

# Measuring Impedance Spectra in Distribution Feeders Using GridSweep

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**ABSTRACT** Peaks and troughs in the subsynchronous impedance spectrum of a distribution feeder may be a useful indication of oscillation risk, or more importantly lack of oscillation risk, if inverter-based resource (IBR) deployments are increased on that feeder. This paper demonstrates that the impedance spectrum can be measured by GridSweep, an instrument device. GridSweep combines an active probing device that modulates a 120-volt 1-kW load sinusoidally at a user-selected GPS-phase locked frequency from 1.0 Hz to 40.0 Hz, and with a recorder that takes ultra-high-precision continuous point-on-wave (CPOW) 120-volt synchrowaveforms at 4 kHz. Our paper reveals that the measured voltage spectra by GridSweep correspond to the subsynchronous impedance spectra of distribution feeders. For demonstration, we construct an electromagnetic transient (EMT) simulation of a single-phase distribution feeder equipped with multiple IBRs. We include a model of the GridSweep probing device, then demonstrate the model's capability of measuring the subsynchronous apparent impedance spectrum of the feeder. In addition, we show that peaks in that spectrum align with the system's dominant oscillation modes caused by IBRs.

**INDEX TERMS** distribution feeder, subsynchronous, impedance measurement, probing.

## I. Introduction

**G**RIDSWEEP is a new instrument developed for the U.S. Department of Energy by Alex McEachern at the Lawrence Berkeley National Laboratory. The instrument conducts active subsynchronous probing at one 120-volt outlet at one location on a distribution feeder, while simultaneously recording GPS-synchronize parts-per-billion voltage synchrowaveforms at another 120-volt outlet which must be at a different location on the same distribution feeder [1]. Fig. 1 shows the voltage spectra measured by GridSweep in a distribution feeder at Idaho Power [2]. Each spectrum is obtained by recording the feeder voltage for 1-kW load probing at a distinct frequency and extracting the corresponding voltage phasor's magnitude. It is noteworthy that GridSweep is capable of extracting 2 Hz - 40 Hz voltage magnitude signals of parts-per-million size from the background voltage noise [3].

The GridSweep concept can be traced back to the Chief Joseph Brake, a 1400-MW switchable resistor built in the 1970s for oscillation damping [4]. Energization of the Chief Joseph Brake provides information about the stability of the WECC system. During 2005 and 2006, real-time phasor

measurement unit (PMU) data were captured from the insertion tests and the dominant oscillation modes (N-S mode at 0.2-0.3 Hz, Alberta mode at 0.37 Hz) were identified [5].

Compared to the Chief Joseph Brake, the GridSweep instrument is tiny, and its 1-kW probing signals result in tiny voltage changes, measured in parts-per-million per-unit or even parts-per-billion per-unit.

The objective of this paper is to answer this question: **What do the measured voltage spectra represent?** To this end, we first conducted a theoretic analysis which leads to the finding that GridSweep's measured voltage spectra correspond to the distribution feeder's impedance spectra. Next, we simulate GridSweep's probing and measurement capability in multiple EMT testbeds with or without explicit knowledge of the impedance. We show that GridSweep approach is capable of measuring apparent subsynchronous impedance of a simulated distribution feeder. We adopt the terminology "apparent impedance" from [6], in which Rygg and Molinas proposed a method based on injection of a small voltage or current at a location and further defined the apparent impedance as the ratio between the voltage and current at the injection point. Note that this impedance is the

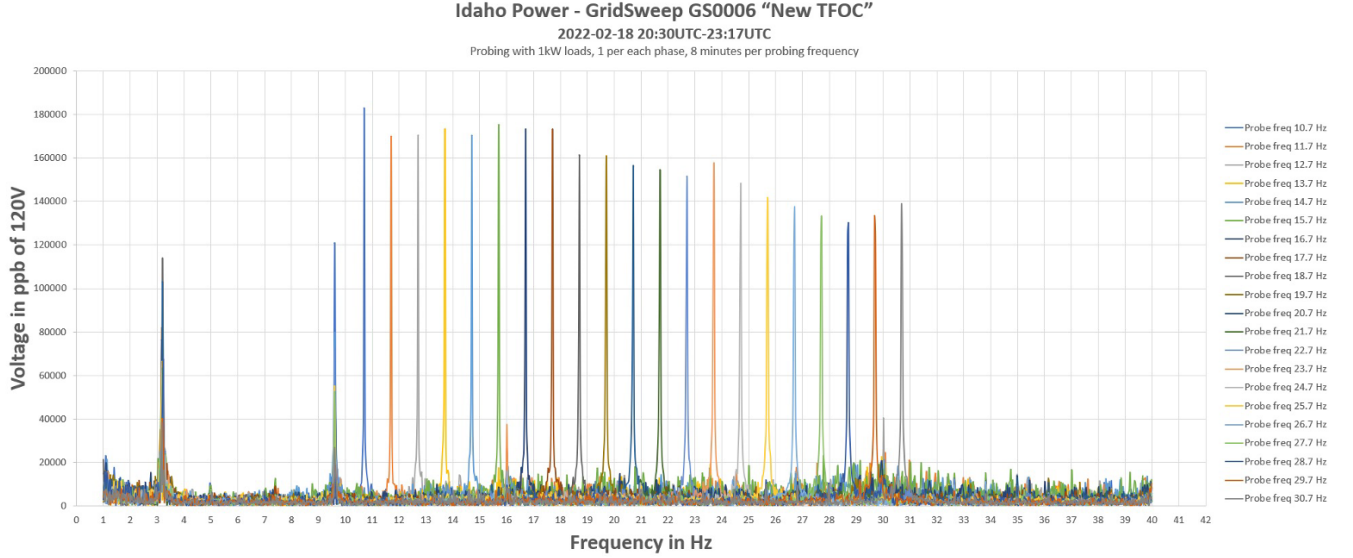


FIGURE 1: Idaho Power-GridSweep's measurement of voltage in parts-per-billion (ppb) of 120 V.

equivalent impedance of the entire system viewed from the probing location. In many other scenarios, researchers measure a device or a subsystem's impedance (e.g., [7]), instead of the impedance of an entire system. Apparent impedance indeed reflects the closed-loop system. Therefore, peaks in the apparent impedance spectra implicate oscillation modes and a sharper peak implicates poorly damped oscillations.

Conventional impedance measurement methods require a probing voltage source or current source. This is the approach taken by the measurement testbed for MW size inverters located in the National Renewable Energy Lab campus [7]. That testbed requires a controllable voltage source at 13.2 kV. Similarly, the impedance measurement requires current sources in [8]. In contrast, GridSweep has the advantage of not requiring an additional source. Instead, it can simply be plugged into 120-volt outlets at the edge of the grid, and conduct subsynchronous measurements of feeders and, in some cases, substations. Essentially GridSweep modulates a resistive load. This probing method is similar to those deployed in the lab scale or computer simulation testbeds where transient time-domain data caused by load switching off has been used for impedance identification [9], [10]. Compared to the load switching probing method, GridSweep has the advantage of providing controllable and continuous probing signals. Additionally, its real-time data streaming capability of continuous power-on-wave signals is of particular interest to capturing fast dynamics caused by IBRs [11].

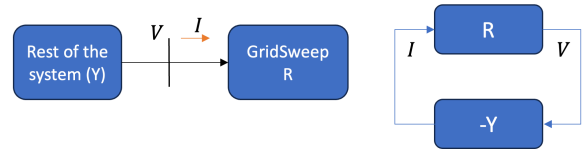
Since the spectra shown in Fig. 1 is related to voltage magnitude, it is reasonable to analyze the relationship between the voltage phasor and the load modulation. Converting a sinusoidal signal to a phasor requires Park transform. With this step, we view signals in a  $dq$  frame. Therefore, in the following, we present the theoretic analysis and EMT

simulation results to demonstrate GridSweep's capability to capture subsynchronous apparent impedance in the  $dq$  frame.

