Power Control of a Three-phase Grid-connected Inverter using a PI Controller under Unbalanced Conditions

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SoutheastCon 2022 | 978-1-6654-0652-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/SoutheastCon48659.2022.9764097

***Abstract*— Under balanced three-phase system conditions, various conventional control methods were applied for controlling a grid-connected three-phase inverter, such as proportional-integral (PI) controller and proportional-resonant (PR) controller. The grid can become imbalanced for a variety of causes, including single-phase loading and single-phase renewable energy sources, impacting inverter operations and other grid-connected load. The PI control method functions poor in an unbalanced three-phase system, as illustrated by a current oscillation. This paper describes a method for converting an unbalanced three-phase system into three balanced components: positive, negative, and zero sequence, utilizing a time-domain symmetrical component extraction method. The symmetrical components currents are controlled by the PI controller. This system is simpler to use than other ways reported in the literature because it only requires one phase-locked loop.**

Keywords— Power control, Three-phase inverter, grid-connected voltage-source inverter system, unbalanced grid, PI controller.

I. INTRODUCTION

Different renewable energy sources such as photovoltaics, fuel cells and wind turbines can affect in the power system operation and diver power to the grid by working as distributed generators (DG) [1,2]. Grid-connected three-phase inverters have been developed in the past years for the interconnection of renewable energy sources with the grid to fulfill the increased electrical load demand and to utilize clean green energy. Proportional-resonant (PR) control method and proportional-integral (PI) control method were used to control the power/current injected by the grid connected three-phase inverter under balanced three-phase system operation [3, 4]. The presence of unbalanced three-phase system can create several power quality problems, affecting on the controller performance and inverter circuit [5].

The PI control method is based on converting the three-phase current signal from abc to dq0 using park's transformation [6]. Under balanced three-phase operation, dq0 transformation will give constant values, which makes the PI controller sufficient to control. However, under unbalanced three phase operation, the values of dq0 will be time varying which creates a problem for the PI controller and make in ineffective. Reference [7] suggested a solution for this problem by converting the three-phase unbalanced currents to its symmetrical components, which are balanced components. The unbalanced three-phase grid system can be converted to three balanced components: positive, negative and zero sequence. The zero-sequence component can be assumed to be zero if the system is ungrounded. This results in two control loops: a positive-sequence and a negative-sequence current reference frame. Double synchronous reference frame is the name given to this method. A direct grid current control method for a three-phase inverter with an LCL-filter was proposed in [8].

A decoupled double synchronous reference frame phase-locked loop (ddsrfPLL) in phase detection has been used in [9]. By removing the second-order harmonics and negative sequence components of the grid voltages, this approach can be employed in both balanced and unbalanced three-phase voltages. Under grid fault conditions, this method can work and detect grid voltages' phase angles.

Optimal control under unbalanced voltage grid has been employed in [10]. The control method was based on dual decoupled positive and negative current reference frame PI dq controllers (DDSRF). In this paper, it was claimed, under unbalanced grid conditions, that the real power output by the PV will have an oscillatory part. The optimal controller goal was to remove this oscillatory part and to obtain the maximum power point tracker (MPPT) by the PV.

A direct phase-angle detection (DPD-SR) method for three-phase inverters for unbalanced grids has been used in [11]. The DPD-SR method can detect the grid voltages' phase angles by using the available voltages measurements under balanced and unbalanced conditions. This method does not require a closed loop PI controller to detect the phase angle, which reduces the complexity and the delay in detecting the phase angle. As a result, this method has a big advantage over the classical phase locked loop (PLL).

In [12], the authors study power control under unbalanced grid voltage conditions for a photovoltaic generation system; the inverter reference current is calculated and updated based on the PV coefficients. While in [13], the authors use symmetrical components to control a four-leg inverter. In this method, it is possible to regulate the voltage at the load terminal or control the power factor through reactive power exchange with the power system, which is well known in literature as a DSTATCOM. The main goal is reactive power compensation.

Power control of grid connected three-phase inverters under unbalanced grid conditions has been discussed using in a P-controller in [14] and a PR-controller in [15].

