

# Inverter-Based Resource Oscillation Source Locating via Passivity

Zhengyu Wang<sup>\*</sup>, *Member, IEEE*, Lingling Fan<sup>†</sup>, *Fellow, IEEE*,  
Zhixin Miao<sup>†</sup>, *Senior Member, IEEE*, Deepak Ramasubramanian<sup>‡</sup>, *Senior Member, IEEE*,  
Lin Zhu<sup>‡</sup>, *Senior Member, IEEE*, Yunzhi Cheng<sup>§</sup>, *Senior Member, IEEE*

<sup>1</sup>Z. Wang is with RWE, Austin, TX 78724.

<sup>2</sup>University of South Florida, Tampa, FL 33620

<sup>3</sup>Electric Power Research Institute, Knoxville, TN 37932

<sup>4</sup>ERCOT, Taylor, TX 76754

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

This work was supported in part by the U.S. Department of Energy under Grant DE-EE-0011474.

**ABSTRACT** This paper presents locating oscillation sources in inverter-based resource (IBR) integrated systems using the oscillation flow approach. The oscillation active or reactive power flow is used as an index of passivity at a particular frequency, which is computed based on the voltage and exporting current phasors of the oscillation frequencies at the IBR point of interconnection. The oscillation power flow direction indicates the oscillation source location against the measurement point. This method is applicable when the system has a dominant natural oscillation mode in either the  $abc$  phase voltage and current or the root mean square (RMS) magnitudes. The method has been tested for four types of oscillations: subsynchronous oscillations due to a type-3 wind farm with radial connection to series compensation, low-frequency weak grid oscillations, phase-locked-loop (PLL)-induced oscillations, and plant control delay caused voltage-var oscillations. The oscillation power flow computed in either the static or the  $dq$  frame is able to detect and locate the oscillation sources in all three scenarios. Additionally, two forced oscillation scenarios are presented to demonstrate the application scope for this method.

**INDEX TERMS** Oscillation source detection, oscillation flow, inverter-based resources.

## I. INTRODUCTION

INVERTER-based resources (IBRs) have introduced many unprecedented dynamics. In a recent paper by IEEE Power & Energy Society IBR SSO task force [1], 19 real-world sub-synchronous oscillation (SSO) events were documented. Among the 19 events, Australian Energy Market Operator (AEMO) reported a 7-Hz solar oscillation event, and it took much effort by AEMO to conduct electromagnetic transient (EMT) simulation and sensitivity analyses to finally locate five solar farms as the main contributors to this event. AEMO has emphasized the importance of having fast oscillation source detection capability. Prior to the source location, it would be necessary to detect the oscillations by use of measurements with a higher sampling rate. SSOs may not be correctly identified when the oscillation frequency is higher than 15 Hz, due to the relatively low reporting rate (e.g., 30 Hz) of today's phasor measurement units (PMUs). Therefore, point-in-the-wave (PoW) measurements of kilo Hz rate are proposed for IBR SSO detection. The objective of this paper is to investigate IBR SSO detection and source

location when the high sampling rate PoW measurements are available. This measurement technology enables data analytics to be carried out in both the static  $abc$  frame and the DQ frame.

### A. State-of-the-art review of oscillation locating tools and the gap

The current source location tools are designed for forced oscillations that interact with natural electromechanical modes of very low frequency in the range of a fraction of Hz to 2 Hz. The state-of-the-art of the popular tools for forced oscillations is summarized as follows.

- Oscillation shape and magnitude method. This method is based on oscillation magnitude or oscillation mode shape. The location with the largest oscillation magnitude or mode shape absolute values is identified as the source. This method is intuitive and simple. It may not be accurate since the source location may not have the highest magnitude.

- Machine learning-based analysis, including pattern recognition, graph neural network, advanced statistical learning, etc [2]: These methods do not rely on physics or system models. They require a lot of data training and usually have poor extrapolation capability. If a pattern has not been trained, the methods lead to failure. Therefore, this method is not an applicable method for not well-studied oscillations, e.g., IBR oscillations.
- Dissipating Energy Flow (DEF) method originally proposed in [3] have been adopted by ISO New England [4] as well as other research projects, e.g., [5], to locate forced oscillation sources and/or electromechanical oscillation sources. This tool calculates the DEF based on PMU measurements (voltage magnitude, phase angle, real and imaginary power from the device to the grid) to detect the oscillation source based on DEF's rate. A positive rate implicates the device behind the measurement point is a source.
- Cross-power spectral density (CPSD) method [6]. With voltage magnitude and angle as input, real and reactive power as the output, CPSD is computed. CPSD can be viewed as the frequency domain DEF method. If the output leads input signal, the device is viewed as the source of oscillations. The branch with the largest imaginary part of CPSD is deemed as a source, and a comparison of the power spectral density of active and reactive power is used to identify the source type. This method requires a long window of data for adequate frequency resolution.

**Gap** It can be seen that for IBR oscillation source location, there are at least two significant gaps. First, there are insufficient case studies and useful data sets that capture the essence of many types of IBR oscillations. Existing papers in this aspect typically focus on only a single type of oscillations, e.g., [7], leaving the general applicability of any proposed method untested across many other events.

The second gap is that many methods have limited capabilities. For example, when tested against IBR-integrated systems, the capability of the DEF method is found to be limited. In our prior collaboration with ISO New England using [8], the conventional DEF approach was examined and found to succeed in detecting oscillations in conventional generator systems but fail in IBR-integrated systems. Experiments conducted in [8] show that DEF works well only if the sources can be viewed as a voltage source. Furthermore, in [8] the DEF expression is examined for its underlying assumption of voltage source representation. This finding resonates with the findings from the other researchers on DEF. In [9], DEF fails to detect the source when the automatic voltage regulator (AVR) oscillation was applied. In [10], the authors found that if the oscillation is originated from the excitation voltage, DEF fails to identify the generator as a source. In [11], the authors conducted the DEF analysis of a TCSC and a STATCOM for low-frequency oscillations. When a grid-following STATCOM operates in

reactive power control, DEF again has difficulty to identify the source correctly.

In the IBR scenarios, IBRs are more aligned to a current source in the subsynchronous frequency region. Therefore, the DEF method has limited use for IBR associated oscillations. Since the CPSD approach is similar to DEF, this method is also not applicable to IBR oscillations.

The goal of this paper is to fill the two significant gaps in IBR oscillation source location. First, we present four distinct type of oscillations generated by three EMT testbeds. We also developed a passivity-based oscillation source locating method based on Point-on-Wave (PoW) measurement data.

## B. Passivity-Based Approach

In the type-3 wind farm subsynchronous resonance (SSR) scenario, it is now known that the equivalent rotor resistor being negative at the SSR frequency is the main contributor to SSR [12], [13]. Prior research has also shown that PLL introduces negative resistance in the  $qq$  component of the IBR impedance [14], and oscillations may occur in the low grid strength conditions. Therefore, we propose to use negative resistance as an index to find oscillation sources. We term that a positive resistance indicates “passivity”, while a zero or negative resistance indicates “non-passivity”.

On the other hand, some other types of oscillations are not caused by negative resistance. One such oscillation is voltage-var oscillations due to IBR power plant voltage control and communication delay, as presented and analyzed in [15]. For an inductive grid, injecting var increases voltage, while absorbing var reduces voltage. The voltage and var relationship is as follows:  $\Delta V \approx X_g \Delta Q$ , where  $X_g$  is the grid reactance.

The relationship holds for small deviation. For voltage oscillations originated from an IBR, then this relationship also means that the oscillation components in the voltage and the exporting reactive power of the IBR are in phase. In the case that an IBR mitigates such voltage oscillations, then the voltage and the reactive power injection to the grid should be out of phase. This type of identification principle has been applied in a real-world oscillation event in Australia west Murray zone, where 7-Hz oscillations appeared in the transmission network's voltage magnitudes. The influencing IBRs are identified by examining whether the voltage and reactive power from an IBR are in phase [16].

Therefore, in voltage-var oscillations, passivity means that the component behaves like an inductive component absorbing reactive power, while non-passivity means that the component behaves like a capacitive component generating reactive power.

When the system has a single dominant oscillation mode, passivity can be easily checked by the relationship between the voltage phasor and the current (flowing out) phasor measured at the terminal of a device. From the two phasors, a complex active is formed. The real part is related to

the energy output from the device. If the real power is greater than 0, this device generates the oscillations. In addition, a complex reactive power is also formed with its real part used for passivity check. If the reactive power is greater than 0, this device generates the volt-var oscillations. The fundamental concept is similar to the harmonic power flow used in the field of power system harmonics [17] and wideband oscillation monitoring technology in [18].

