A Reversed Impedance-Based Stability Criterion for IBR Grids

Preprint

Shahil Shah, Weihang Yan, Przemyslaw Koralewicz, Emanuel Mendiola, and Vahan Gevorgian

National Renewable Energy Laboratory

Presented at the 21st Wind and Solar Integration Workshop
The Hague, Netherlands
October 12-14, 2022

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-84000
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Suggested Citation
Shah, Shahil, Weihang Yan, Przemyslaw Koralewicz, Emanuel Mendiola, and Vahan Gevorgian. 2022. *A Reversed Impedance-Based Stability Criterion for IBR Grids: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-84000. https://www.nrel.gov/docs/fy23osti/84000.pdf.

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A Reversed Impedance-Based Stability Criterion for IBR Grids

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Abstract–**The existing impedance-based stability criterion is effective for analyzing local control interactions; however, it is difficult to scale the existing criterion to analyze wide-area control interactions among numerous IBRs through a complex power system network. The scaled version of the existing criterion requires the impedance response of each IBR in the system as well as of the network looking from all the IBRs. It is quite challenging to obtain all these impedance responses because of the computational effort and the requirement of separately scanning the impedance of the network and the IBRs. We propose a reversed criterion for the impedance-based stability analysis to address these problems. In contrast to the existing criterion, the reversed criterion analyzes the stability of a power system when an IBR is disconnected from the system. The reversed criterion estimates the impact of an IBR on the frequency and damping of power system oscillation modes using the impedance scans of only the IBR and the grid at its terminal. It can be sequentially applied at different IBRs to evaluate their impact on the power system stability. In addition to scalability, the reversed criterion gives flexibility to focus only on a few selected IBRs, depending on their rating, the magnitude of oscillations observed at their terminals, and the vendor support available for implementing stabilizing control system updates. The reversed criterion is demonstrated on a 14-bus power system with 100% IBRs.**

I. INTRODUCTION

Dynamic stability problems resulting from control interactions among inverter-based resources (IBRs) are a major concern for operating power systems with high levels of renewable generation [1]. Most stability events involving IBRs in the past were local in nature, so that a stability problem can be characterized as an unstable interaction between two subsystems—for example, the interaction of a wind or PV power plant with the grid at its terminal because of the low short-circuit strength of the grid or the presence of a series-compensated transmission line [2], [3]; an offshore wind power plant forming an underdamped resonance with the offshore HVDC converter station [4]; or an HVDC converter or a STATCOM oscillating against the ac network at its terminal [5]. Dynamic stability events involving wider network and numerous IBRs, however, are becoming more common because of the ever-increasing levels of IBRs and reducing grid stiffness [6]–[8]. Recent electromagnetic transient (EMT) simulation studies further demonstrate the high risks of system-wide oscillations in power systems with high levels of IBRs [9]–[11]. One important question that arises whenever system-wide oscillations involving tens to hundreds of IBRs are observed in the field or in EMT simulations is: What is the role and participation of different IBRs in the observed oscillation modes? Or, to put it simply: Which IBRs are causing oscillations? The answer is important for designing mitigation methods, including the curtailment or removal of certain IBRs that negatively contribute to the system damping; tuning of IBR control parameters; the selection of IBR control modes, such as reactive power versus voltage control modes; and the deployment of stability-enhancing devices, such as grid-forming inverters and synchronous condensers. Existing stability analysis tools are not capable of answering this question because they depend on publicly available equation-based models of generators, which are not available for IBRs because of their fast and complex controls and because vendors do not disclose internal details of IBRs to protect their intellectual property.

The impedance-based method has become the mainstream approach for stability analysis of converter-grid systems because instead of relying on analytical models, it uses the impedance responses of IBRs and the grid obtained from either direct measurements or EMT simulations [1]. It has been successfully applied for evaluating local control interactions involving IBRs [2], [4], [12], [13]; however, the method in its current form is not suitable for evaluating wide-area oscillations resulting from control interactions among numerous IBRs through the power system network. The evaluation of wide-area oscillations using the existing impedance-based stability criterion requires the impedance response of each IBR in the network as well as of the network looking from all the IBR nodes. Although this approach is feasible for smaller networks with fixed topologies, where the network impedance model can be analytically developed by aggregating the impedance of different elements, it quickly becomes impractical for larger networks.

This paper presents a reversed criterion for the impedance-based stability analysis to evaluate the impact of an IBR on the damping of power system oscillation modes using the impedance scan of only the IBR and the grid at its terminal. The reversed criterion can be sequentially applied to different IBR plants to quantify each of their impact on system stability—this imparts scalability and flexibility to the impedance-based stability analysis. The paper is organized as follows: Section II reviews the existing criterion for the impedance-based stability analysis and discusses its limitations. Section III presents the new reversed

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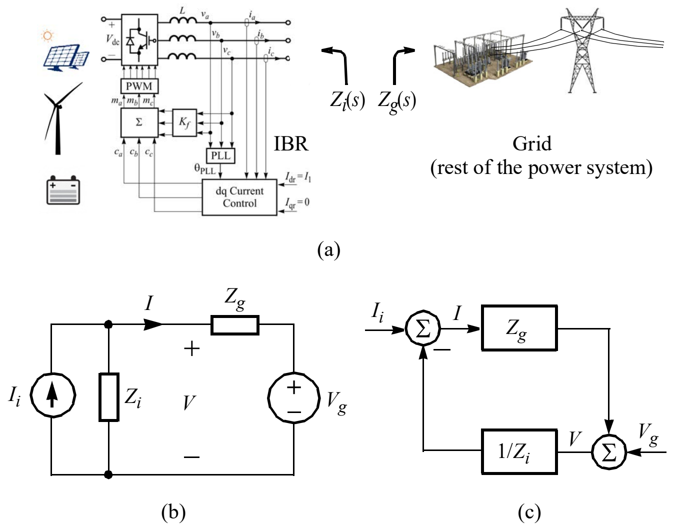

