Power System Stability Analysis & Planning Using Impedance-Based Methods

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Abstract

A power system screening method is introduced to quickly estimate the stability and power transfer limits of an IBR-dominant power system, such as the future resource fleet in the Midcontinent Independent System Operator (MISO) footprint. Today's approaches typically use positive-sequence dynamic simulations or electromagnetic transient (EMT) simulations to evaluate the stability limits of IBR-dominant systems; however, these approaches are computationally burdensome and difficult or unmanageable for large power systems. The new approach combines steady-state voltage stability analysis with focused use of detailed EMT simulations using an impedance-based method to capture specific stability characteristics of different resource technologies (traditional synchronous machines as well as inverter-based resources) in a way that is tractable for use in planning studies on large power systems considering many potential scenarios.

1. Introduction

The transition of the world's electric power systems from synchronous machine-dominant systems to inverter-dominant systems poses numerous challenges to transmission system planners in the industry. Transmission planners have the daunting task of considering very long planning horizons in making massive investment decisions in the ten-plus year timeframe to serve their customers efficiently and reliably. These challenges include understanding the technical capabilities and dynamic stability of the ever-evolving inverter-based resource (IBR) control technologies in system planning studies. The planner needs models with sufficient accuracy while maintaining feasibility to execute planning studies in a timely manner and efficiently analyse the output for the wide range of system operating conditions and disturbances that must be assessed. These challenges are especially pronounced for large system operators with expansive service territories and thousands of resources because the computational and expertise burdens of the analysis grow with the size of the system.

Today's system planners utilize a suite of different software analysis packages for system reliability which can be broadly grouped as steady-state contingency analysis and dynamic stability analysis. The dynamic stability analysis is further subdivided into positive-sequence dynamic simulation (PSDS) and electromagnetic transient (EMT) simulation. Each tool captures different levels of detail for resources and the network, ranging from little detail with only the most basic representation of resources and network elements, as is the case in steady-state simulation models, up through EMT models, which have the most detail and time granularity. The primary trade-off for increasing the level of detail and accuracy (with proper model parameterization) is the burden of using and running the tool, which is illustrated in Figure 1.

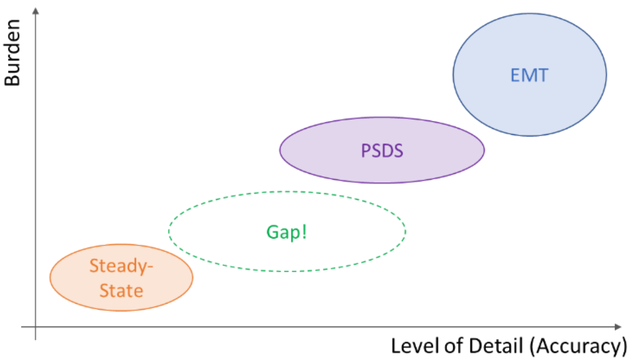

Figure 1: Categories of Power System Stability Analysis

Each tool fits a need. Steady-state tools have the most basic representation of resources and the network. This relative simplicity enables planners to run a very large set of cases over large transmission networks, considering thousands of contingencies combined with numerous operating conditions or future resource and grid topology scenarios. However, the simplicity limits the usefulness of steady-state thermal and voltage violation analysis for certain purposes. The next available step in today's toolset is marked by PSDS software tools, which augment the steady-state model with dynamic representations customized for each individual resource and load type, albeit a simplified dynamic representation for IBR

[1]. While PSDS constitutes a large step forward in the level of detail and includes the ability to perform time-series simulations, the improved simulation capabilities come at a cost. PSDS models require substantially more input data, initialization, and post-processing. There are many more ways for the simulation to fail or be inaccurate, demanding more expertise and experience of users. This forces planners into a practical trade-off where the number of cases must be dramatically reduced from those considered in steady-state analysis to gain detail and fidelity. EMT simulation goes a step further than PSDS by offering the most high-fidelity representation of resources and the network, but also being substantially more demanding than PSDS in terms of input data, computation, and user expertise. This increased burden means that many fewer cases are typically run in EMT, compared to PSDS, if any at all. When viewed graphically, as in Figure 1, there is a clear gap between steady-state analysis and PSDS simulation, which is where the screening analysis proposed in this paper fits.

To span the gap between steady-state and PSDS, a new methodology, referred to as the "Dynamic Impedance Method," is proposed for analysing the stability of inverter-dominant power systems based on power systems fundamentals and impedance-based analysis of resources. The method is applicable to both synchronous and inverter-based resources. This method provides critical insight into dynamic stability of an IBR-dominant system without the extensive use of burdensome time-domain simulations. By reducing the burden, this method enables planners to evaluate a large range of contingencies and future resource scenarios in a time-efficient manner. This allows planners to identify the most challenging scenarios more quickly for evaluation in PSDS and EMT by testing many more scenarios, resource mixes, and IBR technologies like grid-forming (GFM) inverters in their long-range planning processes. Ultimately, this method enables planners to move through the inherently iterative planning process more quickly to evaluate risks and arrive at the most cost-effective solutions for transmission investments, resource additions, and retirements.

