2024 White Paper

Screening Metrics and Stability Risk Identification Procedures for Networks with High Inverter-Based Resources

An Overview of Different Methods and Applications

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INTRODUCTION

With growing penetration of inverter-based resources (IBRs) around the world, an increasing number of events have been reported on adverse interactions between the power-electronic controls and the various elements of the grid [1]. These numerous events have forced system operators and planners to reconsider the traditional processes of system buildouts.

The industry definition of stability has also been evolving as new phenomena emerge. In a recent IEEE article [2], traditional power system stability analyses were extended to include emerging stability considerations due to increase in IBRs in power systems around the world. Table 1 captures the addition of the newer stability considerations.

Table 1. *Classification of Stability Concerns including Emerging Stability Concerns due to Growing IBR Penetration*

Stability concerns due to resonance-driven interactions	Torsional	Torsional Interaction, Torque Amplification: Non-IBR interactions between series compensation and torsional modes of the turbine-generator mechanical shaft Sub-Synchronous Torsional Interaction/Device Dependent Sub-Synchronous Oscillation: interaction of power-electronic controls with mechanical torsional modes of turbine-generator shaft
	Electrical	Induction Generator Effect: Resonant interaction between effective inductance of synchronous generators and series capacitors Sub-Synchronous Controls Interaction: Resonance between Type-3 wind turbine generators and series capacitors
Stability concerns due to non-resonance -driven interactions	Electrical	Low frequency (< ~10 Hz) oscillations due to power electronic-based device control and system strength

Planners and operators now must consider many more attributes while they plan the system. Additionally, because of the complexity of the number of devices that are being interconnected and because of the varied regions in which the devices connect, a planning engineer needs more tools (both simulation and analysis). Finally, there is a large change in the workforce that is ongoing. A majority of the workforce could be retiring soon which results in potential reduction of operational experience (or “institutional knowledge”) within the organization. In this vacuum, a large variety of tools could be applied to help support the workforce so that the same level of reliability and security of supply can be provided.

Also, as the system evolves and newer resources connect at different portions of the network, flows around the network would change. With the buildout of different kinds of transmission topologies and transmission technologies, the types of contingencies needed to be studied also change. The contingencies that are critical at present might not necessarily be the contingencies that would be critical in the future. Also, evaluation of a critical contingency is not a trivial task because numerous combinations can result, even in a simple system with just three lines. Hence a key question is how to identify the critical contingencies of the future and would need to be studied in more detail. Right now, this process is mostly based on system operator experience, but it is important to develop an understanding from an analytical perspective, possibly using graph-theory and other mathematical methods.

Power system planning with increasing attributes and complexities should be approached in a staged manner with four main steps along with a feedback loop.

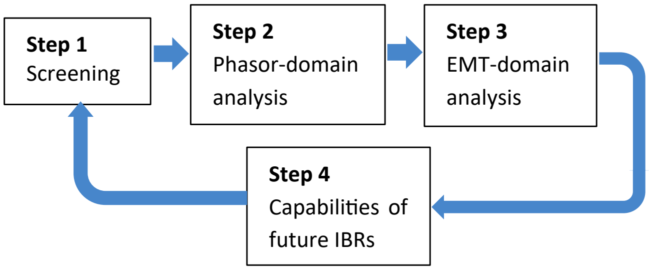


Figure 1. *Four steps of analysis in power system planning with increasing attributes and complexities*

The first step is screening. Analyzing a large system in detail is computationally prohibitive. Screening helps identify the portions of the system that require more detailed evaluation. It also narrows down the operating conditions for analysis, such as contingencies, control modes, etc. Based on the type of analysis, the screening tools need to be carefully selected from a host of available options.

Following the screening step, a phasor domain or positive sequence time domain analysis helps in furthering the analysis and providing insights about possible interaction challenges in the field.

The third step, when needed, involves an even more detailed study in electromagnetic transients (EMT) domain. This step is the most computationally expensive, but with proper modeling and framing of the problem, it also emulates real-life scenarios with increased accuracy. In fact, there is an increasing demand for EMT-domain studies globally. These studies are also the ones that benefit the most from the screening step since it enables an improvement in efficiency of carrying out EMT studies. Note that it is expected that in the future, both phasor domain and EMT domain analyses will be required to complement each other because there are different types of problems that can be studied in each domain.

Based on the analyses of steps two and three, there is a feedback loop which should define services required from the IBRs of the future. These guidelines close the loop in the evolution of IBRs by propelling R&D at original equipment manufacturers (OEMs) without being too prescriptive. Note that with individual OEMs developing features, there is also a need for standardization that enables system planners to be prepared to accommodate new generations of IBRs into their systems. In fact, it is well known that with evolution of IBRs and their controls, the grid supporting capabilities have also been increasing. Figure 2 illustrates this evolution in IBR capabilities. For example, legacy IBRs did not provide any grid support services and only generated active power at unity power factor. However, most present IBRs have the capability to provide both voltage and frequency response. With evolution of technology there is a development of enhanced IBRs with controls that can survive grid conditions with extremely low fault current, which is an increasingly common phenomena in today’s grids with IBRs replacing synchronous machines. Along this evolution path, future IBRs would be capable of blackstart and provide all grid services that are needed for power grids at any point in time.