Fig. 1. Impedance-based stability criterion for analyzing interaction between an inverter-based resource (IBR) or a power converter and the grid. (a) partitioning of the converter-grid system; (b) circuit representation and (c) feedback loop representation of small-signal dynamics.

criterion to address the limitations of the existing criterion. Section IV gives an overview of the National Renewable Energy Laboratory's (NREL's) Grid Impedance Scan Tool (GIST), a software developed for performing the impedance-based stability analysis of power systems. Section V demonstrates stability analysis using the proposed criterion on a 14-bus power system with 100% IBRs. Section VI concludes this paper.

II. Existing Impedance-Based Stability Criterion

A. Base Version

Fig. 1(a) defines the impedance of an IBR as $Z_i(s)$, and the grid at its terminal as $Z_g(s)$. As shown in Fig. 1(b), the IBR can be represented by a Norton equivalent and the grid by a Thevenin equivalent. The small-signal relationship between voltages and currents in the equivalent circuit in Fig. 1(b) can be described by a negative feedback loop as shown in Fig. 1(c), with loop gain:

$$L(s) = Z_g(s)/Z_i(s) \tag{1}$$

According to the existing criterion, the IBR will operate stably if the loop gain, $L(s)$, satisfies the Nyquist criterion. The existing criterion assumes that the grid is stable without the IBR and that the IBR is stable if it is operated with an ideal grid with zero impedance. These assumptions imply that $L(s)$ does not have any right-half plane (RHP) poles, which allows for stability analysis using only the Nyquist plot of $L(s)$ without requiring analytical models of the IBR and the grid for calculating the number of RHP poles of $L(s)$. *In summary, the existing criterion assumes that the IBR and the grid are separately stable, and then it evaluates the stability when the IBR is connected to the grid.* Note that $Z_g(s)$ and $Z_i(s)$ can be defined in different reference frames, such as, dq, sequence, and phasor [14]; and they can be represented as either one or two dimensional transfer functions depending on the presence of frequency coupling in the IBR and the grid impedance responses [15].

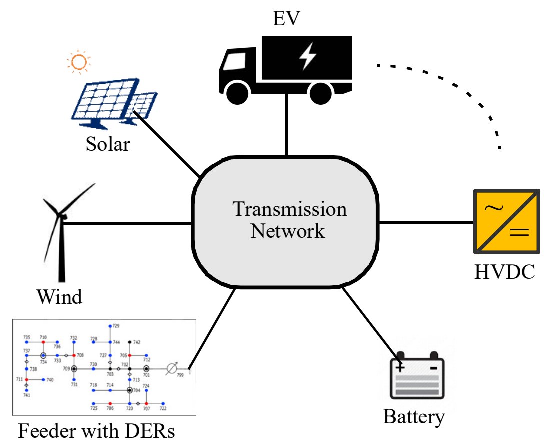

Fig. 2. Power system with high levels of IBRs.

B. Scaled Version

Fig. 2 shows a power system in which IBRs are connected at different nodes of the transmission network. Control interactions among numerous IBRs through the transmission network in such a system can be analyzed by applying the generalized Nyquist criterion to the following loop gain:

$$\mathbf{L}(s) = \mathbf{Z}_g(s) \cdot \mathbf{Y}_i(s) \tag{2}$$

where $\mathbf{Z}_g(s)$ is the impedance of the transmission network looking from all the points of interconnection (POIs) of IBRs, and $\mathbf{Y}_i(s)$ represents a diagonal transfer matrix with admittances of all the IBRs. Note that for n IBRs in the network, both $\mathbf{Z}_g(s)$ and $\mathbf{Y}_i(s)$ are n^{th} order transfer matrices. Moreover, if frequency coupling is considered, the order of these matrices doubles, i.e. $2n$.

To perform the stability analysis using only the impedance/admittance scans of the network and the IBRs, i.e., $\mathbf{Z}_g(s)$ and $\mathbf{Y}_i(s)$, respectively, without requiring their analytical models, the same as in the base version, it is necessary that the loop gain defined in (2) does not contain any RHP poles. This condition requires the following two assumptions:

Assumption #1: All IBRs are stable when they supply to an ideal grid with zero internal impedance.

Assumption #2: The transmission network is stable without all the IBRs.

Even though the condition that each IBR is stable when it is connected to an ideal grid is always met in the standard design process of IBRs, the condition that the transmission network is stable without IBRs results in several limitations for the impedance-based stability analysis using the existing criterion, as discussed in the following.

