CSIRO Australian Research Plan for the G-PST

Task 1 – Inverter Design – Development of capabilities, services, design methodologies and standards for Inverter-Based Resources (IBRs)

Final Report

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Executive Summary

Although the inverter-based resources penetration in the Australian National Electricity Market (NEM) and South West Interconnected System (SWIS) is increasing at a rapid pace, synchronous generators are still constituting a significant portion of generation mix. The NEM, however, is in a rapid transition towards an inverter-dominated structure as the majority of synchronous generators are displaced by inverter-based resources (IBRs) over the next two decades. According to AEMO's Integrated System Plan, it is expected that 63% of coal power plants will be retired by 2040. Most IBRs in the NEM today are grid-following inverters (GFLIs) that rely on other grid resources to set voltage and frequency. Alternative inverter control methods such as grid-forming inverters (GFMIs) are necessary to achieve a secure, stable, reliable, IBR-dominated grid. Such inverters are already being installed in several locations in the NEM, and it is expected their share will only increase in years to come. Development of these methods requires exploration of control strategies, protection schemes and modelling approaches for IBR-dominated grids.

This document outlines a research plan comprising key research questions focused on IBR control, services, capabilities and protection for an IBR-dominated grid. This plan targets various research stakeholders including but not limited to universities, state/federal governments, and research institutes such as Commonwealth Scientific and Industrial Research Organisation (CSIRO). The plan was commissioned by CSIRO and has been synthesised by the Monash University team from a variety of resources: literature surveys, reviews of key projects and publications around the world, interviews with a wide range of industry experts, and knowledge of research currently underway in Australia and Monash University.

The plan identifies five major tasks and five shared tasks with other GPST topics to deliver answers to the identified key research questions. It also outlines linkages and tasks shared with other topic areas of the G-PST and sets out high-level estimates of resources and timeframes required for the major tasks and shared ones.

Table 1. Identified Tasks, adequacy of Australia's research capability, total resources, and timeframes

Major Task / Shared Task	Australia's research capability	Total resources	Timeframe
Major Task 1: Frequency Stability	Adequate	3 junior researchers & 3 senior researchers	2 years
Major Task 2: Voltage Stability	Adequate	1 junior researcher & 1 senior researcher	3 years
Major Task 3: Interaction Mitigation and Oscillation Damping	Adequate	5 junior researchers & 3 senior researchers	3 years
Major Task 4: Protection and Reliability	Limited	4 junior researchers & 4 senior researchers	3 years
Major Task 5: Trending Topics	Adequate	5 junior researchers & 4 senior researchers	3 years
Shared with Topic 2: Stability Tools	Limited	2 junior researchers & 2 senior researchers	2 years

Shared with Topic 3: Future Control Rooms	Limited	1 junior researcher	2 years
Shared with Topic 5: Restoration and Black Start	Limited	1 junior researcher & 1 senior researcher	2 years
Shared with Topic 6: Services	Adequate	1 junior researcher & 1 senior researcher	1 year
Shared with Topic 8+2: DER + Stability Tools	Adequate	1 junior researcher & 1 senior researcher	2 years

List of Acronyms

AEMO	Australian Energy Market Operator
AI	Artificial Intelligence
ARENA	Australian Renewable Energy Agency
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DER	Distributed Energy Resources
DNSP	Distribution Network Service Provider
EMT	Electromagnetic Transient
ESCRI	Energy Storage for Commercial Renewable Integration
ESS	Energy Storage System
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FFR	Fast Frequency Response
GFLI	Grid-Following Inverter
GFMI	Grid-Forming Inverter
G-PST	Global Power System Transformation Consortium
HVDC	High Voltage Direct Current
IBR	Inverter-Based Resource
MIGRATE	Massive InteGRATion of power Electronic devices
NEM	National Electricity Market
OEM	Original Equipment Manufacturer
PMU	Phasor Measurement Unit
PLL	Phase-Locked Loop
PSS/E	Power System Simulator for Engineering
PoC	Point of Connection
PV	Photovoltaic
RES	Renewable Energy Resources
RoCoF	Rate of Change of Frequency
SO	System Operator
SSO	Sub-Synchronous Oscillations
STATCOM	Static Compensator
SynCon	Synchronous Condenser
TNSP	Transmission Network Service Provider
VAR	Volt-Ampere Reactive
VSG	Virtual Synchronous Generator

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1. Introduction

Australia's national grid—the world's longest, thinnest grid—stretches about 5,000 kilometres from Port Lincoln, South Australia, to Port Douglas, Queensland. It has many weak areas with low system strength. It is currently undergoing a major transformation to replace fossil fuels with renewable energy resources (RES), such as solar and wind. According to the Clean Energy Council 2021 report, in 2020, around 27.7% of Australia's total energy generation came from renewables, mainly wind and solar. Generation mix from inverter-based resources (IBRs) such as wind and solar farms creates a power system with low levels of intrinsic inertia, and voltage/frequency control is challenging.

Traditionally, synchronous generator–dominated grids are controlled via established techniques for frequency and voltage control, such as generator-excitation control and turbine-governor control. These control mechanisms ensure tight regulation for both frequency and voltage in the grid while power production and balancing can be shared among generators via governor droop control. This presents a rather stiff grid to which IBRs can interface seamlessly. The vast majority of IBRs in the current Australian National Electricity Market (NEM) are grid-following inverters (GFLIs), meaning they follow the system's voltage and frequency via a phase-locked loop (PLL) to inject real/reactive power into the grid [1, 2]. GFLIs cannot regulate the grid frequency and voltage without relying on an external voltage source. This means if GFLIs are unintentionally islanded, they may not maintain their stability, as the frequency (and often the voltage) of an islanded grid without a synchronous generator is no longer regulated. Additionally, subsequent to a blackout, GFLIs are unable to black start the system.

With the increasing number of retiring synchronous generators, grid locations far from synchronous generators and close to IBRs experience lower fault currents, lower system strength and looser voltage/frequency control. This results in greater sensitivity of the point of connection (PoC) voltage magnitude and phase to IBR output power, which results in several issues for wind and solar farms, including post-fault instability, failure to feed in full power stably under steady-state conditions, start-up and re-synchronisation issues, control interactions and instability, failure to ride through disturbances, poor electromechanical oscillatory stability and islanding issues [3]. In China and the United States, wind farms connected to weak parts of the network have experienced sub-synchronous oscillations (SSO) at 4 Hz or 30 Hz, and, in Australia, SSO at several frequencies has been recently reported [4]. SSO is highly detrimental to the normal operation of power systems, leads to fatigue damage and reduces the shaft life of synchronous generators, which are supposed to generate power at close to 50 Hz. Some wind and solar farms connected to weak parts of the NEM cannot operate at their nominal power levels due to stability issues. A recent example is AEMO limiting the allowable output power of five weakly-integrated solar farms in Vic and NSW to half their rated value [5]. Further, some of the proposed wind and solar farms may not be developed due to stability concerns about the effects of their connection to the NEM's weak areas. It is worth noting that while some of these stability issues have been resolved through control system tuning, such measures will face inherent limitations in future in the absence of system strength services. The reason is that installation of new farms may alter the interaction between the existing farms and the grid leading to various stability issues. Additionally, in the absence of grid strengthening assets, grid following inverters will not be able to maintain their stability below certain short circuit ratios even with proper tuning.

In the absence of synchronous generators in future grids, such issues can be remedied by installing voltage-stiffening assets such as synchronous condensers (SynCons) or battery energy storage systems (BESSs) interfaced to the grid via grid-forming inverters (GFMIs). SynCons can assist the grid and increase its strength but have a very long procurement and installation lead time, are very costly, and are inflexible in a rapidly changing grid. Additionally, SynCons may only contribute to fast-response frequency control and cannot continuously inject active power into the grid due to the absence of a prime mover. A further drawback of adding SynCons to existing systems is the addition of further electromechanical rotor angle stability nodes and oscillatory modes, adding to the system complexity. In contrast, BESSs are comparatively affordable and are seeing widespread implementation worldwide. BESS-based GFMIs can provide voltage/frequency regulation (similar to synchronous generators) via fast frequency response (FFR) mechanisms and can also provide system strength services to the grid (as well as other ancillary services, thanks to the versatility of power electronic converters). BESSs are establishing their roles in maintaining grid security and reliability, and the NEM has almost 7 GW of BESS projects either proposed, in feasibility phase, or being installed [6]. Accompanying and driving this is the constant addition of various types of IBRs to grids in Australia and internationally.

Transitioning from a synchronous generator–based grid to an IBR-dominated grid and, ultimately, to a 100% IBR system requires solutions to many various challenges and obstacles. This research plan aims to 1) provide a comprehensive list of open research questions and challenges focussed on IBR services and capabilities in the context of grid integration of RES, and 2) provide a list of tasks to address these questions/challenges. The target audience is Australian research organisations such as universities, original equipment manufacturers (OEMs), network operators/owners, system operators, and government agencies.

1.1. Research Plan Deliverables

As per the RFQ for this research plan, the following deliverables are covered in this report:

- A detailed work plan outlining the methodology for developing the research plan is provided in Section 2.
- The current status of technology and solutions in the topic area, with a focus on identifying specific areas in which Australia has unique, existing technology, and solutions relevant to the topic is reviewed in Section 3.1.
- Related activities underway by AEMO, networks, government, research organisations, and others, and a discussion of how the plan aligns with these activities is duly discussed in Section 3.2.
- Further refinement and exposition of listed research questions is given in Section 2.1 and Appendices.
- Prioritisation of research questions into which are most applicable for Australian researchers to lead, where Australian researchers might collaborate, and where Australia should learn from others are outlined in Section 4.

- The research plan developed for the topic area, including identification of opportunities for Australian researchers to help answer specific research questions, with specific research activities and outputs specified is provided in Section 4.
- Potential information, data, and resources needed to effectively prosecute the research plan is identified in Section 4.
- The risks associated with the research plan development and mitigation strategies are identified in Section 4.
- The key stakeholders (in Australia and overseas) required to advance Australian research in the topic area are recognized in Section 4.

2. Methodology

Several industry stakeholders and various documents were consulted to develop this research plan. To ensure a wide range of expert viewpoints were captured, thirteen industry stakeholders, including grid operators/owners, OEMs, and consultants, were identified and separately interviewed. This document has been synthesised from an extensive literature review and structured interviews with these stakeholders.

Interviews were around one hour each and structured such that interviewees had the chance to express their views on various challenges around IBR-dominated systems in general and their perceived challenges regarding more specific topics. The outcome of each interview was around ten to fifteen research questions. Naturally, some of these questions overlapped; in such cases, they were combined to form a single, more comprehensive question.

A long list of research questions resulted from combining questions identified in interviews, questions identified in the literature, and questions arising from ongoing Monash University research projects. This list is the primary source for the development of this research plan, and the list is provided as an appendix in this document. After preparing the first research plan draft, the stakeholder experts were engaged for a second time to ensure all their viewpoints were accurately captured, and any further comments/feedback from them were gathered to finalise this document in September 2021. The workflow based on which the research plan is developed is presented in Figure 1.

This research plan is primarily focused on IBRs in the transmission network. It excludes research questions regarding IBRs in the distribution networks. However, the possible links between this plan and the G-PST Topic 8+2 (distributed energy resources [DER] & stability tools) are highlighted for the sake of completeness.

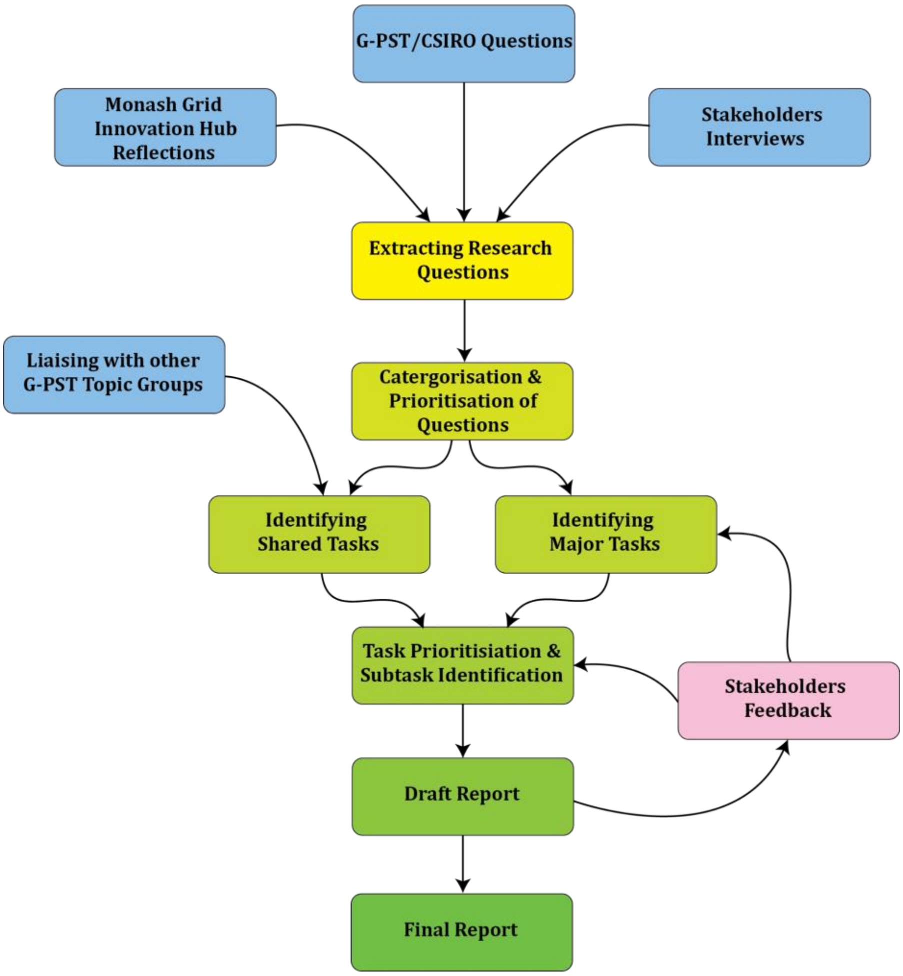

Figure 1. The workflow of the 'Inverter Design' research plan

2.1. Key Research Questions

The key research questions are sourced from the questions provided by CSIRO, stakeholder interviews, and the authors' reflections. The list of research questions given by CSIRO can be found in Appendix A. In addition, a large number of questions (around 40) were gathered from the concerns raised by the stakeholders and the authors' reflections. These research questions were categorised based on keywords assigned by the authors, which can be found in Appendix B. Common themes based on which the research plan has been established are presented as a word cloud in Figure 2. Furthermore, interlinks between research questions raised by the stakeholders and the authors' reflections with the research questions given by CSIRO were determined as per the assigned keywords and can be found in Appendix C.

