

Article

Three-Phase Grid-Connected Inverter Power Control under Unbalanced Grid Conditions Using a Proportional-Resonant Control Method [†]

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Abstract: Proposed in this article is bidirectional real and reactive power control of a three-phase grid-connected inverter under unbalanced grid conditions using a proportional-resonance controller. Different unbalanced grid conditions have been studied, such as unbalanced three-phase load and unbalanced grid impedance. These unbalanced scenarios generate unbalanced grid currents and unbalanced point-of-common-coupling (PCC) voltages, causing large oscillations in both real and reactive power transferred to the grid. The purposes of the suggested technique are to balance the grid currents and point-of-common-coupling voltages as well as control the power injected into the grid. As a result, balanced PCC voltages are guaranteed, the oscillation in real and reactive power is reduced, and power control is achieved. The proposed method's performance has been verified in MATLAB/SIMULINK simulation software, and different experimental results have been obtained using a real-time interface platform, dSPACE DS1202.

Keywords: bidirectional power flow; DC-AC power converters; proportional-resonant controller; PR controller; power control; power conversion; Voltage-source converters



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1. Introduction

Renewable energy resources (RES) have an impact on the electrical grid's operation. The three-phase inverter that is connected to the grid can be used as a power controller. To obtain good performance, the inverter can be connected to different DC sources such as batteries, RES, or combinations of batteries and RES [1,2]. The uncertainty of RES, as well as the imbalances between generation, distribution, and consumption, can cause numerous issues in inverter operations. These problems can be solved by using energy storage systems (ESS) with RES [3]. As a result, ESS can contribute to and maintain load balance by charging or discharging based on the amount of desired and/or available RES power.

A variety of control techniques have been used to control the power and current of grid-connected three-phase inverters, including proportional-integral (PI) and proportional-resonant (PR) control methods [4,5]. These approaches, on the other hand, simply examine balanced grid situations.

When the amplitude and phase of voltages/currents in a three-phase system differ, they are called unbalanced [6]. The three-phase grid system can become unbalanced due to single-phase loads, single-phase renewable energy sources connected to the grid, unbalanced loading, and load changes [7]. This issue has an impact on controller behavior, the inverter circuit's intrinsic character, and other three-phase loads that may be linked to the grid.

The PI control approach performs poorly under unbalanced grid situations, along with current oscillations. The oscillation problem in the PI-controller has been handled

using a variety of control strategies, including the decoupled double synchronous reference frame phase-locked loop (DDSRF PLL) in [8], direct phase-angle detection (DPD-SR) in [9], and optimum control based on DDSRF in [10]. Using two PLLs, the DDSRF method was able to control the grid currents under unbalanced grid conditions. However, this method has been modified and simplified in [11]. So, only one PLL can be used, and power control is achieved as well using a PI-controller in unbalanced grid situations.

Shunt active power filters have been used to improve the harmonic content of the grid current in cases of nonlinear loads. In addition, it has been used to solve three-phase systems under unbalanced situations to balance the grid currents [12]. Using a time-domain symmetrical component extraction approach, the method in [13] demonstrated an easy and efficient solution to balance grid currents in unbalanced conditions. This approach calculates the sequence components without the need for complex transformations by using time delays and basic addition and subtraction.

A time-domain symmetrical component extraction method with a P-controller was used to achieve power control under unbalanced grid situations in [14]. The reference current was obtained from the negative/zero sequence components of the unbalanced load currents as well as the power command current. The control system was simple as only a P-controller was utilized. The P-controller, however, has a steady-state error, which is a disadvantage of this approach. To improve the controller performance, a PR controller was used to eliminate the steady-state error [15].

Several control techniques have been suggested under unbalanced grid voltage conditions [16–22]. Some approaches extracted the symmetrical components of the unbalanced grid voltages (positive and negative phase-sequence) and then tried to balance currents under unbalanced grid voltage conditions. In [17], different control parameters that were used to estimate the grid impedance were discussed, while in [18], the system parameters for balancing the system were estimated.

Many methods were used for unbalanced current compensation or reduction as discussed in [23–26], and different control cases under unbalanced load were discussed in [27,28].

A phase-locked loop (PLL) and a Park transformation are required when using a PI controller. However, the PR controller does not need a Park transformation or a PLL which makes it simpler. In [29], a notch filter was added to improve the PR controller performance. This control scheme can be utilized to reduce the inverter's negative-sequence impedance and decrease the voltage drop. An enhanced proportional-resonant controller (EPR) was developed in [30]. To reduce grid current harmonics induced by a distorted grid, a current controller for a grid-connected solar system was utilized. Under unbalanced grid situations, a modified PR control strategy (MPRS) for controlling the power of grid-connected three-phase inverters was presented in [31]. The premise behind this method is that the system is operating with an unbalanced load and an unbalanced grid current. Two signals have been used to regulate the inverter's reference current: the load current and the inverter current. By avoiding the need for a phase-locked loop, the PR-controller decreases the complexity.

Many approaches to bidirectional power flow are discussed in the literature, but they all worked under balanced grid conditions. In addition, several methods to balance the grid under unbalanced grid conditions without achieving power control have also been described. However, very few researchers discuss achieving both targets (balancing the grid and applying power control). Also, bidirectional power control under unbalanced grid conditions is not discussed.

In the MPRS method, the PR-controller was shown to be effective in unbalanced grid situations. However, this method was applied by neglecting the grid impedance, balanced grid, and PCC voltages. This means the unbalanced scenario was only considered under unbalanced grid currents without considering unbalanced PCC voltages. Furthermore, the power control of a three-phase system under an unbalanced load (unbalanced grid currents) has been achieved in only one direction. The main contribution of this article is to improve and expand the PR-controller approach described in the MPRS method to

get bidirectional power control of the grid-connected inverter in various unbalanced grid situations. So, the proposed technique can simultaneously fulfill these goals: balancing grid currents and point-of-common-coupling voltages and bidirectional power control. MATLAB/SIMULINK studies along with hardware experimental results validate the proposed control method.

The literature discusses balancing the three-phase grid under unbalanced grid conditions and discusses a method of controlling the power and balancing the grid, but that approach was only used under strong grid situations (where the grid impedance was neglected). In addition, power control for an unbalanced load (unbalanced grid currents) has been accomplished in only one direction. But this effort extends the previous research to cover unbalanced grid impedance, unbalanced PCC, and unbalanced grid current situations as well as bidirectional power control.

The novel contributions of this work are as follows:

- Presenting a method of bidirectional power control of real and reactive power under different unbalanced scenarios.
- Balancing the grid currents and PCC voltages.
- Real and reactive power fluctuations under unbalanced grid situations have been minimized.
- If the unbalanced problem is solved, then all other loads connected to the grid will not be affected by the unbalanced load.
- A simpler PR controller was employed, so there is no need for a PLL).

2. Current Control of Grid-Connected Three-Phase Inverter under Unbalanced Conditions

Figure 1 presents the system under investigation in this paper. Power is transferred from/to the grid through a three-phase inverter and LCL filter. For the proposed control approach, the grid currents i_g , the inverter injected currents i_{inv} , the load currents i_L , as well as the voltages at the v_{pcc} , and the grid voltages v_g , are monitored. A battery system can be used as a power source for the three-phase voltage source inverter.