2. Methodology

2.1. A Focus on Voltage Regulation

The new approach combines steady-state voltage stability analysis with focused use of detailed EMT simulations using an impedance-based method to capture specific stability characteristics of different resources, including GFM, grid-following (GFL) inverters, and synchronous machine (SM) resources.

The steady-state analysis performed in this process is focused on the voltage stability limits applicable to the transfer of power across the system, as is commonly depicted in P-V curves [2]. An example of a static voltage stability PV analysis with familiar curves is shown in Figure 2. The declining shape is evidencing increasing reactive power losses as active power transfer is increased, which causes voltage to fall. The increasing active current and increasing reactive current due to increasing Q losses eventually results in a maximum power transfer [3]. For the post-contingency state ("N-1" curve), the net impedance of the grid has increased, increasing losses and reducing the power transfer limit.

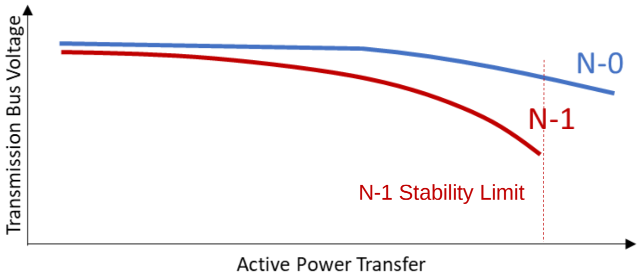

Figure 2: P-V Curves for N-0 and N-1 Conditions at a Transmission Bus

The curve shape depends on the grid location at which P-V analysis is performed. The vertical curvature (voltage) in particular changes, but the maximum transfer does not: it is a systemic limit. Lower voltages are electrically farther from points of voltage regulation. Examining the P-V curve for the same analysis but now at the terminals of an ideal generating resource in Figure 3 will show no voltage deviation until the limit is reached, due to the resource maintaining a fixed terminal voltage.

Figure 3: P-V Curves for N-0 and N-1 Conditions at the Idealized Resource Terminals

While these ideal characteristics are acceptable for steady-state analysis, they constitute an overly optimistic representation of any resource during a dynamic disturbance. During dynamic disturbances like faults or line tripping events, all resource technologies are dynamically adjusting active and reactive power to find a new voltage equilibrium, as shown by the EMT simulations in Figure 4.

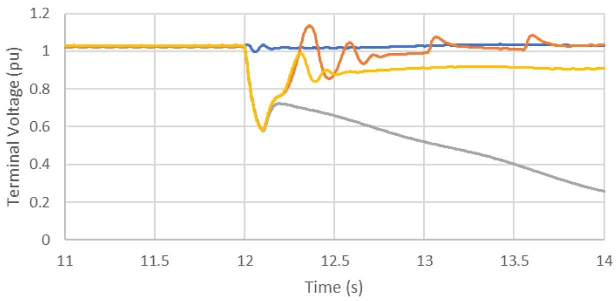

Figure 4: Terminal Voltages in Time-Series for Different Resource Technologies

The transition of voltage from pre-disturbance to post-disturbance conditions can be well-regulated (*blue*) or jagged (*yellow*, *orange*). Further, it can be successful (*blue*, *yellow*, *orange*) or fail to ride-through (*grey*). The result varies depending on the event, the type of disturbance, the technology, and the tuning of the resource's control systems.

Therefore, a resource's quality of voltage regulation is critically important to the dynamic stability of the system. By quality, we mean the effective location of regulation, speed of regulation, smoothness of regulation, and application of equipment self-protection limits. These considerations are the foundation of voltage stability theory, and the new analytical method is developed to characterize resources dynamic responses in a consistent and quantitative manner. This analysis is focused on voltage support in the sub-second time frame, and therefore the impact of the plant controller is considered insignificant and ignored.

2.2. Analysis Framework

An overview of the method's steps is shown in Figure 5. The upper half of the figure describes the steps that would be conducted in a steady-state analysis, where many scenarios and contingencies can be solved quickly, covering a large system operating space. The lower half of the figure shows the high-level steps in which the steady-state analysis is augmented with a dynamic characterization analysis.

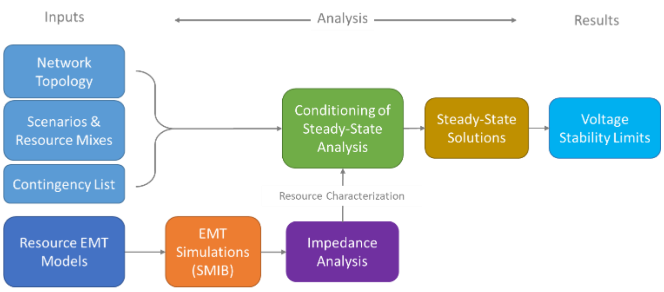

Figure 5: Sequence of Analysis Steps

The resource characterization steps are intentionally designed to be technology agnostic; equally applicable to GFM, GFL, and SM technologies, regardless of whether they are wind, solar, battery, gas-fired, hydro, synchronous condenser, or STATCOM. Each resource (or resource technology provider) is represented with a high-fidelity model – EMT models for IBR – and subjected to a series of simulations in a single-machine infinite bus (SMIB) arrangement to capture the resource's dynamic response to prototypical voltage disturbances. Resource responses are analysed in the frequency domain to elicit critical stability characteristics, which are then distilled into a single value called a "dynamic impedance". The dynamic impedance for each resource is integrated into the network as a Thevenin equivalent impedance located between the terminal bus of the resource and the ideal voltage source. With the dynamic behaviour of each resource approximately represented, the power flow is solved for all the variations of the network for increasing levels of power transfer. The result is the maximum power transfer attainable before voltage stability limits are reached. Each of these steps will now be described in detail.

