Enhancing EMT Analysis for IBRs using Transient Stability Proximity Index: A New York Case Study

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Abstract — **The proliferation of inverter-based resources (IBRs) in modern power grids calls for electromagnetic transient (EMT) models to accurately capture stability interactions between fast-acting power electronics controllers of IBRs and dynamic components of the larger grid. It has been challenging to determine boundary buses of EMT models in IBR studies while maintaining EMT models computationally efficient without sacrificing their accuracy. This paper proposes a framework to determine EMT model boundaries through screening of dynamic components of the larger grid based on their frequency, rate of change of frequency, and voltage couplings with IBRs in compliance with ride-through requirements of IEEE Standard 2800-2022. The EMT model based on the proposed approach not only is small enough to retain computation efficiency but also inclusive enough to model impactful grid dynamic components. Based on the results of testing the proposed approach on an IBR in the western New York State transmission system, it is able to more accurately model EMT dynamics and identify ride-through behaviors in comparison with existing practices.**

Index terms — **Electromagnetic transient (EMT), inverter-based resource (IBR), ride-through, transient stability.**

I. Introduction

The increasing penetration of inverter-based resources (IBRs) in bulk power systems is transforming how grids are modeled and simulated. As conventional synchronous generators are increasingly replaced by IBRs, the phasor-domain and positive-sequence dynamic modeling may not be able to accurately identify grid reliability needs due to emerging conditions associated with IBRs such as fast control dynamics, frequency coupling, etc. This trend necessitates the use of electromagnetic transient (EMT) models to accurately capture stability interactions between power electronic controllers of IBRs and electromechanical dynamics of synchronous machines [1].

It is known that the full-scale EMT modeling of large-scale power systems, such as the U.S. Eastern Interconnection, remains highly computationally intensive and often impractical [2]. Hybrid simulation approaches – integrating EMT and phasor-domain models – have emerged as one of viable solutions with their own challenges. Within these frameworks, a fundamental question is how to determine the EMT model boundaries, i.e., how to identify which parts of the grid require detailed EMT-level representation while simplifying the rest of system without compromising accuracy [2]. In IBR-dominated systems, the boundary definition becomes particularly complex due to dynamic interactions that extend beyond physical proximity. This topic is recently explored in literature.

A two-timescale heterogeneous method is proposed in [2] using a smaller time step for EMT-level of simulation and a larger time step for the rest of the grid to enhance computation efficiency. This method requires an iterative process between the two simulations and is tested on a 39-bus test system; however, its convergence and scalability in larger scale grids may need further tests. Another approach is proposed in [3] with hybrid EMT and transient stability simulations using two open-source tools with a co-simulation tool through an iterative process. Despite being flexible, this method may not be applicable if IBR EMT and grid stability models are developed in commercial software platforms such as PSCAD, which commonly used among most IBR developers. A participation factor-based method is proposed in [4] to define EMT model boundaries for sub-synchronous oscillation (SSO) study of IBRs through including grid components with a high participation for a given contingency. The phasor-domain model is used to estimate participation factor of grid elements in SSO modes at frequencies below 7 Hz.

As the hybrid simulation of EMT and phasor-domain models is a fairly new industry practice, formal guidelines, particularly for defining EMT boundaries, are to be developed. IEEE Standard 2800 [5] recommends minimum performance and modeling requirements for IBR interconnections. Specifically, Clause C.2.6.1.a recommends that the transmission system "upstream" from the IBR Point of Interconnection (POI) be represented in sufficient detail, including elements such as var sources, generation, and load taps. Also, the North American Electric Reliability Corporation (NERC) in a reliability guideline [6] provides high-level recommendations for performing EMT studies and selecting study area for IBRs. It also recommends indices to assess voltage interactions between buses to identify which grid components to be included in the EMT model. However, it does not discuss criteria for evaluating frequency interactions.

While these guidelines provide useful general directions, individual U.S. jurisdictions retain discretion over the scope and depth of EMT analysis. Some regions may require detailed EMT studies for most IBR interconnections, while others only require EMT studies in specific scenarios such as weak grids or POIs with known stability issues. As an example, a hybrid simulation approach is studied in [7] for the Independent System Operator – New England (ISO-NE) area. In this work, the

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IBR under study along with its nearby grid components is included in the EMT detailed model (PSCAD), whereas the rest of the Eastern Interconnection is modeled as an external network in the transient stability phasor-domain model (PSS/E). A co-simulation platform (E-Tran Plus) links the EMT and phasor-domain solution spaces. Boundary buses are selected based on electrical distance, specifically those experiencing a 50% voltage depression during a fault at the IBR bus in the phasor-domain model. However, because frequency interactions are not considered, IBR frequency ride-through is not modeled.

