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Automated Frequency Scan Analysis Tool to Predict Resonant Frequencies at Points of Interconnection

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SUMMARY

Since its first documented observance in 2009, subsynchronous control interaction between nonlinear, inverter-based resources and series-compensated lines has been responsible for outages in transmission systems around the world. To prevent similar incidents in the future, it is critical to screen for vulnerabilities to subsynchronous control interaction and other resonance phenomena prior to interconnecting large renewable power plants. This paper documents the development of a modular, automated, frequency scan analysis tool to identify potential resonant frequencies and instabilities at points of interconnection in Dominion Energy's transmission system. The tool consists of a PSCAD framework to perform dynamic frequency scans of nonlinear devices using a white noise voltage injection method, a Python program to perform passive frequency scans of a transmission system by calculating short-circuit Thevenin-equivalent networks, and a module to combine the frequency-dependent effective impedances obtained by the dynamic and passive frequency scans. The combined impedance plot can be used to predict resonant frequencies and damping characteristics at the point of interconnection (POI). As a proof of concept, preliminary results obtained by analyzing the POI for a large wind power plant in Dominion Energy's system are shown. Automated contingency analysis and guidelines for verifying frequency scan results are left as the subject of future work.

KEYWORDS

Frequency scan, PSCAD, PSS®E, Python, resonance, subsynchronous control interaction

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1. INTRODUCTION

As renewable power capacity grows globally, the detection and mitigation of subsynchronous control interaction (SSCI) has become an increasingly pertinent issue. SSCI is a type of subsynchronous oscillation in which a power electronic device exchanges significant energy with a series-compensated transmission line [1]. As a purely electrical phenomenon, undamped oscillations resulting from SSCI can become unstable much faster than torsional subsynchronous oscillations. and they can cause substantial turbine damage within hundreds of milliseconds [2]. The first documented instance of this phenomenon occurred in 2009, when an unplanned outage in Texas caused a Type III, doubly-fed induction generator (DFIG) wind power plant to become radially connected to a 345 kV line through a series capacitor [3]. Within one second following the fault, subsynchronous currents grew up to 4.0 per unit, ultimately causing a capacitor unit failure [4]. Similar SSCI incidents have also been documented in Guyuan, China between 2012 and 2013 [5]. In 2015, undamped subsynchronous interaction between a wind farm in the Xinjian Uygur Autonomous Region of China, consisting of Type IV permanent magnet synchronous generator (PMSG) turbines and a weak, uncompensated AC grid, caused torsional stress relays to trip all generation units in the area [6]. Prior to this event, PMSG turbines were generally not considered to be susceptible to SSCI [7], [8]. These events, and the evolving understanding of SSCI, highlight the critical need to screen for potential resonant frequencies prior to interconnecting large renewable power plants in order to prevent similar incidents.

One commonly used and efficient method of assessing a point of interconnection (POI) for potential vulnerabilities to SSCI and other subsynchronous resonances (SSRs) is frequency scan analysis. For a renewable power plant connected to a transmission system, frequency scan analysis calculates the effective impedance at the POI, looking both into the grid and into the renewable power plant. The effective impedance characteristics of the grid and the power plant, with respect to frequency, can then be combined and analyzed to predict potential resonant frequencies and damping characteristics across a frequency range of interest.

While this method has been employed by utilities such as Arizona Public Service Company [9] and ERCOT [10] for SSR analysis, Dominion Energy does not currently have an established screening procedure to identify potential vulnerabilities to SSCI. To address this, a modular, automated frequency scan analysis tool was created as a preliminary effort to identify potential resonant frequencies. While points of interconnection for large renewable power plants were the intended application of this tool, it was designed with the flexibility to screen any bus in Dominion Energy's transmission system with a sufficient PSCAD model of the interconnected inverter-based resource or renewable power plant. Additionally, while the primary goal in developing the frequency scan analysis tool was to predict resonances in the subsynchronous and near-synchronous frequency range, the modules can be easily reconfigured to screen for higher order harmonic distortion as well.

The remainder of this paper is organized as follows. Section II explains the general methodology of frequency-scan analysis and describes the differences in implementation between passive and dynamic methods. Section III details the operation of each of the three modules of the automated frequency scan analysis tool. Section IV provides a preliminary case study of the tool applied to the POI of a large wind power plant in Dominion Energy's network. Section V summarizes the contributions of this work and addresses future developments to improve the tool.

