CSIRO Australian Research for the GPST

Topic 2 – Stability Tools and Methods

Electric Power Research Institute

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Executive Summary

As the Australian power system undergoes significant transitions in the coming years – including increasing shares of inverter-based resources (IBR) and distributed energy resources (DER) along with decrease in synchronous generation capacity – enhanced simulation and analytical capability will be required to ensure stable, secure, and reliable system operation. This would in turn require processes and tools to efficiently plan and operate these high-renewables networks, including to procure and manage the various services required. It is acknowledged that there are already several initiatives either recently implemented or actively underway to improve the analysis and simulation tools used in the National Electricity Market (NEM) and Wholesale Electricity Market (WEM), such as increased use of electromagnetic transient (EMT) models for high fidelity simulation. The objective of this research roadmap is to survey key topics with opportunities to further advance power system stability assessment processes to improve management of the network. Such advances are expected to streamline the interconnection process, help reduce the likelihood of large disturbance events, and mitigate loss of power supply in case of such events.

The research topics identified in this roadmap were developed by the Electric Power Research Institute's (EPRI) Transmission Operations and Planning (TO&P) group, based on an initial set of questions (provided by CSIRO) based on work carried out by the Global Power System Transformation (G-PST) Consortium. The topics are also informed by consultations with transmission network service providers (TNSPs) and the Australian Energy Market Operator (AEMO).

This roadmap first summarizes current practice for management of the Australian power system concerning network stability assessment, model validation, contingencies, stability constraints, and other related topics. Next, the roadmap addresses each of nine initial questions for power system planning proposed by the G-PST work, providing a detailed list of considerations required to address each question. The roadmap then presents and discusses twenty-one topics relevant for advancing stability tools and methods, detailing open research questions for each.

Table 1 and Table 2 below provide summaries of (respectively) the *Critical* and *High* priority topic groups identified in this report. While abbreviated notes of key gaps and suggested research outcomes are listed here, the main body of the report provides comprehensive discussion. These priority categories have been defined in part based on our consultations with the TNSPs. The prioritization also takes into consideration the consequence of not addressing the gaps in these categories, with respect to maintaining a stable power system operation.

Table 1. Summary of ***critical*** *topics addressed in this roadmap document along with main research areas*

Topic	Existing Gaps	Suggested Research Outcomes
1. Stability margin evaluation	1. Proprietary IBR control algorithms make evaluation of small and large signal stability challenging 2. Running detailed EMT studies can be a heavy computation burden.	1. Tools to evaluate non-linear stability margins using black-box models. 2. Evaluation of stability at multiple operating points
2. Small signal stability screening methods	1. Impedance scans are widely used in power electronic community but not in power systems. 2. Analytical evaluation of IBR stability is not carried out at the moment.	1. Development of procedures to use impedance-based methods for stability screening. 2. Development of linear analysis techniques with black box IBR models.

Topic	Existing Gaps	Suggested Research Outcomes
3. Voltage stability boundary	1. Variation in IBR output can change the conventional definitions of source and sink for voltage stability analysis 2. With reduced mechanical swing in the system, system operators need visibility of closeness to voltage collapse point	1. Tools to identify new boundaries between source and sink regions 2. Recognize voltage stability boundary as a new constraint/criterion for system operation
4. Voltage control, recovery, collapse	1. Limited current output from IBRs can impact speed of voltage recovery 2. Changes needed in traditional Volt/Var based study process to determine reactive power solutions with IBRs	1. Improvement in way loads and IBRs are considered in Volt/Var tools 2. Tools to assist operator with high voltage mitigation due to increase in IBR output

*Table 2. Summary of **high priority** topics addressed in this roadmap document along with main research areas*

Topic	Existing Gaps	Suggested Research Outcomes
5. Online identification of system strength	1. Traditional system strength metrics may not portray the dynamic characteristics of IBRs. 2. Daily variation in system strength can occur based on system conditions	1. Methods/tools to efficiently identify system strength in real time operations 2. Analytical evaluation of locations at which system strength is to be determined
6. Monitoring inertia in real time	1. Contribution of load and distribution generation to inertia is not explicitly considered 2. Global system inertia can be different from local regional system inertia	1. Tools to identify of levels of demand side inertia contribution 2. Quantify regional inertia impact on frequency response.
7. Modelling and model validation	1. Future studies require an adequate and accurate set of generic models 2. IBR models are only side of the coin. Equally important to have validated models of network, synchronous power plants, and load/DER.	1. Development of generic models for newly emerging IBR control modes. 2. Validation and maintenance of aggregated representation of load and DERs.
8. Voltage and reactive power management	1. Reduction in reactive power resources with increase in current limited IBRs 2. More stringent operating conditions with intermittent output from IBRs	1. Tools to be used in operations to coordinate and control deployment of reactive power devices 2. Determination of area of vulnerability for large loads.
9. Real time simulators	1. In-depth field testing and validation of IBR systems is cost prohibitive 2. Interaction between IBRs controls and protection equipment to be ascertained	1. Development of expertise in utilizing HIL setups. 2. Integrating HIL as part of system planning

Topic	Existing Gaps	Suggested Research Outcomes
10. Critical contingency identification	1. Today contingencies screened and ranked based on time domain studies and engineer experience 2. Daily change in resource mix can result in variation of flow which coupled with node breaker formulations, can complicate identification of critical contingencies	1. Tools to consider IBR dynamics while analytically evaluating and ranking criticality of contingencies 2. Use of machine learning methods to classify and rank evolution of contingencies
11. Real time contingency analysis	1. Final market clearing or dispatch can be different from planned cases. Important to try to assess system stability with this final dispatch levels 2. Coordination between these dispatch levels and outage maintenance crews is essential to improve power system stability.	1. Improvements in multi-core computing to extend the applicability of parallel processing 2. Improved identification of critical contingencies to be evaluated.
12. Protection system operation and coordination	1. Conventional protection operates based on synchronous generator characteristics 2. Representation of IBR and load behaviour in protection studies is still evolving	1. Development of accurate IBR short circuit models for use in simulation tools 2. Tools to carry out advanced fault studies and configure protection relaying settings with change in IBR output.

In addition, two further groups of topics – medium priority and low priority – are identified and discussed. These are topics that are closely linked (though not directly related) to stability tools and methods but are nonetheless important as they can help determine the power flow operating point at which stability of the system would be evaluated.

- Medium priority topics (which can directly influence the stability of the network, but do not directly influence the development of tools to evaluate stability)
  - Harmonics and power quality
  - Outage scheduling with high percentage of IBR
  - Grid enhancing technologies
  - Wide area monitoring systems
- Low priority topics (provide key inputs for stability assessment)
  - Dynamic line rating for effective use of transmission assets
  - Cybersecurity
  - Power system planning for extreme events
  - Resource adequacy
  - Scenario development

A research plan is proposed for each topic area with *Critical*, *High*, and *Medium* priority (in some cases, the research plan is proposed for a cluster of two closely related topics). The research plan proposed for each topic (or topic cluster) specifies preparation and inputs; research projects and objectives; expected outputs; estimated timeline; and required skill sets.

It is recommended to begin work with the *Critical* and *High priority* topics. There are no critical dependencies among any of the identified topics that require them (or any subset of them) to be undertaken in a specific sequence. There is significant overlap among the different concepts used in the evaluation of system stability, and there is no single/unique logically determined sequence to follow in developing the tools discussed here. Many tools may have to be developed in parallel while still being used in a sequential manner. Each topic however does require domain specific knowledge to be applied during the development of the specific tool.

This roadmap provides initial timeline and cost estimates for each of the topics identified. While these estimates apply to initial tool prototype development and implementation efforts, it is recommended that this be followed by a continuous, iterative process of improvement in integrations and input assumptions across the entire suite of tools.

List of Abbreviations

AAR	Ambient Adjusted Ratings
ABB	Asea Brown Boveri
AEMO	Australian Energy Market Operator
AOV	Area of Vulnerability
BESS	Battery Energy Storage Systems
CAISO	California Independent System Operator
CIGRE	International Council on Large Electric Systems
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DER	Distributed Energy Resource
DLR	Dynamic Line Rating
DSA	Dynamic Security Assessment
EISPC	Eastern Interconnection States' Planning Council
EMS	Energy Management System
EMT	Electromagnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESB	Energy Security Board
ESOO	Electricity Statement of Opportunities
FACTS	Flexible Alternating Current Transmission Systems
GET	Grid Enhancing Technologies
G-PST	Global Power System Transformation
HIL	Hardware in the Loop
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IBR	Inverter Based Resource
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO-NE	Independent System Operator – New England
ISP	Integrated System Plan
MISO	Midcontinent Independent System Operator
ML	Machine Learning
MVA	Mega Volt Ampere
NARUC	National Association of Regulatory Utility Commissioners
NASPI	North American SynchroPhasor Initiative
NEM	National Electricity Market
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
NYPA	New York Power Authority
OEM	Original Equipment Manufacturer
PFC	Power Flow Control
PLL	Phase Locked Loop
PMU	Phasor Measurement Unit

PNNL	Pacific Northwest National Laboratory
POD	Power Oscillation Damping
PST	Phase Shifting Transformer
RA	Resource Adequacy
R&D	Research and Development
RoCoF	Rate of Change of Frequency
RTDS	Real Time Digital Simulator
RTE	Réseau de Transport d’Électricité
SCADA	Supervisory Control and Data Acquisition
SCR	Short Circuit Ratio
SE	State Estimation
SEC	Saudi Electric Company
SG	Synchronous Generators
SPS	Special Protection Schemes
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Compensator
TNSP	Transmission Network Service Providers
TO&P	Transmission Operations & Planning
UCD	University College Dublin
VAR	Value at Risk
VLAR	Value of Load at Risk
VOLL	Value of Loss Load
VSC	Voltage Source Converter
WAMS/WAMCS	Wide Area Monitoring (and Control) System
WECC	Western Electricity Coordinating Council
WEM	Wholesale Electricity Market

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1. Introduction

The widespread and rapid increase in inverter-based resources (IBRs) both at the transmission and the distribution levels requires a change in the way the bulk power system is planned and operated.

As power systems across the world are undergoing transformative changes in resource mix, end-use load and transmission technologies, advanced methods and tools are required to study complex phenomena to ensure grid stability. Due to the non-physical nature in which IBRs behave and respond to system events, concepts, tools, and methods that have been used for many decades to evaluate the stability and security of the bulk power system, may have to undergo substantial changes. As inverter technology is poised to dominate the grid, planning and operation engineers will almost certainly require advanced types of tools to study complex phenomena involving inverter-level and plant-level control systems. While there are some existing solutions available, much more research is required to help bring use of such advanced concepts into routine application.

This research roadmap lays out avenues for future research that are targeted towards development of new and improved tools that would help Australian power system engineers with planning and operating the future Australian power network.

1.1. Background

Continuous stable and reliable operation of tomorrow's power system will be significantly more dependent on the stability of IBRs. The number of these devices in power systems worldwide have consistently increased over the past decades and is forecasted to continue to grow. Therefore, mitigation of converter/inverter driven instability will continue to be a priority in the future, and the use of inverters to provide critical reliability services such as frequency and voltage support will become increasingly relevant.

In this discussion, inverter-interfaced devices will be mainly limited to inverter-interfaced generation, such as wind, solar, battery energy storage systems (BESS), although it could be extended to refer to various transmission related technologies devices, such as STATCOMs, SVCs, TCSCs, HVDC stations, and so on. The stable operation of IBRs is highly dependent on the control strategies they use an external network characteristic. In contrast to other assets such as synchronous generators, they do not have an inherent response based on laws in physics.

There have been multiple instances of recorded events where IBR driven instability was the main driving event. Perhaps the most widely observed type of IBR driven instability is the one that arises when converters connect to weak, low short circuit ratio (SCR) networks. Under those conditions, challenges arise primarily from the lack of a proper network voltage reference that the IBR controls can track or follow (e.g., phase locked loop (PLL) unable to track a voltage reference that varies considerably during a disturbance).[1] Another example includes the inability of the IBR to inject power in a network with high driving point impedance, which is an inherent physical limitation that occurs under certain conditions (e.g., a post contingency network configuration with one or more lines out of service). While continuous replacement of conventional synchronous generation will lead to a reduction of available short circuit contribution, network expansions required to accommodate higher levels of renewable penetration will have a counter effect and may help increase overall system

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[1] For detailed insight regarding the mechanism of these instabilities, and future research directions regarding mitigation options, see the companion CSIRO *Australian Research Planning for Global Power Systems Transformation* research roadmap "Inverter Design: Development of capabilities, services, design methodologies and standards for Inverter-Based Resources (IBRs)" (Topic 1).

strength by reducing the total network impedances. A proper understanding of network expansion plans, synchronous generation retirements, IBR penetration levels as well as other system changes should be considered when developing study scenarios. Detail investigation of those scenarios will help anticipate some of those challenges that may arise, as well as identify areas of the system that may be more prone to facing challenges.

A simple way to categorize and evaluate inverter driven stability is by splitting the potential phenomena to be studied into two main categories as defined by the IEEE [1]. Broadly speaking, IBR driven stability phenomena can be grouped into two main categories: slow and fast interactions. Slow interactions tend to be dominated by outer control loops (e.g., terminal reactive power regulator, plant level voltage or reactive power regulators, etc.), which tend to have lower bandwidth. Faster interactions tend to be dominated by inner control loops (e.g., terminal voltage regulators, current regulators, etc.), which tend to have higher bandwidth.

Examples of slow interactions (usually a bandwidth of 0.1Hz to 1Hz) include:

- Voltage control “hunting” or “fighting” among inverters that regulate voltage at points in the network that are electrically close.
- Oscillatory control instability of outer loops (e.g., plant level controls becoming unstable as the system strength deteriorates over a period)
- Cyclic instability that occurs when IBR may toggle through different control modes under weak (loss of element) network conditions
- Voltage instability following a disturbance that causes a reduction in power transfer capability from a IBR plant

Control coordination between discrete devices, such as tap changing transformers and discrete switching devices is also relevant in the context that it may help prevent unacceptable operating conditions and/or reduce the switching frequency, leading to reduced wear on these devices. Coordination studies can be performed and techniques such as time decoupling (i.e., decoupling the timeframe of response, often by an order of magnitude) are effective to achieve proper coordination. More elaborate coordination schemes that use different deadbands for equipment response, hierarchical control strategies to determine device switching order, can also be employed. While it is unlikely that miscoordination between tap changers and switched shunt devices will lead to instability, it may lead to inappropriate operation, unnecessary excessive switching and poor voltage regulation in the areas where it occurs.

Examples of fast converter driven instability include:

- Sub-synchronous control interactions between type 3 wind plants[2] and series compensated lines
- Harmonic resonances between IBR and low order network resonances (such as the ones introduced in offshore collector systems or offshore ac transmission)
- Poorly designed IBR controls that introduce negative damping (oscillatory behaviour) at certain known network resonant frequencies

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[2] Also known commonly as the doubly fed induction generator; contains a wound rotor induction generator connected directly to the grid from its stator along with a rotor-side converter connected back-to-back with a grid side converter, which exchanges power directly with the grid

It is now evident from power systems around the world that these instances of instability, whose occurrence may have previously been few and far in-between, can increase with increased clean energy goals and targets. Pockets of many large power networks have reached instantaneous IBR penetration levels close to 100% for few hours to days while smaller islanded networks have gone even further. Traditional power system security has components associated with stability, voltage margins and profile, frequency adequacy and balancing, and associated ancillary reserves. With increase in IBRs, two additional components added under system security umbrella which have particular relevance in the Australian context are system strength and inertia [2].

In this paradigm of increased IBR percentages, proactive rather than reactive power system planning and operation can have a large positive impact on system reliability. Although it is almost impossible to predict every conceivable scenario that may occur in future, proactive planning thought process along with advancement in tools and methods can be effectively leveraged to identify credible future system conditions

To define advances in such tools and methods, this research roadmap will highlight different sectors of power system planning and operation along with challenges that exist in determination of system stability and security. These topics are complemented by the companion CSIRO *Australian Research Planning for Global Power Systems Transformation* research roadmaps for:

- IBR Design (Topic 1)
- Control Room of the Future (Topic 3)
- Power System Planning (Topic 4)
- Modelling DER (Topic 9)

1.2. Energy Transition Goals

Australia is acknowledged to have the world’s fastest energy transition. A key player in this energy transition is the increase in inverter-based resources both at transmission and distribution levels. Australian Energy Market Operator’s (AEMO) 2020 Integrated System Plan (ISP) [3] projects that the capacity of distributed energy resources may triple in the National Electricity Market (NEM) over the next two decades. This would include both distributed generation and load management at the residential and commercial/industrial level. This increase in capacity is projected to provide up to 22% of the total annual energy consumption in the NEM in 2040 (in the High distributed energy resource (DER) scenario). Further, the ISP projects a midrange estimate of 45 GW of new transmission connected renewable generation by 2040 (in the “Central” scenario), with upper-bound projection of 64 GW (in the “Step Change” scenario). In all scenarios, about half of the new renewable generation capacity is expected to be inverter-connected solar generation. In parallel, 60% of the coal-fired generation in NEM is expected to retire over the same period.

To support this large build out of renewable energy, the ISP recognizes the need for enhanced management of key system services such as voltage control, system strength, frequency control, and ramping and balancing. Additionally, network upgrades (both HVAC and HVDC) have been identified to transfer power to load centres and improve reliability of the network.

The need for enhanced system security in the emerging high-IBR power system is prominently recognized in the Energy Security Board’s (ESB) market reforms options paper, which proposes several market reform pathways to ensure the NEM meets the needs of Australia’s transition to a high-renewables grid [4]. “Essential system services and ahead scheduling” is one of the four pillars of proposed reforms highlighted by the ESB's April 2021 options paper. Notably, the ESB prioritized for immediate reform:

- refining frequency control arrangements and addressing the potential need for enhanced arrangements for primary frequency control and a new market for fast frequency response,
- developing structured procurement arrangements, including for system strength, and
- considering the need to explicitly value operating reserves. The current provision of reserves in operational timeframes is implicitly valued through the energy spot market. New products and services may be required to manage growing forecast uncertainty and variability in net demand over timescales of minutes to hours. A new reserve service market could provide an explicit value for flexible capacity to be available to meet these net demand ramps spanning multiple dispatch intervals.

While the ISP speaks about investments both from generation and transmission network perspective to meet the energy transition, it does not explicitly address the need for enhanced simulation and analytical capability. Such enhancements will be required to efficiently plan and operate such high-renewables networks, including to procure and manage the various services required. Considering this, this research roadmap will help complete the puzzle. The research topics mentioned in this document are aimed at improving the computation and efficiency of managing such a network, which in turn is expected to result in improvements and streamlining of the study and interconnection process. Increased use of such advanced tools can help reduce the likelihood of occurrence of large disturbance events and mitigate loss of power supply in case of occurrence of an event.

In the following chapters, the methodology used to develop the research plan is first discussed. Following this, a deep dive into the state of the art along with a breakdown of the original research questions is provided. Subsequently, using the breakdown of these questions, detailed research topics are identified and discussed.

1.3. Acknowledgements

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2. Methodology

The development of the research plan started with an initial set of questions provided by CSIRO, based on work carried out by the Global Power System Transformation (G-PST) Consortium [5]. These questions cover a large spectrum of topics related to planning and operation of bulk power system with increase in IBRs (see Section 3.3 below). Using this as a starting point, each question was subsequently broken down into multiple categories and questions that address topical areas that relate to the core concept raised by the question.

These initial core questions were elaborated into a series of related topics by the Electric Power Research Institute's (EPRI) Transmission Operations and Planning (TO&P) group. This process was informed by the group's extensive expertise executing studies and tool/model development that help addresses questions and concerns related to assessment of system stability, within its collaborative framework that brings together electric utility companies, software and hardware vendors, reliability organizations, and other research entities. Lessons learned from this extensive body of research work, and future research questions that have been raised as a result of these studies, have been used in addressing the core questions that describe this research roadmap.

Simultaneously, roundtable discussions were held with various transmission network service providers (TNSPs) and the Australian Energy Market Operator (AEMO), the system operator in Australia. These consultations with key management and senior engineer personnel were synthesized into the description of the current state of the art for stability assessment in Australia. They also informed the assessment of challenges and problems to be addressed.

Due to the nature of combination of elements in the power system, research items identified in this roadmap document may have to be complemented by research items from the other topical areas for which research roadmaps are being developed. Where possible, the links to the other topical areas are explicitly noted in this roadmap.

Specifically, Topic 1: IBR Inverter Design and Topic 2: Stability tools are inherently interlinked and coupled with each other. In order to adequately design and parameterize 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. Using this information as feedback, the efficient design of the inverters can be carried out. Simultaneously, any stability tools designed and developed from a system planner/operator perspective can only provide reliable 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.

3. Plan Development

The development of the research plan started with a set of round table discussions with various stakeholders in Australia to understand their present approach and challenges faced. Following this, the original research questions are expanded upon to highlight the nuances involved in each question.

3.1. Current Solutions

To determine the state of the art for bulk power system planning and operation in Australia, consultations were held with several transmission network service providers (TNSPs) and with AEMO. To each of them, a set of questions were posed in relation to their current planning and modelling practices. These questions were formulated to broadly address each topical area covered by the initial research questions raised by CSIRO (see Section 3.3 below). These questions, and their answers, help determine the state of the art with regard to the topical area of this research roadmap. A condensed summary of the replies to each question is provided below.

