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Frequency and voltage droop control of parallel inverters for integrating renewable energy sources in microgrids

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ABSTRACT

In recent years, microgrids are employed exceedingly in distribution power utilities for securing the system's practicality for both islanded and tied modes. The voltage and frequency limits preservation represents the essential challenge in load sharing between the DGs. This paper exhibits a simple and efficient frequency control approach for grid-connected two-distribution sources (DG's) employing droop-logic alongside a traditional PI controller to produce a two-step active and reactive power reference value generation is the main goal in this strategy. The proposed approach allows direct active and reactive power control for two parallel DGs, joined in a microgrid. The proposed algorithm is designed to track the active power reference value based on the grid frequency deviation to enable decentralized power sharing between DG units and improve the system's response to load demands. The MATLAB/Simulink model simulation results confirm the enhancement in power sharing, controllability, and transient response of the power flow due to demand changes. The parallel inverters are governed to supply the demand power and transport the excess to the grid utility.

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1. INTRODUCTION

Clean energy resources and reduced carbon emissions are critical concerns for present-day power networks [1], [2]. Photovoltaic systems, battery energy storage systems (BESS), and wind turbines are among the major components of distributed generation (DG). DG is an approach to power generation that increases the efficiency and controllability of power systems [3]. Regulation of voltage and frequency within the permitted range is critical for microgrids' energy management [4].

Parallel integration of multiple DGs presents several practical difficulties, including circulating currents between inverters, degradation of active/reactive power sharing, and voltage/frequency instability during rapid load changes [5]. The use of multiple power sources to meet the load represents the biggest challenge in microgrids [6]. As a result, linking two or more inverters becomes vital [7]. By combining these diverse elements, the process of power-sharing techniques became more achievable. To resolve parallel inverter operation, the conventional droop control (CDC) uses synchronous generator behavior by relating frequency with active power (P/f) and voltage with reactive power (Q/V) [8], [9]. This behavior is recognized when they try to balance their input mechanical power with the delivered electrical power under steady-state operation. So, if the mechanical power (P_m) is greater than the electrical power (P_e) (P_m>P_e), the extra mechanical power is turned into kinetic energy to speed up the machine's rotor, increasing the system frequency. On the contrary, if the load demand exceeds the input mechanical power (Pm > Pe), the machine

tends to slow down, resulting in a reduction in frequency. The same correlation holds for reactive power and system voltage. When the reactive power is reduced, the voltage level tends to decline, and vice versa. This natural interactivity between these variables (voltage, frequency, and power) is the principal concept of droop-control methods [9].

Many enhanced droop control methods have been proposed to address the limitations in the CDC, but there is no obvious path to these methods based on specific existing problems within their scope. Although there have been some developments in the area, the existing adaptive droop and transient impedance methods produce a large amount of computational complexity and performance reduction in LV microgrid networks. Researchers and engineers face difficulty in figuring out the proper choice to control MG variables.

To overcome the aforementioned limitations, a two-level decentralized droop-PI control scheme for grid-connected parallel inverters in an LV microgrid is proposed in this work. Specifically, the key contributions are i) A simplified frequency-controlled droop control mechanism combined with a double PI controller in the d–q reference frame; ii) Adaptive estimation of the active/reactive power references in response to load demand steps without inter-inverter communication through cables; and iii) An efficient solution verified for LV networks where the line resistance is dominant over the reactance. This method eliminates the risk of any single-point failure in communication and reduces the cost of implementation for the commercial microgrid system. It provides accurate tracking of power, fast transient recovery of frequency, and low harmonic distortion; hence, a practical and realistic method that can be implemented using low-cost DSPs for renewable energy integration.

