

A Frequency-Coupled Two-Port Representation of Inverter-Based Resources for Unbalanced Operation

Rabi Kar, *Member, IEEE*, Zhixin Miao, *Senior Member, IEEE*, Lingling Fan, *Fellow, IEEE*

¹Department of Electrical Engineering, University of South Florida, Tampa, FL 33620

CORRESPONDING AUTHOR: Lingling Fan (e-mail: linglingfan@usf.edu).

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ABSTRACT Penetrations of inverter-based resources (IBRs) in power grids keep increasing. In this paper, we derived a two-port phasor-impedance circuit model for IBRs that includes the frequency coupling effect introduced by asymmetry in the dq -frame control. The physical interpretation of the related phasors of this circuit is also meticulously explained. The two-port circuit model is validated against electromagnetic transient simulation results of an IBR grid integration system subject to an unbalanced grid voltage dip. It is shown that the two-port circuit model achieves better accuracy compared to the decoupled positive- and negative-sequence circuit model (or the single-port model). We also examined the effect of IBR control on significance in frequency coupling and obtained insights regarding the application scopes of the single-port model and the two-port model.

INDEX TERMS Inverter-based resources, two-port representation, admittance model.

I. Introduction

WITH the progress of decarbonizing electricity generation, reliance on renewable sources has grown. Consequently, the use of IBRs has notably risen. The increased use of IBR influences power system transient and dynamic performance. For example, subsynchronous oscillations have been observed in wind farms and solar PVs [1], [2] with a few events showing side-band oscillations with both a primary and a mirror-frequency components. Moreover, IBRs can contribute to the misoperation of protection devices [3]–[10]. For example, the negative-sequence current-based relays become insensitive to faults since IBRs contribute much lower negative sequence current compared to synchronous generators [4]–[10]. Additionally, the angular relation between the negative-sequence voltage and the current phasors is quite different from that of a synchronous generator according to [6]. Therefore, it is imperative to accurately represent IBRs for analysis of unbalanced operating conditions, and in particular considering mirror-frequency oscillation/harmonic components.

A. Literature Review

There are two primary methods for analysis of unbalanced operation: 1) electromagnetic transient (EMT) simulation, and 2) quasi-static phasor-based analysis. Although the EMT

simulation has been adopted by major research organizations (e.g., EPRI and NREL) for IBR fault analysis [11], [12], it is time-consuming and offers limited insights. Instead, the industry prefers fast computing tools for fault analysis. The quasi-static phasor-based analysis fits the need. In this type of analysis, synchronous generators are treated as Thévenin equivalent circuits with transient reactances [13]. On the other hand, for IBRs, their circuit models in fast analysis are still under development.

In the work conducted by EPRI [14]–[16], an IBR is represented as a Norton circuit with a voltage dependent nonlinear current source. In [14], a lookup table representing positive-sequence voltage and positive-sequence current relationship is first obtained through EMT simulation results. The information is then used in the IBR representation. In [16], the IBR is represented by a three-phase current source, and the current phasors are constructed from the positive- and negative-sequence components determined by the control logic. Since these are phasor-domain models, the analysis can be performed using PSS@CAPE and ASPEN, as well as nominal frequency phasor or root mean square (RMS)-based simulation tools such as PSS/E and PSLF. A detailed implementation of the process is mentioned in [17].

There is a gap in the phasor representation. IBRs' positive- and negative-sequence voltage/currents are in fact coupled

[18]–[20]. Under unbalanced operation, IBRs’ instantaneous voltage or current may have three harmonic components: the nominal frequency (or the positive-sequence 60-Hz) component, the negative-sequence 60-Hz (or the -60 -Hz) component, and a positive-sequence 180-Hz component [20]. Similar phenomena can also be seen in type-3 wind turbines equipped with doubly-fed induction generators (DFIG). The stator side’s current space vector may consist of components at different rotating speeds: ω_0 , $-\omega_0$ and $3\omega_0$ (where ω_0 is the nominal frequency or speed) when subject to unbalanced voltage [21]. However, the previous studies all treat the two sequences as decoupled.

In [22], the relationship between the dq -domain admittance and sequence-domain admittance is rigorously established through a transfer-matrix-based impedance modeling framework that unifies the dq , sequence, and phasor domains. In this formulation, coupling effects are mathematically captured through off-diagonal elements and frequency-shifted mappings (i.e., $s \pm j\omega_0$), and the framework is primarily developed for stability analysis. In contrast, the present work focuses specifically on frequency coupling under unbalanced operating conditions and develops a two-port sequence-domain circuit representation that explicitly captures the interaction between positive- and negative-sequence components. The proposed approach emphasizes physical interpretation by representing frequency coupling through their equivalent circuit representation. Furthermore, unlike the transfer-matrix formulation, which remains abstract and is not directly suited for phasor-domain implementations, the proposed model is structured for direct integration into phasor domain analysis and is particularly tailored for fault and unbalanced operation analysis.

Although frequency coupling has been considered in many research related to dynamics, e.g., [20], [23], these Laplace-domain circuits have not been adapted to the positive- and negative-sequence domain for fast fault or unbalance operation analysis. Nor does the previous research provide physical interpretations of the related phasors in the circuit.

B. Contributions

This paper will fill the gap of phasor-impedance IBR circuit derivation to include frequency coupling phenomena. To this end, a two-port circuit will be derived for IBRs.

Our paper presents a detailed approach to convert the dq admittance model into a two-port sequence-domain circuit model. We have meticulously derived and shown the physical interpretations of the phasors in the two-port circuit. Furthermore, we elaborate the significance of the two-port circuit model by comparing it with a decoupled positive and negative-sequence model in analysis. The two-port circuit shows to achieve better accuracy. In addition, we examine the effect of IBR control on strong and weak coupling between the positive and negative sequences.

C. Structure

The paper is structured as follows: the topology of the testbed and the control strategy are first introduced in Section II, and then this section introduces the representation of an IBR as a two-port network, highlighting the presence of mirror frequency components. This section also outlines the derivation of positive- and negative-sequence circuits from the sequence admittance matrix. Section III describes the frequency injection process for extracting the dq admittance matrix and the process of converting it into corresponding positive and negative sequence admittance matrices. The analysis of mirror frequency components is crucial for an accurate system assessment in IBRs and Section IV elaborates on the effect of controller design on these components. Finally, Section VI summarizes the paper and provides a concise conclusion.