IBRs and conventional generators have strict thresholds to protect their facilities against large grid disturbances, including frequency and voltage excursions. However, IEEE Std 2800 [5] mandates that IBRs remain connected (ride-through) during disturbances within specified limits and durations for voltage, frequency, and rate of change of frequency (ROCOF). This ride-through capability of IBRs enhances grid stability and reduces risks of potential cascading trips. If the POI frequency or voltage exceeds these defined limits/durations, IBRs are permitted to disconnect from the grid. Some specific ride-through ranges for IBRs are detailed in Section II.

In light of the reviewed literature, this paper proposes a framework for IBR studies, in which a frequency stability proximity index is introduced to identify dynamic components (e.g., synchronous machines or IBRs) that are impactful to the IBR under study. Similarly, grid components exhibiting strong voltage interactions with the IBR under study are included in the EMT model. This proposed approach determines EMT model boundaries through evaluating frequency, ROCOF, and voltage ride-through capabilities of IBRs in compliance with IEEE Std 2800 [5]. The rest of the grid, which presents a minimal dynamic impact on the IBR under study, is modeled as external networks. The resulting EMT model is both computationally efficient and sufficiently comprehensive to capture critical dynamics. This proposed approach offers a practical alternative to hybrid simulation methods.

The rest of this paper is organized as follows. In Section II, the proposed criteria for selecting grid components in the EMT model are described. Numerical results are presented in Section III on a case study from western New York. Section IV concludes the paper.

II. Proposed Approach for EMT Modeling of IBRs

A. Review of Ride-Through Requirements of IBRs

Based on frequency ride-through requirements for IBRs specified in IEEE Std 2800 [5], as illustrated in Fig. 1, an IBR needs to ride-through only if the cumulative grid frequency deviation from its nominal value is within +3% or -5% for 299 seconds or less within a 10-min window. This corresponds to a ride-through range of [57 Hz, 61.8 Hz] in a 60 Hz system. For instance, an IBR may immediately trip if frequency deviates by +4% from its nominal value. Additionally, IBRs are required to ride-through frequency events where the absolute value of ROCOF does not exceed 5 Hz/s [5]. Voltage ride-through requirements for PV-based IBRs are shown in Fig. 2

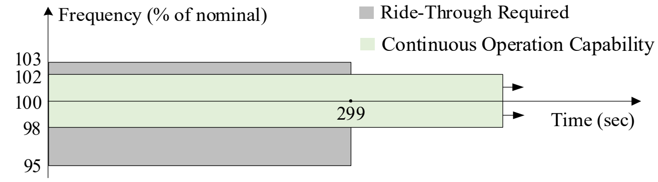

Fig. 1. Frequency ride-through requirements of IBRs per IEEE Std 2800.

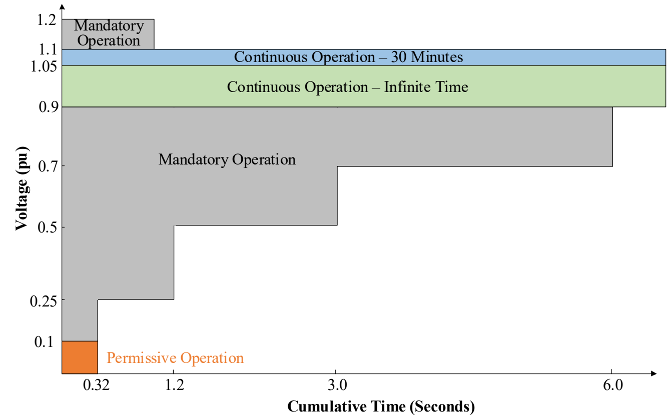

Fig. 2. Voltage ride-through requirements of PV IBRs per IEEE Std 2800.