In time-domain simulations conducted using EMT tools, a line-opening disturbance is simulated, in which the driving point impedance from the inverter looking into the grid suddenly increases, causing a sudden drop in local voltage. The voltage regulation functions of the resource respond with an injection of reactive power to restore voltage towards the desired setpoint. In this transition from one steady-state operating point to another, the dynamic behaviour is observable in Figure 6, where the dynamics are a function of the characteristics of the resource's controls.

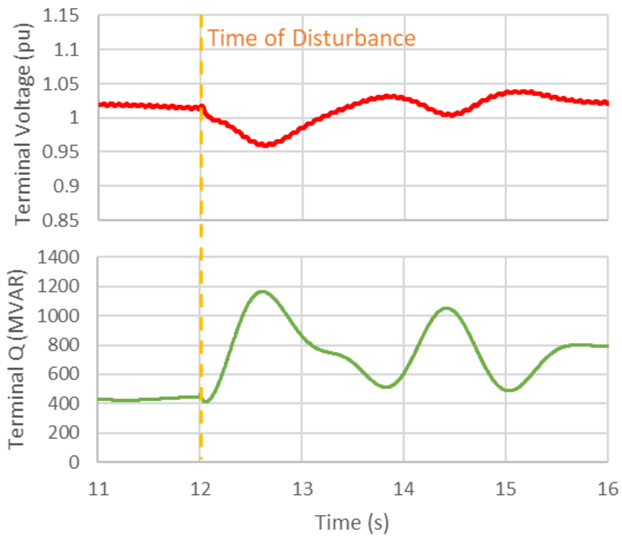

Figure 6: Terminal Voltage and Reactive Power Response to a Disturbance

If the time-varying voltage and reactive power at the terminals of the resource are cross-plotted, the result traces a path in Q-V plane starting at the initial steady-state condition through to the final steady-state condition. The trajectory, shown in *Figure 7* (a), is indicative of important characteristics in the dynamic response of the resource. In particular, the slope of the path, while varying in time, exhibits a near-constant value for most of the dynamic transition. The reciprocal of the slope of the path is a reactance, which is plotted as a function of time in *Figure 7* (b). In this view, while the plot has brief excursions to plus and minus infinity as it reflects the crests and troughs of the damped oscillations of reactive power, a prevailing reactance corresponding to the prevailing slope in the Q-V plot is clearly observable.

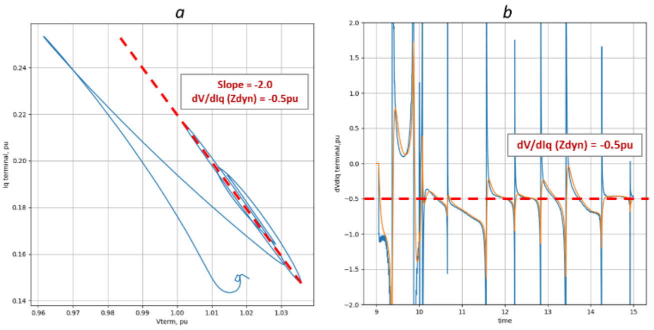

Figure 7: Plots of Iq-V (a) and dV/dI$_q$ (b) for a Synchronous Machine Following a Disturbance

The plot of reactance in time shows the effective reactance between the terminals of the resource and a fixed ideal voltage inside the resource, as depicted in a classic Thevenin equivalent. The value of this reactance and the way it materializes in dynamic timeframes is a critical factor in the ability of a resource and network to be stable during disturbances.

Applying this approach to a synchronous machine where the dynamics are well understood, the effective dynamic reactance is nearly constant in the transient and subtransient time periods, as shown in *Figure 7* (b). This is a familiar and expected result from synchronous machine theory, in which the machine appears as a fixed internal voltage behind a subtransient reactance in short timeframes prior to the impact of the excitation system due to the relatively slow-changing flux dynamics of a solid rotor machine [4].

2.3. Resource Characterization using the Dynamic Impedance

The analytical framework and method are used to extract the critical performance metric – the effective dynamic impedance – from any resource that has a voltage regulating objective, regardless of the underlying technology. This is commonly referred to as an impedance scan of a resource [5]. The resource must be represented using a detailed, validated EMT model such that all behaviours and responses are captured by the model, including plant transformer(s) and AC collector systems up to the transmission interconnection voltage level. An ideal voltage source connected at the transmission point of interconnection (POI) is used to modulate the voltage waveform at the POI when the resource is operating at its rated power output. The relationship of the resource's current response due to the applied voltage perturbation is described in (1). The positive sequence voltage magnitude is modulated with a single sinusoidal waveform at a fixed frequency. This analysis focuses on the admittance Y_{22} from (1), which relates the change in voltage magnitude to the change in reactive current.

