the sequence/application they will be used during system restoration?

iv) Will there be a need for different restoration plans as function of instantaneous penetration of IBR? For example, to what extent could system restoration plans differ with 100% and 90% IBR?

v) What role would system restoration from distribution networks and microgrids play (accounting for both the opportunities and limitations)?

vi) Should intentional islanding and microgrid operation be considered more extensively in an Australian context?

vii) What changes are required to existing coordination approaches between AEMO and other parties?

b) How will control rooms monitor the network to know if they have sufficient grid formation, inertia, system strength during the system restoration process?

i) How extensively should wide-area monitoring systems (WAMS) be implemented in transmission and distribution systems, and integrated into real-time power system operation? Would system restoration in an IBR dominated power system result in the need for a larger number of WAMS installations?

ii) What other real-time measurement systems are required to have a successful system restoration in an IBR dominated power system?

iii) What improvements are required on decision support tools used in the distribution systems and microgrids for use during system restoration? And how can they be integrated into the tools used by AEMO?

iv) To what extent can Australian National Energy Simulator address the deficiencies of conventional dynamic security assessment tools?

v) What improvements are required in the forecasting tools for intermittent renewable energies?

vi) How best should system operators proceed if the exact conditions for which system restoration is required deviate from known system restart plans? What additional information is required to facilitate the decision making?

vii) Considering the increased complexity of analytical tools required in the control room for a successful system restart in an IBR dominated power system, what are the best strategies for learning the necessary skills and knowledge in a control room environment?

c) What additional tools, methods or equipment are needed to support system restoration with a 100% IBR grid?

i) Are electromagnetic transient (EMT) models of grid-following and grid-forming IBR accurate and appropriate for system restoration with high share of IBR?

ii) How best can the impact of protection systems be included in power system restoration studies?

iii) What are the gaps associated with the off-line and real-time EMT simulation for system restoration studies, and how can they be addressed?

iv) To what extent can these gaps be addressed via Australian National Energy Simulator for purposes outside the control room use highlighted under research question (b)(iv)?

v) Is there a need for new simulation tools/techniques not currently available?

vi) Are current storage technologies adequate during system restoration or new storage technologies are required?

vii) Are existing control systems associated with grid-forming and grid-following inverters relevant for system restoration in an IBR dominated power system?

viii) Is there a need for new types of network and generation protection systems?

d) In the context of the evolving risk profile of the power system, what principles should guide industry objectives in relation to the cost and timeframes associated with system restoration?

    i) How best can system restoration be accounted for in planning horizons and investment decision making processes along with other system needs such as system strength and inertia?

    ii) Should generator connection process assess the contribution of each IBR to system restoration? And if so should there be some level of mandatory requirements for all new generators to provide some forms of black start or restoration support capability?

    iii) Should system restart standard account for both generator and load restoration as opposed to generator restoration only?

    iv) Should system restart requirements be coordinated with system resilience requirements to better understand and address the phenomena resulting in the need for system restoration?

    v) Is there a merit to set an upper limit for the maximum duration within which all part of the power system not subject to a physical damage must be restored?

# 6 The Research Plan

## 6.1 The treatment of inverter-based resources during system restoration

Among topics discussed in Section 6, this specific research topic is the most suitable for Australian researchers as several Australian universities are already involved in a wide range of relevant activities from inverter control design to DER impact assessment. As such this research topic is particularly linked with topics 1 and 9 of GPST research program. There are a few actual upcoming grid-forming inverter projects in Australia and the trend is likely to grow. This will provide opportunities for collaboration between industry and academia.

However, unlike many other countries there has not been any practical applications of IBR in Australia for system restoration in bulk power system. It is noted that the use of VSC HVDC directly as a point-to-point link, or within an offshore wind farm has been successfully demonstrated in many European countries and Japan. As discussed in Section 5, there are several worldwide instances of the use of small gird-forming inverters within a larger synchronous generator providing overall black-start capability. It is also noted that most research and development activities within OEM organisations occur overseas. Combination of all these factors provide ample opportunities for Australian researches to learn from international research and development activities.

In addition to academic resources, practical knowledge of power system operation and generator connections, as well as inverter software and hardware design is necessary for this research topic. Key stakeholders to be engaged therefore include OEM and AEMO Engineers and other strong Engineering resources in Australia. However, when specifically relates to system restoration, very few Power System Engineers can be found in Australia with direct modelling and operational experience of various aspects of system restoration. As most solutions for addressing the adverse impact of DER during system restoration should be implemented by DNSPs, they are also considered a key stakeholder.

