

Article

Impact of Impedances and Solar Inverter Grid Controls in Electric Distribution Line with Grid Voltage and Frequency Instability

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Abstract: The penetration of solar energy into centralized electric grids has increased significantly during the last decade. Although the electricity from photovoltaics (PVs) can deliver clean and cost-effective energy, the intermittent nature of the sunlight can lead to challenges with electric grid stability. Smart inverter-based resources (IBRs) can be used to mitigate the impact of such high penetration of renewable energy, as well as to support grid reliability by improving the voltage and frequency stability with embedded control functions such as Volt-VAR, Volt-Watt, and Frequency-Watt. In this work, the results of an extensive experimental study of possible interactions between the unstable grid and two residential-scale inverters from different brands under different active and reactive power controls are presented. Two impedance circuits were installed between Power Hardware-in-the-loop (P-HIL) equipment to represent the impedance in an electric distribution line. Grid voltage and frequency were varied between extreme values outside of the normal range to test the response of the two inverters operating under different controls. The key findings highlighted that different inverters that have met the same requirements of IEEE 1547-2018 responded to grid instabilities differently. Therefore, commissioning tests to ensure inverter performance are crucial. In addition to the grid control, the residential PV installed capacity and physical distances between PV homes and the substation, which impacted the distribution wiring impedance which we characterized by the ratio of the reactive to real impedance (X/R), should be considered when assigning the grid-supporting control setpoints to smart inverters. A higher X/R of 3.5 allowed for more effective control to alleviate both voltage and frequency stability. The elimination of deadband in an aggressive Volt-VAR control also enhanced the ability to control voltage during extreme fluctuation. The analysis of sudden spikes in the grid responses to a large frequency drop showed that a shallow slope of 1.5 kW/Hz in the droop control resulted in a >65% lower sudden reactive power overshoot amplitude than a steeper slope of 2.8 kW/Hz.

Keywords: smart inverter; grid voltage instability; grid frequency instability; grid-supporting functions

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1. Introduction

In electric distributed feeders, the line impedance is characterized by the X/R , which can be used to determine the stability and controllability of the grid [1–5]. In general grid stability studies, a weak grid refers to an electric grid that has an X/R ratio ≤ 1 , and a strong grid can be described with an X/R ratio > 1 , but the specific value is not well defined and can be varied differently based on experiments and simulations [6–9]. There have been limited studies evaluating the impact of grid instability in weak grid compared to strong grid interconnections. A study on the effect of the X/R ratio on an AC distribution line with a 4.5 MW wind turbine integrated was conducted by Chawda et al. [9]. In the study, the X/R ratio at the point of common coupling (PCC) was varied to simulate weak grid conditions ($X/R = 1$) and strong grid conditions ($X/R = 5$). The low value of the

X/R ratio was found to reduce the level of active power generated by wind and decrease the operating voltage at the PCC from 1 p.u. when $X/R = 5$ to 0.89 p.u. when $X/R = 1$. Alizadeh et al. studied the impact of the X/R ratio on voltage stability and response during an increase in wind power penetration in a wind farm model [10]. In a low X/R of a 0.65 distribution line case, the voltage variation can go over 4%, while in a distribution line with an X/R of 1.54, the voltage barely deviates. As a result, it is crucial to study whether different grid conditions and electric distribution line configurations impact the ability of the grid to accommodate higher renewable energy penetration.

In modern grid systems, the power generation at the inverter-based resources (IBRs) leads to a smaller X/R ratio than the conventional power generation systems that have longer feeders, leading to technical issues with the reactive power control at the grid [11]. The effect of the X/R ratio on PV-integrated grid behavior was studied by Sarkar et al. [5]. Their simulation results based on radial distribution networks with varied X/R ratios demonstrated that voltage variation and the permissible photovoltaics (PVs) penetration level can be influenced by a change in the feeder X/R ratio. Ahmed et al. investigated a possible influence of the X/R ratio on the dynamic performance of distributed energy resources (DERs) in a microgrid system [3]. The simulation results showed that when the microgrid becomes more resistive ($X/R \leq 1$) or weaker, the dynamic performance of DERs to implement frequency control using frequency droop was less efficient. To mitigate the effects of instability in renewable-integrated systems, most smart PV inverters manufactured after 2018 are equipped with grid-supporting functionalities, including Volt-VAR, Volt-Watt, and low voltage/frequency ride through, to alleviate grid fluctuations by controlling voltage level, active, and reactive power. As the inverter's dynamic control performance is limited by the inductance and resistance of the local circuit between the inverter and the PCC, the X/R ratio on feeders is an important parameter to consider when evaluating grid controls to minimize instability [12].

While a number of studies on the effects of the X/R ratio on feeders were conducted in wind energy systems, a very limited amount of research was conducted on grid-tied PV systems, and most were conducted using a software simulation as described above. Our work highlights the measured impacts using the Power Hardware-in-the-loop (P-HIL) testbed with actual residential-scale PV system hardware as deployed in PV-connected homes. In general, a P-HIL simulator enables the integration between software simulation and physical hardware components, providing the capability to explore the real-time behavior of the equipment under simulated conditions. The investigation of grid stability and analysis using P-HIL testbeds has been reported [13–17]. In this work, we analyzed the impact of different X/R ratios on grid stability controls and the interaction between two commercially available smart inverters using physical equipment comparable to the ones connected to the utility's feeders. While the interaction between inverters has been investigated only in weak network models [13,18], combinations of strong grids and weak grids are both discussed and compared in this work. A physical distance represented by an actual distribution wiring between the grid connecting point and the IBRs is also an important factor leading to serious impacts on electric grid instability. To achieve a range of realistic X/R ratio conditions representing a range of distribution line distances, impedance circuits were designed and built, allowing us to explore X/R from 0 (purely resistive) to infinity (purely inductive). As the actual smart PV inverters were used in this work, the effects of the smart inverter's internal circuits on the grid fluctuations were taken into account. Additionally, based on the previous findings discussed in [19,20], different inverter limitations can be found in actual operations despite the inverters meeting IEEE 1547-2018 standards. These factors cannot be accurately replicated in modeling software but are useful as lab-scale results to help explain the inverter's operating behavior in the field.

In terms of the impact on grid frequency, a lack of spinning mass and inertia in IBRs can cause a displacement of the overall spinning mass and lower the inertia of the power system, reducing the ability to control the inertia response and affecting the frequency and angular velocity of the grid [21]. Eventually, a low inertia system would suffer a high rate of frequency change and frequency deviation, which possibly leads to a complete system

blackout [22]. A number of frequency response studies have been conducted to observe the impact of high PV penetration on grid stability [21–24]. You et al. modeled the impact of high PV penetration on frequency response in the U.S. Eastern Interconnection system [25]. Their results showed that the performance of the system frequency response decreased with an increasing level of PV penetration. Similarly, Eftekharnajad et al. examined the impact of a reduced inertia system on the frequency transient stability of the Western U.S. interconnection system with different amounts of PV penetration [26]. Their findings also suggested that high PV penetration causes more severe fluctuations in the transient response of real and reactive power.

To maintain the system frequency in the nominal operation range, a frequency droop (also called a Frequency–Watt) control was implemented in most commercially available smart inverters with a certified IEEE 1547-2018 standard to counter overfrequency and underfrequency incidents. By applying the droop control, the frequency can be adjusted by curtailing the active power output of the inverter. In [27,28], the frequency droop characteristics without a deadband showed an improvement in the dynamical performance by a reduction in overshoot compared to controls with the deadband. This also applies to other smart inverter functions such as Volt-VAR and Volt–Watt functions [29,30]. The performance of frequency droop control has been widely investigated in systems with high PV penetration and was proven to enhance the frequency response behavior of the electric system [27,31,32]. Generally, feeders with a higher PV penetration tend to experience overfrequency because generation exceeds load. Consequently, the droop control will start curtailing the active power output when the frequency increases beyond the setpoint to try to restore frequency to a normal operating range [32].

The frequency droop control was proved by several studies to be an effective tool to alleviate the frequency violation issue [33,34]. However, there has been very limited research focusing on the impact of other system factors such as distribution line impedance or differing levels of PV penetration. This may be because the droop control is not yet widely implemented. A P-HIL testbed has been used as a real-time simulated low-voltage electric network since it offers an interface for hardware devices and can be implemented to study interactions between multiple inverters at multiple PCCs on the grid [35]. Nonetheless, most P-HIL test setups reported in the IBRs research field are software simulations [13–17]. Similarly to the voltage instability study, some of the responses cannot be accurately replicated in modeling software because of the device protection and control access by manufacturers. This work highlights the measured impacts using a P-HIL test facility with actual residential-scale PV inverter hardware as deployed in grid-connected homes.

This paper discusses the impacts of different system configurations on the secondary distribution network. The goals are to fill this gap in the existing research and highlight the influence of system components on the inverter control so the grid-supporting functionalities can be modified for the optimum operation based on the system configurations. To analyze the effects of different ratios of reactance to resistance (X/R) connected between the grid and the inverters, the P-HIL testbed was used with integrated line impedances to mimic the residential-scale grid-tied PV systems with different physical distances from the local substation. Grid voltage and frequency fluctuations were simulated and experimented with the two inverters operating under different grid control setpoints. Volt-VAR curves were modified to observe the system performance under unstable grid voltage, while frequency droop curves were adjusted to observe the system performance under unstable frequency conditions. The key contributions of this paper are described below.

- An analysis of the effects of different X/R ratios connected between the grid and/or to the inverters under unstable grid voltage and Volt-VAR control. The physical distances in a distribution system are observed by a range of X/R ratios between the grid and IBRs.
- An evaluation of 16 different operating configurations of the secondary voltage distribution system.

- An analysis of the impacts of the X/R ratio in terms of power reliability, grid fluctuations, and the ability of the inverters to perform frequency droop under unstable grid frequency conditions.
- An evaluation of different frequency droop settings, constant power factors, and the equivalent of physical distances in a distribution system between the grid and IBRs characterized by a range of X/R ratios.
- An observation of possible interactions between smart inverters under the same grid-supporting control mode but different dynamical settings.

This paper is divided into two studies: voltage and frequency instability analyses. Both studies shared the same P-HIL setup and quantitative evaluation method described in Sections 2.1 and 2.2. The results of the unstable grid voltage experiments are presented in Section 3.1, while the results of the unstable grid frequency are reported in Section 3.2.

2. Experimental Setup and Methods

2.1. P-HIL Testbed and Impedance Circuit Configurations

A P-HIL laboratory was used as a testbed where its power and communication configurations were described in [19]. Both smart PV inverters, Inverter-A and Inverter-B, were involved in this work with different grid control setpoints being assigned. To observe the effect of different resistance and inductance combinations on the power quality and grid stability, two impedance circuits were designed and installed between the grid emulator and the inverter AC output to represent the impedance in the local electric distribution lines. As presented in Figure 1, one impedance circuit is tied to the grid emulator before the PCC, while another circuit is tied directly to Inverter-A. As a result, two inverters will operate under different voltages compared to the grid (V1), and the voltage seen by Inverter-A (V3) is different from what is seen by Inverter-B (V2) when the second impedance circuit is connected. This allows for test scenarios where two homes with smart inverters are located some distance apart on the same distribution feeder. Additional information on equipment models can be found in Table S1.

Table 1 describes the impedance circuit combinations that were tested in this work. Each impedance circuit can be configured to have an adjustable X/R ratio from 0 (a pure resistive element) to infinity (a pure inductive element). The second impedance circuit box which was connected to Inverter-A can also be physically moved to Inverter-B, while the first impedance circuit box is always tied to the grid emulator as it was designed with different configurations for the different rated current going through resistors. A combination of line resistors and inductors of the first circuit box is different from the second one after the rated real power on the circuit box was considered to prevent an excessive power dissipation through the resistors, causing device melting or burning.

Table 1. Integrated impedance circuit configurations.