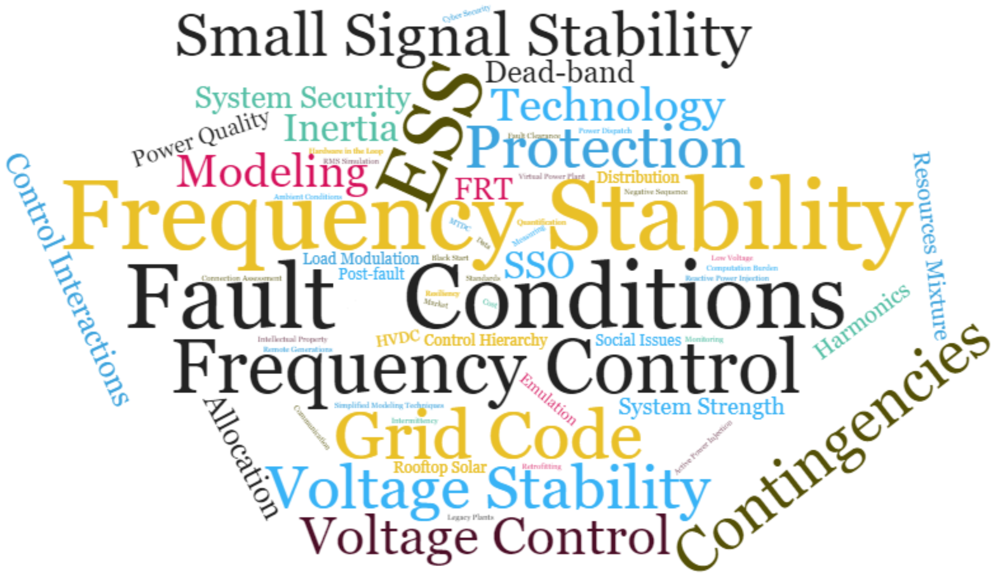

Figure 2. Common themes of the research questions

3. Plan Development

In addition to the literature survey and stakeholder expert interviews, the development of the research plan took account of current practices and a wide range of IBR-related NEM initiatives planned or underway, as well as materials made available by CSIRO in setting the plan development task.

3.1. Current Solutions

To export energy, IBRs must be synchronised with the grid. Their synchronisation is primarily based on control algorithms and differs from the swing-equation-based synchronisation of synchronous generators [7]. Based on their grid synchronisation, two main categories of IBRs exist 1) GFLIs and 2) GFMIs. GFLIs mainly rely on PLLs to get synchronised with the grid [9]. Sensing the PoC voltage, the phase-angle and frequency of the PoC voltage are extracted by a PLL, which is then used in a vector current control strategy to generate inverter gating signals [10, 11, 12]. GFMIs, however, exploit active power-frequency droop control for grid synchronisation [13, 14]. GFMIs regulate the PoC voltage to a frequency and magnitude provided by active/reactive power control loops mainly based on the droop concept. The first category is called grid following as they follow the PoC voltage using a PLL, while the second one is called grid forming as they form the PoC voltage [7].

The vast majority of currently installed IBRs are GFLIs, which are known for their performance challenges in weak grids. Although GFMI controllers can seamlessly operate in weak grid conditions, retrofitting the existing large fleet of GFLI IBRs with the GFMI concept is not an easy task as in addition to upgrading the control platform, GFMIs require a high-voltage capacitor for voltage control, which is not always present in the existing GFLIs. Additionally, GFMIs can exhibit stability issues in stiff or series compensated grids [7]. GFMI technology is also not yet fully mature, and further studies are required for its large-scale deployment as many questions remain to be answered regarding various operational aspects.

GFLIs can seamlessly operate in strong grids to export their maximum power. However, as they rely on PLLs, their performance in weak grids deteriorates, and operation in very weak grids can lead to instability or side-band oscillations [7,15]. These are mainly due to the asymmetrical control dynamics of synchronous reference frame PLLs. Several strategies have been proposed to mitigate the issues PLLs face in weak grids. An asymmetrical PLL that provides phase-angles in both d- and q-axes is proposed in [16]. Embedding a virtual impedance in the PLL structure, the PLL is synchronised with a remote, strong grid in [17]. The negative resistance of the PLL can be damped by tuning a band-pass filter in [18]. In [19], a feed-forward loop from the PLL to the current control loop can achieve symmetrical dynamics in the d- and q-axes. All of these approaches, however, rely on a PLL and require the PoC voltage measurement. GFMIs, on the other hand, face stability issues when operating in stiff grids [7]. In stiff grids, the PoC and the grid are electrically close to each other, meaning that neither the GFMI nor the grid can independently regulate the PoC voltage [20]. Two types of synchronisation instability exist for GFMIs: 1) side-band oscillations and 2) synchronous oscillations. Various strategies have been proposed to mitigate these stability issues in GFMIs [21,22]. GFMIs also cause side-band oscillations in series-compensated, weak grids [24]. A current feed-forward control added to the modulation voltage is adopted to mitigate these oscillations in series-compensated grids in [23].

Moreover, GFMI fault-recovery performance poses challenges as their current must be limited to protect their semiconductors switches [24].

For a 100% IBR grid to be realised, design, control and operational challenges must be rectified as the transition occurs progressively over the next few decades. With the majority of installed IBRs in the grid being GFLIs, knowledge of interactions of GFMIs and GFLIs is still inadequate. The questions outlined in the following sections must be answered to ensure a successful transition.

3.2. Industry Activities

As IBR penetration increases all around the world, several stakeholders have recognised the importance of early exploration of issues pertaining to future IBR-dominated power systems. To this end, several different activities from ideation to large scale field tests have taken place in various projects. Some current and recent activities directly related to inverter design are listed here. These activities were considered in the development of this research plan.

3.2.1. H2020 MIGRATE Project in Europe (Completed)

The massive integration of power electronic devices (MIGRATE) is a project funded under the European union's Horizon2020 framework. The MIGRATE project consisted of 23 stakeholders (10 TSOs, 12 Universities/Labs, and one manufacturer) who examined possible solutions to issues that arise with increased levels of IBR penetration. The work packages covered stability issues, monitoring, control and operation, protection schemes, and power quality issues in transmission networks with a high penetration of IBRs.

3.2.2. AEMO National Energy Simulator (Underway)

AEMO is currently developing an electromagnetic transient (EMT) model of the NEM in HYPERSIM to capture the behaviour of the power system accurately. As the power system is transitioning from conventional synchronous power plants to IBRs, the time scale of power system dynamics shortens, i.e. things happen faster. Conventional phasor-based RMS type simulation models are not accurate enough to capture the dynamics of IBR-dominated power systems. Conventional EMT tools are computationally intensive - a simulation run could take hours to complete. A real-time simulation model has been built in HYPERSIM to fast track the EMT studies. The aim of the national energy simulator is to aid and enhance system planning, security, and reliability of future power systems.

3.2.3. The VSYNC project (Completed)

The virtual synchronous (VSYNC) generator project is implemented to equip distributed generators with the virtual synchronous generator capability to address stability issues in future power systems. The project tested various control techniques used on different types of energy storage systems ranging from laboratory setups to field demonstrations of large and small VSG systems. The demonstration sites consisted of ten 5 kW VSGs in the Netherlands and one 100 kW VSG in Romania. The field tests included frequency control, fault handling, standalone operation, and coordination of storage systems. The results from the field tests clearly demonstrated the capability of VSGs in frequency control, reactive power injection during faults, and an overall solution that enabled a large share of decentralised generation to be hosted.

3.2.4. Dersalloch Wind Farm Black Start Study (Completed)

Recently, ScottishPower successfully demonstrated the black start capabilities of a virtual synchronous machine using the Dersalloch onshore wind farm in South Ayrshire. The Dersalloch wind farm comprises 23x3 MW Siemens Gamesa wind turbines. Black start operations are typically performed by traditional synchronous power plants. However, the wind farm equipped with grid-forming inverter technology was able to successfully restore power to a blacked-out (islanded) part of the network.

3.2.5. ElectraNet Dalrymple ESCRI BESS (Completed)

In this ElectraNet project, referred to as the Energy Storage for Commercial Renewable Integration (ESCRI) project, a 30 MW / 8 MWh grid-connected battery at the Dalrymple substation on the Yorke Peninsula in South Australia was successfully installed and commissioned. The ESCRI project was the first Australian detailed assessment of utility-scale non-hydro storage, in which the battery storage provides both regulated and competitive market services to the NEM. This project provided a business case assessment of BESS as a commercial option for the integration of renewable resources into the grid. Worley Parsons led technology selection, development of technical specifications, timeline and costs estimates in this project.

3.2.6. Alinta Energy Newman BESS (Underway)

In this project, developed, owned and operated by Alinta, a 60 MW AC solar PV integrated with a 35 MW battery storage facility at the Newman gas-fired power station in the Pilbara region of WA will be installed and commissioned. Currently, remote mine sites in the Pilbara rely on diesel or gas generations; however, at the end of this project, up to 100 % of daytime energy requirements for these mining sites will be powered by the renewable energy facility, with remaining power requirements met by gas generation. Fortescue Metal Groups is to be the main energy off-taker. It expects to reduce the use of diesel by around 100 million litres annually. This project will demonstrate the effectiveness of a large-scale hybrid power supply solution combining solar, gas, and storage in an off-grid network from both technical and commercial points of view.

3.2.7. AusNet Services Ballarat BESS (Underway)

In the AusNet Services BESS project, a 30 MW/ 30 MWh grid-connected battery will be installed and commissioned at the Ballarat Terminal station in Victoria. In this project, NuvoGroup (owned by Spotless) is the developer and the lead, Fluence (an AES-Siemens joint venture) is the battery provider, AusNet Services is providing the equity, Energy Australia is the long-term off-taker, and Australian Renewable Energy Agency (ARENA) and the Victorian Government are providers of grant funding. The main target of this project is arbitrage: to store energy at times of relatively low value and use it at times of relatively high value. Provision of other grid services such as frequency control ancillary services and FFR will also be examined.

3.2.8. Monash Grid Innovation Hub: Stability Enhancing Measures for Weak Grids (Underway)

In this ARENA-supported project, system weakness issues and a variety of control schemes and configuration solutions, including new control systems for GFLIs, synchronous condensers, and GFMIs will be investigated. Owing to its current system stability challenges, the West Murray region of the NEM is a case study, which will be adapted to the network conditions and operating decisions in West Murray as they evolve and provide an opportunity for NEM stakeholders to understand and explore emerging issues and potential solutions.

The study aims to achieve the following outcomes:

- reduced grid connection risk for renewable developers,
- increased capacity of weak grids to host variable energy resources, and
- improved understanding of security and reliability in an IBR-dominated power system.

The outcomes of this study will be applicable to Renewable Energy Zones across the broader NEM and the South West Interconnected System in Western Australia.

3.2.9. Powerlink Cost-Effective System Strength Study (Completed)

The Powerlink cost-effective system strength study was undertaken to promote increased awareness of system strength and measures that can be used to manage it, including centralised and coordinated solutions. According to this study, batteries equipped with GFMI capabilities can play a constructive role in enabling the hosting of renewable resources and supporting the operation of the power system. A case study demonstrated that a 100 MW battery could support connection of 300 MW of IBRs, assisting renewable energy developers who seek to connect into areas of low system strength. This reduces barriers to the uptake of renewables.

3.2.10. TransGrid Wallgrove BESS (Underway)

In this TransGrid project, a 50 MW/ 75 MWh lithium-ion battery will be installed and commissioned at the Wallgrove substation in western Sydney. Tesla batteries will be connected to the grid via GFMIs to provide inertia services, such as synthetic inertia and FFR capabilities to enhance network stability. This project has received funding from ARENA as part of ARENA's Advancing Renewables Program and the NSW Government as part of its Emerging Energy Program.