The next SRAS procurement will need to be implemented by AEMO by 30 June 2024. To achieve this outcome, AEMO would typically commence its activities in Q3-Q4 the year before. Rapid uptake of utility-scale IBR and DER, and ongoing withdrawals/retirement of synchronous generators is expected to make a more noticeable impact on system restoration within the next three years. As such it is prudent for this research activity to provide answers to some of the questions below within the next two years. These are referred as quick-wins as highlighted in bold in the bullet points below. However, it is our assessment that this particular research topic is the most involved of all research topics discussed in Section 6. A total timeframe of eight years, accounting for the development of any new IBR technologies and control systems is therefore recommended. This will be discussed further in Section 7.

### 6.1.1 Grid-following inverters

The following research aspects are to be included in relation to the use of grid-following inverters for support system restoration:

- The impact of IBR type, including wind, solar, Battery Energy Storage Systems (BESS), variable speed pumped hydro, and HVDC links.

- **Criteria for deciding when each IBR can be introduced during system restoration, e.g. short circuit ratio, energy source reliability and availability including maximum permissible energy source variations before they can be used.**

- **Impact on existing system restart pathways, and the extent to which the sequence of network switching events would need to be altered.**

- **The level of system-wide constraints required on total IBRs output during restoration to manage system stability and supply intermittency.**

- **Low system strength withstand capability and if this can be improved with the use of a different control strategy, deprioritising some of the objectives of control system response during system intact conditions.**

- **Restoration support services provided by standard design and settings of the control system.**

- Restoration support services provided by enhanced design and settings of the control system.

- **Reactive power control at low or no active power.**

- **Complementary use of grid-following IBR and synchronous condensers.**

- **The risk of adverse control interactions with other network equipment.**

- **The risk of harmonic resonances with the surrounding network due to the presence of low-order high-impedance resonance frequencies during system restoration.**

- Impact of reactive plant switching including harmonic filters, in particular for HVDC links, during early stages of system restoration.

- Impact on network protection systems.

  – Including the need for certain magnitude, rise time, retain time, and sequence of fault currents, e.g. intentional negative-sequence current injection or suppression.

- Managing operating reserves.

- **Whether existing simulation models can accurately represent the response of grid-following IBR during system restoration.**

  – **Subject to receipt of these models Aurecon can assess the above using electromagnetic transient (EMT) simulation with PSCAD simulation models.**

- Physical testing of grid-following IBR unit to confirm their capabilities and limitations, and how best this can be demonstrated in practice, e.g. a dedicated hardware-in-the-loop test centre in Australia.


### 6.1.2 Grid-forming inverters

The following research aspects are to be considered when using grid-forming IBRs as black starters:

- The extent to which grid-forming technologies other than BESS can be used as a black starter.

- **MW and MWh requirements for black start sources.**

- **The extent to which a grid-forming inverter needs to emulate some or all of the following characteristics provided by synchronous generators:**

  – **Certain magnitude of fault current.**

  – **Certain sequence of fault current, i.e. the ratio of negative- to positive-sequence fault current.**

- **Virtual inertia and damping.**
- **Controlled internal voltage phasor.**
- **AVR (automatic voltage regulator) like response to voltage disturbances as opposed to typical low voltage ride-through response typically provided by the IBR.**

- Grid-forming control strategies and their relative merit for system restoration including the following technologies:
  - Droop
  - Virtual synchronous machines
  - Power Synchronisation Control
  - Distributed Phased-Locked Loop
  - Direct Power Control

- Comparison of different storage technologies from a supply/load restoration perspective.

- **Comparison of advantages and disadvantages of grid-forming IBRs as a cranker for a large synchronous generator vs as the main black starter.**

- Impact of additional fault current requirements for grid-forming inverters on inverter hardware design and associated cost.

- The need for specific rise time, retain time, and sequence of fault currents, e.g. intentional negative-sequence current injection or suppression, and how it would potentially need to differ from those of a synchronous generator or grid-following inverter.

- **The trade-off between system normal and black start performance objectives.**

- Ensuring successful switchover between the system normal and black start modes, if the black start IBR has two distinct operating modes.

- **Whether existing simulation models can accurately represent the response of grid-forming IBR during system restoration.**

- Physical testing of grid-forming IBR unit to confirm their capabilities and limitations, and how best this can be demonstrated in practice, e.g. a dedicated hardware-in-the-loop test centre in Australia.

- The risk of adverse control interactions with other network equipment.

- The risk of harmonic resonances with the surrounding network due to the presence of low-order high-impedance resonance frequencies during system restoration.

- **The ratio of MVA rating of grid-forming IBR to the MVA rating of the largest transformer or synchronous generator to be energised by the IBR, and how it is compared to that with a synchronous generator black starter.**

### 6.1.3   Distributed energy resources

The following research topics are to be included to better understand and manage the impact of grid-following DER during system restoration:

- **DER stability, in particular with respect to fault ride-through capability during system restoration.**

- **Calculating the minimum stabilising load requirements for a region during system restoration as function of time and season, and determining whether any mitigation measures are required.**

- **Mitigation measures to address a reduction in the available load for pick up during early stages of system restoration including:**
  - **The use of virtual power plants or aggregators.**
  - **The role of utility-scale and distributed storage.**

- Impact on network reactive power support requirements during system restoration.
- Coordination between transmission and distribution system operator/owner(s).