The aim of this paper is to enhance and simplify using the PI-controller under unbalanced grid conditions. This method is simpler than those already proposed in the literature by using only one phase-locked loop. In addition to injecting power into the grid, the controller will work to balance the grid current. The suggested control mechanism has been supported by MATLAB/SIMULINK findings as well as hardware experimental results.

II. METHODOLOGY

Figure 1 shows a three-phase grid-connected VSI with an LCL-filter, where i_{inv} is the inverter output current, i_g is the grid current and i_L is the load current.

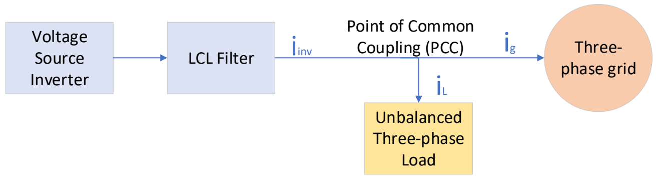

Figure 1: *System Block Diagram*

In general, the conventional PI controller cannot be used in an unbalanced system, because the dq0 transformation will no longer yield constants but sinusoids. Therefore, the PI controller will not be able to track these sinusoids (the PI controller can track a step signal but not sinusoid).

A. Current Control under Unbalanced Grid Conditions

In [6], the authors were able to employ a PI controller under unbalanced grid conditions through the use of symmetrical components. This method introduced a double synchronous reference frame (DSRF) and added a decoupling network for estimating and compensating the undesirable current oscillations. Fig. 2 shows the block diagram of this method where two phase-locked loops (PLL) are required.

In this method, the dq current components in the positive and negative reference frame can be calculated from the over $\alpha\beta$ current components with respect to the positive-sequence angle θ_+ and negative-sequence angle θ_-, which requires two phase-locked loops to obtain those angles.

$$i_{dq}^{+} = \left[e^{-J\theta_+}\right] i_{\alpha\beta} \tag{1}$$

$$i_{dq}^{-} = \left[e^{-J\theta_-}\right] i_{\alpha\beta} \tag{2}$$

Where:

$$\left[e^{-J\theta_-}\right] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{3}$$

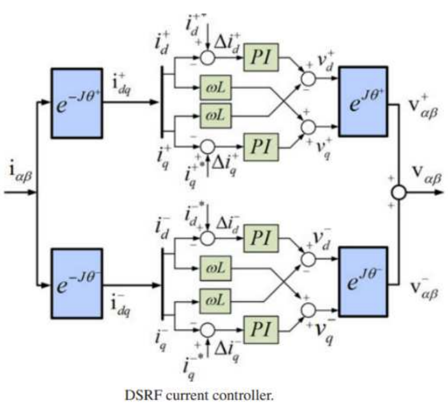

Figure 2: *DSRF method block diagram [6].*

The proposed method is based on using a time-domain symmetrical component extraction method to obtain the symmetrical components. This approach [14] uses time delays as well as simple addition and subtraction. As a consequence, compared to other approaches, this method is more efficient and requires fewer calculations..

$$i_{abc}^{+} = \frac{1}{3}\begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix}[\mathrm{f_a} + \alpha\,\mathrm{f_b} + \alpha^2\mathrm{f_c}] \tag{4}$$

$$i_{abc}^{-} = \frac{1}{3}\begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix}[\mathrm{f_a} + \alpha^2\mathrm{f_b} + \alpha\,\mathrm{f_c}] \tag{5}$$

Where $\alpha = 1\angle 120°$, $\alpha^2 = 1\angle 240°$

The measured grid currents will be converted to their symmetrical components (positive, negative and zero). The new symmetrical currents (i_{abc+}, i_{abc-}, i_{abc0}) are balanced. The system is assumed to be ungrounded which yields $i_{abc0} = 0$. Then, these symmetrical components can be transferred to $dq0$ coordinates with constant values. As a result, a PI controller can be employed. So, it requires only one angle θ, which means only one phase-locked-loop as shown in Fig. 3.