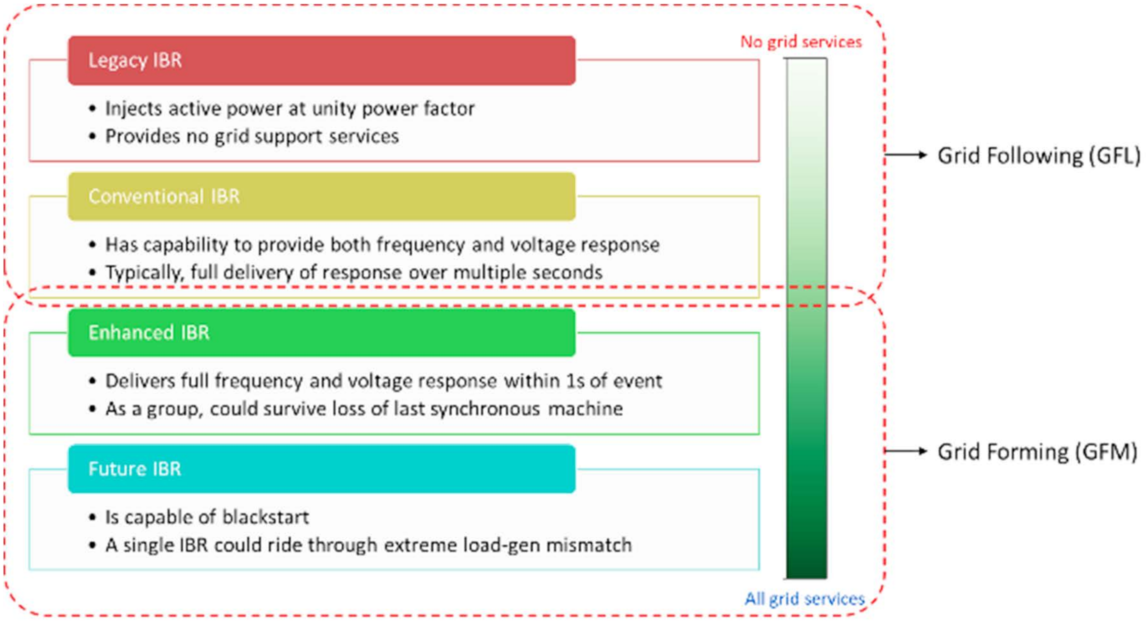


Figure 2. *Evolution of capability of IBRs*

At every step of evaluation, careful attention needs to be paid to model validation regardless of timescale. Even a detailed model obtained from a vendor should be subjected to a set of validation tests since the outcome of the analyses will depend on the quality and suitability of the model for a specific study. While all four steps are important in planning for a future with increased IBR penetration, we focus on the topic of screening and related tools in this paper.

TYPES OF SCREENING METHODS

There are several screening techniques that are used in the industry for addressing different challenges with IBR integration into power systems. In this paper, the methods discussed will be:

- hosting capacity analysis,
- short circuit and remaining MVA estimation,
- frequency spectrum analysis, and
- voltage control area analysis.

Sub-sections (i) through (iv) describe these methods and Table 5 summarizes the uses of these methods for various applications.

i. Hosting Capacity

As the power system component mix changes rapidly with hundreds of IBRs entering the generation interconnection queue every month, there is a need to evaluate their impacts across various areas of the system, since accommodation of the new generation requires displacement of existing, possibly conventional ones. In addition, excess IBRs at one location could compromise the available short circuit capacity, hence it could also be important to limit the use of available short circuit capacity to a certain value to ensure dynamic stability, unless IBRs bring their own robustness to that location. Network security has to be maintained under planned and un-planned outages; hence a comprehensive analysis has to be conducted across all provided contingencies. The profile of a system in summer can be different from that in winter which warrants comparison across different system loading scenarios. System constraints and limits need not be checked all over the interconnection, hence a focused look is needed to restrict limit checks to only required areas, zones, and/or bus kV levels. Such evaluations can require a need to evaluate hosting capacity across the network, to also identify network upgrades.

This evaluation is key to answering questions such as: Can all IBRs in the generation interconnection queue be hosted by the transmission network? If not, what is the limit of the network and where is the limiting element? Is a specific generator retirement scheme better than another scheme? How much load withdrawal can be sustained by the existing network?

The transmission hosting capacity analysis can provide developers information regarding how much hosting capacity is available at each node without assuming copper-plate model of the network. The hosting capacity analysis includes consideration of different generator retirement profiles and can aid in conduction of cluster studies. Figure 3 below shows an example of the amount of hosting capacity color coded by MW hosting capability at different buses shown on a geo-map.