4. The Research Plan

Five major tasks and five shared tasks form the basis of the research plan. They have been defined from a synthesis of the inaugural research agenda of G-PST, numerous interviews of industry experts, review of key publications and projects, and research questions arising from Monash University's Grid Innovation Hub research projects. The five major tasks (see Section 4.1) and five shared tasks with the other G-PST research groups (see Section 4.2) each include several sub-tasks. These major/shared tasks aim to address the CSIRO questions (represented by Q1 to Q11) and the stakeholders/Monash questions (represented by R1 to R41). Corresponding research questions are provided under each major/shared task.

4.1. Major Tasks

The major tasks encompass various aspects of inverter design (see Figure 3), including the development of capabilities and associated services, design methodologies and standards for IBRs.

Figure 3. Major tasks defined for the 'Inverter Design' Research Plan.

4.1.1. Major Task 1: Frequency Stability

Any event that results in an imbalance in power between generation and demand leads to a change in power system frequency. Frequency stability refers to the ability of the system to maintain the frequency within statutory limits following an event. The conventional frequency control framework includes three stages: 1) inertial response to slow down the rate of change of frequency (RoCoF), 2) primary frequency response and load damping to arrest the frequency fall, and 3) automatic generation control to restore the frequency to its nominal value. The RoCoF immediately after a contingency directly correlates to the online inertia in the system. IBRs cannot provide a traditional rotational inertial response as they are electronically coupled to the grid, as opposed to a synchronous machine's magnetic coupling. The synchronous inertia in the system declines as IBR penetration increases. The RoCoF following a contingency could become dangerously high in an IBR-dominated power system.

The online inertia in the NEM is shrinking due to the rapid uptake of large-scale IBR generation, increasing DER penetration and progressive decommissioning of synchronous power plants. Shortfalls in the minimum threshold level of inertia and secure operating level of inertia are projected for the next five years in some regions of the NEM without continuing inertia services contracts. Inertia services must be procured by the local transmission network service provider to address these shortfalls. New IBR-based inertia services could be used to address these shortfalls.

The minimum secure operating limit of inertia depends on the available amount of FFR. As IBR uptake in the NEM increases, so does the potential for providing FFR services from IBRs. IBRs are typically associated with renewable resources, and there could be economic consequences from the reduction of power output to create 'headroom' for FFR. In contrast, IBRs associated with BESSs could be a viable techno-economic solution to provide FFR and maintain the system frequency within statutory limits in IBR-dominated power grids.

The priority research tasks proposed to ensure frequency stability under conditions of high IBR penetration in the Australian power system are

- Defining the required frequency responses of Grid forming and Grid following inverters
- Studying the frequency responses expected of Power-oriented and Energy-oriented batteries
- Investigating distributed FFR control design for coordinated battery energy storage systems, exploiting the capabilities of PMUs.

Corresponding CSIRO Research Questions: Q4, Q6, Q7
Corresponding Monash/Stakeholders Questions: R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R12, R13, R31, R39, R40
Leading Australian Universities: Monash University, University of New South Wales, University of Tasmania, Australian National University, RMIT
Expertise in Australia: Adequate
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Federico Milano - University College Dublin, Prof. Tim Green - Imperial College, Prof. Xiongfei Wang - Aalborg University, Prof. Florian Dörfler - ETHZ, Prof. John Morrow - Queen's University Belfast, Prof. Robert Lasseter - University of Wisconsin Madison

4.1.1.1. Defining the response of GFLIs and GFMIs for a credible contingency

In conventional synchronous power plant–dominated networks, a mismatch between demand and supply leads to a change in the system frequency. The inertia from online synchronous power plants acts as a buffer to smooth out the sudden change in frequency. As IBR penetration increases, the online inertia in the system decreases. Consequently, the RoCoF following a contingency could end up being significant, and lack of inertia could also influence the frequency nadir.

Credible contingencies are mostly attributed to events related to synchronous power plants or large loads. However, as conventional synchronous power plants are increasingly replaced by IBRs, it is worth recognising and understanding the potential risks that could cause frequency instability in IBR-dominated power systems. The events caused by IBRs will increase as the percentage of operational IBRs increases in the grid. Therefore, it is worth identifying the potential risks associated with different IBRs penetration levels.

The current frequency operating standards are primarily based on synchronous power plants and frequency-sensitive loads. However, IBRs are generally capable of operating in a wide range of frequencies and, unlike synchronous machines, can also operate at far finer frequency tolerances and deadbands. Further, the loads in the system are also gradually transforming into power electronic-based loads. Therefore, as the power systems evolve into IBR-dominated grids, it is important to evaluate the consequences of violating the existing frequency operating standards. Further, the appropriate frequency ranges of operation must be assessed for different IBRs penetration levels.

Once the risks that can jeopardise the frequency stability are understood and proper frequency operating standards in IBR-dominated grids are established, appropriate services from IBRs can be procured. GFLIs provide FFR and virtual inertia based on the frequency and RoCoF measurements, respectively. Since FFR and virtual inertia depend on these measurements, they are subject to delays. Conversely, GFMIs are inherently capable of providing a synthetic inertial response similar to synchronous generators. Therefore, based on the IBR penetration level and associated risks, the required response from GFLIs and GFMIs (such as FFR, virtual inertia) must be defined. This will enable the proper tuning of control systems for the required response of GFLIs and GFMIs during contingencies.

Deliverables: 1) A detailed report of potential risks associated with different IBRs penetration levels that can cause frequency instability, 2) A detailed analysis on the consequences of violating the existing frequency operating standards, and assessment of the appropriate frequency ranges of operation for different IBRs penetration levels, 3) required response from GFLIs and GFMIs (such as FFR, virtual inertia) based on the IBR penetration level and associated risks, 4) control strategies that deliver the required performance from GFLIs and GFMIs and their design.
Required Data: EMT model of the grid, Projected IBR penetration levels,
Associated Risks: Inability to access the required data, Inability to access the computational tools to run large simulation models,
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Urgent
Open-ended Project: No

4.1.1.2. Control of ESS based on the capability of the energy source to provide various frequency services

Energy storage systems (ESSs) are an integral part of frequency control in future IBR-dominated grids. Depending on the technology of the energy storage element (e.g., batteries, supercapacitors, flywheels), ESSs' capabilities and available services change. Power-oriented ESSs are capable of providing a high amount of energy within a short period of time (e.g. supercapacitors) and are suitable for primary frequency control. Energy-oriented ESSs are capable of sustained energy provision for a long period of time (e.g. Hydrogen fuel cells) and are more suitable for secondary frequency control. The frequency control consists of two main parts: arrest and recovery of frequency fall. This task aims to study the response expected from each of such ESSs or a combination of them as a hybrid ESS. Also, this task intends to devise control strategies for each type such that their coordinated control can result in seamless recovery of the frequency upon each contingency.

Deliverables: 1) A report that outlines the capabilities and economic viability of various existing and emerging ESSs and hybrid ESSs that can partake in frequency control, 2) A study of the response expected from each of such ESSs or a combination of them as hybrid ESSs, 3) Control strategies for each type of ESS and hybrid ESS such that their coordinated control can result in seamless recovery of the frequency upon each contingency.
Required Data: Detailed models of different ESSs, EMT model of the grid
Associated Risks: Inability to access the required details of the models.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 5 Years
Open-ended Project: No

4.1.1.3. Coordinated/distributed control of BESSs for frequency control

Large-scale BESSs are increasingly deployed to improve grid resilience and reliability in low-inertia power systems. Such power systems are large entities spread over large geographical areas. Due to recent advancements in communication technologies and the deployment of fast 5G networks, wide-area monitoring systems such as phasor measurement units (PMUs) can be leveraged to design fully-fledged distributed FFR controllers that are effective and reliable against contingencies. The majority of existing BESSs utilise local information at their PoC and operate based on droop control. However, droop controllers suffer from several drawbacks, including poor transient performance, frequency deviations, unbalanced harmonic current sharing, heavy reliance on output impedance, and not considering load dynamics [25]. Excessively slow droop controllers are also directly associated with system stability issues [26, 27]. Further, it has been shown that a droop controller with a deadband is unsuitable for injecting a burst of active power during the first 500 ms after a fault [28]. As power systems are being equipped with PMUs, each BESS can have access to the information of other BESSs in the system, hence providing infrastructure for coordinated control of batteries. Using PMUs and the communication network can be effective for identifying a nonparametric linear time-invariant multi-input multi-output model of the system for control design and providing frequency measurements for FFR. Therefore, to utilise the full potential of PMUs together with fast communication networks, distributed FFR control design should be investigated. In distributed FFR control design, BESSs in the same area are allowed to communicate with each other. Therefore, the control signals use both local PMU signals and other PMU signals in the same area, leading to a coordinated response of neighbouring BESSs that can assist in frequency recovery in response to various contingencies. This also minimises the risk of control interactions of independently-controlled BESSs based on droop.

Deliverables: 1) Multi-input multi-output model of the system derived from PMU measurements, 2) Distributed FFR control strategies based on wide area measurement systems.
Required Data: EMT model of grid, data for identification and control
Associated Risks: Inability to access the grid model, Inability to acquire the required data, managing large amounts of data.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 10 years
Open-ended Project: No

4.1.2. Major Task 2: Voltage Stability

Voltage stability issues are one of the main barriers to the development of IBR-dominated grids. These issues are more prevalent in weaker grids like the long stringy grid of the NEM. Increasing IBR penetration can potentially weaken the grid even further. Providing a remedy for these issues is an urgent task. IBRs can play a role in responding to these issues. Utilising GFMIs and enabling/coordinating volt-ampere reactive (VAR) support capabilities of IBRs along with other VAR resources of the grid can provide solutions for voltage stability issues. Synchronous condensers and flexible AC transmission system (FACTS) devices are some notable solutions that are outside the scope of this research plan. Addressing the following sub-tasks and employing their outcomes/suggestions in the NEM can improve the NEM's voltage stability and pave the way for 100% renewable energy generation for Australia.

Corresponding CSIRO Research Questions: Q4, Q5
Corresponding Monash/Stakeholders Questions: R9, R12, R14, R15, R17, R25, R33
Leading Australian Universities: Monash University, University of New South Wales, University of Tasmania, RMIT
Expertise in Australia: Adequate
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Federico Milano - University College Dublin, Prof. Tim Green - Imperial College, Prof. Xiongfei Wang - Aalborg University, Prof. Florian Dörfler - ETHZ

4.1.2.1. Investigation of IBR reactive power provision capabilities against the backdrop of losing synchronous machines

With increasing IBR penetration and gradual retirement of synchronous machines in grids, the grid capability of reactive power provision, mainly maintained by synchronous generators, is reduced, in particular for larger disturbances, when short term reactive power in situations of rapidly moving voltage phase angle is required. Therefore, alternative solutions are required. IBRs themselves can provide reactive power support for the system and VAR requirements, thus making the aforementioned loss mostly manageable. However, some specific IBR characteristics can create barriers, which prioritises the necessity of more studies in this area. IBR-based generations consist of hundreds to thousands of smaller generating units that may be geographically dispersed; therefore, a remarkable VAR capability of these units is consumed in the internal network of the farm, and thus the farm overall VAR capability may be reduced significantly. On the other hand, during and subsequent to faults (especially in the period of transient voltage recovery), the network dynamic VAR capability is highlighted. In traditional networks, synchronous generators play vital roles in the system VAR support since they are capable of withstanding 3–5 per-unit overcurrents for subtransient and transient intervals. In comparison, IBRs can barely withstand 1.2 per-unit overcurrents and, therefore, cannot yet perfectly emulate the role of synchronous generators in grid VAR support. In this regard, grid static VAR planning and dynamic VAR support during and subsequent to faults are areas of research requiring more study and conclusive findings in the coming years.

Deliverables: 1) A detailed report about effects of internal networks of various IBR farms on their overall static VAR capability, 2) A detailed report about effects of internal networks of various IBR farms on their overall dynamic VAR capability during and after faults, especially in the period of transient voltage recovery, 3) A detailed report about effects of intermittency of the energy resources on the farm static and dynamic VAR capabilities, 4) Static VAR planning of the grid with high penetration of IBRs (coordinated reactive power control, autonomous reactive power control, etc.), 5) Dynamic VAR support schemes for IBRs to be used during and subsequent to faults in the IBR-dominated grids.

Required Data: EMT model of the grid, projected IBR penetration levels, IBRs reactive power capability curves, IBRs internal reactive power controllers.

Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs reactive power capability curves, inability to access the IBRs internal reactive power controllers.

Resources: 1 senior researcher

Timeframe Estimation: 2 years

Priority: Next 5 years

Open-ended Project: Yes

4.1.2.2. Interactions between synchronous machine AVR, GFMI AVR and GFLI in providing reactive power support

IBRs are potentially capable of absorbing/injecting reactive power from/into the grid, and, owing to their powerful control systems, IBRs can flexibly respond to the system's needs. In this regard, GFLIs are normally equipped with outer control loops that enable them to control the IBRs' output reactive power. In the case of GFMIs, the IBRs should be equipped with automatic voltage regulators (AVRs) to provide this capability, which mimics synchronous generators' AVR role. Enabling these VAR control mechanisms in an IBR-dominated power system, along with the other conventional VAR/Volt resources/controllers (e.g., FACTS devices, capacitor banks, and transformers tap changes), can provide grid operators with powerful VAR/Volt control tools to more securely operate the grid. However, with hundreds to thousands of IBRs in a grid, it is probable that some of these VAR/Volt control tools will compete with each other in some conditions, which may result in system stability/interaction issues. Therefore, it is necessary to identify likely stability/interaction issues stemming from VAR/Volt control tools and, subsequently, develop a method or process for wide-area control system tuning to manage the coordinated VAR/Volt control system.