2. DROOP CONTROL IN MICROGRIDS

Multiple inverters can be connected in parallel to supply the grid, such that the aggregate output currents are summed at the point of common connection (PCC) equal to the grid current plus the load current, as in (1) and (2) [10], [11].

$$P_n = \frac{\left(|V_n|^2 cos(\delta_n) - |V_n||E| cos(\delta_n + \theta_{Zn})\right)}{|Z_n|} \quad (1)$$

$$Q_n = \frac{\left(|V_n|^2 sin(\delta_n) - |V_n||E| sin(\delta_n + \theta_{Zn})\right)}{|Z_n|} \quad (2)$$

Where, $V_n = |V_n|\angle\theta_{Vn}$, and E= $|E|\angle\theta_E$ are the voltage vectors at the nth inverter output and the PCC, Z_n represents the complex line impedance with angle of θ_{Zn}, also $\delta_n = \theta_{Vn} - \theta_E$ [12].

The line impedance has a great effect on the active and reactive power supplied to the utility [13], [14]. Droop control inverters (DCIs) are typically employed to manage voltage and frequency and to exchange active and reactive power flow between the parallel converters [15], [16]. This is because it has the ability to run quite literally reasonably and steadily [17]. On the other hand, a mismatch between the transmission line and inverter benevolent rate can cause circulating currents, voltage unbalance, and incorrect active and reactive power sharing among the distributed generators (DGS) [18], [19]. Figure 1 shows an overall model diagram of parallel grid-tied inverters with two sources.

Due to the variety in feeder impedance for different DGs, the distributed generator with lower impedance selects many of the transients compared to the one with higher impedance to assist the loads, so it exceeds expectations due to its droop gain [20]. In some research, the techniques of transient or adaptive CDC are adopted; the consequences are degradation in load sharing, frequency, and voltage at steady operation [21]. In this paper, the proposed strategy is carried out under the d-q reference frame. Consequently, this approach facilitates the calculation of the active and reactive power via converting the (abc) voltages and currents into the d-q frame [22]. The resistive component of the line impedance in low voltage (LV) networks is substantially longer than the inductive component. As a result, the inductive component cannot be considered. In addition, because it is likely small, the (1) and (2) can be approximated as in (3) and (4).

$$P_n = \frac{|V_n|\left(|V_n| - |E| cos(\delta_n)\right)}{|R_n|} \approx \frac{|V_n|(|V_n| - |E|)}{|R_n|} \quad (3)$$

$$Q_n = \frac{\left(-|V_n||E| sin(\delta_n)\right)}{|R_n|} \approx \frac{-|V_n||E|(\delta_n)}{|R_n|} \quad (4)$$

Therefore, by adjusting active and reactive power flow appropriately, the voltage and frequency in LV networks can be regulated [23]. The frequency droop relation and voltage curves in this work are implemented, and two PI controllers can control the active and reactive power of the DGs to achieve voltage

and frequency regulation according to these features, respectively [24]. The new requirements are thus accomplished by the DGs under the two controllers' commands.

Figure 2 shows the frequency and voltage droop characteristics for the LV network [10], [25]. Where Pref. and Q_{ref}. are the desired values of active and reactive power, ω_{ref}, and V_{ref} are the command values of the frequency and the inverter output voltage magnitudes. The instantaneous active and reactive powers are computed from the inverters' output currents and the PCC voltage to regulate the inverters in parallel. To achieve the proper power sharing among DGs, the measured powers are subsequently supplied to a droop regulator. The system's steady-state frequency is set to the grid frequency when it is in grid-tied mode. These droop control characteristics can be used to set the DG's active power reference value.