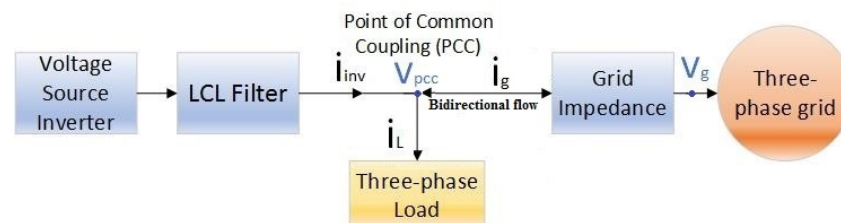


Figure 1. Three-phase grid connected system.

The per-phase LCL filter transfer function [31] is presented in Equation (1)

$$\frac{i_{inv}(s)}{v_g(s)} = \frac{R_D C s + 1}{L_1 L_2 C s^3 + R_D (L_1 + L_2) C s^2 + (L_1 + L_2) s} \quad (1)$$

where R_D is the damping resistor, L_1 is the inverter side inductance, L_2 is the grid side inductance, and C is the capacitance of the filter.

In [31], the output current of a three-phase inverter was controlled using a typical PR controller. The PR controller's transfer function was expressed as in Equation (2).

$$G_{PR}(s) = K_p + K_r \frac{s}{s^2 + \omega_0^2} \quad (2)$$

where K_p is the proportional coefficient, K_r is the resonant coefficient, and ω_0 is the fundamental frequency.

The PR controller will balance the inverter's output current if the three-phase reference currents are considered to be balanced. For simplification, the reference currents and

measurement currents were converted from abc to $\alpha\beta 0$ utilizing a Clarke transformation [32]. The controller could then only be used in two-phases ($\alpha\beta$), as illustrated in Figure 2.

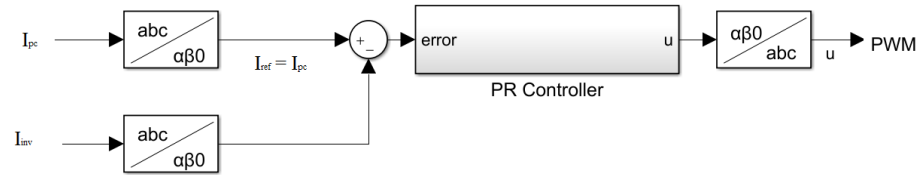


Figure 2. Current control using PR controller.

Power can be transferred from the inverter to the grid and vice versa. Assuming power flow into the grid (i_g injected to the grid) and applying Kirchhoff's current law to the PCC yields Equation (3):

$$i_{inv} = i_g + i_L \quad (3)$$

The PR controller has the ability to make the inverter current equal to the desired current ($i_{inv} = i_{ref} = i_{pc}$); i_{pc} is the reference power command current.

$$i_{pc} = i_g + i_L \rightarrow i_g = i_{pc} - i_L \quad (4)$$

Using Equation (4), the PR controller can balance and control grid currents by adding extra feedback from the load current. The PR controller parameters K_p and K_r can be tuned using [33]. Figure 3 shows the suggested technique.

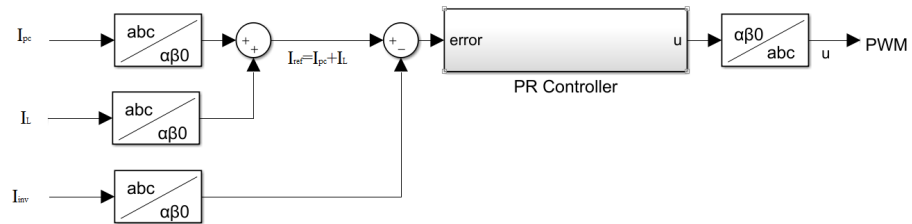


Figure 3. The proposed current control method using PR controller.

3. Power Control of Grid-Connected Three-Phase Inverter under Unbalanced Conditions

Based on Equation (4), the desired reference current i_{pc} can be utilized for bidirectional power control. As illustrated in Equation (5), the reference current or the power command current i_{pc} could be obtained from the desired real and reactive power and the measured PCC voltages as in [34].

$$\bar{S} = P + jQ = V_{\alpha\beta 0}^T i_{\alpha\beta 0}^* \quad (5)$$

$$P + jQ = \left(V_{\alpha} i_{\alpha}^* + V_{\beta} i_{\beta}^* + 2V_0 i_0^* \right) \quad (6)$$

Equation (6) shows that the PCC voltages play an important role in the reference current calculations.

3.1. Unbalanced Three-Phase Load Condition Neglecting the Grid Impedance

When the grid impedance is neglected under balanced three-phase grid voltages and unbalanced three-phase loads, the unbalanced grid currents yield oscillations in the real and reactive power as shown in Figure 4.

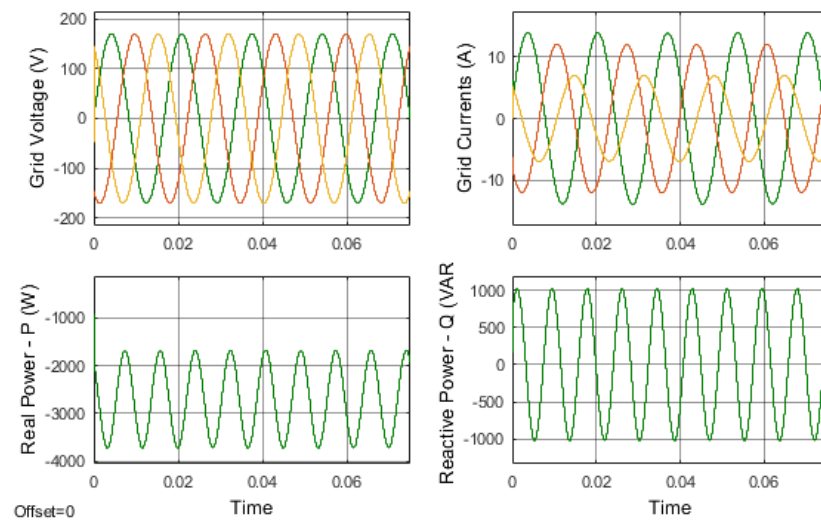


Figure 4. Neglecting the grid impedance under unbalanced load.

Under balanced PCC voltages, the zero component (V_0) is zero. As a result, the term $2v_0i_0$ will be ignored. The complex power equation can be simplified as in [34]:

$$\begin{aligned}
 P + jQ &= v_{\alpha\beta} i_{\alpha\beta}^* = (v_{\alpha} + jv_{\beta})(i_{\alpha} - ji_{\beta}) \\
 P + jQ &= (v_{\alpha}i_{\alpha} + v_{\beta}i_{\beta}) + j(v_{\beta}i_{\alpha} - v_{\alpha}i_{\beta}) \\
 \begin{bmatrix} P \\ Q \end{bmatrix} &= \begin{bmatrix} v_{\alpha} & v_{\beta} \\ v_{\beta} & -v_{\alpha} \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}
 \end{aligned} \quad (7)$$

where $\bar{S}$ is the complex power injected to the grid, P is the real power injected to the grid, Q is the reactive power injected to the grid, $V_{\alpha\beta 0}$ are the PCC voltages in the Clarke transformation domain $\alpha\beta 0$, and $i_{\alpha\beta 0}$ are the grid currents in the $\alpha\beta 0$ domain.

