

Operating-Condition-Adaptive RLC Equivalence of Black-Boxed Inverter-Based Resources for Efficient Oscillations Replication, Elucidation, and Mitigation

Weihua Zhou, *Member, IEEE*

Abstract—The increasing integration of inverter-based resources (IBRs) into power grids, propelled by the global shift toward renewable energy, poses challenges such as sub-synchronous oscillations (SSOs). Traditional methods, including white-box theoretical models, black-box admittance measurements, and electromagnetic transient (EMT) simulations, face limitations due to opacity, the inability to identify specific instability mechanisms, and high computational demands. To overcome these limitations, this letter introduces a novel approach that leverages a minimal set of admittance measurements to construct an RLC circuit equivalence at the oscillation frequency. This method dynamically adjusts RLC parameters based on operating conditions, thereby revealing underlying instability mechanisms, efficiently determining stable operating ranges, and significantly accelerating EMT simulations. Case studies confirm the rapid replication, clear elucidation, and effective mitigation of SSO events in black-boxed IBRs, validating this approach’s effectiveness.

Index Terms—Black box, electromagnetic transient, inverter-based resource, RLC circuit, sub-synchronous oscillation.

I. INTRODUCTION

THE integration of inverter-based resources (IBRs) into modern power grids is escalating, propelled by a global shift towards renewable energy sources [1]. While IBRs bring significant benefits in terms of controllability, flexibility, and efficiency, their interactions with weak grids often lead to sub-synchronous oscillations (SSOs), as recently observed in the 17-19 Hz events in Australia’s West Murray zone [2]. Such incidents underscore the urgent need for effective strategies to replicate, elucidate, and mitigate these oscillations, thereby ensuring the stability and reliability of power systems that are increasingly dependent on IBRs.

Currently, three predominant methodologies are utilized to address the challenges posed by SSO [3], each offering unique advantages but also facing inherent limitations [4]–[14]:

- *White-Box Theoretical-Model-Based Stability Analysis* [4]–[7]: This method employs the IBR’s theoretical state-space model [4], admittance model [5], [6], or closed-loop characteristic equations [7] to elucidate the mechanisms behind instabilities and enable system stability through strategic operational adjustments. However, its utility is often undermined by the opaque, black-box nature of IBRs. The absence of transparency in internal dynamics severely restricts its applicability, particularly in scenarios where proprietary or confidential details of the systems remain undisclosed.
- *Black-Box Admittance-Measurement-Based Stability Analysis* [8]–[11]: This method was developed to address the inherent challenges of black-boxed systems. It utilizes terminal admittance data to bypass the opacity of internal configurations, effectively overcoming the lack of system transparency. However, this method struggles to identify underlying instability mechanisms because it consolidates all IBR dynamics into a single admittance profile. As a result, achieving the oscillation mitigation often involves iterative, trial-and-error adjustments of operating conditions, which can detract from its efficacy in proactive stability management.
- *Time-Domain Electromagnetic Transient (EMT) Simulation* [12]–[15]: Advanced tools such as MATLAB®/Simulink® and PSCAD™/EMTDC™ are employed to meticulously model the control loops of IBRs, facilitating accurate replication of oscillation events at specific frequencies. While this method offers profound insights into the wideband dynamics of IBRs, it is hampered by substantial computational requirements and prolonged simulation times. Consequently, these limitations reduce its viability for rapid analysis or real-time applications, especially in settings with frequently changing operational conditions.

Recognizing the limitations of existing methods, this letter introduces a novel approach tailored to efficiently replicate, elucidate, and mitigate oscillation events in black-boxed IBRs. This advanced method utilizes a minimal set of admittance measurements to construct an RLC circuit equivalence at the oscillation frequency, with dynamic parameterization of circuit elements based on operating conditions. This model not only reveals underlying instability mechanisms—a capability often absent in admittance-measurement techniques and typically reserved for white-box methods—but also analytically identifies stable operating ranges, circumventing the inefficiencies associated with trial-and-error adjustments. Additionally, this approach considerably speeds up EMT simulations, significantly enhancing traditional EMT simulation practices.

The remainder of this letter is organized as follows. Section II formulates the problem under study. Section III details the derivation of the proposed operating-condition-adaptive RLC (OCA-RLC) circuit equivalence. Section IV assesses its performance. Finally, Section V draws the conclusion.