While the physical GridSweep device uses a stepped-in-frequency series of single-frequency subsynchronous injections as perturbation, which is computing expensive, in this simulation we substitute sinusoidal perturbations by step change injection and/or continuously-varied chirp signal injection for quick model identification using advanced system identification methods. The related techniques have been demonstrated in our prior research [10], [12].

## II. Theoretical Analysis: Principle of Measuring Impedance Using GridSweep

GridSweep probing connects a common 1-kW resistive heater, pulse-width modulated at a programmable subsynchronous frequency, located at one 120-volt outlet. GridSweep recording measures the voltage change at this or another 120-volt outlet. If the probing and measurement locations are the same, the measured voltage change is related to the probing current, as shown in Fig. 2.


 FIGURE 2: Illustration of the GridSweep, represented by  $R$ , interacting with the rest of the system, represented by  $Y$ .

With GridSweep modulating a resistive load  $R$  at  $f_p$  frequency, the resulting continuous point-on-wave (CPOW) voltage measurement contains  $(60+f_p)$ -Hz and  $(60-f_p)$ -Hz non-fundamental components due to frequency coupling phenomena [13], [14] (chapter 3). To directly use the CPOW voltage measurements, we have to deal with two non-

fundamental components for a single perturbing subsynchronous signal. Doing so is less convenient than examining voltage's space vector in the  $dq$  synchronous frame. If the single-phase voltage measurement is expressed as follows:

$$v(t) = \hat{v}(t) \cos(\omega_0 t + \theta(t)), \quad (1)$$

where  $\omega_0$  is the nominal frequency in rad/s.  $v(t)$ 's analytical form is notated as

$$\vec{v}(t) = \hat{v}(t) e^{j\theta(t)} e^{j\omega_0 t}. \quad (2)$$

In the  $dq$  frame where the  $d$ -axis is leading the static reference by  $\omega_0 t + \theta_0$ , the voltage vector  $\vec{V}_{dq}$  is expressed as:

$$\vec{V}_{dq} = \hat{v} e^{j(\theta - \theta_0)} = \underbrace{\hat{v} \cos(\theta - \theta_0)}_{v_d} + j \underbrace{\hat{v} \sin(\theta - \theta_0)}_{v_q}. \quad (3)$$

$v_d$  and  $v_q$  can be found directly by averaging the voltage measurement  $v(t)$  after multiplication with sinusoidal signals.

$$v_d = \frac{2}{T} \int_0^T v(t) \cos(\omega_0 t + \theta_0) dt = \hat{v} \cos(\theta - \theta_0),$$

$$v_q = \frac{2}{T} \int_0^T v(t) (-\sin(\omega_0 t + \theta_0)) dt = \hat{v} \sin(\theta - \theta_0), \quad (4)$$

where  $T$  is  $2\pi/\omega_0$ .

Fig. 3(a) shows the preprocessing blocks. The voltage CPOW measurement  $v$  is per unitized and multiplied by 2. Its inner product with the cosine waveform is passed through a low-pass filter (LPF) (e.g., a moving average filter) to have the magnitude associated with  $\cos(\omega_0 t)$  computed. Its inner product with the sine waveform is also passed through a low-pass filter to have the coefficient associated with  $\sin(\omega_0 t)$  computed. From there, the magnitude in pu and the angle in degree are treated as outputs.

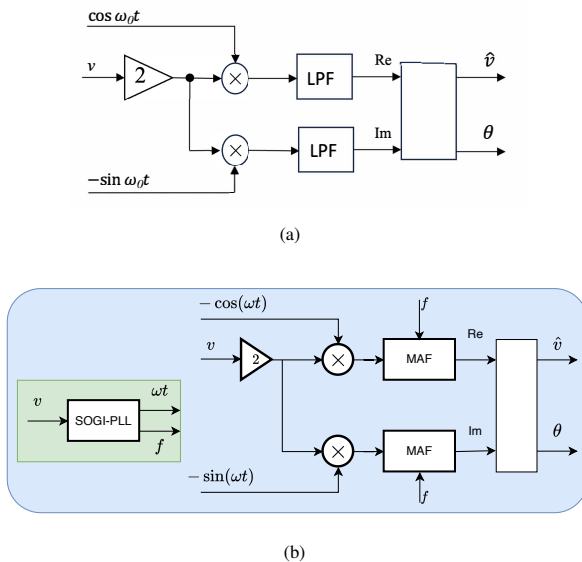


FIGURE 3: Pre-processing CPOW voltage measurement to extract magnitude and angle in the  $dq$  frame. (a) Fixed nominal frequency case; (b) Unknown grid frequency case.

In the  $dq$ -frame, the voltage and current vector are related as follows:

$$\underbrace{\begin{bmatrix} v_d \\ v_q \end{bmatrix}}_{\mathbf{V}} = \underbrace{\begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}}_{\mathbf{R}} \underbrace{\begin{bmatrix} i_d \\ i_q \end{bmatrix}}_{\mathbf{I}} = - \underbrace{\begin{bmatrix} Z_{dd} & Z_{dq} \\ Z_{qd} & Z_{qq} \end{bmatrix}}_{\mathbf{Z}} \mathbf{I}, \quad (5)$$

where  $\mathbf{Z}$  notates the impedance of the rest of the system and its reciprocal is  $\mathbf{Y}$  ( $\mathbf{Y} = \mathbf{Z}^{-1}$ ).  $R$  is varying and can be notated as  $R = R_0(1 + p)$  where  $p$  is the perturbation and  $R_0$  is the resistance of the GridSweep before a perturbation is imposed. The linearized relationship between voltage and current in the  $dq$ -frame becomes as follows:

$$\Delta \mathbf{V} = R_0 \Delta \mathbf{I} + \mathbf{I}_0 \Delta R = R_0 \Delta \mathbf{I} + R_0 \mathbf{I}_0 \cdot p, \quad (6)$$

where subscript 0 notates the initial condition.

Note that  $R_0 \mathbf{I}_0$  can be replaced by  $\mathbf{V}_0$ , the initial voltage vector. Therefore, the block diagram describing the relationship between the perturbation and the voltage vector is shown as Fig. 4.

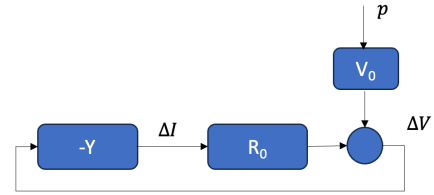


FIGURE 4: Block diagram of the perturbation and voltage relationship.

$$\text{Therefore: } \frac{\Delta \mathbf{V}}{p} = \underbrace{(\mathbf{I} + R_0 \mathbf{Y})^{-1}}_{\mathbf{G}} \mathbf{V}_0 \approx \frac{1}{R_0} \mathbf{Z} \cdot \mathbf{V}_0. \quad (7)$$

The approximation is made since  $R_0$  is very large and all its element of  $R_0 \mathbf{Y}$  is much greater than 1. Therefore, the measured voltage is related to the impedance matrix  $\mathbf{Z}$ . If  $\mathbf{V}_0 = [V_0, 0]^T$ , the input/output models are related to the  $dd$  and  $qd$  components, or the first column of  $\mathbf{Z}$ :

$$\mathbf{G} \mathbf{V}_0 = [G_{11}, G_{21}]^T V_0.$$

where  $\mathbf{G}$  is defined in (7) and  $G_{11}$  and  $G_{21}$  are the elements of the 2-by-2 matrix  $\mathbf{G}$ .