### 6.1.4 The role of synchronous generators and condensers in an IBR dominated power system

Assessing the viability and implications of various generation dispatch patterns for a successful black start and complete system restoration is one of the most fundamental questions that need to be answered. The following are to be included in for this research.

- 100% IBR with grid-forming and grid-following IBRs, with no synchronous machines.
- 100% IBR with grid-forming and grid-following IBRs, with some synchronous condensers but no synchronous generators.
- For both scenarios above, determine the minimum percentage of grid-forming inverters for a successful system restoration.
- 50% and 75% share of IBR including both grid-forming and grid-following IBRs and some synchronous generators.
  - Note that these scenarios are recommended even if the above scenarios are successful. This is needed to identify any key differences that would then be considered when developing system restart plans.
  - Identify the reason why synchronous generators are needed (if any).
  - Gain better understanding of the minimum ratio of synchronous generators to IBR for a successful system restoration.
    - This includes determining whether some large coal fired power station must be always kept in hot and warm start modes in preparation for a black system event.

## 6.2 Impact on network control and protection systems

This research topic covers primary network components and overarching power system control schemes, as well as network and generation secondary (protection) components. The bulk of this research is expected to focus on issues associated with conventional protection systems caused by a reduction in the available fault level and potential modifications required. This topic provides significant research opportunities for Australian researchers; however, it is noted that both Australian industry and academia are lagging well behind the international developments. A further worldwide gap is a disconnection between the Power System Study Engineers and Power System Protection Engineers. Operation in an IBR dominated power system, makes the two aspects increasingly intertwined, making it difficult to thoroughly assess and address the challenges without sufficient knowledge of both. This is further exacerbated by the fact that dynamic modelling of protection systems, whether in phasor-domain (also referred to as root mean square (RMS)) or EMT, is not a common practice for relay OEMs.

Relevant research and development activities are currently being conducted worldwide in particular by relay OEMs, and several US research organisations including EPRI. This provides learning opportunities for Australian Engineers and researchers.

The research topic is related to research topics 1 and 2 of GPST research program noting that modelling, impact assessment and modifications of protection systems in an IBR dominated power system is not only relevant to system restoration, but also applies to day-to-day power system operation.

Considering the need for developing a fresh knowledge and skills base in Australia and the time taken to do so, it is recommended to allow 3 years for this research activity to conclude. A further 5 years is recommended for any modifications in the existing control and protection systems or developing new protection algorithms. Considering lack of expertise within Australia and a relatively lower urgency of issues associated with this sub-topic, no quick wins is recommended.

### 6.2.1 Impact on control systems

The following are to be included in for this research question:

- Dynamic reactive power support plant such as Static Var Compensators (SVCs), Static Compensators (STATCOMs) and Static Synchronous Series Compensator (SSSCs) during system restoration.

- Static reactive power support plant.

- Emergency control schemes such as under-frequency load shedding, over-frequency generation shedding, transient power runbacks and system integrity protection schemes.

  – Note that the intent of this research item is not to assess the role of these emergency control systems in preventing the occurrence of a blackout, but how they can assist or adversely impact system restoration following a black system event.

### 6.2.2 Impact on protection systems

Assessing the impact of changing generation mix on operation of different types of protections systems during system restoration, and in particular the following protection types are to be considered:

- Current-based protection such as overcurrent relays and fuses.

- Impedance-based protection including distance protection.

- Sequence-based protection, i.e. relays such as some of the directional relays which use negative-sequence current for decision making.

- Low frequency demand disconnection (LFDD) caused by a lower inertia and higher RoCoF.

- Earthing requirements if adopting restoration from distribution networks and microgrids.

- Special protection schemes such as power swing blocking and out of step tripping at the transmission network level.

- Motor protection especially those associated with fans and pumps of large thermal power stations to be picked up under scenarios with high but not 100% share of IBR.

Note that whilst some of these challenges are unique during very early stages of system restoration, some others, and in particular the first three bullet points, will also pertain to system normal operating conditions for a power system with a very high IBR share. As such addressing these challenges will assist answering questions beyond system restoration. Whilst this aspect has not been closely associated with any other research topics within the GPST research program, minor relationships exist with research topic 1.

### 6.2.3 Assessing the need for modifications

The following aspects are to be included in further research:

- Whether there is a need to use different settings for certain protection systems, including:

  – Adjusting the settings in phase and ground overcurrent relays to discriminate between load and fault currents correctly.

  – Reconfiguring LFDD relays to accommodate the higher levels of ROCOF.

- Whether there is a need to block certain protection systems during system restoration, and if so

  – The criteria for their blocking/unblocking.