C. Limitations

- *Network Stability Condition*: One approach to ensure that the network is stable without IBRs is to retain only passive equipment, such as transmission lines and cables, transformers, and filters, as part of the network and consider all the active components in the system as IBRs. This approach, as presented in [16], is feasible when the power system is small and contains only a limited number of active devices such as IBRs, synchronous generators, and FACTS and HVDC substations. Hence, this approach will work only for small power systems, such as microgrids, electric ship power systems, aircraft power systems, and data centers. Another approach to meet the network stability condition for larger power systems is to assume that a major part of the system is stable in the absence of the rest of the power system that has high concentration of power electronics. For example, a bulk HVAC grid can be assumed to be stable when analyzing the stability impact of an offshore HVDC transmission network (used for integrating offshore wind generation) or an overlay HVDC macrogrid that is connected to the bulk HVAC grid at multiple points. In this example, the active equipment in only the HVDC grid needs to be treated as "IBRs" for performing the impedance-based stability analysis; the active equipment in the bulk HVAC grid can be included as part of the network for IBR/network partitioning shown in Fig. 2. This discussion shows that the number IBRs whose impedance must be scanned as well as the number of POIs from where the network impedance must be scanned quickly increases to a large number for larger power systems.

- *Focus on Specific IBRs*: A system operator would usually be interested in studying the stability impact of only a few IBRs, depending on their size, the magnitude of oscillations observed at their terminals, and the vendor support available for performing control updates to improve system damping. On the other hand, an IBR plant owner would be interested in understanding the role of only their plant in an oscillation event to ensure that the plant is not penalized in any way because of the oscillation event. However, the existing criterion does not provide flexibility to focus on only a few specific IBRs during stability analysis. It evaluates the stability impact of all the IBRs at the same time, which is neither computationally efficient nor effective in generating results that can be easily interpreted for developing mitigation solutions.
- *Impedance Scan*: Because the existing criterion assumes that IBRs and the network are separately stable to analyze the stability of the integrated system that is formed when the IBRs are connected to the network, the integrated system cannot be assumed to be stable. Hence, the impedance scans of the IBRs and the network must be performed separately. Although it is possible to perform the impedance scans of IBRs independently from the network by connecting them to a test bed grid (e.g., an ideal voltage source behind a reactor), it is challenging to perform the impedance scan of the network looking from all the POIs. One major difficulty is that if the network contains nonlinear elements, its impedance scan must be performed at the same operation point as when the IBRs are connected to the network; preserving the operation point after disconnecting IBRs can be challenging. Even if the network does not contain any nonlinear elements, performing its impedance scan looking from all the POIs is quite challenging because it requires the injection of perturbations and measurements at several nodes using synchronized measurements. The only solution to avoid this type of scan is to assemble the network impedance matrix using the impedance response of each element and the network topology. This type of information is available only for small power systems.

All these limitations restrict the applicability of the existing criterion for the stability analysis to power systems that are small in size, contain only a few numbers of IBRs, whose network topology is well defined, and when the impedance responses of different elements in the network are available beforehand for the stability analysis.

III. A New Impedance-Based Stability Criterion

The main reason behind all the limitations of the existing criterion is that the stability analysis using the existing criterion evaluates the stability impact of all the IBRs simultaneously. For the impedance-based stability analysis to be scalable and applicable to power systems of any size and complexity, it should be possible to analyze the stability impact of one IBR at a time. We present a new criterion in this section to achieve this goal.

A. A Reversed Perspective on Nyquist Stability Criterion

According to the Nyquist stability criterion [17], if $L(s)$ is the loop gain of a negative feedback loop, the following equation relates the number of encirclements of the critical point ($-1+j0$) by the Nyquist plot of $L(s)$ with the number of RHP poles of the closed-loop system and the open-loop system:

$$N = Z - P \tag{3}$$

where N is the number of encirclements; Z is the number of RHP zeros of $1+L(s)$, which is also equal to the number of RHP poles of the closed-loop system; and P is the number of RHP poles $1+L(s)$, which is also equal to the number of RHP poles of the open-loop system. Note that the open-loop system is stable when P is zero, and the closed-loop system is stable when Z is zero.

Generally, the Nyquist criterion is used to determine closed-loop stability when the open-loop stability condition is known, i.e., when P is known. The closed-loop system is stable if $N = -P$. Moreover, if it is known that the open-loop system is stable, i.e., $P = 0$, then the closed-loop system is stable if and only if $N = 0$, i.e., if the Nyquist plot of $L(s)$ does not encircle the critical point.

In this paper, we look at the Nyquist criterion from a reversed perspective; we assume that we know the closed-loop stability condition, i.e., Z is known, and we aim to determine the open-loop stability. Based on (3), the open-loop system is stable if $N = Z$. Moreover, if the closed-loop system is stable, i.e., if $Z = 0$, then the open-loop system is stable if $N = 0$, and it is unstable if N is negative. The negative value of N implies encirclement of the critical point in the opposite direction compared to the direction of the Nyquist path. The clockwise Nyquist path is used in this paper, i.e., frequency, ω, is increased from $-\infty$ to $+\infty$ to obtain the Nyquist plots. Hence, if the closed-loop system is stable, then the open-loop system is stable if the Nyquist plot of $L(s)$ does not encircle the critical point, and it is unstable if the Nyquist plot of $L(s)$ encircles the critical point in the counterclockwise direction.

B. Reversed Criterion for Impedance-Based Stability Analysis

In contrast to the existing criterion that evaluates the stability of a power system when all IBRs are connected to it, we propose a reversed criterion that evaluates the stability of a power system when a specific IBR is "disconnected" from the system. The reason for keeping the word "disconnected" inside quotes here is to highlight the fact that the IBR is not physically disconnected from the system because that might alter the operation point, but rather its dynamics are removed from the dynamics of the rest of the power system to quantify how this specific IBR is impacting the stability of the power system. We make the following two assumptions in the reversed criterion:

Assumption #1: We assume that the IBR selected for the analysis is stable when it is connected to an ideal grid. The same assumption is also made in the existing criterion, and, as mentioned earlier, it is always met through the standard design process of IBRs.