X/R Ratio	At Inverter-A			At Grid		
	R (Ω)	L (mH)	Z (Ω)	R (Ω)	L (mH)	Z (Ω)
0	0.5	None	0.5	0.5	None	0.5
0.5	0.5	0.25	0.509	0.5	0.66	0.559
3.5	0.15	1.33	0.523	0.067	0.66	0.258
∞	None	1	0.377	None	0.66	0.249

The typical range of X/R in low to medium voltage distribution feeders varies from 0.25 to 4, where an $X/R < 1$ is considered low [36,37]. In this work, a grid X/R ratio of 0.5 was considered a low ratio or a weak grid, and 3.5 was considered a high ratio or a strong grid. Note that capacitors were excluded as the effect of capacitance loss was negligibly small. The actual impedance circuits designed can be found in Figure S1. Power dissipation and heating were monitored with an infrared camera and cooling airflow was provided to

the resistors as needed to keep the temperature of each component under 100 °F ($\leq 30\%$ from room temperature).

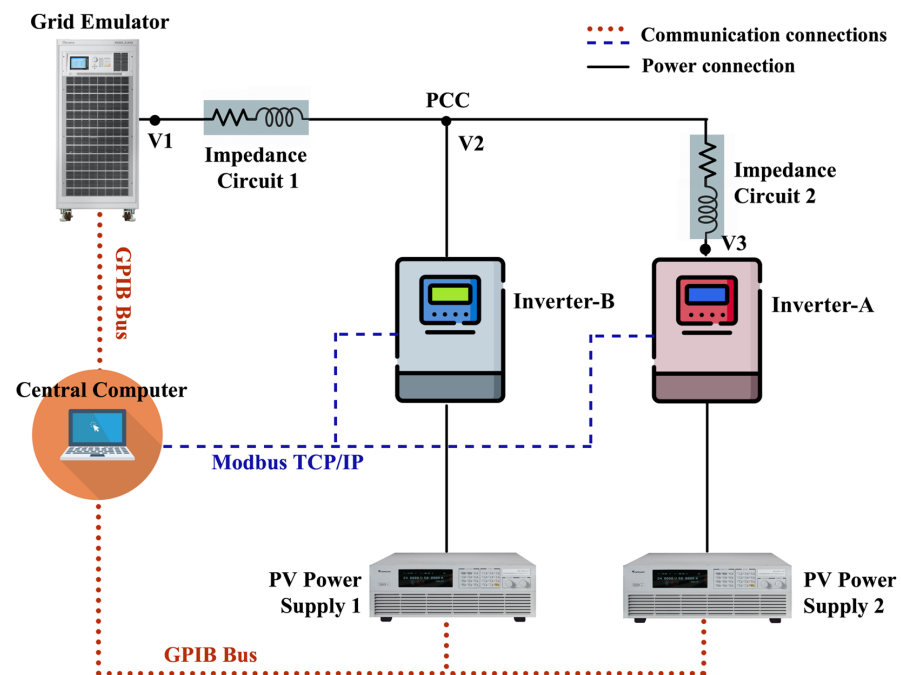


Figure 1. A power and communication diagram of P-HIL setup with integrated impedance circuits.

2.2. Data Acquisition and Stability Evaluation

Voltage and frequency fluctuation profiles were assigned to the grid emulator using SCPI commands to alter the condition every 30 s, and every 1, 3, and 5 s for the shorter voltage fluctuation tests. The full communication diagram of the P-HIL laboratory can be found in Figure S2. Two different PV power levels (600 and 1200 W_{DC}) were assigned to the inverters due to preliminary experiments showing that the fluctuations are larger when two inverters have unequal active power. With the average conversion efficiency of both inverters being 93.6% as reported in [19], the AC power output at 600 and 1200 W_{DC} were approximately 560 and 1120 W_{AC}, respectively. A power analyzer [38] was used to validate the accuracy of the measurements. Every experiment reported in this work was repeated at least three times to establish the repeatability of the results. The first data set of each experiment was selected and presented here after validating that the variance of all repeated tests was lower than 1% compared to the first data set.

For the voltage stability results presented in Section 3.1, we evaluated the performance of the two inverters based on their ability to perform voltage regulation with minimal power fluctuation. For the frequency stability ones in Section 3.2, the performance of the two inverters was assessed based on their ability to perform the active power curtailment using frequency droop control with minimal fluctuations and/or spikes caused by grid frequency variations. Quantitative analyses were performed using a Chi-square (χ^2) model, which is a statistical parameter that has been widely used for fluctuation assessments [39,40]. The calculation of the χ^2 value is obtained from (1) as

$$\chi^2 = \sum \left[\frac{(O_i - E_i)^2}{E_i} \right] \quad (1)$$

where O_i is an observed value and E_i is an expected value at point i . The expected values of the power components (both active and reactive power) were calculated by a sum of the output from the two inverters after the loss in impedance circuits was considered. The results of χ^2 were computed to quantify the severity of the response fluctuations. Normally, a larger value of χ^2 indicates a larger fluctuation. However, the quantitative results in this

work were interpreted into two aspects, especially for the voltage experiments; a fluctuation compared to the grid voltage variation and an inverter's self-fluctuation. As a result, a greater χ^2 would represent a smaller self-fluctuation but larger grid-compared fluctuation.

For the frequency study, χ^2 represents the instability of the grid and AC impedances relative to the PV inverters, so the χ^2 was interpreted as normal; a larger value of χ^2 indicates more severe fluctuation. Our main goal is to evaluate the grid instability affected by different configurations and grid control settings, and thus this section will not discuss any response offsets due to power dissipation through the impedance circuits. For the unstable grid voltage conditions, we will not focus on any inverter voltage offsets occurring normally due to the voltage drops on impedances. Key characteristics of all responses, including the magnitude and period of fluctuations, were seen in all tests except the reactive power spikes on Inverter-B which were random, as elaborately discussed in Section 3.1.2.

In addition to χ^2 , a settling time and normalized peak of the spikes were calculated to quantify the spike magnitude and time for the response to converge back to the stable point of each 30 s time frame for the responses with spikes due to a change in frequency in Section 3.2.1. Figure 2 illustrates the quantifying method to compare the grid and inverter responses of the different configurations. Settling time refers to the time required for the spike to settle down to the normal value and reach 5% of the spike magnitude after being shifted down. This calculation approach with a 5% threshold is widely applied to dynamical control systems [41,42]. To compare the spike magnitude between different system configurations, we shifted the responses to the settling value or the stabilized point of each case by aligning the normal value of reactive power to 0 VAR. For the voltage spikes analysis, all voltage responses were shifted down to 120.0 V to align with the grid operating voltage.

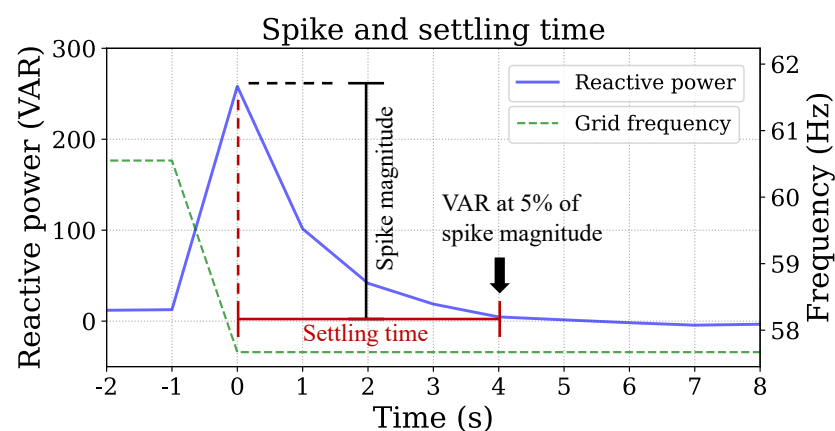


Figure 2. Example of spike magnitude and settling time evaluation.

2.3. Grid Voltage Variation and Inverter Volt-VAR Profiles

To simulate the unstable grid condition, we assigned the grid voltage variation profile shown in Figure 3 in a 30 s interval. The grid frequency was set to 60.0 Hz during all voltage variation tests to study the effects of impedances under each grid condition separately. The grid voltage was changing every 30 s within a range of 116.5 V to 124.5 V to represent extreme grid voltage fluctuations. More extreme grid voltage variations, as shown in Figure 4, with shorter time intervals (1, 3, and 5 s) were also examined to find a stabilization time of the Volt-VAR control.

To study the effect of the X/R ratio on the inverter voltage control, and to observe possible interactions between two inverters, different Volt-VAR characteristics were applied to each inverter based on their abilities and limitations, as shown in Figure 5. The Volt-VAR deadband zone was eliminated to create an aggressive Volt-VAR control on Inverter-A while using IEEE 1547-2018 standard [43] as a reference for the Volt-VAR control on Inverter-B. The reactive power setpoints were modified from $\pm 44\%$ to the maximum reactive

output available for each inverter, which is $\pm 50\%$ and $\pm 60\%$ for Inverter-A and Inverter-B, respectively. These two Volt-VAR characteristics were identified based on literature reviews and technical reports from NREL [29,44–46] as their findings indicated that the aggressive Volt-VAR setting with a fast response time potentially causes smart inverters to have negative interactions [47]. These settings shown in Figure 5 were used in all unstable voltage experiments. In this study, other power controls such as constant PF and Volt-Watt control were excluded for simplification.

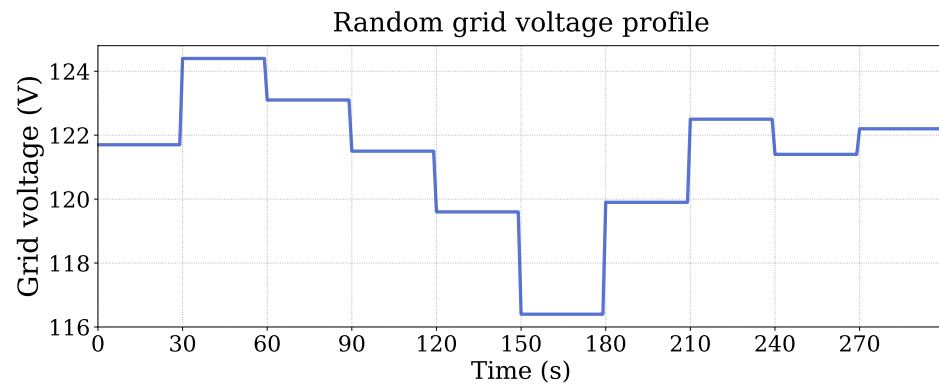


Figure 3. Grid voltage profile assigned to the grid emulator. The voltage was varying every 30 s between 116.5 and 124.5 V.

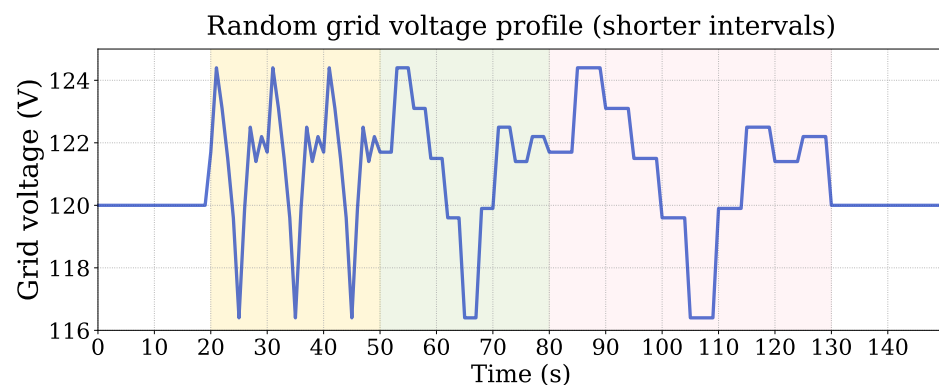


Figure 4. Grid voltage profile assigned to the grid emulator. The voltage varied between 116.5 and 124.5 V. Yellow, green, and pink areas in the plot determine 1, 3, and 5 s grid voltage fluctuations, respectively.