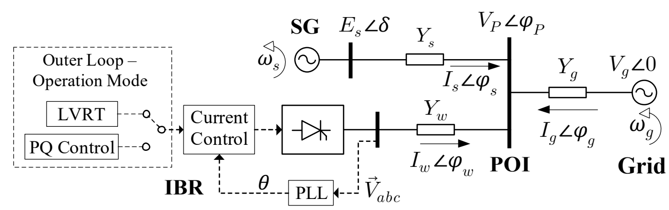

Fig. 3. Synchronous generator and IBR co-located at the same bus.

[5]. As an example, an IBR should ride-through a low voltage event of 0.6 pu if its duration is 3 seconds or less; the IBR may trip if this voltage disturbance persists longer.

B. Stability Coupling between IBR and Synchronous Generators

When a synchronous generator (SG) and IBR are located at the same bus, there is a strong stability coupling between the two. A typical configuration is shown in Fig. 3 [8]. For simplicity, if the dynamics of IBR's phase-locked loop (PLL) are neglected to derive a conceptual model, the SG dynamics in the phasor-domain can be written as [8]:

$$\dot{\delta} = \omega_g(\omega_s - 1) = \omega_g \Delta\omega \tag{1}$$

$$T_J \Delta\dot{\omega} = P_M - P_E - D\Delta\omega \tag{2}$$

where P_M, P_E, T_J, and D are the SG's mechanical power, electrical power, time constant inertia, and damping coefficient, respectively. SG electrical power P_E can be expressed as $P_E = \mathrm{Re}(E_s\angle\delta \cdot I_s\angle\varphi_s)$ or [8]:

$$P_E = \underbrace{E_s V_g |Y_{sg}| \sin\delta}_{P_{sg}} - \underbrace{|Y_{sg}/Y_g| E_s I_w \cos(\delta - \varphi_w)}_{P_w} \tag{3}$$

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where $Y_{sg} = Y_s Y_g / (Y_s + Y_g)$. The term P_w represents power coupling between SG and IBR [8].

As seen from (3), the power coupling P_w depends on IBR current I_w. When an IBR and a SG are located at the same bus (as illustrated in Fig. 3), a SG disturbance would largely impact IBR stability due to having the same bus voltage and angle shared by IBR and SG. However, when the SG is remote from the IBR bus, it may have less impact on IBR stability due to a weaker coupling between SG and IBR. An IBR may have varying degrees of stability couplings with remote SGs regardless of their physical distance from the IBR. This leads to the concept of "stability proximity" between an IBR and other IBRs or SGs.

PLL in Fig. 3 tracks the IBR terminal voltage to synchronize the phase and frequency of the IBR output with the grid. PLL dynamics, which are ignored in (3), are critical in determining the IBR stability, especially when connected to a "weak" grid [5]. Therefore, although (3) explains the stability coupling concepts between IBR and SG in simple terms, it may not accurately model IBR stability due to lack of PLL dynamics. Also, (3) is only valid for the fundamental frequency (phasor-domain) quantities and cannot model voltage and frequency stability issues at sub-synchronous and higher frequencies due to the nature of IBR controllers including PLL. It may be mathematically challenging to derive an analytical expression to include IBR PLL and SG dynamics particularly when remote SGs are considered. As an alternative, numerical sensitivity indices can provide a practically viable solution by preserving detailed PLL and SG dynamic models while allowing the use of commercial EMT simulation tools.

C. EMT Model with Impactful Dynamic Components

To numerically define the frequency stability proximity (FSP) index, a fault is assumed at or near IBR POI (say bus i). The resulting frequency excursion and ROCOF at a remote SG/IBR bus j is obtained by performing the transient stability analysis using a phasor-domain analysis tool (e.g., PSS/E):

$$FSP_{ij} = \Delta f_{ij} \tag{4}$$

where Δf_{ij} is the peak frequency excursion (+/-) at bus j for a fault at bus i. The FSP_{ij} matrix quantifies the extent to which a fault at bus i impacts frequency at bus j. Therefore, it can be simply used as a measure of stability coupling between the two buses. An absolute value of FSP_{ij} or ROCOF exceeding a predefined threshold indicates a strong stability coupling between the two buses, and then, it can be used to determine EMT boundary components.