### C. Our contributions

**First**, a thorough examination of four distinct IBR oscillation types has been presented. Compared to the majority of oscillation source location literature focusing on one type of oscillations only (e.g., forced oscillations of electromechanical nature, or one type of IBR oscillations), we present a thorough examination by demonstrating the oscillation flow approach on four types of IBR-associated oscillation locating, including Type-3 wind SSO, weak grid oscillations, PLL-related oscillations, and plant-level control interaction in multi-IBR system.

**Second**, a rigorous harmonic flow computation in both the static and the rotating frame for cross-validation has been proposed. We refine the harmonic flow method to improve its accuracy by the inclusion of frequency coupling phenomena caused by the unsymmetric IBR control implemented in the  $dq$  frame [19]. To this end, not only  $abc$ -frame measurements but also  $dq$ -frame measurements have been dealt with. The frequency coupling issues are taken care of by the treatment of the primary and mirror frequency modes as a whole. This approach complements the conventional harmonic power flow computing approach, which focuses on the phase domain only. Through all the demonstrated case studies, the oscillation flow-based method shows the capability of successful detectin oscillation source locations regardless of the system types or oscillation characteristics. As a comparison, only the  $abc$ -frame measurements have been used in [7], [20] for computing. While [21] has examined measurements in both frames, the indices developed in [21] are absolute values, which help identify participation factors but does not distinct sources or sinks.

By no means are we claiming that the proposed method is a one-fit-all solution to locating all oscillations. The limitation of the method is also examined. We demonstrate its limitation by testing two forced oscillation scenarios. The proposed method can correctly find the source in one scenario while failing to find the source in another scenario. Explanation on why the oscillation flow-based method may fail is also offered.

### D. Structure

In the remainder of the paper, Section II describes the proposed oscillation active power flow, compared with the DEF method. Section III presents oscillation source detection experiments conducted in three different EMT simulation testbeds and the source locating results by use of the

conventional DEF approach and the proposed approach. The application scope of the proposed approach is further discussed in Section IV. Section V concludes the paper.

## II. Oscillation Source Locating Approaches

### A. Oscillation Flow Approach

Energy is equal to the time integral of instantaneous power. Based on Parseval's theorem, energy can be computed by use of frequency-domain phasors and oscillation active power [17]. Thus, the energy flow in a time period,  $W$ , can be expressed as follows:

$$W = \int_{t_0}^{t_1} p dt = \int_{t_0}^{t_1} (P_f + \hat{P}_h) dt \quad (1)$$

where the total oscillation active power is  $\hat{P}_h = P_{h1} + P_{h2} + \dots + P_{hn}$ , where all the oscillation active power are combined. Subscripts  $f$  and  $h$  are adopted to differentiate the fundamental active power and oscillation active power, respectively. The oscillation active power flow direction can tell the oscillation source's relative location compared to the point of measurement.

This concept is straightforward. A special example is the real power calculation based on the fundamental frequency components. This power flow indeed is used to indicate energy flow at steady state. During oscillation scenarios, the system has not only the fundamental component, but also the oscillation component. In addition, many times an oscillation mode originated from the IBR's control  $dq$  frame results in two oscillation modes in the  $abc$  phase domain. Therefore, a critical technique to deal with IBR oscillations is to examine both the  $dq$  frame and the  $abc$  phase domain and aggregate two related modes together in computation. This technical will be demonstrated in the case studies.

#### 1) $abc$ frame processing

In the  $abc$  frame, the instantaneous power has the following expression:

$$p = v_a i_a + v_b i_b + v_c i_c \quad (2)$$

The oscillation flow for  $h_1$  component and its per unit system are expressed as follows.

$$P_{h_1} = 3 \operatorname{Re}(\bar{V}_{h_1} \bar{I}_{h_1}^*), \text{ text in physical unit} \\ Q_{h_1} = 3 \operatorname{Im}(\bar{V}_{h_1} \bar{I}_{h_1}^*) \text{ in physical unit} \quad (3)$$

$$P_{h_1} = \operatorname{Re}(\bar{V}_{h_1} \bar{I}_{h_1}^*), \text{ in per unit} \\ Q_{h_1} = \operatorname{Im}(\bar{V}_{h_1} \bar{I}_{h_1}^*) \text{ in per unit} \quad (4)$$

where  $\bar{V}_{h_1}$  and  $\bar{I}_{h_1}$  are voltage and current phasors of  $h_1$  oscillation components in phase  $a$  voltage and current. For example, if the phase current has both the fundamental harmonic component of 60 Hz and a sustained oscillation at 20 Hz,  $h_1$  refers to the 20-Hz component.  $\bar{V}_{h_1}$  and  $\bar{I}_{h_1}$  are the phasors corresponding to the  $h_1$  component in voltage and current. The magnitudes of the phasors are the root mean square (RMS) of the component.

## 2) $dq$ frame processing

The  $dq$  frame (the  $q$ -axis leading the  $d$ -axis) is a synchronous reference frame with a constant rotating speed. When the system is in steady state, all the  $dq$  frame measurements are constants. However, if oscillations of  $f$  Hz originate from the  $dq$  frame, the  $dq$  frame measurements consist of both dc values and oscillation frequency at  $f$  Hz.

The instantaneous real power's expression in the  $dq$  frame is as follows:

$$p = \frac{3}{2} (v_d i_d + v_q i_q), \quad q = \frac{3}{2} (-v_d i_q + v_q i_d) \quad (5)$$

Therefore, for  $h_1$  oscillating components' phasors, the oscillation power flow and its per unit system can be found as

$$\begin{aligned} P_f &= \frac{3}{2} \operatorname{Re} (\bar{V}_d \bar{I}_d^* + \bar{V}_q \bar{I}_q^*), \text{ in physical unit} \\ Q_f &= \frac{3}{2} \operatorname{Re} (-\bar{V}_d \bar{I}_q^* + \bar{V}_q \bar{I}_d^*) \text{ in physical unit} \\ P_f &= \frac{1}{2} \operatorname{Re} (\bar{V}_d \bar{I}_d^* + \bar{V}_q \bar{I}_q^*), \text{ in per unit} \\ Q_f &= \frac{1}{2} \operatorname{Re} (-\bar{V}_d \bar{I}_q^* + \bar{V}_q \bar{I}_d^*), \text{ in per unit.} \end{aligned} \quad (6)$$

where  $\bar{V}_d$ ,  $\bar{V}_q$ ,  $\bar{I}_d$ ,  $\bar{I}_q$  are the phasors of the  $f$  oscillating components in  $v_d$ ,  $v_q$ ,  $i_d$  and  $i_q$ .

## 3) Frequency coupling

Frequency coupling phenomena have been observed in IBR systems. Inverter controls are often implemented in the  $dq$  frame, and oscillations originating from those inverter control show as a single mode at  $f$  Hz in the  $dq$  frame. In the  $abc$  frame, sideband oscillations appear:  $(60 + f)$  Hz and  $(60 - f)$  Hz. Ref. [22] has shown a few examples of frequency coupling phenomena. In these scenarios, the two oscillating components at  $(60 + f)$  Hz and  $(60 - f)$  Hz should be treated as a whole. Therefore, the total real power of the oscillation should be  $P_{f\text{Hz}}$  computed from the  $dq$  frame, which is identical to  $P_{(60+f)\text{Hz}} + P_{(60-f)\text{Hz}}$  from the  $abc$  frame. This approach of calculation is also applicable to the reactive power calculation.

## B. Conventional Dissipating Energy Flow Method

As one of the popular oscillation source locating approaches, the conventional DEF method computes the dissipated energy flow from the voltage and current measurements collected at the point of interconnection (POI). The definition of dissipated energy is the integral of the current phasor's conjugate over the voltage phasor [3], which is expressed as follows:

$$W = \int \bar{I}^* d\bar{V}, \quad (7)$$

where  $\bar{V} = V e^{j\theta}$ ,  $\bar{I}^* = (P + jQ)/(V e^{j\theta})$ , and  $d\bar{V} = e^{j\theta} dV + jV e^{j\theta} d\theta$  (where  $P$ ,  $Q$ ,  $V$ ,  $\theta$  are the real power, reactive power, voltage magnitude, and voltage angle are measured at the POI bus).

(7) can also be expressed as follows:

$$\begin{aligned} W &= \int \frac{P + jQ}{V e^{j\theta}} (e^{j\theta} dV + jV e^{j\theta} d\theta) \\ &= \underbrace{\int (-Q) d\theta}_{W_{Q-\theta}} + \underbrace{\int \frac{P}{V} dV}_{W_{P-V}} + j \left( \underbrace{\int P d\theta}_{W_{P-\theta}} + \underbrace{\int \frac{Q}{V} dV}_{W_{Q-V}} \right) \end{aligned} \quad (8)$$

As shown in (8), the complex DE has four components, which associate  $P$  and  $Q$  to  $V$  and  $\theta$  respectively.