2.4. Grid Frequency Variation and Inverter Frequency Droop Profiles

In a related effort, we conducted a study on the impacts of the X/R ratio in the distribution line during unstable grid frequency with inverters operating with different frequency droop characteristics using the same hardware setup described in Section 2.1. Figure 6 represents the grid frequency instability profile developed for the grid emulator to output. The grid frequency was modified every 30 s between 57.5 and 62.0 Hz for 300 s to simulate extreme frequency instability. The fluctuation range was selected using the frequency ride-through mandatory operating range before tripping as a reference [48]. The emulator grid voltage V1 was always set to 120.0 V for all frequency studies.

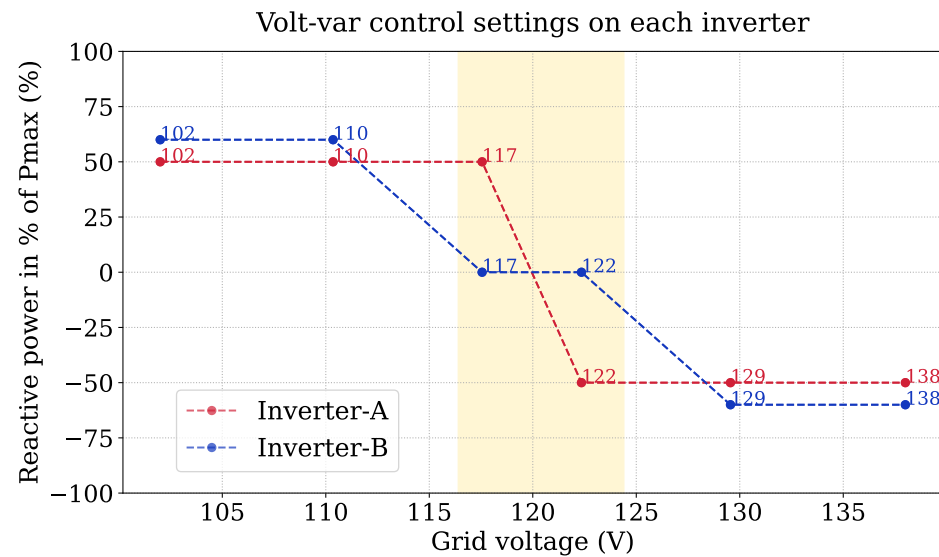


Figure 5. Profiles for inverter Volt-VAR characteristics on each inverter.

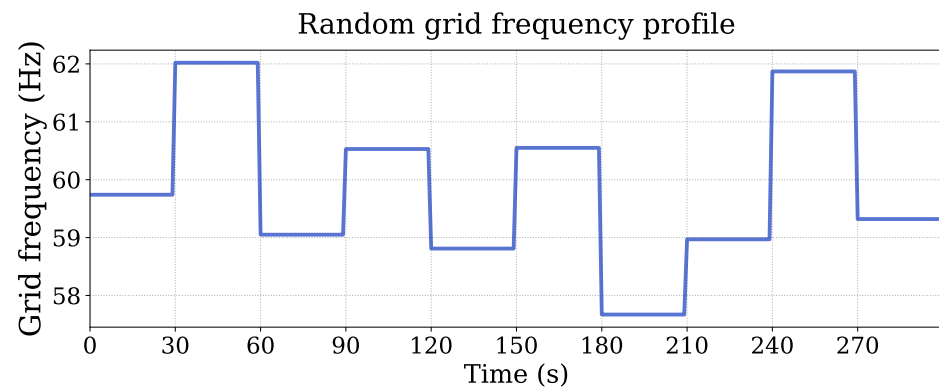


Figure 6. Grid frequency profile assigned to the grid emulator. The frequency was varying every 30 s within a range of 57.5 and 62.0 Hz while the grid voltage was always set to 120.0 V.

Different frequency droop characteristics were assigned to each inverter based on their abilities and limitations. Figure 7 presents frequency droop setpoints for each inverter compared to the droop control for PV inverters recommended by the U.S. Department of Energy's Grid Modernization Laboratory Consortium (GMLC) [49]. These recommended setpoints were also developed using a P-HIL setup to mitigate the overfrequency issues that can be caused by high solar energy penetration. We selected this characteristic as a reference to focus on assessing the active power curtailment of the frequency droop control.

The frequency droop setpoints were modified relative to the GMLC by adjusting the slopes of active power reduction. The Inverter-A and Inverter-B frequency droop controls have a 75%/Hz and 40%/Hz droop slope, respectively. These settings were used in all experiments, and again we excluded other dynamic grid-supporting functionalities such as Volt-VAR and Volt-Watt controls for simplification. The control settings were selected to be above and below the GMLC reference droop slope of 65%/Hz. However, as the objective is to observe impacts in both power components, the two constant PF, 0.85 and 1 (unity PF), were assigned to Inverter-A to compare the effects of impedances and frequency droop controls under different reactive power outputs from the inverter. In all experiments, Inverter-B was always operating at the unity PF.

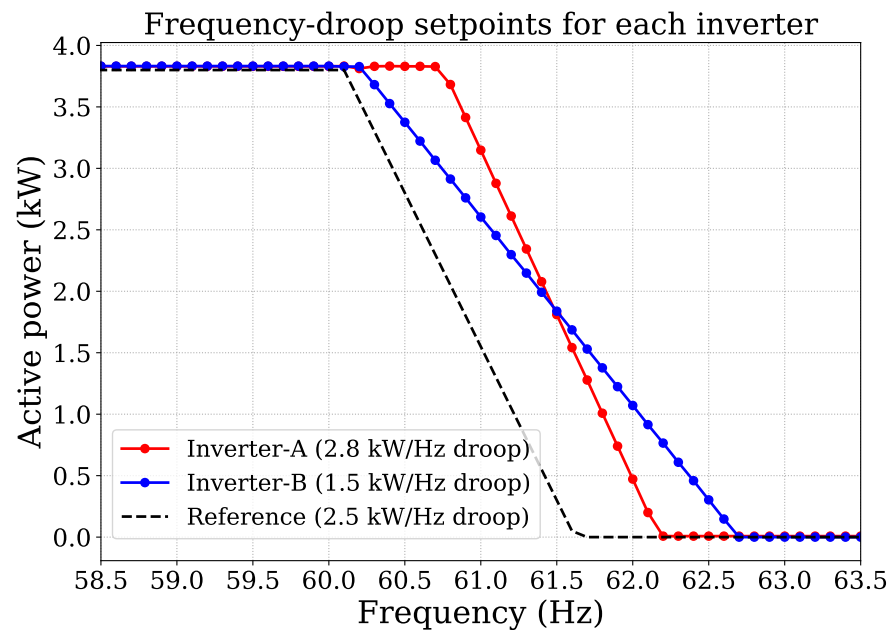


Figure 7. Frequency droop characteristics on Inverter-A and Inverter-B compared to the reference setpoints from GMLC.

The rest of this paper will be divided into two parts. The operating profiles of the grid and inverters are presented separately in Sections 3.1 and 3.2 along with the separate results between the voltage and frequency works to maintain the focus of each study.

3. Results and Discussion

3.1. Grid Voltage Instability Test

The four parameters that were varied in each test were the Volt-VAR controls, grid and inverter X/R ratios, and power dominating. We investigated all 16 possible combinations of the four parameters, as shown in Figure 8. For example, each grid X/R was tested with a different X/R at the inverter. Then, each inverter's X/R was tested under different power domination and Volt-VAR characteristics. This gives us a total of 16 different configurations. The results were analyzed based on three test conditions shown in Table 2.

Table 2. Test conditions for each result section.

Section	Voltage Profile	Fixed Parameter	Varied Parameter
Section 3.1.1	Figure 4	Volt-VAR setpoints Grid X/R = 3.5 $P_A = 600 W_{DC}$ $P_B = 1200 W_{DC}$	Inverter-A X/R
Section 3.1.2	Figure 3	Volt-VAR setpoints $P_A = 600 W_{DC}$ $P_B = 1200 W_{DC}$	Grid X/R Inverter-A X/R
Section 3.1.3	Figure 3	Volt-VAR setpoints Grid X/R = 0.5 Inverter-A X/R = 3.5	Test 1: $P_A = 600 W_{DC}$, $P_B = 1200 W_{DC}$ Test 2: $P_A = 1200 W_{DC}$, $P_B = 600 W_{DC}$

There is a conflicting aspect of the distribution system design where the reactive components can enhance the overall ability of the voltage control by smart inverters, improving grid stability during high PV penetration. However, from a grid operator's standpoint, having a low X/R may help regulate the distribution voltage on their end more

easily using transformers with movable taps. In this work, all the results were discussed mainly based on the influence of X/R on smart inverters to address the distribution system design for higher PV penetration in the future.

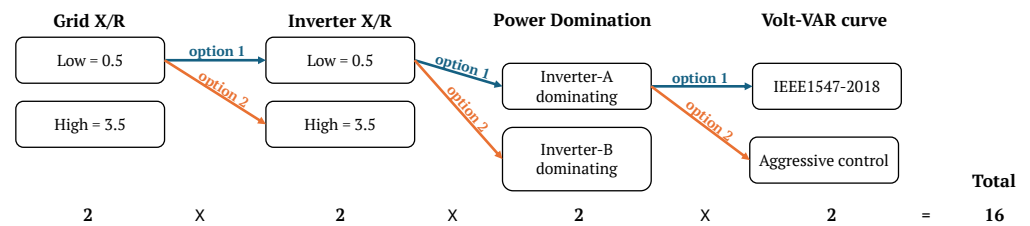


Figure 8. Sixteen possible combinations for the system configurations.

The results and analysis are described in detail in Sections 3.1.1–3.1.3. Here, we summarized the key observations. A combination of resistive and inductive elements in the distribution line has significant influences on the inverter operation and grid stability. PV inverters sharing the same or nearly the same PCC with different Volt-VAR characteristics along with different PV power levels could lead to severe grid fluctuations. The severity of the fluctuations depends significantly on the X/R ratio tied directly to the grid, while the capability of voltage control at the inverter depends on the X/R ratio on the inverter output. The key findings regarding the different impedance configurations are summarized in Table 3.

Table 3. Summary of impacts of different X/R configurations with unstable grid voltage.

X/R	Location	Voltage	Real/Reactive Power
High	Inverter	Better voltage control	No significant fluctuation
High	Grid	Smaller voltage drop	Very low power fluctuation
Low	Inverter	Larger voltage drop	No significant fluctuation
Low	Grid	Larger voltage drop	Large real power fluctuation and random reactive power spikes

3.1.1. Impacts of High X/R Ratio

The results of grid fluctuation with a relatively short grid voltage step duration (1, 3, and 5 s) for Inverter-A are shown in Figure 9 with the IEEE standard control and in Figure 10 with the aggressive control (no deadband, Figure 5). In Figure 9, both inverters were operating under Volt-VAR IEEE 1547-2018 curves, but the reactive power output was modified from $\pm 44\%$ to the maximum reactive output available for each inverter which is $\pm 50\%$ and $\pm 60\%$ for Inverter-A and Inverter-B, respectively. The voltage differences between the grid and Inverter-A are due to the voltage drop across the resistor in the impedance circuit. With higher impedances on the circuit, especially the resistive component, the voltage drop is more pronounced. However, the inverter failed to control its voltage, resulting in overvoltage events throughout these experiments. Since the grid voltage was oscillating within the Volt-VAR deadband (from 0.98 p.u. to 1.02 p.u.) 80% of the time, the Volt-VAR control hardly adjusted the reactive power to control the voltage. We also performed a quantitative analysis to compare voltage responses on Inverter-B to Inverter-A when they both operated with IEEE Volt-VAR and found that they had an identical response ($<0.3\%$ difference on average). Neither of them could control the voltage and eventually followed the grid voltage variations.