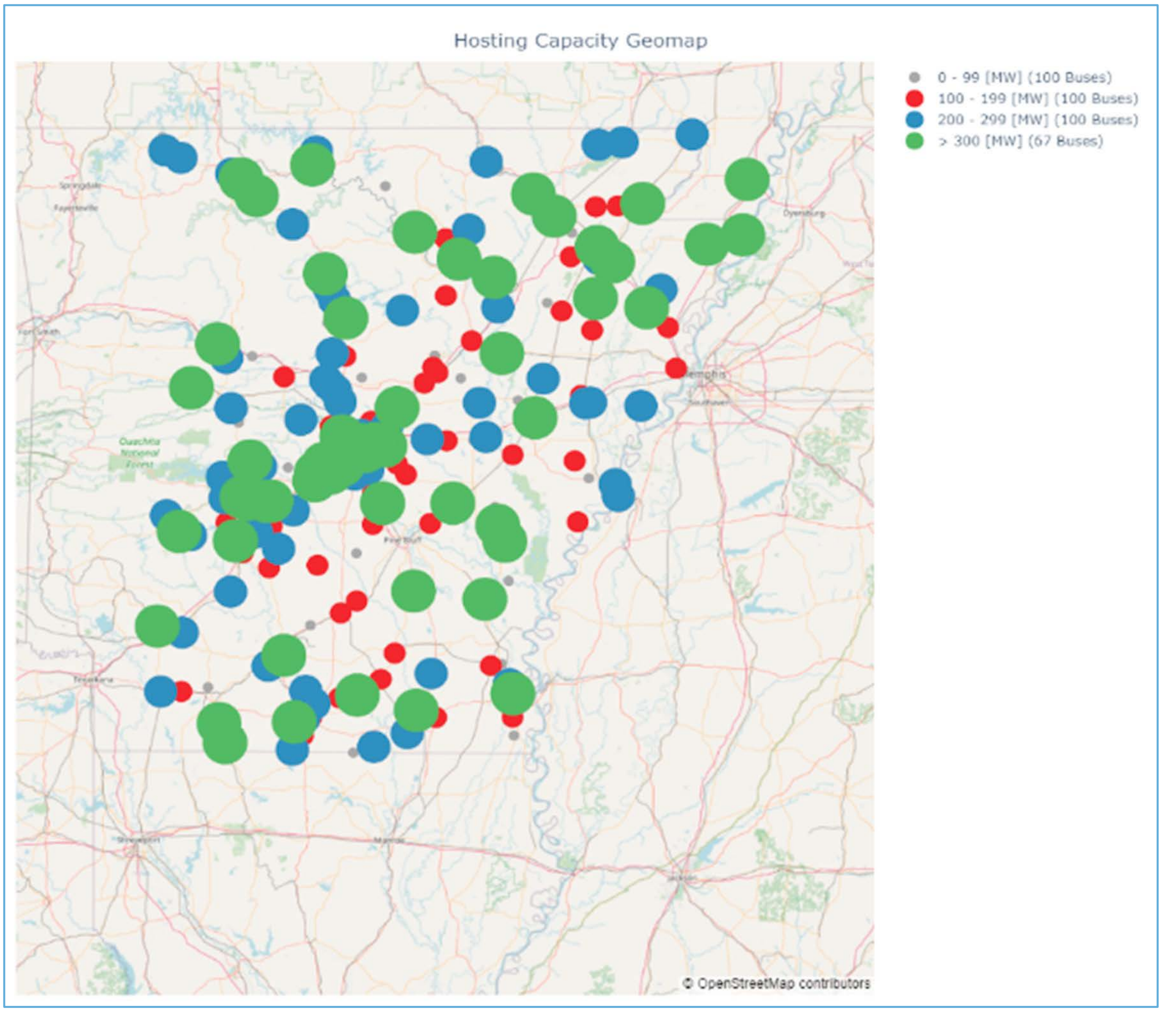


Figure 3. *Geo-map of hosting capacity [3]*

ii. Short Circuit Capacity and Remaining MVA

Grid strength assessment metrics [4] can provide answers to questions from utilities and system operators such as:

- How to evaluate if an IBR at a certain location would be stable?
- Would an EMT study be needed for a particular location?
- Would the interconnecting IBR be required to have advanced inverter controls such as grid-forming controls (GFM)?
- And if GFM is required, what should be the rating?
- Can the power grid host a large percentage of interconnecting IBRs in a stable manner in an area?
- Is there a chance of the interconnecting resource losing synchronism in the event of a fault?

Several short circuit metrics are used in the industry for quantifying the system strength such as generic short circuit ratio (SCR), weighted short circuit ratio (WSCR), and composite short circuit ratio (CSCR). The former is applicable to measure short circuit strength at an isolated IBR location for example, ignoring contribution from other IBRs in the vicinity, while the latter two are used to also take into account the effect of other IBRs in the vicinity of the bus at which the strength is to be determined. However, conventional SCR metrics do not provide the entire picture and should be used carefully and judiciously. Factors affecting inverter plant instability include not only the SCR, but also MW output, plant layout, and controller gains.

In addition to short circuit capacity, another related metric that is very useful is the remaining MVA available. If an interconnecting IBR at a particular location does not provide short circuit current, conceptually it can be thought of as a consumer of short circuit capacity since it needs access to a certain level of short circuit capacity for stable operation. As a sink (rather than a source), it would have the effect of reducing the amount of short circuit capacity available at other locations on the network. Hence, the minimum available short circuit capability estimate provides insight into potential locations of instability based on impact of other IBRs in the network and can be used to determine an initial rating of system strengthening devices that are required. The available short circuit MVA can be evaluated at each IBR plant. A negative value of the available margin indicates the need for more studies. This metric is also important in planning buildouts of future IBRs.

With grid strength screening methods, network locations with low short circuit issues can be quickly identified analytically, thereby avoiding few computationally expensive time domain simulations requiring detailed modeling. Since conventional IBRs need a certain minimum short-circuit level for stable interconnection, this analysis can identify risks in the process. Table 2 shows the results of available MVA analysis in a system with eight buses with a proposed interconnecting IBR at Bus 4. The analysis shows that interconnecting the new IBR at Bus 4 will lower the available MVA at Bus 4 and nearby buses to a negative value, indicating that this IBR has a significant risk of facing stability challenges if interconnected at Bus 4.