2. FREQUENCY SCAN ANALYSIS

Frequency scan analysis assesses the small-signal stability of an interconnected transmission system and machine, inverter-based resource, or renewable power plant by calculating the impedance at the POI as seen by the network and as seen by the resource with respect to frequency. Summing these impedance characteristics and plotting the real and imaginary components of the combined effective impedance, can visually identify potential resonances or SSR vulnerabilities. This procedure is illustrated by the diagram shown in Fig. 1.

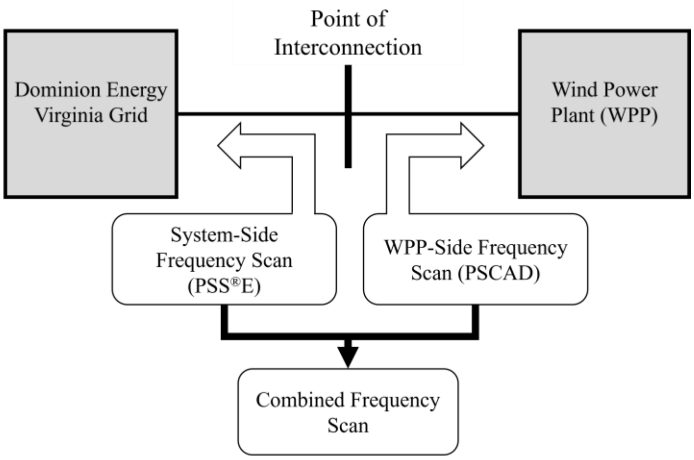

Fig. 1. Diagram of the general procedure of a complete frequency scan analysis at a point of interconnection between a wind power plant and the Dominion Energy Virginia transmission system.

A potential parallel resonance can be identified by a dip of 5% or greater in the effective reactance [11]. A series resonance can be predicted at frequencies where the effective reactance crosses the horizontal axis from negative to positive or vice versa [10], [11]. The reactance behaviors that predict parallel resonances and series resonances are illustrated in a hypothetical plot of effective impedance shown in Fig. 2.

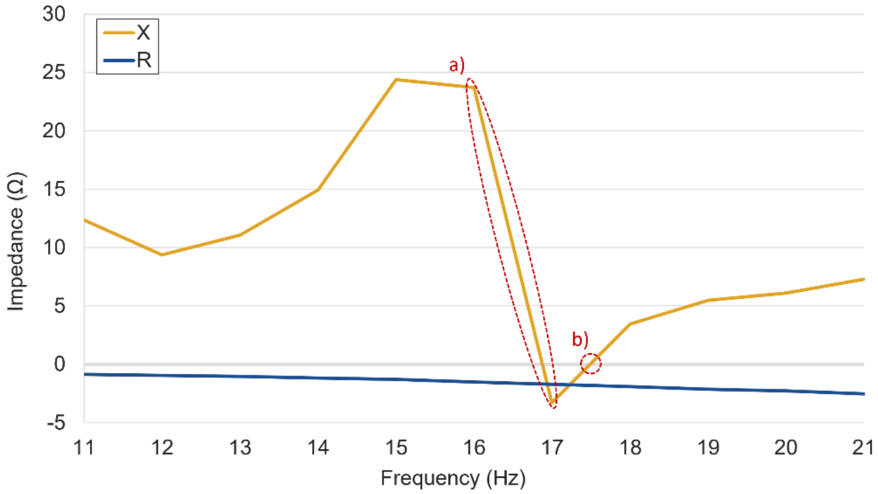

Fig. 2. Example of an effective impedance plot with (a) a potential parallel resonance indicated by a steep dip in reactance, and (b) a potential series resonance indicated by a zero-crossing in reactance.

The effective resistance characteristic indicates the system damping at the POI over the studied frequency range. If the equivalent resistance at a potential resonant frequency is negative, the system may not be able to sufficiently damp oscillations at that frequency, and oscillations may become unstable following a disturbance [12]. While frequency scan analysis can be a valuable screening tool, any resonant frequencies or instabilities it predicts need to be investigated in greater detail through time-domain electromagnetic transient (EMT) simulation before drawing any definitive conclusions [11].

Frequency scan analysis can be performed either passively to calculate the effective impedance of linear networks or dynamically to account for the nonlinearities of wind turbines or other power electronic devices.