## C. Difference between the proposed approach and DEF

It can be seen clearly the proposed approach deals with the oscillation voltage and current and has a very clear physical interpretation. DEF is originally defined as

$$F = \Delta P \Delta \omega + \Delta Q \frac{\Delta \dot{V}}{V},$$

where  $P$ ,  $Q$ ,  $V$  are the generator's exporting real power, reactive power, and terminal voltage, and  $\omega$  is the generator's rotating speed [3], [23], [24]. This definition aligns with a physical interpretation of mechanical dissipation [3]. Based on its original definition, this DEF is applicable for angle and torsional oscillations. In Section III, we will demonstrate the proposed method and the DEF for comparison.

## III. Case Study

To examine the proposed oscillation flow approach, three sets of experimental testbeds are implemented in the EMT simulation environment carried out via MATLAB/Simscap specialized power systems toolbox. Altogether, four different types of natural mode oscillations including SSR caused by type-3 wind farms, low-frequency weak grid oscillations, PLL-induced oscillations, volt-var oscillations, as well as two types of forced oscillations are demonstrated, and the detection processing is presented in detail.

### A. Oscillations in Type-3 wind farm system

As shown in Fig. 1, a 9 MW wind farm that consists of 6 identical 575 V, 1.5 MW turbines is aggregated and represented as one doubly-fed induction generator (DFIG) average model and connected to a 120 kV power grid through a 30-km feeder with two step-up transformers (one 575-V/25-kV and the other one 25-kV/120-kV). The 120-kV circuit is a Thévenin equivalent circuit rather than a single transmission line. Consequently, the total inductive impedance represented by the Thévenin equivalent is significantly greater than that of an individual transmission line. This example testbed has been presented in [25].

The testbed is modified based on Simscap's demonstration model, the DFIG Average Model, which is developed by Richard Gagnon of Hydro-Quebec. On the high-voltage transmission side, a series capacitor with an equivalent impedance of 100  $\Omega$  is inserted in parallel with another line.

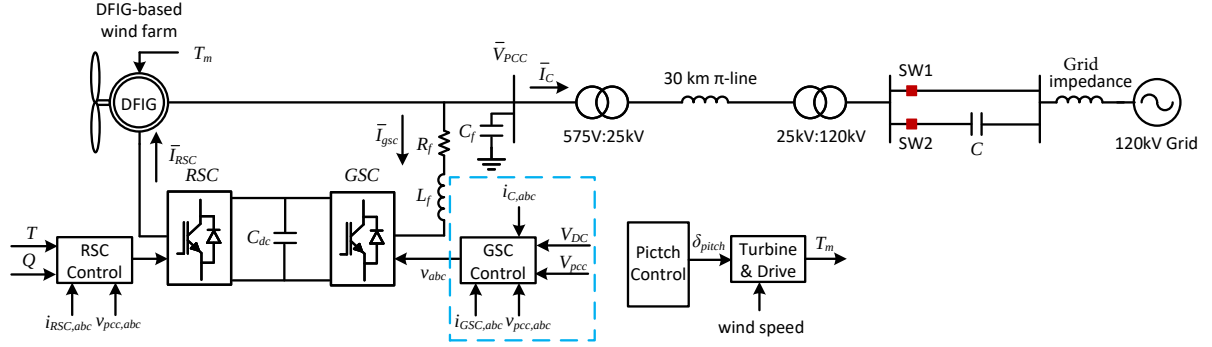


FIGURE 1: Grid-connected Type-3 wind farm system topology.

The base voltage and power are selected as 120 kV and 10 MVA. The line impedance is 0.278 p.u., and the capacitor impedance is 0.0694 p.u., which leads to an equivalent 25% series compensation (SC) ratio. Considering the wind farm's stator and rotor inductance, the overall circuit inductive impedance is much greater (0.618) and the SC ratio of the entire circuit is about 11.24%. The SSR frequency is approximately  $\sqrt{SC}$  of the nominal frequency. In this case, the oscillation frequency should be  $\approx \sqrt{0.1124} \times 60$  Hz (or 20.11 Hz).

Fig. 2 presents the dynamic event designed in this paper: initially, the series capacitor is shorted as the lower line is closed. At 15 s, the uncompensated line is tripped, and the wind farm is then radially connected to the series capacitor. The dynamic response of the system is collected at the 575-V point of common coupling (PCC) bus and presented in Fig. 2a, including three-phase voltage and current measurements, real power, dc-side voltage, and rotor speed. Based on the time-domain results, poorly damped oscillations are observed in the measurements of instantaneous voltages and currents, dc-link voltage, and rotor speed. According to the FFT analysis performed on the Phase A voltage between 16 s and 20 s, which is shown in Fig. 2c, a 20.75-Hz oscillation appears. This oscillation is the typical subsynchronous resonance (SSR) caused by the negative resistance of DFIG in the frequency region.

From the machine rotor speed measurement shown in Fig. 2a, the wind turbine slowed down immediately when the event occurred, implicating kinetic energy release from the rotor to the grid. This fact again implicates that the SSR causes energy flow from the DFIG to the grid. For this scenario, it is known that the type-3 wind is the source of oscillations. Based on the collected terminal measurement, oscillation power flow is computed.

First, the active power flow is calculated from both fundamental frequency components and oscillation components extracted from measurements on *abc* frames via 4. The fundamental frequency component's active power is 0.9113 p.u., and the 20.75-Hz oscillating component active power flow is 0.0192 p.u.. And the active power flow directions of

both components are from DFIG to the grid, which indicates that the 20.75-Hz oscillation source location is at the DFIG side. All phasors and computed active power flows are listed in Table 1.

Afterwards, the *dq*-frame voltage and current components at the PCC bus are extracted on the grid-reference frame and plotted in Fig. 2b, and their FFT analysis results are presented in Fig. 2d. 39.25-Hz and 118-Hz of oscillation components are detected in the *dq* frame, and the 39.25-Hz component is found dominant. The 39.25-Hz oscillation are also observed in the dc-link voltage.

The active power flows computed from the oscillation phasor extracted from *dq* voltage and current components are also listed in Table. 1. By applying 6, the active power of the 39.25-Hz component is  $P_{39.25} = 0.0192$  p.u.. The combined oscillation flows' real power is 0.0192 p.u., which is identical to the *abc* frame harmonic flow's real power. On the other hand, the *dq* frame oscillations' flow is also found to be from DFIG to the grid. According to the oscillation flow results in both *abc* and *dq* frames, the DFIG is identified as the source of oscillations. It can also be seen that the *abc* and *dq* frame analysis results agree with each other. The reactive power flows from the grid to the DFIG based on the results from both frames. This is understandable since the transmission network has a capacitor. In the subsynchronous frequency region, the transmission line is capacitive, generating reactive power, while the DFIG is inductive absorbing reactive power. Therefore, the computed result of reactive power flow is reasonable.

*Remark:* It can be seen that the DFIG wind farm in the 20-Hz region appears as an inductive component with negative resistance.

As a comparison, the conventional DEF approach is applied to detect the oscillation source location. The detection results are presented in Fig. 3. As  $W_{DEF}$  becomes more negative, it is indicated that the oscillation source is opposite to the energy flow direction. Based on DEF, DFIG is not the source of oscillation. DEF *fails* to identify the correct source of SSR.