Deliverables: 1) Scenarios, in which the fast response of an IBR AVR results in instability/interaction with other equipment in the grid, 2) Necessary conditions (in terms of the IBRs penetration ratio, grid

strength, AVR parameters, etc.) for the instability/interaction, 3) A method or process for wide-area control system tuning to avoid the instability/interaction.
Required Data: EMT model of the grid, projected IBR penetration levels, IBRs' AVR parameters.
Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs' AVR parameters.
Resources: 1 junior researcher
Timeframe Estimation: 3 years
Priority: Urgent
Open-ended Project: No

4.1.3. Major Task 3: Interaction Mitigation and Oscillation Damping

Increased IBR penetration and decreased synchronous generation changes the overall power system dynamic behaviour. There is an increased possibility of power oscillations with unusual natural frequencies following events in the system. Even with the current level of IBR penetration in the NEM, several instances of unusual sub-/super-synchronous oscillation have been reported, and it is expected that the probability of encountering unusual oscillations in the grid will increase as more IBRs are commissioned. There is no guarantee that these oscillations are adequately damped. It is quite possible that, in some operating conditions, pairs of poorly-damped/undamped modes exist, which could be easily excited and become unstable. This major task defines several sub-tasks with outcomes to provide grid operators with the capability to identify and resolve such oscillations in the NEM.

Corresponding CSIRO Research Questions: Q2, Q4, Q8, Q9
Corresponding Monash/Stakeholders Questions: R11, R24, R25, R29, R32, R41
Leading Australian Universities: Monash University and University of New South Wales
Expertise in Australia: Adequate
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Federico Milano - University College Dublin, Prof. Tim Green - Imperial College, Prof. Xiongfei Wang and Prof. Frede Blaabjerg - Aalborg University, Prof. Florian Dörfler - ETHZ, Prof. Jian Sun - Rensselaer Polytechnic Institute, Prof. Lingling Fan - University of South Florida

4.1.3.1. Identifying the nature of oscillations in IBR-dominated grids

Prior to the introduction of IBRs in grids, power system dynamics were mainly affected by synchronous generators, and system oscillatory behaviours were characterised by these component dynamics and the dynamics of their excitation systems. Increasing IBR penetration drastically changes the power system dynamics and results in power systems with completely different oscillatory behaviours. Therefore, it is necessary to investigate power system dynamic behaviours at higher levels of IBR penetration and identify the more sensitive dynamic modes, their frequency ranges and their damping ratios, all of which may be completely different from the sensitive modes in traditional power systems. Further, the state variables and system components with greater participation factors in the sensitive modes should be determined. Eventually, to avoid system instability, the ways the identified sensitive modes are stimulated should be determined and prevented.

Deliverables: 1) Low-order yet accurate dynamic models for the IBRs connected to the grid, 2) Dynamic model of the grid in presence of the identified IBRs' dynamic models, 3) Modal analysis results for scenarios with various penetration ratios of IBRs in the grid, 4) Identified sensitive dynamic modes, their frequency ranges and their damping ratios, 5) Identified state variables and system components with greater participation factors in the sensitive modes, 6) A detailed report about effects of IBRs penetration ratio on the sensitive dynamic modes, 7) A detailed report about effects the ways the identified sensitive modes are stimulated.
Required Data: EMT model of the grid, projected IBR penetration levels, IBRs dynamic models.
Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs dynamic models, inability to perform the modal analysis due to the computational burden of simulating an ultra-high order system.
Resources: 2 junior researchers and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Urgent
Open-ended Project: No

4.1.3.2. Standardising the models of IBRs

IBR design and manufacturing is a booming industry due to the rapid uptake of IBRs, and several IBR vendors design and manufacture IBRs for grid-scale applications. The control systems of IBRs from different vendors could be fundamentally different. Different control systems are one of the key factors that provide vendors with a competitive advantage. Therefore, typically, the control systems of an IBR belong to the vendor. As proprietary IBR models are subjected to intellectual property rights, they are typically either blackbox or greybox models, and the inner workings of the controllers are not readily available to third parties. A power system consisting of tens of thousands of IBRs means a very high likelihood of possible interactions between IBRs. Differences in control systems mean information regarding control parameters is not readily available, making it extremely difficult to identify possible interactions between control systems and potentially leading to oscillations. Therefore, it is extremely important to standardise IBR models and facilitate information sharing. It is similar to the situation of the development of control systems, such as AVRs and power system stabilisers in the synchronous plants, where standardised approaches for modelling were developed in the mid-20th century and widely applied since. To this end, making available frequency-domain models specifying salient features of IBRs in crucial frequencies is one possible solution.

Another possible approach is deriving models of IBRs using input and output data. The output data of an IBR subjected to small perturbations can be used to derive linear time-invariant models of the IBR. These models could be used to observe the behaviour of IBRs without violating the vendor's intellectual property rights. However, such a data-driven method would require engagement with transmission network service providers to collect measurement data. As the number of IBRs in the grid increases day by day, it is extremely important and urgent to investigate and evaluate methods to standardise IBR models.

Deliverables: Standard IBR models.
Required Data: Different IBR models from different OEMs, field data to identify the frequency domain models

Associated Risks: Inability to acquire the IBR models from OEMs, inability to acquire the required data for identification, managing large amounts of data
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Urgent
Open-ended Project: Yes

4.1.3.3. Modelling, analysis, control and coordination of IBRs for oscillation damping

Each IBR in the grid is a dynamic system with several control loops and specific dynamic responses. Considering the nominal rating of an IBR unit connected to the grid, there is a need for a huge number of IBRs to supply the system loads—far more than the current number of synchronous generators operating in the system—which significantly increases the system dynamic order and affects power system dynamic behaviour. Therefore, to identify and improve the dynamic behaviour of IBR-dominated power systems, it is necessary to first provide appropriate dynamic models with acceptable dynamic order for both the IBRs and other components of the power system. It is noteworthy that since these dynamic models are intended to be used for dynamic stability studies, such as modal (eigenvalue) analysis and impedance-based analysis for an ultra-high-order system, these models are different from the IBRs standard model. Second, to improve the dynamic response of the power system and increase the damping ratio of the poorly-damped oscillatory modes, these models should be employed to tune/redesign the IBRs control schemes. In this step, coordinated tuning of IBRs controllers for enhancing the damping ratio of poorly-damped inter-area modes should be studied meticulously. It is worth noting that in some cases, the mechanical/chemical dynamics of IBRs energy source components can play an important role in some oscillatory behaviours in the power system. Therefore, appropriate modelling of these components increases the complexity of this task and should be properly addressed.

Deliverables: 1) Dynamic models of the grid-connected IBRs including the mechanical/chemical dynamics of IBRs energy source components, 2) Dynamic model of the grid in presence of the IBRs' dynamic models, 3) Scenarios with stimulated poorly-damped inter-area modes, 4) IBRs participate in the poorly-damped inter-area modes for various operating conditions, 5) IBRs coordinated tuning methods/redesigning procedures for increasing the damping of the poorly-damped inter-area modes.
Required Data: EMT model of the grid, projected IBR penetration levels, IBRs dynamic models including the mechanical/chemical dynamics of IBRs energy source components, IBRs power-level controllers.
Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs dynamic models, inability to access the dynamic models of the energy source components, inability to access the IBRs power-level controllers, inability to perform the modal analysis due to the computational burden of simulating an ultra-high order system.
Resources: 2 junior researchers and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Urgent
Open-ended Project: Yes

4.1.4. Major Task 4: Protection and Reliability

Increasing IBR penetration substantially changes the dynamic and transient behaviour of power systems. This arises from fundamental differences in the physical characteristics of IBRs and synchronous generators. Encountering a fault, an IBR provides less fault current as the fault response depends on the converter control scheme and is limited by the rating of the semiconductor switches. The effect of IBRs on various legacy protection schemes needs further investigation. Increasing the share of IBRs in the NEM means that at some point, the legacy protection schemes will be insufficient. Investigation of upgraded/novel protection schemes is a necessary task for the near-future NEM.

In an IBR-dominated grid, IBRs are pivotal resources for supplying customer load, and their reliable operation is essential. Assessment and enhancement of the reliability of IBRs is another necessary task.

Corresponding CSIRO Research Questions: Q10, Q11
Corresponding Monash/Stakeholders Questions: R16, R18, R19, R26, R27, R28, R29, R36, R37
Leading Australian Universities: Monash University, Victoria University, and University of New South Wales
Expertise in Australia: Limited
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Frede Blaabjerg - Aalborg University, Prof. Jean Mahseredjian - École Polytechnique de Montréal, Prof. Ehab El-Saadany - Khalifa University, Dr Aboutaleb Haddadi - EPRI, Prof. Ali Mehrizi-Sani - Virginia Tech.

4.1.4.1. IBRs effect on existing protection systems

Fast control schemes employed in power electronic converters, their limited overload capabilities and reduced inertia in IBR-dominated grids make the fault response of IBRs completely different from that of synchronous generators. As a result, IBR-dominated systems equipped with existing protection systems may not detect and locate faults accurately. The main reason for this is that existing protection systems are mainly designed based on the fault response characteristics of synchronous generators. Therefore, it is essential to thoroughly study the effect of various IBR control strategies, including GFLI and GFMI controls, on legacy protection devices and their functionalities to identify potential maloperation challenges. This will pave the way towards devising innovative mechanisms in the control of IBRs to enable them to work in harmony with protection systems and avoid maloperation.

Deliverables: 1) IBRs (GFLIs and GFMIs) fault current level during and subsequent to faults (single line to ground, line to line, double line to ground, three-phase to ground), 2) A detailed report about effects of IBRs (GFLIs and GFMIs) control parameters on the IBRs fault current, 3) A detailed report about effects of various control strategies (including control-level overcurrent limitations) on the IBRs fault current, 4) A detailed report showing maloperation of various protection schemes/devices (overcurrent relays, distance relays, differential relays, etc.) under the identified fault currents of the IBRs, 5) Innovative mechanisms in the control of IBRs to enable them to work in harmony with various protection schemes/devices.

Required Data: EMT model of the grid, IBRs control schemes including control-level overcurrent limitations.
Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs control schemes including control-level overcurrent limitations.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Next 5 years
Open-ended Project: Yes

4.1.4.2. Enhancing IBR response during and subsequent to faults

Distinct features of synchronous generators in response to power system faults have led power system operators and manufacturers to design and coordinate most system protection devices based on these responses. The capability to inject considerable amounts of negative sequence currents during faults is one such feature, which the basic control schemes of IBRs often do not provide, and current grid codes also do not have clear requirements in terms of to what extent IBRs should provide negative current support for the system. As a result, IBR-dominated systems equipped with legacy protection systems may not detect and locate faults accurately. Therefore, proposing new control schemes for enhancing IBRs response in IBR-dominated grids during various grid faults (e.g., implementing negative sequence injection requirements) is a priority task for future power systems. In particular, as GFMIs are gradually replacing synchronous generators, they are expected to replace the role of synchronous generators in fault conditions. This task aims to explore how IBRs, both GFMIs and GFLIs, can/should provide zero and negative sequence current during unbalanced faults. Additionally, this task will explore how much fault current (both positive and negative sequences) GFMIs should provide during fault conditions and how this fault current should be sourced. To this end, simulation models for IBRs under fault conditions also need to be developed. Collectively, these outcomes can be leveraged to formulate guidelines and standards to clarify the negative sequence currents injected by IBRs.

In addition to IBR response during faults, IBRs need to have appropriate responses subsequent to faults and recover in an adequately damped fashion. Several studies have shown that IBRs post-fault responses can be oscillatory to a great extent, especially when the IBR is connected to weaker parts of the grid. This is particularly concerning when GFMIs recover from faults. Thus, it is necessary to devise effective solutions for this issue. First, the main reasons for this phenomenon should be identified, and second, based on the network conditions at the PoC, appropriate solutions should be proposed.

Deliverables: 1) Simulation models for IBRs under various fault conditions, 2) Amount of fault currents (positive and negative sequences) should be sourced during various fault conditions by IBRs, 3) Guidelines and standards to clarify the zero and negative sequence currents injected by IBRs, 4) New control schemes for implementing zero and negative sequence injection requirements for GFLIs in IBR-dominated grids during various grid faults, 5) New control schemes for implementing zero and negative sequence injection requirements for GFMIs in IBR-dominated grids during various grid faults, 6) A detailed report about reasons for the oscillatory behaviour of GFMIs when recover from faults, 7) A detailed report about solutions for the oscillatory behaviour of GFMIs when recover from faults.
Required Data: IBRs model including control schemes and control-level overcurrent limitations.