Table 2. *Available Short Circuit MVA Analysis*

Bus Number	MW	Available Short Circuit MVA	With new IBR plant added at Bus 4	Shifting new IBR plant to another bus
1	60	3062.434769	2887.569809	2423.532867
2	26	2441.080475	2347.359848	2125.767136
3	78	264.009094	163.492489	255.09634
4	140	404.690838	-227.195644	2423.532867
5	100	274.402428	-191.264725	238.448906
6	95	-27.467728	-95.020866	-33.635044
7	134	299.682808	-12.28447	268.380928
8		7.052879	-64.403152	-30.564117

In addition, the advanced Fault Ride Through (FRT) capability metric is a completely analytical metric that eliminates the need for dynamic runs, using dynamic data values e.g. controller gains, time constants of the IBR. The FRT metric is expressed as the longest duration fault for successful ride through.

If appropriately tuned, stability of IBRs can be invariant to fault duration. However, changing system conditions can impact the ability of a tuned IBR to successfully ride-through faults. Advanced FRT evaluations provide another metric to understand the potential dynamic behavior of IBRs. Figure 4 shows the schematic for a system used to study the FRT metric. Thirty and thirty-four cycle faults were applied in the system with a BESS IBR and after fault clearing the voltages and real power observed are shown in Figure 5 (a) and Figure 5 (b) respectively. In both cases, with existing control settings, instability is observed showing up as oscillations. However, after the controls were tuned, in both fault duration cases, the system stabilized.

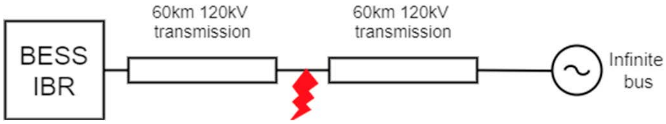
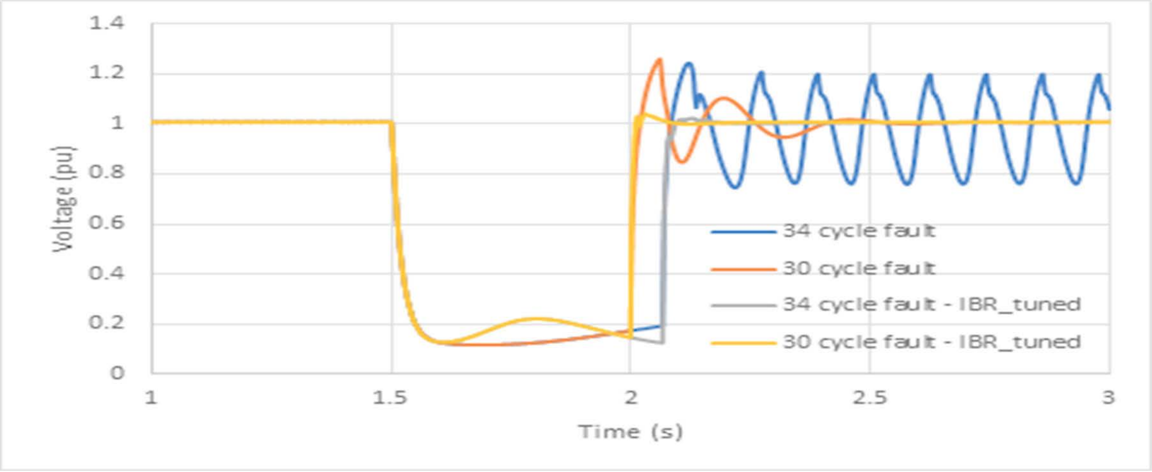
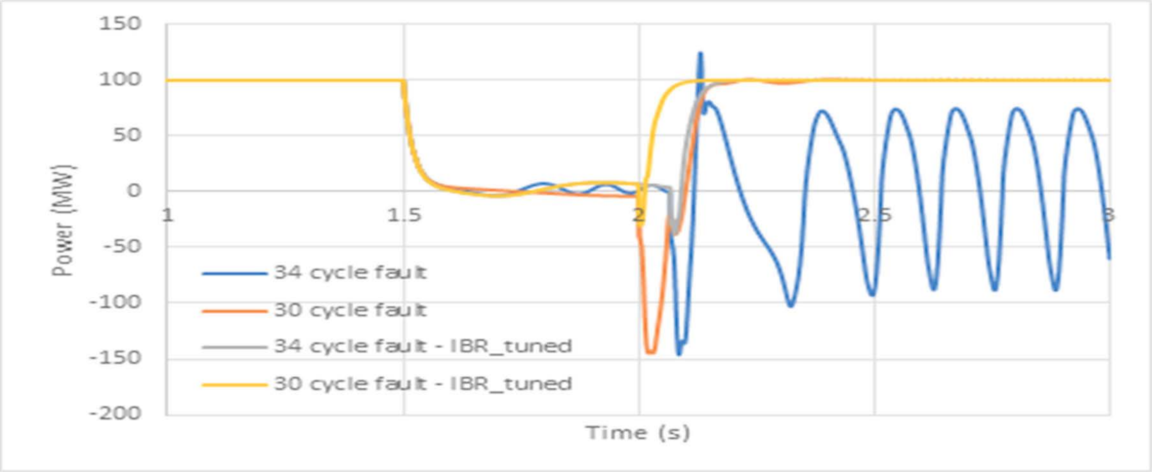


Figure 4. *Schematic for system for fault duration study*



(a)



(b)

Figure 5. *(a) Voltage and (b) Power response for various fault duration*

Table 3 shows the variation of maximum FRT for various PLL gains as obtained analytically and confirmed with simulation results. It can be seen that the FRT metric is a good indicator of the maximum fault duration before instability. Evaluation of the FRT metric also predicts the trajectory of IBR response during fault. The system consists of a wind park and a solid 3-phase fault is applied at the POI of fault duration 0.42s. The curve in blue shows the slow PLL response, whereas the red curve shows the fast PLL response.