Note that when the  $dq$  frame aligns with the voltage vector at the initial steady state, or  $\theta = \theta_0$ , then according to (4),

$$\Delta v_d = \Delta \hat{v}, \quad \Delta v_q = V_0 \Delta \theta \quad (8)$$

Therefore, the magnitude and the angle of the voltage are indeed equal or proportional to  $v_d$  and  $v_q$  viewed in a  $dq$ -frame aligned with the steady-state voltage vector.

In short,

$$\begin{bmatrix} \Delta \hat{v}/p \\ \Delta \theta/p \end{bmatrix} = \begin{bmatrix} G_{11} V_0 \\ G_{21} \end{bmatrix} \approx \frac{1}{R_0} \begin{bmatrix} Z_{dd} V_0 \\ Z_{qd} \end{bmatrix} \quad (9)$$

The above theoretical analysis shows that the magnitude and angle of the fundamental component are related to the two components of the apparent impedance  $\mathbf{Z}$ . Eq. (9)

implicates that the voltage magnitude spectra tracks  $Z_{dd}$  (scaled) and the angle spectra tracks  $Z_{qd}$  (scaled).

#### A. More Realistic Scenarios: Off-nominal Grid Frequency

If the grid frequency drifts away from 60 Hz, the extraction method shown in Fig. 3(a) introduces spectra leakage and imperfect cancellation of the second harmonic product, as rightly mentioned by the reviewer. On the other hand, commercial technology is available to handle spectral leakage and oscillation errors. According to [15], many commercial protective relays and PMUs implement closed-Loop frequency tracking, e.g., phase-locked loop (PLL). With the frequency known, the internal digital signal processing (DSP) dynamically modifies the sampling frequency so that the number of samples per cycle remains fixed and synchronized to the real-world waveform.

When the grid frequency is not known, how to set up a  $dq$  frame that can be aligned with the measured voltage becomes a challenging task. A feasible approach is to rely on a PLL that is suitable for a single-phase sinusoid to generate the angle of the  $dq$  frame. With this angle known, we further generate  $\cos(\omega t)$  and  $\sin(\omega t)$  signals that are used in the phasor extraction block. In addition, the grid frequency can also be measured by the PLL and this frequency is used for the moving average filter (MAF) for transport delay setting.

The block diagram of the phasor extraction unit is shown in Fig. 3(b). The PLL is the second-order generalized integrator (SOGI)-PLL proposed by Ciobotaru, Teodorescu and Blaabjerg in 2006 [16], suitable for angle and frequency tracking based on a single-phase sinusoid signal. More details on SOGI-PLL can be found in Section IV Fig. 16.

### III. Comparison of GridSweep results with Ground Truth

In Section III and Section IV, we present two sets of simulation results to demonstrate the capability of the GridSweep measurements, respectively. For the first set of testbeds presented in Section III, we can find the ground truth since the results can be analytically determined. The GridSweep measurements will be compared with the ground truth. For the second set presented in Section IV, we do not have the knowledge on ground truth. Hence, we will resort to other measures for comparison.

In this section, we perform simulations using RLC source impedances. We investigate three cases of RLC source impedances: (1) an ideal AC voltage source followed by a simple RLC source impedance, probed by the GridSweep-simulating variable resistor, as shown in Fig. 5; (2) we move the source impedance capacitor to a shunt configuration, as shown in Fig. 9; and (3) we explore multiple simulated GridSweep CPOW recordings at locations other than the probing location, as shown in Fig. 13. In each of these three cases, we compare the simulated measured results to the analytically calculated ground truth.

We use the three cases to demonstrate the following:

- GridSweep measurements reflect the apparent impedance components combined with the effect of a low-pass filter in the signal processing.
- Peaks in the GridSweep measurement spectra correspond to oscillation modes.
- If the probing location and measurement location are different, GridSweep's measurements reflect the apparent impedance with a scaling factor.

#### A. Case 1: Measure an RLC circuit

In case 1, the impedance of the RLC circuit in the static frame is  $R + Ls + 1/(Cs)$ . In the  $dq$  frame, the impedance matrix  $\mathbf{Z}$  (reflecting the relationship between the voltage measurement  $v$  and the current injection  $i$ ) is expressed as follows:

$$\mathbf{Z} = \begin{bmatrix} R + Ls + \frac{s}{C(s^2 + \omega_0^2)} & -\omega_0 L + \frac{\omega_0}{C(s^2 + \omega_0^2)} \\ \omega_0 L - \frac{\omega_0}{C(s^2 + \omega_0^2)} & R + Ls + \frac{s}{C(s^2 + \omega_0^2)} \end{bmatrix} \quad (10)$$

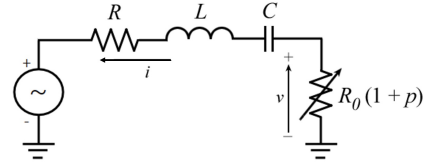


FIGURE 5: Testbed 1.  $R = 0.2$  p.u.,  $X_L = 0.25$  p.u.,  $X_C = 0.1$  p.u.  $R_0 = 10$  p.u.

A testbed of this circuit is built in MATLAB Simscape Specialized Power Systems environment. Fig. 5 shows the testbed along with the GridSweep probing. The parameters of the systems are shown in the figure caption.

Fig. 6a shows the chirp signal perturbation employed and the measurements of voltage magnitude and angle. The chirp signal starts at 0.5 Hz and ends at 20 Hz. It is an efficient way to sweep the frequency spectrum, and has the same characteristics of the single sinusoidal perturbation method used by the GridSweep device. This set of input and output data has been used to carry out system identification to find the input/output transfer function. We have used MATLAB System Identification Toolbox's `tfest` function to conduct identification. The system's order is selected to achieve the best matching between the model's output and the measured output. For this set of data, the 4th order model yields the best result. Fig. 6b shows the comparison results of the measurements and the model's outputs. It can be seen that the matching degrees of 91% and 89% are reached.

The identified model (blue line) is compared with the analytical model  $\mathbf{Z}$ 's  $dd$  and  $qd$  components (black lines). The results are shown in Fig. 7. It can be seen that the identified models lag  $Z_{dd}$  and  $Z_{qd}$ . At 40 Hz, the phase lag is about 60 degrees. Re-examining the phasor extracting process shown in Fig. 3(a), we find that the effect of the LPF has to be considered.

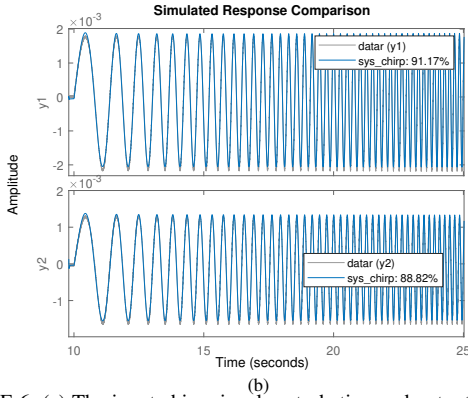
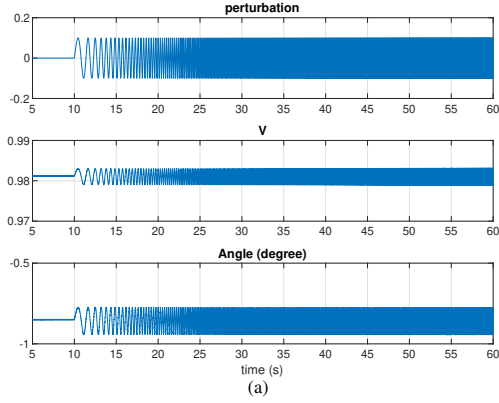


FIGURE 6: (a) The input chirp signal perturbation and output measurement data of voltage magnitude (in pu) and angle (in degree). (b) Comparison of the estimated model output and the measured output.