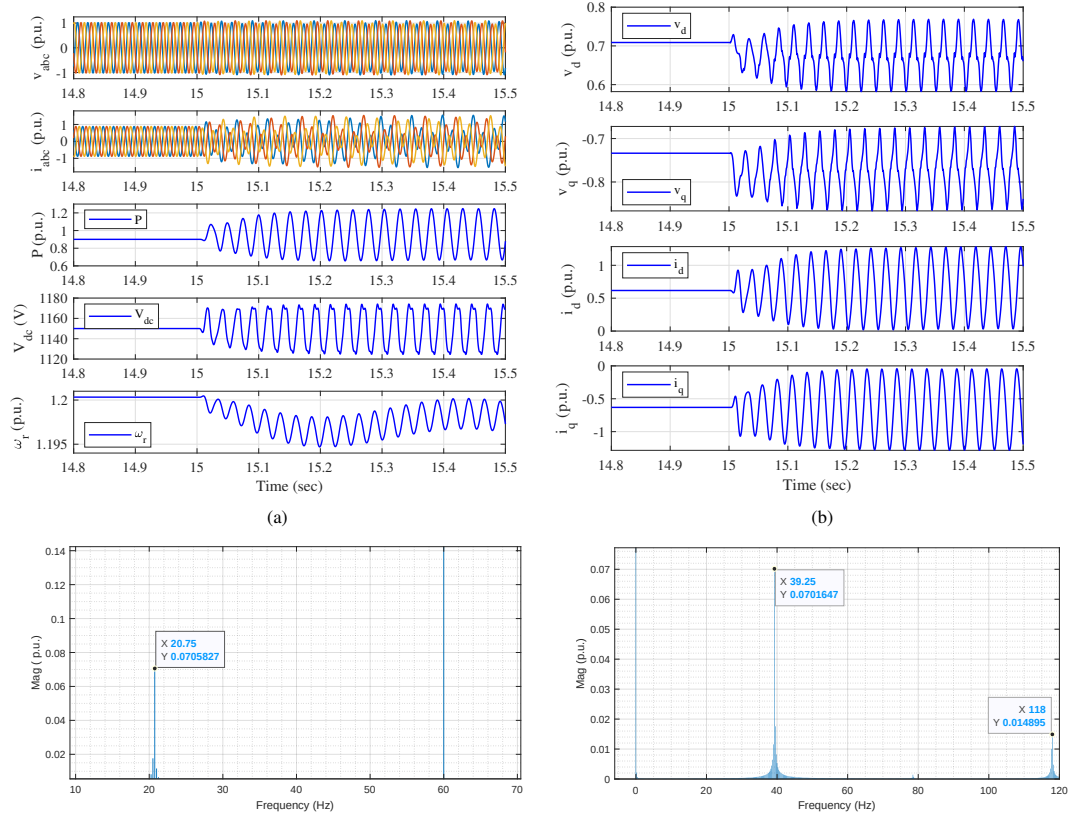


FIGURE 2: EMT simulation results and FFT analysis results for the type-3 wind farm system. (a) At 15 sec, the series compensated line is switched on and the non-compensated line is open. Oscillation is observed. (b) Voltage and current  $dq$  components extracted based on the grid reference frame. (c) FFT analysis of  $abc$  frame voltage measurement from 16 s to 20 s. (d) FFT analysis of  $d$ -axis voltage component from 16 s to 20 s.

TABLE 1: Type-3 Wind Oscillation Source Locating

| $abc$ frame component | Voltage Phasor (p.u.)                                                              | Current Phasor (p.u.)                                                              | Power (p.u.)                                         | Flow Direction                                                   |
|-----------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------|------------------------------------------------------------------|
| 60 Hz                 | $\bar{v}_a = 1.0342 \angle -49.5^\circ$                                            | $\bar{i}_a = 0.8812 \angle -48.8^\circ$                                            | $P_{60} = 0.9113$                                    | <b>DFIG</b> $\rightarrow$ Grid                                   |
| 20.75 Hz              | $\bar{v}_a = 0.0706 \angle 226.3^\circ$                                            | $\bar{i}_a = 0.5666 \angle -72.2^\circ$                                            | $P_{20.75} = 0.0192$<br>$Q_{20.75} = -0.0352$        | <b>DFIG</b> $\rightarrow$ Grid<br>Grid $\rightarrow$ <b>DFIG</b> |
| $dq$ frame component  | Voltage Phasor (p.u.)                                                              | Current Phasor (p.u.)                                                              | Real Power (p.u.)                                    | Flow Direction                                                   |
| DC                    | $v_d = 0.6717$<br>$v_q = -0.7863$                                                  | $i_d = 0.5802$<br>$i_q = -0.6633$                                                  | $P_{dc} = 0.9113$                                    | <b>DFIG</b> $\rightarrow$ Grid                                   |
| 39.25 Hz              | $\bar{v}_d = 0.0702 \angle 219.3^\circ$<br>$\bar{v}_q = 0.0714 \angle -42^\circ$   | $\bar{i}_d = 0.5612 \angle 161.1^\circ$<br>$\bar{i}_q = 0.5736 \angle 253.5^\circ$ | $P_{39.25} = 0.0192$<br>$Q_{39.25} = -0.0351$        | <b>DFIG</b> $\rightarrow$ Grid<br>Grid $\rightarrow$ <b>DFIG</b> |
| 118 Hz                | $\bar{v}_d = 0.0149 \angle -73.8^\circ$<br>$\bar{v}_q = 0.0131 \angle 202.8^\circ$ | $\bar{i}_d = 0.0224 \angle 196.4^\circ$<br>$\bar{i}_q = 0.0126 \angle 126.8^\circ$ | $P_{118} = 2.1 \times 10^{-5}$<br>$Q_{118} = 0.0002$ |                                                                  |

### B. Weak grid oscillations and PLL-related oscillations

In the second testbed, two types of oscillations will be created, and measurements will be used for source locating. In the prior research of the team [26]–[28], several types of weak grid oscillation associated with IBRs have been identified. Oscillations may appear when the power exporting level increases due to dynamic voltage instability [29]. Also stability can be worse at a lowered power exporting level due to insufficient damping of PLL [27]. The same EMT simulation testbed used in [27], [28] is adopted in this

paper to provide oscillations to examine the source location detection by oscillation flow analysis. The circuit topology of the study system is shown in Fig. 4, where a single IBR is connected to the power grid through an RL choke filter, a shunt capacitor, and an RL transmission line. To indicate a weak grid connection, a long line is assumed and reflected by a large line impedance.

The inverter control applied is the grid-following control that regulates the PCC bus exporting real power and ac voltage magnitude. Fig. 5 presents the control structure in