II. IBR representation as a two-port circuit model

Fig. 1a shows the circuit topology of the EMT testbed. The testbed consists of a 1-MW IBR operating under active and reactive power (PQ) control, connected to a 13.2-kV grid through a Y_g – Y_g transformer that allows zero-sequence currents. The grid is represented by a Thévenin equivalent circuit—a constant voltage source behind a grid impedance, which has an XR ratio of 10. The grid impedance is the aggregated representation including a substation transformer and a transmission network. The grid strength is evaluated by the short circuit ratio (SCR) at the point of common coupling (PCC) bus and the SCR is 5. The IBR is connected to the PCC bus through a choke filter represented by an RL circuit (resistance R_f and inductance L_f). For simplicity, the photovoltaic is replaced by an ideal dc voltage source as shown in the figure.

The IBR has its real and reactive power regulated. Fig. 1b shows the control strategy used for the inverter [24]. The control logic is built in the dq -frame with the inner loop current controller controlling the converter exporting current. The outer loop regulates the IBR’s exporting real and reactive power measured at the PCC bus and generates d - and q -axis current orders for the inner current control. A phase-locked loop (PLL) is used as the synchronizing unit which has the PCC bus three-phase voltage as the input and outputs a synchronizing angle for abc/dq frame conversion. The circuit and control parameters are listed in Table 1.

When an IBR is subject to unbalanced voltage, the IBR will export not only negative-sequence current at the fundamental frequency, but also positive-sequence 3rd harmonic current. This phenomenon has been reported in the literature for grid-connected converters [19] and type-3 wind turbines [21]. More generally, when an IBR operating at the nominal frequency ω_0 is perturbed by a sinusoidal voltage at the primary frequency of $(\omega_p + \omega_0)$, its current contains not only $(\omega_p + \omega_0)$ harmonic but also another harmonic at the mirror frequency $(\omega_0 - \omega_p)$. If the $(\omega_p + \omega_0)$ is viewed as a positive-sequence harmonic, the $(\omega_0 - \omega_p)$ component can be

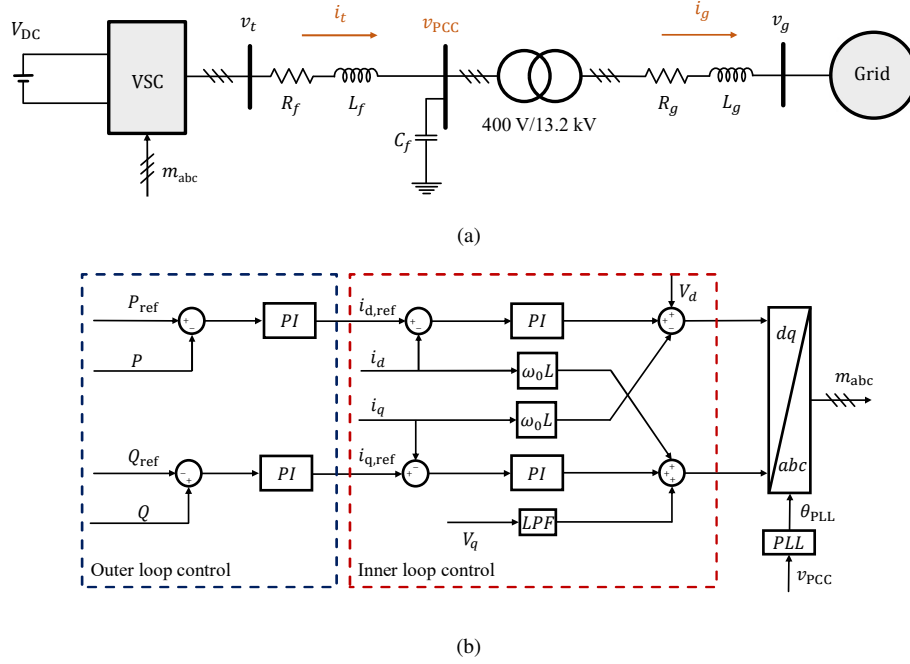


FIGURE 1: (a) The circuit topology of the IBR grid integration system. (b) Control structure of the IBR.

TABLE 1: Parameters of IBR.

Description	Symbols	Values (SI/pu)
Power base	S_b	1 MVA
Voltage base IBR (LL, rms)	V_{b1}	400 V
Voltage base Grid (LL, rms)	V_{b2}	13.2 kV
System frequency	f	60 Hz
DC voltage	V_{DC}	1000 V
Choke filter	R_f	0.0063 pu
Choke filter	X_f	0.1084 pu
Shunt C	C_f	0.0803 pu
Transmission line	R_g	0.02 pu
Transmission line	X_g	0.2 pu
PLL	PI	60+1400/s
Real power control	PI	0.2+20/s
Reactive power control	PI	0.2+20/s
Insignificantly coupled		
Inner d -axis	PI	0.3+5/s
Inner q -axis	PI	0.3+5/s
Significantly coupled		
Inner d -axis	PI	0.05+1/s
Inner q -axis	PI	0.9+5/s

viewed as the negative-sequence harmonic at the frequency of $(\omega_p - \omega_0)$.

For example, if the primary harmonic is at 130 Hz, the mirror frequency harmonic is at -10 Hz. The -10 Hz harmonic is of course a negative-sequence set at 10 Hz. Similarly, if the primary frequency is $70 = 10 + 60$ Hz, then

the mirror-frequency harmonic is at 50 Hz. This harmonic is viewed as the negative sequence of $10 - 60 = -50$ Hz harmonic. Note the latter is not straightforward. Yet this has to be emphasized as we will be dealing with one positive-sequence component and another negative-sequence component symbolically.

The underlying reason of frequency coupling is attributed to the asymmetric IBR control in the dq -frame [18]. To accurately represent the characteristics of an IBR, a two-port representation with both harmonic components coupled will be necessary.

We start by examining the abc phase currents in the space vector form, notated by $\vec{i}$. In the synchronous dq -frame which has a constant speed of ω_0 with the d -axis assuming an angle of $\omega_0 t$ against the static reference frame, the current is viewed as a vector $i_d + ji_q$. And the space vector and the vector in the dq frame are associated as follows:

$$\vec{i}(t) = (i_d(t) + ji_q(t))e^{j\omega_0 t}. \quad (1)$$

If the abc phase currents are a positive-sequence set, i_d and i_q will be constant. During unbalanced and/or harmonic conditions, i_d and i_q may have harmonic components besides the dc component. Suppose that $i_d(t)$ and $i_q(t)$ have a harmonic component and the frequency is ω_p :

$$i_d(t) = \hat{i}_d \cos(\omega_p t + \theta_d) = \frac{1}{2}(\bar{I}_d e^{j\omega_p t} + \bar{I}_d^* e^{-j\omega_p t}), \quad (2)$$

$$i_q(t) = \hat{i}_q \cos(\omega_p t + \theta_q) = \frac{1}{2}(\bar{I}_q e^{j\omega_p t} + \bar{I}_q^* e^{-j\omega_p t}), \quad (3)$$

where $\bar{I}_d$ and $\bar{I}_q$ are the phasors at the frequency of ω_p and

$$\bar{I}_d = \hat{i}_d e^{j\theta_d}, \quad \bar{I}_q = \hat{i}_q e^{j\theta_q}$$