2.1 Passive Frequency Scan Method

The effective impedance of a transmission network generally can be determined by using phasor-domain calculations to assess the short-circuit Thevenin-equivalent network at the bus that serves as the POI [10], [12]. The passive components of the network--such as transformers and transmission lines--are assumed to be linear. This approximation is considered valid in the subsynchronous and near-synchronous range of frequencies, as the frequency-dependent components of line inductance are negligible in this range [13].

For each frequency in the range of interest, the reactances of all components in the network are scaled linearly as shown in Equations 1 and 2. Equation 1 is used to scale the reactances of all the inductive elements such as transformers, transmission lines, shunt reactors, and series reactors in the system. Equation 2 is used to scale the reactances of all the shunt and series capacitors in the system. In these equations, f is the frequency of interest in hertz, f_n is the synchronous frequency of the system in hertz, and $X_L(x)$ and $X_C(x)$ are the inductive and capacitive reactances respectively of a component at a frequency, x.

$$X_L(f) = \frac{f}{f_n} X_L(f_n) \tag{1}$$

$$X_C(f) = \frac{f_n}{f} X_C(f_n) \tag{2}$$

After the reactances of all components in the system have been scaled with respect to the frequency of interest, a short-circuit, Thevenin-equivalent of the network is calculated at the POI. The resulting Thevenin-equivalent impedance approximates the driving-point impedance at the frequency of interest. Due to the linear approximation inherent in this method, it cannot be used to assess the effective impedance of any nonlinear power electronic devices such as wind turbines and STATCOMs. Dynamic frequency scan methods must be used instead.

2.2 Dynamic Frequency Scan Method

To dynamically assess the effective impedance of a nonlinear device or renewable power plant, a white-noise-injection frequency scan method is commonly used [12], [14]. While other injection methods can be used, white-noise injection is generally more efficient, as it excites the system at a wide range of frequencies simultaneously [12]. With this method, a white spectrum of voltages or currents covering the frequency range of interest is injected into an EMT simulation model of the system. The magnitude of these signals must be sufficient to produce an observable frequency response, but small enough so as not to disturb the steady state operating point of the system [12].

The voltage and current at the POI is then measured, and a fast Fourier transform (FFT) is applied to the signals to extract their frequency-dependent magnitude and phase. The effective impedance magnitude can then be calculated using Equation 3 where $V_m(f)$ and $I_m(f)$ are the voltage and current magnitude respectively at a frequency in hertz, f, as determined by the FFT, and $Z_m(f)$ is the impedance magnitude at the same frequency, f.

$$Z_m(f) = \frac{V_m(f)}{I_m(f)} \tag{3}$$

Similarly, the effective impedance phase can be calculated using Equation 4 where $V_p(f)$ and $I_p(f)$ are the voltage and current phase respectively at a frequency in hertz, f, as determined by the FFT, and $Z_p(f)$ is the impedance phase at the same frequency, f.

$$Z_p(f) = V_p(f) - I_p(f) \tag{4}$$

3. AUTOMATED FREQUENCY SCAN TOOL MODULES

The automated frequency scan analysis tool was developed modularly to allow users to analyze the effective impedance of a transmission network or renewable power plant in isolation or the combined effective impedance at their POI.

3.1 Network-Side Frequency Scan

A program was written in Python using the PSS®E API to automate the process of performing passive network-side frequency scans. The structure of the program is summarized by the flowchart shown in Fig. 3.

