Topic 6 – System Services

2024/25

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1. Introduction

System Services refers to characteristic or function of the power system which helps maintain a robust and resilient grid. With the Australian system becoming increasingly dominated by inverter-based resources (IBRs), and the increased understanding that the previous paradigm of synchronous-machine based system services (such as voltage and frequency) are in fact comprised of many more nuanced components that IBRs may or may not elect to provide, there has been a need to revisit what services are both required and may not be inherently present in a 100% IBR system. Furthermore, consideration is needed in how to best incentivize the provision such services, be it through technical standard requirements or ancillary market mechanisms.

This work focuses on how to identify the need for such technical characteristics which will be affected by the material change in generation technology away from synchronous machines to inverter-based resources (IBR) across several categories. Specifically, Stage 4 considers the following:

- Revisiting the roadmap and stepping back to consider a more comprehensive set of essential technical needs of the power system, from slow requirements such as system balancing, down to very fast requirements such as fault current performance. This work is based on up-to-date and comprehensive knowledge of technical and regulatory developments.
    - Such power system needs can be classified into true Services, Technical Requirements, a combination of both, which will be investigated in future research stages.
    - N.B. Services are considered to be provision of a technical quality to the power system with a compensation mechanism that allows efficient and competitive delivery (e.g., frequency control), while technical requirements are firm requirements factored into the design of the plant that support power system needs without any additional compensation (e.g., NER S5.2.5.x requirements).
- Understanding how such power system technical needs evolve as the National Energy Market (NEM) mainland increases in shares of IBR generators, through the development of a reduced order wide-area Electromagnetic Transient (EMT) model of the NEM.
- Through EMT modelling, investigate the operation of the NEM without any synchronous machines (i.e., even without hydro and synchronous condensers, 100% IBR), understand how NEM stability and characteristics change, and what steps should be taken to maintain stability.
- Exploring how many of the conclusions based on the EMT simulations above can be corroborated by the use of more simple and faster Phasor Domain Transient (PDT) modelling and highlight where any key differences may occur. Such insights in modelling differences may potentially lead to faster turnarounds for planning conclusions.

It is important to note that a portion of this work is to revisit the research roadmap itself, hence although all activities are broadly aligned with the original roadmap objectives (investigation of frequency and voltage control needs and metric identification and evaluation), a far broader set of potential system services (and hence, domains of analysis) have been identified.

2. Research completed

The research completed can be broken down into three categories:

1. Roadmap review
2. Prerequisite analysis and modelling
3. Studies and insights

Note that the nature of this work is heavily dependent on quality underlying models being developed and use, hence there has been commensurate effort expended as such.

2.1 Roadmap review

The roadmap review has focused on the following areas:

- Review and redraft of the Topic 6: Services roadmap, factoring in recent changes and developments in the area, including:
  - Extensive literature review.
  - Detailing of system needs across all technical areas.
  - Evaluation of the importance of each aspect's applicability to the evolving NEM.
  - Recommendations on research priority for each aspect.
  - Production of a comprehensive table summarising the above.

In developing the research roadmap, it was acknowledged that previous efforts primarily focused on frequency control and inertia. While these remain critical, a more comprehensive review of all factors contributing to overall system security was deemed necessary. This includes examining various aspects of system stability, system strength, and their relationships with power system protection and power quality.

As a result, the decision was made to prioritise investigating system needs related to faster phenomena, particularly those occurring within a few cycles, such as responses during faults and after fault clearance, specifically fault current magnitude, fault current sequence, fast voltage control, synchronising power, and phase angle jump suppression. This is also consistent with the type of phenomena experienced recently based on real system incidents in practical power systems in Australia and globally. It was also recognised that these types of phenomena often require more detailed power system modelling, with a particular emphasis on EMT simulations.

2.2 Prerequisite modelling

To date this has focused on the following areas:

- Development and sourcing of a suite of generator models to be used in a wide-area (multiple mainland NEM regions comprising 50+ buses and related network elements) EMT platform (both synchronous machine-based and inverter-based), including:
  - 15 synchronous machine models, based on realistic data, with machine parameterisation, automatic voltage regulators, limiters, governors, and stabilisers.
  - Seven type IV wind farm models based on the Electric Power Research Institute (EPRI) open-model, including tuning, parallel processing integration and several initialisation and performance improvements over the original model.
  - Sourcing and limited tuning of eight Original Equipment Manufacturer (OEM)-specific models of solar and battery systems, including identification of model bugs and limitations and parallel processing integration.
  - Five Static Volt-Amp-Reactive (VAR) Compensator (SVC) models based on public data, including tuning and development of low voltage blocking behaviour typically present in real devices.
- Development of a reduced topology 2024 EMT model of the NEM to be used as a baseline for Services comparison.
  - Based on the University of Adelaide 14-generator, 59-bus model, with numerous edits and extensions.
  - Including various dispatch scenarios (high and low operational demand, high and low synchronous versus non-synchronous ratios – all Grid Following (GFL) to reflect current NEM state)
  - Development of visualisations of critical system behaviours.
  - Development of models of generic voltage and frequency protection in line with NER standards.
  - Development of models of under-frequency load shedding schemes.
  - Custom initialisation scripts for fast wide-area EMT updates.
- Comprehensive review of documentation (Integrated System Plan (ISP), Transmission Annual Planning Reports (TAPRs), project reports and website information) on major network upgrades and generator retirement plans between now and 2034 to develop a practical view on a likely 2034 NEM topology from a network and generation perspective.