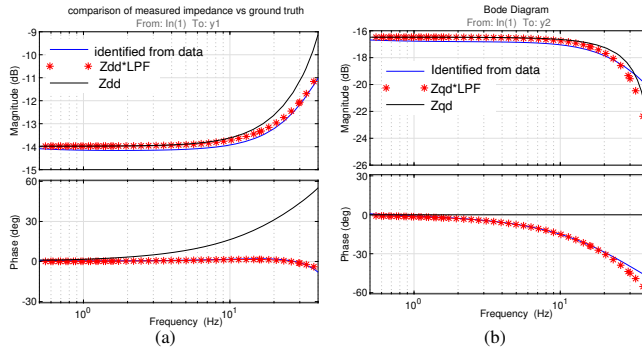


FIGURE 7: Comparison of the impedance components from data and the ground truth: (a) the  $dd$  component; (b) the  $qd$  component.  $Z_{dd}$ ,  $Z_{qd}$ ,  $Z_{dd} \cdot \text{LPF}$  and  $Z_{qd} \cdot \text{LPF}$  are analytical models.

In Testbed 1, we have used a moving-average filter to process data and filter out the second harmonic component generated by the multiplication of two signals of fundamental frequency. This filter integrates a period of data and delivers the average value. Its transfer function can be expressed as follows:

$$\text{LPF} = \frac{1}{T_w} \left( \frac{1}{s} - \frac{e^{-T_w s}}{s} \right), \quad (11)$$

where  $T_w$  is the time period of the 120-Hz harmonic and  $T_w = 1/120$  s.

Once the effect of the LPF is considered, it can be seen from Fig. 7 that the measured impedance components can match  $Z_{dd} \cdot \text{LPF}$  and  $Z_{qd} \cdot \text{LPF}$  very well.

*Remarks:* This case study demonstrates that the GridSweep approach has the capability to identify the first column of the subsynchronous apparent impedance matrix.

Additionally, the grid frequency is changed to be 59.6 Hz in the EMT testbed and the frequency is estimated at the pre-processing step using the block diagram shown in Fig. 3(b) where an SOGI-PLL with its PI control unit as  $60 + 1400/s$  is used. The perturbation, voltage magnitude and angle measurements are shown in Fig. 8(a), while the identified models are shown in Fig. 8(b) and (c).

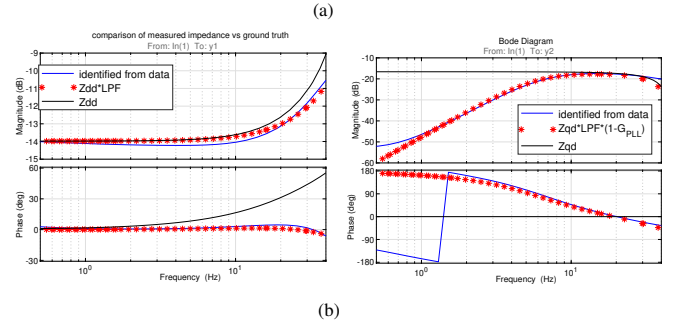
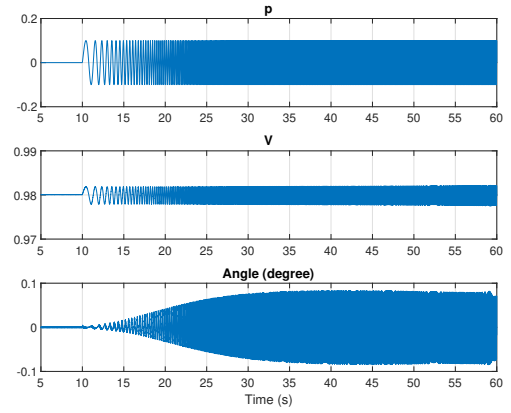


FIGURE 8: (a) Perturbation, voltage and angle measurements. (b) Bode diagrams of the identified models:  $Z_{dd}$  and  $Z_{qd}$ .

Comparing the Bode diagrams of  $Z_{dd}$  in Fig. 7(a) and Fig. 8(b), it can be seen that  $Z_{dd}$  identified does not show significant change in two cases. On the other hand, the identified  $Z_{qd}$  show significant difference. In Fig. 7(b), the system is shown as a low-pass filter, while in Fig. 8(b), the measured system is shown as a high-pass filter.

The difference is due to the inclusion of a PLL and its dynamics influence angle extraction. The measured angle is indeed based on the  $q$ -axis component of the voltage, or  $\theta \approx (\theta_v - \theta_{\text{PLL}})$ , where  $\theta_v$  is the angle of the volt-

age and  $\theta_{PLL}$  is the angle output from the PLL. Since  $\theta_{PLL} = G_{PLL}\theta_v$ , where  $G_{PLL}$  is the PLL's closed-loop transfer function behaving like a low-pass filter, the measured angle  $\theta$  becomes  $(1 - G_{PLL})\theta_v$ .  $(1 - G_{PLL})$  then acts as a high-pass filter.

When the impact of the PLL is included, the measured  $Z_{qd}$  matches well with the analytical result, as shown in Fig. 8(b).

In summary, the pre-processing of the continuous waveform data requires careful design. In particular, while the voltage spectra and the identified  $Z_{dd}$  show consistency with or without a PLL, the angle spectra and the identified  $Z_{qq}$  show significant change in the low-frequency region due to the PLL dynamics.

### B. Case 2: Measure a circuit with shunt compensation

In Case 2, we measure a circuit with shunt compensation and further show that the peaks in the measured spectra correspond to the system's eigenvalues or oscillation modes. The RLC circuit has its parameters configured to create an oscillation mode of 69 Hz. In turn, 9-Hz oscillations will be apparent in the voltage magnitude measurements for this system. This 9-Hz mode will be present in the GridSweep's spectrum measurement as a peak at 9 Hz.

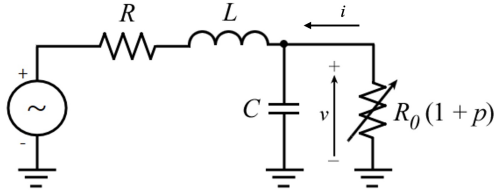


FIGURE 9: Testbed 2.  $R = 0.1$  p.u.,  $X_L = 0.75$  p.u.,  $B = 1$  p.u.  $R_0 = 50$  p.u.

Testbed 2 is shown in Fig. 9. The relationship between the measured voltage  $v$  and the current injection  $i$  in the static frame is as follows:

$$Z(s) = \frac{v}{i} = \frac{1}{Cs + \frac{1}{R+Ls}} = \frac{R + Ls}{LCs^2 + RCs + 1}. \quad (12)$$

For this system, the characteristic polynomial is

$$s^2 + \frac{R}{Ls} + \frac{1}{LC} = 0.$$

Therefore, the natural oscillation mode has a frequency of

$$\omega_n = \sqrt{\frac{1}{LC}} = \frac{\omega_0}{\sqrt{XB}}. \quad (13)$$

If  $X = 0.75$  and  $B = 1$  pu, this mode has 69-Hz as the oscillation frequency. In the  $dq$ -frame and voltage root-mean square (RMS) or power measurements, the oscillation mode appears as a 9-Hz mode. Additionally,  $Z_{dd}$  and  $Z_{qd}$  can be

found as:

$$\begin{aligned} Z_{dd} &= \frac{Z(s + j\omega_0) + Z(s - j\omega_0)}{2}, \\ Z_{qd} &= \frac{Z(s + j\omega_0) - Z(s - j\omega_0)}{2j}. \end{aligned} \quad (14)$$