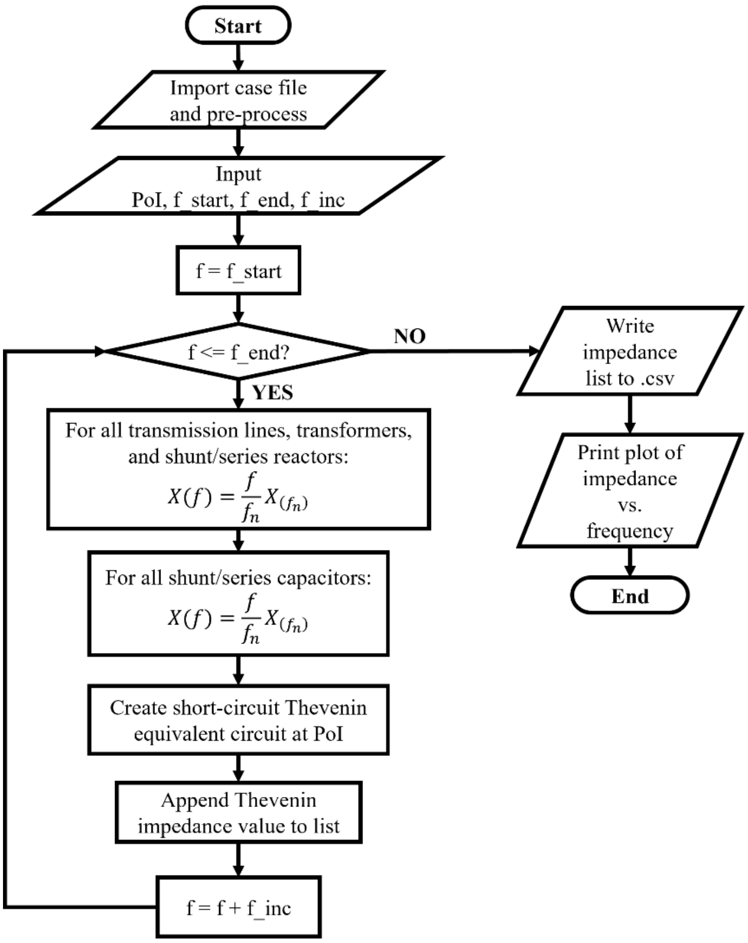

Fig. 3 Flowchart of the automated procedure to perform passive network frequency scans from a user-specified PSS®E case file.

The user is first prompted to provide a PSS®E *.sav* case file that contains a model of the system being studied. In order to use the PSS®E API to construct a short-circuit equivalent network, the case file must be pre-processed to reflect classic short-circuit assumptions. These assumptions require all bus voltages to be initialized to unity amplitude, all bus phase angles to be initialized to zero, and all generator source currents to be initialized to correspond to the flux linkages behind their dynamic impedance [15].

Once the case file has been pre-processed, the user is prompted to input the bus number of the POI and the frequency range of interest. The program scales the reactance of all components in the case file for each frequency, as described previously in Equations 1 and 2. After each component has been properly scaled, the short-circuit Thevenin-equivalent network is calculated at the POI. The network's calculated effective impedance is then extracted and written to a list. The program repeats the process of scaling reactances and calculating the short-circuit-equivalent circuit for the next frequency value. When an impedance value has been acquired for every frequency in the range of interest, the complete list of calculated impedances is then written to a *.csv* file.

3.2 Renewable Power Plant-Side Frequency Scan

To accurately assess the equivalent impedance at the POI for inverter-based devices, an EMT simulation program must be utilized. Therefore, a reusable framework was developed in PSCAD to perform dynamic frequency scans for renewable power plants and other nonlinear devices. This framework can be applied to any linear or nonlinear device; but to reflect its intended purpose, it will be referred to in this work as a renewable power plant-side frequency scan framework. A simplified representation of the framework is shown in Fig. 4.

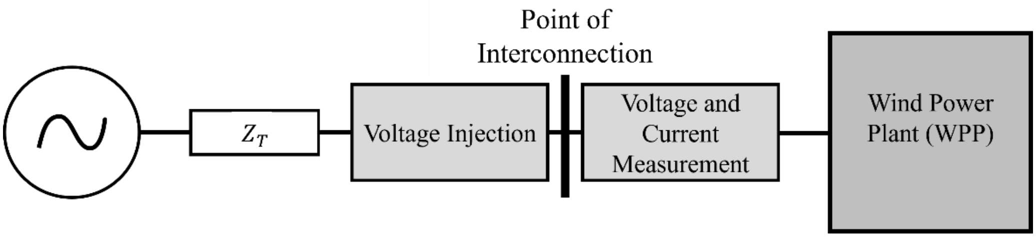

Fig. 4. Simplified representation of the renewable power plant-side frequency scan framework developed in PSCAD

The network is represented by a Thevenin-equivalent network with a unity magnitude, zero-phase-angle voltage source attached to an impedance. The Thevenin impedance value, Z_T, is obtained by computing the short-circuit-equivalent network at the POI.