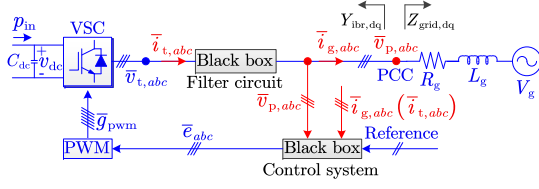


Fig. 1. Configuration of a SMIB system integrated with a black-boxed IBR.

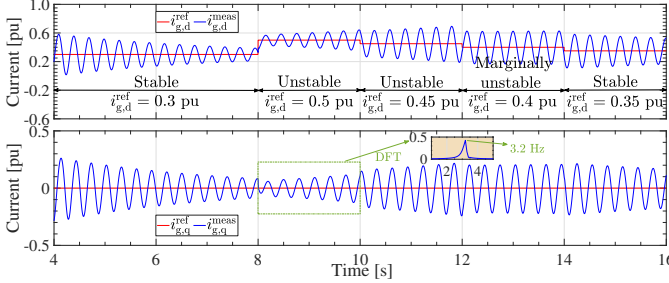


Fig. 2. Simulation results from Fig. 1 showing stability as active current varies.

II. PROBLEM FORMULATION

Fig. 1 depicts a single machine infinite bus (SMIB) system integrated with a black-boxed IBR, the details of which remain undisclosed. This grid setup includes a resistor R_g and an inductor L_g . Fig. 2 displays the simulation waveforms for the measured active and reactive grid currents ($i_{g,d}^{\text{meas}}$ and $i_{g,q}^{\text{meas}}$), conducted within a PSCADTM/EMTDCTM environment. Operating under zero reactive current injection with a short-circuit ratio (SCR) of 2 and $X_g/R_g = 6$, an increase in the active current reference $i_{g,d}^{\text{ref}}$ from 0.3 to 0.5 pu at 8 s triggers a SSO at 3.2 Hz. Subsequent modifications to the active current reference—reducing it sequentially to 0.45 pu at 10 s, 0.4 pu at 12 s, and finally to 0.35 pu at 14 s—demonstrate initial instability followed by a restoration of stability.

The significant impact of operating condition variations on system stability underscores the urgent need for a method that can rapidly replicate oscillation events, elucidate underlying instability mechanisms, and enable swift mitigation through precise operating condition adjustments. However, dependence on the black-boxed EMT model, as illustrated in Fig. 1, introduces several challenges. The detailed modeling of the IBR's control loops significantly extends EMT simulation times; for instance, a 16-s simulation depicted in Fig. 2 takes approximately 24.56 s to execute. Additionally, the opaque nature of black-boxed systems hinders the clear identification of instability mechanisms, and the process of mitigating oscillations through operating condition adjustments often becomes a cumbersome trial-and-error endeavor. To overcome these challenges, Section III introduces the OCA-RLC circuit equivalence, designed to enhance post-accident stability management in systems with black-boxed IBRs.

III. DEVELOPMENT OF THE OCA-RLC EQUIVALENCE

Fig. 3 outlines the development process for the proposed OCA-RLC circuit equivalence, structured into four key steps: admittance transfer function estimation, admittance transfer function reformulation, RLC circuit equivalence construction,

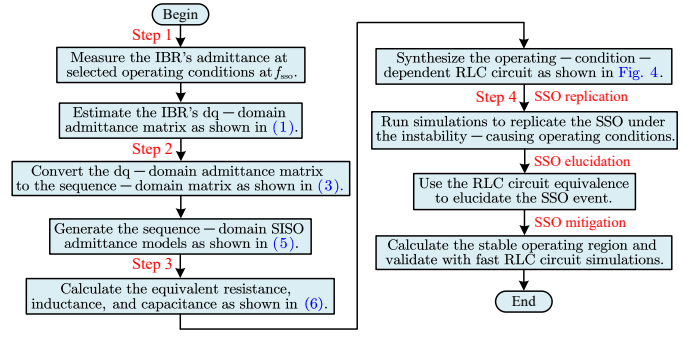


Fig. 3. The development procedure of the OCA-RLC circuit equivalence.

and SSO replication, elucidation and mitigation. Each of these steps is explained in detail in the following subsections.