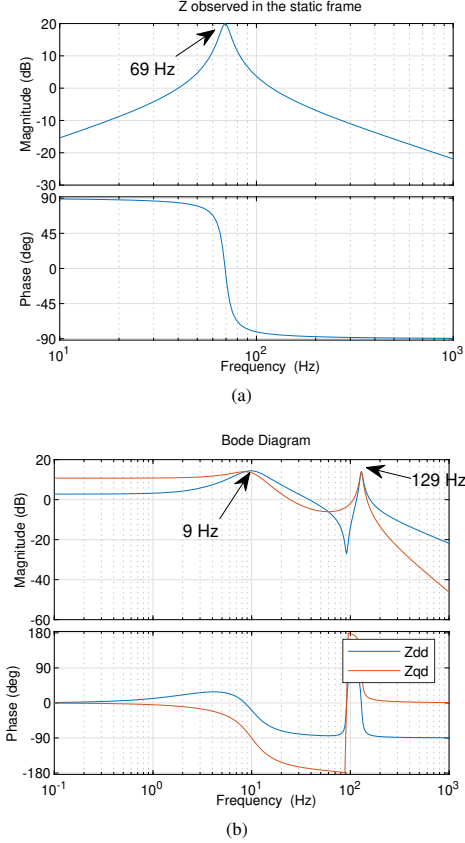


FIGURE 10: The impedance viewed at the probing point for a circuit with shunt compensation. (a)  $Z$  in the static frame. (b)  $Z_{dd}$  and  $Z_{qd}$ .

Fig. 10 shows the impedance viewed from the probing point in two frames: the static frame and the  $dq$  frame. In the static frame, the impedance shows a peak in its Bode diagram's magnitude at 9 Hz; while in the  $dq$  frame, the  $dd$  and  $qd$  components show peaks at 9 Hz and 129 Hz. Using GridSweep, we expect to see 9 Hz in the measured voltage spectra. To confirm this point, we perturbed the GridSweep's resistance and have a step change of 10%.

The nominal GridSweep's resistance is 50 pu. The collected voltage RMS value and the angle measurements are shown in Fig. 11. Based on this set of the data, the input/output models are identified and compared with  $Z_{dd}$  and  $Z_{qd}$ , as shown in Fig. 12. It can be seen that the measured voltage and angle spectra match very well with the expected results and indeed have peaks at 9 Hz.

### C. Case 3: Multiple voltage measurements

While the probing is usually placed at the load side, we may take the voltage measurement at a different location. In

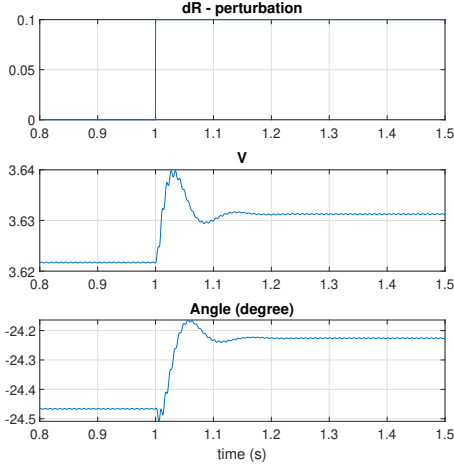


FIGURE 11: The input and output data to identify the transfer functions of  $\hat{v}/p$  and  $\theta/p$ .

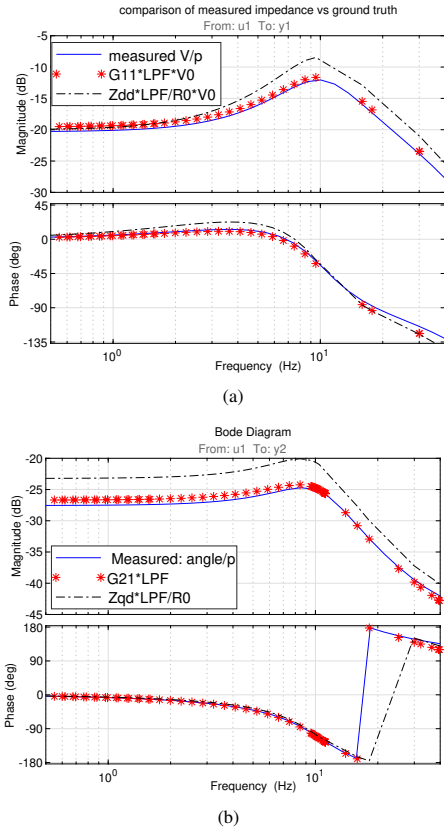


FIGURE 12: The simulated measured impedances vs. the theoretic impedances.

this subsection, we show the relationship between the two voltages, one taken at the upstream while another taken at the probing location.

The circuit in Fig. 13 has two buses: Bus 1 and Bus 2, where Bus 2 is the probing location while Bus 1's voltage will also be recorded.

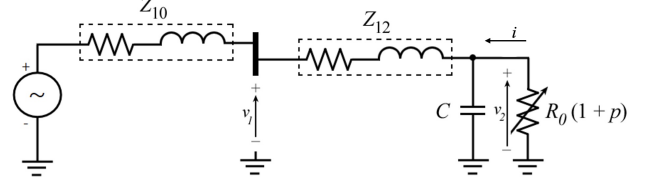


FIGURE 13: Testbed 3.  $Z_{10} = 0.01 + 0.1/s$ ,  $Z_{12} = 0.09 + 0.65/s$ ,  $C = 1$  pu.

If the impedance between Bus 1 and Bus 2 is  $Z_{12}$ , and the Bus 1's Thévenin equivalent impedance viewed from downstream is  $Z_{10}$ , we may find the two voltages are related with each other as follows:

$$\frac{\Delta v_1}{\Delta v_2} = \frac{Z_{10}}{Z_{10} + Z_{12}}. \quad (15)$$

If the impedances are in the  $dq$ -frame and are 2-by-2 matrices, then the relationship between the two voltage vectors are:

$$\begin{aligned} \Delta \mathbf{V}_1 &= \mathbf{Z}_{10}(\mathbf{Z}_{10} + \mathbf{Z}_{12})^{-1} \Delta \mathbf{V}_2 \\ &\approx \mathbf{Z}_{10}(\mathbf{Z}_{10} + \mathbf{Z}_{12})^{-1} \mathbf{Z}_{\text{apparent},c1} \frac{p}{R_0} \mathbf{V}_0 \end{aligned} \quad (16)$$

where  $\mathbf{Z}_{\text{apparent},c1}$  notates the first column of the apparent impedance viewed at the probing location: Bus 2.

Therefore, it can be seen that the voltage measured at the upstream location also contains the information of the apparent impedance. The measured voltage and angle at Bus 1 and Bus 2 vs. the perturbation at Bus 2 are compared with the results based on the analytical equations in (16). Fig. 14 shows the comparison results.

Fig. 14(a) shows the voltage spectra at two locations. Fig. 14(b) shows the angle spectra at two locations. It can be seen that the measured spectra agree with the ground truth very well. All spectra show a peak at 9 Hz, which implicates that at any location, the measurements can always reflect the closed-loop system poles or the system oscillation modes.

#### IV. Simulate measurements of distribution systems with IBRs

Next, we simulate measuring the apparent subsynchronous impedance of a distribution feeder using multiple simulated IBRs, as shown in Fig. 15.