1. *What is the existing process used to analyse and evaluate stability of the network with IBR percentages? Is it purely simulation based?*

   All responses were unanimous with both positive sequence and electromagnetic time (EMT) domain simulation software being the workhorses to evaluate system stability. EMT and positive sequence software are used for planning studies (mid-to-long term) but only positive sequence software are used for operational studies (near real time). Here, it was ascertained that desktop time domain simulation techniques that involve numerically integrating a set of differential algebraic equations over the simulation period is the primary technique. Positive sequence simulation software is used primarily for traditional studies such as frequency response, while studies related to system strength and voltage events are carried out in EMT domain. Very little focus is presently given to use of analytical methods such as small signal analysis with presence of IBRs. Although small signal analysis is widely used by the TNSPs in evaluation of system modes and tuning of power system stabilizers/power oscillation dampers, the present analysis methods/techniques/software rely on having visibility of the block diagrams of the various equipment. This model-based technique however brings up challenges with the reduction in the synchronous machine fleet. This is largely due to the "black box" nature of proprietary IBR control systems, which presently makes it difficult to carry out analytical evaluation of their performance.

2. *What model validation procedures are used?*

   Respondents indicated that, in their experience, the stability of an IBR control system is not necessarily built upon the algorithm used within the controller, but heavily dependent on the coding skills of the engineer who implements the algorithm. There have been multiple instances wherein the underlying control algorithm is good, but its implementation has been bad. An example of this is allowing integrators within the controller to wind up when an event occurs. Considering this, AEMO now requires that every IBR plant owner/developer now must submit both positive sequence and EMT domain tested and validated models of their plant. In this document, such models will henceforth be referred to as models provided by the Original Equipment Manufacturer (OEM). The tests must be carried out in accordance to the guidelines specified in AEMO's Dynamic Model Acceptance Tests [6]. Models in the individual simulation domain must not only satisfy the various tests defined by [6], but must also be benchmarked against each other. Due to this detailed testing and validation process being implemented in earnest in the recent past, models submitted by new IBR plants are considered to be accurate. However, the models submitted by many legacy IBR plants, especially positive sequence models, have been found to be erroneous or even unusable. As a result, the simulation results obtained from positive sequence software suffers from inaccuracy. Also, although primarily the tests to be conducted in the field are restricted to small signal step changes, in weak and isolated areas, real live faults can be applied both to determine stability of the hardware in the field, and to compare with simulation model response. These model validation procedures are for an individual IBR plant. A system wide model validation exercise is carried out every time a major event occurs. It was also mentioned that presently, no defined procedure exists to validate aggregate and composite load models, especially with the increase of distributed energy resources.

3. *How are critical contingencies identified?*

   Presently, critical contingencies are identified either through detailed time domain simulation studies or largely based on experience of operating the network. Even while using simulation studies for this determination, both positive sequence domain and EMT domain is applied. One rule of thumb that is used is the notion that positive sequence dynamic studies typically provide a more optimistic view of the network behaviour. Hence, if a contingency simulation in positive sequence shows a cause for concern, then it can be classified as critical and is further evaluated in EMT domain.

4. *How are stability constraints evaluated and incorporated into Security Constrained Unit Commitment and Economic Dispatch?*

   Presently, the various TNSPs carry out assessments to determine the operation limits for critical transmission corridors. The exporting region develops the limits. These results are then provided to AEMO, where the operation limits are subsequently incorporated into the constraint equations as a security constraint. Thermal and voltage limits are determined from steady state studies, while transient and dynamic limits are identified from positive sequence and EMT domain studies. Where information is available, small signal oscillatory stability limits are also included on selected transmission corridors.

5. *How are the evolution of system modes (either local or inter-area modes) tracked during real time operations?*

   It was mentioned that presently, there are only a few phasor measurement units (PMUs) in the entire mainland network. However, efforts are underway to increase the presence of high-speed monitoring and data transfer. Most of the modes are observed and recorded during commissioning and testing of generation plants. While this was sufficient in the past, a lot more focus is presently being placed on continuous performance and monitoring. New plants that connect to the network must install a PMU and provide a data stream to AEMO. Additional validation of system modes is done whenever a system event occurs. The software used in operations is however increasingly incorporating PMU data streams.

6. *How is frequency response adequacy assessed?*

   This is primarily looked after by AEMO. The TNSPs are responsible for maintaining a desired level of inertia at AEMO's direction, but presently there are limited online inertia monitoring mechanisms (pilot projects are however getting underway to evaluate newer solutions to online inertia monitoring). While the majority of frequency response studies are carried out in positive sequence domain, it was mentioned that either just a simple swing equation-based model is used or a generic model is used to represent the governor response of existing plants. This is again because of limited model validation procedures that were in place in the past. Further, for legacy plants, absence of data also hinders model development and validation. New battery energy storage installations provide frequency response services. In addition, the use of other IBRs to provide frequency response services is actively being explored.

7. *How are voltage stability margins identified?*

   A lot of this analysis is carried out using existing techniques of identifying the transfer capability and knee point of the power-voltage characteristics. Further, reactive power design and planning is carried out using traditional steady state analysis.

8. *How are harmonics and power quality tracked?*

   While IBR developers provide EMT models of their equipment, often it is difficult to identify the magnitude and spectrum of harmonics that are produced. Even when identified, there can be mismatch between the harmonics identified from simulation model and the harmonics identified through test data provided by the OEM. This mismatch may be due to an oversight in the applicable International Electrotechnical Commission (IEC) standard.

9. *How are sub-synchronous resonance and control interactions tracked?*

   This is proactively done every time a series capacitor is placed in the network. Also, more generally, this is carried out as part of system strength studies in EMT domain, especially as a part of contingency analysis. There are also high-speed monitors that are in place to record oscillations in real time.

3.2. Industry Activities

The table below provides a summary of few related activities underway in different organizations in relation to development of stability tools and methods. It is to be noted that due to the wide global nature of research activities, the contents of the table below may not be all encompassing. Further, for new research efforts identified in this roadmap and for tools that are to be developed, the related industry activities denoted in the table below can serve as either a starting point for further Australian research or can equally serve as a wayside benchmark point to compare results from Australian research.

Table 3: Summary of related activities underway in industry and research organizations

Topic	Project Title	Entities	Description	References
Small signal stability screening methods and stability margin evaluation	Screening methods to evaluate system stability	NREL	Summary of impedance methods for analysing the stability impacts of inverter-based resources	• Impedance Methods for Analysing Stability Impacts of Inverter-Based Resources: Stability Analysis Tools

Topic	Project Title	Entities	Description	References
				for Modern Power Systems
	Screening methods to evaluate system stability	Aalborg University	Impedance analysis of power electronic converters from EMT models	- Press release
	Screening methods to evaluate system stability	EPRI	Impedance analysis of power electronic converters and network elements for system stability analysis	- Software tool
	Screening methods to evaluate system stability	Imperial College London	Impedance analysis of power electronic converters and network elements for system stability analysis	- Software tool
	Signal Damping Analysis Tool	EPRI	EPRI has developed a tool that enables a transmission planner to evaluate damping and modal properties of oscillation events using measurement data.	- Signal Damping Analysis Tool (SDAT)
Voltage stability boundary	Tracking of voltage stability boundary	EPRI	EPRI has developed in software a package that provides the capability to automatically identify the voltage magnitude and thermal flow limits that are closest to the operating point.	- Software tool - Method
Voltage control, recovery, collapse	Voltage control, recovery, and collapse	-	Summary of industry practices and tools for voltage/var	- Industry Practices and Tools for Voltage/VAR Planning and

Topic	Project Title	Entities	Description	References
			planning and management	Management (VVPM)
	Voltage Control in Smart Grids	-	Summary of facilities to control the voltage in smart grids	- Challenges and Research Opportunities for Voltage Control in Smart Grids
	Voltage Support from Solar PV Plants	-	Summary of facilities to manage high voltage conditions in the transmission system using PV plants at night	- Strategies and Tools for Managing High Voltage Conditions in Transmission System Operation: Voltage Support from Solar PV Plants at Night
Online identification of system strength	System strength	AEMO	AEMO has developed a methodology for determining system strength requirements and developing impact assessment guidelines	- System Strength Requirements Methodology - System Strength Impact Assessment Guidelines
	System strength	EPRI	EPRI developed a tool that helps evaluate the short circuit strength of a system at user designated buses. The software evaluates steady state short circuit metrics and also provides insight into possible controller interactions and oscillatory issues in a low short circuit environment.	- Grid Strength Assessment Tool (GSAT) Version 4.0 - IBR Modelling Guidelines for Weak Grid Studies and Case Studies

Topic	Project Title	Entities	Description	References
Modelling and model validation	Power System Model Guidelines	AEMO	Overview of power system model guidelines that enable AEMO and the NSPs to implement several obligations under the NER, especially those that relate to meeting AEMO's power system security responsibilities and the management of new connections to the national grid.	• Power System Model Guidelines
	Power Plant Parameter Derivation	EPRI	EPRI developed a tool that can be used for validating and parameter estimation of models for synchronous generator power plant, wind and PV power plants, and static var systems.	• Power Plant Parameter Derivation (PPPD) v13.0
	Load Model Data Processing and Parameter Derivation	EPRI	EPRI has developed a tool that can be used find optimum values of load model parameters using event data collected on distribution feeders.	• Load Model Data Processing and Parameter Derivation (LMDPPD) v6.0
	Model Verification of Aggregate DER Models used in Planning Studies	NERC	NERC published a reliability guideline that provides Transmission Planners (TPs) and Planning Coordinators (PCs) with tools and techniques that can be adapted for their specific systems to verify that the created aggregate DER models are a	• Reliability Guideline: Model Verification of Aggregate DER Models used in Planning Studies

Topic	Project Title	Entities	Description	References
			suitable representation of these resources in planning assessments.	
Voltage and reactive power management	Voltage control and reactive power scheduling tools	EPRI	EPRI developed a tool for identifying areas prone to voltage security problems	- Identification of Critical Voltage Control Areas and Determination of Required Reactive Power Reserves
	VAr Dispatch Scheduling System	AEMO	AEMO developed a tool which implements a tie-line based solution method to determine reactive power dispatch of generators, SVCs, capacitor banks, and other reactive power devices.	- Guide to VAr dispatch
Real time simulators	Real time simulators/hardware-in-the-loop	AEMO, OPAL-RT TECHNOLOGIES	OPAL-RT TECHNOLOGIES to provide Advanced Transmission Simulation Support to the Australian Energy Market Operator (AEMO)	- Software Tool - Press Release
	Maintaining RTDS models of power systems	EPRI, NYPA	In collaboration with New York Power Authority, EPRI has developed a Python-based tool to maintain RTDS models of power systems by reading their corresponding updated Siemens PSS®E models. The update occurs only on model parameters that typically change throughout a year,	- Presentation

Topic	Project Title	Entities	Description	References
			such as load/generation levels.	
Critical contingency identification	Automatic contingency creation	EPRI	EPRI developed a tool that utilizes accurate node-breaker topology information, generation of contingencies definitions for both steady-state and dynamic analysis	• Automated Contingency Generation Tool (ACGT) • Protection Control Group Engine API (PCG Engine)
	Contingency screening and ranking	EPRI	EPRI developed a tool that identifies and prioritizes the most significant events in an automated manner for both dynamic voltage performance and transient stability performance	• Contingency Screening and Ranking Tool - Dynamic Voltage Module • Contingency Screening and Ranking Tool – Transient Stability Module
Real time contingency analysis	Dynamic Security Assessment (DSATools™)	PowerTech Labs	PowerTech Labs developed DSATools™ that provides the capabilities for a complete assessment of system security and support for PMU/WAMS applications.	• Software tool
Protection system operation and coordination	Modification of commercial fault calculation programs for wind turbine generators	Working Group C-24 of the System Protection Subcommittee	Phasor domain programs with iterative solution – for modelling non-linear response	• IEEE PSRC C24 Report
	Computation of active nonlinear network equivalents for short circuit studies	EPRI	EPRI proposed a new concept of voltage dependent network equivalents to	• Equivalencing Methods of Systems with High Levels of Inverter Based

Topic	Project Title	Entities	Description	References
			compute active nonlinear network equivalents for short circuit studies in systems with a high share of IBRs	Resources for Short-Circuit Studies
	Short Circuit Model Validation Tool 2020 For ASPEN OneLiner	EPRI	EPRI developed a tool that runs within ASPEN OneLiner's Power System Simulation Package. It enables the user to perform analytics on power grid transmission line, transformer, and generator models and automatically identify model errors using field measurements.	• Software tool
Harmonics and power quality	Studies of harmonics and power quality	EPRI	EPRI developed a hybrid harmonic modelling approach to simplify the harmonic modelling of IBRs	• Planning for Harmonic Analysis of Utility-Scale Inverter Based Resources: Modelling Inverter-based Generation Resources for Harmonic Studies using EMT Custom Devices
Grid enhancing technologies	Grid Enhancing Technologies	EPRI, ABB, DNV GL, New York Independent System Operator, Pacific Gas and Electric Company	EPRI and other entities show the potential benefits and values of Power Flow Control (PFC) technologies for integration of renewables	• Benefits and Value of New Power Flow Controllers • Improving Transmission Operation with Advanced Technologies: A Review of

Topic	Project Title	Entities	Description	References
				Deployment Experience and Analysis of Incentives
	Transmission Topology Optimization	ERCOT, National Grid UK, PJM	NewGrid has developed NewGrid Router, the first production-grade topology decision support software tool, based on the TCA technology - Practical solution for quickly identifying beneficial reconfiguration of the transmission grid, particularly when severe conditions on the grid place risks on the operations of certain segments or components of the transmission network.	• Presentation
Wide area monitoring and control	Oscillation Source Locating software (OSLp)	ISO-NE	ISO-NE has developed the Dissipating Energy Flow method for locating the source of sustained oscillations in power systems	• Software Tool • Method
	Wide Area Oscillations Damping Control	EPRI, TERNA, NYPA, SEC, HVDC Centre UK	EPRI has developed in both software and hardware a wide-area oscillation damping controller that uses PMU measurements as an input and FACTS, HVDC, Generators, and BESS as actuators to damp inter-area and forced oscillations	• TERNA case study • NYPA case study • SEC case study

Topic	Project Title	Entities	Description	References
	PMU Based Inertia Estimation and Forecasting	National Grid UK, GE, Reactive Technologies	National Grid UK is piloting PMU based inertia estimation and monitoring tools developed by GE and Reactive Technologies	• NASPI Meeting Slides • Press Release
	Learn to Run a Power Network (L2RPN)	RTE, EPRI, UCD, Google, PNNL, V&R Energy	Using machine learning and artificial intelligence techniques, evaluate the ability of operate a power system in real time.	• Website
	WAMCS Testing and Operator Training	-	Summary of facilities to create, model and test WAMCS	• Utilities Current Practice with Real-Time Hardware-in-the-Loop Simulations
Dynamic line rating	Dynamic line rating for effective use of transmission assets	-	Summary of Dynamic Line Rating (DLR) activities	• ENTSOE Report: DLR • IRENA report: DLR
	Overhead Transmission Predictive Rating Methods and Risk Concepts	EPRI	EPRI developed an approach to improve predicted and forecasted ratings using risk informed decision making	• Overhead Transmission Predictive Rating Methods and Risk Concepts
Cybersecurity	Recommended Functionalities for Improving Cybersecurity of Distributed Energy Resources	NREL	NREL published a report, in which it discusses the current industry's best practices related to DER cybersecurity and proposes recommended functionalities for improving the cybersecurity posture of DERs, specifically at the	• Report

Topic	Project Title	Entities	Description	References
			device/distribution level.	
	Cyber Attack and Defense for Smart Inverters in a Distribution System	Washington State University, VirginiaTech	A signature-based Intrusion Detection System (IDS) is developed to detect cyber intrusions of a distribution system with a high level penetration of solar energy.	• Paper
Planning for extreme events	Power system planning for extreme events	PNNL	PNNL developed a tool that finds mitigating actions to reduce the risk of cascading outages in technically sound and effective ways	• Dynamic Contingency Analysis Tool (DCAT)
	Power system planning for extreme events	EPRI	EPRI developed a tool to help transmission planners assess the impacts and consequences resulting from the application of high impact, low frequency contingency events on their systems. The tool determines the risk of adverse system impacts emanating from the extreme contingency event	• Resilient System Investment Framework (RSIF) Version 2.0
	System security and system reliability responses to climate-related risks	-	Summary of climate-related risks when planning the power system, we review studies conducted to date, reports produced by utilities system planners/operators,	• Potential for Incorporating Climate-Related Risks into Transmission Network Planning

Topic	Project Title	Entities	Description	References
			and various planning organizations	
Resource adequacy	Probabilistic Adequacy and Measures	NERC	Summary of existing applications of probabilistic techniques used for reliability assessment and planning studies	• Probabilistic Adequacy and Measures
	Probabilistic Risk Assessment for Transmission Planning	EPRI, EISPC, NARUC	Demonstration of how explicit probabilistic methods could at the very least form an adjunct to the existing deterministic planning methods	• Report
Scenario development	High Level Screening of Hourly Power Flows for Planning Studies	EPRI	EPRI developed a tool that screens through potentially thousands of operating conditions to determine a subset that best captures the essential characteristics of system operation.	• High Level Screening of Hourly Power Flows for Transmission Planning (HiLS)
	ESOO and Reliability Forecast Methodology document	AEMO	AEMO published the ESOO and Reliability Forecast Methodology document, which explain the key supply inputs and methodologies involved in determining the expected USE outcomes, for both the ESOO and the reliability forecast. It also explains how the forecast reliability gap and	• ESOO and Reliability Forecast Methodology Document

Topic	Project Title	Entities	Description	References
			forecast reliability gap period are determined.	
	Electricity Demand Forecasting Methodology	AEMO	forecasting methodologies used by AEMO to provide projections of customer connections, customer technology adoptions, electricity consumption, maximum and minimum demand over a forecast period up to 30 years for each region of the National Electricity Market (NEM) and up to 10 years for the Wholesale Electricity Market	• Electricity Demand Forecasting Methodology

3.3. Key Research Questions

An initial set of research questions, as detailed below, were previously formulated through the Global Power System Transformation (G-PST) Consortium [5]. This initial set was also mentioned in CSIRO's initiative for development of a research roadmap for this topic.

1. What approaches can be taken to near real-time system modelling with large quantities of IBR that make design for system stability sufficiently accurate and still tractable?
2. What methods can be used for off-line and on-line monitoring tools for detecting incipient instabilities? What new capabilities are needed to address these limitations?
3. What type of on-line contingency and stability analyses should be conducted at changing levels of IBR?
4. What analytical tools and models should be provided to planners and operators for robust assessment of system performance?
5. What tools are needed for operational analysis of higher impedance grids?
6. What analytical methods and tools should be used to determine the appropriate mix and capabilities of Grid-Forming and Grid-Following inverters to mitigate low inertia conditions for a given power system?
7. What are the appropriate analytical methods and tools to determine – for a given power system – the extent to which very fast frequency response can substitute for inertia. Relatedly, what tools and methods are needed to effectively compose a mix of Δf and df/dt responses?

8. What tools and methods are needed to identify the best mitigation strategies for voltage-collapse problems under high IBR conditions? And how effective is IBR in recovering from deep voltage dips (bearing in mind lack of short-term overload current)?
9. What are the opportunities and challenges of upgrading existing tools vs. building new ones, and where new tools are required, what are appropriate pathways to conversion?

It is not expected that each question listed above will uniquely map to a particular section of the research roadmap. Rather these questions will serve as a framework to develop the research roadmap and provide conceptual background into various sections of the roadmap. In order to go into the various details and nuances associated with each of these nine questions, each is split into sub-categories and concepts as detailed concisely below. It is to be recognized that there can be overlap between the sub-categories of multiple questions as the same analysis method/tool can be used in multiple situations.

1. *What approaches can be taken to near real-time system modelling with large quantities of IBR that make design for system stability sufficiently accurate and still tractable?*
    a. Exploration of avenues to create a digital twin of the network
    b. Development of methods to estimate the quantity of behind the meter distributed energy resources (DER)
    c. Creation of processes to obtain validated and verified dynamics models of all dynamic devices
    d. Comprehensively update and verify load models to also include DER dynamic behaviour
    e. Incorporate behaviour of protection system elements into dynamic simulation studies
    f. Carry out improvements in setting up and conducting real time contingency analysis beyond N-1 contingencies
2. *What methods can be used for off-line and on-line monitoring tools for detecting incipient instabilities? What new capabilities are needed to address these limitations?*
    a. Develop methods and associated infrastructure to continuously track in real time:
        i. the evolution of damping in the system with changes in system conditions
        ii. the evolution of system strength and incorporate the results into real-time operating decisions
        iii. the available on-line system inertia, not just from transmission connected generators, but also from load and distribution connected generators
        iv. the system operating point with respect to operation boundaries to have visibility on available system stability margin
        v. using ambient data, determination of region of attraction of operation point about system equilibrium to determine stability boundary.
    b. New capabilities that will be needed can include methods to:
        i. evaluate occurrence of instability caused by an initiating large signal event
        ii. evaluate real-time change in network impedance as seen by each device in the network and translate this change to possible change in system modes

        iii. observe and react to change in dynamic line ratings for effective use of transmission assets
        iv. harness and efficiently utilize vast amounts of data generated across the entire network, potentially through use of machine learning algorithms.