  – Whether the is need for additional communication systems.

- Whether there is a need to introduce new relay algorithms/protection philosophies.

- High-level comparison of relative merits of changing protection system device/operating philosophies across the system against the requirements for additional fault current by grid-following and in particular grid-forming IBRs to provide sufficient fault current for correct operation of existing relays.

# 6.3 Tools and techniques

This specific research topic interacts closely with research topics 2 and 3 of GPST research program. It is recommended that research topics proposed in Section 6.3.2 of this report are pursued only once topic 3 of GPST research program is in an advanced shape. Considering both those topics will be delivered by a non-Australian organisation, EPRI, it is to fair to say that these topics have not been researched in Australia as extensively as other topics. This opens significant learning opportunities for Australian researchers.

Furthermore, the nature of these topics is such that they require significant involvement from AEMO as the system operator. This is particularly true for research topic 6.3.2.

When comes to topic 6.3.1, it is recognised that Australian industry is already ahead of other countries with the following major activities. Whilst all these activities primarily relate to the use of wide-area EMT modelling for system normal studies, the skills and knowledge gained from this process would build a substantial foundation for tools and techniques for system restoration with very high share of IBRs. The quick wins are highlighted in bold.

- AEMO has developed a wide-area PSCAD model comprising the four-state mainland states of the NEM for system intact studies. They have also developed and progressively updated over many years the smaller scale regional PSCAD models for black-start studies. However, it is understood that the latter is significantly less IBR focused.

- TasNetworks has implemented a full-scale real-time EMT simulation platform. It is understood that this platform is currently fully functional.

- AEMO is currently developing an *Australian National Energy Simulator* based on real-time EMT simulation.

- CIGRE WG C4.56, *Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter connected generation*, is led by an Australian Convener and includes four other Australian members.

Key stakeholders to be engaged therefore include OEM and AEMO Engineers and other strong Engineering resources in Australia. However, as discussed previously when specifically relates to system restoration, very few Power System Engineers can be found in Australia with direct modelling and operational experience of various aspects of system restoration.

## 6.3.1 Power system modelling and simulation tools

The following will be investigated in this research question.

- **Whether EMT models provided for connection studies need to include additional details when used for black start and restoration studies.**

- Actual network level testing of system restoration performance with grid-forming and grid-following IBRs, and network primary and secondary equipment. This is crucial to gain sufficient confidence in the accuracy of whole-system model under these extreme operating conditions.

- **Relative merits of off-line EMT simulation, e.g. PSCAD/EMTDC, against real-time EMT simulation, e.g. *Australian National Energy Simulator*.**

- The extent to EMT and phasor-domain (also referred to as root mean square (RMS)) simulations could be used complementarily.

- The need for other types of simulation such as frequency-domain techniques to characterise other aspects of system response.

- **The merits of consistent EMT simulation cases for power system stability and system restoration analysis.**

- Integrating the response of protective relays into power system dynamic simulation tools for black start and restoration studies.

- Accurate modelling of motors and their protection associated with fans and pumps of large non-black start synchronous generators.
  - Note that unlike the main generators and associated control systems, very little information generally exists on generator auxiliaries which are primarily induction motors.

### 6.3.2 Decision support tools for control centres

Below is a list of decision support tools to be considered in this research question for integration into control centres to make more judicious and informative decisions during system restoration:

- **Wide-area monitoring systems (WAMS).**
- System strength monitoring tool.
- Inertia monitoring tool.
- Dynamic security assessment.
- **Real-time EMT simulation.**
  - **Including the extent to which it could replace the existing dynamic security assessment tools.**
- **Energy source forecasting and online monitoring.**
- **Demand forecasting.**
- Charge status forecasting for batteries and electric vehicles.
- Network status monitoring to determine damaged/unavailable network circuits.
- **Create up-to-date training programs for control room personnel and operators reflecting increased complexity of the technologies to be involved and associated multi-party communications.**

## 6.4 Technical and regulatory requirements

This research question will investigate the need for any of the additional requirements outlined below. The intention is not to propose new requirements under each category but to gain better understanding of the need for each.

It is noted that this research task is highly dependent on the completion of other research tasks discussed in Sections 6.1 to 6.3, and in particular 6.1. As such the start date for this task is driven by the completion date for those preceding tasks. Furthermore, the skillsets required, learning opportunities for Australian researchers and the types of organisations to be engaged would be same as those discussed previously.

Note that this topic is also very closely related to GPST research topic 6. This is because the existing SRAS procurement framework does not provide sufficient opportunities for mid- and long-term planning for black start capability. As such currently there is not enough incentives for IBRs to provide the black start capability considering the additional cost involved which would likely outweigh the revenue received under the SRAS procurement framework. Whilst the cost of providing a self-start capability could be negligible; it is noted that the contribution provided to the wider power system restoration is what matters most rather than the ability to self-start. This would result in additional requirements for the black-start source such as larger MVA size and storage capability. Furthermore, optimal placement of a black start capable grid-forming IBR would likely differ from that required for provision of other grid support services such as system strength enhancement.