By re-arranging the terms, the reference current (power command current i_{pc} in the $\alpha\beta 0$ domain) can be determined using the Equation (8). Figure 5 shows the block diagram for calculating the reference current.

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} v_{\alpha} & v_{\beta} \\ v_{\beta} & -v_{\alpha} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \quad (8)$$

Figure 5. Reference current calculation under balanced PCC voltages.

3.2. Unbalanced Three-Phase Load Condition Including Balanced and Unbalanced Grid Impedance

When the grid impedance is considered under balanced grid voltages and an unbalanced load, then both the grid currents and the PCC voltages will be unbalanced as shown in Figure 6.

In this situation, the assumption of the zero component of PCC voltages ($V_0 = 0$) is no longer valid, which means the equations discussed in Section 3.1 and in reference [31] are no longer valid.

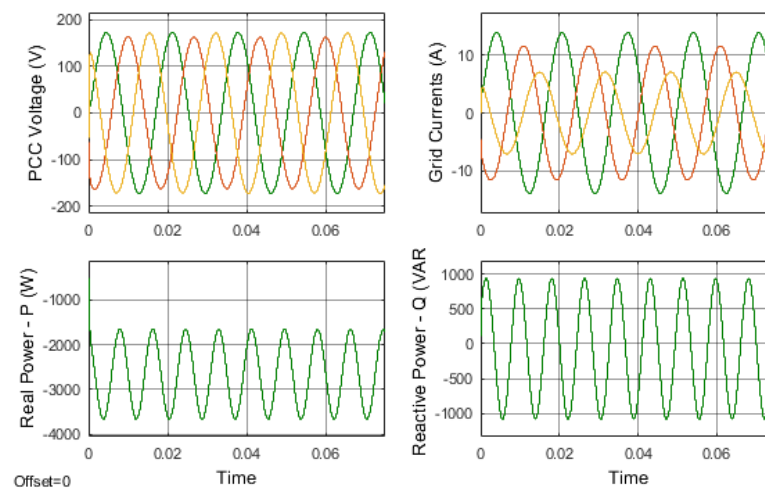


Figure 6. Including the grid impedance under unbalanced load.

To find a solution to this problem, the PCC voltages can be separated into symmetrical components (positive, negative, and zero sequences). Therefore, the fundamental balanced part of the PCC voltage (the positive symmetrical component of the grid voltage V_{abc+}) will be taken into consideration in the reference current calculations. The symmetrical extraction component method in [14] can be used to extract the symmetrical components of the PCC voltages. By having a balanced V_{abc+} , then the assumption $(V_{0+}) = 0$ will be valid and the reference current can be calculated easily by using only the positive symmetrical component V_{abc+} instead of all components of the PCC voltage V_{abc} in the equations of Section 3.1 and shown in Equation (9). Figure 7 shows the new modified block diagram for reference current calculation.

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \frac{1}{v_{\alpha}^{+2} + v_{\beta}^{+2}} \begin{bmatrix} v_{\alpha}^{+} & v_{\beta}^{+} \\ v_{\beta}^{+} & -v_{\alpha}^{+} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \quad (9)$$

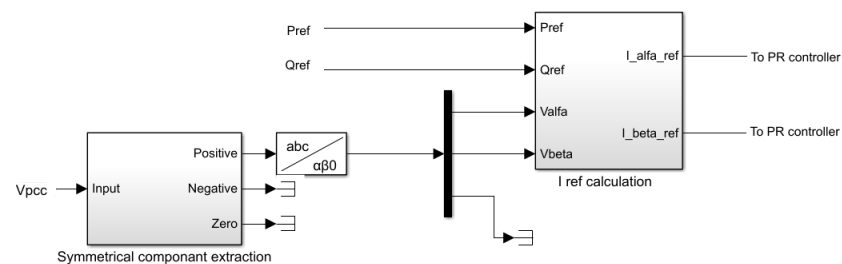


Figure 7. Reference current calculation under unbalanced PCC voltages.

Since the balanced components of V_{pcc} have been used, then the reference current calculation method in Equation (9) and Figure 7 can be used as a general case under either balanced or unbalanced V_{pcc} .

Figure 8 shows the complete block diagram of the control system using a PR controller.

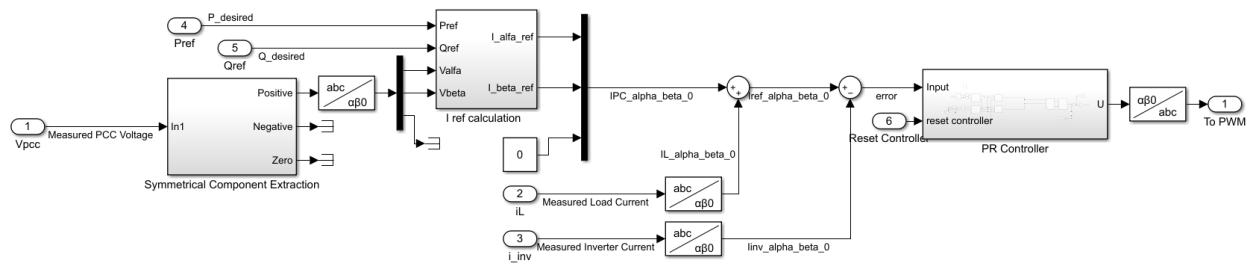


Figure 8. The complete block diagram of the proposed method.

4. Case Studies

The suggested methodology was validated using simulation and hardware studies. The simulation is performed in MATLAB/SIMULINK. A three-phase AgileSwitch 100 kW DC-AC Inverter and a dSPACE DS1202 were utilized in the hardware experiment. Table 1 lists the system parameters. Reference [35] was employed to select LCL filter design parameters, while [33] was used to optimize the PR controller settings.

Table 1. Experimental System Parameters.

f	Grid frequency	60 Hz
V_g	Grid phase voltage	120 V RMS
f_{sw}	Switching frequency	5 kHz
V_{dc}	DC source voltage	400 V
L_1	Inverter side inductor	2.3 mH
L_2	Grid side inductor	0.58 mH
C	Capacitor	15 μ F
R	Damping resistor	1.5 Ω
K_r	Resonant coefficient of PR controller	1800
K_p	Proportional coefficient of PR controller	2.25
Z_{gabc}	Grid Impedance for phases a,b,c	5.1, 4.5, 3 mH
R_{abc}	Three-phase load	8, 16, 32 Ω

The system was operated under unbalanced grid impedance with values of $L_a = 5.1$ mH, $L_b = 4.5$ mH, and $L_c = 3$ mH. The three-phase load was assumed to be unbalanced with $R_a = 8$ Ω , $R_b = 16$ Ω , and $R_c = 32$ Ω . The grid voltages were assumed to be balanced at 120 V RMS. Since the grid impedance was considered under an unbalanced load, then both the grid currents and the PCC voltages will be unbalanced as discussed in Section 3.2.

4.1. Simulation Results

$P_{desired}$, $Q_{desired}$ and the positive symmetrical component of V_{pcc} are used to obtain the power command current i_{pc} for power control, as explained in Equation (9). The Simulink model for the system is shown in Figure 9. Assume that the three-phase grid-connected inverter was energized at $t = 0.1$ s with $P_{desired} = 2$ kW and $Q_{desired} = 0$ var. At $t = 0.25$ s, the desired values have been changed to be $P_{desired} = -1$ kW and $Q_{desired} = 500$ var.

