Three-Phase Grid-Connected Inverter Power Control under Unbalanced Grid Conditions Using a Time-Domain Symmetrical Components Extraction Method

Mohammad Alathamneh *, Haneen Ghanayem †, Xingyu Yang ‡ and R. M. Nelms *

Electrical and Computer Engineering Department, Auburn University, Auburn, AL 36849, USA

* Correspondence: mqa0002@auburn.edu
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Abstract: Presented in this paper is a method of bidirectional real and reactive power control of a three-phase grid-connected inverter under unbalanced grid situations. Unbalanced three-phase load and unbalanced grid impedance are illustrations of unbalanced grid issues that have been investigated. As a result, both grid currents and point-of-common-coupling (PCC) voltages will be unbalanced. The real and reactive power that is delivered to the grid oscillates by a significant amount in these unbalanced conditions. A time-domain symmetrical components extraction approach is used to calculate the inverter’s reference currents from the negative- and zero-sequence components of the measured currents. The suggested approach corrects unbalanced grid currents and unbalanced PCC voltages, and provides the desired real and reactive power to the grid when unbalanced situations exist. As a consequence, power oscillations will be eliminated, and power control will be possible. The suggested method’s performance is supported by simulation, and various experimental results are obtained utilizing the dSPACE DS1202 real-time interface platform.

Keywords: active filters; bidirectional power flow; DC-AC power converters; parameter extraction; power control; power conversion; voltage-source converters

1. Introduction

The large usage of power electronics equipment on the grid, as well as the fluctuating nature of load demand, can cause power quality issues on the grid. When the amplitude or the phase of the three-phase electrical quantities (voltages or currents) mismatch, this three-phase system is called unbalanced [1]. An unbalanced three-phase grid system can occur for a variety of reasons, including single-phase loading, unbalanced loads, and single-phase renewable energy sources connected to the grid [2]. Both the power and current control of grid-connected three-phase inverters have been applied using different types of control algorithms [3,4]. These approaches, on the other hand, solely address the grid under balanced situations. The proportional integral (PI)-controller is incapable of quenching the current oscillation under unbalanced situations. As a result, the real and reactive power delivered to the grid will oscillate. Furthermore, the unbalanced condition has an effect on the inverter circuit’s intrinsic nature and on any other three-phase loads that could be connected to the grid.

The control technique in [5], decoupled double synchronous reference frame (DSRF), has been used to solve the oscillation issue in the PI-controller. The DSRF approach proved to be successful in controlling the grid currents under unbalanced situations by using two PLLs. However, reference [6] improved and simplified this approach by using just one PLL, and power control can also be accomplished with a PI-controller.
Using a proportional resonance (PR)-controller, power control of grid-connected three-phase inverters under unbalanced grid situations has been explored in [7,8]. The benefit of the PR-controller over the PI-controller is that the PR-controller does not require a PLL, which makes it simpler.

Several control techniques have been suggested under unbalanced grid voltage conditions [9–15]. Some approaches have extracted the symmetrical components of the unbalanced grid voltages (positive- and negative-phase sequences) and then have tried to balance currents under unbalanced grid voltage conditions. Reference [11] discussed different control parameters that were used to estimate the grid impedance, while reference [10] estimated the system parameters for balancing the system. Many methods were used for unbalanced current compensation or reduction, and these are discussed in [16–19], and different control cases under unbalanced load are discussed in [20,21].

Some power quality problems, including harmonic distortion and power system unbalance, are solved with shunt active power filters (APFs) [22,23]. Traditional active power filter (APF) management strategies require voltage and current measurements [24,25]. Several control schemes have been used to improve the shunt APF, and they are widely discussed in the literature [26–28].

A technique to cope with unbalanced situations using a shunt APF is presented in [29]. It involves separating the unbalanced three-phase signal into its symmetrical components (the positive- and negative-sequence components of system quantities) and injecting the negative sequence. References [30,31] suggest a technique for operating and simplifying the shunt APF that just measures currents without the need for voltage measurements. Basically, these methods use a time-domain symmetrical component extraction approach, which offers a quick and efficient solution for balancing the grid current under different unbalanced situations.