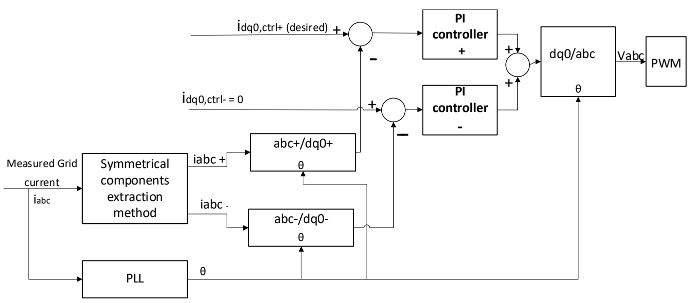

Figure 3: *The block diagram of the improved method (current control).*

If the three-phase reference current i_{abc} is considered to be balanced in case of unbalanced system, the grid current will be balanced by PI controller (the target to let error=0, which means actual grid current =reference current)

$$i_g = i_{ref} = i_{ctrl} \tag{6}$$

B. Power Control under Unbalanced Grid Conditions

The proposed method can be used to correct imbalanced grid currents and govern the amount of power injected into the grid by the inverter. $P_{desired}$, $Q_{desired}$ and V_g provide the reference current (the power control current i_{ctrl}). It can be calculated according to reference [17] as shown below:

$$\bar{S} = P + jQ = v_{dq}^{+} i_{dq}^{*\,+} \tag{7}$$

$$P + jQ = \left(v_d^+ + jv_q^+\right)\left(i_d^+ - ji_q^+\right) \tag{8}$$

$$P + jQ = \left(v_d^+ i_d^+ + v_q^+ i_q^+\right) + j\left(v_q^+ i_d^+ - v_d^+ i_q^+\right) \tag{9}$$

The power control current i_{ctrl} (in $dq0+$ domain) can be found using equation (10).

$$\begin{bmatrix} i_{d\_ctrl}^{+} \\ i_{q\_ctrl}^{+} \end{bmatrix} = \frac{1}{v_\alpha^{2+} + v_\beta^{2+}} \begin{bmatrix} v_d^+ & v_q^+ \\ v_q^+ & -v_d^+ \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{10}$$

The power command current components in the negative and zero sequences will be set to zero since one of the aims is to balance grid currents; this assumption will present a balanced power control current i_{ctrl}. Then, the target of the controller is let the grid current = the reference current (the power control current) as in equation (11). The grid current will be balanced as a result, and power control will be introduced at the same time.

$$i_g = i_{ctrl} = i_{ctrl}^{+} \qquad (11)$$

Note that $i_{ctrl}^{-} = 0$.

Fig . 4 shows a block schematic of the suggested approach for implementing power control.

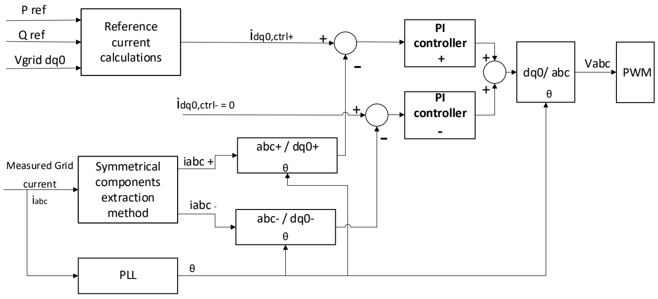

Figure 4: *The block diagram of the improved method (power control).*

TABLE I. TEST SYSTEM PARAMETERS

V_{dc}	DC source voltage	400 V
V_g	Grid phase voltage	120 V RMS
f_g	Grid frequency	60 Hz
f_{sw}	Switching frequency	5 kHz
L_1	Inverter side inductor	2.3 mH
L_2	Grid side inductor	0.58 mH
C	Capacitor	15 µF
R	Dapming resistor	1.5 Ω

III. CASE STUDY

The proposed method was evaluated in simulation and hardware experiment. The system parameters are shown in Table 1.

A. Simulation Results

MATLAB/SIMULINK software was used to test the proposed approach. Fig. 5 shows the Simulink model of the system.