Substituting (2) and (3) into (1) leads to the following:

$$\vec{i} = \underbrace{\frac{\vec{i}_p(t)}{2}}_{\vec{I}_p} e^{j(\omega_p + \omega_0)t} + \underbrace{\left(\frac{\vec{i}_n(t)}{2} \right)^*}_{\vec{I}_n} e^{j(\omega_p - \omega_0)t}. \quad (4)$$

It can be seen that the current has two harmonic components: the positive-sequence component $\vec{i}_p(t)$ at $(\omega_p + \omega_0)$ frequency and the conjugate of $\vec{i}_n$, where $\vec{i}_n$ rotates at $(\omega_p - \omega_0)$ speed or frequency. Note that the conjugate of a space vector can be interpreted as the negative sequence of that space vector. Therefore, $\vec{i}$ can be viewed as consisting of a positive-sequence component and a negative-sequence component.

Note that $\vec{I}_p$ and $\vec{I}_n$ are the phasors of $(\omega_p + \omega_0)$ and $(\omega_p - \omega_0)$ harmonics, respectively. More generally, we use $i_p(s + j\omega_0)$ and $i_n(s - j\omega_0)$ to describe current harmonic phasors where s can be replaced by any perturbing harmonic and $s = j\omega_p$.

In the dq -frame, the relationship between the current flowing out of an IBR and the voltage at the IBR's terminal can be represented as Eq. (5).

$$\begin{bmatrix} \Delta i_d(s) \\ \Delta i_q(s) \end{bmatrix} = - \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix} \times \begin{bmatrix} \Delta v_d(s) \\ \Delta v_q(s) \end{bmatrix}. \quad (5)$$

The dq -frame current and voltage may be transformed to the respective positive- and negative- sequences according to (4).

$$\begin{bmatrix} \Delta i_p(s + j\omega_0) \\ \Delta i_n(s - j\omega_0) \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} \Delta i_d(s) \\ \Delta i_q(s) \end{bmatrix}, \quad (6)$$

$$\begin{bmatrix} \Delta v_p(s + j\omega_0) \\ \Delta v_n(s - j\omega_0) \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} \Delta v_d(s) \\ \Delta v_q(s) \end{bmatrix}, \quad (7)$$

where Δi_p represents change in the positive-sequence current and Δi_n represents change in the negative-sequence current. This relationship between the dq -frame phasors and the positive- and negative(PN)-sequence phasors has also been mentioned in [19].

Based on the above relationship, we may find that:

$$\begin{bmatrix} \Delta i_p(s + j\omega_0) \\ \Delta i_n(s - j\omega_0) \end{bmatrix} = -\mathbf{Y}_{IBR}(s) \begin{bmatrix} \Delta v_p(s + j\omega_0) \\ \Delta v_n(s - j\omega_0) \end{bmatrix}, \quad (8)$$

where

$$\mathbf{Y}_{IBR}(s) = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \times \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix} \times \begin{bmatrix} 1 & 1 \\ -j & j \end{bmatrix}.$$

It can be seen that the IBR can be represented by a two-port element, each port corresponding to one harmonic frequency. For example, when s is evaluated at $j0$, the two-port network has one port for the 60-Hz nominal frequency component, and another port for the negative-sequence -60 Hz component. The negative-sequence -60 Hz component is essentially the same nominal 60-Hz component.

When $s = j\omega_0$, the two-port network associates the 120-Hz harmonic with a dc component. In other words, an IBR's current may possess both dc component and a 2nd

harmonic component. A real-world scenario associated is the inverter-transformer resonance issue or the second harmonic interaction. Such phenomenon has attracted attention from researchers, e.g., [25]. When a transformer operates in a saturated condition, its current contains 2nd harmonics. When the transformer is connected to an IBR or a dc/ac converter, the converter's control attributes to additional dc component in the current. This dc component aggravates the transformer's saturation. In the 1990s, the power grid industry has reported the so-called "core saturation instability" in high voltage DC systems [26], [27].

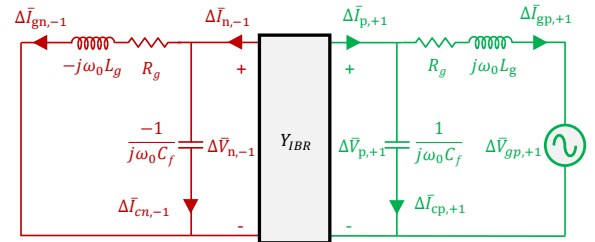
When $s = j2\omega_0$, the two-port network associates the 180-Hz component with the negative-sequence 60-Hz component. This coupling is related to the unbalance operation, as shown in [24]. It shows exactly how the positive-sequence 180-Hz harmonic is generated, when there is a negative-sequence component.

In this paper, we will explicitly express the two-port network in each sequence and use the sequence networks for analysis.

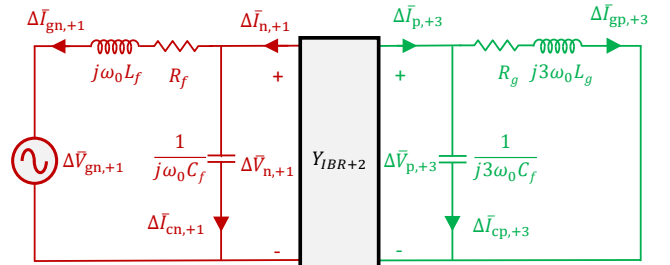
A. Positive-sequence circuit

For phasors, they are notated accordingly in the subscript.

- The positive-sequence component at the nominal frequency is notated as $p, +1$. Its coupling component is the negative sequence of -60 Hz. The phasor of that component is notated as $n, -1$.
- The negative-sequence component is notated as $n, +1$ and its coupling component is the positive-sequence 3rd harmonic, notated as $p, +3$.



(a) Positive sequence circuit.



(b) Negative sequence circuit.

FIGURE 2: The two-port representations of IBR and the associated circuits.