The simulation results for the real and reactive power injected into the grid, load currents (i_L), grid currents (i_g) and inverter injected currents (i_{inv}) are shown in Figure 10.

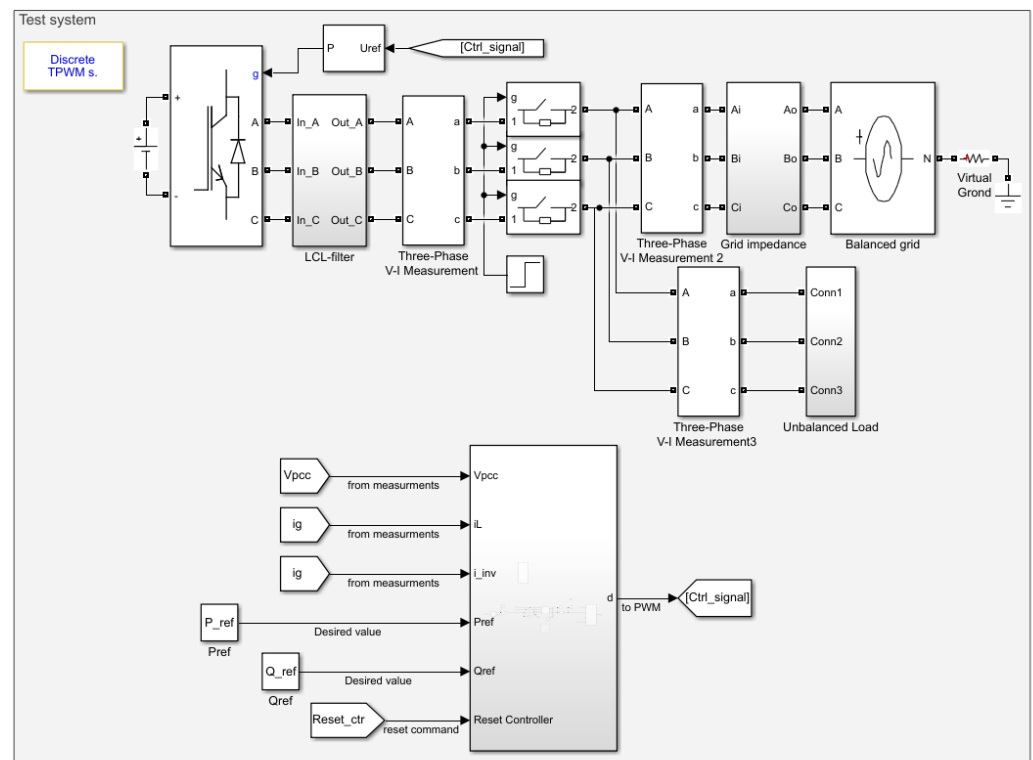


Figure 9. System's Simulink model.

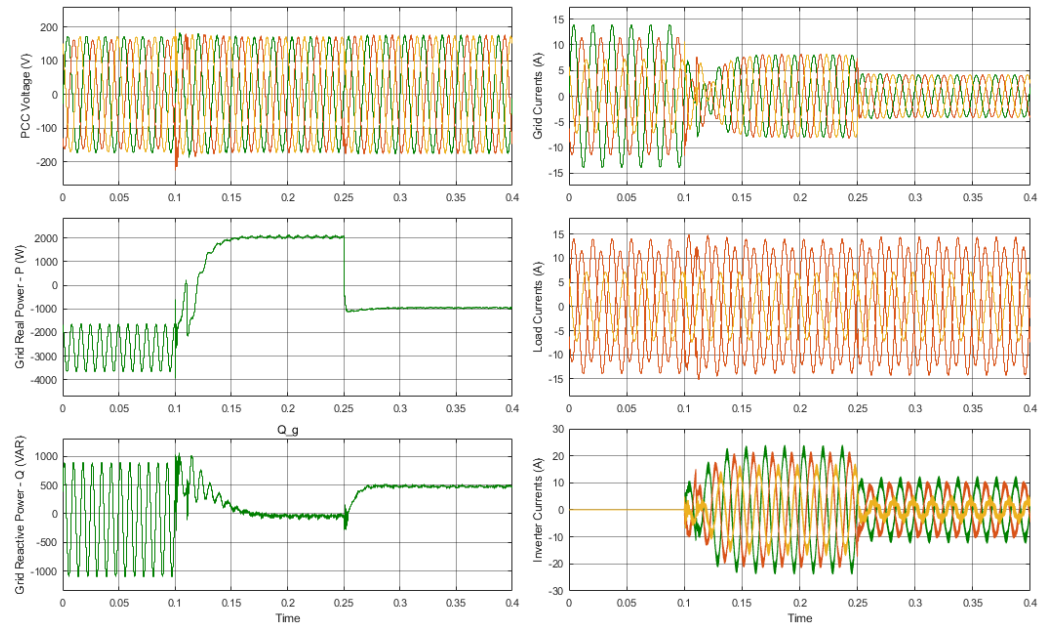


Figure 10. MATLAB/SIMULINK results.

1. For $t < 0.1$ s in simulation time, the unbalanced load was connected to the grid. At this time, both the grid currents and the PCC voltages are unbalanced. Furthermore, the P and Q waveforms of the grid are oscillatory. Other loads linked to the PCC were affected by the unbalanced system.
2. At $t = 0.1$ s, the inverter was turned on and connected to the grid.
3. For $0.1 < t < 0.25$ s, the control approach injected into the grid the desired real and reactive power (2 kW, 0 var) while balancing grid currents during a few milliseconds. Since both the grid currents and PCC voltages are now balanced, the large variations

in P and Q are no longer present. By supplying the desired power into the grid and balancing PCC voltages and grid currents, the effectiveness of the recommended strategy has been proven based on the simulation findings.

4. At $t > 0.25$ s, the injected desired real and reactive power to the grid has been changed to be $(-1 \text{ kW}, 500 \text{ var})$. The negative sign means that the inverter is absorbing real power. The controller took a few milliseconds to correct and track the new desired power value. With these findings, the controller method can be applied to bidirectional power control under unbalanced grid situations.

4.2. Experimental Results

The hardware experiments were performed utilizing the system parameters in Table 1. A battery test system that acts as a DC source (NHR 9210), a DC-AC inverter (AgileSwitch 100 kW), a real-time interface (RTI) (dSPACE DS1202), an LCL filter, a grid simulator (NHR 9410), and current and voltage measuring boards comprised the experimental setup. Variable resistors (RHEOSTAT CR 9296 General Electric Company, Boston, MA, USA) were used as the three-phase load. Figure 11 represents the hardware system setup.