Assumption #2: We assume that the integrated system with all the IBRs is stable. Note that this assumption is opposite to the network stability assumption in the existing criterion, where it is assumed that the network is stable without all the IBRs.

The above assumption that the integrated system with all the IBRs is stable implies that the characteristic equation:

$$1 + L(s) = 0 \tag{4}$$

does not contain any RHP zeros, where $L(s)$ is the loop gain defined in (1), depending on the impedance of the IBR selected for the analysis and the rest of the network or grid looking from the terminal of the IBR. In other words, Z in (3) is zero, and the integrated system does not have any RHP poles. Hence, based on (3), the Nyquist plot of the loop gain, $L(s)$, can be used to determine P, the number of RHP poles of the loop-gain $L(s)$.

Based on (1), the RHP poles of the loop gain, $L(s)$, are combinations of the RHP poles of the grid impedance, $Z_g(s)$, and the RHP zeros of the IBR impedance, $Z_i(s)$. Because the IBR is assumed to be stable with an ideal grid, there are no RHP zeros in $Z_i(s)$. Hence, the number of RHP poles of $L(s)$, i.e., P, is the same as the number of RHP poles of $Z_g(s)$. The poles of $Z_g(s)$ are also the poles of the power system without the IBR; hence, a positive value of P indicates that the power system has RHP poles in the absence of the IBR. In other words, the power system is unstable without the IBR when P is positive, and it is stable if P is equal to zero. As discussed earlier, P is zero if the Nyquist plot of $L(s)$ does not encircle the critical point, and it is positive if the Nyquist plot encircles the critical point in the counterclockwise direction.

The reversed criterion for impedance-based stability analysis can be summarized as follows:

- **IF** an IBR is stable when it is connected to an ideal grid with zero internal impedance, **and if** a power system is stable when the IBR is connected to it, **then** the stability of the power system when the IBR is "disconnected" from it can be determined by using the Nyquist plot of the ratio of the grid impedance and the IBR impedance, i.e., $Z_g(s)/Z_i(s)$.
- The grid impedance, $Z_g(s)$, used for obtaining the Nyquist plot represents the impedance of the rest of the power system looking from the terminal of the IBR.
- The power system remains stable when the IBR is "disconnected" if the Nyquist plot of $Z_g(s)/Z_i(s)$ does not encircle the critical point, and it will become unstable if the Nyquist plot encircles the critical point in the counterclockwise direction.

C. Resonance Frequency and Damping

The reversed criterion for the impedance-based stability analysis can be used to evaluate whether a specific IBR is critical for the stability of a power system; it basically evaluates whether an oscillation mode of a power system will become unstable in the absence of the IBR where the analysis is performed. Hence, the reversed criterion shows whether the damping of an oscillation mode of a power system will become negative when an IBR is disconnected from the power system; however, it cannot explicitly show the impact of the IBR on the magnitude of the damping of an oscillation mode. This information can be obtained using the nodal impedance analysis described in the following.

The nodal impedance, $Z_n(s)$, of a power system represents its impedance looking from a specific node. Hence, for the power system shown in Fig. 1, the nodal impedance at the POI of the IBR with and without the influence of the IBR can be written as:

$$Z_n(s) = \begin{cases} Z_g(s) & \text{without IBR} \\ \dfrac{Z_g(s) \cdot Z_i(s)}{Z_g(s) + Z_i(s)} & \text{with IBR} \end{cases} \tag{5}$$

Note that the nodal impedance contains all the poles or oscillations modes of a power system [18]. Hence, it exhibits a peaking response at resonance frequencies of oscillation modes with damping of small magnitudes [19]. In other words, the resonance frequency of oscillation modes in a power system can be identified from the peaks of its nodal impedance responses. The effect of other modes around the resonance frequency of a particular mode can be ignored if other modes are located farther from the resonance frequency.

Conjugate poles of a power system at resonance frequency, ω_r, can be written as:

$$\lambda_r = \sigma_r \pm j\omega_r = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2} \tag{6}$$

where ω_n and ζ are the natural frequency and damping ratio of the mode, respectively. The resonance frequency of a mode can be found from the corresponding peak of the nodal impedance responses. The magnitude of the damping factor, i.e. $|\zeta|$, on the other hand, can be estimated from:

$$|\zeta| = \frac{\omega_y^2 - \omega_x^2}{4\omega_r^2} \approx \frac{\omega_y - \omega_x}{2\omega_r} \tag{7}$$

where ω_x and ω_y are, respectively, the lower and upper half-power frequencies—that is, frequencies on both sides of the resonance frequency, ω_r, where the magnitude of the nodal impedance is $1/\sqrt{2}$ times its peak value. This method for estimating the resonance frequency and damping of oscillation modes is called the *peak-picking method* [19].

Using this method and the nodal impedance responses with and without the IBR based on (5), one can estimate the resonance frequency and the magnitude of the damping of various oscillation modes of a power system with and without the IBR being analyzed. Note that the damping of all oscillation modes is positive when the IBR is connected to the grid because of the system stability assumption. It can be determined if the damping of an oscillation mode will remain positive or if it will become negative when the IBR is "disconnected" using the reversed criterion. Hence, the reversed criterion and the nodal impedance analysis can estimate the impact of an IBR on the frequency and damping of various oscillation modes.