3. *What type of on-line contingency and stability analyses should be conducted at changing levels of IBR?*
    a. From a small-signal stability perspective, stability analysis should provide observability into:
        i. change in system damping with changes in operating point
        ii. change in system resonant modes with changes in operating point
        iii. evolution of control interaction among various power electronic devices and network elements.
    b. From a large-signal perspective, contingency analysis should provide insight into:
        i. Refine existing or define new contingencies for real time analysis
        ii. largest loss of generation/load that can be tolerated by the system at the present operating point
        iii. ride through confirmation of power electronic devices with change in network topology
        iv. availability of adequate transfer capability over critical flowgates
    c. Few potential new capabilities that would be required are:
        i. evaluation of the presence of new common mode failure points and their impact on the system operation
        ii. faster screening and isolation of contingencies that can bring about potential instabilities in system operation
    d. The above topics should also be coordinated with respective aspects of stability analysis covered in the roadmaps from Topics 1 and 4.
4. *What analytical tools and models should be provided to planners and operators for robust assessment of system performance?*
    a. The ability to accurately simulate and assess system performance depends on the availability of validated models for all power system equipment and not just new devices that interconnect to the network. Models of conventional generators, FACTs devices, and load play a crucial role in depicting sufficient simulation behaviour.
    b. Although OEM provided dynamic models for IBRs are most accurate, such models can exist only once the inverter/turbine developer is known for the plant, and the plant is commissioned. For studies (such as long-term planning studies) where this information will not be available, robust generic models that can be used for preliminary studies are to be developed both in positive sequence domain and EMT domain. These generic models will have to be continuously updated as the state-of-the-art changes.
    c. OEMs presently develop and tune their models based on a single machine infinite bus based representation. But often, system response is determined by the interaction

   between two or more elements in the network. Development of reduced network equivalents that can not only represent the steady state impedance/system strength but also represent the dynamic behaviour of the network will be useful for model validation and tuning.

   d. Many OEMs may use adaptive values of gains that change based on system operating condition. Representation of this behaviour in the associated models will become critical.

   e. Tools to determine and evaluate the adequacy of reactive power in a region and management of voltage profile across interfaces.

   f. New analytical metrics to evaluate adequacy/sufficiency of system strength and inertia.

   g. Methods to evaluate and construct coordination of wide area protection and control schemes

   h. Schemes to schedule and coordinate maintenance outages and evaluation of its associated impact on protection system operation and system stability

   i. Methods to evaluate impact of grid enhancing technologies from a planning perspective.

   j. Methods to evaluate impact of extreme events from a planning perspective.

   k. Methods to determine evolution of system resource adequacy and flexibility while considering the stochastic nature of wind and solar resources

   l. New capabilities are needed to identify complete system oscillatory modes, especially with black box IBR models

   m. New capabilities are also needed to identify contribution of individual devices to observed harmonics and ferroresonance.

5. *What tools are needed for operational analysis of higher impedance grids?*

   a. Evaluation and evolution of system strength with change in unit commitment, maintenance outages, network topology and IBR operation point.

   b. Evaluation of potential of voltage collapse and distance to knee point operation boundary

   c. Operational change in system impedance with change in network topology, unit commitment, and IBR operation point.

   d. Impact of communication delays and loss of communication on control and protection system element operation

   e. Analytical methods and supporting tools to evaluate/compare the use of synchronous condensers, batteries, and other technologies to improve grid strength

   f. Supporting tools and infrastructure to enable potential broader use of hardware-in-the-loop platforms.

6. *What analytical methods and tools should be used to determine the appropriate mix and capabilities of Grid-Forming and Grid-Following inverters to mitigate low inertia conditions for a given power system?*

a. From planning perspective, detailed studies should be performed using the following steps:
    i. Determination of future scenarios for different penetration levels of IBR
    ii. For a given scenario, sensitivity studies should be performed to identify an approximate mix of grid forming and grid following controls for multiple dispatch conditions to assess
        1. frequency response adequacy and prevention of operation of under frequency load shedding schemes
        2. voltage control and recovery following a large disturbance
        3. impact of communication delay and locational impact of response
        4. evolution of system damping
        5. evaluation of harmonic content and power quality of the network
        6. Determination of largest phase angle difference across the network
b. From operations perspective, the following aspects should be considered:
    i. System should be monitored in real time to keep the mix within an acceptable range (need information about controls of individual plants)
    ii. System restoration and blackstart needs should be considered
c. The above topics should also be coordinated with respective analytical methods covered in the roadmaps from Topics 1 and 4

7. *What are the appropriate analytical methods and tools to determine – for a given power system – the extent to which very fast frequency response can substitute for inertia. Relatedly, what tools and methods are needed to effectively compose a mix of Δf and df/dt responses?*
    a. Detailed planning studies should be performed which will involve
        i. looking at various penetration levels of IBR
        ii. for each penetration level, identifying frequency stability issues and looking at efficacy of using FFR from IBRs along with synchronous condensers, BESS as well as end-use load
    b. Additionally, impact of use of VSC-HVDC for transmission system reinforcement and supply of frequency response services.
    c. Coordinate with resource adequacy and dynamic reserves assessments to ensure FFR is available when needed.
    d. From operations perspective,
        i. evaluation of locational spread of frequency response services that will provide an efficient response profile
    e. Better estimation of damping provided by loads
8. *What tools and methods are needed to identify the best mitigation strategies for voltage-collapse problems under high IBR conditions? And how effective is IBR in recovering from deep voltage dips (bearing in mind lack of short-term overload current)?*

   a. Locational determination and size of devices such as FACTs, BESS, and condensers.
   b. Development of scenarios that represent most probable operational profiles
   c. Potential to use grid enhancing technologies
   d. Specification of grid codes to standardize voltage ride through behaviour of IBRs both for balanced and unbalanced events
   e. Development of protocols and practices for good control system development of IBRs

9. *What are the opportunities and challenges of upgrading existing tools vs. building new ones, and where new tools are required, what are appropriate pathways to conversion?*
   a. Opportunities with upgrading existing tools:
      i. Large user base and familiarity can help with adoption of new models and methods in the existing tools
   b. Challenges with upgrading existing tools:
      i. Legacy code and solutions techniques can make existing tools difficult or impossible to adopt for new methods and models
      ii. May not be ready for HPC platforms
   c. The opportunities that can be leveraged for new tools are:
      i. superior computation capability and methods that continue to improve
      ii. distributed and parallel computing
      iii. co-simulation of multiple time scales and sectors
      iv. use of hardware-in-loop platforms
   d. The challenges that can arise to building new tools are:
      i. adequate data security and management. IBR controls are heavily protected by IP and maintaining data security while still being able to carry out accurate studies will be a challenge
      ii. validation and upkeep/maintenance of various models across different simulation platforms.
      iii. training of workforce to get familiar with new tools and capabilities. In general adopting new tools can be challenging if it implies changes in existing planning and operating procedures
      iv. given the complex nature of the challenges, one tool won’t suffice all the needs. It is important to clearly define specifications of the tool
   e. The pathway to appropriate conversion to new tools should involve addressing the challenges mentioned above. In addition, the following steps will be helpful:
      i. Identifying and involving stakeholders as early as possible in the discussion
      ii. Scheduling sufficient time for testing and adopting the tool in the existing framework
      iii. Consideration for computational infrastructure, data management and cybersecurity in the early design stages

In addition to the above questions which are related to conventional and upcoming stability concepts and association tools, methods and associated tools that are presently used to configure the settings of protective relays and ensure coordination among the neighbouring protection zones, will also need to evolve. In particular, such tools should consider and model the complex fault response of IBRs. They should also include new protection functions that are expected to be developed and emerge to ensure a reliable and dependable protection system in IBR-dominated grids. The protection zones are not expected to change, however due to low fault current levels from IBRs, fault detection will be challenging, and differentiation of primary vs backup protection zones will be complex, rendering the coordination of the respective relays within those zones a complex task.

In the subsequent chapter, additional details will be provided related to these topics and concepts.

4. The Research Plan

4.1. Research plan overview

The research plan is structured around twenty-one topic areas that are identified based on the questions and categories identified in the previous chapter. These topics are prioritized into four tiers within this chapter.

1. **Critical topics**
   - If not addressed in the immediate future, can significantly increase the likelihood of stability violations at sustained high levels of IBR penetrations
   - If addressed in an efficient manner, will significantly ease the current computational burden for planning and operation of the network
   - Tools developed from these topics would provide increased situational awareness and analytical capability for the future power network
2. **High priority topics**
   - Work products can serve either as inputs or constraints to the Critical topics
   - Already have some tools and methods developed but can benefit from further improvement as the power system transitions
   - Tools developed from these topics would also provide increased situational awareness and analytical capability for the future power network
3. **Medium priority topics**
   - Can directly influence the stability of the network, but do not directly influence the development of tools to evaluate stability
   - Can be addressed using the tools and methods developed either through the critical or the high priority topics
4. **Low priority topics**
   - Indirectly connected with stability assessment: Outcomes from these topics are used to generate the initial operating condition at which stability of the system is to be evaluated
   - Typically addressed in much more detail in research roadmaps for other CSIRO *Australian Research Planning for Global Power Systems Transformation* topics

The table below tabulates the mapping between these twenty-one topics and the initial G-PST questions. Only the first eight G-PST questions are listed in the table as the ninth question which is related to opportunities and challenges with use of existing tools and development of new tools can span all twenty-one topics.

Table 4: Mapping of twenty-one research topics in this roadmap to original G-PST questions

Priority	Topic	Original G-PST questions							
		1 – Real-time system modelling	**2 – Monitoring for instability**	**3 – On-line contingency analysis**	**4 – Tools and models for performance assessment**	**5 – Operational analysis of high-impedance grids**	**6 – Determining mix of grid-forming and -following**	**7 – Determining substitution of FFR for inertia**	**8 – Mitigation strategies for voltage collapse and recovery**
Critical	1. Stability margin evaluation		✓	✓	✓	✓	✓		
	2. Small signal stability screening methods			✓	✓	✓	✓		
	3. Voltage stability boundary	✓	✓		✓	✓			✓
	4. Voltage control, recovery, collapse			✓	✓	✓	✓		✓
High	5. Online identification of system strength	✓	✓			✓			
	6. Monitoring inertia in real time	✓	✓						
	7. Modelling and model validation	✓		✓	✓		✓	✓	
	8. Voltage and reactive power management		✓		✓	✓			✓
	9. Real time simulators	✓				✓			
	10. Critical contingency identification			✓				✓	
	11. Real time contingency analysis	✓		✓		✓			
	12. Protection system operation and coordination	✓		✓			✓	✓	
Medium	13. Harmonics and power quality				✓		✓		
	14. Outage scheduling			✓					
	15. Grid Enhancing Technologies				✓		✓	✓	
	16. Wide area monitoring and control		✓		✓	✓			✓
Low	17. Dynamic line rating			✓		✓			
	18. Cybersecurity					✓	✓		
	19. Planning for extreme events			✓	✓				
	20. Resource adequacy			✓	✓			✓	
	21. Scenario development				✓		✓	✓	

It is recommended to begin work with the *Critical* and *High priority* topics. Although there are interrelationships among many of the topics identified here, there are no critical dependencies that require any specific sequence for undertaking them. Table 5 below provides initial suggestions for tool development for all topics. Development of each tool requires domain specific knowledge to be applied. Also, in each of these topics, Australian research does not have to start from scratch, as there are complementary efforts underway around the world. Collaboration with these organisations will foster increased and faster application of research.

In the table below, each topic (row) corresponds to a detailed section of the same name that appears later in this chapter. Regarding the columns of the table,

1. *Australian priority* identifies whether the research topic can be a pressing need from an Australian perspective, or can learnings be applied from work from around the world;
2. *Initial tool development timeline* is an estimate for development of a prototype tool and its first implementation in power system planning and operations;

3. *Approximate total budget* is an estimate of the total funding required to complete the initial (prototype) tool development;
4. *Initial tool application horizon* indicates the planning or operations horizon for the first intended application of the tool. As these tools mature and develop further, the application horizon can change. For example, tools to evaluate stability margins can first be applied in the long-term planning horizon. However, as these tools develop and are able to handle various power flow operating points along with black box IBR models, their use can be extended to the near real-time planning and operations horizon;
5. the last column lists names of organizations around the world with whom collaboration projects can be extended, if necessary.

Table 5: Research topic summary for stability tools and methods

Topic	Australian priority	Initial Tool Development Timeline	Approximate Total Budget (AUD)	Initial Tool Application Horizon	Leverage ongoing work from
Critical topics					
Stability margin evaluation	Research may be conducted in Australia	3 years	1,500,000	Long term planning and near real time	Aalborg University Denmark, EPRI USA, Imperial College London, NREL USA
Small signal stability screening methods	Research may be conducted in Australia	3 years	1,500,000	Long term planning and near real time	Aalborg University Denmark, EPRI USA, Imperial College London, NREL USA
Voltage stability boundary	Research may be conducted in Australia	2 years	100,000	Real time and near real time	EPRI-ISONE USA
Voltage recovery and collapse	Learn from others around the world	3 years	600,000	Long term planning and near real time	EPRI USA, IESO Canada, Iowa State and Washington State University USA, National Grid USA
High priority topics					
Online identification of system strength	Research may be conducted in Australia	2 years	150,000	Real time	EPRI USA
Real time inertia monitoring	Learn from others around the world	2 years	150,000	Real time	EPRI USA, National Grid UK, NREL USA, Tokyo Electric Power Japan
Model validation	World leader but room for improvement	3 years	600,000 (including models of existing resources and loads)	Long term planning	EPRI-NERC-PNNL-WECC USA
Voltage and reactive power management	Research may be conducted in Australia	3 years	450,000	Near real time	EPRI USA, ERCOT USA, PJM USA

Topic	Australian priority	Initial Tool Development Timeline	Approximate Total Budget (AUD)	Initial Tool Application Horizon	Leverage ongoing work from
Critical contingency ranking and evaluation	Research may be conducted in Australia	3 years	600,000	Long term planning and near real time	EPRI USA
Real time contingency analysis	World leader but room for improvement	3 years	300,000 (excludes hardware)	Real time	MISO USA
Protection system operation and coordination	Research may be conducted in Australia + Learn from others around the world	3 years	450,000	Long term planning	EPRI USA, National Grid UK, NYPA USA, Sandia National Lab USA, TERNA Italy
Medium priority topics					
Outage scheduling	Research may be conducted in Australia	2 years	200,000	Near real time	CAISO USA, EirGrid Ireland, EPRI USA
Grid Enhancing technologies	Learn from others around the world	2 years	200,000	Long term planning	Hitachi ABB, GE, Siemens, SmartWires
WAMS and WAMCS	Learn from others around the world	3 years	600,000	Near real time	EPRI USA, TERNA Italy
Low priority topics					
Dynamic line rating	Learn from others around the world	3 years	600,000 (excluding hardware)	Real time	Ampacimon, LineVision, EPRI USA, ERCOT USA, Idaho National Laboratory USA
Cyber security	Research may be conducted in Australia	2 years	200,000	Long term planning	EPRI USA

The following sections discuss each topic in detail. A specific research plan is proposed for *Critical*, *High priority*, and *Medium priority* topics that details:

- preparation and inputs
- research projects and objectives
- expected outputs
- estimated timeline
- required skill sets

4.2. Critical topics

The critical topics are those which, if not addressed in the immediate future, can significantly increase the likelihood of stability violations at sustained high levels of IBR penetrations. These are also topics that, if addressed in an efficient manner, will significantly ease the computational burden currently required for carrying out detailed high fidelity EMT studies for planning and operation of the network. The tools developed from these critical topics would provide increased situational awareness and analytical capability for the future power network.

4.2.1. Stability margin evaluation

Discussion

With an increased number of IBRs connected to the transmission system, each with their own proprietary control algorithm, evaluation of large signal stability is traditionally carried out by running computationally intensive EMT domain simulations. While there can be modifications and improvements made in simulation environments and advanced co-simulation packages and techniques can be used, the models used to represent IBRs in these studies are most often blackbox models provided by the OEM. In such a scenario, even with high performance computing facilities (which is still rare outside the research world in the field of power systems), carrying out multiple EMT runs is usually time consuming and data intensive and further, evaluation of the root cause of instabilities is neither trivial nor standardized. Here, large signal stability includes fault ride through.

Analytical evaluation of the performance and stability of blackbox IBR models has so far been largely limited to the small signal domain either through measurement-based [7] or transfer function based [8] impedance analysis. While there exists a vast body of research literature on evaluation and insight into the large signal stability of IBRs, most (if not all) depends upon exact knowledge of the details of the IBR control structure which can subsequently be used to design and tune the controls to bring about robust behavior.

However, from a transmission system planner/operator perspective, knowledge of the IBR control details is generally not available due to IP management of the OEM. Thus, there is a distinct gap in evaluation of the IBR large signal performance. Further, even though the OEM (who does have visibility into the exact control structure) designs their controls to be robust and stable, invariably this exercise is carried out in a single machine infinite bus setup. Thus, stability obtained cannot be guaranteed in a larger network where multiple OEM devices can be present. Stability margin in this context is not only voltage stability margin (covered specifically later on in this chapter). Instead, it can also include a relationship between controller operation and protection operation, which would conceptually be similar to critical clearing time.

Open research questions

Potential open questions on this topic include:

1. Is it possible to evaluate non-linear stability margins using blackbox IBR models? Here, non-linear refers to the large signal behavior of the IBR. Blackbox models should good enough if the model reflects actual device behavior under different conditions. E.g limits modeled properly, controller saturation modeled properly, internal device protection modeled properly etc. The blackbox model should also possibly capture the dynamics of an IBR over a specified frequency range. However, research would need to be done to evaluate whether a non-simulation based analytical process can be used to evaluate the stability margins under varying network behavior.
2. Would there be an approach to construct piecewise impedance scans at different operation points to obtain a large signal picture?
3. How would stability properties of other sources in the network be represented when designing an IBR plant?
4. Would it be possible to efficiently evaluate small signal modes and stability profile with black box models?

4.2.2. Screening methods to evaluate small signal system stability

Discussion

As higher penetration of IBRs become the norm across power systems worldwide, system planners will have to rely on effective methods to study potential converter stability and the use of more refined EMT type models. Methods that can be used at planning stage for screening of stability risks should become more prevalent. The main idea behind screening methods is that they provide simplified but useful information to reduce the total number of scenarios that may need to be looked at in detail, via EMT time domain simulations. One of the most effective methods that has been used and continues to evolve in industry are methods based on impedance-based frequency scans. These methods provide a detailed impedance seen into power system equipment and/or the network, such that resonant conditions or low damping conditions can be identified. The methods can often be run with both positive sequence tools as well as EMT tools and allow the investigation of several network topological conditions as well as operating conditions with a relatively low computational burden.

The electric power industry has widely employed impedance-based methods in the past for the study of sub-synchronous resonances, torsional interactions, and control interactions [9] [10] [11] [12] [13]. While the use of impedance-based methods to identify the risk of these converter driven interactions has been utilized in industry [14] [15] [16] [17], they are not widely employed in most power systems planning groups, often being limited to special studies and advanced power system studies. One reason is that while the use of impedance-based methods is not new, the study approaches to evaluate converter stability risks and how those translate and align with time-domain simulation results have not been extensively documented. Proper documentation of the various methods proposed, simulation domains (EMT and positive sequence), their benefits and limitations, as well as how to use the extracted impedances to evaluate the risk of converter interactions or instabilities should help make these methods more applicable.

Further, impedance-based methods like any small signal stability technique is based on the operating point at which the impedance is evaluated. Small changes in the operating point in relation to angle, voltage magnitude, or reactive power output can lead to differences in stability of the system. In such a scenario, it is important for transmission planners and operators to be able to identify risks to system stability with changes in power flow and voltage across the network. Although AEMO's Power System Model Guidelines [18] prohibits use of a small signal model that is only valid at a single operating point, the black box nature of IBRs can cause challenges in formulation of a suitable small signal model that can be valid over multiple operating points. There are few research efforts underway around the world to tackle the development of such a small signal model, but more work is yet to be done.

Open research areas

In this space, some of the topics that can be addressed in near term research are denoted below.

1. Identification of procedures to use impedance-based methods for stability screening and screening of converter driven stability risks. The methods and practices should be simple and yet reasonably accurate and aimed at reducing the total number of scenarios that need to be investigated with the use of detailed EMT time domain simulations.
2. Documentation of methods that use extracted impedances to screen for risk of converter interactions as well as risk of instability.
3. Continuous development and use of impedance-based tools that can be applied in both positive sequence domains as well as EMT. Positive sequence impedance-based tools can perform accurate scans while considering various network topological conditions with relatively minor computational effort. However, care should be taken to represent inverter

interfaced resources as their impedance characteristics is not easily available and will vary with loading conditions, control modes used, and so on.

4. The use of linear frequency domain methods, such as linear models and eigenvalue analysis is another area that could benefit from additional research. It is well understood that linear methods can be used as an additional tool for the evaluation of some of the converter driven instabilities mentioned in this document. However, detailed linearized models for IBRs is not something that is widely available in industry now. While some commercial applications for linear/small signal analysis exist, those mainly account for models used to study electromechanical modes, such as inter and intra area oscillations. To study faster control interactions, the tools and models used would have to account for the faster regulators that impact a lot of those control instabilities. To what extent linearized models of IBRs can capture some of these phenomena and how those models should be developed is another area that would require further investigation.
5. Development of a multi-operating point small signal model (either impedance based or linearised state space). Here again, there should be close synergy with Topic 1 to develop a multi-operating point model that can also be easily interfaced with existing small signal stability tools used by TNSPs in Australia.

4.2.3. Tracking of voltage stability boundary

Considering that many of the analyses described in this report were initially designed for power systems dominated by synchronized machines, as IBR penetration increases, their asynchronous and deliberate control behaviors begin to dominate system behavior requiring revisions to the analytical processes and the tools to implement them.

Tracking system operating boundaries with respect to voltage stability can be accomplished with two power system analyses. Steady state power flow models can be analyzed with linear approximations to accurately determine the distance from a given operating point to standard voltage limits [19] [20]. While the distance metric can be defined arbitrarily, useful ones are in the voltage control space and in the expected future direction of the operating point.

Steady state power flows can also be analyzed with power transfer analyses to determine the point at which the voltage across an interface (or flow gate) falls below a standard voltage limit or when the Jacobian of the power balance equations becomes ill-conditions, signaling voltage collapse. Alternatively, a power flow formulation using a bus angle + reactive withdrawal [21] representation can maintain Jacobian stability throughout the transfer analysis.