Under the following parameters, the technique has been tested with a balanced grid voltage and an imbalanced load:

- DC source voltage is 400 Volts.
- Balanced three-phase grid voltages with 120 V RMS.
- For phases A, B, and C, the three-phase unbalanced load is considered to be 8, 16, and 32 ohms, respectively.
- The unbalancing in load creates unbalancing in the grid currents as well.
- The values of reference values were assumed as $P_{desired} = 2\ kW$, $Q_{desired} = 0\ kVar$.
- The power control command (i_{pc}) is extracted from $P_{desired}$, $Q_{desired}$ and the grid voltages.

The simulation results for the grid output power (P, Q), load current (i_L), inverter output current (i_{inv}), grid current (i_g) and grid voltage (V_g) are shown in Fig. 7.

In Fig. 7, From $0 \le t \le 0.1\ seconds$, the system was running on an unbalanced load with no inverter. During this time period, the simulation results revealed imbalanced grid currents as well as oscillatory real and reactive power. This imbalanced operation might affect any sensitive loads connected to the PCC.

The inverter was turned on at $t = 0.1$ second, and the proposed control mechanism was applied. The simulation results reveal that the suggested technique balanced the grid currents and injected power into the grid with the desired value in only a few milliseconds. Furthermore, because the I_g

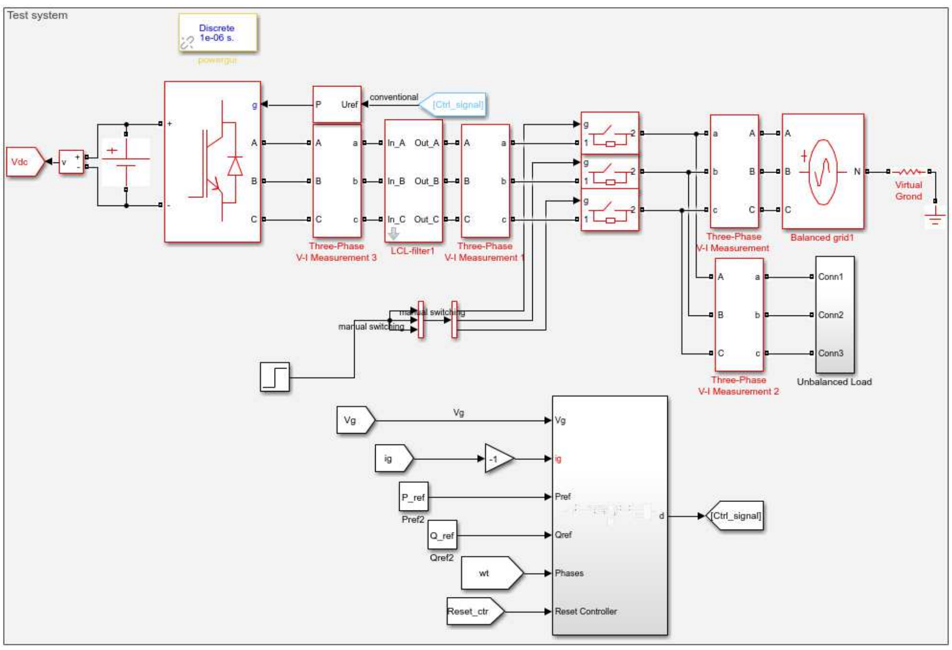

Figure 5: MATLAB/Simulink model of the system.

and V_g are now balanced, real and reactive power oscillations have been abolished. These findings show that the suggested technique is capable of delivering power to the grid while also balancing grid currents.

B. *Experimental Results*

The system's hardware connection is shown in Fig. 6. A variable resistors utilizes as a three-phase load, NHR 9410 utilizes a grid simulator, an NHR 9210 battery test system utilizes as a DC source, while an AgileSwitch 100 kW DC-AC inverter, dSPACE DS1202 represents as a real-time interface (RTI), LCL filter, and measurement boards for currents and voltages are among the experimental devices.