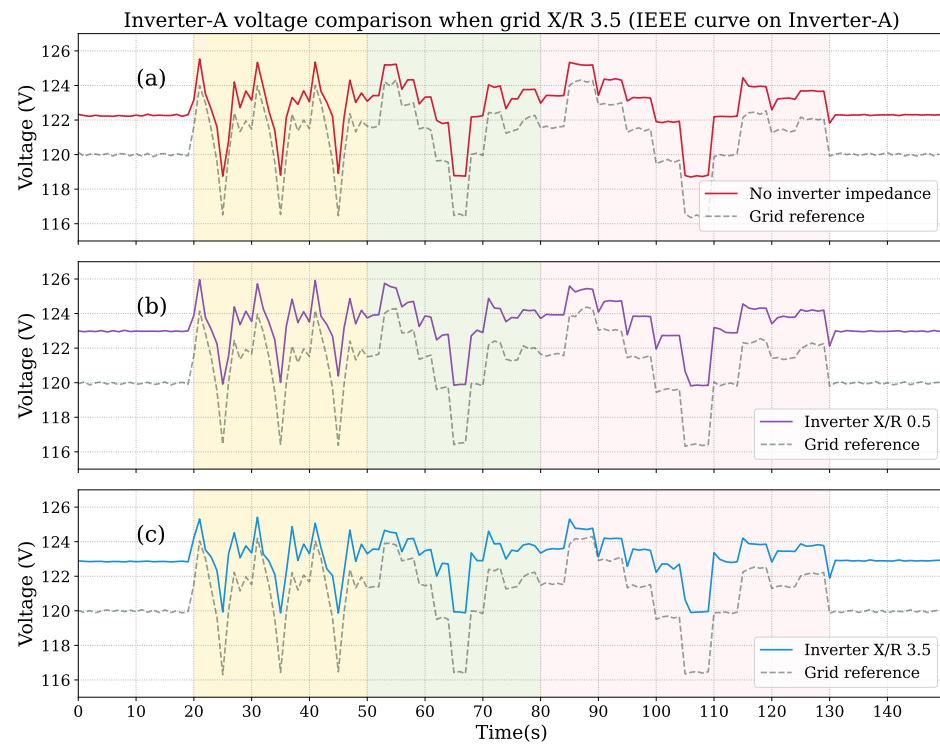


Figure 9. A comparison of voltages at Inverter-A with IEEE 1547 Volt-VAR curve and different X/R ratio at the inverter while having fixed X/R ratio of 3.5 at the grid. Yellow, green, and pink areas in the plot represent 1, 3, and 5 s grid voltage oscillations, respectively. (a) No inverter impedance, (b) low inverter X/R, and (c) high inverter X/R.

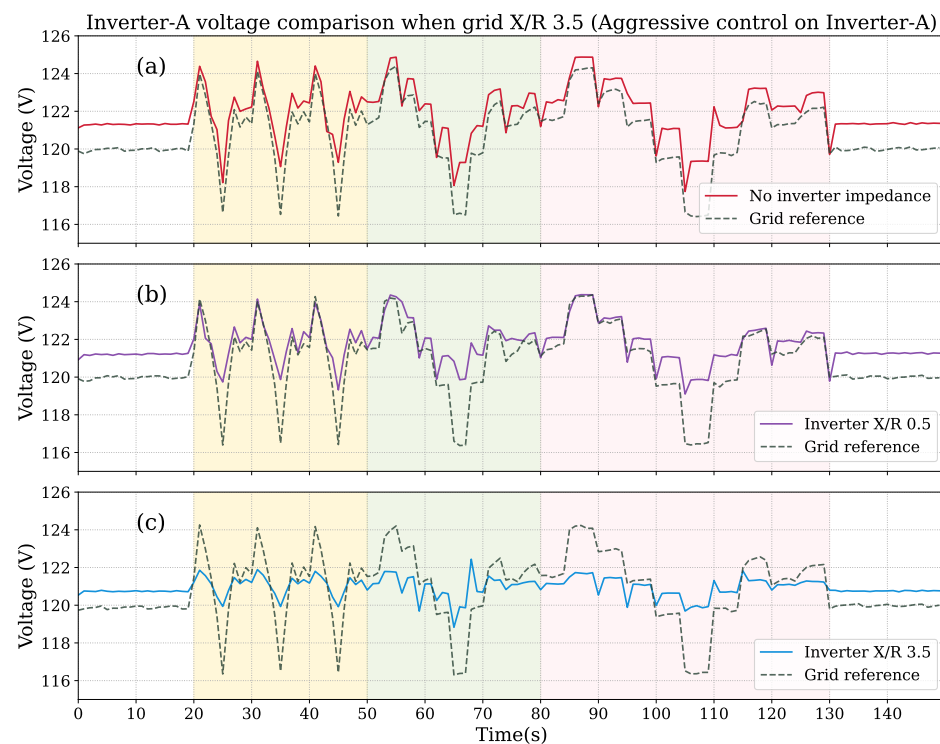


Figure 10. A comparison of voltages at Inverter-A with the aggressive Volt-VAR curve and different X/R ratio at the inverter while having the fixed X/R ratio of 3.5 at the grid. Yellow, green, and pink areas in the plot represent 1, 3, and 5 s grid voltage oscillations, respectively. (a) No inverter impedance, (b) low inverter X/R, and (c) high inverter X/R.

Compared to the same grid and X/R conditions with aggressive Volt-VAR control on Inverter-A as shown in Figure 10, its voltage control was operating more effectively with a high X/R ratio regardless of the severity of the grid voltage variation, as shown in Figure 10c. Additionally, the inverter responses were adequately fast and its voltage was always in phase with the grid voltage. Nonetheless, without the impedance circuit tied to the inverter, even the aggressive Volt-VAR control was not able to maintain the voltage close to 120 V and the inverter voltage kept following the grid variation, as exhibited in Figure 10a. Therefore, a higher X/R ratio in distribution lines can significantly enhance the inverter's voltage control capability when the inverter has aggressive control. We validated these findings by testing the ability of Inverter-B's aggressive control in comparison to its IEEE 1547-2018 Volt-VAR under the same conditions performed on Inverter-A. The results showed good agreement that the aggressive control can strengthen the ability of voltage control of the unstable grid, resulting in its voltage being 98.6% closer to 120 V than the one with the IEEE 1547-2018 curve.

In terms of the grid power quality, the fluctuation in real power is alleviated with the higher X/R on Inverter-A. However, the power fluctuations are insignificant in all cases due to the strong grid condition. The average of the grid real power fluctuations was 5.5% of the estimated grid power coming from the two inverters. We conducted more measurements and adjusted the time intervals to evaluate the stabilization time for the inverter voltage and it was found that the stabilization time was approximately 2 s. As a result, Inverter-A's Volt-VAR control will be less effective if the grid voltage is varying every 2 s or less.

The IEEE 1547.1 standard describes conformance test procedures for equipment interconnecting DERs. The 2005 version of IEEE 1547.1 only described the testing procedure for overvoltage and undervoltage conditions [50], while the grid-supporting function standards, including testing procedures for Volt-VAR and Volt-Watt controls, were introduced later in the IEEE 1547.1-2020 [51]. Consequently, inverters from different manufacturers that certified the IEEE 1547-2018 standard but not IEEE 1547.1-2020 can still have different communication preferences, power-generating capabilities, and control limitations.

Table 4 shows the quantitative results of the performance evaluation of Inverter-A's voltage control presented in Figure 9 and 10 as the χ^2 for the voltage. A higher χ^2 in Group I represents better control since it means the actual voltage was not following the grid voltage fluctuations. A lower χ^2 in Group II represents better control since it means the voltage signal at the inverter has smaller noise.

Table 4. A quantitative assessment of voltages at Inverter-A with IEEE 1547 and aggressive Volt-VAR control performances in terms of grid-compared fluctuation as normalized χ^2 (I) and inverter self-fluctuation as normalized χ^2 (II).

X/R at Inverter-A	Volt-VAR on Inverter-A	χ^2 (I)	χ^2 (II)
None	IEEE 1547	0.167	1
0.5	IEEE 1547	0.293	0.735
3.5	IEEE 1547	0.487	0.547
None	Aggressive	0.273	0.883
0.5	Aggressive	0.465	0.599
3.5	Aggressive	1 (Best)	0.149 (Best)

Overall, Inverter-A showed better voltage control with a higher X/R ratio and with the aggressive Volt-VAR. Additionally, a higher X/R ratio with aggressive control can mitigate the voltage fluctuation of the inverter itself. In comparison to the lower X/R ratio, the inverter self-fluctuation is minimally influenced by the Volt-VAR control mode, yet the aggressive setting could help maintain the voltage level closer to 120 V than the standard setting. Note that all experiments reported in this section to evaluate the voltage control ability were conducted with the high X/R ratio connected to the grid. The impacts of low X/R on the grid are discussed in the next section.

3.1.2. Impacts of Low X/R Ratio

In Section 3.1.1 above, the inverter had an X/R of 3.5, representing a strong grid with low resistive losses. In this section, the results showed that the impedance of the grid has a stronger influence on power stability when having smart inverters operating under the Volt-VAR controls. Figure 11 demonstrates the impact of a low X/R ratio at the grid to the power components. The fluctuation in active power in Figure 11a,b is noticeably large, ± 500 W, relative to the total AC power of ~ 1700 W regardless of the impedance at the inverter. In comparison, Figure 11c shows that with a high X/R connected to the grid, the fluctuation in active power becomes negligible. The reactive power stability from these same three configurations as Figure 11 is shown in Figure 12. Although the inverter will try to regulate the voltage using the aggressive Volt-VAR control due to its impedance, Figure 12a,b exhibit a minor fluctuation in reactive power ± 80 VAR, which is not found with a high grid X/R ratio, as shown in Figure 12c. No significant fluctuation occurs when the grid has a high X/R ratio, as seen in Figure 11c and 12c. Therefore, the higher X/R ratio would provide more stable real and reactive power to the electric network and enhance the ability of voltage control of the inverters. Note that Inverter-A was operating with the aggressive control while Inverter-B was operating with the standard control throughout all experiments in this section (Section 3.1.2).

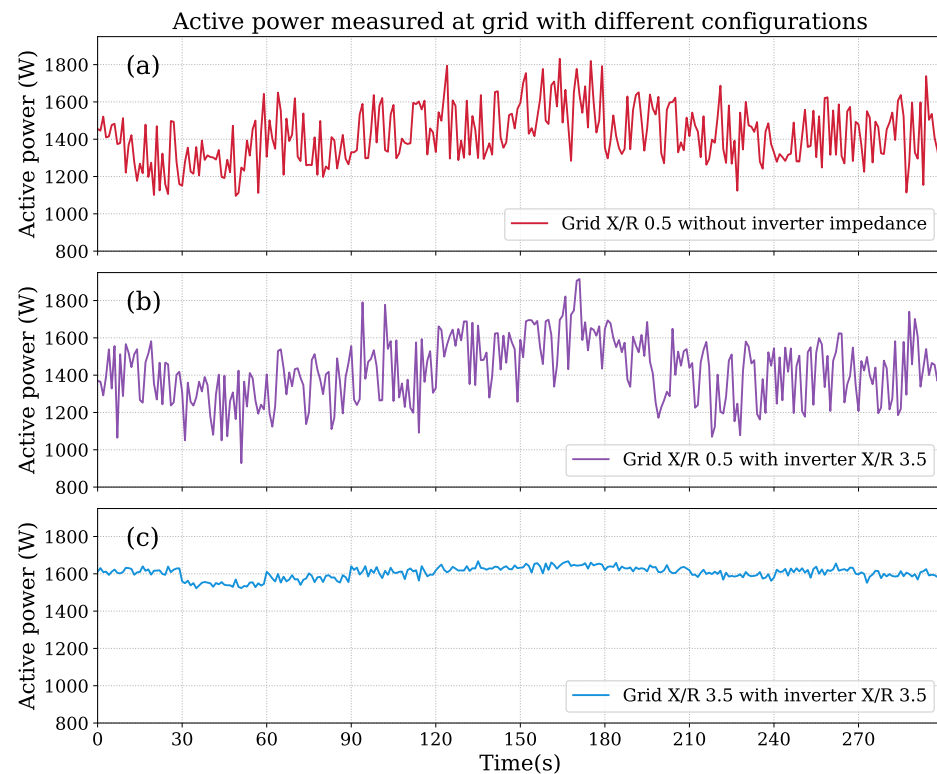


Figure 11. A comparison of the grid active power with different X/R configurations at the grid and Inverter-A. The grid voltage was varied every 30 s. (a) Low grid X/R without inverter impedance, (b) low grid X/R with high inverter X/R, and (c) high X/R at both.

