Topic 1 – Inverter Design

2024/25 - Large-signal Stability Enhancement in IBR-Dominated Grids.

Commonwealth Scientific and Industrial Research Organisation

24 December 2024

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Contents

1. Introduction

The Australian energy system is undergoing a significant transformation, driven by the rapid integration of renewable energy sources such as wind and solar. This shift has led to an increasing reliance on inverter-based resources (IBRs), which are gradually replacing traditional synchronous generators. While this transition supports the global push for a sustainable and low-carbon energy future, it also presents critical challenges in maintaining grid stability, reliability, and resilience.

Grid-forming inverters (GFMIs) have emerged as a key technology for addressing stability issues in networks with high IBR penetration. These inverters are essential because they stabilise the grid by controlling voltage and frequency, even when traditional generators are absent. However, as the complexity of modern power systems grows, understanding the transient and large-signal stability of these systems becomes imperative.

Stage 4 of the GPST research focuses on advancing the understanding and tools required to manage large-signal stability in IBR-dominated grids. Building on the findings from Stage 3, this stage emphasizes four key tasks:

1. **Enhancement of Large-Signal Stability Analysis Tools:** By integrating inverter control dynamics into existing tools, this task aims to provide a comprehensive framework for assessing the stability of IBR-dominated grids during disturbances.
2. **Sensitivity Analysis of GFMIs:** This task investigates the impact of varying inverter control parameters and fault profiles on large-signal stability, enabling the identification of optimal configurations for improved grid performance.
3. **Expansion to Multi-IBR Systems:** This task examines the dynamic interactions among multiple IBRs within diverse network configurations, offering insights into the collective impact of these resources on overall system stability.
4. **Development of Tuning and Design Guidelines:** The culmination of insights from the previous tasks will inform practical guidelines for the design and operation of GFMIs, enhancing the stability and resilience of future power systems.

This research plays a vital role in supporting Australia’s energy transition by addressing these challenges. By enhancing the stability and resilience of IBR-dominated grids, it enables the National Electricity Market (NEM) to integrate renewables at scale, directly contributing to the nation’s decarbonization goals. This alignment with national energy policies ensures that our research efforts are not only timely but also essential for meeting Australia's commitments to renewable energy and carbon reduction targets. Through its contribution to the scientific and practical understanding of power system dynamics, this research not only bolsters Australia's position at the forefront of renewable energy integration but also provides a scalable framework for other countries transitioning to IBR-dominated grids.

2. Research completed

Task 1 - Enhancing the Large-Signal Stability Analysis Tool

Key findings to date:

- **Improved stability margin calculation** method by incorporating the control loop dynamics.
- **Developed a PSCAD model** for the West Murray Zone to support future validations.

The primary goal of Task 1 was to enhance the large-signal stability analysis tool, originally developed in Stage 3, by integrating the dynamics of inverter control loops. This integration aimed to refine the assessment of stability margins within IBR-dominated grids, making it more precise and applicable to real-world scenarios. Initially, the tool utilized a generalized framework suitable for analysing transient stability across large-scale networks, including those with radial and mesh configurations. However, its reliance on static values for critical parameters, such as PCC voltage and grid-following inverters (GFLI) current, limited its effectiveness outside of theoretical applications.

To overcome these limitations, the project team expanded the research to encompass the dynamic effects of control loop parameters particularly those influencing stability margins. Our preliminary studies revealed significant insights into how variations in control loop parameters, such as droop coefficients and voltage setpoints, impact the stability of IBR-dominated grids. These findings have been methodically integrated into the tool, enhancing its robustness and accuracy for stability analysis.

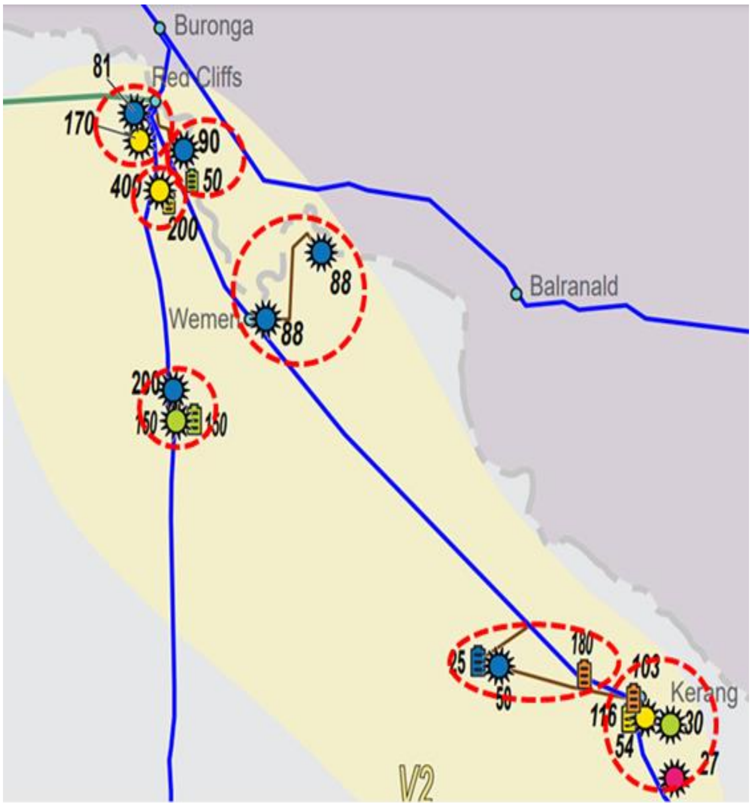

Figure 01: West Murray renewable energy zone with identified clusters (circled in red) for the study [Ref: NEM Generation Maps - 2023]