Impact of increase in IBR percentage

Transfer analyses conventionally assume that a collection of power injection and withdrawal buses can be specified that represent practical changes in the power flow. These changes may be based on historical flow patterns, when the flows are repeated and predictable. Since IBRs include variable and uncertain power injections from wind and solar plants, flow patterns may likewise become variable and uncertain, making this approach less practical. An alternative is to design the transfer (pattern of injections and withdrawals) based on the existing system conditions, as in [22], where important transfers may be the direction of future operating points or the closest pre- and post-contingency voltage limits.

Open research questions

Some avenues for future research include extension of evaluation of critical operating boundaries to

1. Recognize new types of operating criteria, like voltage stability boundaries and transient stability boundaries
2. Trace arbitrary boundaries in a pre-defined subspace of the available controls
3. Define one- or two-dimensional transfer analysis for commercial tools

4.2.4. Voltage control, recovery, and collapse

Discussion

Voltage stability refers to the ability of a power system to maintain steady voltages close to nominal value at all buses in the system after being subjected to a disturbance. It depends on the ability of the combined generation and transmission systems to provide the power/current requested by loads. In the short-term time scale the dynamics of induction motors make a dominant impact while in the long-term time scale thermostatically controlled loads and Load Tap Changers influence the stability. The other factors that contribute to voltage stability include the capability limits of var supplying devices including the synchronous generator. Inverter-based resources impact voltage conditions, primarily the transient voltage recovery process after contingency. This is because unlike synchronous generators, converters generally cannot supply large currents during the fault recovery period. IBR controllers are designed to limit the current within safe levels, even if they are capable of riding through voltage and frequency excursions. Besides, converters have various controllers implemented on them to meet grid codes reliability and performance requirements. These controllers may also influence the short-term voltage stability [1].

Power system utilities perform a variety of system studies on voltage control and reactive power management, in time frames ranging from long-term planning (6-10 years) to real-time assessment. Long-term planning studies are performed by transmission planners to assess expected system performance to ensure future system meets the reliability criteria. The studies identify reactive power deficiencies and indicate solutions or system reinforcement options that need to be pursued to address the identified voltage performance problems. Operational planning studies evaluate whether a transmission outage can be taken on a given set of equipment without compromising the reliability of the power system. The time frame for this analysis is in the window of one or even two years to the day before an outage takes place depending on the utility or reliability coordinator. In real-time operation, the operations staff in the power control centre monitor the network through the Supervisory Control and Data Acquisition (SCADA) and EMS functions to understand the current operating condition for situational awareness purpose. Real-time security assessment through simulation analysis is conducted to prepare for any contingencies or change in the operating condition that may risk operation security [23].

Volt/var assessment studies in planning and operation usually include power flow and contingency analysis, as well as other steady state-based methods like PV and QV analysis. A dynamic analysis is normally performed in long-term planning studies and in many cases as part of an operational planning study in various time frames. Dynamic studies are useful for validating the reactive power requirements determined through the steady state analysis. Additionally, dynamic studies are usually needed to identify the static and dynamic balance of reactive power resources needed to ensure system reliability.

Open research areas

Even though the impact of variable renewable generation and IBR on voltage stability and control has been extensively investigated by the industry and academia, most transmission utilities continue to perform Volt/var control and stability studies using traditional methodologies and tools. Nonetheless, the need to reassess the applicability of traditional methods has been recognized, and currently there are some collaborative industry efforts to address this issue. A joint CIGRE and IEEE working group (CIGRE JWG C4/C2.58/IEEE - Evaluation of Voltage Stability Assessment Methodologies in Transmission Systems) was launched in 2019 with the objective to gather experiences and practices of the power industry on voltage stability assessment in the planning and operational time frame, identify any shortcomings in the classical methodologies, and evaluate new methodologies to assess voltage stability in power systems with increased IBRs. An industry survey conducted as part of the working group activity revealed that many utilities are concerned about the accuracy and validity of Volt/var assessment studies based on classical methodologies and tools. In some cases, entities consider an extra safety factor to cover for possible deficiencies in the evaluation process. Some entities are working on improving load and IBR models suitable for different types of studies. The work of this working group is ongoing, hence there are no conclusions yet on the characteristics and requirements for new voltage stability and control assessment tools, but it is expected that some features of conventional methodologies will need to be adapted and expanded to better assess system conditions with large penetration of IBR.

Other aspects to consider in operation with high level of IBR is the occurrence of high voltage conditions. Worked performed by EPRI on this topic has shown that many transmission companies are experiencing some degree of increasing high voltage occurrences in operation. Various drivers have been identified behind this issue with the most dominant being the extra high voltage transmission system additions to meet reliability needs during peak load periods and retirement of existing generation resources with capability to absorb reactive power. As penetration of IBR displacing conventional generation increases, it is expected that high voltage problem issues will became more prevalent. Entities have been improving operator tools and processes to better deal with high voltage problems, but a gap exists in recommending mitigation actions for operators. In most cases, operators implement control actions from experience rather than based on the outcome of dedicated analysis tools. Therefore, considering the trend toward increasing high voltage problems in operations, the need for improved procedures and suitable analysis tools has become apparent.

Utility scale solar plants with night var capability can provide reactive power at night when no real power is being produced by the solar panels (operation as STATCOM). Hence, they could be complementary measures for controlling high voltage in transmission. In general, the effectiveness of the reactive capability of the solar plants is location and size specific. Detailed analysis for each solar plant with respect to a specific voltage issue would be warranted to determine the impact of having reactive power capability with zero solar irradiance. The design of plant should also be analysed to ensure the inverters and plant equipment are within their respected voltage limits [24] [25].

4.2.5. Research plan for critical topics

The above four critical topics can be further grouped into two clusters with one cluster consisting of the topics on stability screening and stability margin evaluation and with another cluster consisting of the topics on tracking of voltage stability boundary along with evaluation of voltage collapse and recovery. For both these clusters, the following steps are recommended as initial steps to be carried out in application of the roadmap:

1. Stability margin evaluation and small signal stability screening:
    a. Preparation stage:
        i. Consolidate with CSIRO Topic 1 (IBR Design) roadmap to ascertain the challenges associated with evaluation of impact of IBR controls on stability.
        ii. In consultation with IBR OEMs, develop an understanding of IBR controls and their behaviour.
        iii. Get a baseline from IBR OEMs on ways in which they can provide linearised small signal models that can be used at multiple operating points (such as blackbox small signal state space models)

b. Formulate research projects with objectives to:
    i. enable the creation of blackbox small signal state space models
    ii. allow for efficient evaluation of impedance spectrum of both IBR and network at multiple operating points
    iii. investigate use of non-linear stability analysis for large signal stability behaviour of various power electronic equipment
    iv. allow for OEMs to communicate change in control algorithms/parameters and its impact on change of small signal model
c. Expected outputs from these research efforts can be:
    i. modular small signal models of black box IBRs and stability screening methods/process that can be seamlessly integrated into existing small signal analysis software. This would allow for seamless analysis of large networks. This would also require coordination with representatives from existing simulation software.
    ii. Use of the developed models, tools, and analysis to ascertain future deployment of IBR control methods, their ratings, and their locations to bring about stable operation of the grid.
d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
    i. 3 years
    ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.
e. Expected skill sets include understanding of:
    i. power system analysis and dynamics
    ii. power system planning and operation
    iii. control system theory and stability, and mathematical processes and computation techniques
    iv. computer software development and implementation

2. Voltage stability boundary tracking, control, recovery, and collapse:
    a. Preparation stage:
        i. Identify regions/zones of transfer of power over wide range of environmental and operational conditions. This will allow for determination of critical flow paths to monitor for voltage margin reduction.
        ii. Coordinate with Topic 3 research activities to include this information in the control centre
    b. Formulate research projects with objectives to:
        i. evaluate how the voltage profile of the system, and its evolution with respect to the knee point, changes with increase in IBR
        ii. understand if there is a chance of sudden voltage collapse (such as a cliff drop) or would future power network exhibit a more conventional gradual decline of voltage?

        iii. investigate the feasibility of continuing to use existing voltage stability assessment tools for future power networks
        iv. develop methods that will allow for evaluation of night Var capability from IBRs and the management of the network with different reactive power technologies.
        v. develop methods and tools that can screen for short term fault induced voltage collapse, especially due to reduced reactive current contribution from IBRs
    c. Expected outputs from these research efforts can be:
        i. a control centre tool that continuously monitors (or estimates) the voltage and reactive power flow around the network and provides visual output on distance from the stability boundary. Simultaneously, the tool should also evaluate if there is a change in the stability boundary
        ii. a tool to provide real-time decision making capability to deploy reactive power resources to manage voltage levels in the network.
        iii. a tool to provide visibility into area of vulnerability both from the perspective of small signal voltage stability and large signal voltage stability.
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques
        iv. graph theory and network connections
        v. computer software development and implementation

While appropriate methods/tools are being developed for these two critical topic clusters, simultaneously a process can be developed to also address the topics in the second tier of prioritization i.e., the high priority topics. Invariably, the outputs and work products from these second tier topics would serve as direct inputs or constraints that would get used in the methods/tools from the critical tier prioritization.

4.3. High priority topics

The high priority topics are those whose work products can serve either as inputs or constraints to the critical topics. These are also topics that already have some tools and methods developed but can benefit from further improvement as the power system transitions. The tools developed from these high priority topics would also provide increased situational awareness and analytical capability for the future power network.

4.3.1. Online identification of system strength

Lower system strength due to lower fault current in the network can potentially give rise to an increased risk of instability (particularly controller driven instability) and/or voltage variations that could impact system security. While system strength has been traditionally related to the available fault level at a particular bus, no standardised definition is available to quantify the impact of absolute system strength with IBRs. With increase in IBRs, and corresponding retirement of synchronous machines, the available fault level reduces in the network due to two reasons (a) conventional IBR control algorithms require a certain level of short circuit MVA to operate and therefore they 'consume' short circuit MVA, (b) loss of fault contribution from synchronous machine sources. In addition to this, both planned and unplanned outages would result in a change in network topology and possibly online generation which may further reduce system strength. This new reduced value of system strength could be at a value for which the controls of inverter-based generation have not been designed to operate (due to not having visibility into complete system behaviour and instead using a single machine infinite bus representation) and thus, it may cause inverter controller instabilities [26] [27]. Knowledge of the short circuit strength of the local grid is hence essential to achieving a safe and stable system with increased percentage of inverter-based resources. It is even more imperative that observability of the reduction in short circuit strength be obtained in both long term and operational planning system studies.

With many interconnection requests containing inverter-based resources, there is an increasing need to identify potential stability or system strength challenges early in the interconnection process. Most of time, this may imply that detailed electromagnetic simulation studies are to be carried out. This is however a challenge as such simulation studies can be computationally heavy and data intensive. Further, due to the varying nature of wind and solar, it is possible that a daily variation in system strength might occur with high wind in early morning, high solar in the afternoon, along with low wind/solar periods which may require ramping up of other power sources. Due to this daily variation, system operators might need real time visibility of system strength and available fault level across various transmission nodes and generation buses. Such a variation also introduces the concept of appropriate power flow scenario development upon which analysis is to be carried out.

Existing system strength metrics

Increase in IBR in the NEM gave rise to the Fault Level Rule [2] which requires each region's system strength service provider to evaluate and maintain a minimum fault level. But, this value of minimum fault level evaluated with traditional steady state calculations (such as simple short circuit ratio (SCR) or weighted short circuit ratio (WSCR)) [28] may not necessarily imply converter control instability as the controllers may have already been designed and tuned appropriately. Similarly, a high fault level may not guarantee a stable system as the controllers may have not been designed and tuned appropriately. An additional insight can be obtained by using the available fault level metric [28], but even this metric is inherently a steady state metric that is based on IBR manufacturer information regarding minimum short circuit level required by an IBR plant that is already connected to the network. System strength evaluations can also be linked to the X/R ratio of the equivalent impedance seen from a point in the network and/or the available voltage stability margin which can be linked to determination of critical operation boundaries and voltage control areas.

New frontiers

Existing system strength metrics are steady state in nature from which an aim is to infer potential dynamic behavior of IBRs. However, with the development of new IBR performance standards such as IEEE P2800 [29], an opportunity arises to develop metrics that could consider the trajectory of IBR fault response [30] [31] without running a dynamic solution in order to make a determination of available stability margins [32] [33] [34]. These advanced system strength metrics would use dynamic data (controller gains, time constants) of inverter-based resources to identify potential inverter instability.

Online identification of system strength can be challenging due to requiring accurate situation awareness of the network. Here, topology of the network, power flows, voltage levels would be needed. Impact of loss of data or more importantly tampering of data by external actors also needs to be considered and brings about increased focus on the interdependency between the power system and cyber systems. Knowledge of varying system strength and fault levels can then be incorporated into real time market constraints to nudge the unit commitment and dispatch.

An alternative to using short circuit methods to determine system strength in real time can be to use sensitivity-based methods (e.g., dV/dQ). For instance, the total network impedance seen at a bus can be estimated from a capacitor/reactor switching event by dividing the voltage change at a bus by the amount of reactive power change due to the capacitor/reactor switching (dQ), as follows: $X_{grid} \sim dV/dQ$. These methods have the advantage of not requiring a representation of the network topology and may provide reasonable accuracy for most real time applications. However, increase amount of testing and validation is required to ensure accuracy and sufficiency. The methods used to determine system strength online should be merged with improvements in control centres highlighted in Topic 3.

Identification of locations where fault level is to be evaluated can also be refined and varied as the system changes/evolves. In AEMO's existing methodology four categories, (a) metropolitan load centre, (b) synchronous generation centre, (c) regions with high IBR generation, and (d) areas electrically remote from synchronous generation are considered. Power system nodes representing these categories are expected to be nodes that represent the regional behaviour of the network rather than just the local behaviour. Presently, these nodes are however determined based on in-depth knowledge of the network along with engineering judgement. As the system evolves, especially with large increase of DER, a rule-based criteria or method could be developed to verify whether these nodes are still relevant to be considered for system strength evaluation, or would new nodes have to be considered.

Further, in AEMO's existing minimum fault calculation methodology, a pre-requisite is to arrive at a minimum synchronous machine dispatch case. The criteria used to determine such a power flow case is mainly based on generation source fault ride through capability and correct protection system operation. Recognizing that a suitable power flow case with associated unit commitment and dispatch is important in evaluating system strength, one must also consider the impact of changing protection paradigms. As an example, an incorrect operation of protection for a certain synchronous machine dispatch scenario may not necessarily require an increase in the amount of available synchronous machines. Instead, one could also investigate novel and adaptive protection schemes that can cater to a reduced synchronous machine case.

System strength has an inherent link to voltage stability and transient voltage recovery both on generation and load nodes. Following a large signal event such as a three-phase fault, the strength of the network is one of many factors that determine whether there would be an acceptable voltage recovery. The fault ride through capability of individual generation sources can be verified based on expected performance under different system conditions. However, it is not simple to verify the recovery of load pockets, which if unsuccessful in recovering can draw the voltage of a region down thereby further impacting IBRs. Existing methods like a volt/MVA [35] [36] metric allow for preliminary screening of load pockets where voltage recovery can be a concern depending on the load characteristic and network behaviour. The increase in DER percentage could further introduce additional dynamic behaviour that can influence the voltage recovery [37]. Development of voltage recovery metrics that incorporate both load and DER behaviour, along with varying system strength, can provide an efficient analysis of the bulk power system behaviour.

4.3.2. Monitoring inertia in real time and the concept of regional inertia

As the penetration of IBR in power systems increases and displace the conventional synchronous machines, the level of system inertia is inevitably reduced and for some utilities this has begun to raise concerns, or even introduce operational constraints like Critical Inertia Floors, related primarily to peak Rate of Change of Frequency (RoCoF) after a loss of infeed/outfeed and the time available for existing primary frequency response to respond. In response to this, utilities have begun to develop methods for estimating and forecasting power system inertia (control room, real time monitoring against operational constraints) and are performing more detailed dimensioning studies for their responsive resources.

Current practices and estimation solutions

System operators commonly estimate online system inertia by summing the inertia of the Energy Management System (EMS) monitored generators that are online. This process naturally lends itself to forecasting inertia as it can simply be applied to the expected unit commitment for future hours of operation – note, the ability to forecast inertia is essential if it is to form part of operational constraints. Furthermore, this process lends itself to implementation in the control room as the required data feeds are already available.

However, this process only captures the inertia from the ‘supply’ side of the system (EMS monitored generators). In certain systems, the ‘demand’ side of the system can also provide significant inertia. Here the demand side is assumed to incorporate all loads that have rotational energy and all synchronous generation that is either not EMS monitored or does not fall under the category to be considered as a transmission resource. A utility may estimate the inertia of the demand side to have a more accurate understanding of the actual system inertia in meeting Ops constraints and reduce the overall cost of system operation. Estimating this overall system inertia usually requires a measurement-based estimation method in order to efficient. These methods can be separated into large disturbance-based estimation that is mostly applied offline, and those methods based on continuous online monitoring using PMUs (either based on ambient variations or injected power variations). With a system inertia estimate from measurements the demand side inertia is simply the difference between the system inertia estimate and the EMS monitored supply side inertia. More details regarding solutions provided by vendors can be gleaned from [38]. The methods/process used to monitor inertia online should be merged with improvements in control centres highlighted in Topic 3

However, it should be noted that this process is not able to forecast demand side inertia as it requires a measurement-based estimate of system inertia and as such can only be used when such an estimate is available. Thus, to use demand side inertia estimates as part of operations, utilities require the ability to forecast the demand side inertia contribution and not just estimate it in real time/post-mortem. This forecast will entail estimating the demand side inertia based upon known system metrics that are already forecast by the utility. This should include forecasts of behind the meter rotating generation and technological changes in consumer loads like electronic drive adoption, which is quite popular in Australia due to present high energy cost. Also, these estimates may possibly be needed only during off-peak conditions.

Regional inertia

The increasing penetration of IBR (often non-uniform distribution) not only reduces the total system inertia, but it can also cause the sources of inertia to become more sparsely distributed across the system. This may allow local regions to emerge that have low inertia as well as weak dynamic coupling (synchronizing torque) to the other regions of the power system, e.g. regions where a disproportionate displacement of synchronous generation occurs. This reduced dynamic coupling along with the low inertia may potentially allow the local frequency in these regions to vary significantly from the frequency in the rest of the system immediately following an event.

Further challenge posed by such a regional inertia pocket is that the reduced coupling limits the initial benefit it receives from the inertia of the rest of the system. Therefore, whilst the system inertia may be sufficient to limit RoCoF to acceptable levels at the system level, these local regions may be exposed to RoCoFs far in excess of the expected system RoCoF when a loss of infeed/outfeed occurs in the region. Significant regional behaviour may begin to undermine the validity of the systemwide frequency response studies that many utilities use for parts of their frequency response and inertia assessments. Under such conditions, utilities will need to perform regional frequency response studies by assessing the largest credible generation loss within these low inertia regions alongside systemwide frequency response studies. In many utilities these regions may be immediately apparent under their current operation practices; however, as dispatch and commitment become more variable in the future and the number of synchronous units reduces further regions may emerge, move, and merge. This variation in regions may require more complex and adaptive management practices also in procuring fast frequency response services.

Open research questions

In the short term, questions to consider include:

1. Does a system have relevant levels of demand side inertia (rotating loads and distributed synchronous generators)?
2. If demand side inertia is relevant, can a simple forecast method be developed that links demand side inertia to variables that are already forecast by the utility?
3. Is regional inertia emerging in the system and, if so, when is it anticipated to be sufficient to undermine the validity of results from a single frequency model? Is this best addressed by specific studies for certain conditions, a complete move to multi-machine studies or developing coupled single frequency models?

In the long term, questions to consider include:

1. How fast does a fast frequency control response need to be for it to be considered as a direct replacement for inertia? That is, the response is considered to limit the peak RoCoF the system is exposed to and not just provide more time for frequency responsive reserves to respond. This will likely draw heavily on the true equipment withstand for short term high RoCoF.
2. To what extent can HVDC lines across congested transmission corridors be used to mitigate regional inertia through fast control?
3. At what point, possibly far in the future, do synchronous machines begin to become an inconvenience in very high penetration systems? That is, the need to satisfy their requirements limits the operation of a system that is otherwise converter based and can operate securely at 100% – consider the example of a market solution that has one gas turbine but is otherwise entirely converter based, operation without the gas turbine would likely be preferable but omitting it would raise questions of technology neutrality

4.3.3. Modelling and model validation

Discussion

Having adequately validated power plant, transmission device as well a load models plays a pivotal role in simulation studies. Through a concerted industry wide effort, generic models for conventional power plant models (generator, governor, exciter and power system stabilizers) are now available, which provide high-fidelity representations of conventional power plants for most stability studies. Well established techniques also exist for event based as well as staged testing-based validation of these generic models. Large penetration of IBR's which typically tend to have black box models have introduced new challenges for transmission planning engineers in this area of modelling and model validation. The challenges in this area are two-fold. The first challenge is towards development of generic models that can be used to represent IBRs from different OEMs, and the second challenge is on developing protocols for validating the blackbox models that OEMs provide.

Generic model development plays a crucial role in power system planning studies. Generic models help greatly in performing studies to estimate the impacts of new interconnecting equipment even before such projects are approved and the OEM blackbox models are made available. The closer the generic models are to the actual equipment behaviour, the better planners can estimate the benefits or drawbacks of a particular equipment interconnection. Presently, the development of generic models for IBRs is still in its inception, with the modelling community working with key OEMs to develop generic representations of their critical proprietary controls. A lot of research still needs to be done here to develop a library of models that can capture approximately the wide range of control capabilities that IBRs are posed to offer. This becomes more critical with the emergence and popularity of the so-called grid forming inverters and the ability to switch between grid forming and grid following modes.

Model validation for IBRs is closely intertwined with IBR design, which is addressed directly in the companion CSIRO *Australian Research Planning for Global Power Systems Transformation* research roadmap "Inverter Design: Development of capabilities, services, design methodologies and standards for Inverter-Based Resources (IBRs)" (Topic 1). Research work on models and model validation should closely collaborate with work outlined in the Topic 1 research roadmap.