The experiment was conducted with the same conditions/assumptions as in the simulation part. For load phases A, B, and C, the load was considered to be imbalanced with 8, 16, and 32 ohms, respectively. The grid voltages is $V_{gridLN} = 120\, V\, RMS$ and balanced. $P_{desired} = 2\, kW$, $Q_{desired} = 0\, Var$. Fig. 8 shows the hardware experimental findings for (P, Q) injected to the grid, load currents (i_L), inverter injected currents (i_{inv}), grid currents (i_g), and grid voltages (V_g) using the dSPACE ControlDesk. The presented method's transient was just as follows:

$0 \leq t \leq 9.66$ seconds, the imbalanced load was attached to the grid during this time, and i_g were unbalanced at the beginning of the experiment. Because of the imbalanced load, the P and Q waveforms were oscillatory.

Figure 6: Three-phase grid-connected inverter with LCL filter - Hardware experimental connection.

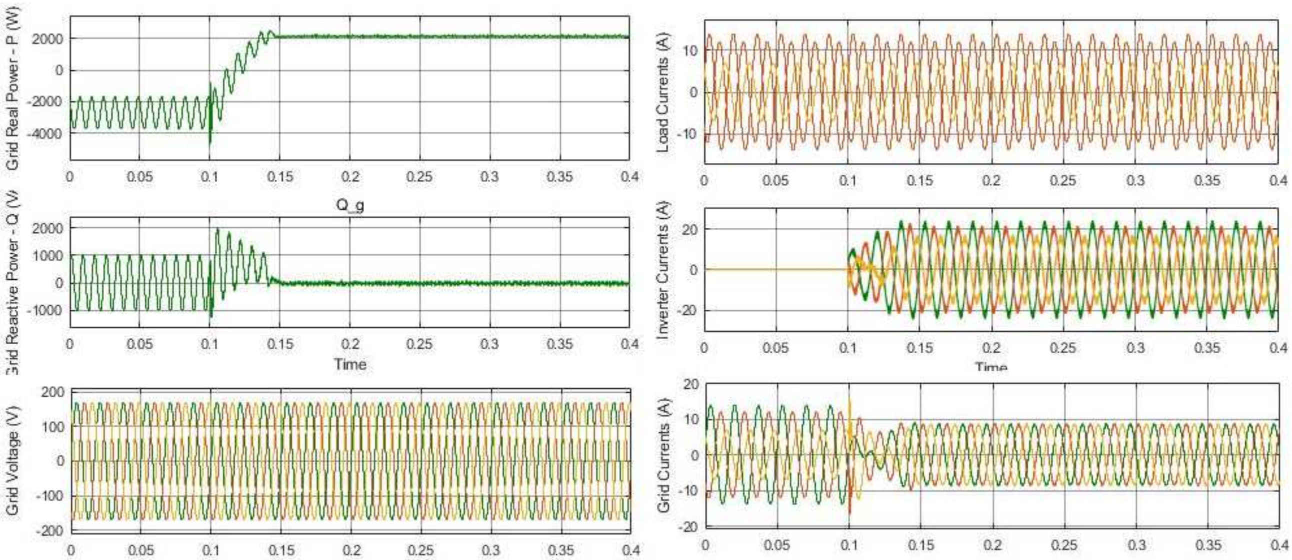

Figure 7: Simulation results of the proposed method under unbalanced load / imbalance grid currents.