For voltage interactions, boundary buses are determined using the electrical distance criterion of 50% voltage depression proposed in [7], where voltage depression of all buses are observed through transient stability analysis using a phasor-domain software tool (e.g., PSS/E) for a fault near or at the IBR bus. Buses experiencing a voltage dip of 50% or more are considered electrically close to the IBR, even if they are geographically distant.

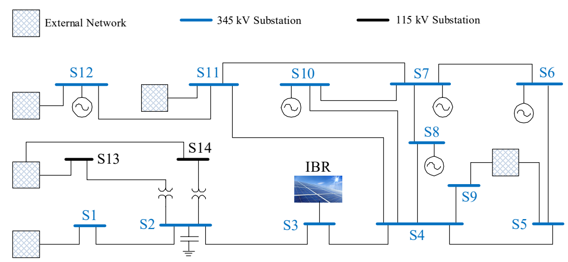

Fig. 4. Simplified one-line diagram of tested western New York 345 kV transmission system.

Based on the screening results obtained from a phasor-domain simulation tool, the following criteria are proposed in this paper to include dynamic devices in the EMT model when studying an IBR at bus i:

- Facilities within a proximity of a pre-defined number of buses/substations from the IBR project are included in the EMT model with the detailed modeling of transmission lines, generators, shunt/series devices, etc. The inclusion of this group of components ensures that the EMT model captures dynamics of nearby elements.
- Remote buses and their associated facilities are added to the EMT model if they exhibit a strong frequency coupling with the IBR POI. These impactful buses may be selected if they show a large frequency excursion ($FSP_{ij} > 3\%$, $FSP_{ij} < -5\%$) or a high frequency rate change ($|ROCOF_{ij}| > 5$ Hz/s). These thresholds are the values recommended by IEEE Std 2800 [5].
- Buses experiencing a voltage dip of 50% or more for a fault at the IBR bus are considered within electrical proximity and are included in the EMT model to capture voltage interactions of impactful components.
- The rest of the grid is modeled as external networks. Since the most impactful components have already been identified and included in the EMT model, this external portion would have negligible dynamic impact on the IBR.

III. Case Study and Results

A. Case Study

The proposed approach is tested on the New York State transmission system using the A-10 stability package [9] obtained from New York Independent System Operator (NYISO) with slight modification. A simplified one-line diagram of the study area and the IBR location is depicted in Fig. 4 (actual substation names are omitted to comply with Avangrid confidentiality requirements). A solar PV IBR rated 100 MW is assumed at 345 kV substation S3 in western New York. EMT analysis is performed using PSCAD, where transmission lines are modeled with frequency-dependent parameters to represent their behavior across a wide range frequency spectrum. Phasor-domain transient stability analysis is conducted using PSS/E. A three-phase fault is applied at substation S8 at 3 seconds and cleared by opening line S4-S8 terminals. Fault impedance in PSS/E and PSCAD is assumed $j5 \times 10^{-10}$ pu and

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0.0001 Ω, respectively. Dynamic models in PSS/E are defined in the A-10 stability package. PSCAD dynamic models are implemented to be consistent with PSS/E models. The block diagram of low-voltage and high-voltage ride-through (LVRT and HVRT) modes used in PSCAD is illustrated in Fig. 5 as an example.

B. Results

Nine generators, historically identified to have stability interactions with the selected IBR location based on transmission owner experience, are evaluated through phasor-domain screening. There has been no other major dynamic component (such as series capacitor or large dynamic load) in the IBR study area.

Results of frequency coupling and ROCOF for these generators relative to the IBR location are presented in Fig. 6. As shown in Fig. 6(a) for the frequency interaction, all examined generators except G7 exhibit strong frequency coupling with the IBR bus (the 3% ride-through threshold is plotted by a dashed line). Following the fault, all generators except G7 show a positive frequency excursion. The negative peak excursion is nearly zero for G1-G6 and G8-G9, and then, it is not visible in Fig. 6(a). Generator G7 demonstrates a weak frequency coupling in both positive and negative excursions.

In terms of ROCOF interaction, as shown in Fig. 6(b), all generators indicate a ROCOF value higher than the ride-through threshold 5 Hz/s (plotted by a dashed line) for the applied fault. These results exhibit that the synchronous generators are potentially impactful on the IBR location and should be included in the EMT model. It is noted that some generator symbols in Fig. 4 represent multiple generation units if those units are located at the same bus.