Beyond the development of generic models, it will also be important to have adequately validated models of IBRs from OEMs. Typically, OEMs provide blackbox models, the inner workings of which are unobservable for transmission planners who use these models for their studies. To ensure that the models work as intended and the planners understand the complete spectrum of their capabilities, the validated models should adequately capture and demonstrate:

- The action of all control limiters that saturate for particular control responses
- The action of the various protection systems and current limiter mechanisms that can act under transient and extended grid disturbances
- Frequency domain transfer function/state-space models within specified frequency ranges so that these results can be used by transmission planners to understand small signal performance of these models.

A significant challenge with blackbox models is updating the models when OEMs carry out over-the-air upgrades of firmware. Ideally, the model should be revalidated every time a material modification to the firmware is carried out. Although over-the-air upgrades may no longer be permitted, the classification of what counts as a material modification is still yet to be standardized.

Apart from IBRs that connect to the system, a significant number of such generators will show up on the distribution system as behind the meter generation. Modelling each individual generator along with the co-located load can be computationally impossible when using an EMT or even a positive sequence simulator. However, modelling such generators along with the loads for dynamics is extremely important as has been shown through experiences in North America as well as other parts of the world. The dimensionality of the problem has been typically addressed through aggregated modelling. Aggregated modelling of loads has been studied for quite some time and it has been established that developing such models for loads can be challenging and requires coordinating with distribution operators as well as investing in measurement devices that can provide data for refining and validating these models. The addition of distributed generators further complicates the process and some additional research is needed to identify the possible challenges as well as additional data that may be required to validate these aggregated models. Additionally, a planner is always dependent on a grid event to test the process and determine its sufficiency, which is a disadvantage by itself. One way to address this challenge is to leverage the detailed modelling capabilities in EMT tools to create detailed 3 phase models of distribution feeders with loads and DERs, create grid disturbances and use the cumulative response measured at the substation head as a proxy for actual disturbances. This approach helps planners to identify measurement and data requirements so that they can leverage actual grid events as an when they happen. Research work in this area should closely collaborate with that in Topic Area 8.

In addition to model validation for planning studies, it is also important to periodically recreate grid disturbances using the different models so that any modelling discrepancy can be noted and rectified. Such an effort would require first creating a case that reflects the grid conditions during the event and then simulating the event. This process is often time consuming and requires significant man hours. Some research efforts will be needed to develop a framework that can automate this process and enable utilities to perform more of this analysis.

Further, OEMs typically parameterize and design their controls based on a single machine infinite bus representation. While TNSPs have wide area models of the network constructed in both positive sequence and EMT domain, OEMs may (in certain cases) have access to only the positive sequence wide area model while they certainly do not have access to a system wide EMT model. Although steady state impedance information can be provided so that IBR controls can be designed over a wide range of system strength and X/R ratio, OEMs would still not have the ability to ascertain whether there can be control interactions with other equipment in the system.

Additionally, even the best and most accurate models are obtained under these conditions, there will be a lowering of efficiency and impact if the system wide tests and analysis are carried out only by one entity. There is a legitimate concern from OEMs regarding sharing of blackbox models across different system providers as it carries their intellectual property. But at the same time, if data cannot be shared across different service providers (whose electrical networks are interconnected with each other), the analysis of the power system can be challenging.

One potential solution proposed at AEMO was the concept of remote access EMT simulations. Essentially, any OEM can remotely connect into AEMO's simulation bank and the entire network looks like a single machine infinite bus from the OEM's perspective. However, in the back end, the entire system gets simulated. This concept requires a lot more research and development as the question of trust and protection of intellectual property is huge in the IBR world.

Another potential solution is the development of network equivalents that not only represent the steady state impedance/system strength but can also provide a representative picture of the dynamic behaviour of the equivalent. In this representation, an individual device from an OEM can now observe a dynamic behaviour from the network equivalent which would be similar to the dynamic behaviour observed from using the entire network representation. These equivalents will also be useful in representing the boundary between two simulation environments when using a co-simulation framework. However, development of such network equivalents with a changing dynamic nature of the network is a challenging task.

Open research areas

From a generator modeling perspective, as the power system gets stressed further, modeling of the reactive power characteristics and magnetic saturation of synchronous machines would need to be re-visited from a transient stability and critical clearing time perspective. For IBRs, investigation is to be carried out on whether the models are able to represent any adaptive change in parameter values, and if so, how would this potential adaptive change have an impact on system stability studies? This may in turn require new forms of power plant parameter derivation and model acceptance tools that are able to excite these adaptive control loops and capture their behavior. The development of generic models for IBRs with new control architectures has to also progress further as these generic models would enable a transmission planner to carry out long term studies.

Although load modeling has come a long way, the task is still challenging and there are areas that require improvement. One of the major challenges with load modeling for a transmission planner or an entity involved in transmission planning is estimating the types of loads on the system and anticipating how this will change over the planning horizon as consumer technologies evolve. Moving forward, to address these challenges, transmission entities will be required to closely coordinate with the distribution companies/entities to perform customer surveys to identify the present stock of consumer loads and anticipate the future trends. The best example of such a change can be accelerated adoption of electric vehicles that many countries are seeing now.

In addition to estimating the types of loads that exist on the system, it is also important to assess the dynamic behavior of both present and upcoming loads on the system. Understanding the dynamic responses of the present stock of loads helps a transmission planner to devise operational tactics or identify reinforcements needed to maintain system reliability during grid disturbances, where the load response can result in unacceptable operating conditions. To better understand the dynamics of existing loads, it is important to invest in laboratory infrastructure where consumer loads like refrigerators, air-conditioner, EV chargers etc. can be bought and tested such that the test results can be used to develop and refine models that can be used for transmission planning studies. In addition to this, entities need to invest in measurement infrastructure such that the grid measurement during events can be utilized to refine the ‘aggregated load model’ such that the fidelity of these models increase.

For loads and load technologies that are not widely used presently, but will show up in the future, the transmission planners need to procure prototypes of such devices and test these in a laboratory set up. The responses of these devices can then be categorized as ‘grid friendly’ or ‘grid un-friendly’ depending on how these devices affect voltage and frequency recovery. The transmission utilities can then coordinate with the manufacturers to deliberate on protection mechanisms that can be installed in these devices so that the devices help grid operations while still not affecting the customer experience of the device safety. Such initiatives can help transmission entities to better tackle the effect of rapid electrification which is an integral part of decarbonization efforts.

4.3.4. Voltage and reactive power management

Discussion

Voltage and reactive power control are essential for securing the proper operation of a power system during both normal and emergency conditions. Large penetration of IBRs in the system displacing synchronous conventional generation will likely cause degradation in the amount of reactive support and voltage control resources available on the transmission system. Voltage fluctuations due to variable output of wind and solar generation are expected to be more pronounced and increasingly difficult to handle because of interaction between controls of existing devices and the renewable generation. These new operating characteristics that emerge from proliferation of IBRs, in addition to changes to how the system must be planned based on regulatory and environmental constraints, have a noticeable impact on the way the system is to be controlled to maintain satisfactory steady-state and dynamic voltage profiles and secure operation.

System operator procedures to manage voltage control and reactive power devices have been mainly based on practical experience, and in some cases supported by limited offline studies. While current processes and methods for Volt/var control have been successfully used for many years, transmission system operators have recognized their major limitations to properly coordinate and implement Volt/var control under the more stringent operating conditions imposed by large integration of IBRs and other system changes. This drives the need for major adaptations of voltage control approaches that require more complex coordination and interactions among controllers.

Advanced voltage control schemes have long been implemented in some systems, like the centralized hierarchical automatic voltage control used in Europe and Asia, and large-scale security-constrained optimal power flow for online applications. Other control schemes, such as the autonomous decentralized control have been developed and tested in pilot mode but not on commercial implementation [39] [40]. Even though these developments represent significant advances in Volt/var control technology, they are not widely used in transmission systems, and may not be the most adequate approaches to face the challenges and highly demanding standards of future power grid. The topics highlighted in this section can be complimented by topics highlighted in the roadmap documents of Topics 6 and 8.

Open research areas

A practical alternative is a software tool to be used in operations to improve control and coordination of various reactive devices, including generator voltage profile, shunt capacitor and reactor banks, static compensation systems and synchronous condensers. Currently there is no commercial tool available to meet this requirement. The Electric Reliability Council of Texas (ERCOT) is presently developing in-house a tool for this purpose [41]. Voltage control and reactive power scheduling tools can help fill this gap in the industry [42]. These tools should provide guidance on how to deploy the available reactive power resources and voltage control devices along a 24-hour period (day-head fashion), while also providing recommendations on possible mitigation actions if deficiencies in reactive power reserve and controls are found. The developed tools would have to be implemented in operation planning environment as part of the day-ahead studies, or alternatively can also be used for performing offline studies to develop guidelines to control reactive power resources in operation. An example of such a tool is AEMO's coordinated reactive power scheduling tool which implements a tie line based solution method to determine reactive power dispatch of generators, SVCs, capacitor banks, and other reactive power devices. It is envisaged that future versions of this tool can be used to send a voltage schedule to generators.

Methods that can identify adequate voltage support mitigation hardware options is another area where more research could be helpful, particularly in the evaluation of new technologies. While voltage controlling devices such as synchronous condensers, SVCs and STATCOMs have well known capabilities and widespread documented applications in addressing power system problems, methods to evaluate their applicability and capabilities can be more formally documented and compared from a technical point of view, especially with changing load profile and increase in distributed energy resources. For instance, some technologies, such as condensers, can not only provide fast, dynamic reactive power support and voltage control, but also provide inertial support, or have enhanced inertial support when coupled with large flywheels. Other technologies, such as BESS can provide all the services described above, as well as primary frequency response. Some of the new emerging control modes (such as grid forming controls) and their impact on system voltage stability and support need to be further studied and documented.

For sensitive loads, such as those in semiconductor manufacturing facilities, where steady voltage regulation is of primary importance, investigation of the area of vulnerability (AoV), herein defined as the geographical area around the load where system events can cause disruptions due to poor voltage quality, is another area that needs to be carefully considered. With a continuous reduction in short circuit contribution capability, it is anticipated that those AoV may grow and that needs to be well understood and will vary from system to system.

4.3.5. Real time simulators/hardware-in-the-loop

Discussion

Due to the complex nature of IBR/DER systems and their interconnection to the grid, the field testing and validation of such systems are cost prohibitive. Additionally, different abnormal operating conditions, such as fault response, low and high frequency resonance, are hard to replicate in the field.

Recently, there has been a growing interest in transmission companies to acquire real-time simulators and build HIL facilities. Examples are Australian Energy Market Operator (AEMO), Commonwealth Edison (ComEd), Korean Electric Power Company (KEPCO), New York Power Authority (NYPA), Southern California Edison (SCE), and Southern Company. However, the challenges of model preparation, validation and maintenance for real-time simulation still exist. Few auxiliary tools have been developed by different companies to smooth out the modeling process, however the tools are designed to either be grid specific or to address a specific problem, leaving most of the mentioned challenges unsolved

Using HIL based testing provides flexibility to create various what-if test scenarios, including abnormal operating conditions, in the laboratory environment with much lower cost and resource requirement. Furthermore, in the HIL testing, data from the real-world systems can be utilized to fine tune the model to replicate real-world devices and systems in high fidelity. The captured events from the already fielded systems can be replayed back in the laboratory using HIL and new controller actions can then be verified.

The continuous developments in standards related to the interconnection of inverter interfaced sources (e.g., IEEE P2800 - Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems [29]) provides baseline performance requirements for regulatory authorities, which may soon expand its mandatory standards to account for more strict performance requirements that aid in improving and maintaining grid reliability. Even without mandatory standards in place, this service would provide an opportunity for industry leaders to take initiative to demonstrate best practices in industry, thus showing their commitment and leadership towards maintaining a reliable electric grid.

Therefore, there is a need to develop procedures, methods and tools for validation and verification of the new as well as other applicable performance standards and grid code compliance. The validation processes can be realized by leveraging advanced simulation and hardware-in-the-loop (HIL) technologies to provide a platform for verification of functionalities that are harder to test in the field, especially the ones that may require large system disturbances to be validated, such as voltage and frequency ride through features, absence of momentary cessation, and synthetic inertia.

Areas of improvement with HIL

It is worth noting that the HIL setup is built upon the utilization of a digital real-time grid simulator, which is a main component of the setup and all the testing and demonstration rely upon. The simulator will have to include hardware-in-the-loop capabilities with the ability to directly interface external control devices and software systems. However, challenges still exist to model and simulate real power grids on such simulators, for example, due to the trade-off between the size of the power system and the computational power of real-time simulators. Even with sufficiently powerful real-time simulators, the following challenges exist that prohibit the use of HIL tests to be brought to the mainstream of power system studies:

1. Real-time simulators and their peripherals require considerably higher financial investment when compared to offline simulation tools.
2. Majority of engineers in the power system industry lack the required expertise to utilize HIL setups.
3. While it is not practical to build models of large power grids for real-time simulation from scratch, there do not exist mature tools to convert large grid models from the offline simulation platforms such as positive sequence platforms to real-time simulation platforms. The output models of the currently available converters often require tedious manual adjustments before they become readable, organized, and stably running.
4. The standard library of power components and controllers (including IBR/DER systems) in real-time simulators are typically limited compared to that of the offline simulation platforms. Hence, the converted models lack the power components and the controllers that do not exist in the standard library of the real-time simulators, which, in turn, requires extra expertise and manual work to implement them.
5. Aging of the models in real-time simulation platforms is another important concern. Operation and planning engineers often update power grid information, embedded in the offline models, several times a year. Since it is a time-consuming process to repeat the whole conversion process for every update in the offline models, tools are needed to automatically update the models in real-time simulators by reading their counterparts in the offline simulation platforms.

4.3.6. Identification of critical contingencies

Discussion

Contingency generation is one of the most time consuming and error-prone tasks planning engineers undertake. Furthermore, evaluation of critical contingencies and their relationship to the operating condition, is crucial to conduct adequate planning analysis of the network. With the change in resource mix, both behavioural and locational, it is possible that the definition of contingencies and their criticality would change with a higher frequency than that observed in today's power network.

Today, detailed time domain simulations and system operator/planner experience is relied upon to evaluate critical contingencies. As the system evolves, sophisticated analytical tools may be required to inform and compliment time domain simulations and operator/planner experience. These advanced tools would need to cover a both:

1. Automatic contingency creation: Utilizing accurate node-breaker topology information, generation of contingencies definitions for both steady-state and dynamic analysis [43] [44].
2. Contingency screening and ranking: Based on the impact of contingency events, identify and prioritize the most significant events in an automated manner. The evaluation should not be based on any particular modelling pre-requisites and should be simulation platform agnostic. Selected outputs from time domain analysis can be used as inputs. The screening and ranking of contingencies can be further split into two categories:
    a. Screening for dynamic voltage performance: Here, use of load model characteristics is critical to understand the behaviour of the system for extreme events. With accurate representation of load (and distributed energy resources), the impact of these elements on voltage recovery can be ascertained [45].
    b. Screening for transient stability performance: Here, adequate representation of the dynamic behaviour of sources such as synchronous machines and IBRs is critical [46].

Open research areas

Presently, analytical methods of contingency generation, screening, and ranking that can be scaled up for use in large system analysis have primarily focused on leveraging performance-based criteria and applying rule-based scoring functions to rank the impact of different contingencies. As computation capability and data availability increase, continency ranking and screening processes are highly amenable to advanced analytic applications. Future research can focus on the application of supervised and unsupervised learning methods to classify, rank, and screening the results of dynamic simulations.

4.3.7. Real time contingency analysis

Discussion

When moving from a desktop planning realm to the real-time operations realm the topic of carrying out contingency analysis is important to be considered. This topic goes together with identification of critical contingencies. Real time contingency analysis is typically carried out after the market clears and determines the final dispatch and schedule for the next hour of operation. Although this analysis is primarily carried out in a positive sequence environment, there are still significant challenges to obtain an efficient analysis, given the time frame within which it should be carried out. The primary challenge with real time analysis is the extreme number of contingencies that may have to be evaluated. Generally, the overall simulation time can be linearly proportional to the total number of contingencies. This can sometimes involve into tens of thousands of contingencies depending on the size of the system. A further challenge that is encountered is use of more accurate node-breaker system models as opposed to bus-branch representation of the network. Since many high impact system events occur as a result of multiple component failure, use of a node-breaker representation provides the ability to obtain visibility into such failure modes. However, this representation can further increase the total number of combinations of contingencies that can occur and hence are to be studied. The computational burden increases yet again if transient stability analysis is also to be carried out in addition to steady state contingency analysis.

Open research areas

Three main areas that can be leveraged to reduce the computational burden of real time contingency analysis are:

1. Taking the advantage of multi-core computing power, contingencies can be analysed in parallel. While this results in an increased investment cost, there is a finite limit to which an analysis can be split into parallel components. This is because parallel computing introduces communication overhead between the client and the servers. Once this limit is crossed, overhead in communication and processing of results can negate any benefits brought about by the parallel process.
2. Approximate methods such as dc power flow analysis can significantly reduce the computation time for steady state contingency analysis. However, these approximate methods are based on certain sets of assumptions over and beyond the assumptions used in a traditional power flow analysis. As a result, there can be concern regarding the accuracy of using such methods, especially if they are used to screen critical contingencies. Development of improved and more robust approximate methods can help increase the confidence of using such methods in real time contingency analysis.
3. Identification of critical contingencies themselves can be a real challenge. As the system moves forward with increase in IBR percentage, the criticality of a contingency can be determined by the dynamic behaviour of the IBR rather than the steady state response. In such a scenario, development of analytical metrics and models that can provide a representation of critical contingencies will be important.
4. Since parallel computing requires the use of a network based or cloud-based computing platform, integrity and security of the entire platform is also to be considered. Some questions that cater to this topic are: Can different levels of access be provided to different system users? Can the entire network be shielded from an external intruder (a bit more on this aspect is highlighted in the cybersecurity section of this chapter)? Would the communication protocol become a bottleneck?

4.3.8. Protection system operation and coordination

Discussion

In a decarbonized power system, the majority of the generating resources is expected to be renewables which are interfaced to the grid through power electronic inverters and known as IBRs. This power electronic interface is a fundamental physical difference between IBRs and traditional synchronous generators (SGs) and results in different fault current characteristics for IBRs compared to SGs. The fault current of a SG is of high amplitude, uncontrolled, and pre-dominantly defined by the electrical parameters of the source and the impedance of short-circuit path; by contrast, the fault current of an IBR typically has a low amplitude and is tightly controlled through fast switching of power electronics devices dependent upon manufacturer specific and often proprietary IBR control scheme. The most influential factor determining the fault response of an IBR is the control scheme which manages the fast switching of the power electronics to achieve a number of control objectives. A key objective is to constrain the magnitude of current within the thermal withstand capability of power electronic switches, that is why IBRs are current limited devices. Other control objectives may be imposed by grid codes.

The different fault current response of an IBR has an anticipated impact on the performance of legacy protective relays and corresponding schemes such as distance, overcurrent and differential protection. Traditionally, relays have been set with expectation of fault current signatures of a SG-dominated power system, i.e., a high amplitude and inductive short-circuit current, which enable them to operate where they should and not operate where they should not. Decarbonization resulting in increased IBR levels and the ensuing changes in short-circuit behaviour of the power system, may mean that these two fundamental principles of power system protection cannot be met, with potential risk for relay mis-operations. This presents a challenge for protection engineers to identify such mis-operation scenarios and develop remedial solutions to ensure efficient protection under high shares of IBRs.

Given the complex fault response of IBRs that is dependent on controls, circuit-based time-domain simulation methods and tools such as EMT tools would be suitable to capture that behaviour. However, below are listed challenges related to conducting protection studies for large scale systems using EMT tools.

1. Engineering time and modelling effort concerns
2. Need for EMT IBR models that accurately represent IBR controls
3. Need for EMT relay models that accurately represent relay signal processing algorithms

Given the above, it is a common practice to perform short circuit analysis in phasor domain and avoid time domain methods. These methods and associated commercial tools have been used in the industry for decades, and one of their advantages is the availability of extensive and detailed vendor relay models. Therefore, it has been recognized as an industry need to include precise phasor models of IBRs in the state-of-the-art engineering tools of protection studies that rely on phasor solvers.

A recently developed and industry accepted modelling approach for IBRs in steady-state short circuit analysis is to represent them with a voltage controlled current source. This current source is nonlinear due to current limiters and other controls. Its active and reactive components in the sequence domains largely depend on the control scheme employed in VSCs. The transient period following the fault inception is very short, i.e., typically under 1 cycle, and is ignored. This approach has been demonstrated to successfully match detailed EMT-type models in steady state as long as the current source is computed according to the control schemes of IBRs and current limiters.

Another potential approach is the development of co-simulation platforms that combine EMT simulations with steady state short circuit programs, leveraging the advantages of both modelling approaches. In particular, with such a co-simulation the EMT simulation offers the advantage of accurately modelling inverter controls and capturing the IBR fault response, while the steady-state fault analysis programs would model in detail the protection system and associated relays and settings.

Additionally, short circuit models of transmission networks have not commonly included loads. The reason is that the fault current from synchronous generators are many times higher than the load current and highly reactive, and hence omission of load current does not reduce the accuracy of short circuit results. Furthermore, if the load is modelled it is typically necessary to create realistic generator dispatch scenarios for the power-flow simulation to solve; this can require a significant resource to establish and maintain.

Nevertheless, this modelling practice may no longer be appropriate for an IBR-dominated grid or grid region; the fault current of an IBR is comparable to load current and, depending on inverter terminal voltage, can have a considerable active component. To numerically accommodate this active current, it may become necessary to model loads. Without load models, the circulating active current can skew the amplitude and phase angle of fault current flows, thus leading to inconsistent short circuit results.