D. *Analysis with Frequency Coupling in Sequence Impedance*

It is important to consider frequency coupling in the sequence impedance responses of the IBR and the grid when analyzing low-frequency oscillation modes, particularly those with resonance frequencies smaller than a couple hundred Hz [14]. In such cases, both $Z_i(s)$ and $Z_g(s)$ will be second-order transfer matrices. Because of this, the loop gain, $L(s)$, will also be a second-order transfer matrix, and the generalized Nyquist criterion must be used for performing the stability analysis using the reversed criterion. In the generalized Nyquist criterion, the encirclements of the Nyquist plots of the eigenvalues of $L(s)$ are counted for the stability analysis. Note that $L(s)$ will have two eigenvalues when frequency coupling is considered. The critical point for counting encirclements of eigenvalues remains the same as $(-1+j0)$. It is also possible to use the Nyquist plot of the determinant of $[I + L(s)]$ for performing the stability analysis, in which case encirclements of the origin are counted for determining whether the power system will remain stable when the IBR is "disconnected."

Based on (5), the nodal impedance, $Z_n(s)$, at the POI of an IBR will be a second-order transfer matrix when the frequency coupling is considered. In such cases, the peaking behavior near the resonance frequencies might not be visible in the elements of the nodal impedance matrix, depending on how the corresponding poles are distributed among the four elements of the nodal impedance; however, resonance can be directly observed in the magnitude response of the two eigenvalues of the nodal impedance, $Z_n(s)$. The eigenvalues of an impedance matrix are also referred to as modal impedances because they capture information on the oscillation modes. Hence, the magnitude response of the eigenvalues of $Z_n(s)$ obtained from (5) can be used to estimate the impact of the IBR on the resonance frequency and the magnitude of the damping ratio of various oscillations modes in the system [20].

E. *Validity of System Stability Assumption*

The proposed reversed impedance-based stability analysis criterion assumes that the power system is stable with all the IBRs, and it then aims to analyze the system stability when a specific IBR is "disconnected" from the system. Because the existing impedance criterion assumes that the network is stable only without IBRs, it is reasonable to question the validity of the system stability assumption employed in the proposed reversed criterion. Moreover, because the motivation for performing the impedance-based stability analysis is generally an unstable oscillation event observed either in the field or in EMT simulation studies, one might question how a system can be assumed to be stable with all the IBRs. This section addresses these concerns on the system stability assumption.

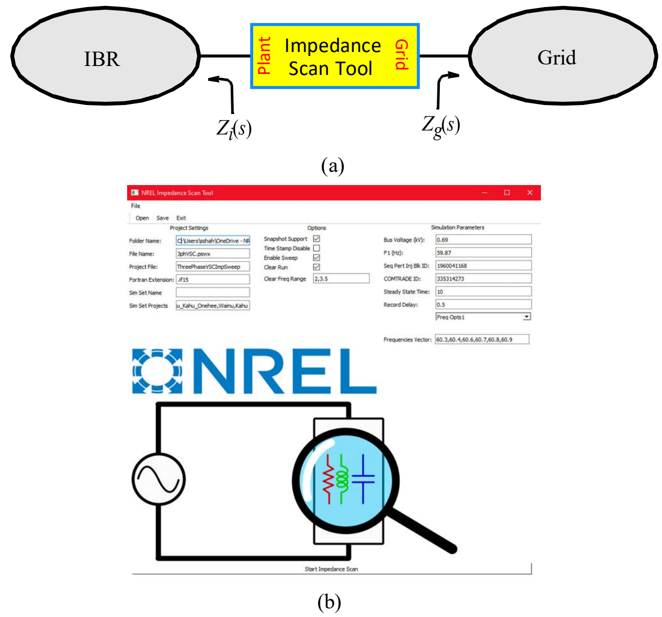

Fig. 3. NREL's Grid Impedance Scan Tool (GIST) for PSCAD models: (a) impedance scan block in PSCAD of the GIST software for simultaneous scan of an IBR plant and the grid at its terminal, and (b) GUI of the GIST software.

A power system is always stable before oscillations are triggered by a contingency event. The existing criterion aims to analyze the system that is formed after the contingency, which cannot be assumed to be stable; however, there are many limitations to this approach, as discussed in Section II. On the other hand, as shown in the previous section, there are many advantages to analyzing the stable system that exists before the contingency event using the proposed reversed criterion. A contingency would not change how an IBR is impacting different stability modes; it would only change a marginally stable mode to an unstable mode. The impedance-based stability analysis of a stable power system also helps in identifying solutions to improve stability margins without waiting for an unstable oscillation event.

IV. NREL's Grid Impedance Scan Tool

NREL has developed a PSCAD-based GIST to support the impedance-based stability analysis of power systems with high levels of IBRs. For using GIST to evaluate the stability impact of an IBR using the reversed criterion, an impedance scan block is inserted between the IBR and the rest of the power system in the PSCAD model, as shown in Fig. 3(a). This impedance scan block is controlled by a graphical user interface (GUI) shown in Fig. 3(b). The GIST software simultaneously scans the impedance response of both the IBR and the grid at its terminal without breaking the system model in PSCAD. The software considers the frequency coupling, the reference frame of the impedance, and the impact of the fundamental frequency on the accuracy of the impedance scans. More details on GIST can be found in [21].