By setting $s = j0$ in Eq. (8), the relationship between current and voltage can be expressed.

$$\begin{bmatrix} \Delta \bar{I}_{p,+1} \\ \Delta \bar{I}_{n,-1} \end{bmatrix} = - \underbrace{\begin{bmatrix} Y_{pp}(j0) & Y_{pn}(j0) \\ Y_{np}(j0) & Y_{nn}(j0) \end{bmatrix}}_{Y_{IBR}(j0)} \begin{bmatrix} \Delta \bar{V}_{p,+1} \\ \Delta \bar{V}_{n,-1} \end{bmatrix}. \quad (9)$$

Fig. 2a represents the positive sequence circuit. Note that the IBR is represented by a two-port element in the circuit. The right port is connected to the circuit of the +60-Hz harmonics while the left port is connected to the circuit of the -60 Hz harmonic. When $s \neq j0$, the two ports are corresponding to harmonics at different frequency. $s = j0$ is a special case, since the two ports are referring to the same +60-Hz harmonic, with +60 Hz as the primary frequency, its mirror frequency is also +60 Hz, which is treated as the negative sequence of -60-Hz harmonic.

Therefore, both $\bar{V}_{p,+1}$ and $\bar{V}_{n,-1}^*$ are coefficients of $e^{j\omega_0 t}$ in the space vector expression of the voltage. The voltage phasors of the 60 Hz are their sum: $\bar{V}_{p,+1} + \bar{V}_{n,-1}^*$. Similarly, this also applies to the currents.

For the entire circuit, the KCL is as follows:

$$(Y_g + Y_c + Y_{IBR}(j0)) \begin{bmatrix} \Delta \bar{V}_{p,+1} \\ \Delta \bar{V}_{n,-1} \end{bmatrix} = Y_g \begin{bmatrix} \Delta \bar{V}_{gp,+1} \\ 0 \end{bmatrix}, \quad (10)$$

where

$$Y_c = \begin{bmatrix} j\omega_0 C_f & 0 \\ 0 & -j\omega_0 C_f \end{bmatrix},$$

$$Y_g = \begin{bmatrix} \frac{1}{R+j\omega_0 L} & 0 \\ 0 & \frac{1}{R-j\omega_0 L} \end{bmatrix}.$$

B. Negative-sequence circuit

Using Eq. (8), the two-port network expression for the negative-sequence circuit can be derived, Eq. (11).

$$\begin{bmatrix} \Delta \bar{I}_{p,+3} \\ \Delta \bar{I}_{n,+1} \end{bmatrix} = -Y_{IBR}(j2\omega_0) \times \begin{bmatrix} \Delta \bar{V}_{p,+3} \\ \Delta \bar{V}_{n,+1} \end{bmatrix}. \quad (11)$$

The equivalent circuit is designed for the negative sequence, shown in Fig. 2b, where $Y_{IBR,+2}$ represents the inverter admittance matrix in the sequence domain is evaluated for the 120 Hz perturbation. The left side of the circuit represents the negative sequence and the right side of the circuit represents the third harmonic positive sequence component. During an unbalance grid voltage dip, the grid will not inject any third harmonic voltage into the system. Hence, the third harmonic component of the grid is represented by a short circuit, and the negative sequence component of the grid voltage is represented as $\Delta \bar{V}_{gn,+1}$, Fig. 2b.

For the entire circuit, the voltage and current relationship is as follows:

$$(Y_g + Y_c + Y_{IBR}(j2\omega_0)) \begin{bmatrix} \Delta \bar{V}_{p,+3} \\ \Delta \bar{V}_{n,+1} \end{bmatrix} = Y_g \begin{bmatrix} \Delta \bar{V}_{gp,+3} \\ \Delta \bar{V}_{gn,+1} \end{bmatrix}, \quad (12)$$

where

$$Y_c = \begin{bmatrix} j3\omega_0 C_f & 0 \\ 0 & j\omega_0 C_f \end{bmatrix},$$

$$Y_g = \begin{bmatrix} \frac{1}{R+j3\omega_0 L} & 0 \\ 0 & \frac{1}{R+j\omega_0 L} \end{bmatrix}.$$

III. Validation of the two-port model

In this section, we verify the two circuits in Fig. 2. In order to have the admittance matrix of the IBR, we first measure the dq -frame admittance.

A. DQ admittance measurement

This section shows the method of extracting the dq admittance matrix from measurements. Alternatively, if the control information is transparent, the dq admittance matrix can be found through analytical derivation [28], [29]. However, this is usually not the case in the real world. Original equipment manufacturers (OEMs) usually provide black-box EMT models of IBRs. Therefore, measurement-based methods are adopted.

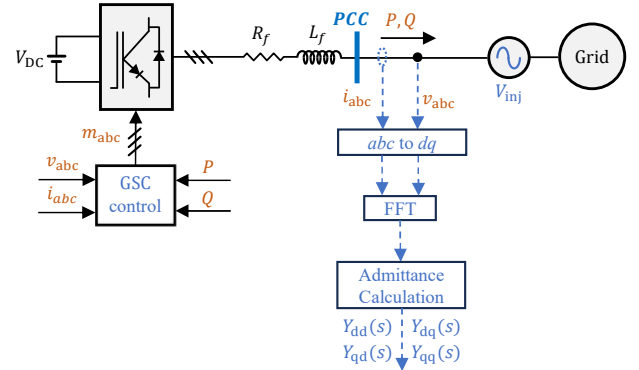
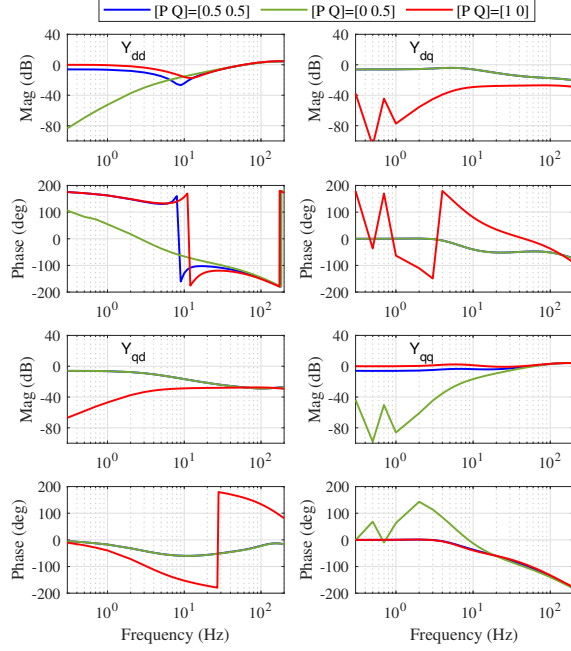