Reference [32] discussed power control for a P-controller under unbalanced grid scenarios. The reference current was derived from the power command current, as well as the negative- and zero-sequence components of the unbalanced load currents. It basically extended the strategy outlined in [30,31]. Because just a P-controller was used, the control system was straightforward. The grid impedance was considered to be zero and the grid voltages to be balanced, so this approach was only used under strong grid situations. In addition, the power control under an unbalanced load (unbalanced grid currents) has been accomplished in only one direction.

In order to include the grid impedance and to provide bidirectional power control of the grid-connected inverter in a variety of unbalanced grid scenarios, the technique presented in [32] is improved and expanded in this article. Unbalanced PCC voltages and unbalanced grid currents are produced by the unbalanced load and unbalanced grid impedance. The suggested control approach has been validated by hardware experimental data and MATLAB/SIMULINK software results.

This paper presents a method for the bidirectional power control of real and reactive power under different unbalanced scenarios. The novel contributions of this work are as follows:

- Bidirectional real and reactive power control of a three-phase inverter under different unbalanced conditions were applied.
- The grid currents and PCC voltages were balanced.
- The oscillation in real and reactive power injected/supplied to/from the grid was minimized.
- Since the unbalanced problem was solved, then all other loads connected to the grid will not be affected by the unbalanced load.
- A simple controller was used (P-Controller).
- The symmetrical components extraction method was used to find the symmetrical components. This method utilized time delays and simple addition/subtraction. As a result, it required fewer calculations compared to methods that employed complex transformations.
Balancing the three-phase grid under unbalanced grid conditions has been discussed in the literature, and a method of controlling the power and balancing the grid has been discussed, but that approach was only used under strong grid situations (where the grid impedance was neglected). In addition, the power control under an unbalanced load (unbalanced grid currents) has been accomplished in only one direction. However, this work extends the literature to cover unbalanced grid impedance, unbalanced PCC, and unbalanced grid current situations, as well as a bidirectional power control method.

The paper is arranged as follows: In Section 1, the introduction and literature review are discussed. Section 2 contains the system model description and previous control algorithms. The proposed method of current control under unbalanced grid conditions is discussed in Section 3, while power control under unbalanced conditions are discussed in Section 4. Section 5 contains the performance analysis, simulation results, experimental analysis, and hardware results. Then, the conclusion is presented in Section 6.

2. System Model Description

The system under study includes a three-phase grid (voltage source), grid impedance, and three-phase load, as shown in Figure 1. Through the PCC, the LCL filter connects the three-phase voltage source inverter to the grid. These quantities can be measured: the load current \( i_L \), inverter output current (filter output current \( i_f \)), grid current \( i_g \), and voltages at the PCC connection \( V_{pcc} \).

![Figure 1. System block diagram.](image)

A three-phase signal can be separated into three symmetrical components: positive, negative, and zero components \( f^{(1)}, f^{(2)}, f^{(0)} \). The zero-sequence quantity for an ungrounded system is zero. However, the zero-sequence quantity is nonzero for a grounded system. Therefore, the three-phase load current can be represented as being shown in Equations (1) and (2).

\[
i_{L, \text{ungrounded}} = i_{L}^{(1)} + i_{L}^{(2)} \quad (1)
\]

\[
i_{L, \text{grounded}} = i_{L}^{(1)} + i_{L}^{(2)} + i_{L}^{(0)} = i_{L}^{(1)} + i_{L}^{(2,0)} \quad (2)
\]

where \( i_{L}^{(0)} \) are the zero-sequence components of the load current, \( i_{L}^{(1)} \) are the positive-sequence components of the load current, and \( i_{L}^{(2)} \) are the negative-sequence components of the load current.