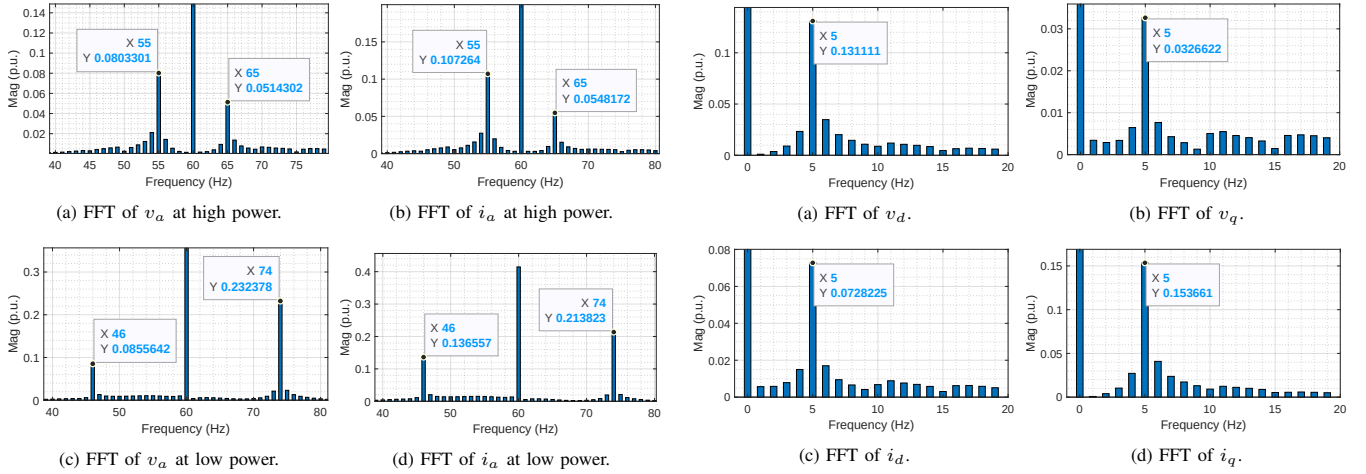


TABLE 2: PLL-related Oscillation Source Locating - High Power

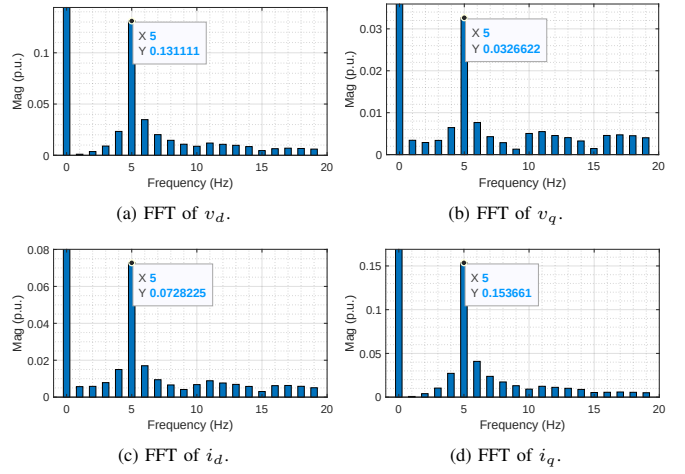
| <i>abc</i> frame component | Voltage Phasor (p.u.)                                                            | Current Phasor (p.u.)                                                            | Power (p.u.)                     | Flow Direction                                   |
|----------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------|--------------------------------------------------|
| 60 Hz                      | $\bar{v}_a = 0.9974\angle -58.9^\circ$                                           | $\bar{i}_a = 1.2752\angle 47.4^\circ$                                            | $P_{60} = 1.2463$                | <b>Inverter</b> → Grid                           |
| 55 Hz                      | $\bar{v}_a = 0.0803\angle -42.3^\circ$                                           | $\bar{i}_a = 0.1073\angle 241.1^\circ$                                           | $P_{55} = 0.002$                 | <b>Inverter</b> → Grid                           |
| 65 Hz                      | $\bar{v}_a = 0.0514\angle 55.6^\circ$                                            | $\bar{i}_a = 0.0548\angle -22.6^\circ$                                           | $P_{65} = 5.8 \times 10^{-4}$    | <b>Inverter</b> → Grid                           |
| <i>dq</i> frame component  | Voltage Phasor (p.u.)                                                            | Current Phasor (p.u.)                                                            | Real Power (p.u.)                | Flow Direction                                   |
| DC                         | $v_d = 0.5153$<br>$v_q = 0.8538$                                                 | $i_d = 0.8626$<br>$i_q = 0.9396$                                                 | $P_{dc} = 1.2467$                | <b>Inverter</b> → Grid                           |
| 5 Hz                       | $\bar{v}_d = 0.1311\angle 137.4^\circ$<br>$\bar{v}_q = 0.0327\angle 201.8^\circ$ | $\bar{i}_d = 0.0728\angle 180.5^\circ$<br>$\bar{i}_q = 0.1537\angle -48.2^\circ$ | $P_5 = 0.0026$<br>$Q_5 = 0.0111$ | <b>Inverter</b> → Grid<br><b>Inverter</b> → Grid |

TABLE 3: PLL-related Oscillation Source Locating - Low Power

| <i>abc</i> frame component | Voltage Phasor (p.u.)                                                          | Current Phasor (p.u.)                                                           | Power (p.u.)                         | Flow Direction                                   |
|----------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------|--------------------------------------------------|
| 60 Hz                      | $\bar{v}_a = 1.0236\angle 16.5^\circ$                                          | $\bar{i}_a = 0.4146\angle 35.9^\circ$                                           | $P_{60} = 0.4003$                    | <b>Inverter</b> → Grid                           |
| 46 Hz                      | $\bar{v}_a = 0.0856\angle 260^\circ$                                           | $\bar{i}_a = 0.1366\angle 186.2^\circ$                                          | $P_{46} = 0.0033$                    | <b>Inverter</b> → Grid                           |
| 74 Hz                      | $\bar{v}_a = 0.2324\angle 137.8^\circ$                                         | $\bar{i}_a = 0.2138\angle 59^\circ$                                             | $P_{74} = 0.0096$                    | <b>Inverter</b> → Grid                           |
| <i>dq</i> frame component  | Voltage Phasor (p.u.)                                                          | Current Phasor (p.u.)                                                           | Real Power (p.u.)                    | Flow Direction                                   |
| DC                         | $v_d = 0.9808$<br>$v_q = 0.2916$                                               | $i_d = 0.3356$<br>$i_q = 0.2424$                                                | $P_{dc} = 0.3998$                    | <b>Inverter</b> → Grid                           |
| 14 Hz                      | $\bar{v}_d = 0.3049\angle 218^\circ$<br>$\bar{v}_q = 0.173\angle 155.4^\circ$  | $\bar{i}_d = 0.2001\angle 187.5^\circ$<br>$\bar{i}_q = 0.2971\angle 34.1^\circ$ | $P_{14} = 0.0129$<br>$Q_{14} = 0.06$ | <b>Inverter</b> → Grid<br><b>Inverter</b> → Grid |
| 28 Hz                      | $\bar{v}_d = 0.0188\angle 218^\circ$<br>$\bar{v}_q = 0.0351\angle 111.5^\circ$ | $\bar{i}_d = 0.0377\angle 96.5^\circ$<br>$\bar{i}_q = 0.0196\angle 112.6^\circ$ | $P_{28} = 1.2 \times 10^{-4}$        | <b>Inverter</b> → Grid                           |

FIGURE 7: FFT analysis of *abc* frame PCC bus voltages and currents: (a)  $v_a$  in high power oscillations; (b)  $i_a$  in high power oscillations; (c)  $v_a$  in low power oscillations; (b)  $i_a$  in low power oscillations

active power flow. The fundamental frequency components' active power is calculated as 1.2463 p.u., while the total active power of the dominant oscillations (55 Hz and 65 Hz) is 0.0026 p.u. Both active power flows are from the inverter to the grid, which indicates the oscillation source is the inverter. The detection results from *dq* frame show

FIGURE 8: FFT analysis of *dq* frame PCC bus voltages and currents for the 5-Hz oscillation.

the DC components' active power is 1.2467 p.u., while the 5 Hz oscillations active power is 0.0026 p.u.. The active power flow directions are also from the inverter to the grid. *dq* frame detection results closely match *abc* frame detection.

Next, the oscillation active power flow analysis is conducted for the low-power weak grid oscillation. By calculat-

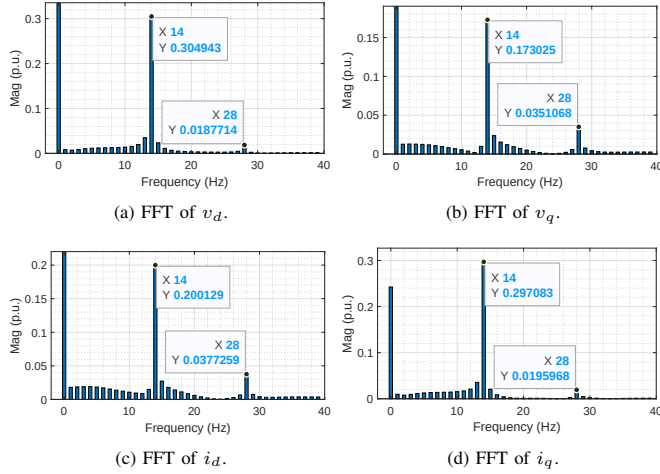


FIGURE 9: FFT analysis of  $dq$  frame PCC bus voltages and currents for the 14-Hz oscillation.

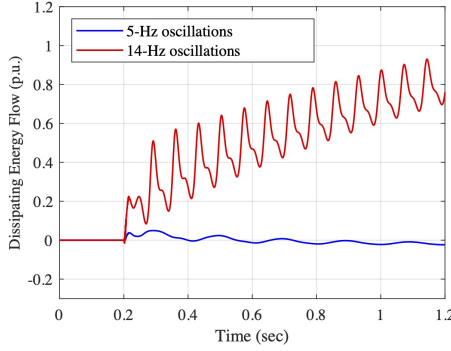


FIGURE 10: DEF approach detection results based on two types of weak grid oscillations.

ing the active power flows from voltage and current phasor extracted from  $abc$ -frame measurements, the fundamental frequency active power is obtained as 0.4003 p.u., which is similar to the active flow calculated from DC components extracted from  $dq$ -frame measurements. On the other hand, the total oscillation active power flow from 46 Hz and 74 Hz components found in  $abc$ -frame measurements is 0.0129 p.u., which also matches the total oscillation active power flow of the 14 Hz and 28 Hz components extracted from  $dq$ -frame measurements. All the active power flows observed are from the inverter to the grid. Table 3 presents all the extracted phasors and oscillation power flows in the low-power weak grid oscillation.

For the reactive power flow, for both the 5-Hz and 14-Hz modes, Table 3 shows that the inverter generates reactive power.

*Remark:* It can be seen that the inverter is capacitive with negative resistance in the 5 – 14-Hz region.

The DEF approach is again applied to detect the two types of weak grid oscillations. The detection results are shown in Fig. 10, where it fails to detect the source that generates the

5-Hz oscillations, while succeeds in detection the source of 14-Hz oscillations.

It is summarized that the weak grid oscillation source location in the presented grid-following inverter integrated system can be detected by the proposed oscillation active power flow method, while DEF may fail to give the correct prediction.

### C. Volt-var oscillations in a two-inverter system

In the above case studies, the oscillation flow approach has been applied in a single IBR-integrated system and is shown to be capable of detecting the oscillation source location successfully. Further, the approach will be examined in a two-IBR system. The testbed is implemented in the authors' recent oscillation source locating study in [8], and the system topology is presented in Fig. 11. Note that the inverters are identical.