- Development of a new reduced (67-node) 2034 NEM topology map.
  - Factoring in ISP network actionable projects between now and 2034 (including where possible, detailed technical specifications from published documentation).
  - Up to 20 publicly declared Renewable Energy Zones (REZs) included (depending on case demand), consisting of wind, solar and BESS in each (where appropriate).
  - Generator retirements and conversions considered.
- Production of a reduced 2034 NEM EMT network model.
  - Assumptions on new network impedance based on common tower and bundling arrangements and conductors used in the NEM.
  - Additive approach generally used to augment existing model with additional infrastructure to be built.
- Production of a replicable/scalable REZ generator model for use in the 2034 NEM studies.
  - Complex multi-device model based on EPRI models of wind turbines, GFL solar farms, GFL and GFM batteries.

The ultimate 2034 simplified NEM model has undergone substantial modifications and significant enhancements, making it notably different from the original version provided by the University of Adelaide.

2.3 Studies and insights

To date this has focused on the following areas:

- Baseline studies completed for the 2024 NEM model focusing on fast voltage management & containment, phase angle variations, fault current provision, negative sequence fault current provision, and system robustness for:
  - High and low operational demand scenarios (8 GW and 28 GW)
  - Varying penetration levels of IBR (from 40% to 115%, depending on scenario)
  - Varying levels of battery penetration within IBR penetration, including GFM vs GFL devices.
  - Fault robustness studies (whether the system returns to equilibrium rapidly, without non-faulted element protection tripping, and without major voltage and frequency excursions) and islanding studies (whether the separate parts of the system return to equilibrium without unreasonable loss of load and/or generation).
- Baseline studies completed for the 2034 NEM model, with the same focus areas as the 2024 model, including:
  - High and low operational demand scenarios (8 GW and 36 GW)
  - Moderate and low amounts of online synchronous machines.
  - Conversions of synchronous machines to synchronous condensers.
- Initial studies of a 2034 mainland NEM model operating with zero spinning machines, both at minimum and maximum demand.

Simulation-based insights to date have been relatively limited due to the large amount of development required to establish and tune the wide-area models required in which to generate the studies. Once these models are ready for use however, it is expected that studies can be completed in relatively rapid fashion and insights obtained.

The above notwithstanding, within the studies performed for the 2024 baseline model, an emerging trend has been observed across multiple runs; **negative sequence current supply during faults is reduced** for scenarios where inverter-based resource penetration increases (displacing synchronous generators).

If this trend continues for higher levels of inverter penetration, this could potentially lead to:

- An inability of relays reliant on certain amount of negative sequence current, such as some types of directional protection relays, to discriminate a fault location, leading to out-of-zone operation and unintended disconnection of unfaulted equipment.
  - This may necessitate the prioritisation of IBR devices to provide greater unbalanced fault current than is currently called for within the rules of the NEM, along with the potential for greater overcurrent provision from IBR devices.

- Greater voltage imbalances during fault conditions, potentially exposing the system to increased risks of cascaded over-voltage tripping, or breaching of equipment voltage withstand limits.

This trend will be investigated in further studies within this stage, although the presence of grid-forming technology, which is expected to increase in the coming years, may alleviate this trend and allow existing protection strategies and equipment to remain serviceable. This assumption will be evaluated in studies within the 2030+ cases being developed in this stage.

3. Outstanding activities

The following activities remain in this Stage 4 project:

- Completion of the reduced order 2027 and 2030 NEM EMT model, including scenario variations relating to operational demand and proportions of inverter-based generation in the system.
- Additional studies using the 2034 NEM EMT model to be compared against the 2024 NEM EMT model results. This includes identification of material variations in system stability and consideration of critical capabilities from plant and REZs which could dominate a 2034 NEM.
- An investigation into the ability of PDT modelling to identify the critical services and behaviour of a system dominated by IBR.
- A set of releasable models for the research community.
- A final report for publication.

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

4. Progress against the Roadmap

The work focuses on the new 2024 roadmap findings under several items marked as “high priority”. Given the breadth of new items identified for investigation in this roadmap review, not all can be investigated simultaneously, so it was decided to begin with a focus on faster phenomena:

- Fault current waveform, magnitude and sequence.
- Fast voltage control.
- Synchronising power.
- Phase angle jump suppression.
- Damping ability of the system.