In conjunction with these methodological advancements, we developed a PSCAD model tailored to the West Murray Zone. This model divides the zone into clusters, with batteries modelled as GFMIs and solar farms as GFLIs, as depicted in Figure 1. The upcoming validation phase will leverage this PSCAD model to simulate a variety of network configurations and operating conditions specific to the West Murray Zone. This critical phase aims to validate the enhanced capabilities of the tool and identify the most stable and feasible network arrangements for practical implementation. These efforts include examining radial and mesh configurations, alongside different dispatch levels and line impedances.

The outcomes of this validation are anticipated to confirm the tool's capacity to pinpoint the most stable configurations, thereby supporting a detailed analysis of stability across different network settings.

Task 2 – Sensitivity Analysis of GFMI Stability with Respect to Parameter Variations and Fault Profiles

Key findings to date:

- **Developed novel methodology** for analysing transient stability using Lyapunov's direct method.
- **Conducted extensive simulations** to evaluate the impact of inverter control parameters on transient stability.

The objective of Task 2 is to develop a novel methodology for analysing the transient stability of GFMIs, focusing on the impact of parameter variations and fault profiles. This task builds upon a comprehensive review of existing methods and extensive simulations to address the limitations of conventional approaches and propose actionable strategies for system design and operation.

A detailed literature review identified Lyapunov's direct method as the most appropriate framework for this analysis. Unlike traditional techniques such as power-angle and phase portrait analysis, which are computationally intensive or provide only qualitative insights, Lyapunov's method offers a systematic approach to calculate the domain of attraction (DOA) and critical clearing time (CCT). This method effectively quantifies system stability without requiring extensive trial-and-error simulations, making it particularly suitable for inverter-dominated grids. Based on these findings, a Lyapunov function tailored to grid-forming inverters is being developed to establish a robust foundation for stability assessment under varying grid conditions and fault scenarios.

Extensive simulations have been performed to evaluate the impact of key inverter control parameters, such as droop coefficients and inertia constants, on transient stability. These studies demonstrated that active power control loop parameters are the primary drivers of stability, whereas reactive power control loops and inner loop dynamics exhibit less impact. These insights are being integrated into the methodology to enable a focused and efficient approach to enhancing stability margins.

The identified parameters and grid conditions are being incorporated into the formulation of the Lyapunov function, ensuring that the method is both accurate and practical for real-world applications. To date, a Lyapunov function for the virtual synchronous generator (VSG) has been developed and validated through simulations, demonstrating its capability to assess and quantify transient stability. The next phase of this work focuses on further refining the Lyapunov function to extend its applicability to various GFMI types, providing a versatile framework for analysing stability across diverse operational scenarios.

3. Outstanding activities

Task 3: Extension to Multi-IBR Systems

Task 3 focuses on extending the transient stability analysis framework developed in Task 2 to evaluate the collective impact of multiple IBRs on system stability. The objective is to provide a comprehensive understanding of the dynamic interactions among diverse GFMI types within multi-IBR systems.

The primary activity involves expanding the Lyapunov-based methodology to accommodate multi-IBR systems. This requires adapting the Lyapunov function, initially developed for GFMIs, to analyse the transient stability of interconnected systems with multiple inverters. By incorporating the dynamics of interactions between various IBRs and their configurations, the framework will enable a thorough evaluation of stability margins across diverse network topologies.

By the end of Q1 2025, this analysis aims to provide a comprehensive understanding of the dynamic interactions among diverse GFMI types within multi-IBR systems. This work is crucial for improving the multi-IBR system analysis, ensuring reliability in renewable-heavy zones, and reducing operational risks for network operators.

Task 4: Development of Tuning and Design Guidelines for IBRs

Task 4 builds upon the findings and methodologies developed in the preceding tasks to establish practical tuning and design guidelines for IBRs. These guidelines are intended to optimize the stability and operational performance of IBR-dominated grids across a range of network conditions. The remaining activities focus on synthesizing the insights gained from earlier tasks and translating them into actionable recommendations for industry adoption.

The primary activity involves integrating the outcomes of the Lyapunov-based stability analysis and sensitivity studies conducted in Tasks 2 and 3. This process requires leveraging critical insights into parameters such as droop coefficients, inertia constants, and fault response behaviours to formulate generalized tuning strategies for grid-forming. These strategies must comprehensively address steady-state performance as well as transient stability, ensuring robust operation under varying grid conditions.