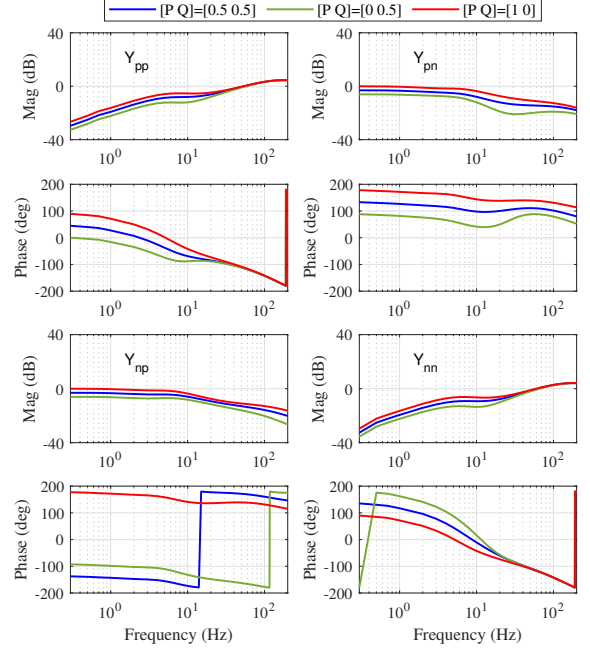
FIGURE 3: The measurement testbed for dq admittance matrix extraction.

In this paper, we extract the dq admittance through frequency scan, a popular method for obtaining non-parametric frequency-domain models. The frequency scan method is also called single-frequency injection method injection, where we perform voltage injection at a different frequency at a time. Fig. 3 shows the measurement testbed used for voltage injection and dq admittance calibration. The perturbation is applied at the point of common coupling (PCC), and the resulting admittance matrix captured includes the inverter along with the choke filter.

The perturbing frequency varies from 0.1 Hz to 200 Hz. The the current flowing out of the IBR i_t will be recorded and post-processed to have harmonic phasors extracted through fast Fourier transform (FFT). Eq. (13) is the relationship between voltage, current, and admittance in the dq -frame, where the admittance matrix is evaluated at each injected frequency by replacing s with $j2\pi f_{inj}$.



(a) dq admittance model.



(b) pn admittance model.

FIGURE 4: The admittance matrix of dq and pn at different operating conditions.

$$\begin{aligned} Y_{dd}(s) &= - \left. \frac{i_d(s)}{v_d(s)} \right|_{v_q=0}, & Y_{dq}(s) &= - \left. \frac{i_d(s)}{v_q(s)} \right|_{v_d=0}, \\ Y_{qd}(s) &= - \left. \frac{i_q(s)}{v_d(s)} \right|_{v_q=0}, & Y_{qq}(s) &= - \left. \frac{i_q(s)}{v_q(s)} \right|_{v_d=0}. \end{aligned} \quad (13)$$

Based on Eq. (13), the Bode plots of the admittance matrix in dq -frame can be obtained. Fig. 4a shows the dq domain admittance matrix. Furthermore, the Bode plots for the pn admittance matrix can be plotted and shown in Fig. 4b. For analysis of the positive- or negative- sequence circuits, the 0.1 Hz or 120 Hz component of the admittance is extracted from Fig. 4b. We use the measurements at 0.1 Hz as the approximation of the measurements at 0 Hz.

B. Validation of the two-port representation

The positive and negative-sequence circuit representations will be verified by use of an unbalanced grid voltage dip. Phase a of the grid voltage is subject to 20% voltage dip. With the grid voltage decomposed into a positive-sequence set and a negative-sequence set, two decoupled circuits are obtained and used for analysis. The analysis results are compared with the EMT testbed simulation results. The testbed shown in Fig. 1a used for this experiment.

1) Positive-sequence model validation

The process of determining the admittance matrix for the positive sequence involves employing low-frequency injection, typically at frequencies below 1 Hz. This approach allows for a comprehensive understanding of the system's behavior. As outlined in [30], the low-frequency admittance matrix sheds light on the operational dynamics of the system.

Eq. (14) describes the steady-state dq admittance when the IBR is in real and reactive power regulation control mode [30], while Eq. (15) is the sequence-domain conversion of the dq admittance matrix. These equations serve as fundamental tools in characterizing the system's response to different operational conditions.

For visualization and analysis purposes, the positive-sequence circuit configuration is depicted in Fig. 2a, providing a clear representation of the system under consideration.

Notably, when observing the system in the dq -frame, the frequency is effectively 0 Hz when steady-state operation is considered. Therefore, the derivation of the admittance matrix is performed at frequencies below 1 Hz to ensure consistency with the operational context. To verify the efficacy of this approach, the admittance matrix is specifically extracted at a frequency of 0.1 Hz, facilitating a targeted assessment of the system's behavior under realistic operating conditions.

$$Y_{+0,DQ}(j0) = \frac{1}{V^2} \begin{bmatrix} P & -Q \\ -Q & -P \end{bmatrix}, \quad (14)$$

$$Y_{+0,PN}(j0) = \frac{1}{V^2} \begin{bmatrix} 0 & P - jQ \\ P + jQ & 0 \end{bmatrix}. \quad (15)$$

The admittance matrix of the system under different operational conditions $((P, Q) = (1, 0), (0, 0.5), (0.5, 0.5))$ is illustrated in Fig. 4.

Eqs. (16) to (18) present the sequence-domain admittance matrices obtained from measurements corresponding to these varied operating conditions. Each matrix encapsulates the admittance characteristics of the system under distinct power injections, enabling a comprehensive assessment of its behavior.

$$Y_{+0,PN} = \begin{bmatrix} 0.04/-90^\circ & 0.99/0^\circ \\ 0.99/0^\circ & 0.036/-90^\circ \end{bmatrix}_{P=1, Q=0}, \quad (16)$$

$$Y_{+0,PN} = \begin{bmatrix} 0.02/180^\circ & 0.5/-90^\circ \\ 0.5/90^\circ & 0.02/180^\circ \end{bmatrix}_{P=0, Q=0.5}, \quad (17)$$

$$Y_{+0,PN} = \begin{bmatrix} 0.03/44^\circ & 0.7/-47^\circ \\ 0.7/-137.3^\circ & 0.03/45^\circ \end{bmatrix}_{P=0.5, Q=0.5}. \quad (18)$$

Utilizing the measured positive-sequence admittance matrix, calibration of the positive sequence circuit's in Fig. 2a is conducted. This validation process ensures that the circuit model accurately represents the system's behavior under various operating conditions. Table 2 presents the validation results, showcasing the agreement between simulated and calculated voltage and current. As the disturbance is small, the admittance/impedance model-based analysis can effectively capture the system's dynamic response to changing conditions.