To observe how the equivalent impedance of the renewable power plant varies with frequency, a white spectrum of voltages within a user-specified range of frequencies is injected into the system. The magnitude of these injections can have a significant impact on the validity of the frequency scan results, so the voltage spectrum magnitude is set by a variable input slider to allow users to experiment to easily determine an appropriate magnitude. Graph frames are also included in the simulation environment so the user can monitor the three-phase voltage and current waveforms at the POI for distortion that may indicate an excessively large injection magnitude. The phase angle of the voltage spectrum is also set by a variable input slider, as shifting the angle of the injected spectrum can prevent amplitude spikes that may disturb the steady state operating point of the system [16].

Next, voltage and current measurements are taken at the POI, and an FFT is applied to both measurements to extract their frequency-dependent magnitude and phase. As described previously in Equations 3 and 4, the FFT of these measurements is then used to calculate the effective impedance. After the simulation runs for several seconds, a *.csv* file is generated containing the calculated impedance magnitude and phase for each frequency in the range of interest.

3.3 Combined Frequency Scan

The final module of the tool combines the frequency scan results obtained by the previous two modules. The combined frequency scan is an extension of the network-side frequency scan program. To create a combined frequency scan plot, the user sets a flag prior to running the network-side frequency scan program. Then the user is prompted to provide the *.csv* file generated by the renewable power plant-side frequency scan framework. This file's effective impedance magnitude and phase are added to the corresponding values obtained from the network-side frequency scan. The combined values are converted into pairs of reactances and resistances, and their values are exported as a *.csv* file. The combined effective impedance provides a complete picture of the impedance characteristic at the POI and can be used to predict any resonant frequencies and instabilities that may exist at that bus.

4. CASE STUDY

To illustrate the functionality of the automated frequency scan analysis tool, a simple analysis of a large wind power plant interconnected with Dominion Energy's transmission system was performed. This case study represents a preliminary investigation of the impedance characteristics of the POIn under a single loading condition, with no contingencies considered.

First, the PSCAD frequency scan framework was applied to an aggregated model of a large wind power plant connected to a Thevenin-equivalent representation of Dominion Energy's transmission system. A spectrum of voltages from 1 Hz to 120 Hz with a magnitude of 0.01 per unit and a phase angle of 37 degrees was injected at the POI. After several seconds of simulation, the equivalent impedance at the POI was calculated as shown in Fig. 5.

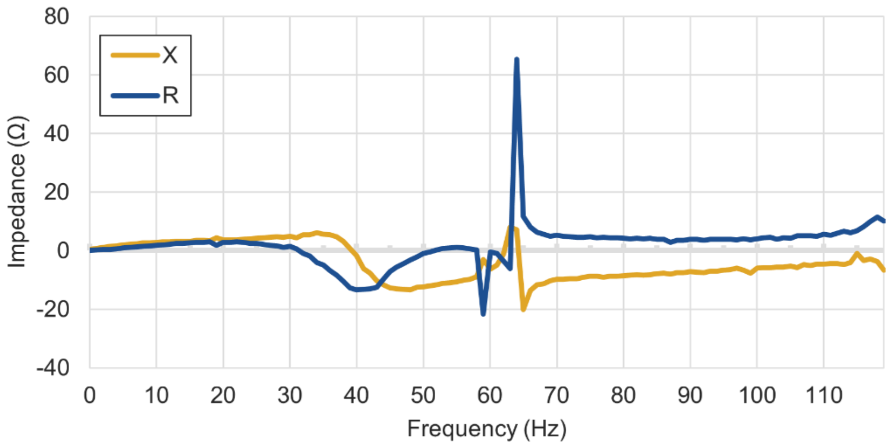

Fig. 5. Equivalent impedance calculated from the point of interconnection looking into a large wind power plant over a range of subsynchronous and near-synchronous frequencies.

Next, a PSS®E case file of Dominion Energy's transmission system under light loading conditions was imported into the Python program to perform a network-side frequency scan. The POI to the large wind power plant was selected as the bus to be studied. The frequency range was 1 Hz to 120 Hz, in increments of 1 Hz. The resulting plot of equivalent impedance is shown in Fig. 6. The near-linear behavior of the reactance increasing with respect to frequency and the near-constant, near-zero behavior of the resistance are consistent with the expected impedance behavior of a stable, linear grid.