IBR ride-through performance of voltage, frequency, and ROCOF is presented in Fig. 7 for the case where the identified impactful generators are included in the EMT model. To better visualize voltage variations, the RMS value of three-phase voltages is plotted instead of their instantaneous waveforms. PSCAD frequency measurement meter is used to measure voltage frequency. The low-voltage ride-through is evaluated using the lowest magnitude of fundamental frequency phasor component of three-phase voltages, in accordance with IEEE Std 2800 [5].

As shown in the top plot of Fig. 7, although IBR POI experiences voltage dips as low as 0.4 pu, the duration of low voltage does not exceed the ride-through threshold for the IBR to trip. The cumulative time that voltage remains below 0.9 pu, 0.7 pu, and 0.5 pu is approximately 1.8 sec, 1 sec, and 0.3 sec, respectively – well within the trip threshold of 6 sec, 3 sec and 1.2 sec, respectively (as defined in Fig. 2). Therefore, the IBR is expected to ride-through these voltage disturbances.

In contrast, the IBR frequency, as shown in the middle plot of Fig. 7, reaches both the lower and upper ride-through thresholds indicating that the IBR is not required to ride-through under these conditions (upper and lower thresholds are plotted by horizontal lines). The rate of frequency change, as shown in the bottom plot of Fig. 7, is within the ride-through thresholds of ±5 Hz/s, satisfying the ride-through requirements. Overall,

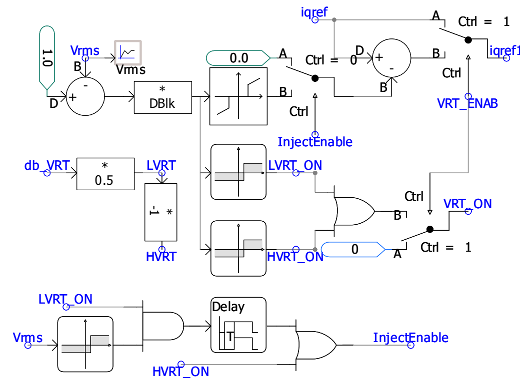

Fig. 5. Block diagram of LVRT and HVRT modes of the IBR model.

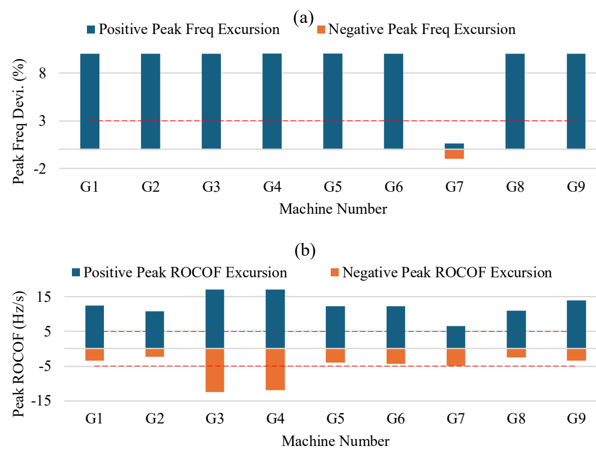

Fig. 6. Frequency coupling results: (a) Frequency deviations; (b) ROCOF.

due to the significant frequency excursions, the IBR is not obligated to ride-through the event.

To evaluate the impact of including the impactful generators in the EMT model, a proximity-based case is also examined, where only components within a pre-defined proximity of the IBR location are included. We here choose two-bus proximity as it is used in some industry-level EMT studies, although any number may also be selected. As illustrated in Fig. 4, this two-bus proximity captures a subset of impactful synchronous generators, but not all nine generators of Fig. 6. Results are presented in Fig. 8 for the EMT model with the two-bus proximity. The IBR is expected to ride-through because voltage, frequency, and ROCOF remain withing the ride-through limits. The voltage briefly drops to 0.8 pu for about 0.3 second following the fault; however, its duration is well below the trip threshold (e.g., the IBR should ride-through if the voltage goes below 0.9 pu for 6 seconds or less). The frequency also shows minor excursions, but within the ride-through range. Similarly, the rate of frequency change variations is small and stayed within the ±5 Hz/s range. Therefore, under this proximity-based EMT model, the IBR is not expected to trip.