The overall importance of this research topic is that a clear definition of power system needs and associated technical requirements would provide sufficient guidance to OEMs and developers to deliver system restoration capabilities according to the power system needs.

It is recommended that this task will take one year to complete, whose resourcing will comprise Australian researchers and practicing Engineers considering the need for intimate knowledge of Australian power system, and relevant technical and regulatory requirements.

Below provides a breakdown of key activities to be conducted for this task (note that unlike most other tasks discussed in Section 6, this task cannot be addressed by research alone).

- Generator technical requirements

  - Assess the need for different performance standards for IBRs between system intact and system restoration.

  - Assess the need for any additional performance requirements for grid-forming IBRs, or a more detailed specification of existing technical requirements, i.e. what grid-formation means in the context of system restart.

  - These additional requirements could be set out in any of the respective generator performance standards, the SRAS contract, or a new black start service procurement framework. It is not the intention of this research to make recommendations on suitability of one or the other.

- Transmission and distribution network technical requirements

  - Dynamic reactive support performance.

  - DER response.

  - Microgrid performance requirements in terms of black start provision under islanded mode.

- Power system technical requirements (consolidating both the network and generation and their interactions)

  - Grid-forming or synchronous characteristics, their definitions and the quantity/type needed

    - Unlike the corresponding item under generator technical requirements, the focus of this item is primarily on how this capability will be seen by the wider power system and what are the interplays with other power system equipment and different aspects of power system performance.

  - Dynamic performance success criteria during system restoration in terms of rise time, settling time, damping and magnitude of the response in an IBR dominated or 100% IBR power system.

- **Merits of accounting for system restart needs in long-term power system planning along with other aspects such as voltage and frequency control, and system strength and inertia needs.**

- **Whilst the intent of this document is to discuss about research and development aspects of system restoration, it is recommended that this alone will not be sufficient to address the gaps associated with regulatory frameworks. New black start source with sufficient capability to replace the existing sources can be introduced, for example, by:**

  - Funding of up to 50% of the value of the project by ARENA or CEFC.

  - Auction-based funding for pre-selected locations/areas by various state governments in the same fashion some state governments have been supporting the development of new IBR connections to meet the renewable energy targets.

## 6.5 End-to-end system restoration in power systems with high share of inverter-based resources

This research activity is similar to Section 6.4 in such a way that it is highly dependent on the completion of other research tasks discussed in Sections 6.1 to 6.3, and even to some to extent to Section 6.4. As such the start date for this task is driven by the completion date for those preceding tasks. Furthermore, the skillsets required, learning opportunities for Australian researchers and the types of organisations to be engaged would be similar to those discussed previously. However, there is a stronger need for involvement from people with system operations experience including AEMO.

Many Australian researchers have been involved in various aspects of microgrids, albeit with less of a focus on black start applications. The same applies to practical applications where, as discussed in Section 5.1, there are already several practical Australian examples of the use of grid-forming IBRs for black starting microgrids and fringe of the grid applications.

It is recommended that aspects related to bottom-up restoration, and activities listed in Sections 6.5.3 and 6.5.4 are considered as matter of priority such that they can be reflected into AEMO's next system restart procurement and associated restart plan development to be in place by 30 June 2024 (also refer to relevant note under 6.1 on timeframe and dependencies).

It is also recommended that system restoration from the distribution networks can be considered as a lower priority item. This is because there are very few if any distribution connected IBRs or synchronous generators, with sufficient capability to restart upstream transmission networks. However, microgrids within the distribution network would be an important aspect of expediting load restoration, and reducing the burden on bottom up restoration approach.

## 6.5.1 Restoration from transmission network

### Bottom-up restoration

In this approach the system operator performs first steps of grid energisation with contracted black start generators, regardless of whether or not black start support can be provided from the neighbouring regions.

Section 6.1 presents various research activities to assess the component-level black start capability of various IBR technologies. The activities set out below will aim to assess the complementary capability of the black start source and the surrounding power system, and the value the IBR can provide to the wider power system.

- **Optimal placement of grid-forming black starter IBR considering the proximity to the following system aspects:**
  - **Load centres.**
  - **Areas of concentration of synchronous generators.**
  - **Areas of concentration of non-black start IBR.**
- The use of various storage technologies as stabilising loads.
- **Determining whether a re-sequencing or complete avoidance of some restart pathways might be required under high DER conditions.**
- Complementary use of synchronous condensers and grid-following inverters as black start providers.
- The coordination of responses of grid-forming black-start IBRs and synchronous generators and condensers during system built up. This includes:
  - Assessing the risk of sub-synchronous torsional interaction (SSTI) between inverter controls and rotating masses of synchronous machines, and in particular synchronous generators.
- Synchronising two or more IBR only power islands.