Table 5 compares χ^2 values of different grid and inverter X/R configurations to evaluate the grid responses discussed in Figures 11 and 12. To calculate the normalized χ^2 , the expected active power at the grid is determined by a sum of the active power outputs of both inverters in each configuration under ideal conditions. As the reactive power at both inverters was not absorbed at a constant level due to the Volt-VAR, we identified the expected reactive power based on the average reactive power output at the grid in each interval (every 30 s). The results indicated that a high X/R at the grid and Inverter-A demonstrates the most stable responses in both real and reactive power,

whereas a lower X/R at the grid can lead to a significant fluctuation in active power at the grid. Referring to Section 2.1, the impedances at Inverter-A represent the further distance between a distribution feeder and a house, so now the V3 at Inverter-A is different from what V2 Inverter-B responds to, resulting in a possible interaction between two different Volt-VAR controls impacting the overall power quality at the grid. The grid fluctuation is seen to be slightly less severe when both inverters are reading the same grid voltage. However, the active power still shows a large fluctuation due to the low X/R ratio. These findings support the results in Section 3.1.1 that the best configuration for the distribution feeder could be line impedances with the a X/R ratio at the PCC and the residential ends.

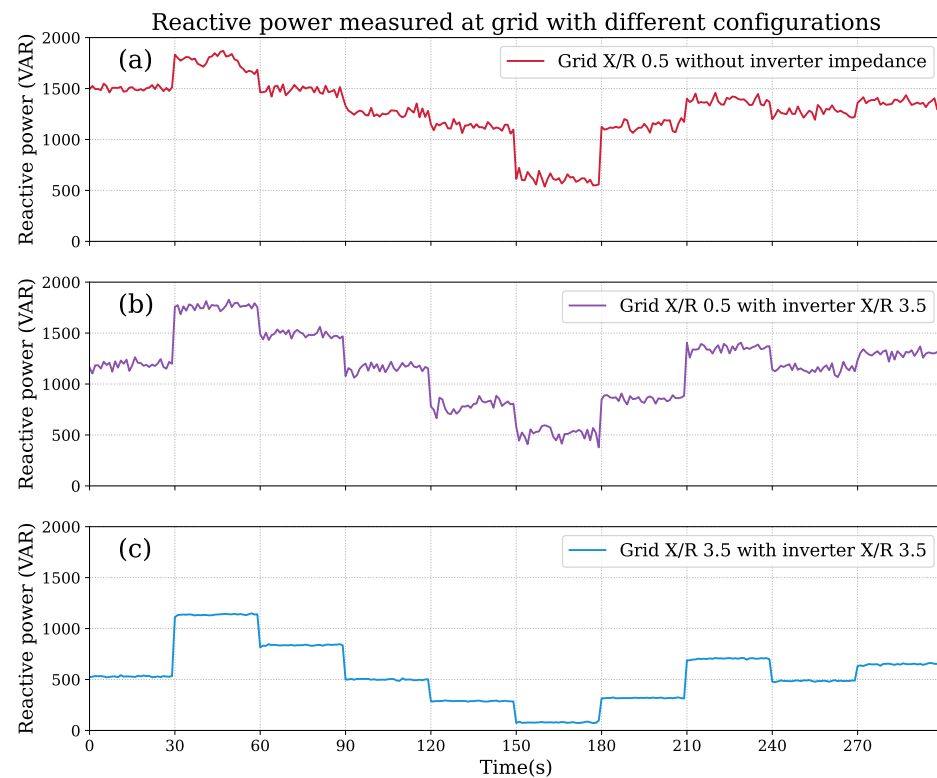


Figure 12. A comparison of the grid reactive power with different X/R configurations at the grid and Inverter-A. The grid voltage was varied every 30 s. (a) Low grid X/R without inverter impedance, (b) low grid X/R with high inverter X/R, and (c) high X/R at both.

Table 5. A quantitative assessment of the power quality at the grid with different configurations in terms of grid fluctuation as normalized χ^2 (P) and χ^2 (Q) for real (Figure 11) and reactive power (Figure 12), respectively.

Grid X/R	Inverter-A X/R	χ^2 (P)	χ^2 (Q)
0.5	None	0.887	0.742
0.5	3.5	1	1
3.5	3.5	0.088 (Best)	0.043 (Best)

Another observation from the experiment with the X/R ratio of 0.5 at the grid-connected point is that the reactive power at Inverter-B showed fluctuations at random voltage levels during unstable grid conditions, as shown in Figure 13, for three identical voltage scans. The reactive power of the inverter can oscillate in a range of ± 300 VAR and randomly occur with Inverter-B. After several experiments with different time intervals of the grid voltage variation, we found that the reactive power spikes only occur with a low grid X/R and will be seen randomly independent of the grid voltage level. It is suspected

that this behavior is a particular characteristic of Inverter-B and this information will be valuable to the manufacturer for further investigation.

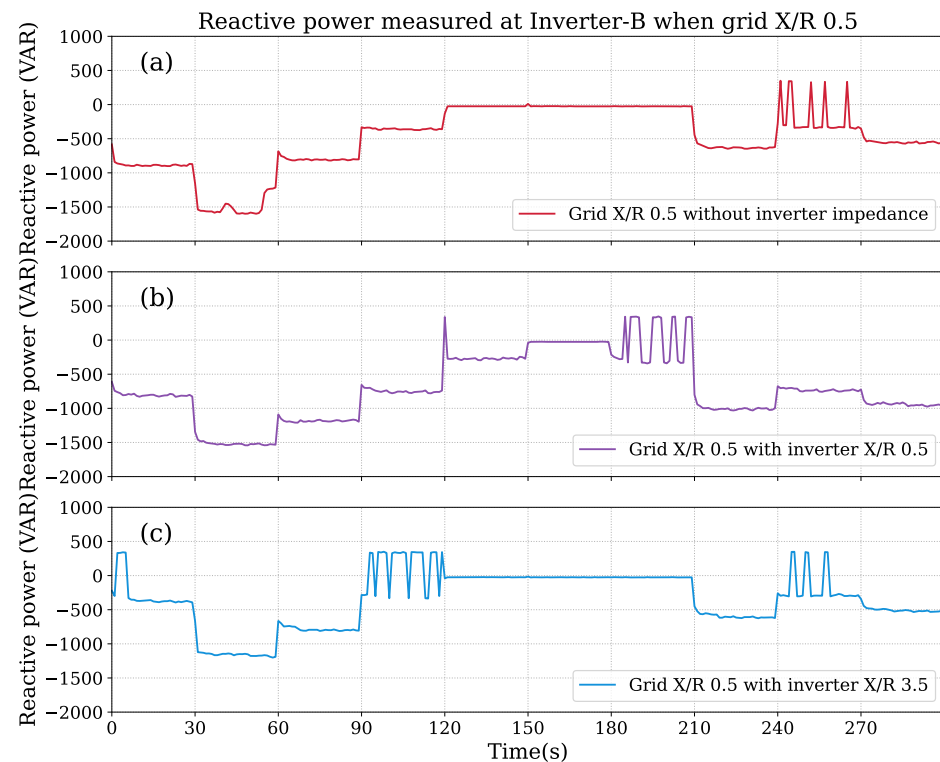


Figure 13. Unexpected spikes in reactive power on Inverter-B when the grid has a low X/R ratio which does not occur in the strong grid. Results from three identical scans are shown. (a) Low grid X/R without inverter impedance, (b) low grid and Inverter-A X/R, and (c) low grid but high Inverter-A X/R.

3.1.3. Interactions Between Two Inverters

In the experiments described above in Sections 3.1.1 and 3.1.2, Inverter-B always had 1,200 W_{DC} with the standard IEEE Volt-VAR control and Inverter-A had a 600 W_{DC} input with the aggressive Volt-VAR control while the X/R ratio and impedance location was varied. To investigate possible interactions between smart inverters under different Volt-VAR characteristics, two sets of experiments were conducted where the PV power output of each inverter was interchanged, so one inverter was always set to operate at the output twice as often as another one (see Table 2). The inverter voltage, active, and reactive power of each set were analyzed to observe the possible influence of a mismatch in the Volt-VAR setpoints of the inverters at the same PCC. Figure 14 presents the grid responses, where the grid impedance has an X/R of 0.5 and Inverter-A has an X/R of 3.5 while switching the power levels between the two inverters. There is a clear difference in the active power when Inverter-B power-dominated Inverter-A, as presented in Figure 14b.

The fluctuation is suspected to be larger if the inverter with lower impedance tied on its side has a higher PV output, causing its control and/or the connected impedances to have more influence on the electric network. In this case, with the weak grid, Inverter-B was operating with IEEE 1547 control, so the reactive and active power quality was not as stable as when Inverter-A had dominant power with an aggressive Volt-VAR. The results were confirmed by a quantitative comparison shown in Table 6. The grid voltage response in each interval is not influenced by the different power levels as the χ^2 of voltage in each case is negligible. While the grid reactive power has a substantial fluctuation in the Inverter-B-dominated case, the real power shows the most unstable response among all

grid parameters. This finding indicates that the real power instability can be alleviated by the power-dominating inverter having a high X/R, as displayed in Figure 14.

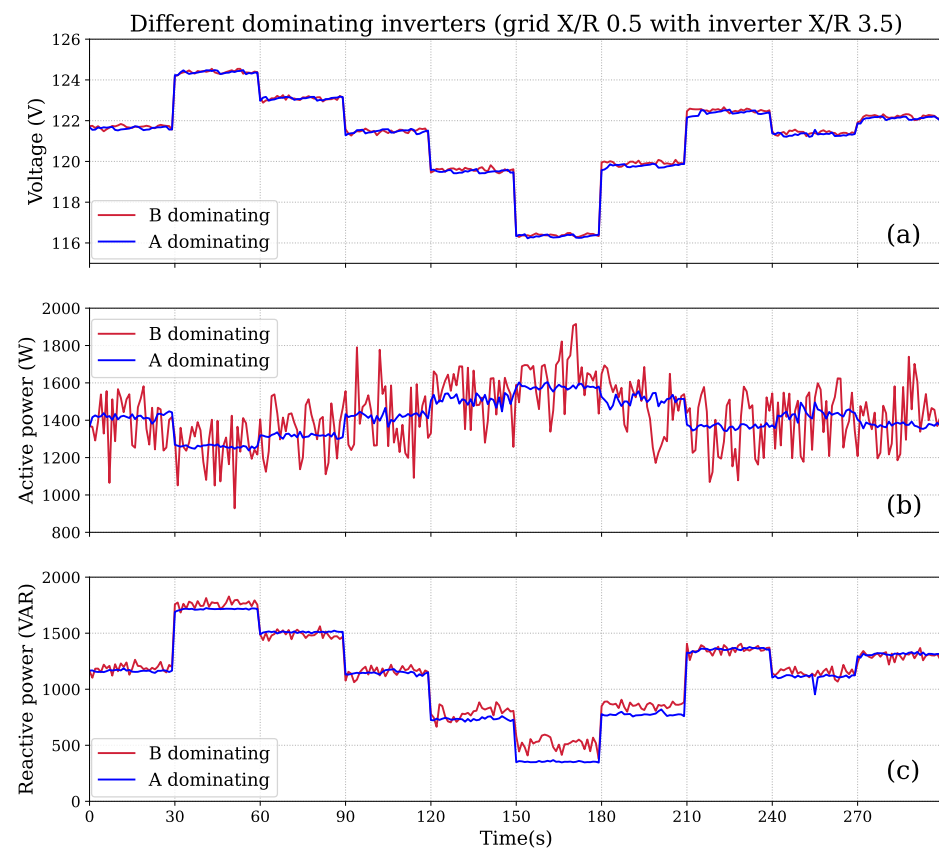


Figure 14. A comparison of grid responses with different weak grids and high X/R at Inverter-A. The grid voltage was varied every 30 s. The dominating inverter was operating at 1200 W while another inverter was operating at 600 W. (a) Grid voltage, (b) grid active power, and (c) grid reactive power.