A comparison between of the proximity-based EMT model, which includes a subset of impactful generators based on predefined proximity (Fig. 8), and the FSP-based EMT model, which includes all impactful generators (Fig. 7), reveals that

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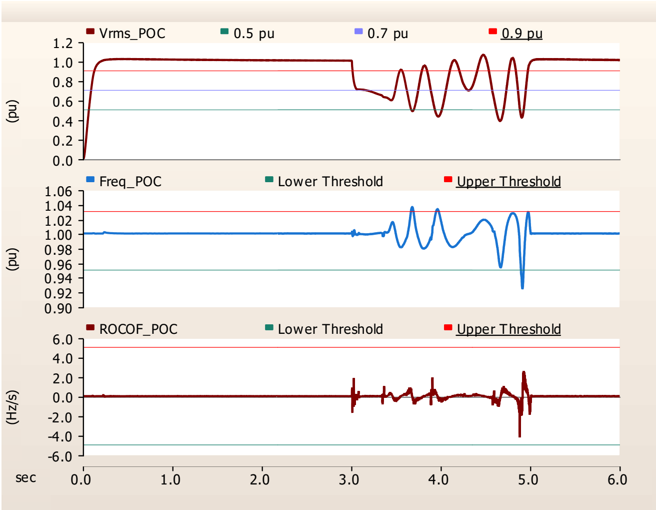

Fig. 7. IBR POC results with modeling impactful generators: RMS voltage; frequency; ROCOF.

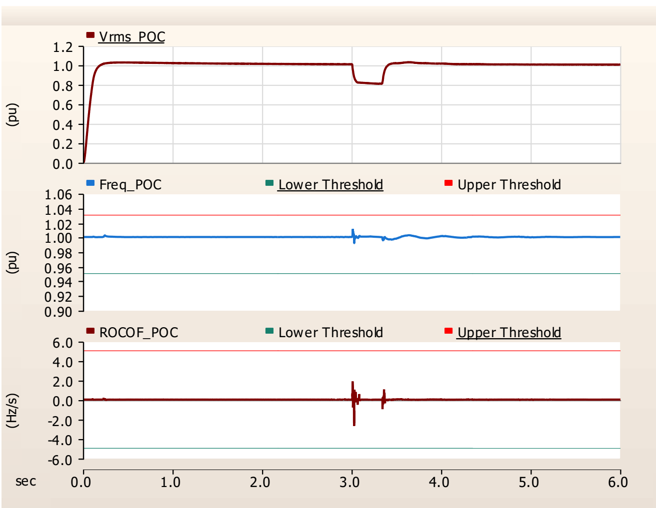

Fig. 8. IBR POC results without modeling impactful generators: RMS voltage; frequency; ROCOF.

the proximity-based EMT model fails to accurately capture the IBR trip event. Although the excluded synchronous generators in the proximity-based EMT model is remote to the IBR, they exhibit strong stability interactions with the IBR location. Without these generators, Thevenin equivalent used to represent the external network fails to model dynamic behaviors and stability couplings with the IBR. In fact, based on phasor-domain simulations, multiple synchronous generators shown in Fig. 4 undergo cascading trips following the fault, primarily due to generator overspeed (a generic overspeed relay with a setting of 110% of generator nominal speed). The FSP-based EMT model replicates these cascading trips, showing that the trip of impactful generators intensifies the voltage and frequency excursions initiated by the fault. In contrast, the proximity-based EMT model fails to capture these dynamic behaviors.

IV. Conclusions

A framework is proposed in this paper to evaluate frequency, ROCOF, and voltage interactions between IBRs and dynamic components of the broader grid to determine impactful components for inclusion in the EMT model based on ride-through requirements outlined in IEEE Std 2800-2022 for IBRs. Applying the proposed framework to an IBR in western New York, the EMT analysis shows that although the IBR experience voltage dip as low as 0.4 pu, the duration of low voltage is insufficient to trigger IBR trip. However, frequency excursions exceed ride-through thresholds, allowing the IBR to trip. Comparing the results of the proposed approach with a pre-defined proximity-based approach reveals that the EMT model with the proposed method more accurately identifies ride-through violations. The proximity-based approach fails to do so because it excludes several synchronous generators, despite being geographically remote, that have strong stability interactions with the IBR. Without these generators, the model cannot fully capture essential stability behaviors and leads to an incomplete representation of system dynamics.

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