In this case study, both grid-following inverters are operated under closed-loop controllers, including plant-level control and inverter-level control. To create oscillations, the plant-level controller's gain in IBR-2 is increased along with its communication delay. At 3 s, the changes are made, and 1.5-Hz oscillations gradually appear. Consistent oscillation is observed after 5 seconds. The  $abc$ -frame dynamic responses of the two-IBR system are shown in Fig. 12a and the  $dq$ -frame measurements are presented in Fig. 12b.

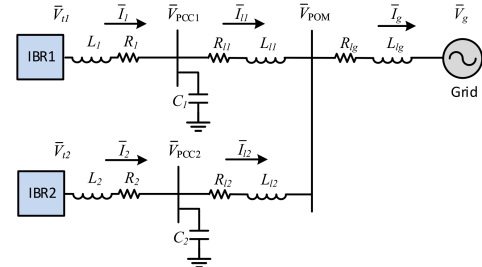


FIGURE 11: Circuit topology of the two-IBR testbed.

TABLE 4: Volt-var Oscillation Source Locating

| $abc$   | Voltage Phasor (p.u.)                      | Current Phasor (p.u.)                      | Power (p.u.)          | Flow Direction                |
|---------|--------------------------------------------|--------------------------------------------|-----------------------|-------------------------------|
| 60 Hz   | $\bar{v}_{a1} = 1.0011 \angle 10.3^\circ$  | $\bar{i}_{a1} = 0.3331 \angle 35.2^\circ$  | $P_{1,60} = 0.3025$   | Inverter 1 $\rightarrow$ Grid |
|         | $\bar{v}_{a2} = 1.0094 \angle 10.1^\circ$  | $\bar{i}_{a2} = 0.3068 \angle 29^\circ$    | $P_{2,60} = 0.2930$   | Inverter 2 $\rightarrow$ Grid |
| 58.5 Hz | $\bar{v}_{a1} = 0.0742 \angle 79.3^\circ$  | $\bar{i}_{a1} = 0.0531 \angle -40.6^\circ$ | $P_{1,58.5} = -0.002$ | Grid $\rightarrow$ Inverter 1 |
|         | $\bar{v}_{a2} = 0.1193 \angle 88.3^\circ$  | $\bar{i}_{a2} = 0.2703 \angle 8.8^\circ$   | $P_{2,58.5} = 0.0059$ | Inverter 2 $\rightarrow$ Grid |
| 61.5 Hz | $\bar{v}_{a1} = 0.0669 \angle -270^\circ$  | $\bar{i}_{a1} = 0.0255 \angle 216.8^\circ$ | $P_{1,61.5} = 0.001$  | Inverter 1 $\rightarrow$ Grid |
|         | $\bar{v}_{a2} = 0.0669 \angle 266.2^\circ$ | $\bar{i}_{a2} = 0.2478 \angle 180.4^\circ$ | $P_{2,61.5} = 0.0012$ | Inverter 2 $\rightarrow$ Grid |
| $dq$    | Voltage Phasor (p.u.)                      | Current Phasor (p.u.)                      | Real Power (p.u.)     | Flow Direction                |
| DC      | $v_{d1} = 0.9850$                          | $i_{d1} = 0.2720$                          | $P_{1,dc} = 0.3023$   | Inverter 1 $\rightarrow$ Grid |
|         | $v_{q1} = 0.1786$                          | $i_{q1} = 0.1922$                          |                       |                               |
|         | $v_{d2} = 0.9939$                          | $i_{d2} = 0.2677$                          | $P_{2,dc} = 0.2923$   | Inverter 2 $\rightarrow$ Grid |
|         | $v_{q2} = 0.1766$                          | $i_{q2} = 0.1488$                          |                       |                               |
| 1.5 Hz  | $\bar{v}_{d1} = 0.1405 \angle 5.6^\circ$   | $\bar{i}_{d1} = 0.0276 \angle 134.3^\circ$ | $P_{1,1.5} = -0.0010$ | Inverter 1 $\rightarrow$ Grid |
|         | $\bar{v}_{q1} = 0.0152 \angle 155.8^\circ$ | $\bar{i}_{q1} = 0.0787 \angle 219.4^\circ$ | $Q_{1,1.5} = 0.0048$  |                               |
|         | $\bar{v}_{d2} = 0.2343 \angle -1^\circ$    | $\bar{i}_{d2} = 0.0464 \angle 23.1^\circ$  | $P_{2,1.5} = 0.0079$  | Inverter 2 $\rightarrow$ Grid |
|         | $\bar{v}_{q2} = 0.0122 \angle 156.1^\circ$ | $\bar{i}_{q2} = 0.5164 \angle 175.6^\circ$ | $Q_{2,1.5} = 0.0602$  |                               |

Similarly, the FFT analysis is performed on  $abc$  and  $dq$  frame oscillation measurements to extract their oscillations'

phasors for oscillation source locating. The spectrum plots of *abc* frame Phase A voltage and current measurements of both inverters are shown in Fig. 13. It can be seen that 58.5 Hz and 61.5 Hz are the dominant oscillations in the *abc* frame measurements. Such oscillation is caused by the plant-level controller hitting the saturation limit. Besides the dominant oscillations, the 3<sup>rd</sup> order oscillations are also existing. Due to the size differences among different oscillations, only the dominant ones are included in the analysis.

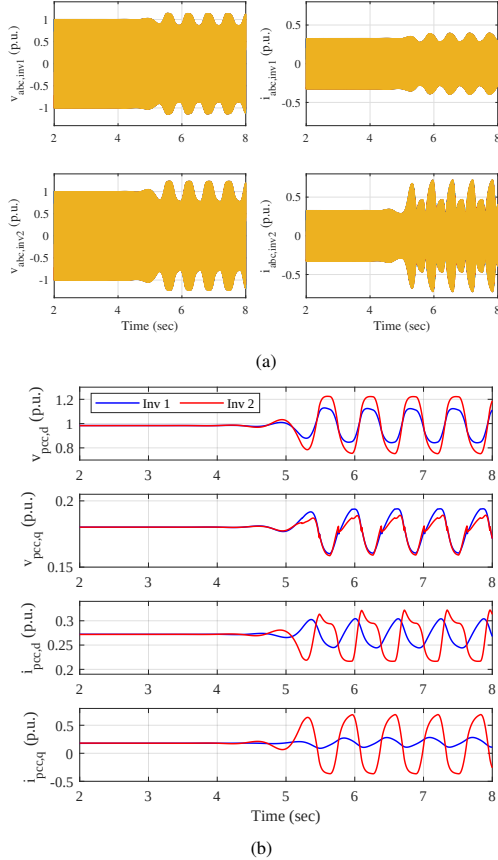


FIGURE 12: EMT simulation results of the two-IBR system. (a) *abc* frame PCC bus voltage and current measurements. (b) *dq* frame PCC bus voltages and currents measurements. At 3 s, the plant-level control of IBR-2 has changes applied and oscillations kick off at 3 s.

Table 4 lists the phasor values of oscillations extracted from FFT analysis of *abc* and *dq* frame measurements, as well as the active power flow of all aspects. Based on the *abc*-frame calculation results, the total oscillation active power flow of Inverter 1 is -0.001 p.u.. Therefore, IBR-1 is not the source of oscillation. The total oscillation active power flow of Inverter 2 is 0.0071 p.u. This shows that IBR-2 is the source of the oscillations. As IBR-2's controller gain is changed and causing the oscillation, the oscillation source is indeed IBR-2.

From the calculation carried out from *dq*-frame measurements, the oscillation active power flows of the 1.5-Hz components that came out from the two inverters are -0.001

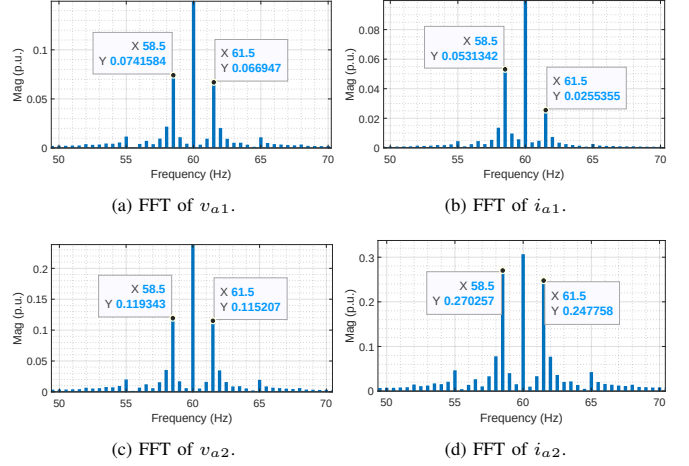


FIGURE 13: FFT analysis of *abc* frame PCC bus voltages and currents of two-inverter system with control interaction oscillation.

p.u. and 0.0079 p.u., respectively. For IBR-1, the oscillations active power flows from the grid to the inverter, and it is the opposite for IBR-2. *dq*-oscillation harmonic active power flow approach leads to the same detection results as the *abc*-frame detection, and both detection results successfully locate the oscillation source, which is IBR-2 in this case study.