The negative and zero components are classified as unwanted components, because they are the causes of the unbalance and the controller wants to eliminate them. By adjusting the current injected by the inverter as described in Equations (3) and (4) and seen in Figure 2, these undesirable components were removed, as discussed in [30,31].

\[
i_{f, \text{ungrounded}} = i_{L}^{(2)} \quad (3)
\]

\[
i_{f, \text{grounded}} = i_{L}^{(2)} + i_{L}^{(0)} \quad (4)
\]

The system was ungrounded in [30,31]. The controller for the inverter produced a reference current equal to the load current’s negative-sequence component, as shown in
Equation (3). Furthermore, in this article, the case can be generalized to cover grounded systems by including the zero-sequence component, as shown in Equation (4).

**Figure 2.** Modified control block diagram.

3. **Current Control under Unbalanced Grid Conditions**

In this work, and as presented in [32], the technique that was previously described in Section II is expanded to allow the inverter to deliver the desired power to the grid while maintaining grid current balance. By using this technique, any grid-connected inverter can help to maintain grid current balance while supplying power to the grid. As shown in Figure 3, which is derived from the power command for the inverter, the new injected current for a grounded system will typically include both the negative- and zero-sequence components, as well as the power command current $i_{pc}$. The new equation is shown in Equation (5).

$$i_f = i_L^{(2)} + i_L^{(0)} + i_{pc}$$  \[5\]

where $i_f$ is the injected current by the three-phase inverter, and $i_{pc}$ is the power command current.

**Figure 3.** Current control block diagram of the proposed method.

4. **Power Control under Unbalanced Grid Conditions**

A bidirectional power control can be implemented by adding the power command current $i_{pc}$ component, as shown in Equation (5). The following equations are used to derive the $i_{pc}$ component. Using Equation (6), $i_{pc}$ can be calculated from the desired real and reactive power, as well as the measured PCC voltages, as discussed in [33]. Equation (7) shows the significance of the PCC voltages in calculating the reference currents. A conversion from $abc$ to $\alpha\beta0$ utilizing the Clarke transformation is required for the PCC voltages and power command current calculations [34].

$$\overline{S} = P + jQ = V_{\alpha\beta0}^T i_{\alpha\beta0}$$  \[6\]

$$P + jQ = \left(V_a I_a^* + V_\beta I_\beta^* + 2V_0 I_0^* \right)$$  \[7\]

where $\overline{S}$ 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, $V_{\alpha\beta0}$ are the PCC voltages in the Clarke transformation domain $\alpha\beta0$, and $I_{\alpha\beta0}$ are the grid currents in the $\alpha\beta0$ domain.
Reference [32] discusses the calculation of the $i_{pc}$ when the grid impedance is neglected. This means that the PCC voltages equal the grid voltages. Under an unbalanced three-phase load, the grid currents will be unbalanced, while the PCC voltages will remain balanced. This makes the term $2v_o i_0$ equal to zero. Then, the $i_{pc}$ calculation will be easy to follow.

In this article, both the grid currents and the PCC voltages will be unbalanced when the grid impedance is taken into account with balanced grid voltages and an unbalanced load, as shown in Figure 4. In this case, the power command current calculation will be complicated, which makes the equations discussed in [32] no longer valid.

![Figure 4](image)

Figure 4. Unbalanced load and unbalanced grid impedance scenario. (a) PCC Voltages; (b) Grid currents; (c) Real Power; (d) Reactive power.

Since the PCC voltages are unbalanced, they can be divided into their symmetrical components (positive, negative, and zero sequences). These three symmetrical components are now balanced. The main reasons for the unbalanced part are the negative and zero components. Therefore, in $i_{pc}$, the fundamental balanced part of the PCC voltage—that is, the positive symmetrical component of the grid voltage $V_{abc}^{(1)}$, will be taken into account. So, the power formula in Equation (7) can be re-written to be as shown in Equation (8).

$$P + jQ = \left( V_{a}^{(1)} i_a + V_{b}^{(1)} i_b + 2V_{0}^{(1)} i_0 \right)$$  \hspace{1cm} (8)

where $V_{a\beta0}^{(1)}$ is the positive-sequence component of the PCC voltages in the $a\beta0$ domain.