As shown in Figure 6, the WP is able to ride-through the long duration fault when slower PLL settings are used.

Table 3. *Variation of maximum FRT duration with change of PLL gains*

WPs	PLL GAINS	MAXIMUM FRT DURATION EVALUATED	MAXIMUM FRT DURATION SIMULATION
4	Kp=7.5 Ki = 300	0.48	~0.5
	Kp=60 Ki = 1400	0.19	~0.24

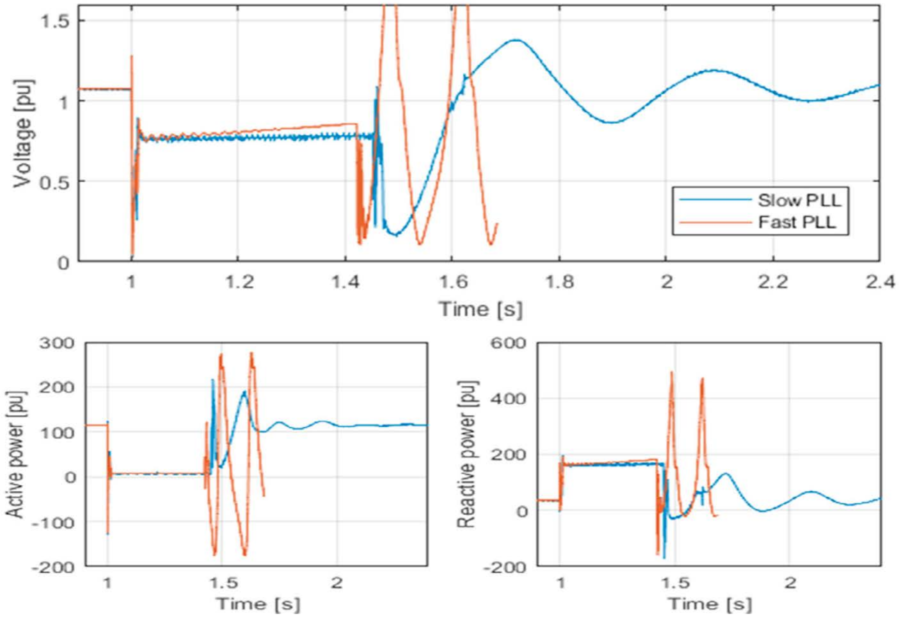


Figure 6. *Voltage, Active power, and Reactive power*

The following case study shows a system (Figure 7) with high IBR penetration. Each IBR can operate with a minimum SCR of 1.0pu. Tripping of one synchronous machine at Bus 1 causes instability as predicted by the negative value of remaining MVA at the location. Table 4 shows these values before and after the synchronous machine trip.

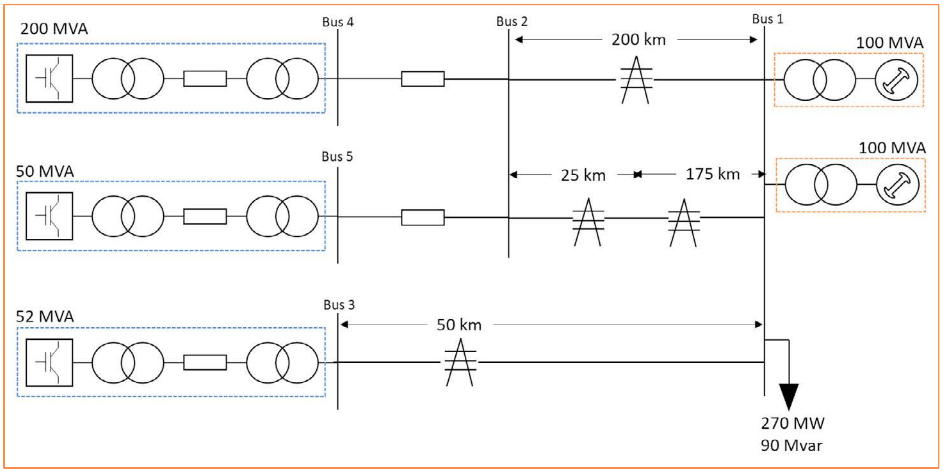


Figure 7. *Schematic of system for which SCR and remaining MVA metrics are evaluated is presented in Table 4*

Table 4. *Short circuit metrics for system in Figure 7*

Location	SCR	Remaining SCC MVA	Location	SCR	Remaining SCC MVA
Bus 1	12.36	1028	Bus 1	6.44	466
Bus 2	6.44	460	Bus 2	4.30	244
Bus 3	8.75	752	Bus 3	5.34	390
Bus 4	6.02	424	Bus 4	4.1	228
Bus 5	6.02	437	Bus 5	4.1	238
IBR terminal – Bus 3	4.91	197	IBR terminal – Bus 3	4.17	151
IBR terminal – Bus 4	1.13	19	IBR terminal – Bus 4	0.96	-16
IBR terminal – Bus 5	4.51	160	IBR terminal – Bus 5	3.85	119

In another case study on a synthetic power network that mimics the National Electricity Market (NEM) power system in Australia, the available SC MVA is plotted on a heat map using approximate geographical coordinates of IBR locations as shown in Figure 8 and Figure 9 [5]. After the analyses, several IBRs were identified with negative available MVA and the controls were modified from grid following to grid forming as shown in Figure 2. As a result, the instability noted in time domain simulations was mitigated as shown in Figure 10.