2) Negative-sequence model validation

To verify the operation of the negative-sequence circuit during an unbalanced grid voltage dip, the negative-sequence component of the grid voltage is assessed. When the grid voltage is unbalanced, it exhibits positive-, negative-, and zero-sequence components, with the third harmonics being absent. This scenario is depicted in Fig. 2b, where the third harmonic component of the grid voltage is set to zero, and only the negative-sequence component is considered.

The PN admittance matrix can be found by converting the dq admittance at 120 Hz. The numerical values are as follows:

$$Y_{+2,PN} = \begin{bmatrix} 1.5646/-152.32^\circ & 0.1369/124.77^\circ \\ 0.1321/124.70^\circ & 1.4858/-152.80^\circ \end{bmatrix}. \quad (19)$$

The sequence-domain admittance matrix used in the negative-sequence circuit corresponds to the one evaluated at the 120 Hz frequency. The admittance matrix shown in Eq. (19) is extracted from Fig. 4b at a frequency of 120 Hz.

The circuit analysis is conducted according to Eq. (12) and Table 3 provides a comparison table that validates the

negative-sequence circuit model against the EMT simulation results. The results demonstrate that the two-port circuit model produces accurate results, confirming the validity of the negative sequence circuit model.

IV. Effect of control on sequence coupling

The previous section discusses on how third harmonic component plays a vital role in the negative-sequence circuit analysis. This component has been ignored in the single-port representation. In this section, we explain our claim of the importance of a two-port representation over a single-port representation (shown in Fig. 5). Furthermore, how controller design affects the discrepancy between the two representations is also explained.

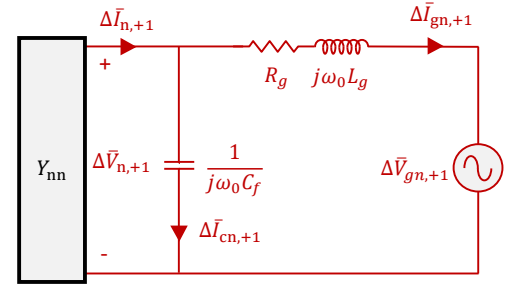


FIGURE 5: Single-port representation of an IBR integrated system for the negative sequence.

Two scenarios are used to compare the effect of control on frequency or sequence coupling manifested in the admittance matrix:

- Significant coupling: Use different values of k_p and k_i for the inner loop for d and q axis control.
- Insignificant coupling: Use same values of k_p and k_i for the inner loop for d and q axis control.

A. Scenario 1: significant coupling

The objective of this experiment is to demonstrate significant sequence coupling and its effect on calculation based on two representations. The significant coupling means that the non-diagonal terms cannot be ignored, as shown in the blue plots in Fig. 6b. When the inner current control adopts different values for its d and q axes, significant coupling may occur. The Bode plots of the admittance matrix in dq and pn are shown in Figs. 6a and 6b.

For the analysis process, the 120 Hz component of the admittance matrix is extracted from Fig. 6b. Eq. (20) shows the IBR admittance matrix. Comparing the admittance matrix of Eqs. (20) and (21), the diagonal components, the values of Y_{pn} and Y_{np} are relatively closer to the value of Y_{pp} and Y_{nn} respectively, which suggest that the negative sequence and the third harmonics are strongly coupled.

TABLE 2: Positive-sequence model validation.

	P=1, Q=0		P=0, Q=0.5		P=0.5, Q=0.5	
	EMT	Analysis	EMT	Analysis	EMT	Analysis
$\Delta I_{gp,+1}$	0.081/39.05°	0.0803/36.08°	0.0247/-90/67°	0.0253/-92.6°	0.0439/-32.99°	0.0419/-34.92°
$\Delta I_{p,+1}$	0.0802/34.96°	0.0795/33.87°	0.0396/-90.67°	0.0306/-92.06°	0.0454/-27.23°	0.0436/-40.6°
$\Delta V_{p,+1}$	0.77/169.18°	0.77/169.57°	0.0616/-179.67°	0.0616/-179.30°	0.0632/172.77°	0.0616/-174.18°

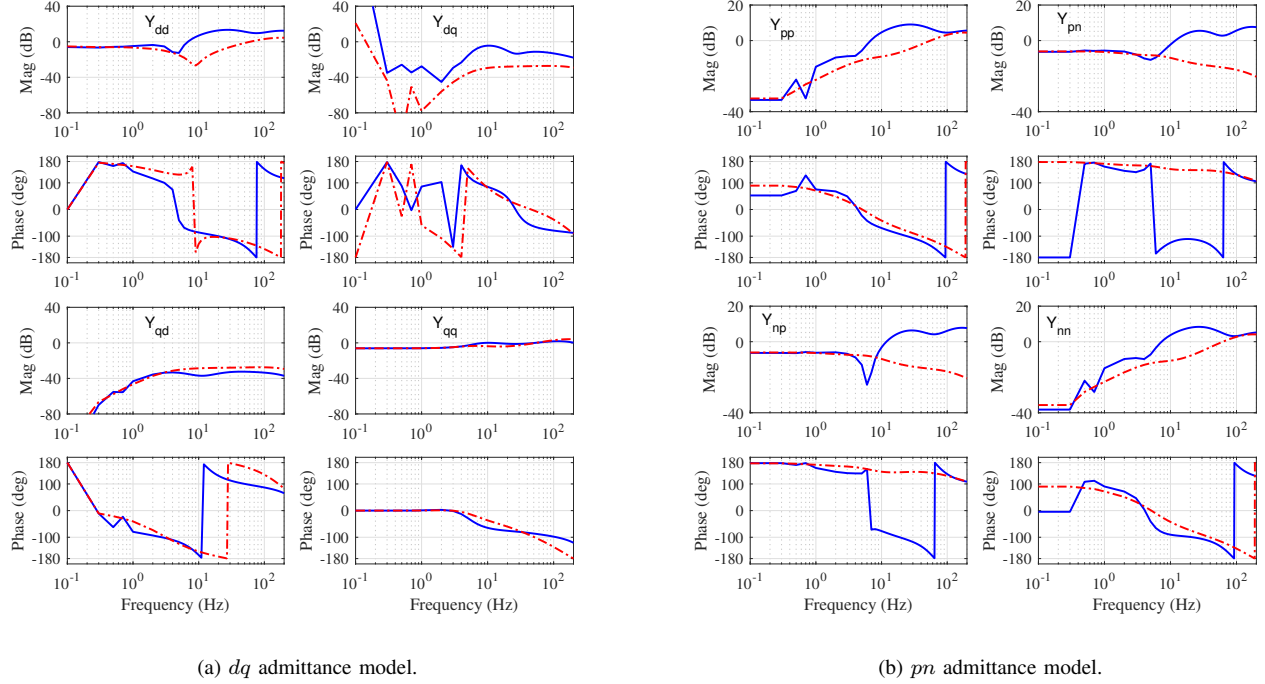
FIGURE 6: (a) dq admittance. (b) pn admittance. Red: inner current control $k_p = 0.3$ and $k_i = 5$ (the same gain of the PI controller for the d and q axis), shows insignificantly coupled IBR. Blue: $k_{pd} = 0.05$, $k_{id} = 1$ and $k_{pq} = 0.9$, $k_{iq} = 5$, shows significantly coupled IBR.