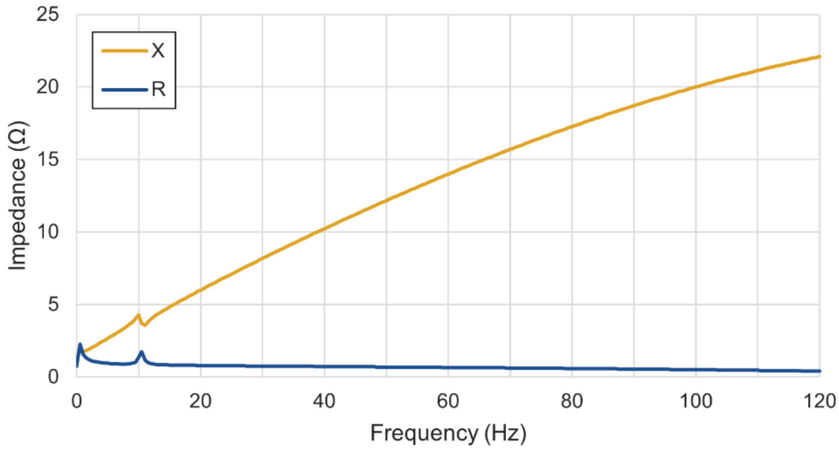

Fig. 6. Equivalent impedance calculated from the point of interconnection looking into the Dominion Energy transmission system over a range of subsynchronous and near-synchronous frequencies.

Finally, the impedance plots obtained from the plant-side and network-side frequency scans were automatically combined with the third module of the analysis tool. The resulting plot, shown in Fig. 7, provides a complete view of the effective impedance at the POI. A significant dip in reactance around 66 Hz predicted a parallel resonance; however the significant peak in resistance at the same frequency suggested that the system may have been sufficiently damped at that frequency to prevent any instabilities. Additionally, a zero-crossing in the reactance, coupled with a negative resistance at around 49.5 Hz, may have indicated an insufficiently damped resonance. As a follow up study, a detailed time-domain EMT simulation should be performed to analyze the voltage and current response of the system at the POI around 66 Hz and 49.5 Hz to determine if these frequencies represent any appreciable risks.

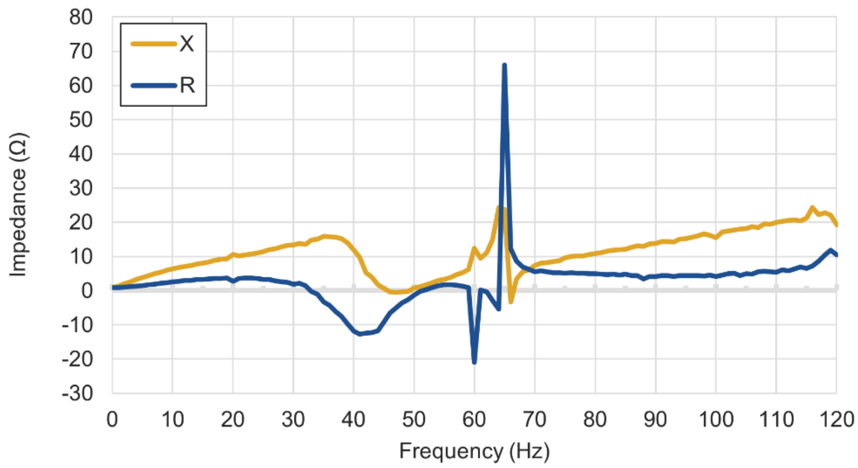

Fig. 7. Equivalent impedance at the point of interconnection obtained by combining the equivalent impedance plots shown in Fig. 5 and Fig. 6.

5. CONTRIBUTIONS AND FUTURE WORK

The automated frequency scan analysis tool developed in this work provides Dominion Energy with a simple method to screen for resonances and instabilities at any bus in its system. The modular tool can be used to calculate the effective impedance of any nonlinear device or renewable power plant modeled in PSCAD, the transmission system at any bus included in a PSS®E case file, and the POI between the two.

While the tool currently can only analyze a single contingency at a time, a primary focus of future work will be expanding the tool to consider all possible contingencies simultaneously. Automated contingency analysis would assist in identifying which transmission system topology configurations potentially cause resonances or exacerbate the effect of existing resonances at a POI.

Additionally, guidelines will be developed to help users develop detailed time-domain EMT simulations to verify any resonant frequencies and instabilities predicted by the frequency scan analysis tool.

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