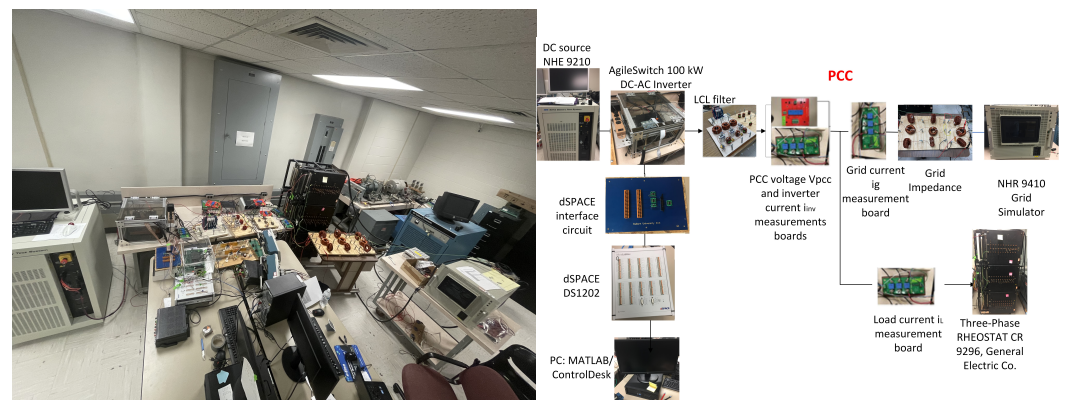


Figure 11. Hardware test system.

The same conditions in the simulation were applied to the hardware setup. The unbalanced grid impedance values were 5.1 mH, 4.5 mH, and 3 mH, and the unbalanced loads were 8 Ω , 16 Ω and 16 Ω for phases A, B, and C, respectively. Under this scenario, both the grid currents and the PCC voltages will be unbalanced.

Different power control cases have been studied as follows:

1. The grid was initially assumed to be connected to the load without connecting the inverter. In this case, the grid currents and PCC voltages will be unbalanced, while the grid voltages were balanced as shown in Figure 12. These results were captured using a Tektronix MDO3024 oscilloscope.
2. The inverter was energized and the proposed method was applied assuming $P_{desired} = 2 \text{ kW}$ and $Q_{desired} = 0 \text{ var}$. The system took a few milliseconds to balance the grid currents, balance the PCC voltages, and power control. Figure 13 displays the experimental data, which was obtained using the dSPACE ControlDesk toolbox. Figure 14 shows the experimental results for grid voltages, PCC voltages, grid currents, inverter currents, and load currents obtained using a Tektronix MDO3024 oscilloscope. The value of the total harmonic distortion percentage (%THD) for the grid currents is 3.3%. This is considered an acceptable value. This proposed method aims to achieve power control as well as clear the unbalance of the grid currents, so the contribution doesn't include improving the %THD.
3. Assuming the $P_{desired} = -1 \text{ kW}$ and $Q_{desired} = 500 \text{ var}$, the system can do bidirectional power control as well as balancing the grid currents and the PCC voltages. Figure 15 shows the experimental results using the oscilloscope. The %THD of the

grid currents is 4.0%. Figure 16 displays the experimental data using the dSPACE ControlDesk toolbox.

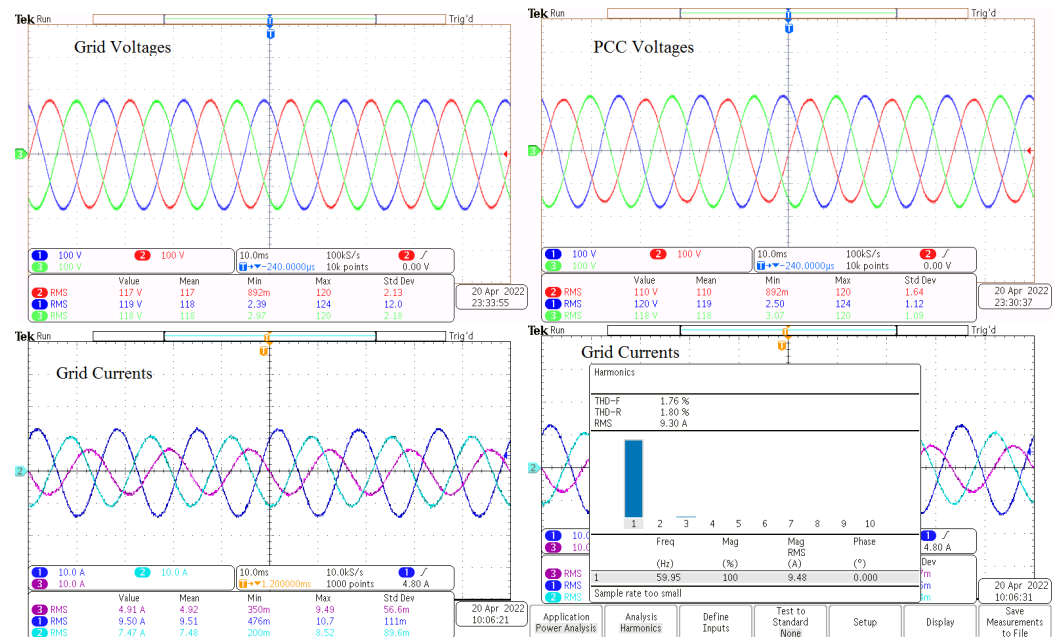


Figure 12. Experimental results before energizing the inverter.

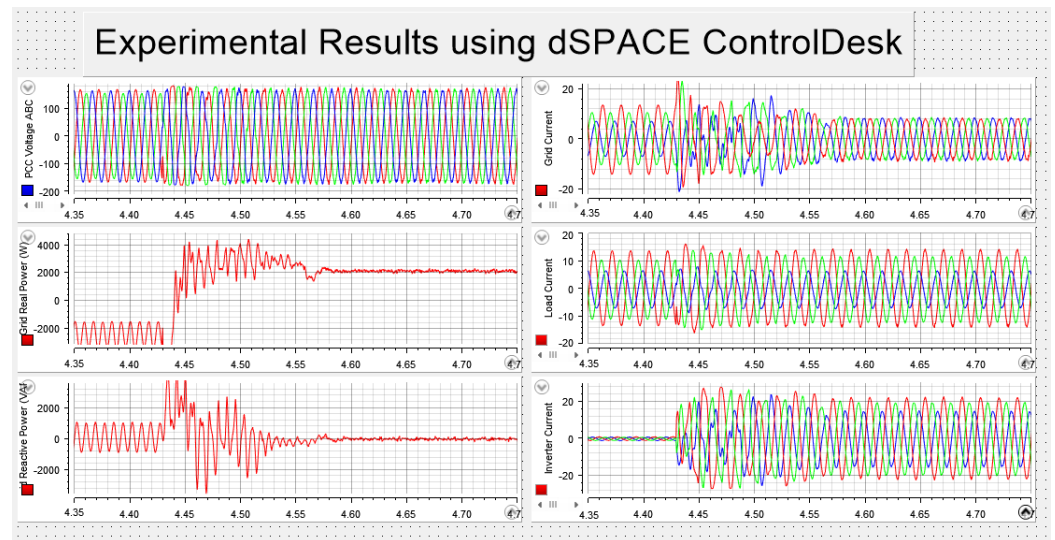


Figure 13. Experimental results at $P = 2 \text{ kW}$, $Q = 0 \text{ var}$ using dSPACE Control desk.

- At $P_{desired} = 1.5 \text{ kW}$ and $Q_{desired} = -500 \text{ var}$, the system can work in four-quadrant power control in addition to balancing the grid currents and the PCC voltages. Figure 17 shows the results obtained using the Tektronix MDO3024 oscilloscope. The %THD of the grid currents is 2.83%. Figure 18 displays the experimental data using the dSPACE ControlDesk toolbox.