Table 6. A quantitative assessment of the grid responses with different power levels between both inverters shown in Figure 14 as χ^2 .

Grid Parameter	Inverter-A (W)	Inverter-B (W)	χ^2
Voltage	1200	600	0.014
Voltage	600	1200	0.016
Real power	1200	600	67.8
Real power	600	1200	4140
Reactive power	1200	600	54.6
Reactive power	600	1200	494

However, the effects of the power-dominating inverter were investigated and showed that the ability to mitigate real power fluctuation is also dependent on inverter brands. Figure 15 compares real power responses measured at the grid under different configurations and dominating inverters. While Inverter-B could not help mitigate the grid fluctuation even with the aggressive Volt-VAR, Inverter-A demonstrated the ability to alleviate the fluctuation, and the different combinations of the X/R and Volt-VAR curves can lead to different levels of mitigation of the fluctuation. To quantitatively analyze and compare the effectiveness of different configurations, the expected active power was calculated.

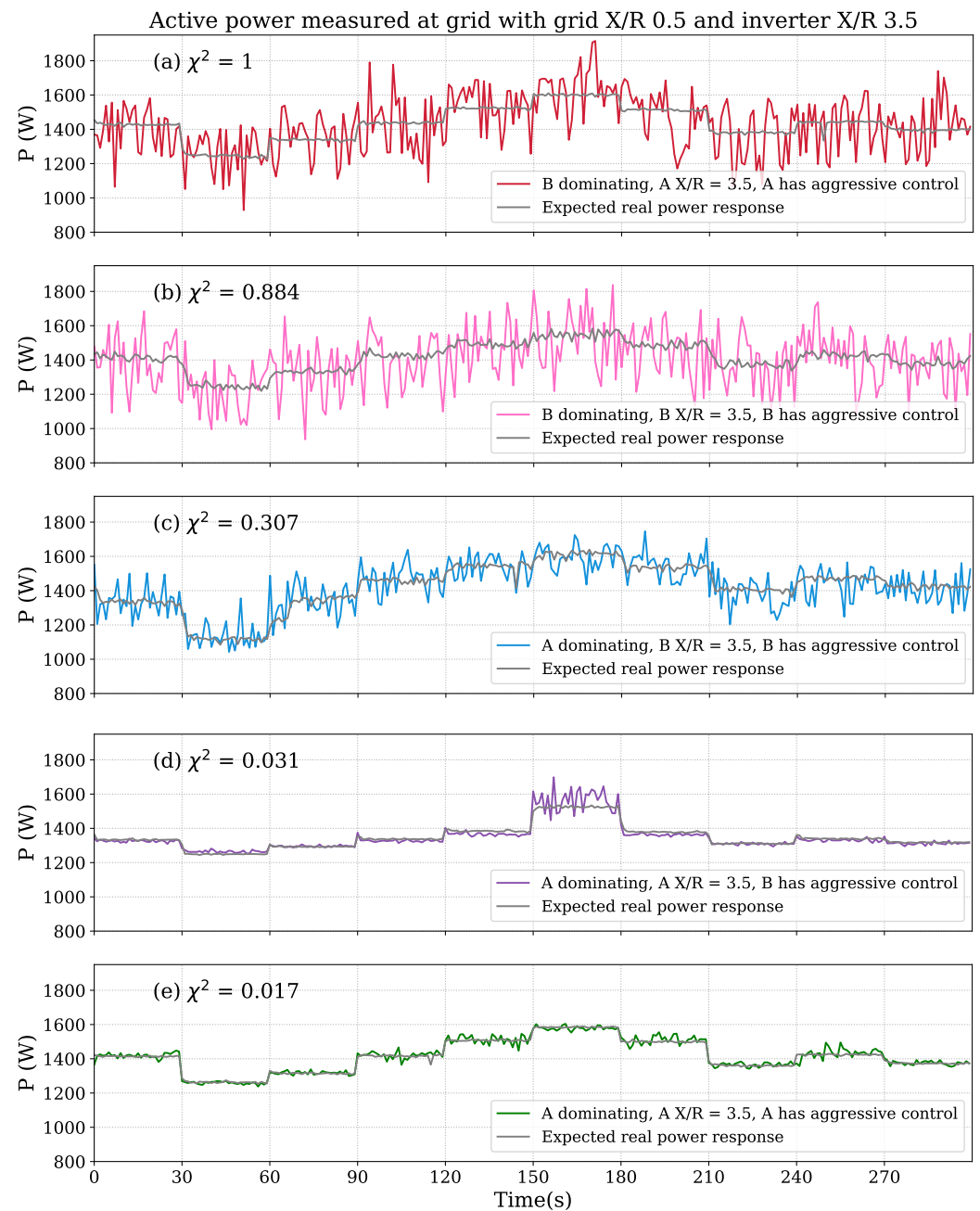


Figure 15. A comparison of weak grid responses with high X/R at the different inverters. The grid voltage was varied every 30 s. The dominating inverter was operating at 1200 W while another inverter was operating at 600 W. Both inverters always operated with different Volt-VAR setpoints. When one operated with the IEEE 1547 curve, another one would operate with the aggressive control.

The result of the quantitative analysis shown in Table 7 indicates that the real power fluctuation at the grid can be alleviated when Inverter-A has dominating power at 1200 W_{DC}. Additionally, the best configuration to reduce the grid fluctuation is when Inverter-A has a high X/R ratio connected at the inverter, as shown in Figure 15e. At the lowest grid voltage of 116.5 V, Inverter-A can help stabilize the grid's real power with its aggressive Volt-VAR, resulting in the lowest χ^2 value (0.017). When repeating the experiments with Inverter-B being power-dominated, it could not help mitigate the grid fluctuation regardless of the X/R and inverter control. This leads to the conclusion that the inverters from different manufacturers have their own levels of grid-supporting capability based on the inverter's

internal circuit, and each inverter may have a different optimal X/R ratio that can help stabilize the grid fluctuation.

Table 7. A quantitative assessment of the grid active power with different configurations shown in Figure 15 as normalized χ^2 .

Dominating Inverter	Inverter X/R	Volt-VAR Control	χ^2
Inverter-B (Figure 15a)	Inverter-A = 3.5	Inverter-A aggressive Inverter-B IEEE 1547	1
Inverter-B (Figure 15b)	Inverter-B = 3.5	Inverter-A IEEE 1547 Inverter-B aggressive	0.884
Inverter-A (Figure 15c)	Inverter-B = 3.5	Inverter-A IEEE 1547 Inverter-B aggressive	0.307
Inverter-A (Figure 15d)	Inverter-A = 3.5	Inverter-A IEEE 1547 Inverter-B aggressive	0.031
Inverter-A (Figure 15e)	Inverter-A = 3.5	Inverter-A aggressive Inverter-B IEEE 1547	0.017

Within our P-HIL laboratory environment, it is challenging to find evidence of inverter interactions as only two interconnected split-phase inverters are evaluated. To create undesirable interactions among PV inverters, it was reported that more than 10 of 3–5 kW split-phase inverters need to be involved [52]. However, we were able to simulate and observe the fluctuations where the conditions of large grid impedance with Volt-VAR controls have also been supported by other literature. The reported findings here will be useful for field tests where the effects and interactions of more inverters are considered.

3.2. Grid Frequency Instability Test

All findings can be categorized into two groups based on the pattern of responses as discussed in Sections 3.2.1 and 3.2.2. While there were sudden spikes of reactive power and voltage due to a change in frequency, neither the active power nor current showed spikes. Nonetheless, active power fluctuations were exhibited in some ranges of grid frequency, whereas the reactive power showed minimal fluctuation during those time frames and voltage showed no fluctuation at all. We analyzed the impacts of three system factors on the grid and inverter responses, which are inverter power domination, X/R ratios, and constant PF.

3.2.1. Spikes in Reactive Power and Voltage Responses

The sudden spikes were observed in the inverter's reactive power and voltage every time the grid frequency changed, affecting the grid's reactive power stability. We defined the directions of spikes as overshoots (positive spikes) and undershoots (negative spikes). Based on data visualization and quantitative analysis, the spike direction was always the opposite of the direction of frequency alteration. For example, when the grid frequency drops, there will be a reactive power jump or overshoot. Also, the magnitude of the spikes was correlated with the magnitude of the change in frequency. For instance, the spikes would become larger when the grid frequency significantly drops [53]. Figure 16a shows the grid reactive power responses with different X/R ratios and active power domination.

The key finding is that different inverters' power domination significantly impacts the spikes, whereas X/R ratios show minimal influence. Note that the results discussed in this section were plotted from $t = 0 - 180$ s to have a clearer visualization and to emphasize findings that only occurred in that period. Table 8 shows a comparison of the reactive power responses in terms of the spike amplitude and settling time at the maximum reactive power overshoot occurring at $t = 180$ s in every case. Overall, the quantitative results show that the reactive power spikes have a strong dependence on the dominating inverter. Inverter-B provides higher stability by having a smaller spike magnitude, reducing by 57%

the average reactive power spikes (both undershoot and overshoot) compared to Inverter-A. By only switching the dominating inverter, the maximum reactive power overshoot caused by the largest frequency drop is reduced by 67.5%. Note that the first 30 s time frame shows the difference in the grid's reactive power level due to the inverter domination. As Inverter-A was operating with 0.85 PF, the grid reactive power would absorb more reactive power when Inverter-A was dominating.