Validation of the proposed tuning and design guidelines through rigorous simulations and case studies is a crucial objective of Task 4, targeting completion by the end of Q1 2025. This validation is crucial for ensuring that the guidelines are practically applicable and effective in real-world settings. Upon completion, this task will provide a comprehensive framework for IBR design and tuning, aligned with modern grid requirements and enhancing the stability and reliability of renewable energy systems. The development and implementation of these guidelines are essential for manufacturers and system designers, offering standardized practices that reduce risks associated with grid instabilities. Consequently, this task plays a pivotal role in supporting the industry's efforts to enhance the integration of renewable resources, significantly boosting the resilience and efficiency of power systems.

4. Progress against the Roadmap

Table 01: Outlines the overall research progress in comparison to the full program as defined in the Roadmap.

Task		Related Task in stage 4	Stage 4 progress	Key accomplishments
Major Task 4: Protection and Reliability Sensitivity analysis of GFMI stability with respect to parameter variation and fault profile.				
4.1	IBRs effect on existing protection systems	Sensitivity analysis of GFMI stability with respect to parameter variation and fault profile. Extension to Multi-IBR Systems.	70%	Developed and validated Lyapunov-based method for transient stability analysis. Laying the groundwork for multi-IBR system application.
4.3	Assessment and enhancement of IBRs reliability	Enhancing the Large-Signal Stability Analysis Tool Extension to Multi-IBR Systems. Tuning/Design Guidelines for IBRs	85%	Improved stability margin calculation method by incorporating the control loop dynamics. Laying the groundwork for multi-IBR system application.
4.2	Enhancing IBR response during and subsequent to faults	Development of Tuning and Design Guidelines	60%	Conducted a literature review to identify current challenges in IBR tuning and design.

5. Research relevance to Australia

Australia's transition to a renewable energy future brings unique challenges, particularly as the National Electricity Market (NEM) undergoes a shift from synchronous generator-dominated systems to grids primarily powered by IBRs such as wind and solar farms. This transformation aligns with the country's decarbonization goals but introduces complexities in maintaining grid stability, resilience, and reliability. As the grid loses the inherent inertia and voltage control provided by traditional synchronous generators, it becomes increasingly vulnerable to disturbances, especially in areas with weak system strength, such as the West Murray Zone.

The research conducted in Stage 4 directly addresses these challenges by enhancing tools and methodologies to support Australia's evolving grid. By developing advanced stability analysis tools, optimizing GFMI configurations, and improving multi-IBR system stability, the research strengthens renewable energy zones (REZs) and ensures effective renewable integration. Practical guidelines developed as part of this work help reduce the need for costly infrastructure upgrades, making the energy transition more economical. For instance, optimizing configurations in weak zones like the West Murray Zone could save millions in capital expenses by reducing the need for additional infrastructure.

Moreover, this research not only supports Australia's renewable energy goals but also provides scalable frameworks for other countries transitioning to IBR-dominated grids. By laying the groundwork for international best practices in renewable integration, Australia demonstrates leadership in this area, contributing valuable insights that can be adapted globally to enhance grid stability and reliability amidst increasing renewable energy adoption.

6. Recommendation research priorities

Short term: Study of the Impact of Current Limiters on Stability Margins and Domain of Attraction

1) **Investigate the influence of current limiters on the stability margin and domain of attraction of GFMIs.** Building on Stage 4 findings, this study will analyse how current limiters influence the stability margin and domain of attraction of grid-forming inverters (GFMIs), with a focus on their transient stability under fault scenarios. The research will aim to identify critical limitations imposed by current limiters and propose strategies to mitigate adverse effects. By enhancing the understanding of fault dynamics, this work will provide key insights to strengthen grid resilience and guide the development of more fault-tolerant and robust inverter designs.
2) **Investigate Transient Stability of GFMIs Under Asymmetrical Faults:** Expand the transient stability analysis of grid-forming inverters (GFMIs) to include scenarios involving asymmetrical faults, such as line-to-ground (L-G) and line-to-line (L-L) faults. These faults represent common but complex disturbances in modern power systems, requiring detailed studies to understand their unique impact on stability margins and dynamic responses. By leveraging advanced simulation techniques and experimental validations, this task aims to identify critical parameters influencing stability during such faults. Insights gained will guide the development of fault-tolerant GFMI designs and operational strategies, ensuring robust performance under real-world fault conditions. This research will be instrumental in enhancing the resilience of renewable-dominated grids, especially in weak areas prone to asymmetrical faults.

Medium term: Development of a Transient Stability Improvement Method for GFMIs

and studies on the impact of current limiters, the next phase should focus on developing a method to improve transient stability applicable to various types of GFMIs. This method will aim to address the challenges identified during the stage 4 and provide a generalized approach to enhance stability across different operating conditions. This initiative is crucial for optimizing the immediate operational stability of GFMIs and should be prioritized.

Long term: Extension of the Transient Stability Improvement Method to Multi-IBR Systems

Following the development of a transient stability improvement method for individual GFMIs, future work should extend this approach to multi-IBR systems. This will involve analysing the collective behaviour of multiple IBRs and ensuring the applicability of the stability improvement method in interconnected, complex network configurations. This expansion is essential for ensuring the holistic stability of Australia's increasingly diverse and integrated renewable energy systems.