Due to the complexity of this configuration, the apparent subsynchronous impedance of the system cannot be found analytically. So we chose a different method to determine ground truth: compare the results of our simulated GridSweep measurement with the results of a different probing method that relies on a current source to find the apparent subsynchronous impedance (Section B). We simulate with both a weak grid and a strong grid, as shown in Table 1. As expected, the strong grid does not show significant oscillations, while the weak grid shows oscillations. In Section C, we compare the GridSweep measurements when IBR2's control varies in a weak grid. In Section D, we

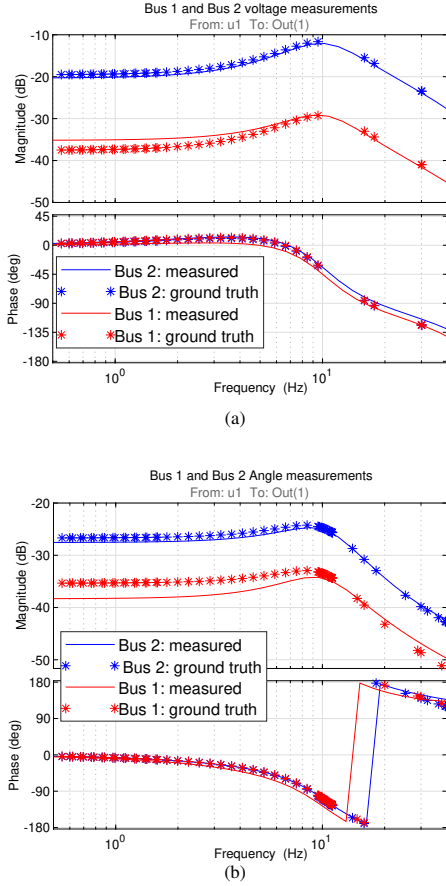


FIGURE 14: Comparison of the voltage spectra and angle spectra from data and the ground truth: (a) the voltage spectra that tracks  $Z_{dd}$ ; (b) the angle spectra that tracks  $Z_{qd}$ .

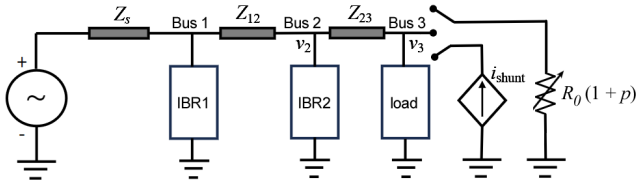


FIGURE 15: A single-phase distribution feeder with multiple IBRs.

examine the GridSweep measurements at different locations of a strong grid.

TABLE 1: Two scenarios of the distribution feeder.

|             | $Z_s$         | $Z_{12}$     | $Z_{23}$     | $Z_{load}$ |
|-------------|---------------|--------------|--------------|------------|
| Weak grid   | $0.5 + j0.25$ | $0.2 + j0.2$ | $0.1 + j0.1$ | 0.7        |
| Strong grid | $0.1 + j0.1$  | $0.2 + j0.2$ | $0.1 + j0.1$ | 0.4        |

### A. Description of Two Scenarios

The distribution feeder's line impedances  $Z_s$ ,  $Z_{12}$ ,  $Z_{23}$  will be set differently for two scenarios, as shown in Table 1.

The first scenario in sections B and C demonstrates oscillatory characteristics under weak grid conditions. The apparent

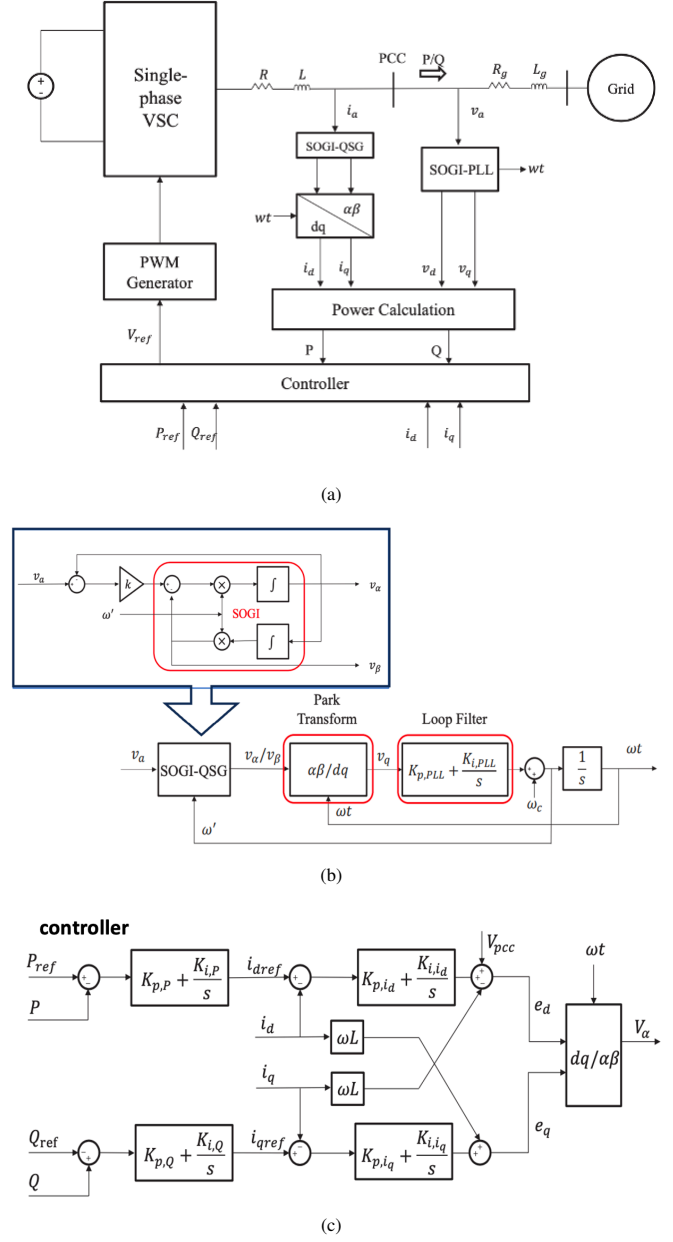


FIGURE 16: (a) Overall IBR control structure and its circuit topology ( $R$  and  $L$  are for the choke filter); (b) the SOGI-PLL structure, and (c) the PQ controller structure.

impedance shows peaks in its subsynchronous spectra. The peaks imply that the system has poorly damped oscillation modes. In contrast, the second scenario in Section D has a relatively stiff feeder. Simulated measurements show the lack of peaks in the subsynchronous spectra, implying low risk of oscillation.

In our simulation the single-phase distribution feeder's nominal RMS voltage is set to 190.52 V and the power rating is set as 4-kW. This is also the rating of the two IBRs. The single-phase IBR's dc side is directly connected to a 400-V dc voltage source. Fig. 16 shows the overall control structure of a grid-following converter and the circuit topology. The