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{pmatrix} \delta \\ V_{mag} \end{pmatrix} \quad (1)$$

The time-series response is post-processed with a Fast Fourier Transformation (FFT) to produce the frequency domain result. This process is repeated numerous times with one sinusoidal stimulus at a time to determine the values of Y_{22} as a function of perturbation frequency. The perturbation frequencies span the range of 0.2 Hz to 32 Hz, which are in the dq0 reference frame. The magnitude of the stimulus is initially selected to be a small-signal stimulus of 2% of nominal voltage. At the frequency of the applied voltage perturbation, the reactive current in (2) is highest and is used to calculate the impedance.

$$I_q = \frac{V_a(I_c - I_b) + V_b(I_a - I_c) + V_c(I_b - I_a)}{V_{mag}} \quad (2)$$

In addition, the phase relationship between the voltage and reactive current at the perturbation is calculated from the resulting FFT. In an ideal case, the phase relationship will be 180 degrees, indicating negative feedback for all perturbation frequencies. Phase relationships that deviate significantly from 180 degrees are less effective in controlling voltage at that perturbation frequency, and in an extreme case, phase relationships of less than 90 degrees constitute positive feedback and unstable voltage control. The impedance at each perturbation frequency is adjusted by the phase relationship between voltage and reactive current as in (3).

$$Y_{adj} = \frac{dI_q}{dV_{mag}} \cos\left(\phi_v - \phi_{Iq} - \pi\right) \quad (3)$$

The dynamic admittance is converted to a dynamic impedance as in (4), which is then incorporated as the Thevenin impedance of the resource model in the steady-state analysis. In this way, the quality of dynamic voltage regulation from detailed resource characterization can be represented in scalable steady-state analysis, useful for evaluation of very large systems.

$$Z_{dyn} = \frac{1}{Y_{adj}} \quad (4)$$

2.4. Application to Steady-State Voltage Stability Analysis

For each resource characterized, a Thevenin impedance is applied in the steady state powerflow model at the generator bus, as shown in Figure 8. A new bus is created in the powerflow case, representing the internal voltage, and the generator is set to regulate voltage at the internal bus to the pre-contingency value of the internal bus voltage.

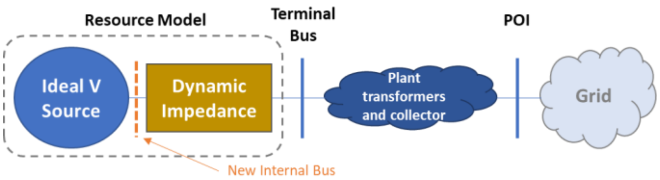

Figure 8: Application of Dynamic Impedance in System Powerflow Model

This method introduces challenges in applying resource reactive power (Q) limits. In steady state powerflow, the Q limits are applied at the internal bus by default. However, the Q limits must still be applied at the terminal bus. The Q limits are applied at the terminal bus by iteratively adjusting the resource Q limits to account for the Q losses across the Thevenin impedance.

2.5. Modelling on a Reduced Transmission Systems

The method is demonstrated on a simplified model of a portion of the MISO high voltage transmission system. The reduced model is represented in both steady-state and in EMT. A high-level representation of the system is shown in Figure 9, where each node consists of a single large resource representing the aggregate generation of that region of the grid. The system power transfer limit is tested by increasing generation at the sending end resource and increasing load at the sinking end. The power transmission paths each consist of 2-6 parallel circuits connected with intermediate transmission buses. Increased power transfer pushes voltages in the system lower, reducing the system stability margin.

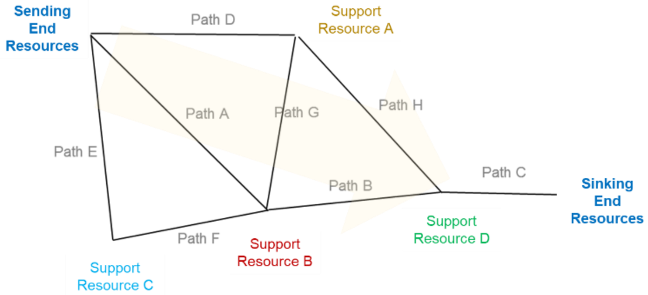

Figure 9: Reduced System Diagram

3. Results

3.1. Impedance Scan Characterization of Resources

The method of resource characterization is applied to several different resource types and tuning of IBR controls. From the resulting plot in Figure 10, critical stability characteristics of a resource are immediately apparent and readily compared. Looking at the characteristics of the grid-forming (GFM) resource, it exhibits a high and relatively constant admittance across the frequency range evaluated. As a Thevenin equivalent, the GFM resource has a low impedance to its idealized voltage source, providing good voltage support across a large band of frequencies or for short and long periods following a disturbance.