A consideration to reduce the error is to include loads in the short circuit model. However, in practice, creating and maintaining load models may be burdensome for protection engineers. Alternatives for consideration are listed below:

1. Only model loads close to the fault location. However, the challenge in this case is to define a small yet adequate boundary around the fault to include loads. The selection of boundary may require engineering judgement, and further research is needed to develop a more systematic approach
2. If there are loads in close vicinity of IBRs, modelling those loads may improve accuracy.
3. Re-parameterize the IBR model to eliminate the active current component, or put artificial loads at IBR model terminals to locally absorb the injected active power. However, these techniques may not improve accuracy in networks where load is located far away from IBRs.

Network equivalencing is another fault analysis process that needs to evolve for IBR dominated grids. In conventional grids, a network equivalent for short circuit studies represents a large transmission network by a voltage source behind impedance. Network equivalents facilitate sharing network data with neighbouring utilities and distribution companies. Their computation is straightforward and well documented for systems where conventional synchronous generators are the principal source of generation. However, the increasing share of IBRs requires revising the way network equivalents are defined.

Identification of network equivalents for systems with high share of IBRs to be used in short circuit studies, is an emerging research and development (R&D) topic, with the objective to develop a network equivalent representing the steady-state short circuit response of a system with high share of IBRs. It is expected that a non-linear network equivalent model will be needed, that will be integrated using an iterative solution with the rest of the network. This is different compared to a classical Thevenin equivalent linear model typically used.

Open Research Questions

R&D is essential to address open research questions related to the protection of future grids dominated by inverter based resources. Such R&D topics are listed below:

1. Design and integration in relays of novel protection schemes that are reliable and dependable despite the unique fault response characteristics of IBR dominated grids.
2. Development and adoption of accurate IBR short-circuit models that capture the unique fault response characteristics of IBR dominated grids.
3. Development and adoption of advanced simulation tools for fault studies and protective relaying settings configuration that consider the unique fault response characteristics of IBR dominated grids.

4.3.9. Research plan for high priority topics

The high priority topics can be further grouped into six clusters. For these clusters, the following steps are recommended as initial steps to be carried out in application of the roadmap:

1. Online estimation of system strength and regional inertia
    a. Preparation stage:
        i. develop background on effectiveness of existing system strength metrics and inertia estimation in serving as an accurate screening method
        ii. get a baseline from IBR OEMs on various methods in which IBRs can contribute towards system strength and inertial energy injection
    b. Formulate research projects with objectives to:

    i. verify and validate the use of existing system strength metrics. Consider the impact of different control methods and tuning rules when evaluating the effectiveness of a screening technique
    ii. develop new screening methods and analysis procedures that go beyond conventional steady state system and inertia estimation metrics.
    iii. ascertain locations in the network where system strength is to be evaluated and whether these locations would change as the loading and system dispatch changes.
    iv. identify contribution of load and distributed energy resources to inertial energy injection
    v. develop methods to include IBR fast frequency response into network inertia estimation
    vi. identify areas or zones in the network where local inertia and system strength issues may arise, and how the boundary of such areas may change as the network topology and operating point changes.
    vii. utilize estimated inertia and system strength values in dispatch and unit commitment of the network.

c. Expected outputs from these research efforts can be:
    i. new system strength metrics that consider the dynamic trajectory of IBR control systems and their impact on small and large signal stability of the network.
    ii. method and processes to estimate regional inertia in the network while considering the contribution from load, DER, and fast frequency response from IBRs.
    iii. new constraint equations that include the newer metrics developed and formulated.

d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
    i. 2 years
    ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.

e. Expected skill sets include understanding of:
    i. power system analysis and dynamics
    ii. power system planning and operation
    iii. control system theory and stability, and mathematical processes and computation techniques
    iv. computer software development and implementation
    v. signal processing and graph theory
    vi. load dynamic behaviour

2. Modelling and model validation
    a. Preparation stage:
        i. develop background on effectiveness of existing dynamic model acceptance tests and lessons learned, especially to consider future IBR behaviour
        ii. get a baseline on status of accuracy of load models for inclusion of induction motor dynamics and distributed energy resource dynamics
        iii. consolidate with Topic 1 (IBR design) on development of models for new IBR control architectures
        iv. consolidate with Topic 9 (DER and stability) on evolution of load and DER dynamic behaviour
    b. Formulate research projects with objectives to:
        i. investigate accuracy of synchronous machine models, especially regarding saturation characteristic as increased IBR penetration can cause higher reactive power requirements on machines. Further, with potential use of synchronous condensers, it is important that these reactive power characteristics are accurately captured.
        ii. develop, maintain, and update generic models of IBRs with emerging control architecture, for use in future planning studies to enable ease of identification of transmission upgrades or changes in grid code requirements. These generic models should keep track of latest IBR response trends and work towards integrating new features as they become available.
        iii. estimate load characteristic nature and the potential change in its dynamic behaviour with change in consumer technologies. These updated models can then inform system stability behaviour and analytical representation of the load trajectory can be used in stability tools.
    c. Expected outputs from these research efforts can be:
        i. new or updated models for synchronous machines, IBRs, and load (with DER)
        ii. methods and processes to analytically include the dynamic trajectory of these devices as inputs to the stability screening and voltage collapse tools
        iii. new procedures to ensure continuous model validation for new IBR control structures
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed models and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation

        iii. control system theory and stability, and mathematical processes and computation techniques
        iv. computer software development and implementation
        v. signal processing and graph theory
        vi. load dynamic behaviour

3. Voltage and reactive power management
    a. Preparation stage:
        i. develop detailed documentation on present system operator procedures to manage voltage and procure reactive power resources
        ii. get a baseline on various schemes available (both presently implemented in the system and new products available) for enhanced voltage management
    b. Formulate research projects with objectives to:
        i. improve existing reactive power scheduling tools to incorporate system wide ac power flow solution based techniques to obtain more accurate solutions
        ii. improve existing tools to be able to send voltage schedule commands to various resources around the system in a seamless and automated manner. These should take into consideration any services provided by either behind the meter DER or utility scale DER resources (either individually or through an aggregator)
        iii. estimate margin of reliability with regard to change in area of vulnerability from the perspective of sensitive loads for whom steady voltage profile is important
    c. Expected outputs from these research efforts can be:
        i. new robust reactive power scheduling tools that can handle ac power flow solution techniques
        ii. advanced reactive power management solutions that can serve as inputs to estimation of voltage stability boundary
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed models and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques

        iv. computer software development and implementation
        v. signal processing and graph theory
        vi. load dynamic behaviour
        vii. matrix theory and power flow solution methods
        viii. optimization techniques

4. Real time simulators/hardware-in-the-loop
    a. Preparation stage:
        i. develop overview of state of art real time analysis process and tools used
        ii. develop a process document of various factors to be considered by carrying out real time simulations
    b. Formulate research projects with objectives to:
        i. identify specific scenarios and situations under which real time simulation is necessary. Although the computation capability may be available, it is always good engineering practice to identify situations and scenarios when this capability is needed.
        ii. develop robust tools and methods to convert network information and models from positive sequence domain to real time simulation environment. Some aspects of this challenge might be mitigated by having an EMT model already developed. In this regard then robust tools to be developed to maintain, and update models as necessary.
        iii. develop a library of models to be used in the real time simulation software libraries.
    c. Expected outputs from these research efforts can be:
        i. new screening methods and techniques to identify use cases for real time simulations
        ii. advanced data management tools that can maintain the network model in various simulation platforms
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed models and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques

        iv. computer software development and implementation
        v. signal processing and graph theory

5. Identification of critical contingencies and real time contingency analysis
    a. Preparation stage:
        i. develop overview of state of art process used to identify critical contingencies
        ii. develop a process document of various factors to be considered by carrying out real time contingency analysis
    b. Formulate research projects with objectives to:
        i. identify factors that can play a role in determining whether a contingency is critical or not.
        ii. develop robust analytical methods that can use prediction of the dynamic trajectory of various devices in the network and make an estimate of the criticality of a particular contingency.
        iii. map the evolution of critical contingencies (and possibility of development of new critical contingencies) in the system as the characteristics of the system change
        iv. develop new power flow solution methods and dynamic integration methods that can increase the speed of evaluating and processing contingencies in real time.
    c. Expected outputs from these research efforts can be:
        i. new screening methods and techniques to estimate and rank the critical nature of various contingencies. This will further allow for determination of which contingencies need detailed studies and analysis.
        ii. advanced power flow solution techniques that can be included in existing software to carry out efficient real time contingency analysis
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed models and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques
        iv. computer software development and implementation
        v. signal processing and graph theory

6. Protection system operation and coordination
    a. Preparation stage:
        i. develop overview of state of art process used to represent IBRs and other devices in short circuit studies
        ii. document instances of protection system mis-operation due to increase in IBRs in the system
    b. Formulate research projects with objectives to:
        i. design and develop new novel protection schemes that may not require generation sources to mimic and represent synchronous machine behaviour
        ii. develop robust models that can be parameterized to capture behaviour of IBRs for short circuit studies and protection coordination.
        iii. map the evolution of protection system settings as dynamic behaviour of the grid changes
        iv. develop new methods to represent the rest of the network (such as load) while carrying out short circuit studies
    c. Expected outputs from these research efforts can be:
        i. new setting less protection techniques which can identify the change in system dynamic behaviour and adapt to the same
        ii. advanced short circuit models and parameterization methods to appropriately capture fault current contribution of IBRs.
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed models and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques
        iv. computer software development and implementation
        v. signal processing and protection operation and coordination

4.4. Medium priority topics

These topics that are denoted as medium priority are those which can directly influence the stability of the network, but they do not directly influence the development of tools to evaluate stability. The concepts outlined in this section can be addressed using the tools and methods developed either through the critical or the high priority topics, albeit with appropriate settings and parameterizations.

4.4.1. Harmonics and power quality

Discussion

One of the operational challenges of IBRs is the increase in harmonic distortion, particularly in weak systems. EPRI has seen an increase in voltage harmonic distortion at the transmission level, raising concern among utility members. For example, Figure 1 below shows the general increase in harmonics over a 3-year period in an area that saw an increase in penetration of IBR [47]. Over the measurement period, new wind power plants were commissioned nearby at both transmission and distribution levels. In addition to the general upward trend in distortion levels it can be seen that the distortion tends to be higher during the low load period in summer, which is also the main outage season, in comparison to the peak demand period in winter [48].

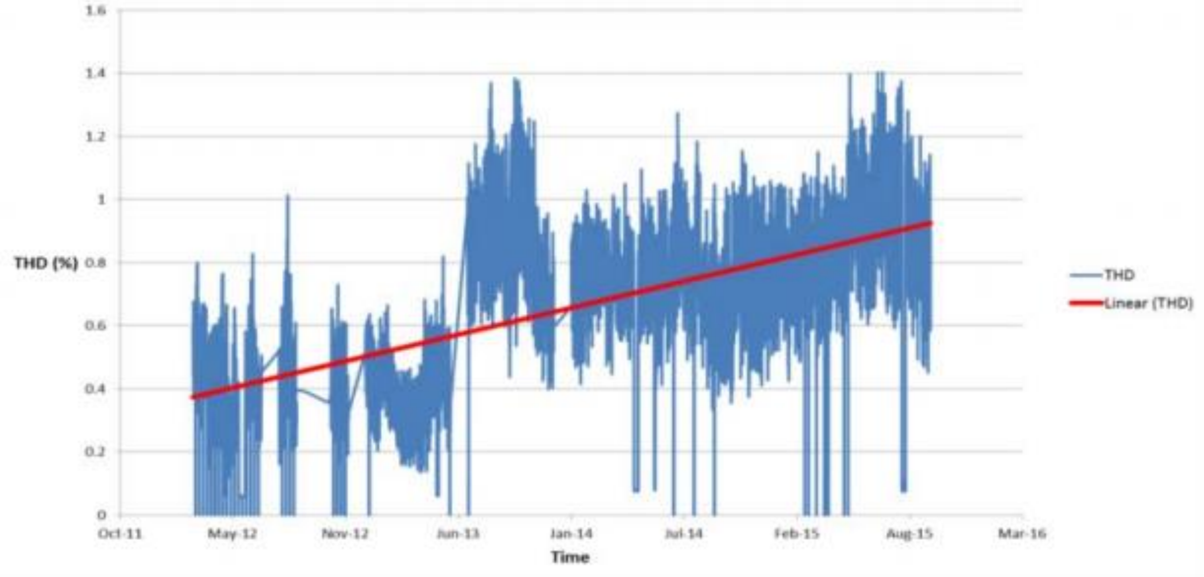


Figure 1: Example of voltage total harmonic distortion variation at a 110kV transmission grid station between 2012 and 2015 [47]

Because of this increase, models of IBRs for harmonic studies are needed to evaluate their responses before connecting to the network. Unfortunately, time-domain models of IBRs with power electronic switches face several issues due to the lack of availability of information about inverter topologies, controls, and filter structures, as well as the complexity of control loops. Additionally, simulating detailed time-domain IBR models is computationally intensive as it requires simulation time steps in the order of a few microseconds. Thus, it takes a much longer time to complete.

Open research questions

In the effort to simplify the harmonic modeling of IBR, development of a hybrid harmonic modeling approach is being presently researched [49]. This type of model requires the manufacturer's test reports on harmonic currents (magnitudes and phase angles) produced by the inverter. The test reports, when available, typically supply harmonic current data at the rated or a fraction of the rated power. If the manufacturer's report is not made available, research work is to be done to develop a set of representative values for a given inverter-based resource power generation based on generic or known inverters of a similar size. By appropriately scaling the inverter fundamental and harmonic current magnitudes, the hybrid model can then be extended to represent an entire inverter-based resource generating at a given power level along with its interconnection transformer. The hybrid model can be used to study harmonic interactions between inverter-based resources, evaluate harmonic diversity arising from multiple IBG plants in each network, evaluate impacts of inverter-based the on weak grids, and develop and evaluate mitigation solutions.

In addition to the harmonics generated by the IBR, the collector networks and the IBR interconnection method can also create harmonic issues. Figure 2 illustrates an example of an IBR interconnection which contains capacitor compensation on its collector network [49]. Research is to be carried out to continue to evaluate harmonic distortions contributed by the IBR plant, analyze a resonance condition resulting in excessive distortion, and evaluate the effectiveness of harmonic filters to mitigate the resonance condition. Additionally, research is required to identify contribution of individual elements towards harmonics observed in the network. If harmonic distortion is not mitigated in a timely manner, then growth of this distortion over a period of time can result in excitation of a super-synchronous resonance mode which can subsequently possibly introduce an instability in the network.

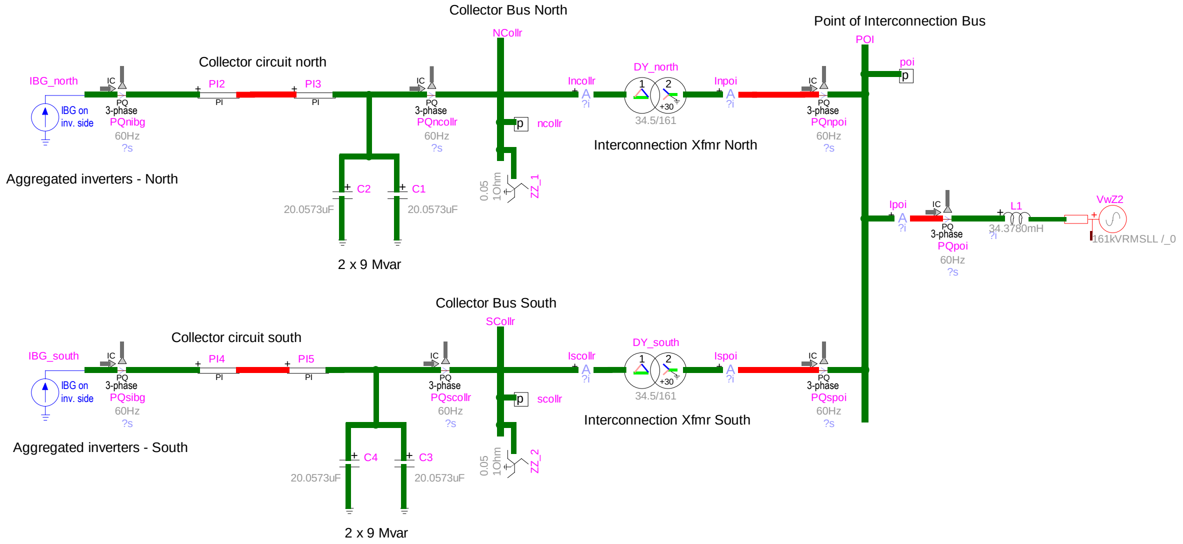


Figure 2: A one line diagram of a 150 MW solar plant connected to a 161kV point of interconnection

4.4.2. Outage scheduling with high percentage of IBR

Discussion

Planned outages are necessary to perform maintenance on all assets of the system while maintaining system reliability and economic efficiency. The outage scheduling process is a continuous process for utilities, system operators and asset owners. It is a complex scheduling process with multiple stakeholders and requires accurate forecasts of system resources and demand from years ahead to daily operations. Transmission and generation asset owners submit requests to reliability coordinators who assess the request and grant outage permissions. Historically, it has been relatively straightforward to estimate the system conditions in the near future. But with the changes occurring in the power system, estimating the system's needs in the near future with higher uncertainty of both generation and demand make the outage scheduling process more difficult.

In recent years, areas with high adoption rates of emerging resources, which are often IBRs like photovoltaics and wind, require more and more studies not only including interconnection but also outage studies. The sheer volume of the number of studies has put pressure on study engineers and increased the need for further automation and improved feedback mechanisms between the asset owner and the utility or system operator. There are opportunities to further optimize and leverage across outage studies to potentially reduce the workload and take advantage of opportunistic outages but requires improved information exchange between parties and new tools.

Regulatory drivers such as NERC and ENTSO-E standards by which reliability is assessed remain relatively constant, but with the increasing number of varied technologies deployed in the power system can pose new challenges to reliability under certain conditions and increase reliability in others. System operators and reliability coordinators will have to ensure that tools and methods they use are suitable, to extract the necessary support capabilities from these new technologies, as well as assessing their potential impact on system reliability.

Renewables provide a specific set of challenges that need to be addressed in the long-term and short-term outage planning time frames:

1. By their nature they are stochastic, so while it may be possible to predict production levels relatively well for the next twenty-four hours, how can this be achieved for the next 3 months during a critical outage? The stochastic nature of these forms of renewable generation manifests itself in two forms i.e. the total capacity available (distributed PV in particular) and weather driven uncertainty.
2. Flow levels on transmission and distribution lines as well as distribution transformers can reverse with the installation of solar PV or wind generation at the distribution level.
3. Adequate load modelling in power flow studies that have significant makeup of wind or solar production. Similar concerns arise related to the assessment of short circuit levels and transient stability issues, particularly with respect to frequency stability in the presence of reducing inertial capability.

As the penetration of renewables increases the need for ancillary services also increases. Both transmission and generation outage scheduling may have to account for this i.e. outages which restrict or halt ancillary services from either a section of the network or from a generator may not be possible or face restrictions. Finally, it should be noted that the advent of significant levels of renewable generation may lead to increased cycling of steam and gas turbine plants thus altering their maintenance cycles.

It is also worth noting that other technologies are evolving at the same time, which includes DERs that can impact demand forecasts and load models, dynamic-line rating technologies and power flow control devices that can impact the reliability limits, and special protection schemes (SPS) that can impact the topology and outage feasibility.

Open research areas

From the perspective of a reliability coordinator, several conditions must be checked in advance of granting an outage request to a generation or transmission facility. These analyses will be influenced by the same emerging factors such as IBRs. Where these processes exist already, they will have to evolve to meet the needs of the system in the future. In general, reliability evaluations will need to consider a wider range of resources providing extended support to the system through ancillary services or mandated capabilities. Processes will also need to include a more probabilistic approach, given the uncertainties surrounding renewable production, demand and forced outages and planned outage durations. Further automation and integration of existing or modified tools will be important next steps to help with short-term needs (processing more outages) but also longer-term needs (incorporating flexibility requirements).

Multiple improved processes and tools will likely be needed for outage scheduling in the future. One change might be to couple the outage studies with a scheduling sub-system. The scheduling tool would be used to optimize outages based on windows of opportunity provided by the asset operator. This would be a very large optimization problem and would, in effect, change many existing outage scheduling systems from permission-based systems to a quasi-optimized system. Improved coordination internally within the system operator with focus on similar asset classes could also provide efficiency benefits. As outage studies are often based on peak load scenarios, under increased variable resources and demand more off-peak scenarios and varied scenarios need to be considered in all time frames to ensure reliability. For instance, high renewable and low demand periods, high ramping periods for particular resources, or potential extreme weather events. Data intensive scenario selection and generation tools should also be developed to consider higher risk periods at different planning and operational time frames. Tools that study capacity adequacy and system flexibility may also need to be integrated in more detail in the outage planning process. Furthermore, ancillary services to meet flexibility requirements may also need to be considered if an outage would force it to be inadequate. Finally, risk-based planning tools that use condition-based or historical outage rates could be explored to study more likely forced outages and further refine the contingencies used in the reliability analysis or provide further metrics similar to expected unserved energy and loss of load expectation.

4.4.3. Grid Enhancing Technologies

Discussion

Grid-enhancing technologies (GET) refer to a set of hardware and software solutions to aid operational efficiency and capabilities of the transmission grid which help realize maximum utilization of the existing infrastructure. GET are supported by new technological advancement in power electronics, advanced metering and communication, computational processing power, and innovative optimization algorithms. GETs can in certain circumstances relieve transmission constraints, thus increasing capability of existing transmission network and improve the operation of new or existing transmission facilities. While there is no strict definition of GET and the specific technologies comprised within this concept, the following technologies are commonly considered: advanced line rating management, power flow control, storage as transmission, transmission topology control [50].