Associated Risks: Inability to access the IBRs model including control schemes and control-level overcurrent limitations, intrinsic limits of IBRs for provision of required fault currents.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Urgent
Open-ended Project: No

4.1.4.3. Assessment and enhancement of IBRs reliability

The reliability of IBR-dominated power grids directly depends on the reliability of power electronic converters. IBRs reliability is paramount for securely operating IBR-dominated power systems, which mainly depend on the lifetime of semiconductor devices, capacitors and other components inside the converter. Several important factors affect the lifetime of semiconductor devices and capacitors, such as control strategies, mission profile (operating and ambient conditions), switching schemes, IBR structure and cooling system. Mission profile analysis is adopted for different failure mechanisms of devices using the physics-of-failure analysis to model the reliability of IBRs. This will facilitate identifying the weakest links in IBRs and corresponding devices, which in turn helps improve the overall IBR reliability. Considering technology growth and the increasing level of uncertainties in power networks, novel lifetime models and reliability evaluation techniques are required for IBR-dominated networks. Further, system-level approaches need to be developed to enhance the reliability of such networks employing design-for-reliability techniques, maintenance scheduling and so on. This task aims to develop models and procedures that can evaluate and enhance the reliability of IBR-dominated grids via considering device-level to system-level phenomena.

Deliverables: 1) Novel lifetime models for IBRs in the IBR-dominated networks, 2) Reliability evaluation techniques based on the developed IBRs lifetime models for enhancing the reliability of IBR-dominated grids via considering device-level to system-level phenomena.
Required Data: IBRs device-level model, single-line diagram of the grid.
Associated Risks: Inability to access the IBRs device-level model, inability to access the single-line diagram of the grid.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Next 10 years
Open-ended Project: Yes

4.1.4.4. Cyber-secure inverter design for grid-connected applications

Grid-connected inverters, both at the distribution and transmission levels, are increasingly network-enabled and use communication links for their normal operation, making them vulnerable to various cyberattacks. With 5G communication networks already deployed and the widespread availability of various communication links, it is expected that the number of grid-connected, network-enabled inverters with smart sensors will increase in the coming years. Although the effects of cyberattacks on large-scale inverters can be devastating for grid security, this topic has not been thoroughly studied in the literature. Typically, the firmware update of most grid-connected inverters is carried out remotely via communication channels. Moreover, for most services provided by inverters, various sensor measurements are communicated to the inverters. Hence, both the firmware and sensors used in such inverters can be targets for cyberattacks. This task aims to develop cyber-physical models of inverters and adopt emerging technologies (e.g., blockchain technology to design cyber-secure firmware) to ensure the security of IBR-dominated grids and design cyber-secure inverters. Additionally, this task investigates and develops various cyber shields to ensure the integrity and accuracy of sensor measurements.

Deliverables: 1) A report that identifies the assets related to IBRs that are vulnerable to cyber attacks, 2) cyber-physical models based on emerging technologies such as blockchain technology, 3) cyber shields to protect sensor measurements, and 4) IBRs immune to cyber attacks.
Required Data: Network layer models of IBRs
Associated Risks: Inability to acquire models from OEMs
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Next 5 years
Open-ended Project: Yes

4.1.5. Major Task 5: Trending Topics

The majority of the services and capabilities of the current power system (including frequency control, voltage control and maintaining system strength) are provided by synchronous machines. The retirement of synchronous machines in favour of IBRs in power systems means the services and capabilities currently provided by synchronous machines must be delivered by IBRs. To this end, grid-forming inverter technology has been a focus of Australian researchers and industries. Transmission level GFMI technology is still in its infancy, and the control techniques, challenges and applications of GFMIs are relatively unknown compared to GFLIs. The power system engineering community has not reached a consensus on the definition of GFMIs, unlike the more established GFLI technology. The lack of standards for GFMI services and capabilities is slowing GFMI development. Other emerging technologies like artificial intelligence (AI) can also be used for a variety of challenges associated with IBR-dominated grids. The following sub-tasks serve as research tasks to develop these emerging trends and topics for future IBR-dominated grids, to facilitate the achievement of 100% renewable generation in the NEM.

Corresponding CSIRO Research Questions: Q2, Q3, Q4
Corresponding Monash/Stakeholders Questions: R8, R20, R24, R25, R31, R32, R33, R34, R38
Leading Australian Universities: Monash University and University of New South Wales
Expertise in Australia: Adequate
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Tim Green - Imperial College, Prof. Xiongfei Wang and Prof. Frede Blaabjerg - Aalborg University, Prof. Marco Liserre - Christian-Albrechts-Universität zu Kiel, Prof. Nicolaos A. Cutululis - Technical University of Denmark.

4.1.5.1. Developing alternative control methodologies for GFMIs

As power systems move away from synchronous generators, the core services and capabilities currently provided by synchronous generators must be supplied by IBRs. Many of the services and capabilities of synchronous power plants depend heavily on the physical parameters of the synchronous machines that remain the same throughout their lifetime (unless a costly replacement is undertaken). Conversely, IBRs offer superior flexibility as their services and capabilities (except the ratings of semiconductor switches) are governed by the design of the control systems, which are easily programmable to cater to varying requirements. Presently, the control design of GFMIs mainly focuses on emulating the characteristics of synchronous machines (e.g., virtual synchronous generator [VSG] and synchronverter). Consequently, current GFMIs are capable of providing similar features and services to those of synchronous machines. However, IBRs (GFMIs in particular) are capable of providing more flexibility compared to synchronous generators, and designing them to behave in the same way as synchronous generators may be hampering their full potential. Mimicking the characteristics of synchronous machines is advantageous in replicating the characteristics and services provided by synchronous machines, but it is vital to identify the deficiencies of emulating these characteristics. For example, inter-area oscillations are a major shortcoming of synchronous machine-dominated grids. It is essential to investigate whether modelling GFMIs based on synchronous machines could lead to similar phenomena in GFMI-dominated networks. Control interactions between controllers with similar bandwidths could also lead to oscillations. Further, there could be control techniques superior to synchronous machine emulation that can overcome the deficiencies in synchronous machines while providing similar, if not better, services. Therefore, it is worth investigating when to break away from designing control systems that emulate synchronous machines and start thinking about control methods that can leverage the flexibility offered by GFMIs to have features that supersede the capabilities of synchronous machines.

Deliverables: 1) Shortcomings of modelling GFMIs based on synchronous machines, 2) grid-forming control strategies to circumvent the issues identified.
Required Data: EMT model of the grid
Associated Risks: Inability to access the EMT model of the grid, lack of a consensus on what is considered to be a GFMI.
Resources: 2 junior researchers and 2 senior researchers
Timeframe Estimation: 3 years
Priority: Next 5 years
Open-ended Project: Yes

4.1.5.2. Grid-forming capability for HVDC stations and wind and solar farms

The primary sources of generation in future IBR-dominated power systems will most likely be based on RES. Although it is expected that most such RES-based IBRs will operate in a grid-following mode, there are various benefits in equipping some wind and solar power plants with grid-forming capabilities to operate in the bulk power systems. Grid-forming capability can be particularly beneficial for RES-based IBRs connected to weak parts of the network, as the performance of GFLIs deteriorates under weak-grid conditions while GFMIs can operate seamlessly in weak grids and provide system strength. In such cases, for the momentary inertial support, either energy storage should be installed in the farm or, in the case of wind farms, kinetic energy from the turbine rotors should be utilised. If the energy is extracted from the rotor, the power extraction could decrease and ultimately result in worse inertial performance. Further, HVDC connections could also be equipped with grid-forming capabilities. This could result in improving the system strength and also potentially be utilised in offshore wind farm connections. Although GFMI control is becoming more established, providing the grid-forming capability for RES-based IBRs and HVDC connections is still in its infancy, and control strategies and their tuning are yet to be explored and studied.

Deliverables: Grid-forming inverter control strategies for RES-generators such as wind, solar and HVDC links.
Required Data: EMT model of the grid
Associated Risks: Inability to access the EMT model of the grid, lack of a consensus on what is considered to be a GFMI.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 5 years
Open-ended Project: No

4.1.5.3. AI in IBRs control

AI can be used to address a number of problems associated with inverter-dominated grids. AI can map non-linear relationships with great accuracy and learn from data obtained from real-time measurements or detailed simulations. In the past few years, AI has been applied to a variety of problems for grid-connected inverters, such as control of inverters, selecting adaptive inertia for VSG control strategies, stability region determination for networks dominated by IBRs, and low-frequency modulation. Reported advantages include improved reference tracking, reduced total harmonic distortion and robustness against grid-impedance variations. As the NEM transitions from a synchronous generator–dominated grid to a mixture of IBRs and synchronous generators, the system inertia will be reduced. This issue can be addressed by employing the VSG control technique for power converters to mimic the inertial response of synchronous generators. With IBRs, this parameter can be altered in real-time to provide the 'optimal' inertia constant for the current condition of the network. To this end, artificial neural networks can be used to adaptively tune the inertia constant, with the aim of enhancing frequency stability against disturbances in the presence of various GFMIs and GFLIs. This can enhance the transient stability under large faults in IBR-dominated grids. Further, these artificial neural networks could be extended to consider other control parameters, with the aim of identifying the optimal set of parameters to ensure frequency stability against disturbances.

Deliverables: 1) A report on different opportunities identified for AI in IBR control, 2) the model of the plant identified from neural networks, 3) control techniques based on neural networks.
Required Data: Data from the network for identification and control, EMT model of the grid
Associated Risks: Managing large amounts of data
Resources: 2 junior researchers and 1 senior researcher
Timeframe Estimation: 3 years
Priority: Next 10 years
Open-ended Project: Yes

4.2. Shared Tasks and Links with Other Australian G-PST Research Plans

The full Australian G-PST research program includes nine topics as follows:

- Topic 1: Inverter Design

- Topic 2: Stability Tools
- Topic 3: Future Control Rooms
- Topic 4: Planning
- Topic 5: Restoration and Black Start
- Topic 6: Services
- Topic 7: Architecture
- Topic 8: DER
- Topic 8+2: DER + stability tools

The following links between Topic 1 and Topics 2, 3, 5, 6 and 8+2 have been identified (see Figure 4). The tasks pertaining to these identified links are elaborated in this section.

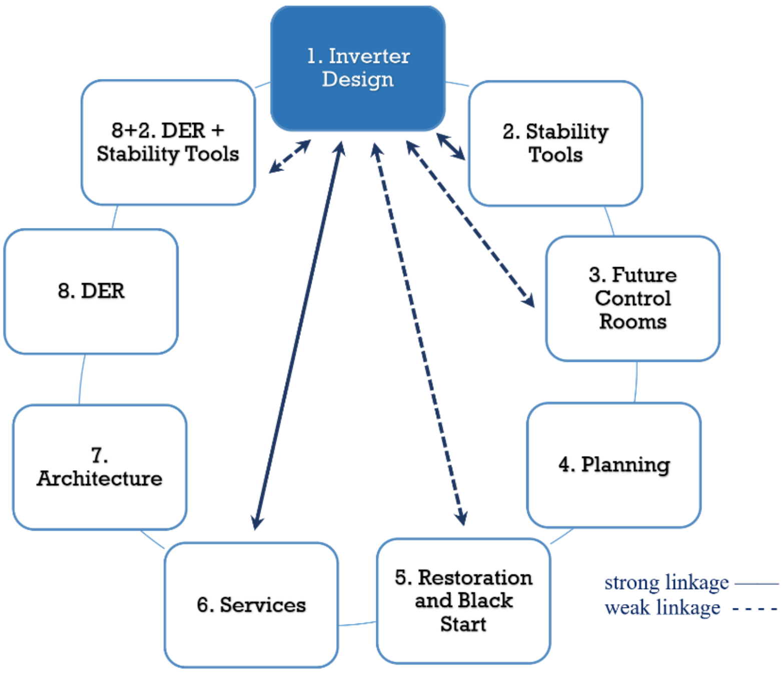

Figure 4. Links between 'Inverter Design' and the other Australian G-PST research programs.

4.2.1. Shared Tasks with Topic 2: Stability Tools

The topics of IBR Inverter Design and Stability Tools are inherently interlinked and coupled with each other. In order to adequately design and parameterise the IBR control system, it is important to not only have visibility of the stability and performance of the control topology from a single machine infinite bus perspective but also to have visibility on the stability and performance in a larger system with multiple IBRs. The efficient design of the inverters can be carried out using this information as feedback. Simultaneously, any stability tools designed and developed from a system planner/operator perspective can only provide sufficient results if it has a fair representation of the dynamic characteristics of the individual IBRs, which themselves depend on the design and control structure. Thus, this closed-loop relationship is to be kept in mind for each Task/Topic discussed in the research roadmaps of both Topic 1 and Topic 2. Considering the role IBRs play in the NEM, researchers, network operators and OEMs can clearly benefit from the outputs of these topics to upgrade the grids to host more renewable energy while they can have a better understanding of the grid stability status.

- Required from Topic 2: Specification of requirements of IBR models for use in system stability tools
- Desired from Topic 2: Knowledge of key behavioural characteristics of IBRs that impact system stability
- Required for Topic 2: IBR mathematical models that can be used in system stability tools developed in Topic 2
- Desired for Topic 2: IBR software models that can be used in system stability tools developed in Topic 2

Corresponding CSIRO Research Questions: Q2, Q5, Q8, Q9
Corresponding Monash/Stakeholders Questions: R11, R20, R21, R22, R23, R24, R25, R32, R35, R41
Leading Australian Universities: University of Adelaide
Expertise in Australia: Limited
Stakeholders for Collaboration: AEMO, TNSPs, OEMs
International Researchers for Collaboration: Prof. Mario Paolone - EPFL, Prof. Jean Mahseredjian - École Polytechnique de Montréal, Jean Bélanger - Opal RT, Deepak Ramasubramanian - EPRI.