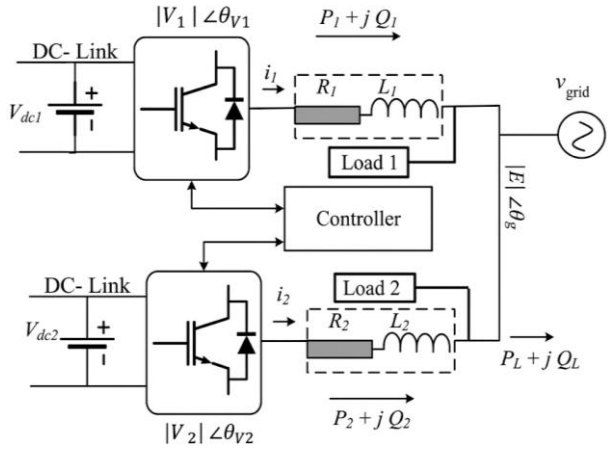

Figure 1. Overall model diagram of parallel grid-tied inverters with two sources

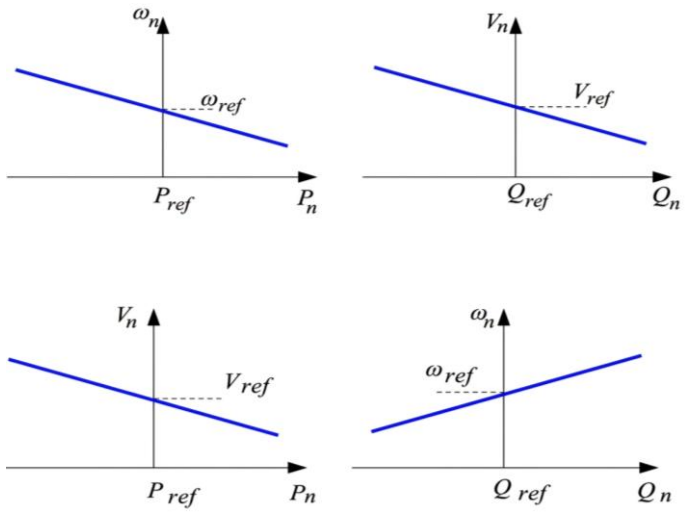

Figure 2. Droop characteristics in inductive and resistive grids

2.1. Procedures/implementation steps

The implementation procedure consists of three main steps, as described below:

i) Sampling and transformation: Obtain the three-phase voltages (V_{abc}) and currents (I_{abc}) from the PCC and transform them into the d–q frame using Park's transformation.

ii) Droop reference calculation: Calculate the frequency error ($\Delta\omega$) and voltage error (ΔV) to obtain inputs for the outer proportional-integral (PI) regulators, hence obtaining the active (P_{ref}) and reactive (Q_{ref}) power references.

iii) Inner loop processing: Perform inner loop processing using the d-q current errors by using the inner proportional-integral current regulator (Kp = 55.9, Ki = 56,000).

2.2. Validation and verification approach

The validation procedure applies three sequential load steps of 20 kW, 15 kW, and 10 kW during a 1.0 s simulation period. These steps are used to examine the system response under varying load conditions. The selected loading levels allow both transient and steady-state performance evaluation. The power-tracking error, defined as (P_{actual} - P_{ref}), is evaluated to calculate the accuracy of active-power regulation. The time required for the frequency to return to its nominal value is also measured after each load change. These indicators reflect the controller's tracking performance and dynamic stability. Finally, the current total harmonic distortion (THD%) is calculated to assess output waveform quality. Keeping low THD during load transitions confirms good power quality. Collectively, these metrics validate the effectiveness of the proposed control strategy.

2.3. Characteristics of feeder impedance and closed-loop stability

In LV microgrids' distribution lines, feeder sections have an R-L impedance characteristic. For the physical parameters of the system under study, as shown in Table 1, the total line impedance is ≈ 0.104 Ω, with an impedance angle of 73°. Since the value of θ_z is not negligible, the coupling between active and reactive power flow occurs due to both the phase angle of voltage δ and voltage deviation ΔV. To avoid cross-coupling effects and circulating currents in such an R-L line, the suggested control scheme uses inner synchronous reference frame (d-q) control to directly generate the active and reactive power references. Transforming terminal variables into the rotating d-q frame decouples the active and reactive current components (id and iq, respectively).

This study focuses on developing a simple control strategy to calculate the reference active and reactive power for the parallel operation of inverter-based microgrids. Therefore, the stability analysis of the suggested control system must be considered, which can be evaluated using different approaches such as transient response, the bounded-input bounded-output (BIBO) criterion, or a complete analysis based on eigenvalue analysis. But, with the assumption that the two inverters have identical control parameters and line impedance, proportional power sharing is expected at steady state. For the studied load conditions shown in Table 1, the corresponding equilibrium power values for inverter 1 are 10 kW active power and 2.5 kVAr reactive power; for inverter 2, they are 7.5 kW active power and 2.25 kVAr reactive power; and for inverter 3, they are 5 kW active power and 1.5 kVAr reactive power. The system provides good stability under load changes, as shown in Figures 3-7. At the same time, the suggested droop control and the outer and inner control loops ensure that the responses of voltage, frequency, active power, and reactive power remain within defined limits. As a result, the system remains within these limits. It stabilizes at a new operating point after each load change, without sustained oscillations, confirming the stability of the transient behavior and BIBO-compliant operation under the conditions studied.