A. Step 1: Admittance Transfer Function Estimation

This step involves measuring the IBR's admittance frequency responses at several arbitrary operating conditions at the SSO frequency, f_{SSO} . Subsequently, an admittance transfer function matrix at f_{SSO} is derived from these measurements, parameterized by operating conditions such as point-of-common-coupling voltage v_d , d-axis current i_d , and q-axis current i_q [16]:

$$y_{\text{ibr},\eta}^{\text{oc}} = \frac{\sum_{m=0}^M \sum_{i=0}^m \sum_{j=0}^{m-i} (b_{\eta,n} v_d^i i_d^j i_q^{m-i-j})}{\sum_{m=0}^M \sum_{i=0}^m \sum_{j=0}^{m-i} (a_{\eta,n} v_d^i i_d^j i_q^{m-i-j})}, \quad (1)$$

where η represents dd, dq, qd, or qq, and M is the highest order of the polynomial terms involving v_d , i_d , and i_q . The superscript oc indicates that this parameter is dependent on the operating condition. The coefficients $b_{\eta,n}$ and $a_{\eta,n}$ correspond to the polynomial terms in the numerator and denominator, respectively, with the index n calculated as:

$$n = \frac{m(m+1)(m+2)}{6} - \frac{i(i-2m-3)}{2} + j. \quad (2)$$

B. Step 2: Admittance Transfer Function Reformulation

In this step, the dq-domain admittance transfer matrix, as expressed in (1), is first transformed into the sequence-domain admittance transfer matrix:

$$\begin{bmatrix} y_{\text{ibr},\text{pp}}^{\text{oc}} & y_{\text{ibr},\text{pn}}^{\text{oc}} \\ y_{\text{ibr},\text{np}}^{\text{oc}} & y_{\text{ibr},\text{nn}}^{\text{oc}} \end{bmatrix} = A_{\text{reform}} \begin{bmatrix} y_{\text{ibr},\text{dd}}^{\text{oc}} & y_{\text{ibr},\text{dq}}^{\text{oc}} \\ y_{\text{ibr},\text{qd}}^{\text{oc}} & y_{\text{ibr},\text{qq}}^{\text{oc}} \end{bmatrix} A_{\text{reform}}^{-1}, \quad (3)$$

where $A_{\text{reform}} = [1, j; 1, -j]/\sqrt{2}$ is the transformation matrix. Next, by combining (3) with the grid's sequence-domain admittance transfer function:

$$\begin{bmatrix} y_{\text{grid},\text{pp}} & y_{\text{grid},\text{pn}} \\ y_{\text{grid},\text{np}} & y_{\text{grid},\text{nn}} \end{bmatrix} = \begin{bmatrix} \frac{1}{R_g + (s+jw_1)L_g} & 0 \\ 0 & \frac{1}{R_g + (s-jw_1)L_g} \end{bmatrix}, \quad (4)$$

the IBR's and grid's sequence-domain SISO admittance models can be derived as [17]:

$$y_{\text{ibr},\text{siso}}^{\text{oc}} = y_{\text{ibr},\text{pp}}^{\text{oc}} - \frac{y_{\text{ibr},\text{pn}}^{\text{oc}} (y_{\text{grid},\text{np}} + y_{\text{ibr},\text{np}}^{\text{oc}})}{y_{\text{grid},\text{nn}} + y_{\text{ibr},\text{nn}}^{\text{oc}}}, \quad (5)$$

$$y_{\text{grid},\text{siso}}^{\text{oc}} = y_{\text{grid},\text{pp}} - \frac{y_{\text{grid},\text{pn}} (y_{\text{grid},\text{np}} + y_{\text{ibr},\text{np}}^{\text{oc}})}{y_{\text{grid},\text{nn}} + y_{\text{ibr},\text{nn}}^{\text{oc}}}.$$

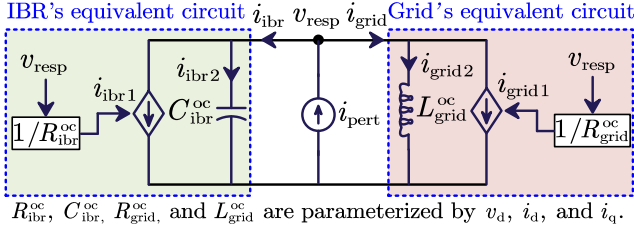


Fig. 4. Developed OCA-RLC circuit equivalence in PSCAD™/EMTDC™ for a SMIB system as shown in Fig. 1.