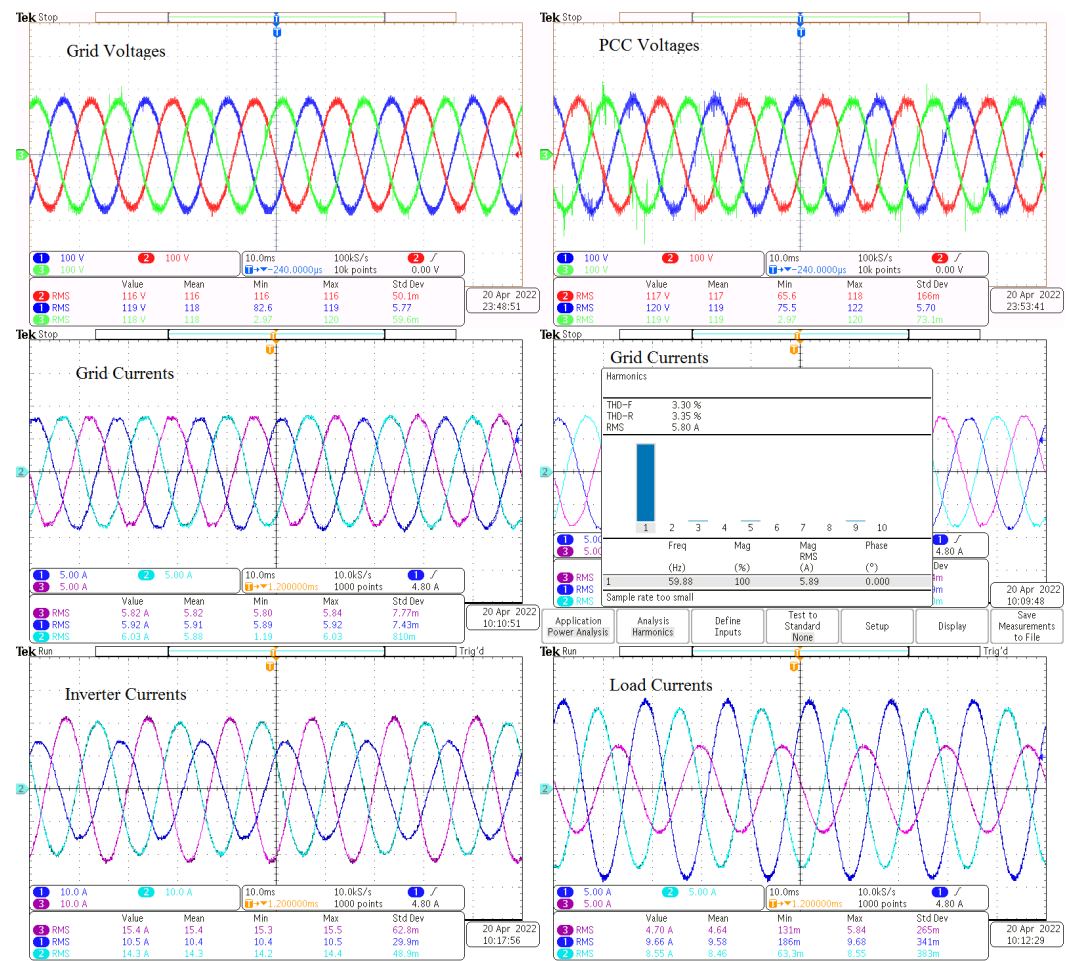


Figure 14. Experimental results at $P = 2$ kW, $Q = 0$ var using Tektronix MDO3024 oscilloscope.

- The system has been tested with multiple scenarios as shown in Figure 19. At $t = 4.5$ s, $P_{desired} = 2$ kW and $Q_{desired} = 0$ var. Then, $P_{desired} = -1$ kW at $t = 9.5$ s and $Q_{desired} = 500$ var at $t = 11$ s. At $t = 23$ s, the desired power was assumed as $P_{desired} = 1.5$ kW, and at $t = 25$ s $Q_{desired} = -500$ var. The NHR 9400 Panel was used to obtain the grid simulator readings.

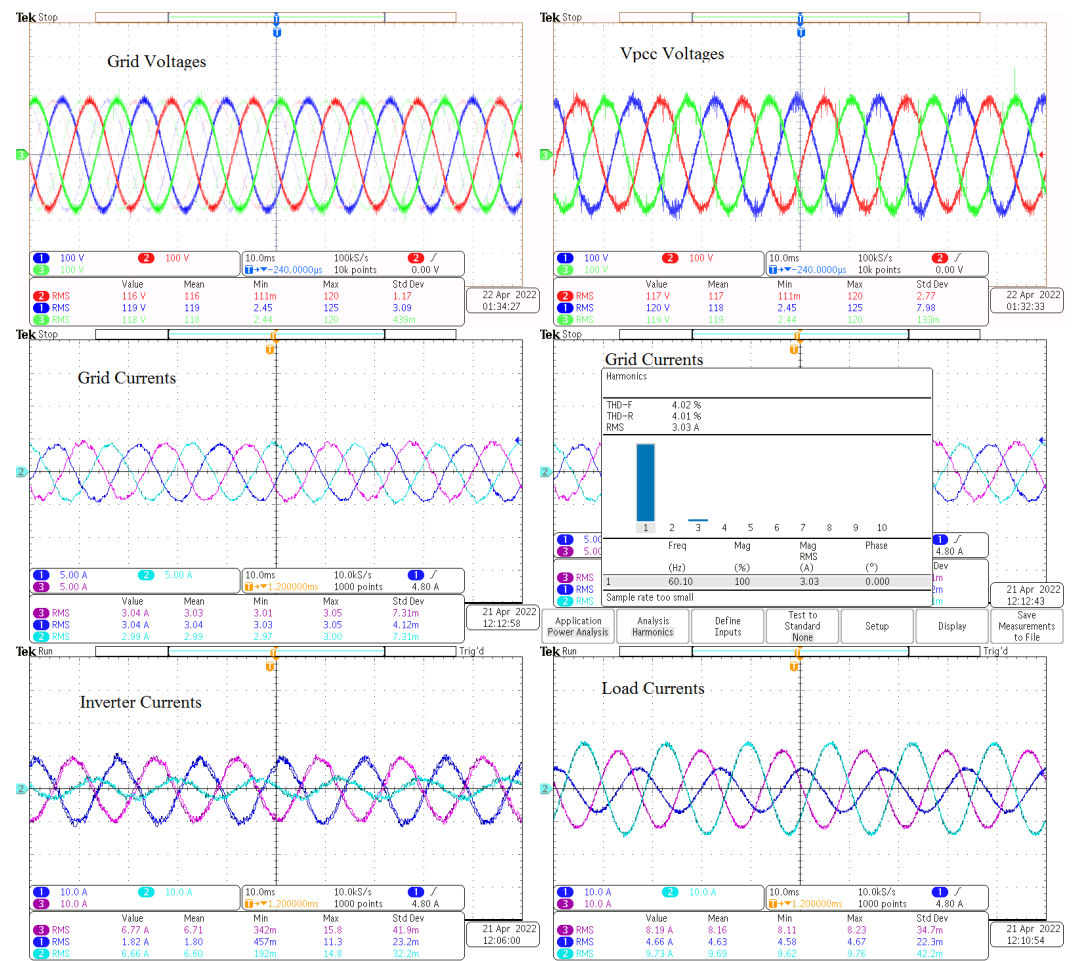


Figure 15. Experimental results at $P = -1$ kW, $Q = 500$ var using Tektronix MDO3024 oscilloscope.