Table 4 also shows that significant reactive power of 1.5 Hz flows from IBR-2 to the grid. Comparison of numerical values of real and reactive power show that reactive power flow is dominant. This case clearly shows that the oscillations are indeed predominantly related to reactive power.

*Remark:* It can be seen that IBR-2 exhibits capacitive behavior with a slight negative resistance in the 1.5-Hz region.

Fig. 14 indicates that the conventional DEF approach has difficulty detecting the oscillation source location in the controller interaction event, which is also mentioned in [8]. The detection result is that IBR-1 is the source. This result is incorrect.

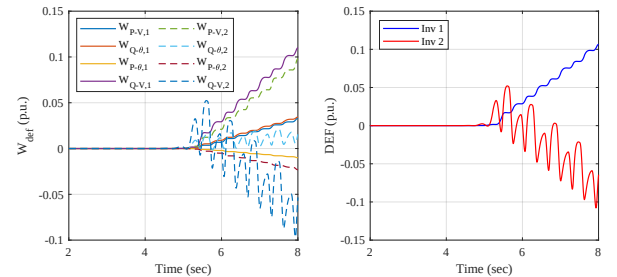


FIGURE 14: Detection results of the DEF approach based on data in Fig. 12.

#### IV. Application scope of oscillation flow method

The proposed harmonic flow is based on the passivity detection for a single dominant oscillation mode. This approach has shown to be successful and can be generalized for

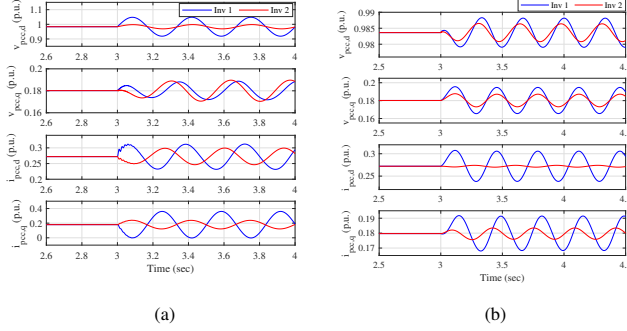


FIGURE 15: Forced oscillation scenarios. (a) 3 Hz harmonics injected in  $d$ -axis terminal voltage of IBR1 (no inverter control). (b) 3-Hz oscillation injected at IBR-1's active power reference.

those oscillations caused by non-passivity. Obviously, it also has its limitations. When the oscillation is caused by the interaction of two IBRs, e.g., the inter-IBR oscillations, this method will have predictable difficulty. According to [30]–[32], the inter-IBR oscillation mode is usually accompanied by an aggregated mode of the similar frequency region. This causes difficulty in separating modes in the frequency spectrum. Furthermore, even this mode can be extracted, since both IBRs contribute to inter-IBR mode, passivity and non-passivity are difficult to be used to distinguish IBRs. Therefore, an obvious scenario that the proposed method cannot be applied to is the inter-IBR modes and/or inter-area oscillations.

TABLE 5: Forced Oscillation originated in IBR-1

|      | Voltage Phasor (p.u.)                     | Current Phasor (p.u.)                     | Real Power (p.u.)                | Flow Direction    |
|------|-------------------------------------------|-------------------------------------------|----------------------------------|-------------------|
| DC   | $v_{d1} = 0.9836$                         | $i_{d1} = 0.1799$                         | $P_{1,dc} = 0.2991$              | Inverter 1 → Grid |
|      | $v_{q1} = 0.1799$                         | $i_{q1} = 0.1796$                         |                                  |                   |
|      | $v_{d2} = 0.9836$                         | $i_{d2} = 0.2724$                         | $P_{2,dc} = 0.3003$              | Inverter 2 → Grid |
|      | $v_{q2} = 0.1801$                         | $i_{q2} = 0.1799$                         |                                  |                   |
| 3 Hz | $\bar{v}_{d1} = 0.0647\angle -1.7^\circ$  | $\bar{i}_{d1} = 0.0403\angle 32.7^\circ$  | $P_{1,3} = 0.0009$               | Inverter 1 → Grid |
|      | $\bar{v}_{q1} = 0.0085\angle 76.4^\circ$  | $\bar{i}_{q1} = 0.1813\angle 177.8^\circ$ |                                  |                   |
|      | $\bar{v}_{d2} = 0.0145\angle -7.9^\circ$  | $\bar{i}_{d2} = 0.0265\angle 158.2^\circ$ | $P_{2,3} = -3.18 \times 10^{-4}$ | Grid → Inverter 2 |
|      | $\bar{v}_{q2} = 0.0096\angle 120.6^\circ$ | $\bar{i}_{q2} = 0.0586\angle 2.8^\circ$   |                                  |                   |

TABLE 6: Forced Oscillation originated in IBR-2

|      | Voltage Phasor (p.u.)                     | Current Phasor (p.u.)                     | Real Power (p.u.)              | Flow Direction    |
|------|-------------------------------------------|-------------------------------------------|--------------------------------|-------------------|
| DC   | $v_{d1} = 0.9836$                         | $i_{d1} = 0.2721$                         | $P_{1,dc} = 0.3$               | Inverter 1 → Grid |
|      | $v_{q1} = 0.1802$                         | $i_{q1} = 0.1798$                         |                                |                   |
|      | $v_{d2} = 0.9836$                         | $i_{d2} = 0.2721$                         | $P_{2,dc} = 0.3$               | Inverter 2 → Grid |
|      | $v_{q2} = 0.1802$                         | $i_{q2} = 0.1796$                         |                                |                   |
| 3 Hz | $\bar{v}_{d1} = 0.0046\angle 91.8^\circ$  | $\bar{i}_{d1} = 0.0338\angle -40.1^\circ$ | $P_{1,3} = 4.1 \times 10^{-5}$ | Inverter 1 → Grid |
|      | $\bar{v}_{q1} = 0.0146\angle -40.7^\circ$ | $\bar{i}_{q1} = 0.0116\angle -78.7^\circ$ |                                |                   |
|      | $\bar{v}_{d2} = 0.0028\angle 117.4^\circ$ | $\bar{i}_{d2} = 0.0021\angle 154.9^\circ$ | $P_{2,3} = 8.0 \times 10^{-6}$ | Inverter 2 → Grid |
|      | $\bar{v}_{q2} = 0.0071\angle -41.2^\circ$ | $\bar{i}_{q2} = 0.0038\angle -5.5^\circ$  |                                |                   |

The second case is the forced oscillation scenario. If an IBR has forced oscillation imposed, on the other hand, its own characteristic is passive at this frequency, it is possible that the energy injected by the source be consumed by the IBR entirely. Therefore, the terminal measurement may not show the IBR as a source. Additionally, if an IBR is not

creating oscillations, however, it is non-passive at the forced oscillation, the harmonic flow method may identify this IBR as a source. We demonstrate two forced oscillation scenarios to show that the proposed method gives random results and therefore is not applicable to the forced oscillation source locating.

In the same two-inverter system, two more case studies were conducted to provide the harmonic flow approach's scope of work. Mainly, these studies focus on the detection of forced oscillation injection. In the first experiment, forced oscillation is applied when both inverters are operated by open-loop voltage control. In the second experiment, both inverters are under closed-loop control while forced oscillation is injected. From the comparison, we show that the proposed harmonic flow oscillation source detection approach does have limitations in certain scenarios.

Fig. 15a shows Scenario 1 when a 3 Hz sinusoidal harmonic is injected into the  $d$ -axis terminal voltage component of IBR-1 at 3 s. Fig. 15b shows Scenario 2 when a 3 Hz sinusoidal harmonic is injected into the power reference of IBR-1 at 3 s.

The final results from the harmonic flow are shown in Table V and Table VI. It can be seen that the harmonic flow method correctly identifies IBR-1 as the source in the first scenario. In the second scenario, the method identifies IBR-1 as the major source of oscillations. On the other hand, IBR-2 is also shown as a source. Therefore, the result has to be interpreted with caution.