TABLE 3: Validation of negative-sequence circuit model.

	EMT	Analysis	Error(%)
$\Delta \bar{V}_{p,+3}$	0.0071/126.5°	0.0071/125.74°	0
$\Delta \bar{V}_{n,+1}$	0.074/154.9°	0.0742/153.9°	0.27
$\Delta \bar{I}_{p,+3}$	0.0069/38.43°	0.0069/37.67°	0
$\Delta \bar{I}_{n,+1}$	0.1106/2.166°	0.1166/1.97°	5.42
$\Delta \bar{I}_{gp,+3}$	0.0086/38.04°	0.0086/37.29°	0
$\Delta \bar{I}_{gn,+1}$	0.1134/4.828°	0.1195/4.487°	5.37

$$\mathbf{Y}_{+2,PN} = \begin{bmatrix} 1.5273/172.35^\circ & 1.357/146.28^\circ \\ 1.3987/148.76^\circ & 1.45/169.51^\circ \end{bmatrix}. \quad (20)$$

Fig. 7a shows the instantaneous voltage and current measured at the PCC bus and the grid bus, respectively. The plot

for the current shows harmonic components other than the fundamental components.

Table 4 compares the result of a two-port model with a single-port model. It is clear that the two-port model achieves much more accurate results compared to the single-port model. The comparison demonstrates the importance of considering a two-port model for IBR fault or unbalance operation analysis.

B. Scenario 2: insignificant coupling

The second scenario is to examine the analysis results using two circuit models when there is insignificant coupling in IBR. To create this scenario, the current controller parameters were set with the same PI control parameters for the inner loop for d and q axis respectively. The parameter of the EMT model is shown in Table 1.

TABLE 4: Comparison of EMT simulation with single port and two-port circuit for IBR with significant and insignificantly coupling.

	Significantly coupled admittance matrix			Insignificantly coupled admittance matrix		
	EMT	Two-port	Single-port	EMT	Two-port	Single-port
$\Delta I_{gn,+1}$	0.043/14.47°	0.0466/10.74°	0.0829/-27.58°	0.1134/4.83°	0.1195/4.487°	0.1123/5.2517°
$\Delta I_{gp,+3}$	0.059/103.6°	0.06/103.89°	N/A	0.0086/38.04°	0.0086/37.29°	N/A
$\Delta V_{gn,+1}$	0.0667/180°	0.0667/180°	0.0667/180°	0.0667/180°	0.0667/180°	0.0667/180°
$\Delta V_{gp,+3}$	0	0	N/A	0	0	N/A
$\Delta I_{n,+1}$	0.041/7.32°	0.0448/4.11°	0.0836/-30.66°	0.1106/2.166°	0.1166/1.97°	0.1095/2.62°
$\Delta I_{p,+3}$	0.0474/104°	0.049/104.26°	N/A	0.0069/38.43°	0.0069/37.67°	N/A
$\Delta V_{n,+1}$	0.0696/170.20°	0.0692/169.47°	0.0579/160.69°	0.074/154.9°	0.0742/153.9°	0.0737/155.43°
$\Delta V_{p,+3}$	0.0482/-168°	0.0492/-167.65°	N/A	0.0071/126.5°	0.0071/125.74°	N/A

Using the method explained in Section III, the admittance matrix of the inverter is calculated. The Bode plot of the admittance matrix show in red is extracted using frequency injection Fig. 6. Using Eq. (8) the dq domain admittance matrix is converted into sequence domain admittance matrix and presented in Fig. 6b.

For validation purposes, the admittance matrix is extracted from Fig. 6b at the frequency of 120 Hz. Eq. (21) shows the sequence domain admittance matrix at injection at 120 Hz using the parameters shown in Table 1.

$$Y_{+2,PN} = \begin{bmatrix} 1.5708/-152.8^\circ & 0.1369/124.31^\circ \\ 0.13195/124.76^\circ & 1.488/-153.30^\circ \end{bmatrix}. \quad (21)$$

The results of the EMT simulation are compared with the calculation results of the two-port circuit, Fig. 2b and the single-port network circuit, Fig. 5. In Fig. 5, $Y_{nn} = 1.488/-153.30^\circ$, is the negative-sequence admittance.

Based on the Bode plot in Fig. 6b, and Eq. (21), the coupling between the third harmonic component of the positive sequence and the fundamental component of the negative sequence is weak. As a result, the measurement of the third harmonic component is small, and hence the positive sequence third harmonic component can be ignored from the calculation. On the basis of the above observation, Fig. 5 can be used as the simplified equivalent circuit. Table 4 shows the comparison of the EMT model with analysis using two-port and single-port models. Both the single-port as well as two-port circuit will be effective for the insignificantly coupled IBR admittance matrix. Also, as analyzed above, the effect of the third harmonic component is much less in case of insignificant coupling compared to the case of significant coupling.

The EMT simulation results are shown in Fig. 7b. It can be verified that the instantaneous voltage and current waveforms are sinusoidal. This manifests that the fundamental component is dominant while the third harmonic component is negligible.

Remark 1:

While the single-port representation may be used in the weakly coupling scenarios, in general, the inclusion of

coupling frequency components in the analysis is essential. Therefore, it is clear that the two-port model shall be considered for fault and unbalanced operation analysis to enhance accuracy.