V. Case Study: 14-Bus System with 100% IBRs

This section applies the reversed criterion for impedance-based

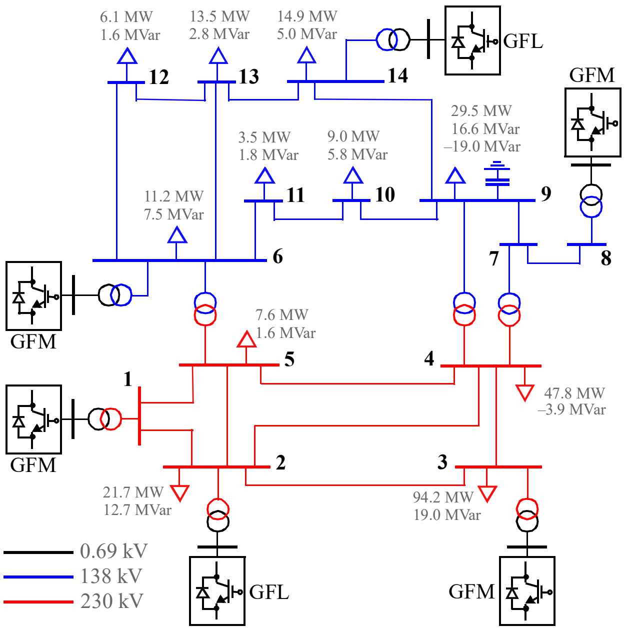

Fig. 4. Modified IEEE 14-bus system simulated in PSCAD.

TABLE I Power Output and Voltages at IBRs

Bus #	Active Power (MW)	Reactive Power (MVAr)	Bus Voltage (p.u.)	Capacity (MVA)
1	133	51.6	1.06	300
2	40	13	1.03	100
3	0	18.7	0.98	40
6	0	11.6	0.99	25
8	0	11.3	1.01	25
14	100	–24.72	0.96	150

stability analysis of the modified IEEE 14-bus system shown in Fig. 4. The system is simulated in PSCAD, and it has grid-forming (GFM) IBRs at buses 1, 3, 6, and 8 and grid-following (GFL) IBRs at buses 2 and 14. The active power output of the IBRs at buses 3, 6, and 8 is kept at 0 for replacing the synchronous condensers in the original IEEE 14-bus system [22] without disturbing the power flow condition. The control strategies and circuit parameters for both GFM and GFL IBRs are provided in [23]. The power generation of each IBR and their bus voltages are given in Table I. Table II shows the control parameters of the GFM and GFL IBRs.

Fig. 5 shows the simulated response of the active power output of all the IBRs when a three-phase one-cycle fault is applied at bus 12. It shows underdamped oscillations at 2.5 Hz. It is important to understand the role of individual IBRs in this oscillation mode to develop mitigation solutions and improve system damping.

A. Stability Analysis Using the Reversed Criterion

We start analysis at the GFM IBR at bus 3 because of the higher amplitude of oscillations at its terminal, as shown in Fig. 5. The first step is to scan the impedance/admittance response of the IBR and the grid at its terminal by inserting the impedance scan

TABLE II Control Parameters of IBRs

Parameter	Value
Current controller, $H_i(s)$	$0.00255 + 3.06s$
Power controller, $H_p(s)$	$0.00029 + 0.0114s$
PLL compensator, $H_{PLL}(s)$	$(0.237 + 44.64s)/s$
Voltage controller, $H_v(s)$ (IBRs at buses 3 &6)	$1.522 + 21.27s$
Voltage controller (IBR at bus 8)	$1.522 + 212.76s$
Droop gains (IBR at bus 1)	*P-f*: 0.05 p.u.; *Q-V*: 0.05 p.u.
Droop gains (IBRs at buses 3 & 6)	*P-f*: 0.01 p.u.; *Q-V*: 0.05 p.u.
Droop gains (IBR at bus 8)	*P-f*: 0.1 p.u.; *Q-V*: 0.05 p.u.

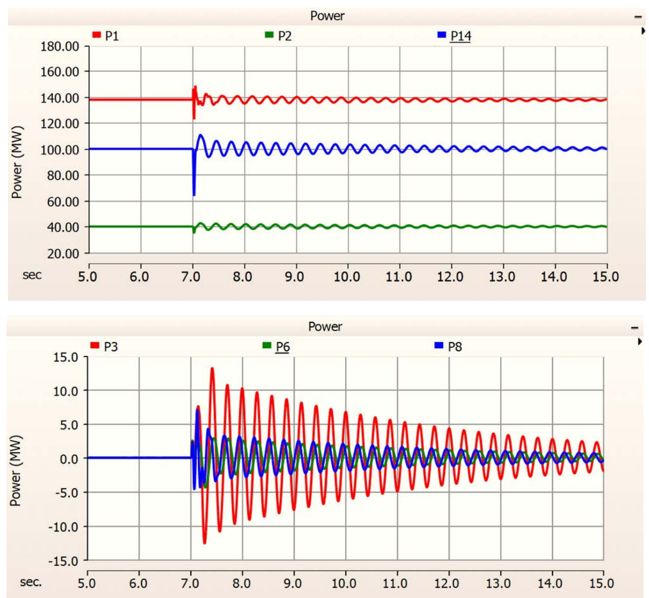

Fig. 5. Active power oscillations in the modified IEEE 14-bus system following a one-cycle (16 ms) three-phase fault on bus 12.

block of NREL's GIST software between the IBR and the grid.