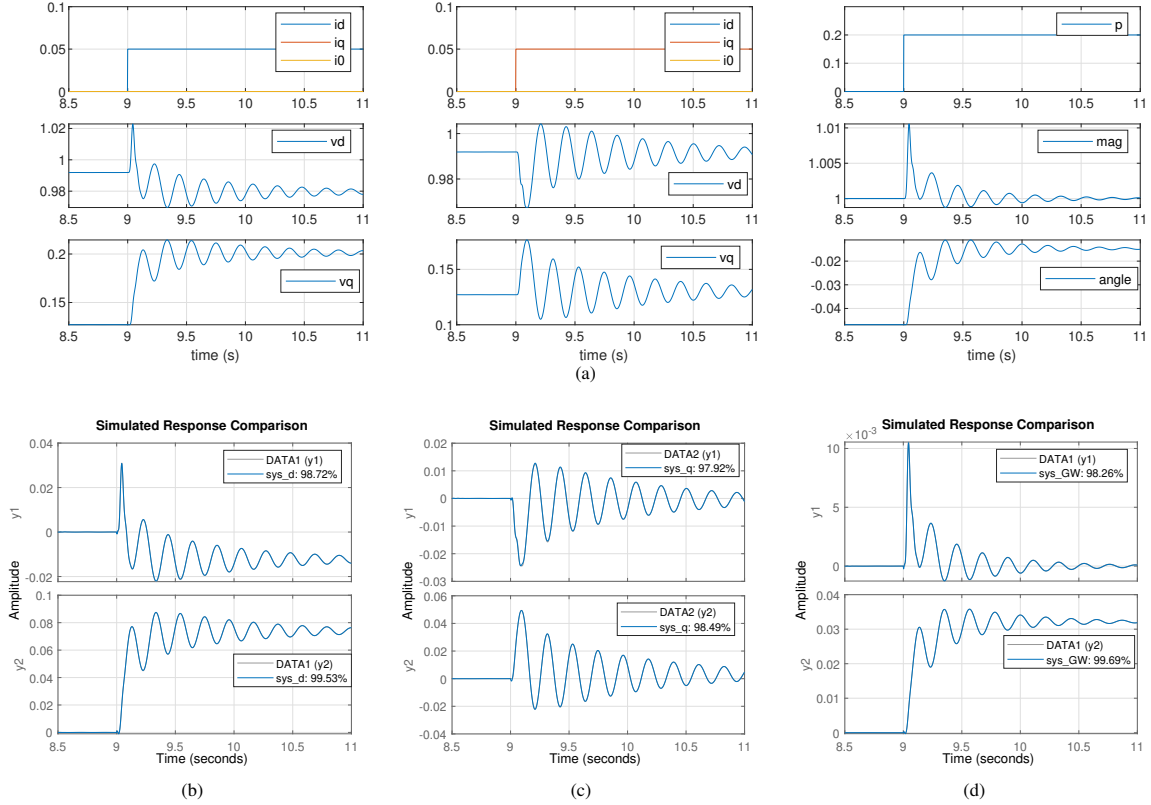


FIGURE 17: (a) Step response data collected. Columns 1&2: current injection. Column 3: GridSweep. (b)(c)(d) System identification by use of the input/output data. (b)  $d$ -axis shunt current injection. (c)  $q$ -axis shunt current injection. (d) GridSweep.

control has two main blocks: the synchronizing unit and the controller that regulate real power and voltage (or reactive power).

The detailed synchronizing unit and the PQ controller are also shown in Fig. 16(b)(c). The synchronizing unit consists of two major blocks: a second-order generalized integrator based quadrature signal generator (SOGI-QSG), and a phase-locked-loop (PLL). This type of PLL is suitable for single-phase synchronization. The SOGI-QSG has a single-phase voltage as the input, and generates a copy of the input  $v_\alpha$  and its Hilbert transform  $v_\beta$ , as shown in Fig. 16(b). The quadrature signals are then used for Park transformation. The design philosophy has been presented in [16]. The resulting relationship is shown below:

$$\begin{aligned} \frac{v_\alpha}{v} &= \frac{k \frac{\omega' s}{s^2 + \omega'^2}}{1 + k \frac{\omega' s}{s^2 + \omega'^2}} = \frac{k \omega' s}{s^2 + k \omega' s + \omega'^2}, \\ \frac{v_\beta}{v} &= \frac{v_\beta \omega'}{v s} = \frac{k \omega'^2}{s^2 + k \omega' s + \omega'^2}. \end{aligned} \quad (17)$$

The quadrature signals are converted to the  $dq$ -frame variables by use of the PLL's output angle. Enforcing the  $q$ -axis component to 0 aligns the voltage space vector with the  $d$ -axis of the PLL frame. Therefore, the PLL frame tracks

the voltage space vector and the PLL's output angle aligns with the voltage phase angle at steady state.

Table 2 lists the IBR control and circuit parameters.

TABLE 2: Circuit and control parameters for IBRs.

| Description            | Parameters           | Values           |
|------------------------|----------------------|------------------|
| Power Base             | $S_b$                | 4 kW             |
| Converter Voltage Base | $V_b$                | 190 V            |
| Nominal Frequency      | $\omega_0$           | 2 $\pi$ 60 rad/s |
| Grid Voltage           | $V_g$                | 1 pu             |
| Choke Filter           | $R, L$               | 0.005, 0.15 pu   |
| Inner Loop Control     | $k_{ip}, k_{ii}$     | 0.3, 5 pu        |
| $P$ control            | $k_{Pp}, k_{Pi}$     | 0.4, 40 pu       |
| $V$ or $Q$ control     | $k_{Vp}, k_{Vi}$     | 0.4, 40 pu       |
| PLL                    | $k_{pPLL}, k_{iPLL}$ | 100, 1400 pu     |

## B. Comparison of GridSweep Measurements vs. Current Injection-based Measurements

This system is complicated, so it is difficult to find an analytical form of the apparent impedance. Instead, as a reference, we use current injection perturbation and voltage measurements to identify the apparent impedance, similar to [6]. This measured impedance is treated as the benchmark

to provide a comparison against the impedance found from GridSweep.

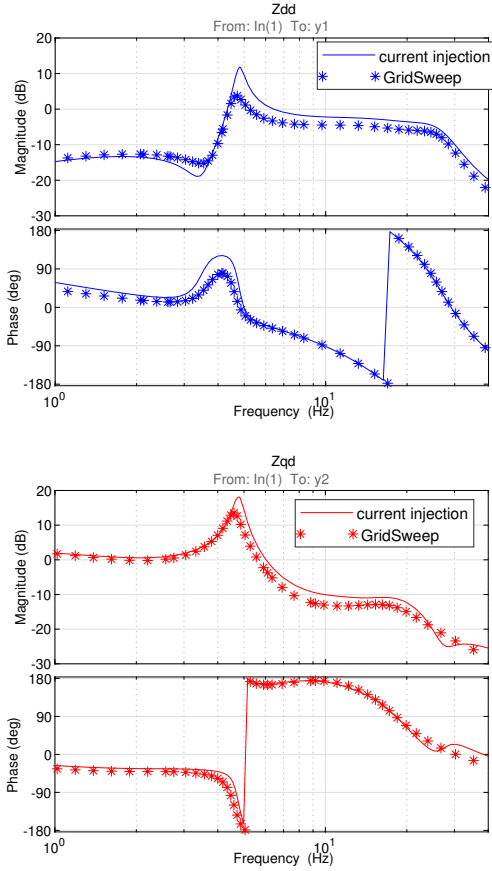


FIGURE 18: Comparison of the impedance measurements from the two methods: current injection and GridSweep.

The testbed is shown in Fig. 15, along with the current injection perturbation as well as the GridSweep perturbation. The current injection perturbation is conducted in two steps. First, the  $d$ -axis current is perturbed using a step change. The  $dq$ -axis voltage measurements are recorded. Then, the  $q$ -axis current is perturbed by a step change and the  $dq$ -axis voltage measurements are recorded. The two sets of the data are used for model identification, as shown in Fig. 17. The  $dq$  frame is a synchronous rotating frame aligned with the grid voltage. Therefore, the measured impedance is based on the grid  $dq$  frame. On the other hand, the impedance that GridSweep can observe is based on the probing site voltage. This  $dq$  frame and the grid  $dq$  frame may have an angle  $\delta$ , and  $\delta$  influences the two impedances, as follows:

$$\mathbf{Z}_{GW} = T \mathbf{Z}_{\text{grid}} T^{-1}, \quad (18)$$

where  $\mathbf{Z}_{GW}$  is the impedance that can be detected by GridSweep while  $\mathbf{Z}_{\text{grid}}$  is the impedance based on the grid  $dq$  frame.  $T$  is the transformation matrix and the above

relationship has been derived in [17].

$$T = \begin{bmatrix} \cos \delta & -\sin \delta \\ \sin \delta & \cos \delta \end{bmatrix} \quad (19)$$

Fig. 18 shows the comparison of the  $dd$  and  $qd$  components of the impedance based on the two methods: current injection and GridSweep. Both impedances are based on the  $dq$  frame aligned with the voltage at the local probing bus. It can be seen that both methods lead to comparable results. We conclude that the GridSweep method is capable of identifying the subsynchronous apparent impedance.