Table 1. System parameters

Grid nominal voltage	Vgrid	380 V (RMS, L-L)	Grid nominal voltage	Vgrid	380 V (RMS, L-L)
Grid nominal frequency	fgrid	50 Hz	PI voltage controller gains	Kp, Ki	0.2, 50
Inverter filter resistance	Rf	0.1 Ω	PI current controller gains	Kp, Ki	55.9, 56000
Inverter filter inductance	Lf	0.0035 H	Load stage1 (t = 0.0-0.2 s)	PL1, QL1	20 kW, 5 kVAr's
Feeder line resistance	Rline	0.03 Ω	Load stage2 (t = 0.2-0.4 s)	PL2, QL2	15 kW, 4.5 kVAr's
Feeder line inductance	Lline	0.000318 H	Load stage3 (t = 0.4-1.0 s)	PL3, QL3	10 kW, 3 kVAr's

3. SIMULATION AND RESULTS

3.1. Presentation of results

Two parallel sources BESS are connected to a common grid via two inverters. The model is simulated using MATLAB/Simulink. The active and reactive loads are abruptly changed in three steps during the simulation. The system parameters are as shown in Table 1. The proposed control scheme results in minimal transient impact on the power grid during the three-step change in load. This can be seen in Figure 3, where the grid frequency is limited between 49.996 Hz and 50.0078 Hz during the step changes at t = 0.2 s and t = 0.4 s, then quickly recovers to 50.00 Hz after 0.05 s.

Figures 4 and 5 illustrate that the active power outputs of sources 1 and 2 closely match their references. Figure 6 shows the combined generation of active and reactive power of source 1, whereas Figure 7 demonstrates the distribution of active power between both sources and the grid. Three-phase voltages and currents in Figures 8 and 9 remain balanced and sinusoidal during all sudden changes in load. The analysis of the output current THD of source 1 via FFT shows a value of 1.44%, which is below the IEEE519 standard limit (<5%), as shown in Figure 10.