4.2.1.1. Implementation of efficient simulation tools

The frequencies of interest are typically low in synchronous generator–dominated networks. Therefore, the dynamics in a synchronous machine–dominated network are generally analysed using root mean square (RMS)-based simulation platforms (e.g., PSS/E). Since IBRs introduce much faster dynamics to the system, electromagnetic transient (EMT)-based simulation platforms are typically preferred to simulate IBR-dominated networks. However, EMT-based simulations become computationally intensive as the network gets larger and the number of IBRs increases. Therefore, developing computationally less intensive yet accurate simulation tools is needed for simulating large-scale IBR-dominated grids.

Alternatively, several novel simulation techniques (e.g., dynamic phasor-based methods) have been proposed in the literature as less computationally intensive than EMT-based simulation but more accurate than RMS-based methods for dynamic studies of IBR-dominated networks. Developing novel simulation tools based on these simulation techniques is the suggested focus in this research plan.

On the other hand, real-time simulators equipped with higher computational power than standard desktop PCs can be used as an alternative solution to simulate bulk IBR-dominated grids. In this regard, standard yet efficient procedures for employing real-time simulators for simulation of bulk IBR-dominated grids for various studies need to be developed. It is noteworthy that real-time simulators can facilitate hardware-in-the-loop (HIL) experiments. Thus, actual IBRs can be connected to real-time simulators to assess their performance and stability.

Deliverables: 1) Novel simulation techniques (e.g., dynamic phasor-based methods) with less computational burden in comparison with EMT-based simulation but more accurate than RMS-based methods for dynamic studies of IBR-dominated networks, 2) Novel simulation tools based on the novel developed simulation techniques, 3) Standard yet efficient procedures for employing real-time

simulators for simulation of bulk IBR-dominated grids for various studies, 4) Standard yet efficient procedures for employing real-time simulators for assessing the performance and stability of actual IBRs via HIL experiments.
Required Data: N/A.
Associated Risks: Inability to derive the aforementioned simulation technique.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 5 years
Open-ended Project: Yes

4.2.1.2. Determination of the best level of modelling detail for different phenomena in IBR-dominated grids

Compared to synchronous generator–dominated power systems, the frequencies of interest pertinent to crucial dynamics in IBR-dominated networks are higher due to the nature of IBRs. Therefore, it becomes an arduous exercise to model all the dynamics in IBR-dominated bulk power systems. Instead, it may be efficient to model the system to a certain required level of detail to help study only the phenomenon of interest. This requires identifying the possible phenomena in IBR-dominated grids and determining the appropriate level of detail such that it is computationally efficient while accurately modelling the dominant dynamics.

Alternatively, several model reduction methods (e.g., slow coherency and modal-based methods) in the literature can be used to reduce the system order and computational burden to a great extent. However, these methods have mainly been developed for synchronous generator–dominated bulk grids. Therefore, it is necessary to investigate approaches to expand these methods for IBR-dominated grids.

On the other hand, as the network grows, if the focus of a study is only on one part of the network, it may be effective to investigate that part in detail while modelling the other parts of the network at a different level of detail to reduce the computational complexity. However, this must not lead to inaccuracy or oversimplifying crucial dynamics that are of interest. Therefore, there is a need for more study in this area.

Deliverables: 1) A detailed report about the best level of IBR modelling details for various studies, 2) Appropriate model reduction method for reducing the IBR-dominated grid model with various IBR penetration levels, 3) Reduced-order grid model including the aggregated models of IBRs.
Required Data: EMT model of the grid, projected IBR penetration levels, IBRs dynamic models.
Associated Risks: Inability to access the EMT model of the grid, inability to access the IBRs dynamic models, inability to perform the modal analysis due to the computational burden of simulating an ultra-high order system.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 5 years
Open-ended Project: Yes

4.2.2. Shared Tasks with Topic 3: Future Control Rooms

The increasing role of IBRs in IBR-dominated grids creates a very complex control challenge for grid operators, and there will be a tremendous number of variables that need to be observed at faster rates. Control rooms are at the core of all efforts to monitor these data and maintain the system operational requirements in the face of shifting power system conditions. Moreover, as the grid becomes more dynamic and stochastic, a control room must be capable of collecting, processing and reacting to significantly more information and higher volumes of data than ever before. There is another topic (Topic 3: Future Control Rooms) dedicated to these issues, which are outside the scope of this research plan. Currently, this research plan assumes that all the issues regarding the collection, processing and transmission of the data required for the tasks around inverter design are already managed by the outcomes of Topic 3, and the required data are accessible by the upgraded control rooms. However, there are still some issues that can be studied in terms of shared tasks between topics 1 and 3. Since the provision of frequency stability services (discussed in Major Task 1) are highly dependent on the accuracy and availability of the system frequency indices (within the scope of topic 3), providing new measuring and monitoring systems for frequency and RoCoF is one of these shared tasks. As further discussed in this section, the performance of measuring frequency stability indices degrades in weak-grid conditions and solutions are required for this. It is worth mentioning that these solutions are beneficial for the Australian context, as there are several weak spots in the NEM, and the provided solutions can be employed by the Australian grid operators to have better observability on the frequency stability indices.

Corresponding CSIRO Research Questions: -
Corresponding Monash/Stakeholders Questions: R7, R20
Leading Australian Universities: Monash University
Expertise in Australia: Limited
Stakeholders for Collaboration: SO, DNSPs, TNSPs
International Researchers for Collaboration: Prof. Mario Paolone - EPFL, Prof. Federico E. Milano - University College Dublin, Adrian Kelly - EPRI.

4.2.2.1. New measuring and monitoring systems for frequency and RoCoF

Since inertia decreases as IBR penetration increases, the time left for activation and deployment of FFR and synthetic inertia reduces significantly. Services such as FFR and synthetic inertia depend heavily on the measured frequency indices of the grid, such as frequency and RoCoF. Therefore, the accuracy and availability of the measurements are extremely important for the successful deployment of these services. Typically, frequency and RoCoF are measured using PLLs or frequency-lock loops. Successful operation and deployment of FFR and synthetic inertia could be negatively affected as the performance of PLLs degrade in certain grid conditions (e.g., weak grids) and due to the noisy nature of RoCoF. In synchronous generator–dominated grids, more sophisticated methods such as fast Fourier transform, which are used in PMUs, have shown promising results in terms of accuracy of frequency and RoCoF measurements. However, in their current form, these methods are computationally intensive, and their applicability to IBR-dominated grids is limited. Highly accurate and noise-free yet computationally efficient method development for frequency and RoCoF measurement could significantly increase the performance of FFR and synthetic inertia services.

Therefore, further studies on the development of new measuring and monitoring methods for frequency and RoCoF are required.

Deliverables: 1) Highly accurate and noise-free yet computationally efficient method development for frequency and RoCoF measurement of IBRs.
Required Data: N/A.
Associated Risks: Insufficiency of the communication links speed/bandwidth utilized for sending the measured data.
Resources: 1 junior researcher
Timeframe Estimation: 2 years
Priority: Urgent
Open-ended Project: No

4.2.3. Shared Tasks with Topic 5: Restoration and Black Start

Any power system carries the risk of blackouts. Therefore, proper measures should be in place to restore the system to normal if a blackout occurs. In conventional power systems, black start and restoration activities are primarily based on synchronous power plants. However, as IBR penetration increases, the IBRs must be integrated into the black start and restoration plans. The 2016 South Australia blackout highlighted the importance of investigating the involvement of IBRs in assisting black start and restoration activities in future IBR-dominated grids.

Corresponding CSIRO Research Questions: Q3
Corresponding Monash/Stakeholders Questions: R10, R33, R36
Leading Australian Universities/Companies: Monash University, and University of New South Wales. Aurecon
Expertise in Australia: Limited
Stakeholders for Collaboration: SO, TNSP, DNSP
International Researchers for Collaboration: Prof. Federico Milano - University College Dublin, Prof. Tim Green - Imperial College, Prof. Xiongfei Wang - Aalborg University, Prof. Florian Dörfler - ETHZ

4.2.3.1. IBR control for black start and restoration

Black start and system restoration schemes in conventional power systems are primarily based on synchronous machines. As conventional power grids transform into IBR-dominated power grids, black start and system restoration activities must be performed by IBRs. GFMIs operate as controllable voltage sources, being able to dynamically control the voltage magnitude and phase angle of the point of common coupling. Therefore, GFMIs can be used to energise the grid. Typically, sequential hard switching and soft start are the two main approaches used to energise the system. The energisation of transformers using hard switching draws a large inrush current causing a dip in the voltage. Further, charging long, lightly loaded transmission lines with open ends causes an overvoltage due to the Ferranti effect. In addition, low-order harmonic resonance can occur due to the insufficient loads and generators available for damping. Advanced methods such as point-on-wave switching, delayed closing strategy, Smart Energize, and pre-fluxing can be used to limit the inrush current.

On the other hand, soft-switching starts the restoration process from a low voltage level and smoothly ramps up to energise the network. The HVDC links with soft start capability have been shown to limit the inrush currents, avoid transient overvoltages, and reduce the risk of system re-collapse. Therefore, HVDC-connected offshore wind farms equipped with GFMI technology could be promising for black start operations in IBR-dominated networks. However, excessive soft starting could lead to transformers being improperly energised due to insufficient overcurrent. Consequently, the risk of system re-collapse increases due to the high total harmonic distortion and unintended protection relay operations. Therefore, black start and system restoration activities using GFMIs must be properly investigated.

Not all types of IBRs are suitable for black start operation. For example, GFLIs are not suitable for black start operations as GFLIs require a healthy grid for stable operation. GFLIs use a synchronisation mechanism (e.g., PLL) to track the phase angle of the grid voltage and dynamically adjust the phase angle of terminal voltage to inject the required current. Once the grid voltage is established, GFLIs could be used in system restore activities to bring the system back to normal. Since the grid is not completely healthy during the restoration process, GFLI-based IBRs could be operating under completely different grid conditions to the nominal system their control systems are tuned to. This could lead to adverse effects on the IBRs, system and restoration process. Therefore, how GFLIs can be used in the restoration process must be investigated. Subsequently, the effects of the control parameters of GFLIs operating in extreme conditions such as the system restoration process must be identified. Finally, the control systems in GFLIs must be tuned to aid the restoration process.

Deliverables: 1) Different technologies with grid-forming capabilities that are capable of black starting the system, 2) Control design of GFMIs to assist black start operations, 3) A detailed report on the implications of integrating GFLIs for the restoration process, 4) Robust control strategies for GFLIs to operate securely in extreme operating conditions.
Required Data: EMT model of the grid
Associated Risks:
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 years
Priority: Next 5 years
Open-ended Project: Yes

4.2.4. Shared Tasks with Topic 6: Services

Replacement of conventional synchronous generators with IBRs requires that several services provided by these rotating machines be provided by IBRs. These services include frequency support (e.g., inertia and FFR provision) and VAR/Volt support, which were elaborated on earlier in corresponding major tasks. Several other aspects and services are within the scope of the other G-PST research group working on Topic 6 and outside the scope of topic 1. However, some special services can be studied in terms of shared tasks between topics 1 and 6. Fast response voltage control is one of the special services that IBRs are supposed to provide in an IBR-dominated power system. IBRs connected to the weak spots of the grid encounter challenges in the provision of fast response voltage control services and satisfying some of the voltage requirements of the grid codes. Therefore, it is necessary to devise solutions for this issue. The growing share of IBRs in the NEM and the NEM's long and stringy structure means the number of weak spots in the NEM is increasing. Therefore, Australia can clearly benefit from this task by addressing this issue.

Corresponding CSIRO Research Questions: Q1, Q4, Q5, Q6
Corresponding Monash/Stakeholders Questions: R1, R3, R4, R5, R13, R30, R31, R39, R40
Leading Australian Universities: Monash University, RMIT, University of Queensland, and University of New South Wales, University of Tasmania
Expertise in Australia: Adequate
Stakeholders for Collaboration: SO, TNSP, DNSP
International Researchers for Collaboration: Prof. Federico Milano - University College Dublin, Prof. Tim Green - Imperial College, Prof. Xiongfei Wang - Aalborg University, Prof. Frede Blaabjerg - Aalborg University, Prof. Florian Dörfler - ETHZ

4.2.4.1. Fast response voltage control in IBR-dominated power systems

In an IBR-dominated power system, IBRs are responsible for providing several services for the grid to keep the voltage within operational limits. Fast response voltage control, as stated in the grid codes, is one of these services, which provides rapid adjustments in reactive power to support voltage stability during and after system disturbances. Adequate reactive reserves also need to be maintained to ensure the security of the transmission system. Nonetheless, in low-strength spots of IBR-dominated grids and for some types of IBR resources, it is sometimes too challenging to satisfy these VAR requirements of the grid codes. Employing IBRs with grid-forming capability is a promising solution for these conditions since they can emulate the behaviour of conventional synchronous generators in several aspects. However, since IBRs are intrinsically incapable of withstanding overcurrents even for a short period of time, they cannot directly mimic all the VAR capabilities of synchronous generators. Noting that IBRs are potentially more flexible than synchronous generators, devising novel fast response voltage control schemes for IBRs connected to low-strength spots in an IBR-dominated grid is a research topic requiring further attention. It is also worth mentioning that several original equipment manufacturers have requested a grid code upgrade, especially to update the requirements regarding fast response voltage control service in IBR-dominated grids. This may be considered a complementary part of this task but is outside the scope of this research plan and not elaborated on here.