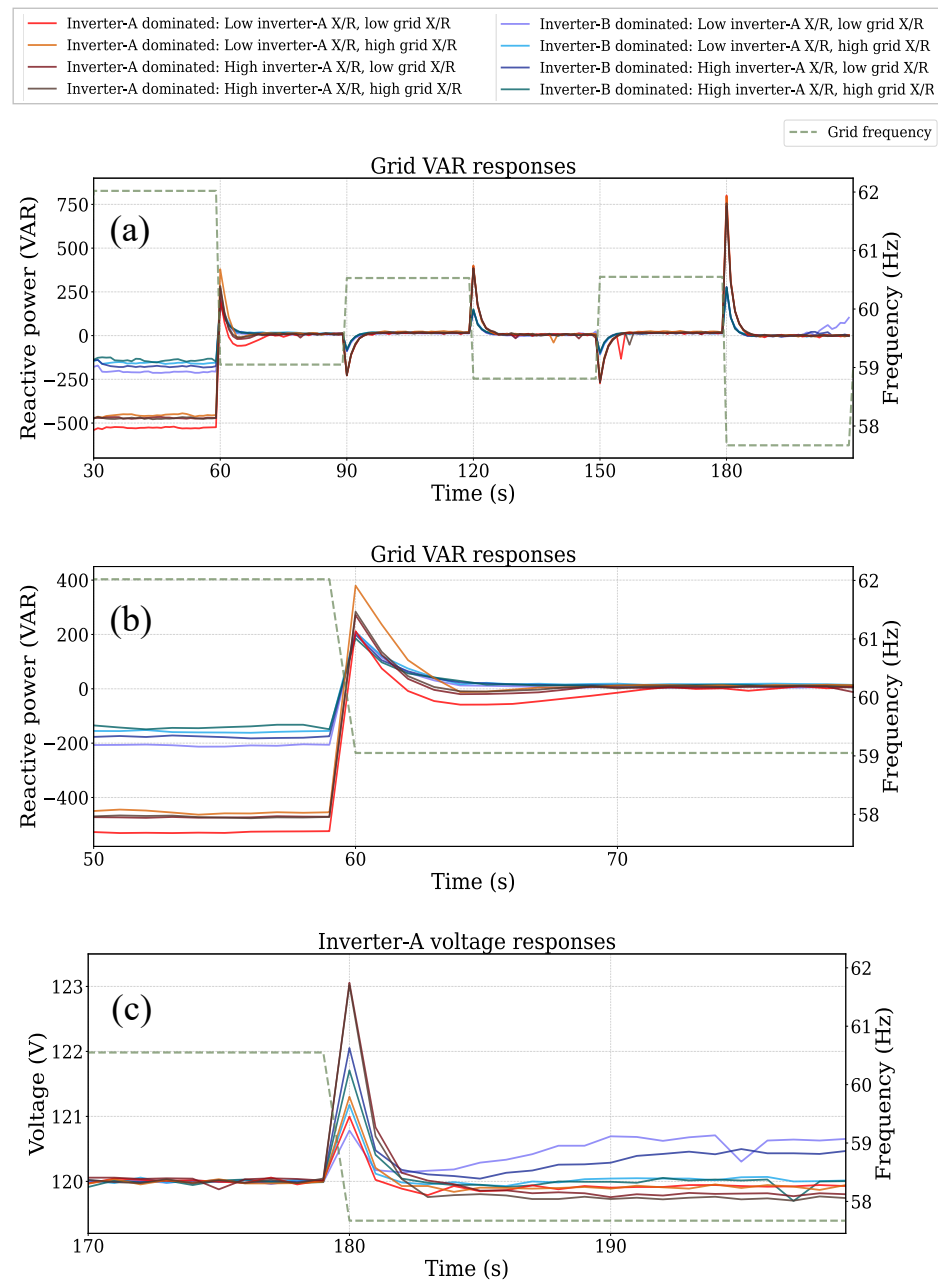


Figure 16. Grid and Inverter-A responses under different power domination and X/R ratios at each location. Inverter-B was operating with the unity PF while Inverter-A was operating with 0.85 PF. (a) Grid VAR responses for 6 frequency steps, (b) grid VAR responses for a single step in higher resolution, and (c) Inverter-A voltage responses for a different single step to show the largest voltage spikes.

Additionally, there was a subsequent dip due to a large frequency drop (2.97 Hz) after the overfrequency event at $t = 60$ s. This type of response dip can be seen in all Inverter-A-dominated cases yet was not seen in the Inverter-B-dominated ones. Figure 16b

presents the grid reactive power responses in Figure 16a but examines the subsequent dip of 3.0 Hz around 60 s more closely. This can be expected as a characteristic of particular inverters where reactive power outputs can diverge from their expected values during fast frequency transients [49]. For example, a large generator source suddenly going offline can lead to a large decrease in frequency. As Inverter-A has a steeper droop slope (75%), it leads to more fluctuation due to its control sensitivity. This result indicates that the grid reactive power stability can be strengthened when the inverter with a gentler droop slope dominates by its PV power.

Table 8. A quantitative comparison of reactive power responses under each system configuration. The settling time at the maximum Q spike at $t = 180$ s is always at 5 s regardless of the system configuration.

Dominating Inverter	Inverter X/R	Grid X/R	Responses		
			Average Settling Time (sec)	Settling Time for Subsequent Dip at $t = 60$ s (sec)	Maximum Q Spike Amplitude at $t = 180$ s Second (VAR)
Inverter-B	Low	Low	5.8	No subsequent dip	260
	Low	High	6.0		269
	High	Low	5.9		280
	High	High	5.6		274
Inverter-A	Low	Low	6.5 (Longest)	11 (Longest)	801 (Highest)
	Low	High	5.6	5	795
	High	Low	6.4	9	739
	High	High	6.0	7	756

In terms of the impact of distribution line impedances, the X/R ratio at the grid has more influence on the subsequent dip than the X/R connected to the inverter. The strong grid can alleviate the dip while the weak grid with a low inverter X/R leads to the largest dip, as shown in the red line in Figure 16b. It has been speculated that the observed instability is due to internal inductive and capacitive components inside the inverters. Others also have reported the same reactive power behavior due to a change in frequency without explanations being provided [53–55].

As listed in Table 8, a typical settling time for both inverters to clear out the spikes was in a range of 5–6.5 s. However, in some cases where the grid experienced subsequent dips due to Inverter-A domination, the settling time for the dips was in a range of 7–11 s depending on the X/R ratios. A combination of low X/R ratios at both locations leads to the highest grid instability due to the largest overshoot and the longest average settling time. This shows the impact of X/R ratios in the low-voltage distribution system, which is also supported by Zhang et al., who showed that the interaction between grid impedance and inverter control can lead to system instability in weak electric networks [56].

The same pattern of spike direction and amplitude was found in the grid voltage responses, as shown in Figure 16c. Voltage depends more on the inverter X/R than the power domination, yet the Inverter-B-dominated cases still showed smaller overshoot during the largest frequency drop at $t = 180$ s. The results indicate that a high X/R at the inverter leads to the largest voltage overshoot while the X/R at the grid shows minimal impact. The previous work on voltage instability (Section 3.1) suggested that the high X/R ratio connected to the PV inverter shows a significant improvement in voltage control ability. This emphasizes that the ability of inverter grid-support controls to provide stabilizing value to the grid depends on the local grid conditions.

Note that all the results in Figure 16 are presented with Inverter-B having the unity PF and Inverter-A having a constant 0.85 PF. The results were verified with both inverters operating with the unity PF to ensure the analysis. The dominating inverter with less

sensitive frequency droop control was found to alleviate the grid reactive power overshoots even with both inverters having the same PF. The only impact of different PFs is the overshoot amplitude as 0.85 PF leads to a higher amount of reactive power output, resulting in a higher potential of severe spikes.

3.2.2. Fluctuation in Active Power and Current Responses

The impacts of three system factors, inverter power domination, X/R ratios, and PF, were also evaluated in terms of response fluctuation. The term fluctuation in this section does not represent the spikes but any response with a noise amplitude larger than 5% of the expected value (as seen in $210 \leq t \leq 240$ s in Figure 17) to provide a clear distinction between the two response types. While reactive power and voltage had substantial spikes due to a change in frequency, the responses of active power and current showed no spikes but had fluctuations in some frequency variations. The noise in the reactive power and voltage was negligibly small, with $<2.5\%$ deviation from the expected value compared to the active power. Therefore, the fluctuation in reactive power and voltage will not be discussed here.

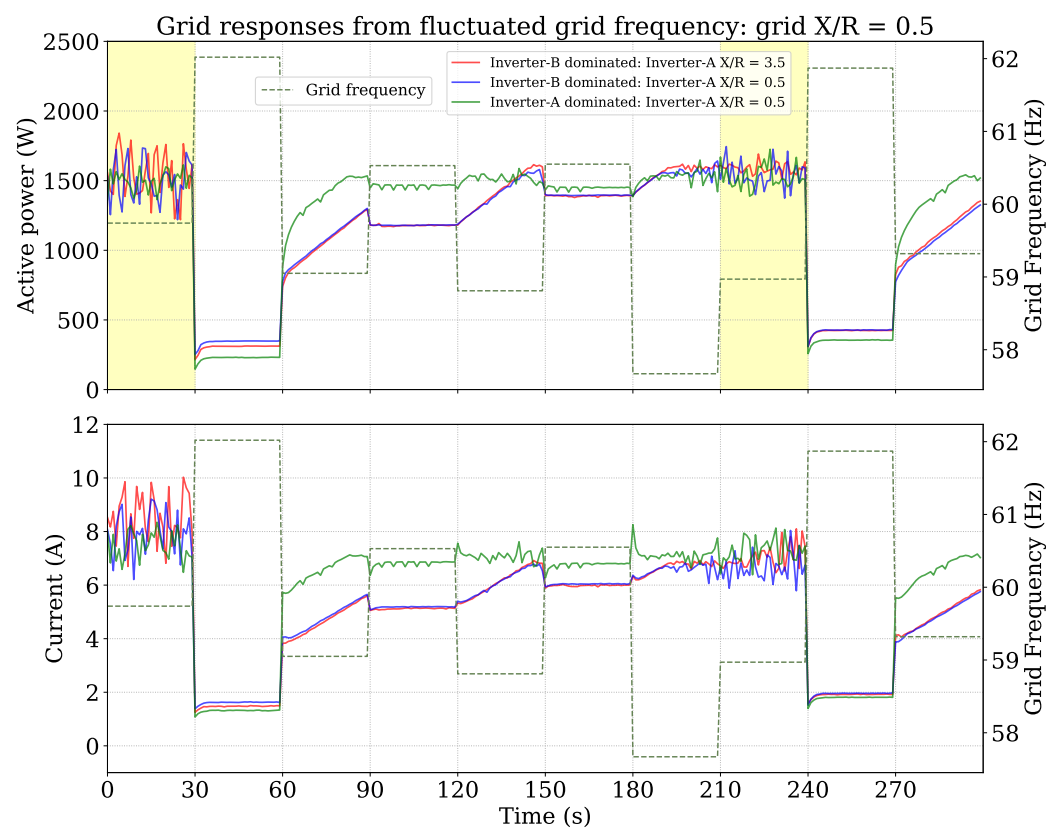


Figure 17. Measurements of the grid active power and current under different domination and Inverter-A X/R with constant grid X/R = 0.5.

Figures 17 and 18 demonstrate the grid's real power and current responses under different power domination and the X/R ratios. Note that they have identical trends and features, suggesting that the current is responsible for the observed instabilities (both slow and fast) in active power. Rapid oscillations were observed, which did not occur in the reactive power and voltage response, as shown in Figure 16. The most severe fluctuations occurred from 0 to $t = 30$ s and again when $210 \leq t \leq 240$ s, as shown in Figure 17. These responses during the two time frames were validated to be repeatable using the method described in Section 2.2. The active power ramp is typically required for smart PV inverters to manage PV intermittency by mitigating a sudden increase in real power following curtailment [57,58]. Each inverter has a different response time to reach its designated

point. This can conceal the fluctuated responses due to the ramp-up period. Additionally, this type of unstable grid behavior is seen only in the weak grid regardless of the inverter power domination and X/R ratio at the inverter. In the previous analysis explained in Section 3.1, the weak grid led to a similar rapid fluctuation in the active power fed to the grid even when the inverters were operating under the Volt-VAR control as long as the operating frequency was relatively steady at 60.0 Hz. Therefore, the active power fluctuation in the weak electric network will be more pronounced when the frequency droop control is inactive or operating during underfrequency conditions when there is no active power curtailment.