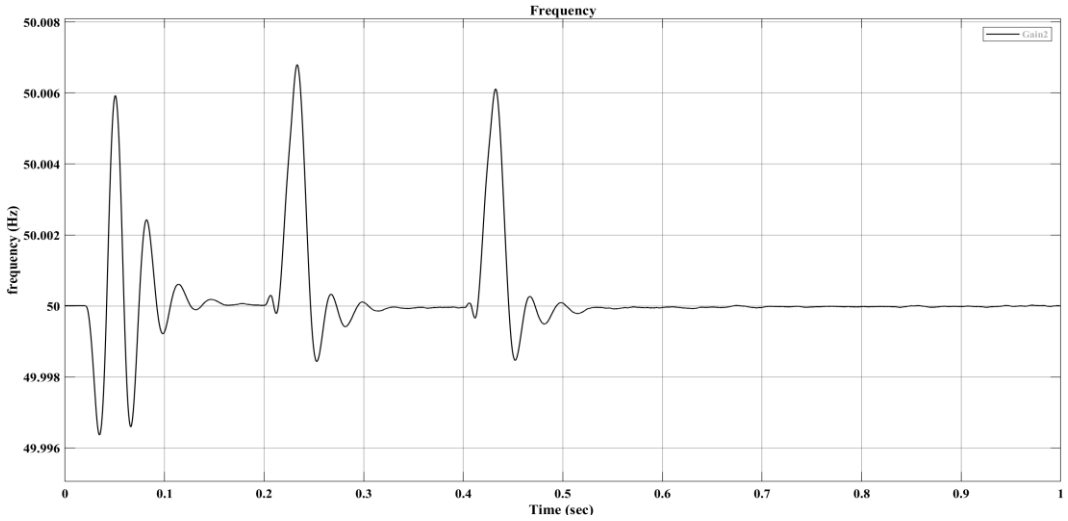

Figure 3. Frequency change

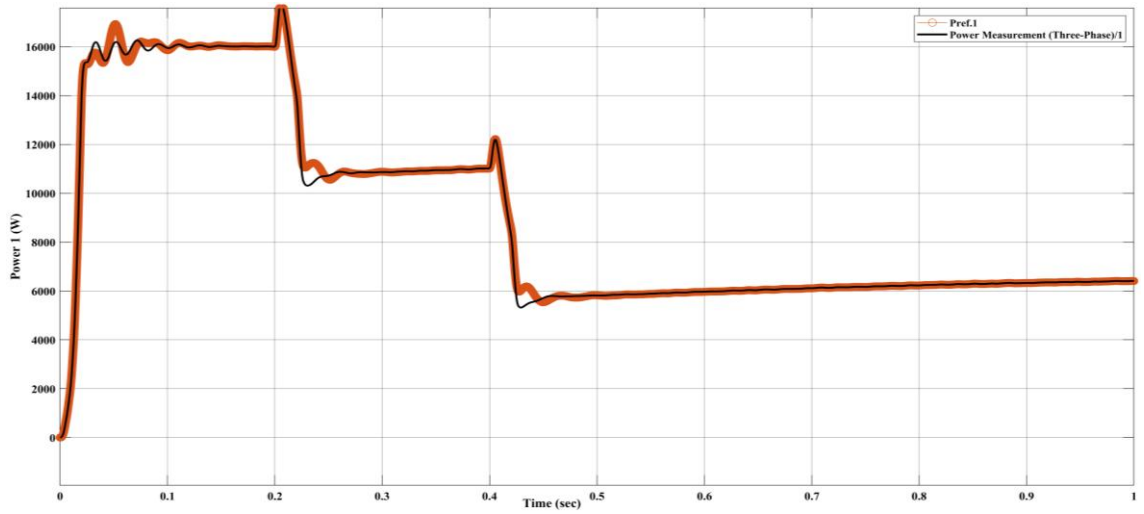

Figure 4. P_{ref1} with measured power 1

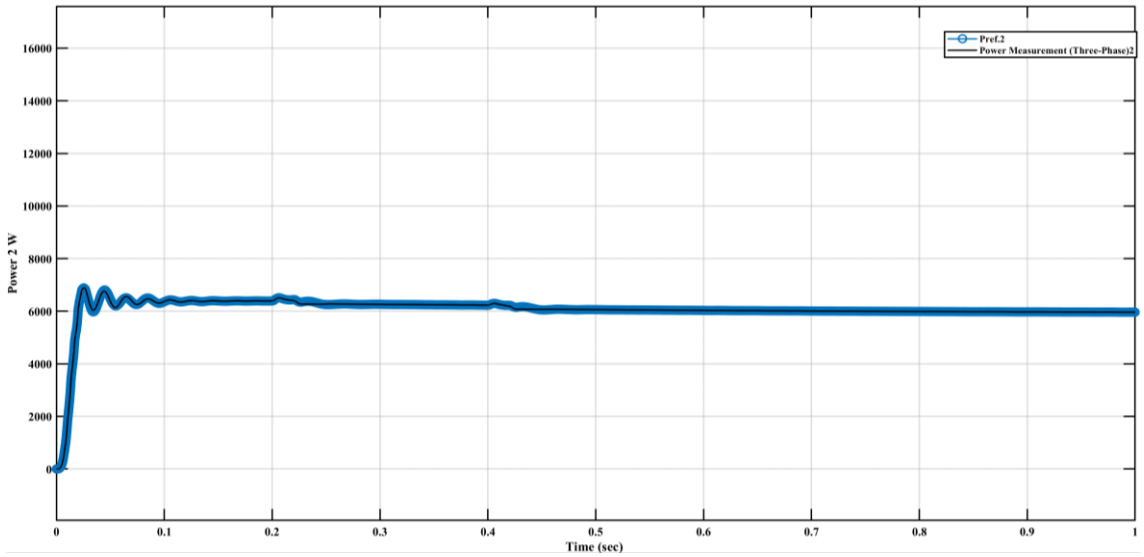

Figure 5. Reference active power 2 with measured power