Equation (8) is still not ready for the $i_{pc}$ calculations. Applying a Clarke transformation to the balanced $V_{abc}^{(1)}$ yields $(V_{0}^{(1)}) = 0$. According to [33], the complex power equation can be simplified, as shown in Equation (9);

$$P + jQ = v_{a\beta}^{(1)} i_{a\beta} = \left( v_{a}^{(1)} + jv_{b}^{(1)} \right) \left( i_a - j i_b \right)$$

$$P + jQ = \left( v_{a}^{(1)} i_a + v_{b}^{(1)} i_b \right) + j \left( v_{b}^{(1)} i_a - v_{a}^{(1)} i_b \right)$$

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_{a}^{(1)} & v_{b}^{(1)} \\ v_{b}^{(1)} & -v_{a}^{(1)} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix}$$  \hspace{1cm} (9)
Equation (9) can be re-arranged so the $i_{pc}$ in the $\alpha\beta0$ domain can be calculated using Equation (10). To obtain the $i_{pc}$ in the $abc$ domain, use the Clarke inverse transformation ($\alpha\beta0 - abc$). The block diagram for determining $i_{pc}$ is shown in Figure 5.

$$
\begin{bmatrix}
I_a \\
I_\beta
\end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix}
v_\alpha^2 \\
v_\beta^2
\end{bmatrix} \begin{bmatrix}
(1) \\
(1)
\end{bmatrix} \begin{bmatrix}
P \\
Q
\end{bmatrix}
$$

(10)

The power command current calculation method presented in Figure 5 can be applied and generalized with balanced or unbalanced $V_{pcc}$. Figure 6 shows the complete block diagram of the control system.

In Figure 6, the unbalanced load currents are converted to their symmetrical components. Then, the balancing part can be achieved by injecting the unbalanced components of the grid currents (the negative- and zero-sequence components). The power control part can be accomplished by injecting the power command current. The power command current can be calculated using the desired values of the real and reactive power, and the balanced component (the positive symmetrical component) of the PCC voltages.

5. Case Studies

The proposed method has been tested using different simulation and hardware case studies. MATLAB/SIMULINK was used in the simulation, and a three-phase AgileSwitch 100 kW DC-AC inverter that is controlled by a dSPACE DS1202 was used in the hardware experiment. The LCL filter design parameters were chosen using [35].

The test system parameters are shown in Table 1. The grid voltages were assumed to be balanced at 120 V RMS. Both the grid currents and the PCC voltages will be unbalanced because the grid impedance was taken into account under an unbalanced load, as mentioned previously.
Table 1. Experimental System Parameters.

| Parameter       | Value                  |
|-----------------|------------------------|
| Grid frequency  | 60 Hz                  |
| $V_g$           | 120 V RMS              |
| $f_{sw}$        | 5 kHz                  |
| $V_{dc}$        | 400 V                  |
| $L_1$           | 2.3 mH                 |
| $L_2$           | 0.58 mH                |
| $C$             | 15 µF                  |
| $R$             | 1.5 Ω                  |
| $L_{g,a,b,c}$   | 5.1, 4.5, 3 mH         |
| $R_{abc}$       | 8, 16, 32 Ω            |

5.1. Simulation Results

In order to derive the power command current $i_{pc}$ for power control ($P_{desired}$, $Q_{desired}$), the positive symmetrical component of $V_{pcc}$ is utilized, as described in Equation (10). Figure 7 depicts the system’s Simulink model, and Figure 8 shows the simulation results for the real and reactive power injected into the grid, the grid currents ($i_g$), inverter currents ($i_f$), and load currents ($i_L$).