Additional phenomena may be evaluated as the research indicates it is of importance and can be readily accommodated.

The work being performed in this stage is deliberately technical in nature and is not considering economics and market structures of system services contemplated as part of the original roadmap. This is by virtue of the roadmap review undertaken, which identified that a far larger set of technical needs of the power system may exist than previously considered. These technical needs should be carefully evaluated for characteristic changes as the system evolves to higher levels of inverter-based resources. Once there has been further clarity established in this regard, it is expected that future G-PST research stages can focus on economic evaluations of the most efficient and effective mechanisms to ensure that the system has its essential services maintained (i.e., market or technical requirement).

5. Research relevance to Australia

The work being completed in this Stage and Topic is directly related to the evolution of the Australian power system as it evolves to an inverter-dominated paradigm. Specifically:

- The models being developed are of the mainland NEM.
- The network developments being considered are based AEMO's ISP and the Transmission Annual Planning Reports of Australian transmission network service providers.
- The modelling of generator and REZ locations are based on published data for the east-coast electricity system evolution.
- The specific scenarios the wide-area models consider are based on existing or realistic dispatch scenarios that have occurred, or are forecast to occur, in the Australian-east coast network.

Many of the insights are expected to reveal how system stability depends on the profile of generation dispatch setpoints across the power system (e.g., proportion of synchronous versus IBR) and the controller dynamics governing the behaviour of the inverter-based generators (e.g., grid-following versus grid-forming control). Additionally, the wide area network model will allow investigation of how to best source services, given the quintessentially Australian problem of very long distances between generation centres and load centres, and long distances between synchronous and IBR centres. Many of the investigations in this Stage will focus on the limits of IBRs that the power system can reliably accommodate, and conversely, what properties must IBRs offer to the power system to ensure secure uptake of such technologies. In this way, although the insights and conclusions will have been generated in an Australian context they are expected to be applicable to a variety of systems experiencing a similar ratios of IBR uptake. Where it is discernible that a specific conclusion is topology specific, efforts will be made to clearly flag this as such in the research output.

Furthermore, excluding any confidential or sensitive data used, the EMT models developed will be released to CSIRO to share with the research community to scrutinise, change, grow, or otherwise use as they see fit. Confidential models used in the analysis will be so identified and replaced for the model release with a non-confidential equivalent.

6. Recommendation on research priorities

Based on this 2024 research roadmap review, the following aspects have a residual importance of "high" for the 2024 work and beyond:

Technical Need	Technology Gap Necessitating Research
Fault current sequence	Current limited nature of all IBRs
Fault current waveform	While this topic warrants significant research, based on experience to date it is unlikely that a GFM fault current waveform will only contain fundamental frequency
Fast load reduction / increase	The capabilities and limitations of demand response are not well known
Operation beyond the maximum power	Technology capability and limitation, including impact on the lifetime, is not well understood at this point
Operation beyond the registered Generator Performance Standards (GPS)	Technology capability and limitation, including impact on the lifetime, is not well understood at this point
Quasi-static harmonic mitigation	Bandwidth limitation of all IBRs

Damping of electrical sub-synchronous resonances	Lack of sufficient understanding if GFM can adversely interact between themselves or with GFL.
Damping of electrical super-synchronous resonances	GFM can suppress super-synchronous up to its bandwidth.
Grid-forming inverter headroom	GFM stability can be degraded if operated current limited. Reserving some headroom below the current rating at all times will ensure that the GFM will not hit the limit during or after the disturbance, and can therefore provide its best performance.
Voltage waveform improvement	GFMs are shown to improve the damping of sub-synchronous oscillations. However, the impact will be on frequency components up to its bandwidth and won't be effective on harmonics above ~5-7 order.
Active power ramping control	Wind and solar with better ramping control capability

In addition to the above, further research is recommended to investigate:

- Expansion and further refinement of the wide-area EMT model to consider additional scenarios and ensure its fitness-for-purpose for evaluation of a wider set of system needs / potential system services.
- Expanding technical needs and potential services evaluation studies to additional areas identified in the Topic 6 roadmap review, with priority for:
    - Evaluating the effect of an IBR-dominated system on the operation of protection relay models that rely on specific fault current characteristics (magnitude, waveshape, sequences) to discern fault presence.
    - Evaluating the effect of an IBR-dominated system on stability of aggregated distribution connected Distributed Energy Resources (DER) and Consumer Energy Resources (CER) (e.g., rooftop PV, heat-pumps, EV chargers, residential BESS) from perspectives of:
        - Control system stability
        - Protection activation
    - Evaluation of services DER could provide to an IBR-dominant NEM at bulk supply points.
- Research and consider how any additional identified power system technical needs following this work should be incentivized and maintained, either through technical standards or ancillary market mechanisms.
- How the definition of known offline study stability evaluation metrics and criteria such as damping will evolve as the generation mix changes and what resultant impact it might have on the calculation methodologies used, for example the extent to which Fourier transform can be reliably used?