Fig. 6 shows the sequence admittance response, including the frequency coupling of the GFM IBR at bus 3 and the grid at its terminal. Fig. 7(a) shows the magnitude response of the two modal impedances of the nodal impedance, $Z_n(s)$, at the POI of the GFM IBR at bus 3. Modal impedance responses are obtained from the IBR and grid impedances, $Z_i(s)$ and $Z_g(s)$, respectively, using (5). Note that impedances $Z_i(s)$ and $Z_g(s)$ are inverse of the admittance responses, $Y_i(s)$ and $Y_g(s)$, shown in Fig. 6. The modal impedance responses in Fig. 7(a) identify a resonant mode at 2.5 Hz in the presence of the IBR, whose frequency changes to 2.36 Hz when the IBR at bus 3 is "disconnected." Hence, it can be inferred that the IBR increases the resonance frequency of the mode by 0.14 Hz. Using (7), it is also found that the magnitude of the damping ratio, $|\zeta|$, of the 2.5 Hz mode is 13.3% with the IBR and 5.93% without the IBR. Because the power system is stable with all the IBRs, ζ is positive in the presence of the IBR, i.e. it is +13.3%; however, it is not possible to know whether the damping ratio is +5.93% or –5.93% when the IBR is "disconnected" from the system using the modal impedance responses shown in Fig.

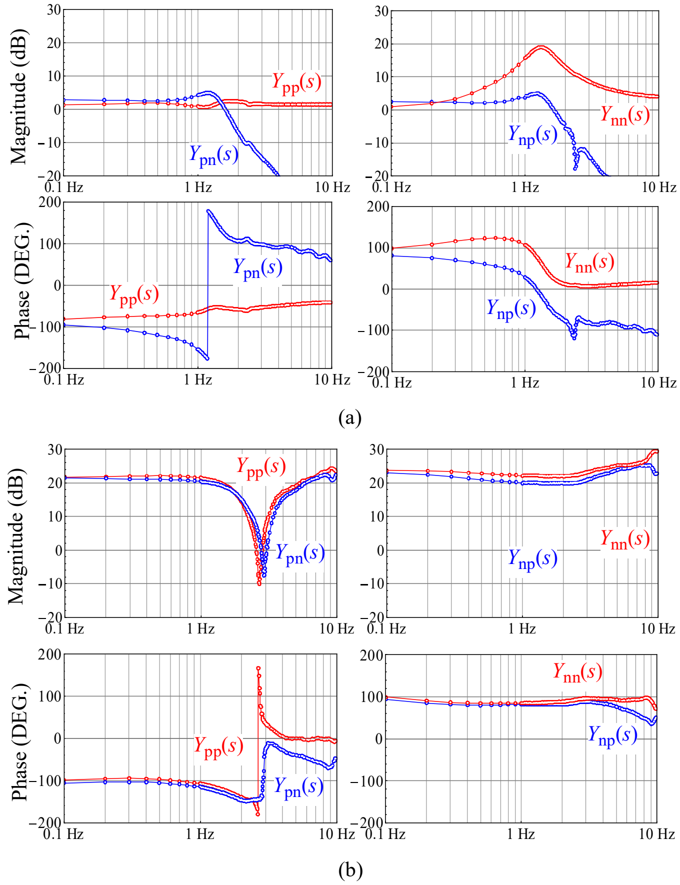

Fig. 6. Sequence admittance scan at the GFM IBR at bus 3: (a) response of the IBR, $Y_i(s)$, and (b) the grid at the terminal of the IBR, $Y_g(s)$.

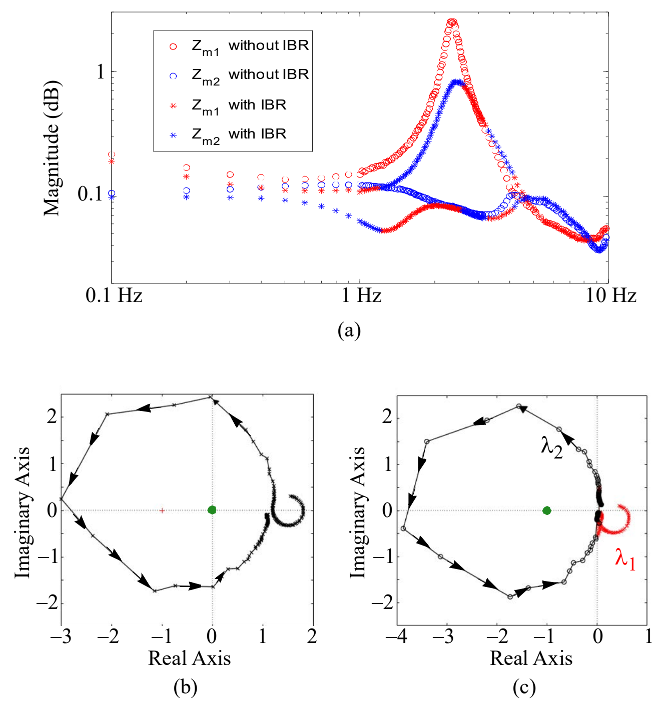

Fig. 7. Stability analysis for the GFM IBR at bus 3: (a) response of the modal impedances at bus 3 with (stars) and without (circles) the GFM IBR at the bus, (b) Nyquist plot of the determinant of [I + $L(s)$], and (c) Nyquist plot of the eigenvalues of $L(s)$. Note that $L(s) = Z_g(s) \cdot Y_i(s)$ is the loop gain for applying the impedance-based reversed criterion to the IBR at bus 3.