Deliverables: 1) Novel fast response voltage control schemes for IBRs connected to low-strength spots in an IBR-dominated grid in order to satisfy the VAR requirements of the grid codes.
Required Data: N/A.
Associated Risks: Intrinsic limits of IBRs in terms of required VAR capabilities.
Resources: 1 junior researcher and 1 senior researcher
Timeframe Estimation: 2 year
Priority: Urgent
Open-ended Project: No

4.2.5. Shared Tasks with Topic 8+2: DER & Stability Tools

The distribution networks are currently being flooded with an unprecedented number of IBRs, including residential photovoltaic (PV) inverters (some equipped with batteries), electric vehicles (EVs) chargers and community batteries, which are typically categorised as DERs. If coordinated, DERs can influence transmission networks and assist with frequency control at the transmission level. Distributed PV systems in Australia are already influencing the frequency stability in the NEM. For example, subsequent to a voltage dip caused by a credible contingency in the network, distributed PV systems could get disconnected from the grid, increasing the contingency size, leading to more severe frequency excursion.

As distributed IBR penetration increases, the aggregated response of distributed IBRs becomes significant. To this end, concepts such as virtual power plants have emerged. The primary objective of virtual power plants is to control and coordinate a network of distributed IBRs to emulate a power plant. In Australia, AGL has already launched a program to coordinate behind-the-meter solar batteries. However, as IBR penetration increases, the effects of aggregated responses of distributed IBRs on the transmission network must be investigated. The following task is designed to investigate the effects of DER on the transmission system.

Corresponding CSIRO Research Questions: -
Corresponding Monash/Stakeholders Questions: R12
Leading Australian Universities: Monash University, University of New South Wales, and University of Melbourne
Expertise in Australia: Adequate
Stakeholders for Collaboration: SO, TNSP, DNSP
International Researchers for Collaboration: Prof. Joseph Guerrero - Aalborg University, Prof. Mario Paolone - EPFL, Prof. Mahmud Fotuhi-Firuzabad - Sharif University of Technology, Prof. Mohammad Shahidehpour - Illinois Institute of Technology

4.2.5.1. Effects of a high level of DERs on the transmission system

One particularly important type of DER that can have a significant effect on transmission networks is EVs. EVs are equipped with relatively large batteries (often above 30 kWh) that, if coordinated and controlled appropriately, can have a combined significant effect on the transmission level. Additionally, an increasing number of residential PV systems are being equipped with BESSs. However, EV chargers and most other DERs operate based on grid-following control, which means they typically cannot provide grid support services such as voltage/frequency control and system strength. One possible approach could be operating such assets (EV chargers in particular) with grid-forming control to assist with system strength issues and frequency/voltage control. This task will investigate how distribution-level assets can be equipped with control strategies that can support frequency and voltage control at both the distribution and transmission levels. This will lead to distribution and transmission grid resilience and reliability enhancement with minimal changes in the low-voltage distribution feeders.

Deliverables: 1) Coordinated control of EVs, 2) Grid-forming control strategies for EVs, 3) Control strategies for distributed level assets to provide frequency and voltage support to the transmission grid.

Required Data: EMT model of the transmission grid, EMT model of the distribution grid, dynamic models of EVs

Associated Risks: Difficulty in integrating transmission and distribution level models, extremely large size of the combined model of the transmission and distribution grid, inability to access powerful computers to run the computationally heavy models.

Resources: 1 junior researcher and 1 senior researcher

Timeframe Estimation: 2 years

Priority: Next 5 years

Open-ended Project: Yes

4.3. Priorities, Types, Resources, Deliverables, and Timelines Estimation

The suggested priorities, types, resources required, deliverables and time frames to complete the sub-tasks are given in Table 2. Please note that these are just rough estimates.

Table 2. Priority, types, resources, deliverables and timelines for the subtasks

Major Task/ Shared Task	Subtask	Priority	Open-ended	Resources*	Time-frame	Deliverables
Frequency Stability	Defining the response of GFLIs and GFMIs for a credible contingency	Urgent	No	1 JR & 1 SR	2 years	1) A detailed report of potential risks associated with different IBRs penetration levels that can cause frequency instability 2) A detailed analysis on the consequences of violating the existing frequency operating standards, and assessment of the appropriate frequency ranges of operation for different IBRs penetration levels 3) Required response from GFLIs and GFMIs (such as FFR, virtual inertia) based on the IBR penetration level and associated risks 4) Control strategies that deliver the required performance from GFLIs and GFMIs and their design.
	Control of ESS based on the capability of the energy source to provide various frequency services	Next 5 years	No	1 JR & 1 SR	2 years	1) A report that outlines the capabilities and economic viability of various existing and emerging ESSs and hybrid ESSs that can partake in frequency control 2) A study of the response expected from each of such ESSs or a combination of them as hybrid ESSs 3) Control strategies for each type of ESS and hybrid ESS such that their coordinated control can result in seamless recovery of the frequency upon each contingency.
	Coordinated/distributed control of BESSs for frequency control	Next 10 years	No	1 JR & 1 SR	2 years	1) Multi-input multi-output model of the system derived from PMU measurements 2) Distributed FFR control strategies based on wide area measurement systems.

Voltage Stability	Investigation of IBR reactive power provision capabilities against the backdrop of losing synchronous machines	Next 5 years	Yes	1 SR	2 years	1) A detailed report about effects of internal networks of various IBR farms on their overall static VAR capability 2) A detailed report about effects of internal networks of various IBR farms on their overall dynamic VAR capability during and after faults, especially in the period of transient voltage recovery 3) A detailed report about effects of intermittency of the energy resources on the farm static and dynamic VAR capabilities 4) Static VAR planning of the grid with high penetration of IBRs (coordinated reactive power control, autonomous reactive power control, etc.) 5) Dynamic VAR support schemes for IBRs to be used during and subsequent to faults in the IBR-dominated grids
	Interactions between synchronous machine AVR, GFMI AVR and GFLI in providing reactive power support	Urgent	No	1 JR	3 years	1) Scenarios, in which the fast response of an IBR AVR results in instability/interaction with other equipment in the grid 2) Necessary conditions (in terms of the IBRs penetration ratio, grid strength, AVR parameters, etc.) for the instability/interaction 3) A method or process for wide-area control system tuning to avoid the instability/interaction.
Interaction Mitigation and Oscillation Damping	Identifying the nature of oscillations in IBR-dominated grids	Urgent	No	2 JRs & 1 SR	3 years	1) Low-order yet accurate dynamic models for the IBRs connected to the grid 2) Dynamic model of the grid in presence of the identified IBRs' dynamic models 3) Modal analysis results for scenarios with various penetration ratios of IBRs in the grid 4) Identified sensitive dynamic modes, their frequency ranges and their damping ratios 5) Identified state variables and system components with greater participation factors in the sensitive modes 6) A detailed report about effects of IBRs penetration ratio on the sensitive dynamic modes 7) A detailed report about the ways the identified sensitive modes are stimulated
	Standardising the models of IBRs	Urgent	Yes	1 JR & 1 SR	3 years	1) Standard IBR models
	Modelling, analysis, control and coordination of IBRs for oscillation damping	Urgent	No	2 JRs & 1 SRs	3 years	1) Dynamic models of the grid-connected IBRs including the mechanical/chemical dynamics of IBRs energy source components 2) Dynamic model of the grid in presence of the IBRs' dynamic models

						3) Scenarios with stimulated poorly-damped inter-area modes 4) IBRs participate in the poorly-damped inter-area modes for various operating conditions 5) IBRs coordinated tuning methods/redesigning procedures for increasing the damping of the poorly-damped inter-area modes
Protection and Reliability	IBRs effect on existing protection systems	Next 5 years	Yes	1 JRs & 1 SR	3 years	1) IBRs (GFLIs and GFMIs) fault current level during and subsequent to faults (single line to ground, line to line, double line to ground, three-phase to ground) 2) A detailed report about effects of IBRs (GFLIs and GFMIs) control parameters on the IBRs fault current 3) A detailed report about effects of various control strategies (including control-level overcurrent limitations) on the IBRs fault current 4) A detailed report showing maloperation of various protection schemes/devices (overcurrent relays, distance relays, differential relays, etc.) under the identified fault currents of the IBRs 5) Innovative mechanisms in the control of IBRs to enable them to work in harmony with various protection schemes/devices
	Enhancing IBR response during and subsequent to faults	Urgent	No	1 JR & 1 SR	3 years	1) Simulation models for IBRs under various fault conditions 2) Amount of fault currents (positive and negative sequences) should be sourced during various fault conditions by IBRs 3) Guidelines and standards to clarify the zero and negative sequence currents injected by IBRs 4) New control schemes for implementing zero and negative sequence injection requirements for GFLIs in IBR-dominated grids during various grid faults 5) New control schemes for implementing zero and negative sequence injection requirements for GFMIs in IBR-dominated grids during various grid faults 6) A detailed report about reasons for the oscillatory behaviour of GFMIs when recover from faults 7) A detailed report about solutions for the oscillatory behaviour of GFMIs when recover from faults
	Assessment and enhancement of IBRs reliability	Next 10 years	Yes	1 JRs & 1 SR	3 years	1) Novel lifetime models for IBRs in the IBR-dominated networks 2) Reliability evaluation techniques based on the developed IBRs lifetime models for enhancing the reliability of IBR-dominated grids via considering device-level to system-level phenomena.

	Cyber-secure inverter design for grid-connected applications	Next 5 years	Yes	1 JR & 1 SR	3 years	1) A report that identifies the assets related to IBRs that are vulnerable to cyber attacks 2) Cyber-physical models based on emerging technologies such as blockchain technology 3) Cyber shields to protect sensor measurements, and 4) IBRs immune to cyber attacks.
Trending Topics	Developing alternative control methodologies for GFMIs	Next 5 years	Yes	2 JRs & 2 SRs	3 years	1) Shortcomings of modelling GFMIs based on synchronous machines 2) Grid-forming control strategies to circumvent the issues identified.
	Grid-forming capability for HVDC stations and wind and solar farms	Next 5 years	No	1 JR & 1 SR	2 years	1)Grid-forming inverter control strategies for RES-generators such as wind, solar and HVDC links.
	AI in IBRs control	Next 10 years	Yes	2 JRs & 1 SR	3 years	1) A report on different opportunities identified for AI in IBR control 2) The model of the plant identified from neural networks 3) Control techniques based on neural networks.
with Topic 2: Stability Tools	Implementation of efficient simulation tools	Next 5 years	Yes	1 JR & 1 SR	2 years	1) Novel simulation techniques (e.g., dynamic phasor-based methods) with less computational burden in comparison with EMT-based simulation but more accurate than RMS-based methods for dynamic studies of IBR-dominated networks 2) Novel simulation tools based on the novel developed simulation techniques 3) Standard yet efficient procedures for employing real-time simulators for simulation of bulk IBR-dominated grids for various studies 4) Standard yet efficient procedures for employing real-time simulators for assessing the performance and stability of actual IBRs via HIL experiments.
	Determination of the best level of modelling detail for different phenomena in IBR-dominated grids	Next 5 years	Yes	1 JR & 1 SR	2 years	1) A detailed report about the best level of IBR modelling details for various studies 2) Appropriate model reduction method for reducing the IBR-dominated grid model with various IBR penetration levels 3) Reduced-order grid model including the aggregated models of IBRs
with Topic 3: Future Control Rooms	New measuring and monitoring systems for frequency and RoCoF	Urgent	No	1 JR	2 years	1) Highly accurate and noise-free yet computationally efficient method development for frequency and RoCoF measurement of IBRs

with Topic 5: Restoration and Black Start	IBR control for black start and restoration	Next 5 years	Yes	1 JR & 1 SR	2 years	1) Different technologies with grid-forming capabilities that are capable of black starting the system 2) Control design of GFMIs to assist black start operations 3) A detailed report on the implications of integrating GFLIs for the restoration process 4) Robust control strategies for GFLIs to operate securely in extreme operating conditions.
with Topic 6: Services	Fast response voltage control in IBR-dominated power systems	Urgent	No	1 JR & 1 SR	1 year	1) Novel fast response voltage control schemes for IBRs connected to low-strength spots in an IBR-dominated grid in order to satisfy the VAR requirements of the grid codes
with Topic 8+2: DER & Stability Tools	Effects of a high level of DERs on the transmission system	Next 5 years	Yes	1 JR & 1 SR	2 years	1) Coordinated control of EVs 2) Grid-forming control strategies for EVs 3) Control strategies for distributed level assets to provide frequency and voltage support to the transmission grid.