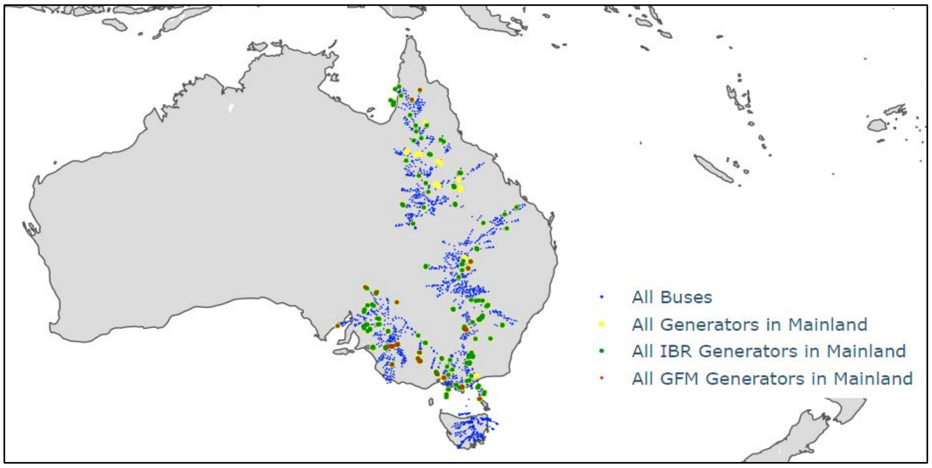
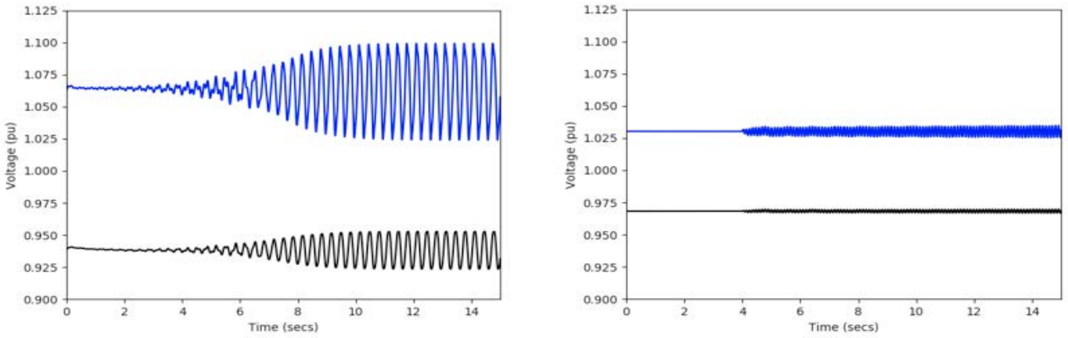


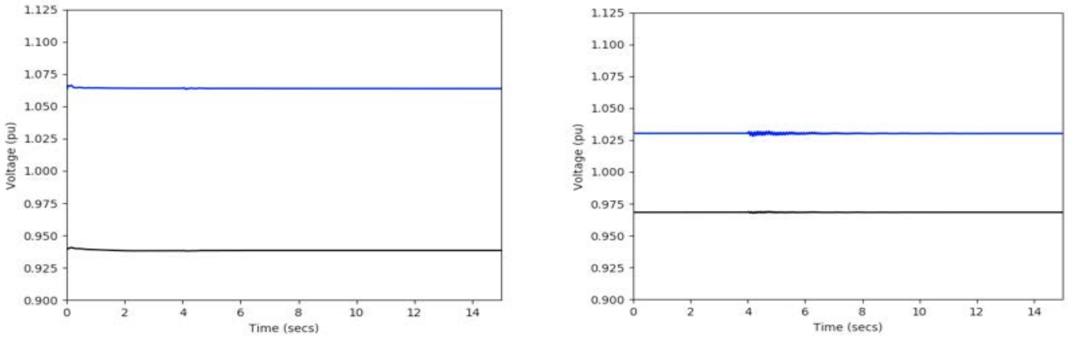
Figure 8. *Approximate geographical location of buses of synthetic Australian system, with generators color coded by control type, GFM or non-GFM*

Figure 9. *Available MVA at different generator buses displayed on an approximate geographical location. A darker pink shade indicates more negative available MVA and hence greater risk of instability*



Hour 11 (light load) with GFL controls

Hour 19 (peak load) with GFL controls



Hour 11 (light load) with GFM controls

Hour 19 (peak load) with GFM controls

Figure 10. *Mitigation of instability (top two plots showing oscillations in voltages at two POIs at two different snapshots of time) by replacing generators with negative available MVA with generators with grid-forming controls*

Hence, using the short circuit metric, IBR locations can be identified that may have instabilities and challenges. When coupled with advanced and robust IBR dynamic models, the region of interest for EMT studies can be further refined. Also, these metrics can identify locations where advanced IBRs (such as GFM) need to be connected, and their approximate rating.

iii. Frequency Spectrum

Frequency domain analysis provides another perspective into the stability of a system. Impedance scans i.e. impedance versus frequency plots can provide insights about the small-signal stability. It is well-known that eigen value analysis is the most widely used method for small signal stability evaluation. It can provide the modes of the system under consideration. However, eigen values can be computed if the system under consideration can be modeled by linearization around an operating point of interest, which in turn requires knowledge of the system model. However, with many of these systems, especially IBRs, the white-box models are not easy to obtain. Instead, OEMs might only provide black-box models to protect proprietary content. Impedance scanning methods can address this issue by characterizing the impedance vs. frequency model of the system for a certain operating point, even when the scanned device is black-boxed. Based on these scans, vector fitting methods can be used to create a linearized state space model from where eigen values can be computed, or even just the scans can provide the modes of the system.