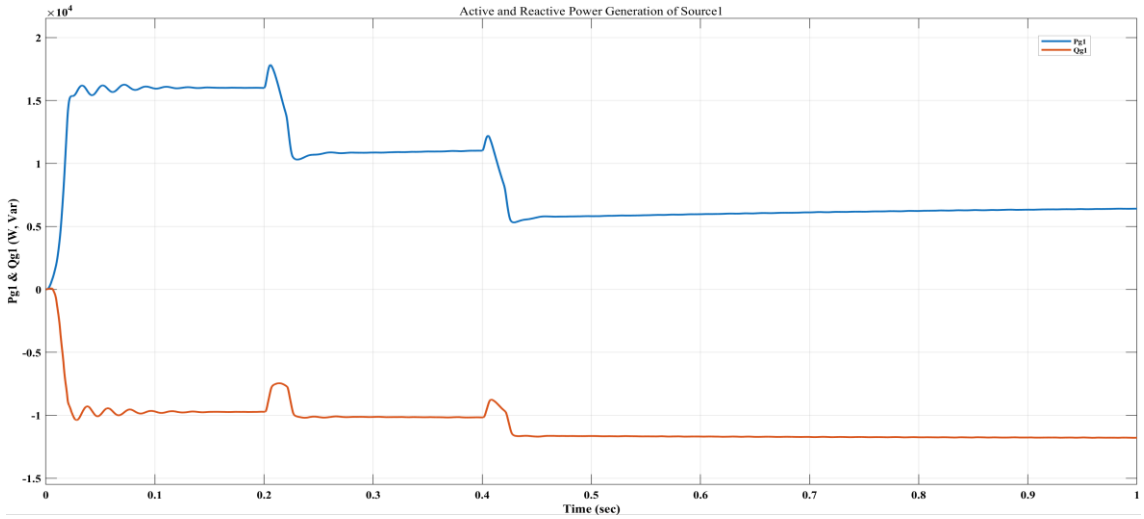

Figure 6. Active and reactive power source 1

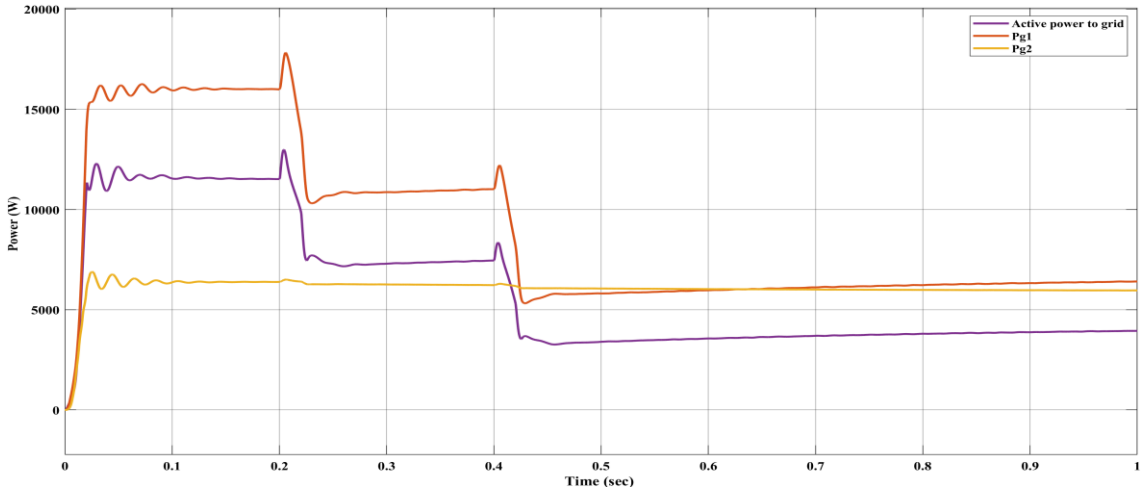

Figure 7. Active power for the two sources and the grid with changes in source loads