### Top-down restoration

In general, the top-down strategy uses backbone of transmission system from bordering regions. If the HV path is very long, dynamic reactive support plant can be used for voltage control. The following will be considered in this option:

- The use of HVDC links[2].
  - Both black start (grid-forming) and non-black start capable HVDC links are suggested.
- The extent to which IBRs, whether grid-forming or grid-following, or synchronous condensers nearby an interconnector can facilitate energising one region from a neighbouring region by providing voltage support.

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[2] Note that restoration from AC interconnectors is excluded as a research topic due to very little unknowns associated with.

### Hybrid restoration

This generally refers to the simultaneous use of top-down and bottom-up approaches. This means that system restoration will proceed concurrently with the use of designated black start sources in the region under restoration, as well as the use of interconnectors to supplement restoration from adjacent healthy networks.

### 6.5.2 Restoration from distribution network

### Wide-area distribution network

Due to their size and limited generation resources, distribution power islands have different electrical characteristics compared to a large power grid. The following challenges could be exacerbated compared to restoration from transmission network:

- Low system strength.
- Low system inertia.
- Voltage control (in particular during high DER scenarios).
- High variability of load and generation.
- Load pick-up capability.
- Power system oscillations.

These differences will result in several operational challenges such as voltage control, protection adequacy and frequency stability.

Restoration options with the following strategies are to be included in for further research:

- Synchronising with or creating an adjacent distribution power island through distribution interconnection.
- Back energising a sub-transmission transformer and connecting additional generation at the sub-transmission level.
- Energising an adjacent sub-transmission substation from the top down.
- Energising the transmission network.

### Microgrids

A microgrid is a group of interconnected loads and DER with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes.

Microgrids can support system restoration in several capacities:

- Islanding system loads and re-synchronising when the nearby system is restored.
- Expanding the microgrid island to include additional nearby system loads.
- Reducing cold load pickup when restoring loads.

The following research activities are to be included to better understand and utilise microgrids for system restoration:

- Optimal placement of microgrids for black start provision.
- Coordination with bulk system restoration, including criteria for microgrid reconnection.
- Determining key differences with wide-area distribution system restoration discussed above.
- Intentional Islanding and the ability to operate part of the grid using microgrid.
  - This is an important topic as major supply disruption events do not always result in a full black system. It is therefore prudent to maintain continuous operation of parts of the transmission and distribution

networks not impacted by the major supply disruption. This is particularly relevant to distribution systems due to closer proximity to loads.

■ Strategies to manage higher variability of load and generation compared to transmission and distribution systems.

■ Earthing design for microgrids used for system black start.

– It is noted that unless microgrids are purposely designed for intentional islanding, they may not have the same level of earthing as the higher voltage distribution feeders. Note that if the lower voltage parts of the distribution system are to be treated as microgrids, they have sometimes relied on earthing provided by the upstream feeders. This is not an issue for day-to-day system operation, however, would be a concern during system restoration.

■ Microgrid clustering during system restoration and the coordination between them

– Independent microgrids may fail to support their own loads due to the intermittency of renewable energy sources affected by variable wind or solar, or sudden changes in load. The sensitivity of such microgrids can be mitigated by interconnecting several microgrids to form a larger power island.

### 6.5.3 Commissioning and model validation tests for end-to-end black start capability

Considering the increasing complexity of system restoration in an IBR dominated power system, it is prudent to gain confidence in the response of actual control and protection systems that would be involved during an actual system restoration. This could be achieved by having a hardware-in-the-loop simulation platform whereby the response of actual protection systems and control-hardware-in-the-loop simulation of IBR, and the overall response of the power system can be assessed. This would allow making the necessary modifications to control and protection systems. It would also assist in validating conventional EMT models used for developing end-to-end system restart plans.

It is also highly beneficial to conduct real power system restart tests involving grid-forming and grid-following inverters and network primary and secondary components, similar to those reported from various European countries.

The use of the most detailed power system simulation models alone will not be sufficient to provide the level of confidence required unless accompanied by observing real power system responses. As such this research activity forms a key component of research sub-topic on power system modelling tools.

### 6.5.4 Representative example of end-to-end system restoration in power systems with high share of IBR

A representative example will be developed to demonstrate the sequence of switching and restoration steps accounting for the following:

■ Start the black starter IBRs.

■ Resupply house load for substations and non-black start generators by energising network transformers and transmission lines.

■ Create a viable island with sufficient stabilising loads.

■ Define preferential load pick-up, accounting for unintended DER pick-up.

■ Extend the restored system by energising additional generation and network sections.

■ Re-synchronise and re-connect islands restored by various black start sources.

■ Commence further load restoration.

The ultimate objective is to identify the key differences compared to conventional system restoration and their implications.

These steps will need to be verified by wide-area offline EMT studies.