7(a). This can be achieved using the reversed impedance criterion. Fig. 7(b) shows the Nyquist plot of the determinant of [$I + L(s)$], which encircles the origin in the counterclockwise direction; this implies that the power system will be unstable when the GFM IBR at bus 3 is "disconnected." Similarly, Fig. 7(c) shows the Nyquist plot of the two eigenvalues of $L(s)$, one of which encircles the critical point, (–1+j0), in the counterclockwise direction, which again confirms the instability of the power system when the IBR at bus 3 is "disconnected." Hence, the damping ratio of the oscillation mode at 2.5 Hz is negative without the IBR; it is –5.93%. The simulations in Fig. 8 confirm the instability of the system when the GFM IBR at bus 3 is tripped from the system.

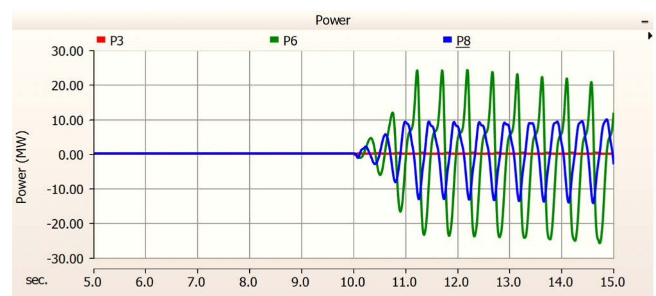

Fig. 8. Response when the GFM IBR at bus 3 is suddenly disconnected at 10s.

Based on this analysis, it can be summarized that the GFM IBR at bus 3 increases the resonance frequency of the oscillation mode from 2.36 Hz to 2.5 Hz and the damping ratio of the mode from –5.93% to 13.3%—resulting in the total improvement of +19.2% in the damping of the mode.

Stability analyses at other IBRs can be similarly performed to evaluate their impact on the 2.5 Hz oscillation mode. For example, Fig. 9 shows the analysis at the GFL IBR at bus 2. Following the same steps as before, it can be estimated from the modal impedance responses in Fig. 9(a) that the IBR at bus 2 increases the resonance frequency of the mode from 2 to 2.5 Hz and the magnitude of the damping ratio from 9.25% to 15%. Moreover, because the Nyquist plot of the determinant of [$I + L(s)$] shown in

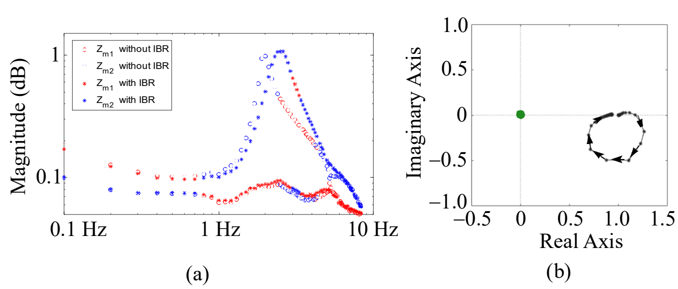

Fig. 9. Stability analysis at the GFL IBR at bus 2: (a) response of the modal impedances at bus 2 with and without the GFL IBR, and (b) Nyquist plot of the determinant of [I + $L(s)$] for IBR at bus 2.

Fig. 9(b) does not encircle the origin, it can be inferred that the power system remains stable when the GFL IBR at bus 2 is "disconnected." In other words, the damping ratio, ζ, of the mode

TABLE III OSCILLATION MODE IDENTIFIED IN THE SYSTEM

Resonance Frequency (f_r)	Damping Ratio (ζ)
2.5 Hz	+12 to +15%

TABLE IV IMPACT OF DIFFERENT IBRS ON 2.5 HZ MODE

IBR	Change in Res. Freq. (Δf_r)	Change in Damping ($\Delta\zeta$)
GFM IBR at Bus 3	0.14 Hz	+19.2%
GFL IBR at Bus 2	0.5 Hz	+5.7%
GFM IBR at Bus 6	0 Hz	+21%
GFL IBR at Bus 14	1.3 Hz	–4.5%

without the IBR remains positive. Hence, the GFL IBR at bus 2 increases the damping of the 2.5 Hz mode from +9.25% to +15%—resulting in the improvement of +5.75% in the damping.

The stability analysis is repeated at the GFM IBR at bus 3 and the GFL IBR at bus 14. Table III shows the resonance frequency and the damping of the mode identified by analysis at four IBRs. The damping is provided as a range covering the estimated values at different IBRs—some variation in the estimation of modal parameters are expected at different IBRs. Table IV shows how each of the four IBRs are impacting the resonance frequency and the damping of the 2.5 Hz mode; it is evident that the IBRs at buses 3, 2, and 6 contribute positively, and the IBR at bus 14 contributes negatively to the damping.

VI. CONCLUSIONS

The reversed criterion presented in this paper fundamentally changes how the impedance-based stability analysis is performed —it enables the evaluation of the impact of one IBR at a time on the frequency and damping of power system oscillation modes. The proposed reversed criterion imparts scalability and flexibility to the impedance-based stability analysis, and makes it feasible to study control interactions among numerous IBRs connected at different nodes of a complex power system network. The reversed criterion is not a replacement for the existing impedance-based stability criterion: the existing criterion should be applied for studying stability when a new IBR is connected to a power system or for analyzing local control interactions, and the new reversed criterion should be applied for studying system-wide oscillation modes resulting from control interactions among numerous IBRs. It can identify oscillation modes in a power system and answer the question: Which IBRs are causing oscillations? The reversed impedance-based stability criterion does eliminate the requirement of the scaled version of the existing impedance-based stability criterion, which is neither effective nor feasible for studying the stability of large power systems with high levels of IBRs.

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