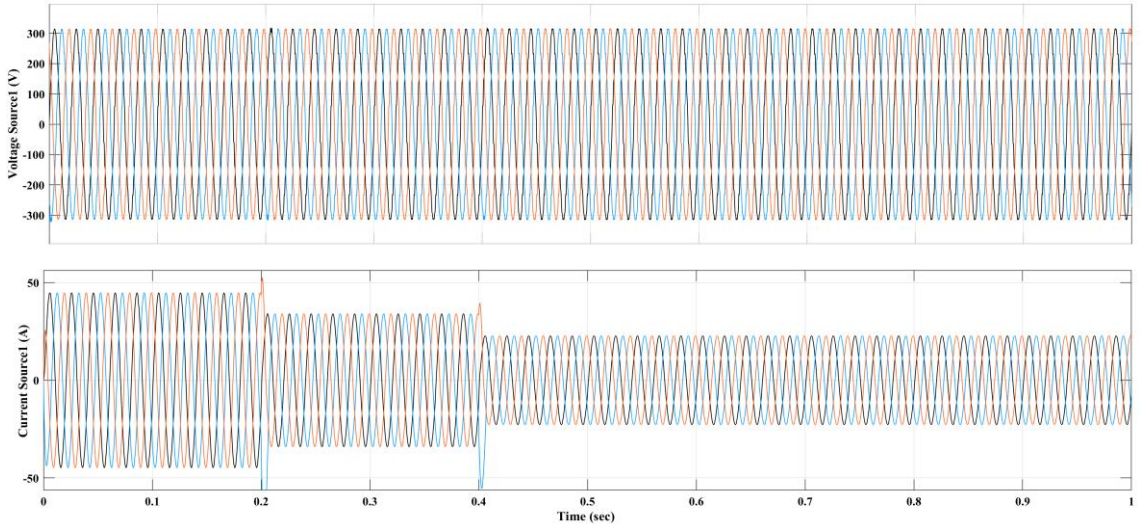

Figure 8. Three-phase voltages and currents at the output of inverter1

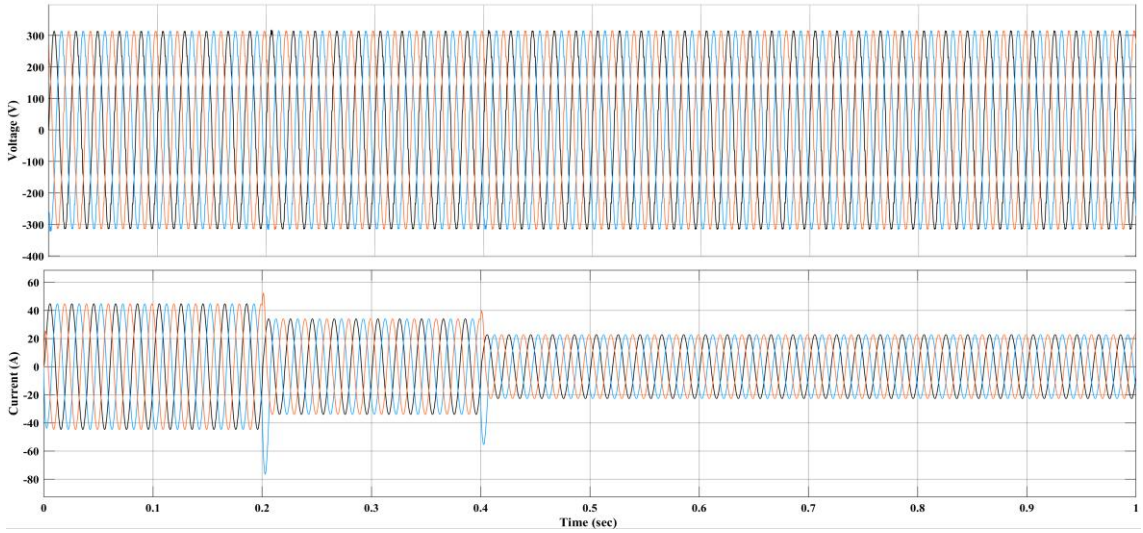

Figure 9. Three-phase voltages and currents at the output of inverter2

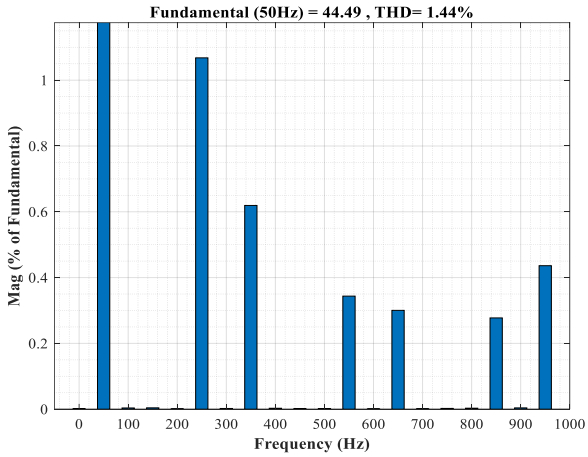

Figure 10. THD for the output current of source 1

3.2. Analysis and interpretation

The fact that the recovery time for frequency is quite short (0.05 s) suggests that the addition of the droop control strategy in conjunction with the tuned d-q control loops (with Kp = 55.9 and Ki = 56,000) successfully prevents power oscillations. The THD of 1.44% obtained from Source 2 indicates that the LC filter (with Rf = 0.1 Ω and Lf = 0.0035 H) significantly attenuates switching harmonics. When the load decreases, the excess active power can be readily transferred back to the grid (Figure 8) without causing overvoltage at the PCC.

3.3. Comparison with previous works

In Table 2, a comparison of quantitative performance under a 5-kW step load variation is shown with the literature [18], [21], and [19]. The comparison took in account the main factors to judge on the system performance including frequence (settling time, drop Δf). Also, the real power maximum overshoot and the load current THD are considered.

Table 2. A comparison of quantitative performance

Performance criterion	Conventional droop control	Proposed droop-PI control	Percentage increase/decrease
Time for frequency restoration (ts)	0.18s	<0.05 s	72.2% decrease
Maximum transient frequency drop (Δf)	0.024 Hz	0.0078 Hz	67.5% decrease
Real power overshoot (Mp)	14.2%	2.1%	8.5% reduction
Power-sharing steady-state error	3.8%	<0.4%	≈0 error