# 7 Conclusions

## 7.1 Relationship with other GPST research topics

Figure 7-1 shows the inter-dependencies between each of the five key research questions for topic 5, and other research topics within the overall Australian GPST research program. Topics 1-3 are considered most closely related to topic 5.

**Figure 7-1 Relationship with other GPST research topics**
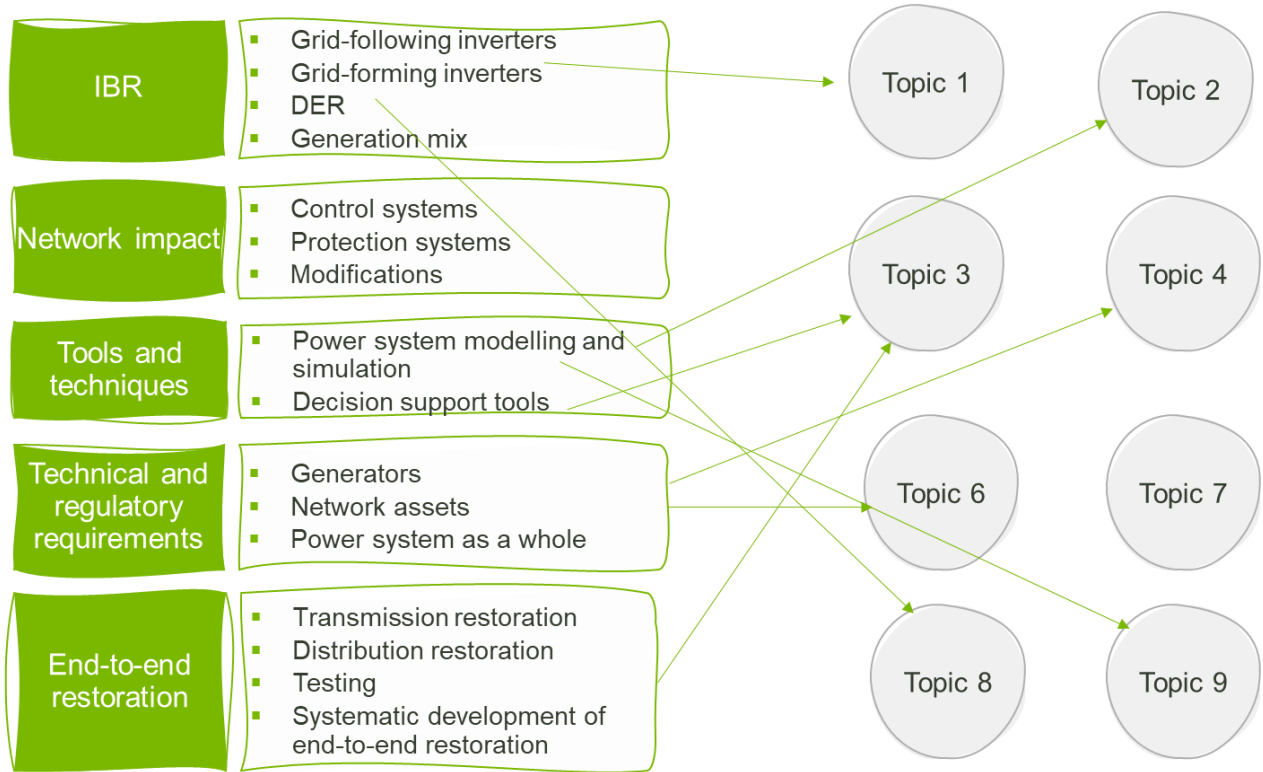


## 7.2 Inter-dependencies between topic 5 sub-topics

Table 7-1 shows the priorities, dependencies, duration and resourcing for the five sub-topics of research topic 5 whereby the following is accounted for.

**Table 7-2 Priority, dependencies, duration and resourcing for five sub-topics**

| Sub-topic | Priority | Dependencies | Duration | Resources | Quick-wins examples |
|-----------|----------|--------------|----------|-----------|---------------------|
| IBR (I) | 1 | III | 8 years | 8E+15A | ▪ The use of grid-following inverters as restoration support.<br>▪ Functional requirements for grid-forming inverters<br>▪ Managing DER impact |
| Network impact (II) | 4 | I and III | 8 years | 7E+9A | N/A |
| Tools and techniques (III) | 2 | N/A | 8 years | 10E+12A | ▪ Wide-area EMT models (both offline and real-time)<br>▪ WAMS<br>▪ Energy and demand forecasting tools |
| Technical and regulatory requirements (IV) | 3 | I-III | 4 years | 4E+3A | Incorporating black start needs into long-term power system planning considerations |
| End-to-end restoration (V) | 5 | I-IV | 3 years | 3E+5A | ▪ Optimal location of grid-forming inverters<br>▪ Restoration re-sequencing due to DER |

▪ Priority: The order of relevance from an Australian perspective, also accounting for the availability of Australian research capability and the relative urgency by which its lack of understanding could adversely impact system restoration.