For resonant-driven instabilities, impedance scanning techniques are useful in identifying the risks by quickly computing the resistance and reactance of the network vs. frequency for various topological configurations. It can also account for impedance characteristics of other IBRs in the network based on the impedance scanning method.

These methods are extremely effective in screening for risks of sub-synchronous resonance, sub-synchronous controls interactions, and sub-synchronous torsional interactions.

While the zero-crossing of reactance identifies the system resonant points, the resistance at those frequencies indicates the amount of available damping to mitigate onset of any oscillations.

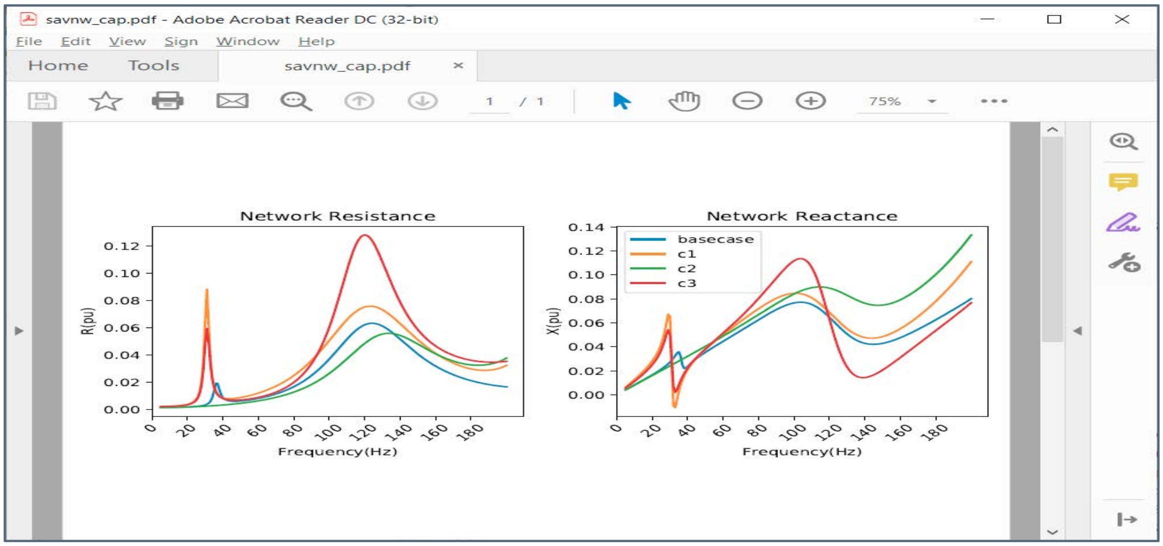


Figure 11. Impedance scans [6] (Resistance and reactance vs. frequency plots for various system conditions such as contingencies)

Scanning methods at system level might often ignore other active devices in the vicinity of the bus from where the scan is performed. However, it is important to incorporate non-linearities of other IBRs, PE devices in the system as shown in Figure 12. The incorporation of non-linearity of impedance from active devices is more pronounced when the scanning bus has more of these devices in the vicinity.

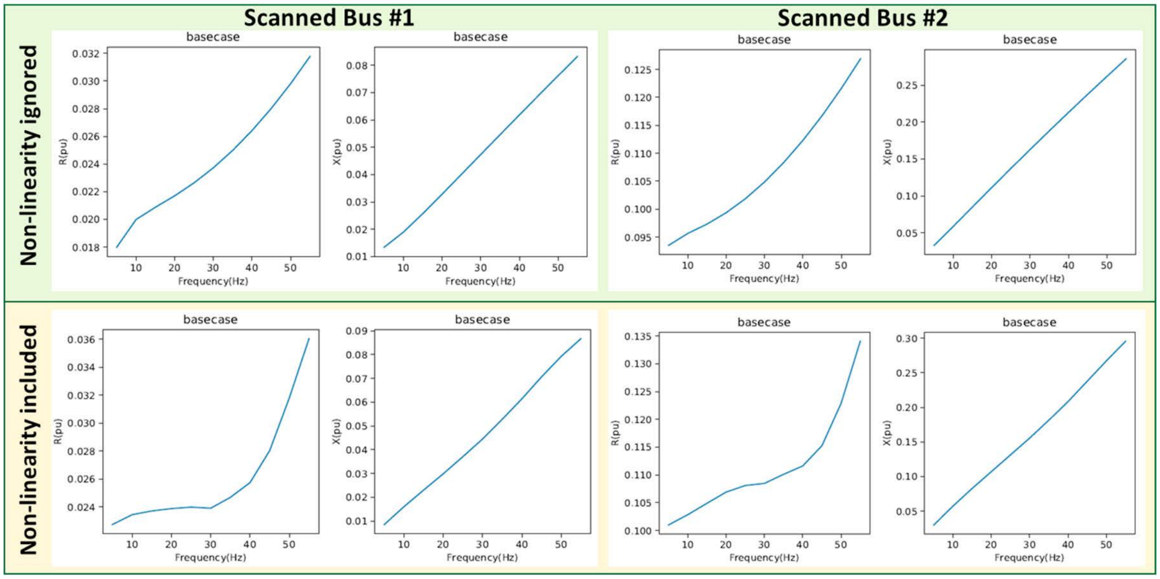


Figure 12. Importance of incorporating effect on non-linear impedances of active devices in positive sequence domain impedance scans