The Midcontinent Independent System Operator (MISO) has recently completed a comprehensive renewable penetration study to evaluate the impact of increasing amounts of wind and solar resources on the Eastern Interconnection bulk electric system, with a focus on the MISO footprint [51]. Results of the study show with large renewable penetration level, beyond 30%, the variety and magnitude of the bulk electric system needs and risks increase significantly. The study identifies the adverse impact of renewable generation on system stability as one of the major risks. It also finds that periods of highest stress on the transmission system shift from peak demand to times when most of the load is supplied by renewables and long-distance power transfers increase. This condition changes the way the system needs to be planned and operated. The study also concludes that insufficient transmission represents a serious barrier for integration of ambitious renewable target as the current transmission infrastructure becomes unable to deliver energy to load.

GETs can be used in many cases to address some of these transmission challenges imposed by large integration of variable renewable generation. Power flow control (PFC) devices that operate in a meshed network can alter the natural power flow through the system by different means. Traditional technology solutions to control power flow—such as phase-shifting transformers (PSTs)—have been used extensively for reducing loop flows or to maintain scheduled power flow on certain paths [52]. They have also been used in some cases to reduce overloads by diverting power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and consequently reducing the need for certain transmission upgrades. In recent years, new power flow control technologies have been developed, such as the modular Static Synchronous Series Compensator. Relative to the more traditional power flow technologies these new devices are modular and scalable, can be manufactured and installed in a shorter time, and in some cases, are available in mobile form that can be easily redeployed. Many studies conducted by EPRI and other entities on actual power systems show the potential benefits of PFC technologies for integration of renewables [53] [54].

Power flow controllers developed by Smart Wires are being installed in Australia as part of the Victoria – New South Wales Interconnector Upgrade. The project involves an upgrade of TransGrid's Stockdill Substation in the Australian Capital Territory using Smart Wires technology. These modular power flow controllers will allow to increase transfer capacity on 330 kV Upper Tumut – Canberra and Upper Tumut – Yass lines by balancing power flow among transmission circuits. The devices will detect areas of congestion in the network, under certain network scenarios, and automatically redirects flows to less congested lines.

Large scale energy storage devices, such as batteries, can also be controlled to inject or withdraw power at specific substations to eliminate transmission overloads during contingency events, thereby allowing the congestion transmission limit to be increased. Australia has pioneered the use of battery technology to grid problems at both transmission and distribution networks. Battery storage for renewable energy has been increasingly used in a variety of designs, purposes, sizes and locations, with more than 40 built or planned across the country. The most prominent installations are the 300 megawatts/450 megawatt-hours - Victorian Big Battery - in Geelong, Victoria (under construction), and the 100 MW/129 MWh battery farm in Hornsdale in South Australia. These huge energy storage installations are intended to provide several services to the system including network support, firming renewables and frequency control. Victorian Big Battery will provide an automatic response in the event of an unexpected network outage to help maintain grid stability. While these massive installations provide benefits to the system from multiple functions, smaller energy storage installations sited in strategic locations in the grid could provide overload relieve under contingencies. In such applications the batteries provide post-contingency or remedial action control.

Open research areas

Even though transmission expansion projects will continue to be the backbone of grid development, the use of these advanced technologies allows a planner to design more adaptable transmission expansion plans which are critical to mitigate capital losses and reduce reliability risks associated with possible system future changes and unforeseen situations. To design and evaluate transmission solutions that combine in an effective manner the capability of various technologies, planners need analytical methods and tools [55]. These tools should be intended to identify optimal solutions for mitigating thermal overloads in a power system over a range of operating scenarios. The optimum solution should be determined from a given set of candidate projects that may include power flow controllers (phase shifting transformers, fixed series reactors), battery energy storage, as well as traditional expansion projects such as new and/or upgraded transmission lines and substations. The optimization approach is intended to provide the best location and size of the devices to be installed in the system to solve overloads in the considered scenarios. The outcome of the optimization process gives a preliminary solution. Following that first step, more planning studies need to be conducted to refine the solution and determine other relevant parameters. For example, in the case of phase-shifting transformers, additional system studies are needed to determine the type, impedance, number of tap changers for the specific applications. Clearly, once the preliminary projects are selected, detail technical studies are to be performed to determined complete technical specs according to the applicable standards.

4.4.4. Phasor Measurement Units and Wide Area Monitoring Systems for Stability Tools

Today's state-of-the art in grid monitoring and control is based on the SCADA system as well as the EMS. These systems are the backbone infrastructure of monitoring and control of the transmission and generation systems to ensure reliability, and to the extent possible, optimize the use of available facilities. The current grid monitoring and control center technologies have served the electric power systems and society well for over 50 years. While they have taken advantage of better communications and computing technologies, the main architectural functions have had only incremental changes over this period.

The increasing deployment in the power system grids of PMUs and other devices that provide high-resolution synchronized measurements, has resulted in the development of numerous synchrophasor-based applications, both for offline and online environment that target to enhance grid operations and planning and are expected to contribute to the improvement of grid reliability and security.

A PMU-based Wide Area Monitoring System (WAMS) comprises of synchronized measurements collected from PMUs at various substations across the system and sent to the control room. Based on these measurements a WAMS platform performs analytics including situational awareness and security assessment to provide actionable information to the operators. Compared to SCADA/EMS the main advantage of a WAMS is the ability to monitor and analyse the dynamics of power systems due to the high resolution, synchronized and accurately time stamped measurements.

Decarbonization, and in particular increasing amounts of renewable energy resources that are being connected to the transmission network, as well as distributed energy resources connected at the distribution systems close to the consumption, are drastically changing the dynamic characteristics of the electrical system, because they are interfaced to it using power electronics based converters. The system is expected to have reduced inertia and low strength, which combined with the intermittency, variability and uncertainty introduced by renewable resources is expected to result in fast and large variations of electrical quantities such as frequency and voltage. Mitigation of reliability concerns due to these variations, as well as frequency and voltage control will require new approaches in the way the grid is monitored and controlled. Meanwhile these new connected resources will have to provide these reliability services. WAMS applications should be developed that address the reliability challenges introduced by IBRs.

Extending WAMS towards a Wide Area Monitoring and Control System (WAMCS) to perform closed-loop grid control is also emerging. The state-of-the-art centralized SCADA/EMS based control is anticipated to not be able to meet faster control actions needed to ensure grid reliability. The time synchronization of synchrophasor measurements as well as their high resolution, in conjunction with actuators such as IBRs with fast active and reactive power modulation capabilities, enable the development and application of wide-area fast control schemes that may improve grid reliability.

Next, a list of advanced WAMCS applications and a corresponding summary is provided.

Oscillations Monitoring, Analysis, and Control

Due to the increasing integration of renewables and the retirement of conventional generators, the oscillation modes in a power grid could change significantly with the variations of the grid's operating condition. Moreover, new oscillation modes may be introduced due to the dynamics of IBRs. The retirement of conventional plants will result in insufficient stabilizing capability from the remaining generators, the location of which may also render them inappropriate to suppress these oscillations. A WAMS that monitors and analyses oscillations, low-frequency or sub-synchronous, and interarea or local oscillations is expected to be of great value.

In addition to monitoring and analysis, mitigation of such oscillations can be achieved through a WAMCS. Power electronics-based devices such as IBRs, BESS, FACTS and HVDC transmission systems can provide fast oscillation damping control. Wide-area power oscillation damping (POD) controllers is an emerging technology to better suppress such oscillations. PMUs can be used to monitor the network state, identify network oscillatory modes and locations and arm POD controllers based on the real-time PMU measurements. An adaptive design of POD control is highly desirable to account for variations in operating conditions that become increasingly dramatic and frequent.

Machine Learning / Artificial Intelligence

Another area of research that has recently attracted the interest of the industry, is the application of artificial intelligence and machine learning (ML) techniques for providing situational awareness to the system operators. Such techniques could be developed and integrated with a WAMS to derive metrics that can be used as precursors of system insecurity, as well as system performance indicators. They could classify normal (typical) from abnormal (atypical) operating conditions and provide guidance to system operators and engineers to further investigate whether an abnormal operating condition could result in a security threat to the system or not.

ML based state estimation (SE) is also being explored in the R & D community as a way to overcome limitations of conventional model and SCADA based SE, or the limited observability from PMUs for PMU-based linear SE.

WAMS/EMS Integration

Presently online Dynamic Security Assessment (DSA) is implemented by integrating simulation tools with the EMS to perform the analysis in operational mode. This is referred to as model-based analysis, with a snapshot of the model provided by the State Estimator which is used as the input to the DSA simulation engine. The main advantage of model-based analysis is that the security of the system can be assessed for a variety of operating scenarios under single (N-1) and multiple contingency conditions, and the operators can follow already developed operating guidelines which involve system re-dispatch to ensure satisfactory stability performance, in anticipation of the next contingency (i.e. under N-1 condition).

On the other hand, WAMS applications are considered measurement-based and can evaluate stability performance in the immediate time window, identify a potential instability condition, and activate a remedial, automated control action to address the instability condition. Such techniques implemented in a real-time online environment as part of a WAMS can obviate the need for an anticipatory action, thus potentially eliminating the associated economic penalties.

Integration of WAMS with EMS would enable hybrid DSA approaches that combine the benefits of model-based and measurement-based methods.

Data Quality Conditioning

Despite the wide recognition that synchrophasor-based applications and WAMS could significantly improve power system operations, monitoring and control, one of the main existing challenges is the data quality of streaming synchrophasors that may impact the robustness of WAMS. There are several drivers of impaired synchrophasor data, such as PMU hardware failure, poor communications network performance etc. WAMS should include synchrophasor data conditioning functionalities that will continuously monitor the quality of the streaming data and accurately differentiate bad data from abnormal measurement values due to a system contingency is necessary.

WAMCS Testing and Operator Training

PMUs and WAMCS are being widely deployed in power systems worldwide, and have proven to be a very valuable resource to observe the power system dynamics in the control room and provide advanced situational awareness and dynamic security assessment. Given their value, many utilities and research organizations are establishing advanced laboratory facilities to create, model and test WAMCS. Real time simulators are a critical component of these facilities and are expected to benefit and accelerate the advancement and deployment of WAMC systems, as well as operator training.

Another application of WAMS is real-time estimation and monitoring of system inertia which has been covered previously in this chapter. Additionally, development and use of WAMCS and PMU based applications should be complimented with research items discussed in the roadmap document of Topic 3 of this initiative.

Open research areas

R&D is essential to address open research questions related to the development, testing and adoption of novel PMU applications and WAMC systems, to ensure reliability and efficiency of future grids dominated by IBRs. Such R&D topics are listed below:

1. Design and implementation of a monitoring and control infrastructure, with metering units providing high resolution measurements that capture the wide range of frequency of grid dynamics, and a combination of local and wide-area control systems that mitigate reliability issues caused by grid disturbances.
2. Development and industry adoption of measurement based inertia estimation techniques that capture inertia contribution from generating sources and loads, including “synthetic” or “emulated” inertia provided by IBRs
3. Development and adoption of artificial intelligence based techniques that use all available data in a control center, including SCADA and PMU measurements, to assess the “health” of the grid and provide actionable information to system operators
4. Next generation EMS with seamless integration of state-of-the-art EMS applications with novel WAMC systems

4.4.5. Research plan for medium priority topics

The medium priority topics hold their own category for each topic. For each topic, the following steps are recommended as initial steps to be carried out in application of the roadmap:

1. Harmonics and power quality:
    a. Preparation stage:
        i. develop background on level of harmonics generated by IBR and DER in the network.
        ii. get an understanding of any prevalent resonant modes in the system, both at transmission and distribution level
        iii. consolidate with Topic 1 (IBR design) on relationships between IBR control architecture and harmonic profile
    b. Formulate research projects with objectives to:

        i. verify accuracy of harmonic models provided by IBR OEMs based on measurement data
        ii. ascertain the relationships and coupling that may arise from harmonic spectrum of an IBR and the evolution of system oscillatory modes
        iii. evaluate the ability of supplementary IBR devices to mitigate harmonic distortion and its impact on stability profile of the network
    c. Expected outputs from these research efforts can be:
        i. new models that adequately represent the harmonic profile of the IBR
        ii. new analysis techniques that may allow for harmonic content representation to serve as an input in tracking evolution of super-synchronous modes in the system.
    d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
        i. 3 years
        ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.
    e. Expected skill sets include understanding of:
        i. power system analysis and dynamics
        ii. power system planning and operation
        iii. control system theory and stability, and mathematical processes and computation techniques
        iv. computer software development and implementation
        v. signal processing and graph theory

2. Outage scheduling with high percentage of IBR
    a. Preparation stage:
        i. develop background on criteria presently considered to schedule maintenance outages in the network
        ii. get an understanding of any outage can impact the operation of the system
    b. Formulate research projects with objectives to:
        i. evaluate the coupling between a system outage and stability of a system. For example, will taking a line out for maintenance outage result in reduced damping of a small signal mode when PV output is at its peak?
        ii. develop analytical techniques and tools to formulate a feedback process between outage scheduling and stability evaluation
        iii. evaluate the possibility of linking this feedback process to the generator scheduling process

c. Expected outputs from these research efforts can be:
    i. new insight into the methods and considerations to be considered before granting an outage request
    ii. new tools that use outputs from a stability analysis as inputs into outage scheduling and vice versa.
d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
    i. 2 years
    ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.
e. Expected skill sets include understanding of:
    i. power system analysis and dynamics
    ii. power system planning and operation
    iii. control system theory and stability, and mathematical processes and computation techniques
    iv. computer software development and implementation
    v. signal processing and graph theory
    vi. optimization techniques and probability theory

3. Grid enhancing technologies
    a. Preparation stage:
        i. develop background on various technologies available to mitigate transmission congestion and their impact on power flow across the network
    b. Formulate research projects with objectives to:
        i. evaluate the impact of inclusion of grid enhancing technologies on stability of the network. For example, addition of a power electronics based phase shifter could introduce sun-synchronous control oscillations. Or it could change the voltage stability boundary of the network
        ii. develop analytical models for various grid enhancing technologies so that they can be seamlessly integrated into the stability tools that are developed
        iii. develop analytical tools that can control the setpoints of grid enhancing technologies not just from a steady state thermal constrain perspective, but also from a stability constraint perspective.
    c. Expected outputs from these research efforts can be:
        i. new insight into the impact of grid enhancing technology operation on bulk power system stability, especially interactions with other equipment.

    ii. new tools/models that include the small signal and large signal stability model of grid enhancing technologies into existing or newly developed stability analysis software.

  d. Expected timeline to develop prototypes that can be readily applied in large system analysis:

    i. 2 years

    ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.

  e. Expected skill sets include understanding of:

    i. power system analysis and dynamics

    ii. power system planning and operation

    iii. control system theory and stability, and mathematical processes and computation techniques

    iv. computer software development and implementation

    v. signal processing and graph theory

    vi. optimization techniques and probability theory

4. Wide area monitoring and control system

  a. Preparation stage:

    i. develop background on present status of wide area monitoring and control efforts

    ii. get a baseline from various vendors, including EMS software vendors, on capabilities that can be leveraged.

    iii. Consolidate with Topic 3 (Control Center of the Future) on integration of suggested efforts into the control center

  b. Formulate research projects with objectives to:

    i. evaluate the depth of unobservability that can be attained while still allowing for adequate monitoring and control of relevant oscillatory modes in the system

    ii. develop analytical and computational based tools that can first predict the onset of instability using streamed data and situational awareness of the network and subsequently estimate the control actions to be taken to mitigate or increase damping in the network.

    iii. develop tools and methods that can integrate the above analysis into real time contingency evaluations.

  c. Expected outputs from these research efforts can be:

    i. new, and more importantly, efficient ways to track the evolution of system oscillator modes

    ii. new tools/models that can estimate the onset of instability in a one-hour ahead manner that allows for sufficient action to be taken.

d. Expected timeline to develop prototypes that can be readily applied in large system analysis:
    i. 3 years
    ii. This however does not include time for continuous improvement and expansion of the developed tools and methods.
e. Expected skill sets include understanding of:
    i. power system analysis and dynamics
    ii. power system planning and operation
    iii. control system theory and stability, and mathematical processes and computation techniques
    iv. computer software development and implementation
    v. signal processing and graph theory
    vi. optimization techniques and probability theory
    vii. supervised and unsupervised learning algorithms

4.5. Low priority topics

The low priority topics are those that, although they do not bear directly on stability assessment, are nonetheless relevant because outputs from these processes indirectly influence stability assessment, as their outcomes are invariably used in determining the initial operating condition at which system stability is evaluated. The topics covered in this section are designated as low priority only from the perspective of their immediate relevance to system stability tools. It is also likely that these topics are covered in much more detail in the other research roadmaps.

4.5.1. Dynamic line rating for effective use of transmission assets

Discussion

The thermal rating of overhead transmission lines is highly affected by ambient weather conditions, mainly air temperature, wind speed and direction, and solar radiation. Advanced line rating methods adapt line thermal ratings to actual weather conditions to adjust line capacity. This approach represents an advantage over traditional rating methods wherein transmission line rating is determined based on conservative ambient values to cover the worst-case possible conditions for the region where the transmission line passes. The different methods vary on how often line ratings are adapted to the changing ambient conditions. Ambient adjusted ratings (AAR) approach adapts line ratings on a daily or hourly basis based only on ambient air temperature. Air temperature is the only time-sensitive data considered, wind speed and solar radiation are assumed fixed. Even though this method does not consider wind speed and direction to adjust line ratings, it represents an important improvement over static rating and seasonal rating methods. Various entities, among them ERCOT, have used AARs in operations, reporting significant savings in congestion cost. Dynamic line rating (DLR) technologies adjust line rating in real-time based on actual measured ambient conditions. Field data used to estimate rating include weather conditions, ambient temperature, solar radiation, and wind speed and direction, along with line variables such as current, ground clearance, conductor sag, tension, and temperature.

Open research areas

Experience from actual implementation of DLR system has revealed that line rating is most of the time significantly higher than the static rating determined with conservative assumptions. Several studies have shown the benefits of using DLR to improve integration of wind and solar generation by reducing curtailment due to limited transmission capacity. DLR can also help improve reliability and resiliency by providing grid operators with enhanced situational awareness of current condition of assets. Newer DLR technologies incorporate transmission rating forecasting capability, that uses advanced weather forecasts to predict transmission line capacity several hours ahead of time. Forecasted line capacity can be used in day-ahead operations allowing more efficient dispatch, thus reducing congestion cost, and improving operation efficiency. Even though DLR technology has great potential for improving transmission efficiency and utilization and realizing important cost savings, several barriers and limitations need to be overcome for widespread adoption in system operation. Among the many barriers, accuracy and reliability of the calculated rating is of main concern. DLR systems may not have the resolution and accuracy to always represent the actual line rating. Errors in line rating calculation can weaken operator confidence in the capability of DLR to perform accurately and reliably. Other barriers described in various technical reports include volatility of rating, challenges for integration into system operation processes and tools, difficulties for identification of critical spans, forecast inaccuracies, financial impact and monetization of economic benefits [56] [57] [58].

4.5.2. Cybersecurity

Discussion

Securing inverter interconnected systems and the power network, which exchange critical data and commands to and from these systems, is critical to maintain grid reliability and resilience. Increase in adoption of IBRs is creating a connected ecosystem of multiple interfacing parties, including grid operators, customers, aggregators, and manufacturers. These entities may deploy centralized systems that remotely manage and control the inverters via public or private communication networks. The stakes for cybersecurity investments are high. For example, breach of these management system or networks which controls and monitors a large number of IBRs could lead to an unexpectedly high peak demand or severe loss of generation capacity. At the customer level, cyberattack on a smart inverter in a rooftop solar system could provide opportunities for cyber threats to propagate to grid operator’s servers that controls hundreds or even thousands of IBRs connected to the grid— potentially leading to grid outages.

As deployment of high-power IBRs proliferates, these integrated systems and grid planning will need to be designed so that capacities are allocated and sized for the worst-case cybersecurity threat scenarios. Therefore, a multi-layer mitigation strategy will need to be inherently designed for this ecosystem, but implementing cybersecurity can be complex. Security measures are needed for dozens of connected sub-systems and components, yet the industry currently lacks a unform way to specify what cybersecurity safeguards should be implemented. The current state of standards does not reflect security-by-design considerations, and this threatens IBR interoperability objectives if entities continue to define their own specifications for security infrastructure.

Open research areas

Research opportunities should include practical mitigation approaches which encompass how interfacing systems should prevent, localize, and isolate security issues faster than their effects are felt in broader parts of the grid system. These opportunities can include:

1. Design, creation, and testing of cybersecurity communication protocols specific to IBR interoperability design requirements
2. Public key infrastructure, blockchain, and other trust platforms which provide assurances in the authenticity and integrity of exchanged data among interfacing systems
3. Integrated grid system cybersecurity risk assessment tools to determine security controls for networks, systems, sub-systems, and components which are appropriately commensurate to potential risks against reliability, safety, and customer privacy.
4. Development of a holistic cybersecurity certification framework and mainstreaming control implementation though prototype and reference design development.
5. Testing methodologies to inform how entities and their systems be certified for cybersecurity compliance and interoperability.
6. Cloud computing guidance for grid operators and aggregators who leverage cloud computing tools to manage fleets of DERs and their applications

Customer privacy impact assessment and guidance to understand and protection against implications to personal identifiable information (PII), payment card industry (PCI) data, and energy usage and generation data

4.5.3. Power system planning for extreme events

Discussion

Power system planning needs for Australia are addressed directly in the companion CSIRO *Australian Research Planning for Global Power Systems Transformation* research roadmap on “Planning – New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix” (Topic 4). The following discussion and research recommendations are offered as a complement to the discussion in the Topic 4 roadmap.