▪ Dependencies: Input required from some of the questions in other research sub-topics, e.g. the availability of accurate simulation models from sub-topic III for studies required under sub-topics I and II. Despite these dependencies, it is recommended that sub-topics I-III can proceed largely in parallel whereas bulk of sub-topics IV-V can only be meaningfully assessed when sub-topics I-III are in reasonably advanced stages.

▪ Duration: End-to-end duration of each research sub-topic. Sub-topics I-III will require developing new products and capabilities, or modification in existing capabilities. For this reason a timeframe of 3 years for the initial research and 5 years for the development, evolution, testing and stakeholder liaison of those capabilities has been accounted for. The timeframe of 4 years for the sub-topic technical and regulatory requirements accounts for 1 year of initial desktop studies and a typical 3 years process for rule changes and regulatory framework developments. Lastly, a timeframe of 3 years for the end-to-end system restoration largely accounts for AEMO's work as the system operator for most of Australia, and some academic research.

▪ Resources: A mixture of resources from Academia (A) and Engineering (E) are recommended for all five sub-topics. The following sub-division is recommended as shown in Table 7-2. In the table the category ''others'' refers to the likes of Generators and consultancies. It is expected that most expertise required under IBR and relay OEMs, and software vendors will need to be provided by experts outside Australia. Furthermore, Table 7-3 provides a segregation of academic resources in terms of Australian vs

international research collaboration, and key reasons on why international collaboration would be valuable.

- Quick-wins: Refers to those activities which either have already been started or there is a strong base in the industry or academia. Note that a more comprehensive list of quick-wins for each of the five sub-topics was provided in Section 6.

**Table 7-2 Further elaboration of resourcing for practicing Engineers**

| Sub-topic | IBR OEM | Relay OEM | Software vendor | System operator | TNSP | Others |
|---|---|---|---|---|---|---|
| IBR (I) | 4 | | 1 | 1 | 1 | 1 |
| Network impact (II) | 1 | 3 | | 1 | 1 | 1 |
| Tools and techniques (III) | 1 | 1 | 3 | 2 | 1 | 2 |
| Technical and regulatory requirements (IV) | | | | 2 | 1 | 1 |
| End-to-end restoration (V) | | | | 2 | 1 | |

**Table 7-3 Australian vs international research**

| Sub-topic | Australia | International | Key international contribution |
|---|---|---|---|
| IBR (I) | 12 | 3 | More advanced research in grid-forming inverters other than BESS, better knowledge of protection systems |
| Network impact (II) | 6 | 3 | Very little focus if any in Australian academia in terms of protection system design, modelling and impact assessment |
| Tools and techniques (III) | 10 | 2 | International research is ahead of Australia in the use of decision support tools |
| Technical and regulatory requirements (IV) | 3 | | N/A |
| End-to-end restoration (V) | 4 | 1 | Knowledge of HVDC links and restoration from distribution network and microgrids |

## 7.3 Risks and mitigation measures

Table 7-3 provides key risks and mitigation measures associated with research topic 5.

**Table 7-3 Key risks and mitigation measures**

| Risk | Mitigation measure |
|---|---|
| Scarcity of resources with relevant experience in particular within academia | ■ Developing expertise in Australian Universities<br>■ Better collaboration between industry and academia within Australia, and with their international peers |
| Topic 5 is one of the research topics requiring most involvement from the practicing Engineers, who may not be as available as academic researchers. | ■ Agreement with key industry resources/organisations<br>■ Provision of industrial funding in addition to academic funding |
| Scarcity of skilled resources in power system protection | ■ Develop expertise in both the academia and industry<br>■ Collaboration with industry and academia internationally<br>■ Hire international experts in both the Australian industry and academia |
| Exchange of confidential models and data including:<br><br>■ Access to practical data and models by academia<br>■ Exchange of confidential models and data across the industry including access to:<br>  – Tuneable dynamic models by non-OEM organisations<br>  – Wide-area EMT models by non-AEMO/NSP organisations | ■ Develop the IT infrastructure and implement any necessary rule changes to allow exchange of individual and wide-area models of sufficient accuracy between academia and industry and within various industry organisations such as OEMs and system operators |
| Lack of trial and commercial projects based on emerging technologies | ■ Liaise with ARENA for funding of grid-forming inverter projects with black start capability.<br>■ Revise current regulatory frameworks to provide better incentives for new entrant SRAS providers. |
| The use of more complex and diverse tools within the control rooms | ■ Investigate new ways of operator training (to be done under research topic 3)<br>■ Better and more automated integration between desktop analysis tools and decision support tools used in control rooms<br>■ Bring in new skillsets/capabilities within control rooms in addition to traditional skillsets and capabilities |

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