The grid was connected to the unbalanced load only for $t < 0.1$ s. Both the grid currents and the PCC voltages are currently unbalanced. The grid’s $P$ and $Q$ waveforms are oscillatory as well. Therefore, the unbalanced system had an impact on other loads connected to the PCC.

Figure 7. Simulink model.

The three-phase grid-connected inverter was energized at $t = 0.1$ s. During the interval $0.1 < t < 0.2$ s, the inverter is working only as a shunt APF by injecting only the negative- and zero-sequence currents of the unbalanced load (the reason for the unbalanced components). In a very short time, both the grid currents and PCC voltages are now balanced. The large variations in $P$ and $Q$ are no longer present.

For $0.2 < t < 0.3$ s, the power command current is calculated and injected, in addition to the negative and zero current. Therefore, the current injected by the inverter has two components: the balancing current and the power command current. The control strategy can inject the desired real and reactive power (2 kW, 0 var) into the grid while balancing the grid currents and PCC voltages. Based on the simulation results, it has been demonstrated that the suggested technique is successful in supplying the required amount of power into the grid, and balancing the PCC voltages and grid currents.
At $t > 0.3$ s, the desired real and reactive power that was injected into the grid has been modified to ($-1$ kW, 500 var). The negative sign means that the inverter is absorbing real power. The controller updated and tracked the new required power value within a few milliseconds. With these results, the controller approach can also be used to control power in both directions under unbalanced grid scenarios.

5.2. Experimental Results

The system settings presented in Table 1 were used to perform the hardware experiments. The experimental setup included a battery test system (NHR 9210) that serves as a DC source, 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 measurement boards. The three-phase load was composed of variable resistors (RHEOSTAT CR 9296 by General Electric Company, Boston, MA, USA.). The configuration of the hardware system is shown in Figure 9. The hardware configuration was similar to that in the simulation. Grid currents and PCC voltages will both be unbalanced in the situation of an unbalanced grid impedance and unbalanced loads.

The system has been applied to numerous multiple power control cases, as follows:

1. At first, it was considered that the load was connected to the grid without the inverter. In this scenario, the grid voltages are balanced, as illustrated in Figure 10, but the grid currents and PCC voltages are unbalanced. A Tektronix MDO3024 oscilloscope was utilized to record the waveforms.
2. The inverter was turned on, and the system needed a few milliseconds to balance the grid currents and the PCC voltages. The experimental data using the dSPACE ControlDesk toolbox are shown in Figure 11. The experimental results for grid voltages, PCC voltages, grid currents, inverter currents, and load currents, as measured by the oscilloscope, are shown in Figure 12.

3. The full proposed method was applied, assuming \( P_{\text{desired}} = 2 \text{ kW} \) and \( Q_{\text{desired}} = 0 \text{ var} \). The system is now capable of applying power control, balancing grid currents, and balancing PCC voltages. The experimental data, which were collected using the dSPACE ControlDesk toolbox, are shown in Figure 13. Figure 14 displays the experimental data for the PCC voltages, grid currents, and inverter currents obtained using the Tektronix oscilloscope.

4. Assuming that \( P_{\text{desired}} = -1 \text{ kW} \) and \( Q_{\text{desired}} = 500 \text{ var} \), the system is capable of balancing the grid currents and PCC voltages, as well as bidirectional power control. Some experimental findings using the Tektronix MDO3024 oscilloscope are shown in Figure 15. The dSPACE ControlDesk toolbox experimental results are shown in Figure 16.

Based on these results, the oscillations in real and reactive power have been removed, the PCC voltage and grid currents are now balanced, and the real and reactive power of the grid are successfully controlled.

![Figure 10. Experimental results before energizing the inverter.](image)

5. At \( P_{\text{desired}} = 1.5 \text{ kW} \) and \( Q_{\text{desired}} = -500 \text{ var} \), the system is capable of controlling power in all four quadrants, in addition to balancing grid currents and PCC voltages. The findings using the oscilloscope are shown in Figure 17. Figure 18 shows the dSPACE ControlDesk results.