Load current THD	3.8%	1.44%	Meets IEEE 519 Standards

4. CONCLUSION

This paper has presented a decentralized frequency- and power-sharing control scheme for two parallel BESS connected to a low-voltage microgrid via grid-tied inverters, implemented in the MATLAB/Simulink environment. The proposed strategy combines frequency-based droop logic with conventional PI controllers operating in the d-q reference frame, producing two-step active- and reactive-power reference signals that independently drive each inverter. The main results and findings are listed as: i) Accurate tracking: The outputs of active power generation were close to the reference setpoints during all the load changes (20 kW -> 15 kW -> 10 kW); ii) Quick convergence: Frequency deviations from the nominal value did not exceed ±0.008 Hz, and the stabilization time was less than 0.05 s; and iii) The THD of load current was equal to 1.44% and was below the threshold of grid requirements for high power quality. The analysis does not account for voltage distortion or voltage unbalance in the BESS DC-link and grid contingencies. Future investigations will focus on validating the method under hardware-in-the-loop conditions, incorporating variability from renewable sources, and extending the control framework to enable seamless implementation of islanding mode. In the future, the researchers will focus on HIL experiments with variable photovoltaic generation and on implementing islanding mode.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Riyadh G. Omar	✓	✓			✓	✓			✓	✓				
Auday A. H. Mohamad		✓	✓	✓	✓	✓			✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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