### C. Comparison of GridSweep Measurements for Different IBR Controls

We further compare the GridSweep simulated measurements for the same distribution feeder, except that IBR2's  $q$ -axis outer control has been changed from voltage control to reactive power control. In the first case, the distribution feeder has a damped oscillation mode at 4.5 Hz; while in the second case, the distribution feeder has a poorly damped oscillation mode at 6 Hz. Fig. 19(a) show the simulated GridSweep perturbation and output data. The measured spectra based on the sets of the data are shown in Fig. 19(b). It can be clearly seen that the spectra show a sharp peak at 6 Hz implicating poorly damped oscillations.

The time-domain data in Fig. 19(a) show that the voltage magnitude has a larger steady-state increase for case 2; while the angle has a greater steady-state increase for case 1. This observation matches the  $Z_{dd}$  and  $Z_{qd}$ 's characteristics for the two cases in the low-frequency region. Additionally, the time-domain data show 4.5-Hz damped oscillation in case 1 and 6-Hz poorly damped oscillations in case 2. This observation also matches the peaks in  $Z_{dd}$  and  $Z_{qd}$  for the two cases. For case 1, the peak appears at 4.5 Hz, while for case 2, the peak appears at 6 Hz. The 6-Hz peak is much sharper compared to the 4.5-Hz peak, implicating a much more poorly damped oscillation mode.

We conclude, again, that the subsynchronous spectra measurement of GridSweep method can capture the subsynchronous oscillation modes in an IBR-intense feeder.

### D. Comparison of measurements at different locations

In this comparison, the distribution feeder has its impedances configured to represent a strong grid condition. In this scenario, the system experiences minimal oscillations. The voltage measurements at two locations (Bus 2 and Bus 3) are recorded for analysis. Note that Bus 3 is the probing location, and the measured voltage and angle spectra directly indicate the apparent impedance viewed at Bus 3. Bus 2's measurements reflect the apparent impedance viewed at Bus 3 multiplied by a ratio of Bus 2's upstream impedance ( $Z_2$ ) vs  $Z_2 + Z_{23}$ :  $\text{ratio} = \frac{Z_2}{Z_2 + Z_{23}}$ .  $Z_2$  is the impedance viewed from the Bus 2's terminal of Line 2-3.  $Z_2$  can be expressed as follows:

$$Z_2 = (Z_{12} + Z_1) // Z_{\text{IBR2}}, \quad Z_1 = Z_s // Z_{\text{IBR1}}. \quad (20)$$

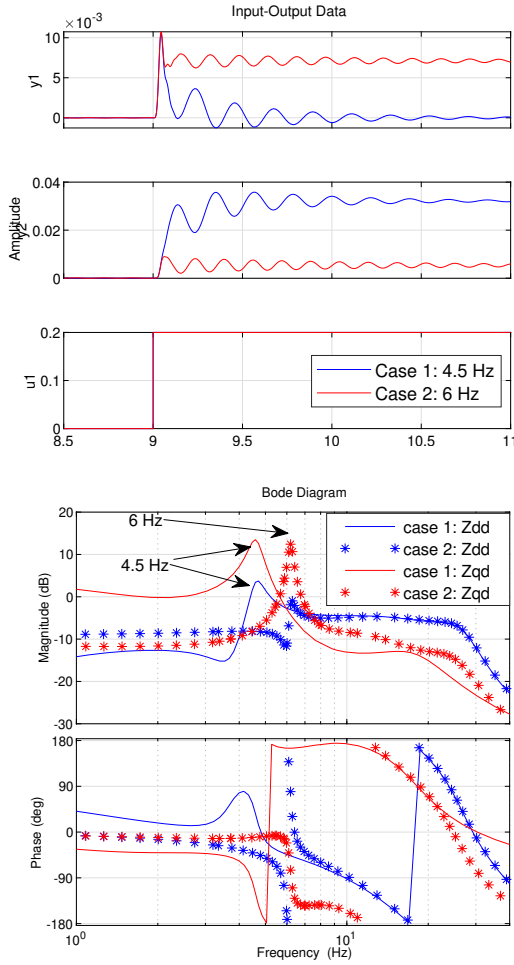


FIGURE 19: Comparison of the GridSweep measurements for damped 4.5-Hz oscillations vs marginally damped 6-Hz oscillations. (a) The perturbation and the output data. (b) The resulting spectra.

This ratio is always less than 1. Therefore, the magnitudes of the spectra at Bus 2 are less compared to those at Bus 3.

This point has been confirmed by Fig. 20. Fig. 20(a) shows the perturbed responses collected at Bus 2 and Bus 3, while Fig. 20(b) shows the measured impedance components. It is important to note that the overall shape for the frequency response is visible from both measurements, suggesting that if there were an oscillatory mode it would be visible from both locations.

## V. Conclusion

This paper examines GridSweep's probing and measuring approach for determining the subsynchronous apparent impedance of a distribution grid. Using simple cases where the apparent impedance can be explicitly calculated, we demonstrate that by extracting the voltage magnitude and phase angle from the continuous point-on-wave voltage measurement and identifying the relationship between the two components and the perturbation, the GridSweep approach provides relevant information on subsynchronous apparent

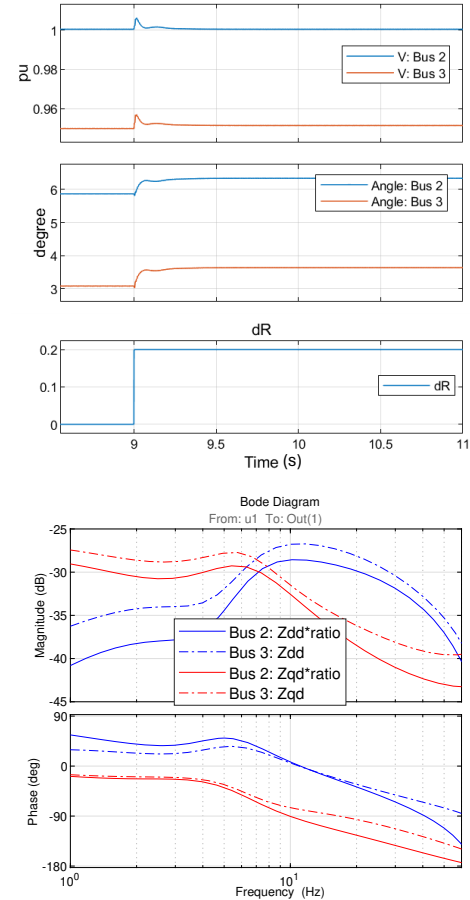


FIGURE 20: Comparison of the voltage measurements at Bus 2 and Bus 3. (a) Time-domain data. (b) Identified impedance components.

impedance spectra. Because the GridSweep approach provides a method of measuring the subsynchronous impedance of a distribution feeder using only 120-volt outlet connections, we conclude that this measurement method may well be useful for evaluating risk of oscillation in distributed IBR deployments.

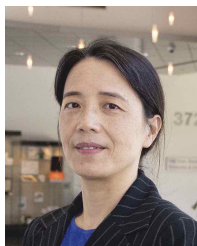
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