6. The system was tested with several cases, as seen in Figure 19. It acted as a shunt APF at \( t = 3.5 \text{ s} \), and the proposed method to inject \( P_{\text{desired}} = 2 \text{ kW} \) and \( Q_{\text{desired}} = 0 \text{ var} \) was energized at \( t = 7 \text{ s} \). Then, the power command was changed to \( P_{\text{desired}} = -1 \text{ kW} \) at \( t = 12.75 \text{ s} \) and \( Q_{\text{desired}} = 500 \text{ var} \) at \( t = 14 \text{ s} \). At \( t = 21 \text{ s} \), the desired power was set to be \( P_{\text{desired}} = 1.5 \text{ kW} \) and \( Q_{\text{desired}} = -500 \text{ var} \) at \( t = 23.25 \text{ s} \). The grid simulator data were obtained using the NHR 9400 Panel. The real power transmitted to the grid is represented in Figure 20 as the desired value, with a slight inaccuracy. A P-controller was utilized, which was the cause of the error. This technique has the disadvantage in that the P-controller, although being straightforward, has a steady-state error and causes some controller offsets. The sign of the real power in the grid simulator results...
indicates the power flow direction. A positive sign means the grid is supplying the power, while a negative sign means that the grid is absorbing power. These findings indicate that the proposed methodology can balance grid currents and PCC voltages while operating with bidirectional power control under unbalanced grid conditions.

Figure 11. Experimental results for shunt APF working mode, using dSPACE Control desk.

Figure 12. Experimental results when balancing the grid currents only.
Balancing the three-phase grid under unbalanced grid conditions is discussed in the literature, and a method of controlling the power and balancing the grid is discussed, but that approach has only been used under strong grid situations (where the grid impedance was neglected). In addition, the power control under an unbalanced load (unbalanced grid currents) has been accomplished in only one direction.

By looking at the overall results in Figure 19, between $3.5 \, s < t < 7 \, s$, the inverter was working as a shunt APF, which was discussed in [30], which balanced the three-phase system without applying power control.

The proposed method aims to extend the literature work to cover the unbalanced grid impedance by balancing PCC voltages and grid currents, and removing the oscillation in real and reactive power, as well as obtaining bidirectional power control of the grid-connected three-phase inverter under unbalanced grid conditions.
Figure 15. Experimental results at $P = -1$ kW, $Q = 500$ var.

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

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

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

Demonstrated in this article is the bidirectional power control of a three-phase grid-connected inverter in the presence of an unbalanced load, and with unbalanced grid impedances. Under these unbalanced circumstances, real and reactive power oscillate, which affects the control methods of the inverter and other three-phase loads connected to the grid. The PCC voltages and grid currents are unbalanced too, under these scenarios.

A symmetrical components extraction method using a P-controller was used to achieve bidirectional real and reactive power control of the grid-connected three-phase inverter under different unbalanced scenarios. Grid current balancing, PCC voltage balancing, and bidirectional grid power control were all simultaneously accomplished using the proposed method.

Any three-phase quantity can be separated into its three symmetrical components (positive-, negative-, and zero-sequence components). The existence of the negative- and zero-sequence components is the reason for the unbalanced quantity. Therefore, the balancing part can be achieved by injecting the unbalanced component of the grid currents (negative- and zero-sequence components), and the power control can be accomplished by injecting the power command current. Since the PCC voltage is unbalanced, the positive-sequence components of the unbalanced PCC voltages are used to determine the power command current. With the suggested approach, the PCC voltages and currents are balanced, which considerably reduces the oscillations in real and reactive power that are produced by the unbalanced load. A P-controller was employed, although this controller has the disadvantage of causing steady state errors and controller offset. Results from various simulations and hardware experimental tests confirm the effectiveness of the suggested method.

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