iv. Voltage Control Area

Analyses of voltage control areas can identify locations with voltage problems and would benefit with control adjustments. Buses can be clustered into groups and transformer tap adjustments, shunt references, and generator voltage control setpoints can be optimized to achieve a more uniform voltage profile around nominal voltage, which in turn also lowers reactive power losses across the system. Figure 13 shows the distribution of bus voltages before and after implementing optimal control settings based on clusters of buses obtained by screening the system to identify voltage areas, including those that are potentially problematic.

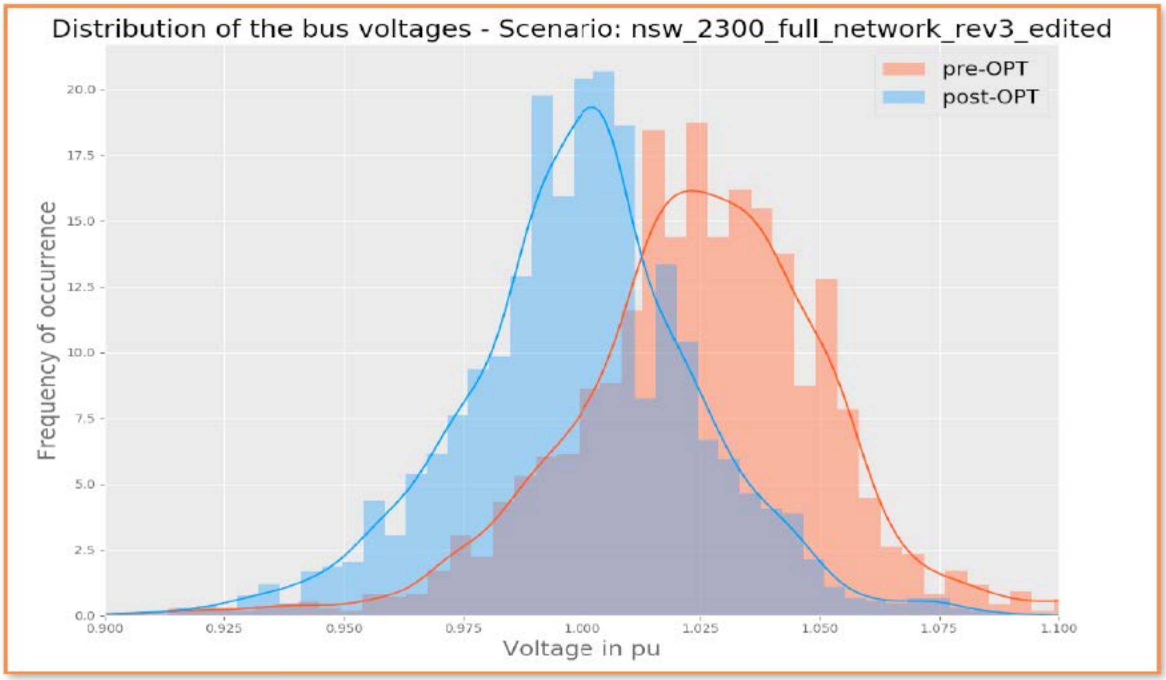


Figure 13. *Distribution of bus voltages before and after implementing optimal control settings [7]*

CONCLUSIONS

The aim of this document is to provide an overview of screening methods to approach modeling and analysis of low short circuit networks, especially with a lot of inverter-based resources. Most of this approach is from a transmission system planning and operations perspective, not necessarily from a distribution or micro grid perspective.

It is important to make a proper selection of the screening method/tool since each has a different application. In this paper, some of the commonly used metrics have been discussed. For a quick comparison of their capabilities, Table 5 has been provided. The proper choice requires planner's experience and awareness.

Table 5. *Summary of screening methods and capabilities*

	HOSTING CAPACITY	GRID STRENGTH	FREQUENCY SPECTRUM	VOLTAGE CONTROL AREA
Provide insight regarding where detailed EMT studies are required		√	√	
Day-to-day operations use		√	√	√
Speed up interconnection process	√	√	√	
Screening metrics to find issues before hand	√	√	√	
Identify regions where issues are present	√	√	√	√

To operate a system without synchronous machines, it should be possible to operate the future inverters with other inverters in a cohesive and stable manner, positively contribute to load generation balancing, positively contribute to voltage control, and have a robust fault right through at the very least. Thus, development of inverters should be directed towards providing services while meeting the existing metrics, fully recognizing that even these metrics might need to evolve. Hence, flexibility is key.

Recent events in power systems around the world have created a need to rethink the way system planning and analysis is performed. This requires a lot of different models, tools, and techniques. And even before any kind of model validation or modeling study is performed in time domain, a screening analysis needs to be carried out to narrow down the search space by reducing the number of contingencies and/or isolating the regions that warrant further study. Also, it is important to be cognizant of the fact that following the screening step, when a time domain study is required, models are needed which should be properly validated. It should not be assumed that the models are correct as available, whether they are detailed or undetailed, generic or user defined.

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