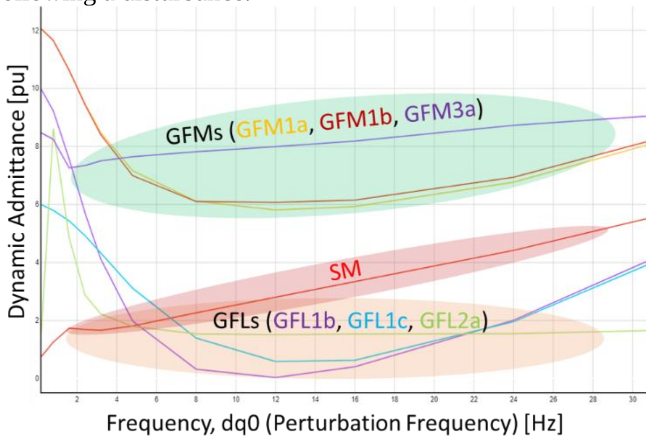

Figure 10: Dynamic Admittance of GFM, GFL, and SM Resources

Examining the characteristic curve of the synchronous machine (SM) without an excitation system, the SM exhibits a low admittance for low frequencies, where the admittance increasing perturbation frequencies. This is consistent with the expectation from synchronous machine theory where the machine exhibits an inductive characteristic in which the reactance is the relatively high synchronous reactance (low admittance) at very low perturbation frequencies. For higher perturbation frequencies, SMs exhibit relatively lower transient and subtransient reactances (higher admittances). While the excitation system does impact the dynamic impedance determined from an SM resource by increasing the dynamic admittance, it does so only for very low perturbation frequencies (below 2Hz) because the bandwidth of the automatic voltage regulation function of the exciter is limited by the long rotor flux time constant.

The grid-following (GFL) resources evaluated show a range of characteristics, with responses heavily dependent on control tuning. GFL resources significantly under-perform GFM resources across the frequency range. At lower frequencies, the GFL voltage regulation is effective and provides a stabilizing and strengthening effect to system stability. These lower frequencies correspond with longer time periods, for instance, when the grid is closer to steady-state conditions. At higher frequencies, which correspond with shorter timeframes after the disturbance, voltage regulation from GFLs is poor. This indicates that immediately following a disturbance or during highly dynamic conditions, the GFL resource is not effectively regulating voltage, and therefore is not able to support grid stability during these periods.

It is important to note that these responses are for small-signal disturbances. For large disturbances like close-in faults, the curves may change significantly depending on the resource technology type. For instance, SM characteristic curves tend to retain their essential shape; this is expected because SMs behave consistently based on physical properties and have high short-term over-current capabilities. In contrast, IBR have much lower current limits and may exhibit highly non-linear current-limiting behaviour when large disturbances push these resources into their limits.

Resources are characterized as an admittance to align with the familiar power engineering concept of grid strength, where grid strength is quantified as a short-circuit MVA value [6]. Considering a source with fixed nominal voltage, and the fact that transmission system X/R ratios are typically high enough to only consider the reactive component of impedance, grid strength is effectively the reciprocal of the driving point reactance, which is an admittance. From this perspective, higher admittance values are associated with increased grid strength provided by the resource.

3.2. P-V Analysis on the Reduced System

A P-V analysis is performed on the reduced system, where the sending end resource is evaluated as exclusively GFL, or GFM, or SM resources while SM resources are located at the supporting and sinking end locations. The resulting P-V analysis for a single transmission contingency is shown in Figure 11, where P is the flow out of the sending end bus and V is the transmission voltage at the sending end bus. In each plot, the Ideal Source curve in blue is identical, reflecting a voltage source with zero dynamic impedance at the sending end resource, which is typical of today's P-V analysis methods. Beyond the highest active power transfer point of this curve, the system is steady-state unstable.

Resource-specific curves in Figure 11 are the result of considering each resource's dynamic impedance in the model, which causes the curve to drop and end sooner. Beyond these resource-dependent curves, the system is dynamically unstable, and within these curves (i.e., to the left of the "nose") the system is stable. These plots, using representative dynamic impedance values for each resource type, show how system stability can vary dramatically depending on the quality of voltage regulation of a given resource, as reflected in the value of the dynamic impedance.