*JR: Junior Research, SR: Senior Researcher

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Appendix

Appendix A – CSIRO Questions

Table 3. Research questions provided by CSIRO

Research Question*	Keywords**	Related Tasks***
(Q1) For each potential service: how feasible is it to provide from IBR, what "cost" does it add and what limitations exist on its magnitude and duration of service? What implications do these have for system operations? (G-PST Q2)	Services	ST6
(Q2) What design standards should be introduced to avoid instability (e.g., caused by phase-locked loop or other elements) in weak grids? (G-PST Q4: ...This is a more widely drawn version of the question on minimum ratios of grid-forming to grid-following inverters.)	Stability, Control design, Weak grids	MT3, MT5, ST2
(Q3) At what point is it better to break from trying to replicate synchronous machine features and exploit the wider flexibility of inverters? (G-PST Q11)	GFMI, Control design	MT5, ST5
(Q4) What are the appropriate inverter capabilities and, consequently, control design methods for operation in grids with high percentage of IBR? (G-PST Q5: ...Are standard configurations and combination of services helpful in simplifying operational decision making?)	Control design, Capabilities	MT1, MT2, MT3, MT5, ST6
(Q5) How can IBR capabilities be integrated into operations to leverage power system stability? (G-PST Q1: What are the needs for a power system (to achieve security and good regulation) expressed in technology neutral form and how do these needs map to services that any resource, including IBR or synchronous machine, can provide?)	Stability, Capabilities	MT2, ST2, ST6
(Q6) What are the limitations of each IBR technology option to provide frequency control and virtual inertia? (G-PST Q3: ...and how do the various frequency services overlap and compete?)	Frequency control	MT1, ST6
(Q7) What is the future of frequency control as the synchronous generation fraction reduces? Might tightened or loosened frequency limits lead to a more reliable, secure, lower cost IBR-based power system? (G-PST Q10)	Frequency control	MT1
(Q8) Are the impedance-spectrum models favoured by manufacturers for disclosure sufficient for stability assurance and system design across all problem types? (G-PST Q6: Are the black-box models(impedance-spectrum and binary code) favoured by manufacturers...)	Modelling, Stability, Control design	MT3, ST2

(Q9) What recommendations should be made for standard behaviours of IBR in certain frequency ranges for different power system conditions to aid system design? (G-PST Q7: ...For example, should a contribution to damping be mandatory at certain frequencies?)	Modelling	MT3, ST2
(Q10) How will protection systems need to change to accommodate high penetrations of IBR and what possible actions might an inverter take during a fault that would aid fault detection and location? (G-PST Q9)	Protection, Fault handling	MT4
(Q11) What impedance requirements should be placed on IBR to suppress negative-sequence and low order harmonic currents? (G-PST Q8)	Protection, Power quality	MT4

* Corresponding G-PST question numbers and their explanations are included in round brackets.

**In the keyword list, 'Stability' excludes Frequency stability and 'Services' excludes Frequency services.

***MT: Major Task, ST: Shared Task.

Appendix B – Stakeholders Questions and Monash University Team Reflections

Table 4. Research questions based on stakeholder concerns and Monash University team reflections

Research Question	Keywords	Links to CSIRO Questions	Related Tasks
(R1) In terms of frequency stability, how to design inverter control systems to act on contingencies that happen in a long stringy network like Australia?	Control design, Frequency control, Weak grids	Q2, Q3, Q4, Q6, Q7	MT1, ST6
(R2) In an IBR dominated grid, what are the appropriate frequency ranges the grid can operate at? In what type of contingencies we can exceed these ranges?	Frequency control	Q6, Q7	MT1
(R3) How/To what extent can IBR play roles in the provision of frequency services like FFR and primary frequency response?	Frequency control, Services	Q1, Q6, Q7	MT1, ST6
(R4) Is it really necessary for the frequency control to be as complex as it is right now in a 100% IBR network? What would be the role of FFR, GFMIs and new control schemes?	Frequency control, GFMI, Control design	Q2, Q3, Q4, Q6, Q7	MT1, ST6
(R5) In a high IBR-dominated system, which types of events can give rise to frequency stability issues? How does the frequency behave during contingencies? If all the IBRs in different levels respond to a significant outage, what would be the response and the cost?	Frequency control, Services	Q1, Q6, Q7	MT1, ST6
(R6) What is the optimum frequency deadband (if there should be any) in an IBR dominated grid? Do tighter frequency limits increase the control interactions? How should the generators operate within and outside frequencies bands the grid can operate at?	Frequency control	Q6, Q7	MT1
(R7) How can we provide new measurements and monitoring techniques for frequency and RoCoF measurement in IBR-dominated grids?	Frequency control	Q6, Q7	MT1, ST3
(R8) What technologies would be the best to serve as bulk energy storage systems in IBR-dominated grids? Do they need any special control structures to make them participate more efficiently in the frequency response of the system? What mixture of these storage systems should be adopted to best serve the needs of the system?	Capabilities, Control design, Frequency control	Q2, Q3, Q4, Q5, Q6, Q7	MT1, MT5

(R9) How to employ ESSs more efficiently to compensate for the stochastic nature of IBR resources? Can ESS be utilised like STATCOM to provide voltage support for the system?	Capabilities, Stability	Q4, Q5, Q2, Q5, Q8	MT1, MT2
(R10) How to plan/allocate/design/control/coordinate ESSs to make the power system more resilient? Is it a valid suggestion to have centralised BESSs? How to locate the centralised BESSs?	Frequency control, Capabilities, Stability, Services, GFMI	Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8	MT1, ST5
(R11) How to control ESSs to reduce the inter-area power flows in the system? How to coordinate multiple ESSs to counteract the inter-area angle instability?	Stability, modelling, Control design	Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9	MT3, ST2
(R12) What should be the best response of ESSs at different levels (residential, transmission, etc.) to make sure the stability is preserved in the whole system? What is the optimal method to unlock the potential of residential ESS (utilising local measurements, sub-second communication links, etc.) to support the grid?	Frequency control, Stability	Q2, Q5, Q6, Q7, Q8	MT1, MT2, ST8+2
(R13) Considering the ESS capabilities, how can a faster algorithm than Automatic Generation Control (between autonomous and 5 min) be employed to help the overall system frequency control? What are the implications of making the dispatch time frame 1 minute instead of the current 5 minutes?	Frequency control, Capabilities	Q4, Q5, Q6, Q7	MT1, ST6
(R14) In an IBR-dominated grid, how to optimally control the voltage at different voltage levels? Can we utilise centralised voltage control systems for IBRs? How can the fast voltage recovery capability of IBRs be used for improving the system voltage stability?	Stability, Control design	Q2, Q3, Q4, Q5, Q8,	MT2
(R15) In weak grids, how can we decouple voltage and frequency control? How can IBR be optimally controlled to inject power while regulating the voltage? How to design an IBR control system so that it is robust to severe voltage disturbances?	Weak grids, Stability, Fault handling, Control design	Q2, Q3, Q4, Q5, Q8, Q10	MT2
(R16) In an IBR dominated system, how should an IBR ride through a fault? How/which IBRs should provide the disturbance rejection capability for the system? How should the IBRs control mechanisms be designed so that they can contribute to different faults with different locations and types?	Fault handling, Control design, Protection	Q2, Q3, Q4, Q10, Q11	MT4
(R17) In terms of coordination between several IBRs, what is the best practice to recover the active power injections of IBRs?	Stability, Control design	Q2, Q3, Q4, Q5, Q8	MT2
(R18) In an IBR dominated grid, what is the optimum reactive current percentage to inject during a fault considering the strength of the network?	Fault handling, Weak grids, Protection	Q2, Q10, Q11	MT4

(R19) In different scenarios, how much fault current is required to be supplied by the IBRs? How should IBRs participate in the negative sequence current provision of the system during and after faults?	Fault handling, Protection	Q10, Q11	MT4
(R20) How can the computational burden of modelling/simulations in a high IBR penetrated system be improved? What's the best level of detail for components modelling? What is the role of data science in future IBR dominated power systems?	Modelling	Q9	MT5, ST2, ST3
(R21) How can we share the information and standardise proprietary models of IBRs?	Modelling	Q9	ST2
(R22) How can we model the existing oscillations in the NEM accurately and computationally efficiently? Can we use simplified modelling techniques to indicate the possible control interactions and oscillations in IBR dominated systems? What are the scenarios where RMS simulation tools can be still used in IBR dominated grid studies?	Modelling	Q9	ST2
(R23) How can we perform Hardware-in-the-loop experiments for IBR dominated grids, and what are the consequent advantages?	Modelling	Q9	ST2
(R24) How would IBRs change the nature of oscillations in an IBR-dominated grid? How are the inter-area modes affected by introducing IBRs into the system? How network topology affects the results? How can we identify them? How can we provide enough active and reactive power oscillation damping for IBR dominated systems, especially when we are losing PSSs in the system?	Control design, Stability	Q2, Q3, Q4, Q5, Q8	MT3, MT5, ST2
(R25) As a function of network requirements and conditions (e.g. grid strength), how should IBR controllers be tuned in terms of required rise time and settling time?	Control design, Weak grids, Stability	Q2, Q3, Q4, Q5, Q8	MT2, MT3, MT5, ST2
(R26) What is the best way to detect and distinguish faults in a future IBR dominated grid, especially for the asymmetrical faults? Drawing experiences of other electrical domains, is there any potential for employing non-fundamental frequencies for the protection systems?	Protection, Fault handling	Q10, Q11	MT4
(R27) How should we coordinate the protection devices in IBR dominated grids? How can we characterise the fault response of IBRs with minimal changes to the current fault detection methods? How can distant relays be used in a 100% IBR dominated system?	Protection, Fault handling	Q10, Q11	MT4
(R28) In an IBR dominated grid, how can we design protection systems that would work in both normal conditions and faulted conditions resulting in several islands from the bulk power system?	Protection	Q10, Q11	MT4
(R29) How can we design a robust inverter with self-healing capabilities to minimise control interactions and also damp the oscillations?	Stability, Reliability, Protection, Self-healing		MT3, MT4

(R30) In an IBR dominated grid, what is the optimum percentage between the grid following inverters and the grid forming inverters?	Services	Q1	ST6
(R31) How do GFMIs and synchronous machines physically provide inertia for the system? What is the minimum inertia requirement in terms of keeping the frequency within the bounds? How much inertia should change during the operation of the grid? Currently, it is assumed it is constant, but could this be variable during the operation of the grid?	Frequency control, GFMI	Q3, Q6, Q7	MT1, MT5, ST6
(R32) In an IBR dominated grid, what is the level of impact on the small-signal stability from GFLs and GFMs? Will there be inter-area modes/ interplant modes in a GFMI dominated network? Is there a point where the majority of IBRs are GFMIs trying to fight with each other? What are the stability conditions of grid-forming inverters themselves?	GFMI, Stability	Q2, Q3, Q5, Q8	MT3, MT5, ST2
(R33) In an IBR dominated grid, how to determine where the grid-forming inverters are required? Do GFIMs need to emulate what the synchronous machines are doing? How can we retrofit the existing GFLI fleet with state-of-the-art GFMI technology? In terms of transmission networks, how can GFMIs play a role in the voltage stability of the system?	GFMI, Stability	Q2, Q3, Q5, Q8	MT2, MT5, ST5
(R34) How high penetration of IBRs can affect the techno-economic issues regarding the development of HVDC systems? What is the role of Multi-Terminal DC in a future IBR dominated network?	HVDC		MT5
(R35) In an IBR dominated grid, how can we conduct harmonic stability research? How much do the harmonic performance and power quality deteriorate as the IBR percentage increases? How can we improve the post fault harmonic performance?	Power quality	Q8	ST2
(R36) How to improve the system security/reliability/resiliency in IBR dominated grids? (In terms of allocation, etc.) How can we ensure the inverter is immune to cyber-attacks?	Reliability, Cyber security		MT4, ST5
(R37) How ambient temperature affects the IBRs stability, and how can it be improved?	Reliability		MT4
(R38) What social issues do we have to consider for approaching the 100% RES network? Is there any community constraint for ESS locations?	Social issues		MT5
(R39) What are the impacts of reducing inertia in small, isolated power systems like NEM? How can we arrest fast frequency falls in these grids? What would be the role of hydropower plants in 100% IBR penetrated systems? How grid operators can make up for the lost mechanical inertia in IBR dominated networks, especially in small, isolated power systems like NEM? How should virtual synthetic inertia be provided? How do services such as FFR and primary frequency response can be used to quantify inertia instead of as a physical parameter?	Frequency control, Weak grids	Q2, Q6, Q7	MT1, ST6
(R40) In an IBR dominated grid, what is the best economic model for modifying the frequency hierarchy control? How can we optimise energy and frequency control simultaneously in IBR dominated grids?	Frequency control	Q6, Q7	MT1, ST6

(R41) What behaviours are expected from IBRs in case of contingencies, especially in more sensitive grids? How to define the strength of the system by taking the interactions of IBRs into account instead of a single number based on the impedance?	Services, Weak grids	Q1, Q2	MT3, ST2

Appendix C – Research Questions Classification

Table 5. Classification of research questions: CSIRO questions and questions based on stakeholder concerns and Monash University team reflections

Keywords	CSIRO Questions	Stakeholders Questions and Monash University Team Reflections
Capabilities	Q4, Q5	R8, R9, R10, R13
Control design	Q2, Q3, Q4	R1, R4, R8, R11, R14, R15, R16, R17, R24, R25
Fault handling	Q10	R15, R16, R18, R19, R26, R27
Frequency control	Q6, Q7	R1, R2, R3, R4, R5, R6, R7, R8, R10, R12, R13, R31, R39, R40
GFMI	Q3	R4, R10, R31, R32, R33
Modelling	Q9	R11, R20, R21, R22, R23
Power quality	Q8	R35
Protection	Q10, Q11	R16, R18, R19, R26, R27, R28, R29
Services	Q1	R3, R5, R10, R30
Stability	Q2, Q5, Q8	R9, R10, R11, R12, R14, R15, R17, R24, R25, R29, R32, R33, R35, R41
Weak grids	Q2	R1, R15, R18, R25, R39, R41
Cyber security		R36
HVDC		R34
Reliability		R29, R36, R37
Self-healing		R29
Social issues		R38