## V. Conclusion

In this paper, an active and reactive power flow approach is proposed to detect oscillation source locations in IBR-integrated systems. Using the extracted voltage and current phasors at the oscillation frequencies, the active or reactive power flow is computed, and the flow direction indicates the relative location of the oscillation source against the measurement point. A total of four types of IBR autonomous oscillations and two types of IBR forced oscillations have been produced to demonstrate the efficacy of the proposed method and its application scope. The method is found to be effective for scenarios with a single dominant natural mode, while it is not applicable for forced oscillation source detection.

Oscillation source location methods typically identify one or more components associated with an oscillation event. However, this level of identification remains relatively coarse. Greater practical value can be achieved by moving toward a more granular characterization of the source. In this paper, we advance this direction by further differentiating oscillations based on active and reactive power contributions. For instance, in the volt-var oscillation case, reactive power is shown to play a more dominant role. This represents one example of progressing toward a more detailed and mechanism-oriented source identification.

## REFERENCES

- [1] Y. Cheng, L. Fan, J. Rose, S.-H. Huang, J. Schmall, X. Wang, X. Xie, J. Shair, J. R. Ramamurthy, N. Modi, C. Li, C. Wang, S. Shah, B. Pal, Z. Miao, A. Isaacs, J. Mahseredjian, and J. Zhou, "Real-world subsynchronous oscillation events in power grids with high penetrations of inverter-based resources," *IEEE Transactions on Power Systems*, vol. 38, no. 1, pp. 316–330, 2023.
- [2] G. Zheng, H. Wang, S. Liu, and M. M. Farrokhifard, "2021 IEEE-NASPI Oscillation Source Location Contest: Team Woodpecker," in *2022 IEEE Power & Energy Society General Meeting (PESGM)*, 2022, pp. 1–5.
- [3] L. Chen, Y. Min, and W. Hu, "An energy-based method for location of power system oscillation source," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 828–836, 2013.
- [4] S. Maslennikov and E. Litvinov, "Iso new england experience in locating the source of oscillations online," *IEEE Transactions on Power Systems*, vol. PP, pp. 1–1, 07 2020.
- [5] S. Biswas, J. Follum, and J. H. Eto, "Confidence assessment for regional forced oscillation source localization: Formulation and field validation," *IEEE Transactions on Power Delivery*, vol. 38, no. 6, pp. 3739–3748, 2023.
- [6] D. Osipov, S. Konstantinopoulos, and J. H. Chow, "A cross-power spectral density method for locating oscillation sources using synchrophasor measurements," *IEEE Transactions on Power Systems*, vol. 38, no. 6, pp. 5526–5534, 2022.
- [7] X. Xie, Y. Zhan, J. Shair, Z. Ka, and X. Chang, "Identifying the source of subsynchronous control interaction via wide-area monitoring of sub/super-synchronous power flows," *IEEE Transactions on Power Delivery*, vol. 35, no. 5, pp. 2177–2185, 2019.
- [8] L. Fan, Z. Wang, Z. Miao, and S. Maslennikov, "Oscillation Source Detection for Inverter-Based Resources via Dissipative Energy Flow," 3 2023. [Online]. Available: [https://www.techrxiv.org/articles/preprint/Oscillation\\_Source\\_Detection\\_for\\_Inverter-Based\\_Resources\\_via\\_Dissipative\\_Energy\\_Flow/22178966](https://www.techrxiv.org/articles/preprint/Oscillation_Source_Detection_for_Inverter-Based_Resources_via_Dissipative_Energy_Flow/22178966)
- [9] S. Chevalier, P. Vorobev, and K. Turitsyn, "A passivity interpretation of energy-based forced oscillation source location methods," *IEEE Transactions on Power Systems*, vol. 35, no. 5, pp. 3588–3602, 2020.
- [10] Y. Zhi and V. Venkatasubramanian, "Analysis of energy flow method for oscillation source location," *IEEE Transactions on Power Systems*, vol. 36, no. 2, pp. 1338–1349, 2021.
- [11] K. Chatterjee, S. Samanta, and N. R. Chaudhuri, "Insights into dissipating energy-based source/sink characterization of TCSC and STATCOM for low-frequency oscillations," *IEEE Transactions on Power Delivery*, vol. 38, no. 2, pp. 1426–1439, 2023.
- [12] L. Fan, R. Kavasseri, Z. L. Miao, and C. Zhu, "Modeling of DFIG-based wind farms for SSR analysis," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2073–2082, 2010.
- [13] L. Fan and Z. Miao, "Nyquist-stability-criterion-based SSR explanation for type-3 wind generators," *IEEE Transactions on Energy Conversion*, vol. 27, no. 3, pp. 807–809, 2012.
- [14] B. Wen, D. Boroyevich, R. Burgos, P. Mattavelli, and Z. Shen, "Analysis of dq small-signal impedance of grid-tied inverters," *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 675–687, 2015.
- [15] L. Fan, Z. Miao, D. Ramasubramanian, and H. Ding, "Operational challenges of solar PV plus storage power plants and modeling recommendations," *IEEE Open Access Journal of Power and Energy*, 2023.
- [16] A. Jalali, B. Badrzadeh, J. Lu, N. Modi, and M. Gordon, "System strength challenges and solutions developed for a remote area of australian power system with high penetration of inverter-based resources," *CIGRE Sci. Eng. J.*, vol. 20, no. 2, pp. 27–37, 2021.
- [17] J. Das, *Power system harmonics and passive filter designs*. John Wiley & Sons, 2015.
- [18] L. Chen, X. Xie, J. He, T. Xu, D. Xu, and N. Ma, "Wideband oscillation monitoring in power systems with high-penetration of renewable energy sources and power electronics: A review," *Renewable and Sustainable Energy Reviews*, vol. 175, p. 113148, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032123000047>
- [19] M. Kazem Bakhshizadeh, X. Wang, F. Blaabjerg, J. Hjerild, L. Kocewiak, C. L. Bak, and B. Hesselbæk, "Couplings in phase domain impedance modeling of grid-connected converters," *IEEE Transactions on Power Electronics*, vol. 31, no. 10, pp. 6792–6796, 2016.
- [20] W. Xu, J. Yong, H. J. Marquez, and C. Li, "Interharmonic power—a new concept for power system oscillation source location," *IEEE Transactions on Power Systems*, vol. 40, no. 5, pp. 4367–4379, 2025.
- [21] P. G. Estevez and S. Maslennikov, "Extension of the complex dissipating energy flow method for sub/super-synchronous oscillation source location," *IEEE Transactions on Power Systems*, vol. 41, no. 1, pp. 654–666, 2026.
- [22] L. Fan, Z. Miao, S. Shah, Y. Cheng, J. Rose, S.-H. Huang, B. Pal, X. Xie, N. Modi, S. Wang *et al.*, "Real-world 20-hz IBR subsynchronous oscillations: Signatures and mechanism analysis," *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2863–2873, 2022.
- [23] Y. Gu. (2024) Tracing the oscillations – a few pieces of the puzzle. [Online]. Available: <https://www.esig.energy/event/2024-esig-g-pst-special-topic-workshop-a-deeper-look-at-oscillations/>
- [24] S. Maslennikov, B. Wang, and E. Litvinov, "Dissipating energy flow method for locating the source of sustained oscillations," *International Journal of Electrical Power & Energy Systems*, vol. 88, pp. 55–62, 2017.
- [25] L. Fan and Z. Miao, *Modeling and Stability Analysis of Inverter-Based Resources*. CRC Press, Jun 2023.
- [26] L. Fan, "Modeling type-4 wind in weak grids," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 853–864, 2019.
- [27] L. Fan, Z. Miao, and Z. Wang, "A new type of weak grid ibr oscillations," *IEEE Transactions on Power Systems*, vol. 38, no. 1, pp. 988–991, 2023.
- [28] Z. Wang, L. Fan, and Z. Miao, "The cause of insufficient damping in phase-locked-loop and its influence," in *2023 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 2023, pp. 1–5.
- [29] L. Fan and Z. Miao, "An explanation of oscillations due to wind power plants weak grid interconnection," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 1, pp. 488–490, 2018.
- [30] L. Fan, "Inter-IBR oscillation modes," *IEEE Transactions on Power Systems*, vol. 37, no. 1, pp. 824–827, 2021.
- [31] L. Fan, Z. Miao, and S. Shah, "Mechanism analysis of wind turbine var oscillations," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 10, pp. 10 750–10 754, 2022.
- [32] M. Zhang, Z. Miao, L. Fan, and S. Shah, "Data-driven interarea oscillation analysis for a 100% IBR-penetrated power grid," *IEEE Open Access Journal of Power and Energy*, vol. 10, pp. 93–103, 2022.