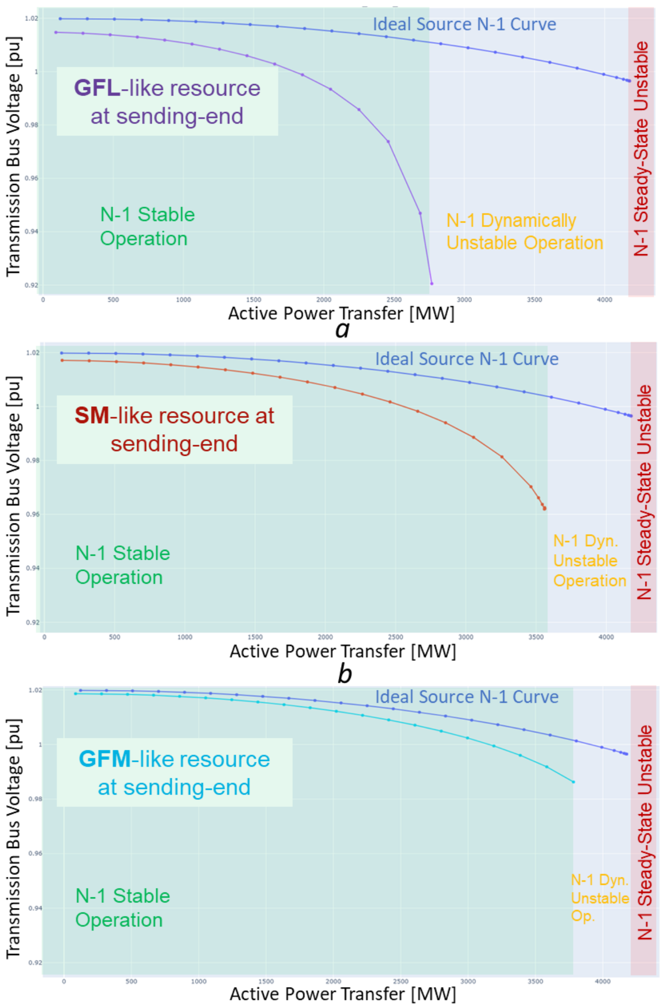

Figure 11: N-1 P-V Curves for GFL (a), SM (b), and GFM (c) Resources and an Idealized Resource on the Reduced System

4. Validation of Methodology

4.1. Validation of Impedance Scans

The dynamic impedance of the resource is calculated by taking the ratio of the voltage stimulus to the current response. This method is first verified by applying it to an ideal voltage source behind a series resistance and inductance. Comparing the calculated impedance with the impedance scans from PSCAD in Figure 12 shows a near-perfect match using this simple circuit.

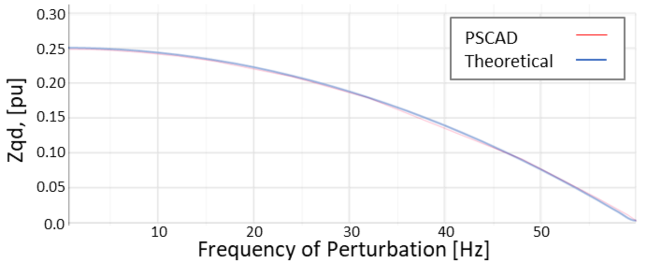

Figure 12: Verification of Impedance Scan Using R-L Circuit

Next, the same PSCAD impedance scan is performed for a synchronous machine resource and the results are compared to known synchronous machine impedance characteristics as a function of frequency. When a series of small signal stimuli are applied to a synchronous machine resource as described and plotted in the stationary reference frame, the resulting impedance curve closely approximates the reactance of the machine as it varies from subtransient to transient to synchronous values, as shown in Figure 13.

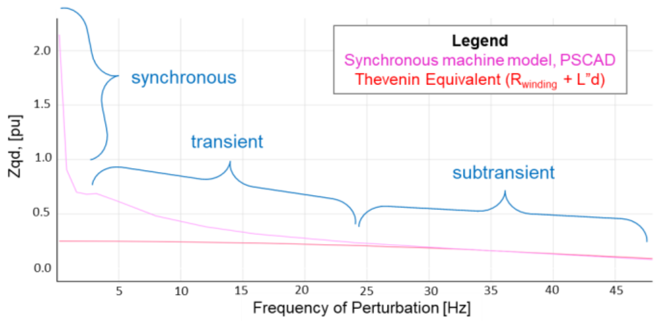

Figure 13: Verification of Impedance Scan of a Synchronous Machine

4.2. Validation of Methodology Against EMT Simulation

To validate the methodology, stability limits predicted by the Dynamic Impedance Method are compared against detailed time-series EMT simulations. Validation is performed on the reduced network model, considering many different operating conditions and disturbances, including:

- 14 different resource mixes (combinations of SM, GFL, GFM and locations)
- Disturbances on 3 different paths (paths A, B, D)
- Fault-and-clear disturbances and line-switching (no fault) disturbances
- 2 different severities of disturbances, where 1 or 2 circuits are cleared from the path with the disturbance
- 4 different product-specific IBR models from 3 different manufacturers.

The dynamic impedance is computed as the reciprocal of the dynamic admittance, as shown in Figure 14. For resources with a relatively constant impedance characteristic across the frequency range, like the GFMs, selection of a representative admittance is straight-forward. For resources where the impedance varies across the frequency range, the selection of a representative impedance requires more judgment and calibration. This work has found that critical responses occur in the 0.1 second period, corresponding to the 10 Hz frequency band, which is highlighted in Figure 14.

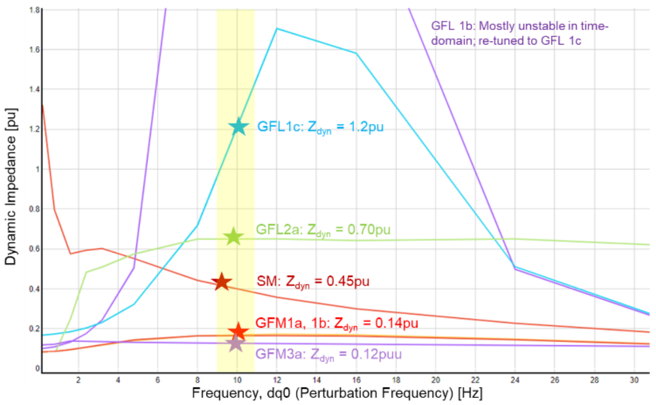

Figure 14: Selection of Dynamic Impedance for P-V Stability Analysis

To compare the Dynamic Impedance Method prediction of the stability limit resulting from the steady-state analysis (as a maximum power transfer) against the EMT analysis, the stability limit must be estimated from the time-series EMT simulation results, a non-trivial task that has plagued planners for years even before complexities introduced by high levels of IBR. To estimate the stability limits, six criteria, based on existing stability criteria from system operators [7], are defined and analysed from the time-series waveforms. These criteria are applied to all transmission buses and resources within the reduced system.