It is human nature to under-estimate the likelihood of extreme events. However, with a changing power network, their consideration is important as,

1. Impactful weather events are increasing in frequency, and intensity, and geographic expanse, and duration. This combination of factors is dramatically influencing the number and severity of weather-induced events in the electric power industry [59].
2. In projecting disruptive weather event probabilities moving forward, systems planning for electric reliability requires incorporation of this rate of change in the planning process. The historical probabilities for the frequency, intensity, geographic scope, and duration of weather events need to be adjusted upwards to take recent climate trends into account. Probabilistic weather forecasts are another tool that can help deal with rising frequency, intensity, and duration of extreme weather events.
3. Extreme events and their impacts occur over a wide range of severities, and hence a probabilistic framework in assessing and forecasting these events and their trends may be called for. Extreme events can be both probabilistically assessed and, with current and evolving methodologies for weather forecasting, be probabilistically forecast. By this, we mean that for any given extreme weather system in the near-term forecast (within 7- 10 days), we can evaluate the probabilities of each level of potential intensity for a given location, and for the geographic coverage of the storm overall.

Across topics varying from weather to fuel supply and cyber security, today’s power industry employs planning methods that tend to understate the probability of supply disruptions affecting multiple units and their impact on consumers and the system itself. The electric power industry is moving inexorably into a new era in which generation portfolios are changing, a larger proportion of generating assets are variable renewable resources, generation occurs behind as well as in front of the meter, the economy has become increasingly dependent on a reliable supply of electricity, and consumer preferences for reliability and the carbon content of their energy supplies are rapidly evolving. As these changes are occurring, the industry needs to be planning for resource adequacy in a manner that will make electric service more resilient to significant disruptions of supply whether they are the result of weather, cyber / physically attacks, or multi-factor events [60] [61].

As part of evaluating system resilience and reliability, it is very important to measure the depth and frequency of outages. These are the factors that have significant customer impacts. The notion of value of loss load (VOLL) translates unserved energy into the estimated dollar cost to customers of an outage. Many studies have been done to ascertain VOLL, which varies by customer class, individual customers preference, time of the year, and other factors. Unfortunately, very few studies have been done that look at outages that extend for more than a day [62] [63] [64].

The cost of an outage to the customer increases as its duration extends. For most consumers, the initial cost for kWh of unserved energy in an hour long or momentary interruption is higher than the average cost per kWh of unserved energy over a four - sixteen hours loss of service. Limited data are available on the costs to customers of longer duration outages. In longer outages, different customers will realize differing opportunities to adapt to the loss of power. A given manufacturing facility might be able to tolerate being out for a few hours and then catch up on its production over the next few days. However, if the outage goes on for days or weeks, the economic losses likely will mount. For example, fuel diversity, fuel source diversity (e.g., multiple pipelines or multiple rail links), geographic diversity, storage, microgrids, and demand response contribute to resilience but potentially at a cost. Common mode events are not included in standard system expansion models, but it is important to plan for them.

Extreme events can simultaneously impact various portions of the electrical network resulting in a either N-k or cascading failures. As a result, it is important for stability tools to recognize the occurrence of such an event (can either be as a user input for N-k or learning based analysis for cascading failures) in order to determine system stability.

Along with consideration and definition of extreme events, it is also important to evaluate resiliency of the network [65]. Resilience of the transmission system will become increasingly critical as the impacts of climate change drive more frequent extreme contingency events that will impact the operation and planning of future power systems [66]. Understanding and preparing for these impacts now is critical to identify the infrastructure decisions that need to be made in the present to ensure secure, reliable, and resilient operation of the power system in the future. Here, defining system resiliency is the first step to be tackled. As the system changes, the various methods/metrics described above can be used to determine resiliency of the system. Further, if system reinforcements are defined, then it is necessary to evaluate the cost-benefits of the same. The primary objective of such an analysis will be to efficiently evaluate the consequences of a defined set of extreme events on multiple network topologies and identify potential transmission system candidates for resilience hardening. Evaluation of the impacts of potential paths of cascading failures and determination of the risk of lost load and generation present in the system will also have to be carried out.

Open research areas

The objective here is to develop a set of recommendations for enhancing resource adequacy with extreme events including further data development and detailed analyses and methodological development to improve the understanding of and planning for response to high impact events in both the long and short term.

The recommendations provided here are divided into those associated with weather, events associated with fuel security – specifically interruptions in the supply of natural gas, improving capacity value calculations, and using new techniques for resource planning that account for high impact common mode events.

1. Develop scenarios by region of high impact common mode events (both more and less likely events) and estimate the probability distributions of the scenarios' physical impacts and associated economic costs. This would involve a build of a catalogue of external events that have a sufficiently high cost and probability to merit consideration for regional scenarios in terms of resource planning; this should include events with moderately high cost and high probability of occurrence as well as events with a high potential cost and somewhat lower probability. The type of events, their cost, and their probabilities will vary by region. For example, wildfires deserve the most consideration in the Western region of the North American power system, while natural gas disruptions incur the highest impact in North Eastern region. Scenarios that are deemed to be significant would be prioritized for further analysis.
2. Coordinate the development of regional VOLL studies, including updating and extending available estimates of customer outage costs, estimating the distribution of outage costs in different customer groups and addressing how outage costs may change during widespread and/or long-duration outages. In addition, support the development of regional models for estimating the economic impacts of long-duration outages. This initiative should address gaps in the regional coverage of recent outage cost studies, consider the specific types of widespread and long-duration events that may be relevant in each region, and enable estimates of the indirect economic impacts of extended service interruptions.
3. Model the gas-electric interactions that occur over natural gas and electric physical infrastructures to incorporate the effects of natural gas supply interruption on power system resource adequacy. The modeling framework would combine an operational physical model of natural gas pipeline network with a physical model of electric network typically used in production costing planning studies. That model would be capable of explicitly simulating the effects of common mode failures such as loss of pressure on the availability of gas fleet and utilize this information in resource adequacy assessment. The framework would incorporate a probabilistic weather – driven model of regional spatially distributed natural gas and electricity demand and availability of variable wind and solar generation. The model of the gas pipeline network would evaluate physical availability of natural gas delivery to serve electric generation. The model of the electric network would assess the adequacy of the power system subject to gas availability determined by pipeline physics and by the gas – electric interaction dynamics. A substantial effort should also be placed on the development of regional gas – electric modelling datasets with particular emphasis on overcoming challenges associated with collecting pipeline data. However, the projection of forecast use of gas can be used to determine the priority for updates in the gas-electric models. The focus of this research area is an expansion of gas/electric modeling applied to various timeframes. The gas and electric sectors are highly linked, but often simulations ignore detailed representation of the gas network and assume that fuel is always readily available. In furthering this modeling, we suggest the use of probabilistic forecasts for use in several timeframes, including operations. There could be some benefit to using the forecasts as they are produced today so that the impact of gas/electric modeling can be understood. However, there would also be benefit in using other methods that could be used in the future, including the Bayesian approach [67] [68]
4. Develop a classification system of disruptive weather events that includes intensity, geographic scope, and duration that is directly targeted for use by the electricity market. While certain types of storms (e.g., landfalling tropical cyclones) could use a single set of thresholds across the nation for measuring severity (e.g., the Beaufort scale), this proposed classification system would consider regional variations where relevant (e.g., the U.S. National Weather Service uses a regional storm impact index to accommodate the fact that six inches of snow in Buffalo causes less impact than six inches of snow in Atlanta). Geographic scope (how much population or how many square miles are impacted) would be considered, as

would the duration of the weather event. These weather events would be directly correlated to outage data measured by number of customers with interrupted service, and total outage minutes for each event. Once these data are collected and analyzed, explicit weather scenarios by region will be defined with thresholds for high impact disruptive weather events defined by weather type.

5. Develop the concept of Value of Load at Risk (VLAR) for the electric utility industry that would be the analogue of Value at Risk (VAR) in finance to provide a probabilistic dollar value for unserved energy. This would specifically help address the need for performance metrics surrounding reliability and resilience that measure unserved energy and the economic impacts that result. Presently in the NEM this is measured through the reliability standard of 0.002%. Whether focused on resource adequacy or more narrowly on responses to high impact events that disrupt the supply of power, the challenge is the development of a universally applicable metric or set of metrics that reflect the frequency, duration and depth of potential outages, the probability of different outage states, and the resulting economic costs to customers and society given the portfolio of generation assets and responsive loads available to utility planners. The development of VLAR will need to build on the mathematics and modelling of the financial services industry. It will extend VAR with an objective to focus on the performance of an electric asset portfolio as opposed to the return from financial instruments. The goal will be to develop an economic metric that reflects the stochastic / probabilistic nature of VLAR. Most current reliability metrics focus on an expected quantity of unserved energy but do not address the economic costs and societal consequences of shedding load. With an increase in extreme events, the economic consequences will become increasingly important alongside typical reliability metrics. Development of such a metric could build on the existing concepts in Australia and extend to economic indicators and metrics.
6. Develop resource planning models that use stochastic mathematical programming which would allow incorporation of extreme events directly into the optimization framework. The stochastic framework will provide important insights into how to develop resilient resource plans. Since many externally driven high impact events do not happen often, planning cannot be done assuming that such an event will happen with a high frequency. These events would be represented by “states of the world” that have low probability weights. An optimal solution would consider the possibility of a high cost events and hedge them within the resource plan. The stochastic model’s objective function can for example be the minimization of the present value of the sum of expected capital cost, operating and maintenance cost, fuel cost, and unserved energy cost or for widespread long-duration events expected macroeconomic impacts. Unserved energy costs represent customers’ willingness to pay for energy and could be specified as several steps reflecting different customer classes. In an optimal solution, the unserved energy component should be modest in most states of the world. In states that represent extreme events, however, unserved energy costs (or macroeconomic impacts) could be high. With today's capability to do parallel computation in a cloud environment, solving what would have been an infeasibly large problem a few years ago is now straightforward. The model’s reporting function should record detailed results for all states of the world in a database. It would then be possible to investigate how the optimal solution performed in each state of the world. The reporting function should also summarize (and produce distributions for) high-level results such as production cost, unserved energy, unserved energy cost, carbon, and other emissions across state of the world. This will facilitate further analysis of states of the world that had a high impact on the optimal resource plan. The model and its reporting function could also be utilized to perform scenario analysis. If a resource plan was proved as an input (rather than determined by the model), the model’s state-of-the-world subproblems would calculate key parameters for the input system for future years.

From a system resiliency perspective, future research would have to include understanding the impacts of increased IBRs and how they can participate in the operation and planning of more resilient power system. Current processes and tools primarily evaluate the steady-state planning impacts, but future research will have to adapt and evolve to quantify the impacts of extreme contingency events dynamically. This will require expanded and more detailed protection models as part of the positive-sequence time-domain studies to capture cascading impacts and consequences.

4.5.4. Resource Adequacy

Discussion

A lower emission electricity sector will be foundational for decarbonizing other energy sectors through electrifying segments of the transport, buildings, and industry sectors. With more of the energy economy dependent on the electricity sector, the reliability and resiliency of the supply of electricity will need to increase to meet societal expectations. A key capability will be for electric utilities to be able to assess whether existing and emerging resources are adequate for meeting electricity demand for future scenarios, such as changing climate and extreme weather scenarios. As recent supply deficiency events have shown, however, existing resource adequacy (RA) processes, metrics and tools may be insufficient and need to evolve to address the rising trend in disruptive events, while also considering the changing resource mix. Existing tools may also understate the probability and depth of many common mode events. A lot of aspects related to stability of the power network is dependent on the pre-disturbance operating point (or power flow solution) of the network. For example, an energy source operating at 50% of its rating can have a higher stability margin as compared to an energy source operating at 95% of its rating. This is further coupled with the amount of reactive power support provided by each energy source. In order to get a good picture of system stability it is therefore important to have an accurate picture of the system operating point, which is in turn governed in part by a resource adequacy analysis.

Further insight into resource adequacy research topics is included the companion CSIRO *Australian Research Planning for Global Power Systems Transformation* research roadmap on “Planning – New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix” (Topic 4).

For a complete insight into research topics under resources adequacy, the roadmap document from Topic 4 can be referred.

Open research questions

Aspects of resource adequacy that would have bearing in the future power network and that can have a relationship with evaluation of stability and system dynamic security are:

1. Development of appropriate assessment metrics and minimum criteria for low-carbon systems. The developed metrics should better reflect the nature of the outages, the consequence of deficiency supply, and that capture chronological, energy-limited and common-mode aspects. Additionally, adequacy criteria should be determined based on specific needs of the system, while keeping in perspective the regulatory/market context.
2. Development of models and process for scenario creation that incorporates future climate and extreme weather, societal trends, and interdependence between various sectors such as electricity, gas, and water.

4.5.5. Scenario development

Discussion

With significant amounts of variable inverter-based generation in the system, the more prevalent practice of performing a power flow and stability assessment for a peak and an off-peak condition may not be sufficient. Several other operating conditions may require assessment in addition to a peak and off-peak operating condition. Figure 3 [69] and Figure 4 [70] show examples of the different operating conditions that might arise with high penetration of variable generation resources. As such, planning engineers must analyze their forecasted hourly/sub-hourly load shapes as well as variable generation profiles to identify scenarios of interest.

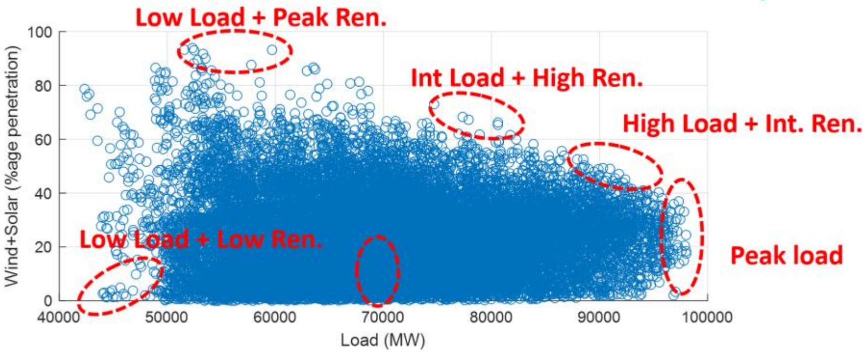
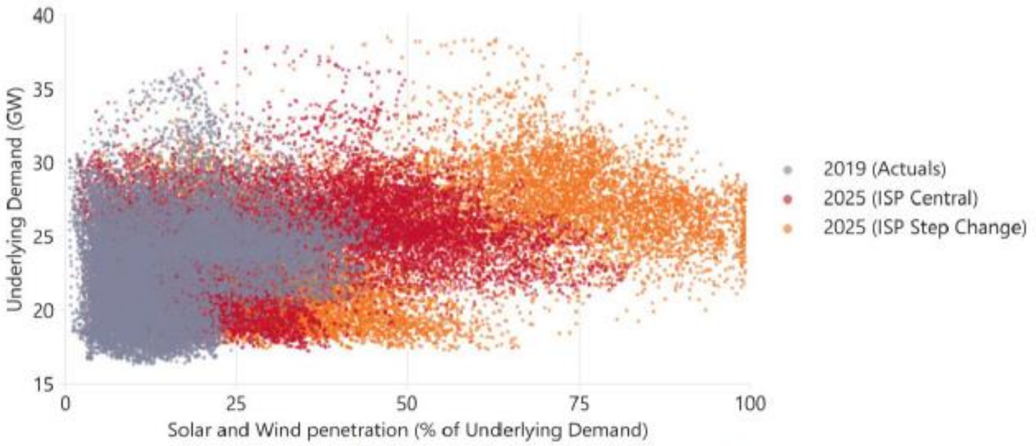


Figure 3: Different load and variable (wind+solar) generation scenarios in a possible future planning year



Note: Penetration on this graph represent NEM half-hourly wind and solar generation divided by the underlying demand which includes demand response, energy storage, and coupled sectors such as gas and the electrification of transport.

Figure 4: 2019 actual and 2025 forecast instantaneous penetration of wind and solar generation compared against demand in the network [70]

As shown here, these cases correspond to peak load conditions, high load and high variable generation conditions, highest penetration conditions and low load conditions, all of which occurs during different loading levels in the system. Each of these conditions can have reliability concerns depending on loading levels as well as distribution of variable and conventional generation levels in the system.

The example shown here only considers load and variable generation shapes to identify critical operating conditions. A utility may want to take this process a step further by developing hourly and sub-hourly power flow cases based on load shapes, variable generation outputs and production cost modeling results considering ramping and other operational restrictions. These hourly/sub hourly power flow cases may then be clustered based on additional characteristics like load distribution, variable generation distribution, system inertia, loading on key transmission paths etc. Further, based on individual state targets for distributed energy resources, the impact of DER on the net load shape (complimented by research activities identified in Topic 4) should also be considered. A single candidate power flow case can then be picked from each of these clusters and examined in great details to understand reliability concerns during the planning phase [71].

Open research questions

The key research initiatives here are:

1. Development of a framework that can host, and if queried return, forecasted load shapes and variable generation profiles and provide data analytics and visualization capabilities for transmission planners to identify scenarios of interest.
2. Develop workflows and automation tools for seamless creation of power flow cases from hourly/sub-hourly production cost models to enable the assessment of multiple scenarios
3. Develop clustering techniques that have the 'intelligence' to identify key features based on the case data and then further cluster cases that have distinctly similar features.

4.6. Risks and mitigation associated with the research plan

Stability assessment both at the device level and the system level has inherent risks. Even in a system with conventional generation, while it may be relatively easier to evaluate both small signal and large signal stability for an individual device, scalability of these techniques for multi-machine large system analysis is not straightforward. Although knowledge of synchronous machine electromagnetic magnetic behavior has continuously improved over the past two decades, many large signal stability analysis techniques continue to use a simple two state swing equation model due to the complexity involved in representing the electrical characteristics of the machine. This challenge is further compounded with IBRs whose dynamic behavior is dominated by lines of computer code (that are hidden for intellectual property reasons) rather than laws of physics. In such a situation, it may be concluded that running extensive time domain simulations is the only approach that can be followed to identify the stability of the network, its voltage characteristics, and the operation of its protection equipment.

With blackbox IBR control models, without collaboration and coordination with OEMs, it can be a significant burden to develop stability tools and methods. Although measurement-based techniques exist, extrapolation of the results from one operating point to the next can be challenging. This makes it difficult to not only predict stability margins and boundaries but also to understand the trajectory of the dynamic response and its relationship to voltage stability and operational boundaries. Tools and methods that are to being applied in real-time or near real time can suffer if there is loss of visibility and situational awareness of the network and its associated components.

While these risks to the development of stability tools and methods may seem insurmountable, few approximations and engineering judgements can be applied. The improvements in standardization of dynamic response of bulk power system connected IBRs through efforts such as the draft IEEE P2800 standard allow for a baseline performance of IBRs against which system stability tools can be developed. This baseline can then be used from a screening perspective to identify scenarios that might push against the stability boundary. Use of generic dynamic behavior trends can also be an option to set the baseline from a screening perspective. Additionally, improvements in mathematical computational analysis allow for obtaining the solution of equations with increased complexity.

5. Recommendations

Begin with high priority topics. It is recommended to begin work with the *Critical* and *High priority* topics. There are no critical dependencies among any of the identified topics that require them (or any subset of them) to be undertaken in a specific sequence.

The topic prioritization is summarized in Table 4 (page 27) and Table 5 (page 28).

The C*ritical* topics are:

1. Stability margin evaluation
2. Small signal stability screening methods
3. Voltage stability boundary
4. Voltage control, recovery, collapse

The *High priority* topics are:

5. Online identification of system strength
6. Monitoring inertia in real time
7. Modelling and model validation
8. Voltage and reactive power management
9. Real time simulators
10. Critical contingency identification
11. Real time contingency analysis
12. Protection system operation and coordination

Address topics in parallel. Many tools may have to be developed in parallel while still being used in a sequential manner.

Continuous development beyond initial development of advanced prototypes. System stability assessment by its nature involves a suite of inter-related tools. Advances in one tool may create an opportunity to update, or optimize integration with, a second tool – even if the second tool has already undergone a significant development process. While this roadmap estimates timelines and costs for a focused tool prototype development and implementation effort, this should be followed by a continuous, iterative process of improvement in integrations and input assumptions across the entire suite of tools.

Implement collaboratively. For each topic, the tool development process can significantly benefit from collaboration among Australian utilities, AEMO, research organizations like CSIRO, academia, and equipment vendors. Some of the ways the roadmap can be implemented include:

1. Strong power engineering program to introduce the latest topics at the undergraduate and graduate level.
2. Funding for graduate research on specific topics at graduate and Ph.D. levels

3. Inter-disciplinary course work in universities that allow power engineers to also learn about controls systems, power electronics, computer programming, applied mathematics, and operation research to enable future generation of engineers to deal with the challenges mentioned in the roadmap and help develop and improve solutions.
4. Strong internship programs at utilities to expose students to these challenges at an early stage.
5. Opportunities to improve skillsets of existing utility staff by providing practical training on the topics. Work with subject matter experts to develop suitable training material.
6. Collaborate with leading entities across the world to develop the tools/methods where Australia may not have enough expertise.
7. Develop yearly plans to implement the critical and high priority topics for next 3 years. Many of these topics will be worked in parallel.
8. Start engaging software vendors and OEMs as early as possible to keep them in the loop.

Ensure AEMO practices are aligned with stability assessment research plans. AEMO should review existing procedures based on the roadmap and identify need for refinement – e.g. DMAT, System Strength Guidelines, outage scheduling, evaluation of critical contingencies.

Enhance network data collection to meet future stability assessment needs. Encourage data collection at generation POI, transmission and distribution levels using high fidelity data acquisition devices. Actual measurements will be very important as the new stability issues need to be analysed.

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Appendices

Appendix A – Research Question Change Log

While no changes have been made to the original research questions, the original research questions have been expanded upon as listed in Chapter 3.