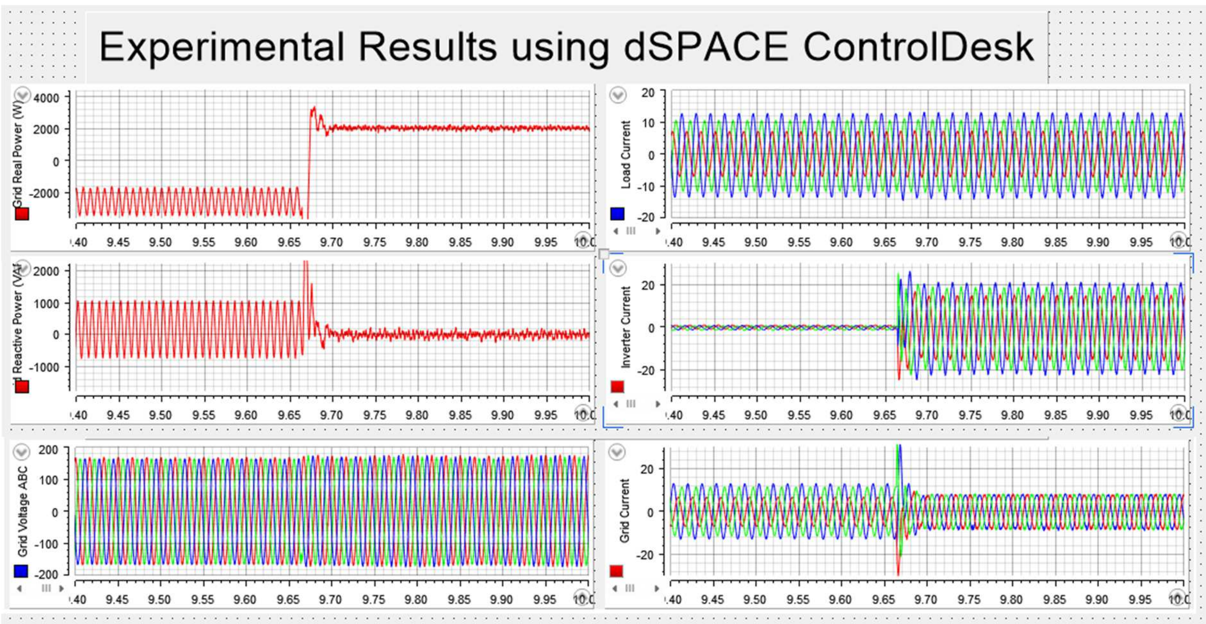

Figure 8: The proposed method's experimental results utilizing dSPACE ControlDesk.

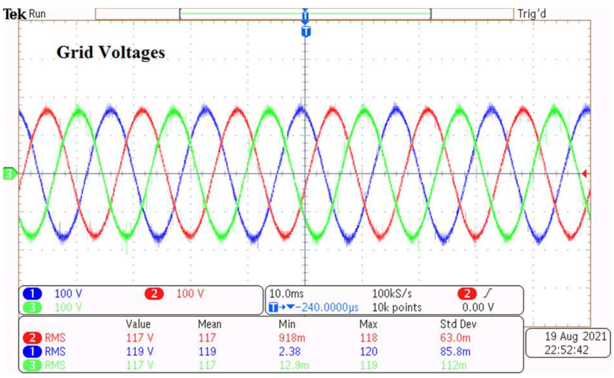

Figure 9: V_g hardware results.

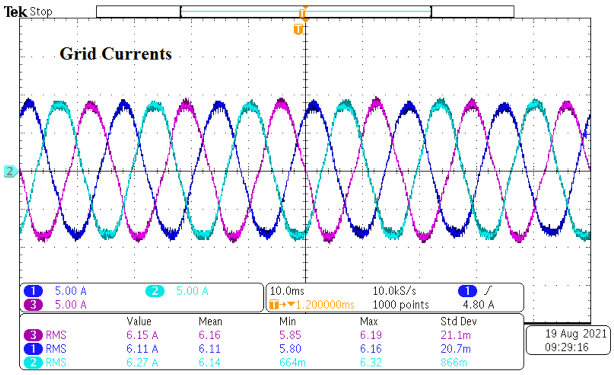

Figure 10:i_g hardware results.

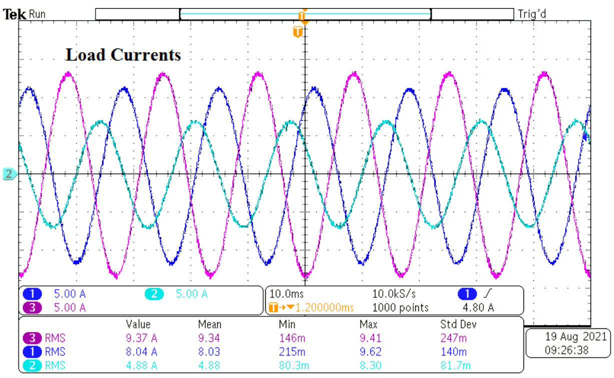

Figure 11: i_L hardware results.