Criterion Name	Description
Power Recovery	Active power > 80% of its pre-disturbance value
Voltage Recovery	Voltage > 70% at 6 cycles after the disturbance
Voltage Dip	Voltage dip on first transient swing > 70%
Voltage Sag	Voltage must not be below 80% for > 0.6 sec
Voltage Sustained	Voltage > 90% 6-8 sec after disturbance
Damping	Damping ratio > 0.4

Table 1: Validation Criteria used in EMT Simulations

For each of the 168 scenarios in the validation matrix, EMT analysis considers four power transfer levels at values of 70%, 90%, 105%, and 130% of the maximum power transfer limit at the sending end as predicted by the P-V analysis, resulting in a total of 672 EMT simulations. At each power transfer level, the six stability criteria are evaluated. The maximum stable power transfer is estimated for each scenario through interpolation across its power transfer levels.

The stability limit predicted by the Dynamic Impedance Method is compared with the stability limit estimated from EMT simulations and plotted by resource type. Figure 15 shows (a) the synchronous machine only mix, (b) five mixes that are GFM-dominant, and (c) six mixes that are GFL-dominant. The colour of the points indicates different resource mixes.

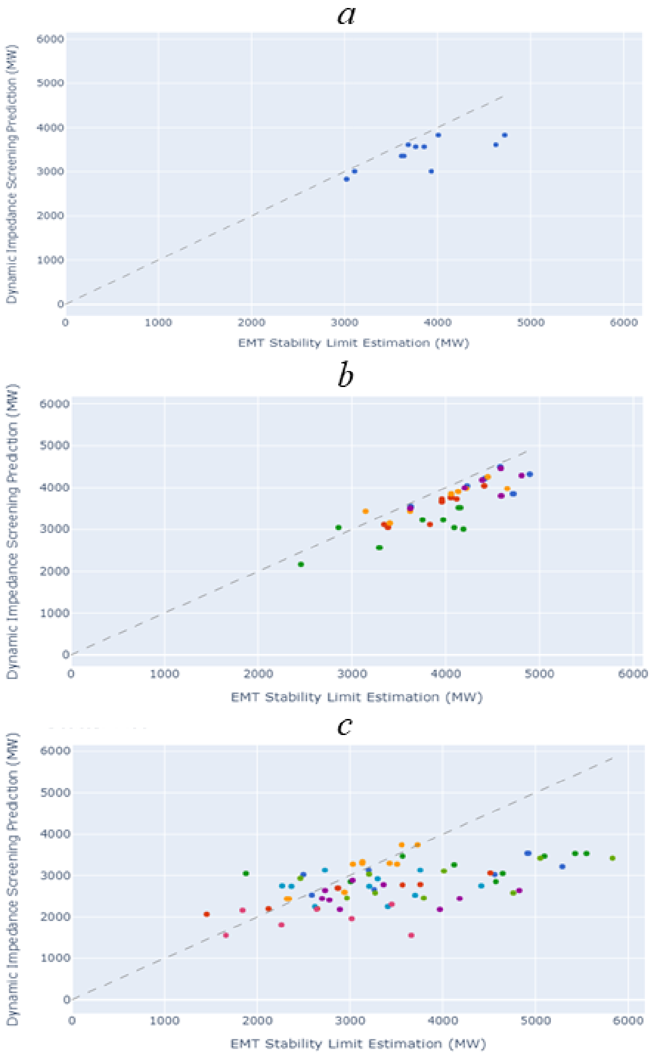

Figure 15: Comparison of Method to EMT Simulation by Resource Type for (a) Synchronous Machines, (b) GFM-Dominant Mixes, (c) GFL-Dominant Mixes

Points near the dashed line indicate a match between the Dynamic Impedance Method prediction and the EMT estimation results. Points falling to the left of the ideal line indicate that the Dynamic Impedance Method is optimistic relative to EMT simulation, predicting a higher limit compared to detailed EMT analysis, whereas points to the right indicate that the Dynamic Impedance Method is conservative., predicting a lower limit. All plots in Figure 15 reflect in intentional bias to the right, a conservative result in which the EMT simulations reflect slightly higher power transfer capability. The SM and GFM-dominant scenarios show a tight clustering near the ideal (zero error) line, indicating that the method predicts the stability limit well for these technologies. In contrast, the GFL-dominant scenarios show an increased spread relative to the SM and GFM scenarios, indicating that the performance of GFL is more variable due to more non-linear voltage regulation behaviour of GFL technologies.

Closer examination of the results by disturbance type, as shown in Figure 16, reveals a trend that fault-and-clear disturbances fall to the right of line-switching disturbances. This trend is emphasized for GFL-dominant scenarios, where GFL resources perform better for small disturbances than for large disturbances. Larger disturbances excite behaviour in the GFL resources that is captured by impedance scans at 10Hz +/-1Hz, as shown in Figure 14. Therefore, the Dynamic Impedance Method results using values derived from this frequency range yield better results that capture performance for large disturbances like for fault-and-clear events. The selection of dynamic impedance is intentionally conservative, favouring better representation of the most severe planning events, which are fault-and-clear disturbances, and giving conservative estimates for small disturbances.