C. Step 3: RLC Circuit Equivalence Construction

The equivalent resistance R_{ibr}^{oc} and capacitance C_{ibr}^{oc} of the IBR, as well as the equivalent resistance R_{grid}^{oc} and inductance L_{grid}^{oc} of the grid at the SSO frequency, f_{sso} , can be derived from (5) as:

$$R_{ibr}^{oc} = \frac{1}{\Re(y_{ibr,siso}^{oc})}, \quad C_{ibr}^{oc} = \frac{\Im(y_{ibr,siso}^{oc})}{2\pi f_{sso}},$$

$$R_{grid}^{oc} = \frac{1}{\Re(y_{grid,siso}^{oc})}, \quad L_{grid}^{oc} = \frac{-1}{2\pi f_{sso} \Im(y_{grid,siso}^{oc})}, \quad (6)$$

where these parameters are functions of the operating conditions. Here, $\Re$ and $\Im$ represent the real and imaginary parts, respectively.

Fig. 4 illustrates the developed OCA-RLC circuit equivalence, which includes two voltage-controlled current sources, i_{ibr1} and i_{ibr2} , to emulate the behavior of R_{ibr}^{oc} and R_{grid}^{oc} , accounting for their potential negative values.

D. Step 4: SSO Replication, Elucidation, and Mitigation

By setting the operating conditions in Fig. 4 to match those under which the SSO occurs and applying a DC current source i_{pert} to excite the system's dynamic responses, the SSO at f_{sso} observed in Fig. 1 can be effectively replicated. Unlike the black-box model in Fig. 1, the second-order RLC circuit in Fig. 4 facilitates clearer elucidation of the SSO mechanism: the IBR's equivalent capacitance C_{ibr}^{oc} and the grid's equivalent inductance L_{grid}^{oc} resonate at f_{sso} , while the total equivalent admittance, $\frac{1}{R_{ibr}^{oc}} + \frac{1}{R_{grid}^{oc}}$, becomes negative at f_{sso} , resulting in negative damping. This oscillation mechanism reveals that SSO can be mitigated by adjusting the active power output to ensure that the total equivalent admittance remains positive at the resonance frequency, as expressed by:

$$\frac{1}{R_{ibr}^{oc}} + \frac{1}{R_{grid}^{oc}} > 0 \text{ at frequency } \frac{1}{2\pi\sqrt{C_{ibr}^{oc}L_{grid}^{oc}}}. \quad (7)$$

This condition defines the feasible range of active current output, i_d , for any given reactive current output, i_q , enabled by the operating-condition parameterization of R_{ibr}^{oc} and R_{grid}^{oc} .

IV. PERFORMANCE EVALUATION

SSO Replication: The admittance of the black-boxed IBR in Fig. 1, when connected to a grid emulated by an ideal voltage source, at seven ($M = 1$) distinct operating conditions at the

TABLE I
MEASURED ADMITTANCES OF THE IBR AT 3.2 HZ SSO FREQUENCY

(v_d, i_d, i_q)	$y_{ibr,dd}^{oc}$	$y_{ibr,dq}^{oc}$	$y_{ibr,qd}^{oc}$	$y_{ibr,qq}^{oc}$
(1.00, 0.70, -0.55)	(0.12 + j0.25)	(-0.060 + j0.064)	(0.0030 + j0.0053)	(-0.23 + j0.24)
(1.00, 0.39, -0.11)	(0.12 + j0.25)	(-0.012 + j0.010)	(0.0039 + j0.0018)	(-0.19 + j0.21)
(1.00, 0.71, 0.32)	(0.12 + j0.25)	(0.036 - j0.043)	(0.0046 + j0.0029)	(-0.23 + j0.25)
(1.00, 0.49, -0.42)	(0.12 + j0.25)	(-0.046 + j0.049)	(0.0033 + j0.00091)	(-0.20 + j0.22)
(1.00, 0.51, 0.37)	(0.12 + j0.25)	(-0.041 - j0.049)	(0.0047 + j0.0031)	(-0.20 + j0.22)
(1.00, 0.11, -0.06)	(0.12 + j0.25)	(-0.0059 + j0.0039)	(0.0040 + j0.0020)	(-0.16 + j0.17)
(1.00, 0.79, 0.80)	(0.12 + j0.25)	(0.089 - j0.10)	(0.0055 + j0.0043)	(-0.23 + j0.26)