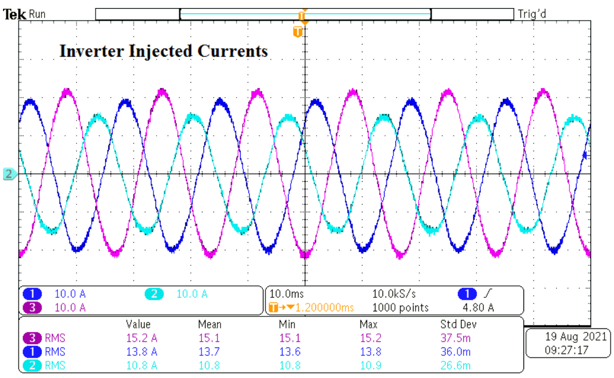

Figure 12: i_{inv} hardware results.

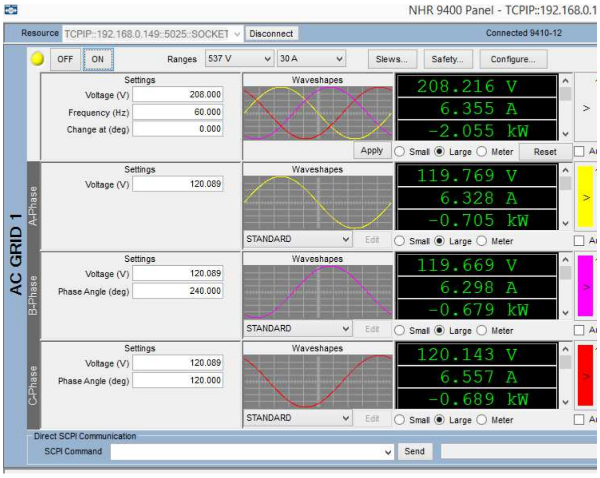

Figure 13: Grid Simulator hardware results with $P_{injected}$.

The inverter was energized and utilized the suggested control technique at $t = 9.66$ seconds. The grid currents were regulated to be balanced in milliseconds, and constant power was injected to the grid. Once the i_g were balanced, the huge fluctuations in P and Q were removed. These findings demonstrate that the proposed methodology works since the inverter can both send desired P and Q to the grid and balance i_g at the same time.

Grid voltages, grid currents, load currents, and inverter currents were all measured using an MDO3024 Tektronix oscilloscope, as illustrated in Fig.9, Fig.10, Fig.11, and Fig. 12, respectively. Grid voltages, grid currents, load currents, and inverter currents were all measured using an MDO3024 Tektronix oscilloscope, as illustrated in Fig.9, Fig.10, Fig.11, and Fig. 12, respectively. The NHR 9400 Panel was used to obtain the grid simulator readings. In Fig. 13, the power transferred to the grid is reported as -2.055 kW. The the negative sign shows that the inverter was delivering power to the grid simulator.

The method's efficacy has been shown based on the experimental results. As a result, after activating the controller, the delivered to the grid may be controlled while the grid current is balanced in a matter of milliseconds. Because the grid is now balanced, the significant oscillation problem in P and Q was resolved.

IV. CONCLUSIONS

This paper describes a method for injecting power into the grid while balancing grid currents in the presence of an imbalanced load using a three-phase inverter. The real and reactive power oscillates in an imbalanced grid, which has an effect on the inverter's power control and other grid-connected loads. The suggested method has the ability to both balance and remove grid current fluctuations. The suggested technique has been validated by simulation and hardware experiments.

The proposed method's strengths over other methods are: 1) one PLL is needed while the DSRF requires two PLL, 2) less complexity because the DSRF analysis requires: $abc \rightarrow \alpha\beta\gamma \rightarrow symmetrical\ components \rightarrow dq0$ while the proposed method requires $abc \rightarrow symmetrical\ components \rightarrow dq0$, and 3) time-domain symmetrical extraction component method is simpler than literature.

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