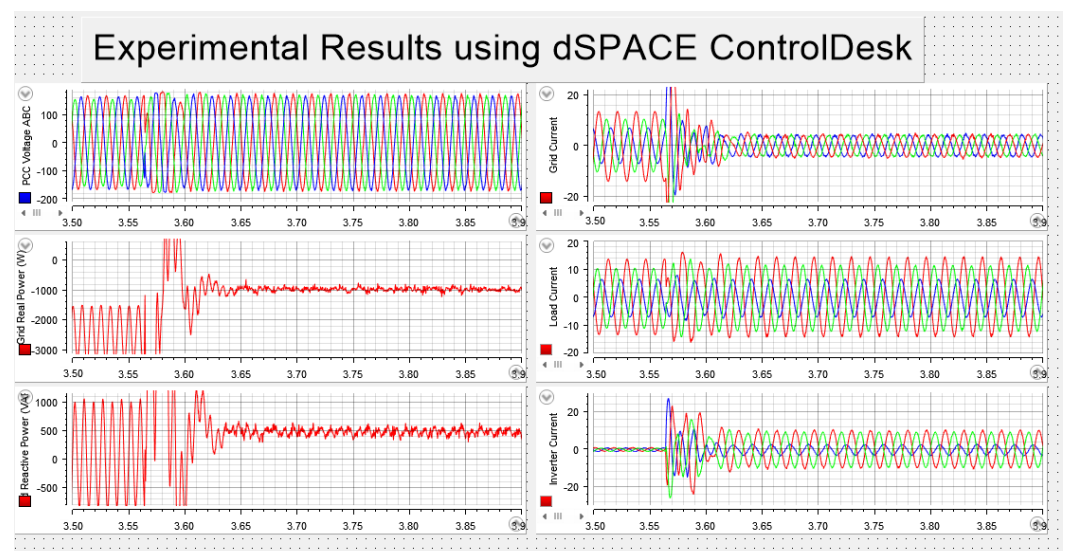


Figure 16. Experimental results at $P = -1$ kW, $Q = 500$ var using dSPACE Control desk.

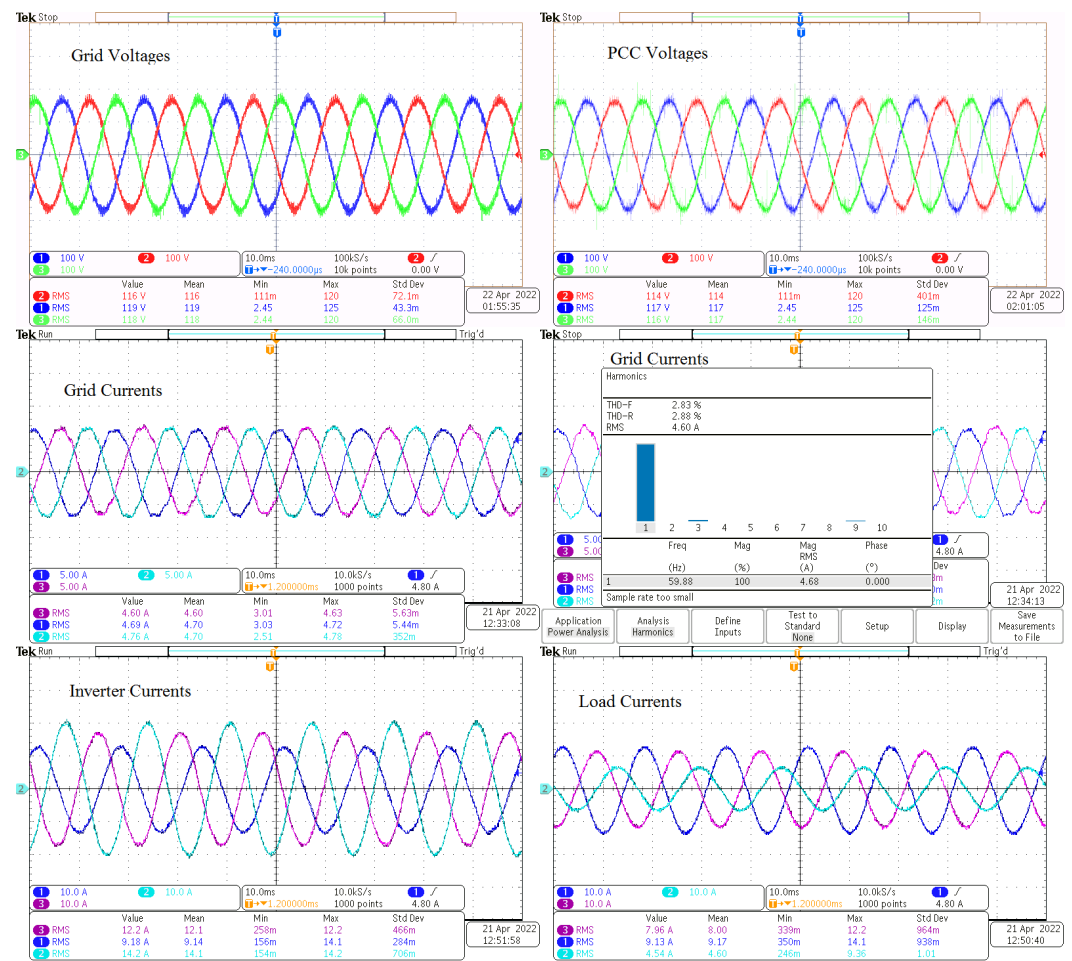


Figure 17. Experimental results at $P = 1.5$ kW, $Q = -500$ var using Tektronix MDO3024 oscilloscope.

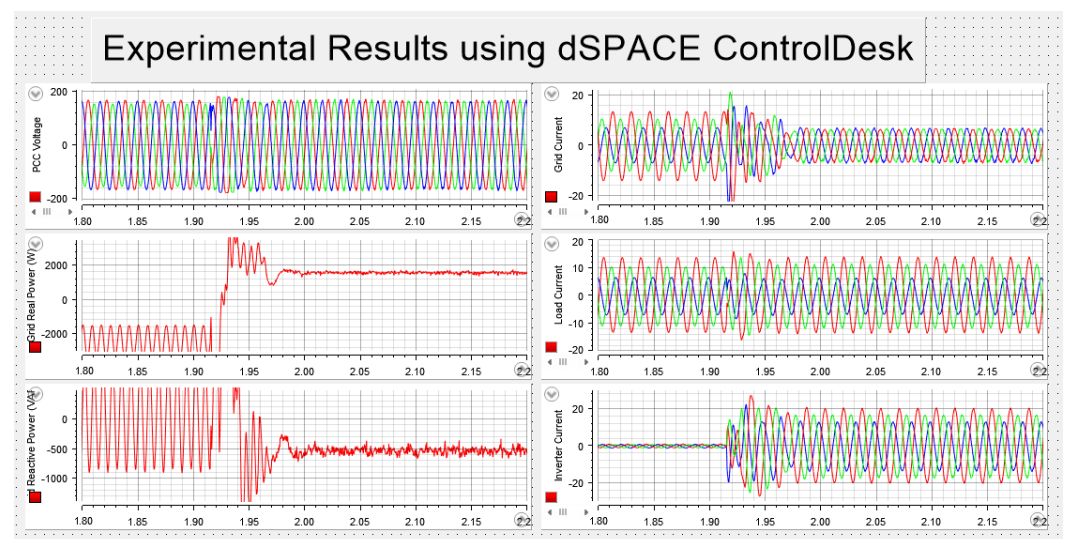


Figure 18. Experimental results at $P = 1.5$ kW, $Q = 500$ var using dSPACE Control desk.