SSO frequency of 3.2 Hz, is measured and shown in Table I. Using these measurements, the four admittance transfer functions in the form of (1) are estimated at 3.2 Hz, as shown in (8). By transforming the dq-domain admittance matrix from (8) into the sequence-domain admittance matrix in (3), and then combining it with the grid's sequence-domain admittance matrix (4) at SCR = 2 and $X_g/R_g = 6$, the IBR's and grid's sequence-domain SISO admittance models at $i_d = 0.5$ pu and $i_q = 0$ pu (where the 3.2-Hz SSO occurs in Fig. 2) can be derived as:

$$y_{ibr,siso}^{oc} = -0.0583 + j0.2898 \quad \text{at 3.2 Hz,}$$

$$y_{grid,siso}^{oc} = 0.0458 - j0.2920 \quad \text{at 3.2 Hz.} \quad (9)$$

Based on these values, the RLC circuit equivalence in Fig. 4 can be calculated from (6) as:

$$R_{ibr}^{oc} = -17.1388 \, \Omega, \quad C_{ibr}^{oc} = 0.0144 \, \text{F},$$

$$R_{grid}^{oc} = 21.8313 \, \Omega, \quad L_{grid}^{oc} = 0.1703 \, \text{H}. \quad (10)$$

Using a 1-kA DC current source, i_{pert} , as the excitation, the time-domain simulation results for the IBR's equivalent circuit current, i_{ibr} , and the grid's equivalent circuit current, i_{grid} , are presented in Fig. 5(a). A 3.2-Hz SSO is successfully replicated, precisely matching the original 3.2-Hz SSO observed in the black-boxed system shown in Fig. 1.

SSO Elucidation: The constructed RLC circuit equivalence provides key insights into the 3.2-Hz SSO. The resonance occurs between the IBR's equivalent capacitance C_{ibr}^{oc} and the grid's equivalent inductance L_{grid}^{oc} at a frequency of $\frac{1}{2\pi\sqrt{C_{ibr}^{oc}L_{grid}^{oc}}} = 3.2$ Hz. Additionally, the total conductance at 3.2 Hz, given by $\frac{1}{R_{ibr}^{oc}} + \frac{1}{R_{grid}^{oc}} = -0.013 \, \Omega$, is negative, indicating the presence of negative damping.

SSO Mitigation: Based on the stabilization criterion in (7), the maximum allowable active current output that ensures positive total conductance can be directly and analytically calculated as 0.4 pu. This is confirmed in Fig. 5(b), where constant-magnitude oscillations (i.e., indicating zero damping) are observed, consistent with the results in Fig. 2. However, in Fig. 2, this maximum active current limit was determined through a trial-and-error process.

In summary, Step 1 requires admittance measurements at only a few operating conditions for the black-boxed IBR, avoiding repetitive, time-consuming admittance measurements. Step 2 involves straightforward matrix manipulation. Step 3 constructs a simple second-order RLC circuit, and Step 4 leverages accelerated EMT simulations of the RLC circuit equivalence for SSO mitigation. This approach proves particularly valuable when testing multiple scenarios across different operating conditions.