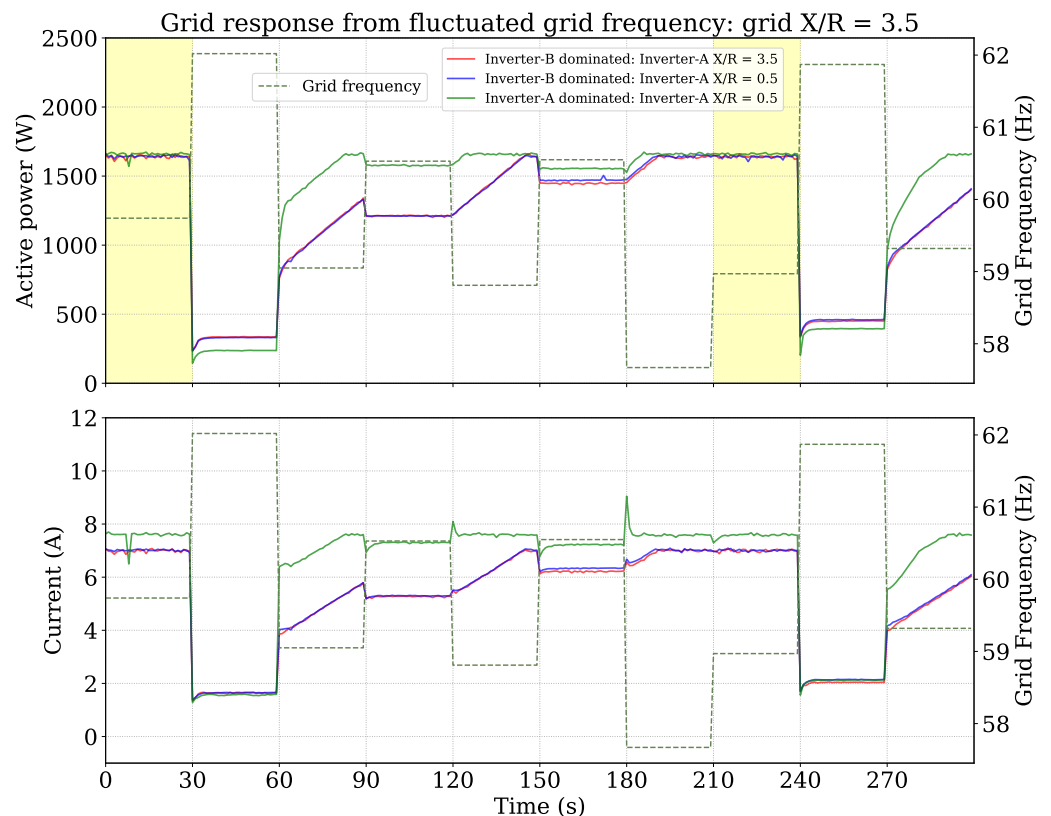


Figure 18. Measurements of the grid active power and current under the same conditions as Figure 17 except grid X/R = 3.5.

This also applies to the grid current as the inverters were operating at 240.0 V, and thus the inverter currents were altered to perform power output curtailment. A difference in response time among the inverters could affect the grid voltage. This is why the IEEE 1547-2018 recommends the frequency droop to operate with other voltage controls. Figure 19 presents the responses of the grid and inverters under different X/R combinations and power domination. There is a noticeable difference in the grid response between different inverter dominations. While the Inverter-B-dominating configuration offered smoother reactive power and voltage responses by lowering the spike magnitude, the active power needed more time to reach the designated point after the overfrequency event had been cleared as the ramp rate on Inverter-B was lower by default, as shown in a shorter dash line in Figure 19. This was confirmed by the Inverter-A-dominating cases where the active power increased much faster than the one dominated by Inverter-B.

In comparison to Inverter-B, Inverter-A had a faster ramp rate so the active power can increase faster, reaching the setpoint within 20 s. This analysis also indicates that different PV inverters can have different abilities to provide grid-supporting functions. Note that the slightly lower power output in the weak grid system was caused by the real power being dissipated through a larger resistor compared to the strong grid. The ramp in grid active

power appeared to be heavily influenced by Inverter-B since it had a slower ramp rate than Inverter-A. Consequently, the grid ramp rate would coordinate with Inverter-B and result in a slow change in active power over time.

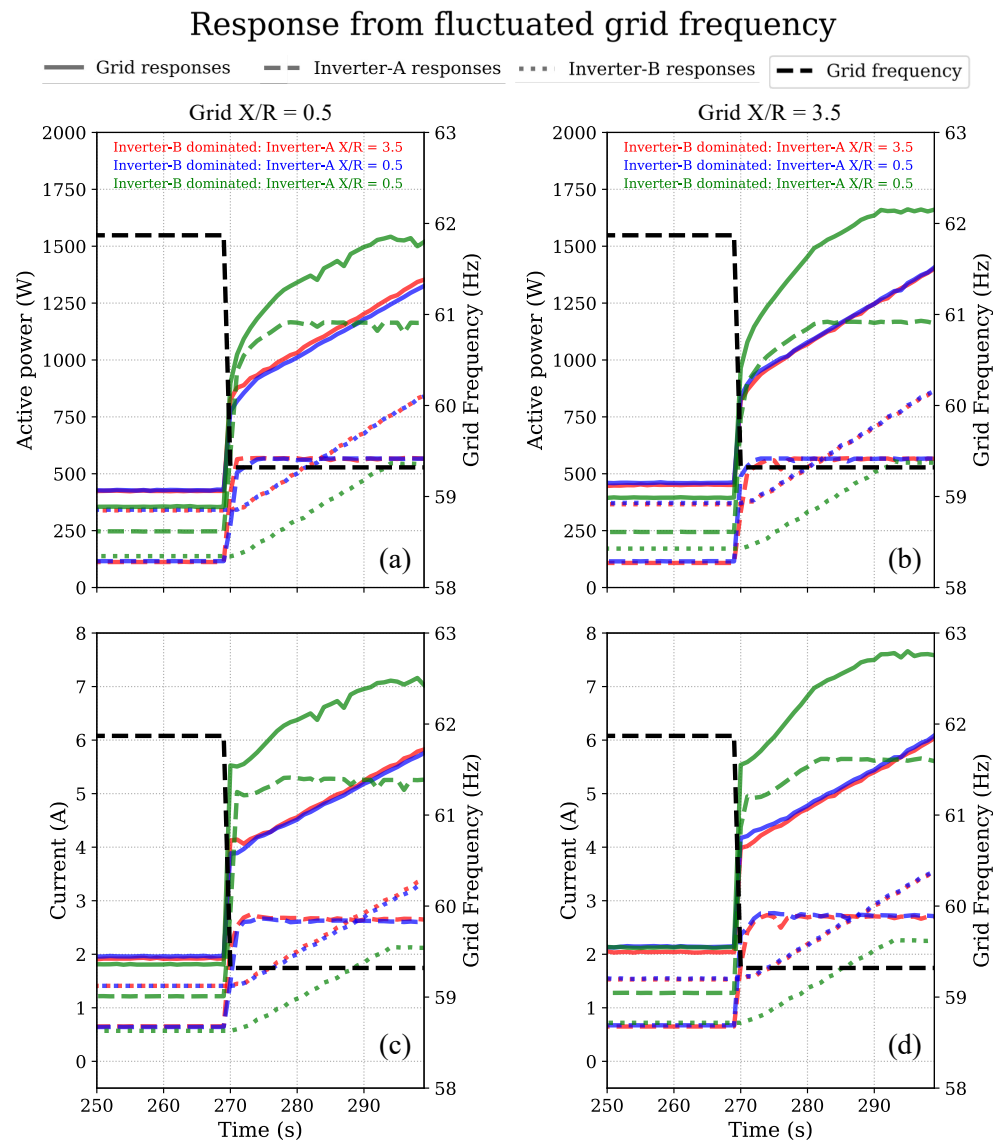


Figure 19. Measurements of the grid and inverter responses in Figures 17 and 18 expanded to show between $250 \leq t \leq 300$ s under different configurations. Top sub-figures show all the active power responses under (a) Low grid X/R and (b) High grid X/R. The bottom sub-figures show all the current responses under (c) Low grid X/R and (d) High grid X/R.

In addition to the effect of power domination, the grid X/R also plays an important role in the ramping behavior as a higher X/R means the system has a large inductive (L) but a small resistive (R) component. Since the system time constant (τ) is calculated from $\tau = L/R$, a larger L results in a higher τ , which leads to more effectiveness in opposing variations because more time will be required for the energy to be discharged or stored in a larger inductor. Consequently, the strong grid would require slightly more time for the active power to increase the active power after the overfrequency event has been cleared.

Another key result of the grid fluctuation from a quantitative analysis is presented in Table 9. The fluctuations in current and active power are affected by the impedances and their location. Overall, the strong grid can reduce the active power fluctuation by 99.4%, calculated from the normalized χ^2 . So long as the grid has a high X/R, the grid fluctuation

is negligibly small even with a low inverter's X/R as the strong grid offers higher stability due to a longer τ . However, switching the X/R ratios between the two locations allows the weak grid to dominate the system, leading to the largest fluctuation. A possible reason for the smaller fluctuation when switching a low X/R to the inverter is that the active power dissipating through a larger resistor might help smooth out the change in the PV power fed to the grid. As a conceptual study of X/R ratios with the frequency droop control is relatively new and the interactions are complex, more evidence is needed to understand the impact of the X/R ratios and operating conditions in different locations.

Table 9. A quantitative comparison of active power fluctuation under each system configuration. Values are normalized to the largest value.

Dominating Inverter	Inverter X/R	Grid X/R	Normalized χ^2	
			P	I
Inverter-B	High	High	0.005	0.004
Inverter-B	Low	High	0.002	0.001
Inverter-A	Low	High	0.009	0.054
Inverter-B	High	Low	1.000	1.000
Inverter-B	Low	Low	0.771	0.793
Inverter-A	Low	Low	0.143	0.335

Table 10 qualitatively summarizes the impact of each component on the grid and inverter responses. Power domination has the most significant impact on the grid responses in terms of both spikes and fluctuations, followed by the secondary voltage distribution line impedance. With repeated experiments, the results indicated that the unity PF slightly helps alleviate the severity of reactive power overshoot, yet it does not show any positive impact on voltage violations or active power fluctuations.

Table 10. A qualitative summary of the level of impact of the four parameters on each response type that leads to an electric grid's instability issue.

Response Type	Impacted Parameter	Level of Impact			
		Power Domination	Inverter X/R	Grid X/R	PF
Spike	Reactive power Voltage	High	High	Low	Low
Fluctuation	Active power Current		Low	High	

4. Conclusions

This paper analyzes the impacts of the X/R ratio of the distribution lines, power domination, and inverter grid-supporting control settings on the secondary voltage distribution grid and the inverter's performance during extreme variations of the grid voltage and frequency. Two impedance circuits were designed and integrated into the P-HIL testbed to create a simulated distribution line with different distances from the grid to the PV households. Volt-VAR and frequency droop characteristics were tested on both residential PV inverters. The key findings are summarized in two parts based on the unstable grid conditions.

For the unstable grid voltage condition, the key findings indicate that the performance of smart PV inverters and grid stability could be influenced by the X/R ratio and the distribution lines. With the inverters' Volt-VAR control, a high X/R (X/R = 3.5) would provide higher stability in both real and reactive power due to the higher time constant ($\tau = L/R$) determined by the sizes of inductive and resistive components. The larger the

inductance, the more effectiveness in opposing variations as more time will be required for the energy to be discharged or stored in a larger inductor. On the contrary, a lower X/R ratio could weaken the inverter's ability for voltage regulation and cause critical instability to the real power at the feeder. Regarding the performance of the inverter's Volt-VAR control, the aggressive Volt-VAR enhances the ability of voltage control during an extreme grid voltage fluctuation compared to the IEEE 1547-2018 Volt-VAR and will be most effective when operating in a high X/R ratio electric network. Additionally, the relative size of the inverter power outputs of residential PV systems can affect the grid power stability where the grid controls of the inverter with the larger power export will dominate the grid stability. Different inverters can have their abilities to mitigate real power fluctuation at the grid when they are power dominating.

For the unstable grid frequency condition, the key findings show the influence of the power-dominating inverter that can lead to severe grid instability based on the slope of the inverter's dynamical control. The analysis of the sudden spike in the grid responses indicates that the inverter with a lower % droop slope or a shallower decline in active power can help mitigate the sudden reactive power overshoots as the control operates with a gentle power curtailment. If the dominating inverter has an aggressive characteristic, the X/R ratios in the system would determine how long the system would take to stabilize the grid. Furthermore, while the grid X/R ratio plays an important role in mitigating active power fluctuation, the power domination of different inverters has a strong impact on active power ramp behavior. The strong grid significantly alleviates the active power and current fluctuation. In terms of the active power ramp, the dominating inverter with the aggressive droop slope can help the grid recover from the overfrequency event faster by ramping up the power output to the designated point at a lower time.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/en17215503/s1>: Figure S1: Actual photos of the two impedance circuits installed (a) at the grid emulator and (b) at Inverter-A. The green lines represent the resistors soldered together inside the circuit box to have fixed parallel connections; Figure S2: Communication diagram of the P-HIL laboratory. Modbus port ID is 502; Table S1: Description of P-HIL equipment.

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