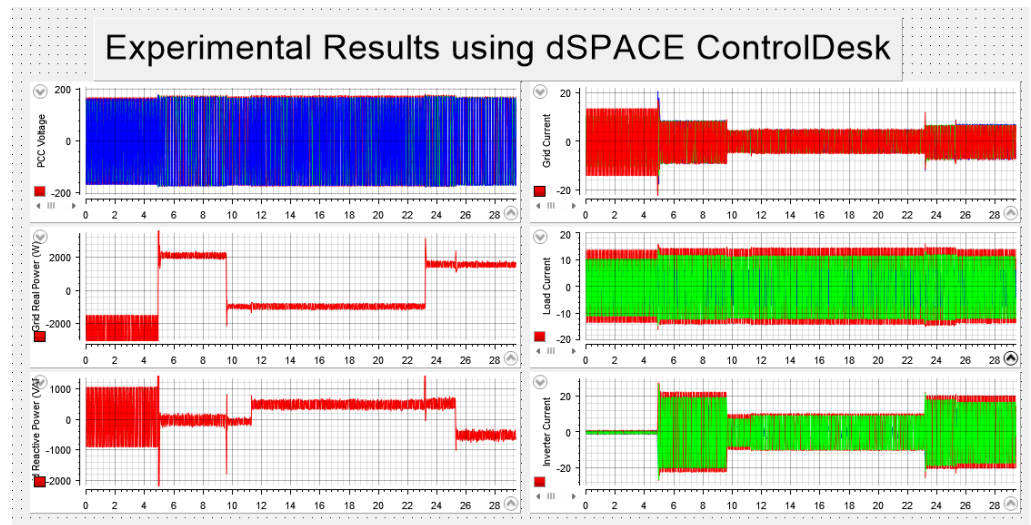


Figure 19. Experimental results overall cases, using dSPACE Control desk.

Figure 20 represents the real power sent to the grid as the required value with a small error. The negative sign means the real power is delivered into the grid, while the positive sign means the real power direction is out of the grid.

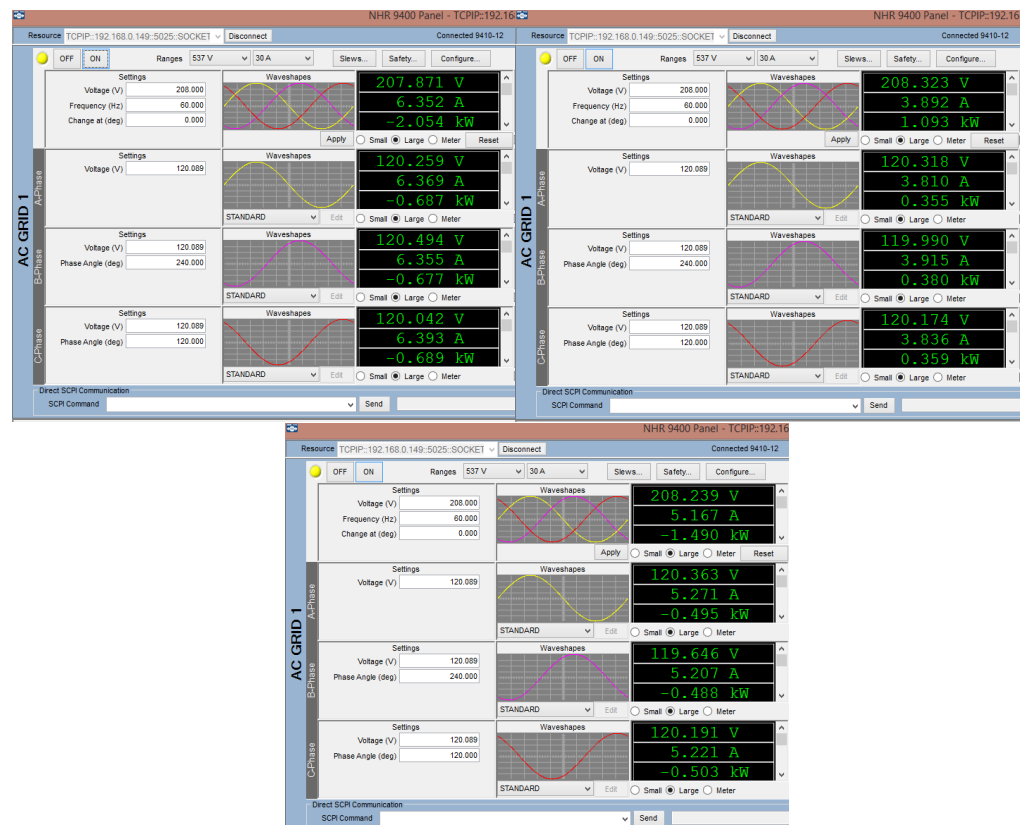


Figure 20. Experimental results using grid simulator NHR 9400 panel.

These observations indicate that the proposed technique can provide bidirectional power control under unbalanced grid operation, as well as balance grid currents and PCC voltages.

The proposed approach contributes to balancing PCC voltages because, in the cases presented, the voltage unbalance is caused by the unbalanced currents and grid impedances.

If the unbalance source was the grid source voltages, the proposed inverter control would only reduce the unbalanced ratio of the PCC voltages.

To calculate the error, the following formula was utilized:

$$\% \text{Relative Error} = \left| \frac{\text{Experimental} - \text{Simulated}}{\text{Experimental}} \right| \times 100\% \quad (10)$$

Based on Equation (10), the relative error for real and reactive power for all three cases is shown in Table 2

Table 2. Relative error calculation.

Case Study	Relative Error of Real Power	Relative Error of Reactive Power
P = 2 kW, Q = 0 var	0.334%	2%
P = 1.5 kW, Q = 500 var	0.667%	0.968%
P = −1 kW, Q = 500 var	1.093%	0.968%

5. Conclusions

Demonstrated in this article is the use of a three-phase inverter to inject power into or absorb power from the grid in the situation of an unbalanced load and unbalanced grid impedances. Real and reactive power fluctuate under these unbalanced grid situations, impacting the power control of the inverter and other three-phase loads connected to the grid. The PCC voltages and grid currents are unbalanced too under these scenarios.

The proposed approach using the PR controller achieves all three aims at once: grid current balancing, PCC voltage balancing, and bidirectional grid power control. For reference power calculations, the positive sequence components of the unbalanced PCC voltages were utilized. The PCC voltages and currents are both balanced, which makes the real and reactive power fluctuations significantly lower. Because a PR controller was used, there was no need for a PLL. Different simulation and hardware testing results verify the proposed technique's efficacy.

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Abbreviations

The following abbreviations are used in this manuscript:

APF	Active power filters
DDSRF PLL	Decoupled double synchronous reference frame phase-locked loop
DPD-SR	Direct phase-angle detection
EPR	Enhanced proportional-resonant controller
ESS	Energy storage systems
MPRS	modified PR control strategy
PCC	Point-of-common-coupling
PI	Proportional-integral
PLL	Phase-locked loop
PR	Proportional-resonant
RES	Renewable energy resources

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