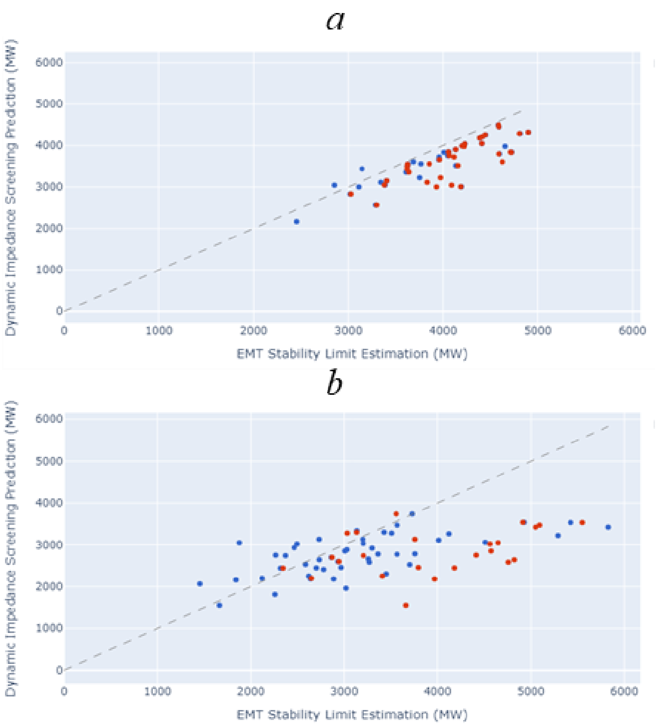

Figure 16: Comparison of Method to EMT Simulation by Disturbance (blue: fault-and-clear; red: line switching) for (a) SM and GFM-Dominant Mixes, (b) GFL-Dominant Mixes

5. Conclusions

The new Dynamic Impedance Method of screening large systems for voltage stability risk using fast and tractable steady-state P-V analysis informed by detailed EMT resource models shows strong predictive performance when compared against full EMT time-series simulations on a simplified transmission system, as shown in Figure 9, for all fault-and-clear disturbances only. The Dynamic Impedance Method works particularly well for SM and GFM-like resources evaluated, which respond with a more consistent, linear terminal voltage regulation scheme relative to the GFL-like resources evaluated.

A statistical analysis of the validation shows the error has a mean of 358 MW, evidence of the intentional conservative bias. The errors are quantified as a percentage on the mean power transfer level of 3132MW. Fitting the errors to a Gaussian Distribution, shown in the orange curve in Figure 17b, we can estimate with 95% confidence (shaded orange region of Figure 17b) that the Dynamic Impedance Method is conservative and the error on the optimistic side is bounded to 7% of the power transfer level.

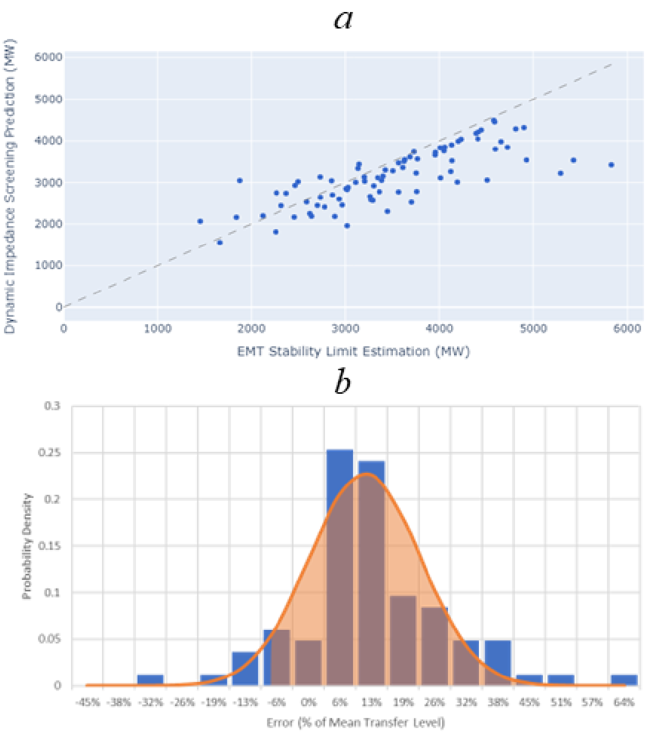

Figure 17: Comparison of Method to EMT Simulation, All Fault-and-Clear Scenarios (a) scatter, (b) histogram

This analysis evaluated five different IBR manufacturer-specific models from three different inverter manufacturers. The two different GFM manufacturers evaluated use different GFM control approaches; one uses a droop approach and the other uses a virtual synchronous machine approach. Even with these different control approaches, both GFM have similar performance and performance is predicted very well using the new Dynamic Impedance Method.

This effort opens a new avenue of analysis methods, where future work includes application of the method for active power and frequency response in an analogous form, benchmarking against conventional short-circuit ratio screening methods, testing against asymmetric disturbances, among others.

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7. References

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