V. Discussions

A. Extend the application to IBR power plants

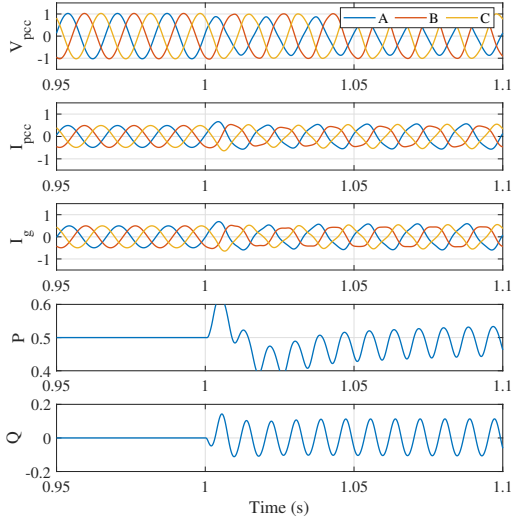
In this paper, a device-level IBR representation under fixed real and reactive power references has been developed and tested. In order to extend the method for plant-level studies, the dq -frame admittance should reflect a power plant. This requires the measurement point to be located at the point-of-interconnection (POI). With a controllable voltage source connected to the POI, the current responses towards the voltage source's perturbation reflect the entire IBR power plant's admittance characteristics. Additionally, if the POI voltage is regulated in the power plant level, direct connecting the POI to a voltage source leads the malfunctioning of the voltage control. It is suggested to have a small impedance between the POI and the voltage source. Therefore, the measured impedance of the IBR power plant includes the small impedance. The effect of the small impedance can be taken out.

B. Applicability of the two-port circuit representation

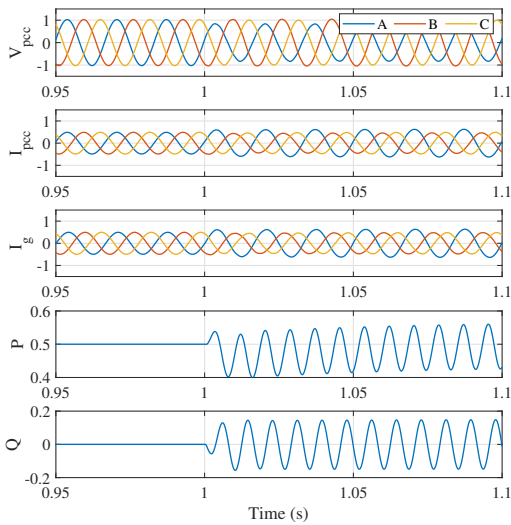
While the paper uses a grid-following IBR as an example, the method is applicable to an IBR with other types of control, e.g., grid forming. Different control schemes lead to different dq -frame admittance or impedance. Given that the dq -frame admittance/impedance of an IBR can be measured, the procedure of forming a two-port circuit will be the same regardless the internal control algorithms of a device.

Therefore, the proposed two-port circuit is feasible for many devices connected to a grid, e.g., an IBR with asymmetric dq -frame control, a synchronous generator, or an induction machine with asymmetric rotor circuit. In all three cases, a device has asymmetric dq -frame characteristics, which lead to the coupling of two harmonics that can be well represented by a two-port circuit.

A symmetric induction machine's phasor-impedance circuit was developed in the 1900s by Charles Steinmetz.



(a) Significantly coupled admittance matrix.



(b) Insignificantly coupled admittance matrix.

FIGURE 7: The figure shows the instantaneous plot of voltages, currents and power showing the difference in the output for significantly coupled and insignificantly coupled network.

Its symmetric characteristics lead to decoupled sequence-domain 2×2 admittance matrix. Therefore, for an induction machine, there is no issue of harmonic coupling and the sequence circuits are concise. On the other hand, when its rotor circuit is asymmetric, frequency coupling phenomena appear. Two-port circuit models for induction machines in such cases have been developed by Garbarino and Gross in the 1950s [31]. In 2022, the authors re-derived those circuit models and confirmed their accuracy through EMT simulation-based validation [32].

Further investigation by the senior authors shows that a synchronous generator can be represented by two-port phasor-impedance circuit as well [33].

Therefore, it can be seen that the two-port circuit representation is applicable to devices with asymmetry and experiencing frequency coupling phenomena.

VI. Conclusion

Although most of the current research on IBR representation in fault analysis ignores the mirror frequency characteristics, it is verified that inclusion of the mirror frequency component is equally important. This paper introduces a new two-port circuit model for IBR which includes the frequency coupling effect. The introduced circuit model is generalized and applicable to many devices with asymmetric characteristics, e.g. a GFL-IBR with asymmetric dq-frame control, a synchronous generator, and an induction motor with unbalanced rotor characteristic. Comparison of the analysis results against the EMT simulation results shows significant improvement in accuracy when the two-port circuit model is adopted. While this paper has a limited application scope to unbalanced operation, the proposed two-port IBR circuit will be equally insightful for quantitative analysis of transformer-converter interactions or core saturation instability.

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Rabi Shankar Kar(Member, IEEE) received the B.S degree in electrical engineering from the Biju Patnaik University of technology, Odisha, India, in 2012, and the M.S.E.E degree from the University of South Florida, Tampa, FL, USA, in 2017. He received his Ph.D degree at the Smart Grid Power System laboratory in University of South Florida in 2024. His research interests include modeling and control, harmonic analysis, and protection studies for inverter-based resources.



Zhixin Miao(Senior Member, IEEE) received the B.S.E.E. degree from the Huazhong University of Science and Technology, Wuhan, China, in 1992, the M.S.E.E. degree from the Graduate School, Nanjing Automation Research Institute (Nanjing, China) in 1997, and the Ph.D. degree in electrical engineering from West Virginia University, Morgantown, in 2002.

Currently, he is with the University of South Florida (USF), Tampa. Prior to joining USF in 2009, he was with the Transmission Asset Management Department with Midwest ISO, St. Paul, MN, from 2002 to 2009. His research interests include power system stability, microgrids, and renewable energy. Dr. Miao serves as an associate editor for IEEE Transactions on Sustainable Energy.



Lingling Fan(Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from Southeast University, Nanjing, China, in 1994 and 1997, respectively, and the Ph.D. degree in electrical engineering from West Virginia University, Morgantown, in 2001.

Currently, she is a full professor at the University of South Florida, Tampa, Florida. She was a Senior Engineer in the Transmission Asset Management Department, Midwest ISO, St. Paul, MN, from 2001 to 2007, and an Assistant Professor with North Dakota State University, Fargo, from 2007 to 2009. Her research interests include power systems and power electronics. Dr. Fan served as the Editor-in-Chief for IEEE Electrification Magazine from 2020 to 2024. Since 2026, she serves as the Editor-in-Chief of IEEE Open Access Journal of Power and Energy. Dr. Fan was elevated to the IEEE Fellow Class of 2022 for her contributions to the stability analysis and control of inverter-based resources. She received the 2024 Energy Systems Integration Group (ESIG) Excellence Award in recognition of her contributions to the analysis of power system dynamics and oscillations in power systems with inverter-based resources. In 2025, she was named the recipient of the IEEE PES Wanda Reder Pioneer in Power Award for her leadership in technical innovations in power grid stability analysis and her dedicated service to IEEE PES publications and education.