$$\begin{aligned}
y_{ibr,dd}^{oc} &= \frac{0.125 + j0.253 + (-1.48 \times 10^{-3} - j2.86 \times 10^{-3}) v_d + (-1.72 \times 10^{-5} - j3.64 \times 10^{-5}) i_d + (3.31 \times 10^{-5} + 9.21 \times 10^{-5} i) i_q}{1 + (-1.14 \times 10^{-2} + j2.14 \times 10^{-4}) v_d + (-1.20 \times 10^{-4} - j2.14 \times 10^{-5}) i_d + (3.43 \times 10^{-4} + j3.86 \times 10^{-5}) i_q}, \\
y_{ibr,dq}^{oc} &= \frac{3.86 \times 10^{-3} - 3.88 \times 10^{-3} + (-3.84 \times 10^{-5} + j9.06 \times 10^{-6}) v_d + (2.43 \times 10^{-6} - j1.14 \times 10^{-5}) i_d + (7.83 \times 10^{-3} - j8.78 \times 10^{-3}) i_q}{1 + (-4.86 \times 10^{-5} - j2.77 \times 10^{-5}) v_d + (2.28 \times 10^{-5} - 4.94 \times 10^{-5}) i_d + (-2.44 \times 10^{-4} + j2.68 \times 10^{-4}) i_q}, \\
y_{ibr,qd}^{oc} &= \frac{-8.52 \times 10^{-3} - j2.28 \times 10^{-2} + (2.24 \times 10^{-4} + j3.35 \times 10^{-4}) v_d + (1.64 \times 10^{-5} - j1.45 \times 10^{-5}) i_d + (3.50 \times 10^{-4} + j6.30 \times 10^{-4}) i_q}{1 + (2.19 \times 10^{-2} + j2.60 \times 10^{-3}) v_d + (6.27 \times 10^{-3} + j7.30 \times 10^{-4}) i_d + (-2.82 \times 10^{-4} - j4.00 \times 10^{-5}) i_q}, \\
y_{ibr,qq}^{oc} &= \frac{-0.132 + j0.144 + (-2.74 \times 10^{-3} + j1.52 \times 10^{-3}) v_d + (-2.05 \times 10^{-2} + j1.58 \times 10^{-2}) i_d + (1.23 \times 10^{-4} - j7.96 \times 10^{-5} i) i_q}{1 + (1.28 \times 10^{-2} + j4.40 \times 10^{-3}) v_d + (2.40 \times 10^{-4} - j1.11 \times 10^{-5}) i_d + (-1.02 \times 10^{-3} + j3.35 \times 10^{-4}) i_q}, \quad (8)
\end{aligned}$$

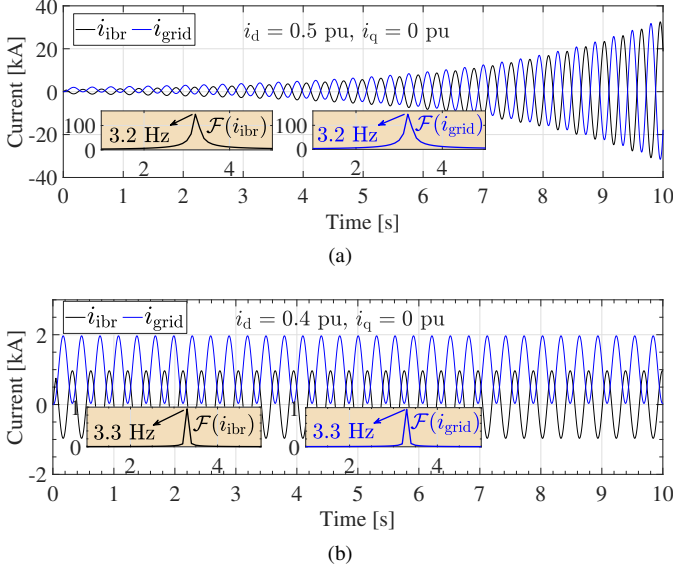


Fig. 5. Simulation results from Fig. 4 as (a) $i_d = 0.5$ pu and $i_q = 0$ pu, and (b) $i_d = 0.4$ pu and $i_q = 0$ pu.

V. CONCLUSION

This letter introduced the OCA-RLC method, a pivotal advancement in managing SSOs within IBR-rich power grids. By using only a minimal set of admittance measurements, the OCA-RLC method not only replicates and mitigates oscillation events efficiently but also clarifies instability mechanisms and provides a direct analytical pathway to stable operating conditions. This method eliminates the labor-intensive trial-and-error processes typical of traditional approaches. Moreover, it significantly accelerates EMT simulations, enabling timely and comprehensive analyses under dynamic operating conditions. Future research could aim to extend the OCA-RLC to capture wideband admittance features of IBRs, improving early-stage oscillation event detection and monitoring.

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