



Received May 05, 2026; Received in revised form July 28, 2026, September 14, 2026; Accepted September 28, 2026; Date of publication October 08, 2026.

The review of this paper was arranged by Associate Editor Victor F. Mendes<sup>✉</sup> and Editor-in-Chief Allan F. Cupertino<sup>✉</sup>.

Digital Object Identifier <http://doi.org/10.18618/REP.e202631>

# A Current-Scaling Strategy for Droop-Controlled Grid-Forming Inverters in Off-Grid Systems

Samuel C. Schüler<sup>✉1</sup>, Mateus Radke<sup>✉1</sup>, Paulo J. D. de O. Evald<sup>✉1,\*</sup>,  
Telles B. Lazzarin<sup>✉2</sup>

<sup>1</sup>Federal University of Pelotas, Intelligent Systems and Control Group, Pelotas – RS, Brazil.

<sup>2</sup>Federal University of Santa Catarina, Institute of Power Electronics, Santa Catarina – SC, Brazil.

e-mail: samuel.schuler@ufpel.edu.br, mateus.radke@ufpel.edu.br, paulo.evald@ufpel.edu.br\*, telles.bl@ufsc.br

\*Corresponding author.

**ABSTRACT** The progressive replacement of synchronous generation by inverter-based renewable energy resources is altering the dynamical structure of modern power systems, reducing system strength due to the inertia curtailment. In this context, grid-forming inverters have emerged as a fundamental technology capable of establishing voltage and frequency in inverter-dominated grids. However, their effective deployment is intrinsically dependent on the control framework that must guarantee stability, robustness, and interoperability under complex and uncertain operating conditions. The most adopted grid-forming control strategy is droop control. This work presents a proportional scaling strategy in the inner current loop for droop-controlled grid-forming inverters, which preserves the current angle, reducing only its magnitude if a large disturbance occurs. Moreover, an innovative grid-forming controller parametrization procedure based on hybrid jellyfish search and particle swarm optimizer is also provided. This methodology avoids empirical tuning and allows incorporating system constraints in the controller tuning procedure. Hardware-in-the-loop results demonstrate high performance of the optimized droop under nominal operation, load variation, black-start, and faults.

**KEYWORDS** Current limiters, Fault-ride through capability, Meta-heuristic optimization, Renewable energy.

## I. INTRODUCTION

As electrical power systems go through a transformation, the traditional architecture of centralized and inertia-rich power generation is moving to a decentralized landscape dominated by renewable energy sources [1]. Technologies like solar photovoltaic [2] and wind turbines [3] are essential for decarbonization. These power conversion systems are interfaced with the grid through power electronics inverters [4]. This change alters how the grid behaves due to an absence of inertia inherent to synchronous machines (SM) [5]. One of the most promising solutions to maintain stability in the modern power grid is the grid-forming (GFM) inverters [6].

Unlike conventional grid-following controllers, which need to synchronize to an established grid voltage waveform to regulate power generation, such in [7]–[9], GFM inverters create and regulate voltage and frequency, while emulating inertia and enabling grid-supportive operation in off-grid systems [10]. These units mimic the behavior of SMs, providing necessary services for the grid formation even in the absence of mechanical inertia [11]. This capability becomes critical as the share of inverter-based resources (IBRs) increases, especially in scenarios where conventional generators are ceased. However, enabling GFM behavior is not simply a matter of hardware.

Functional GFM inverters require a proper control system to ensure that these inverters can operate autonomously, supplying the power demand, and respond dynamically to disturbances. They must balance competing objectives: stability, robustness, efficiency, and scalability. Control strategies like droop control [12]–[14], virtual synchronous machines [15]–[17], and virtual oscillator control [18]–[20] are being developed to address these challenges. Between these approaches, droop control is widely adopted, being currently one of the most popular GFM control strategies [21]. Although droop control strategies are simpler than other approaches, the controller's performance depends on how well it is tuned. In this sense, the contributions of this work are threefold:

- A droop control with a proportional scaling strategy in the inner current loop that preserves the current angle, reducing its magnitude if a large disturbance occurs;
- An innovative GFM controller parametrization procedure based on hybrid jellyfish search and particle swarm optimizer (JS-PSO);
- Virtual hardware-in-the-loop (HIL) validation considering load variation, short-circuit faults, black start, and imbalance.

The remainder of this work is organized as follows: Section II describes the system, followed by control strategy formulation and systematic tuning procedure in Section III. Next, Section IV discusses the virtual HIL results, and Section V gives the conclusions of this work.

## II. SYSTEM DESCRIPTION

The system, illustrated in Fig. 1, consists of a three-wire inverter operating in islanded mode and forming a stable electrical grid, maintaining voltage and frequency within pre-established limits, even under variations in load or operation. The coupling between the inverter and the loads is achieved through an LCL filter, whose purpose is to attenuate the high-frequency harmonics generated by the inverter switching dynamics, ensuring compliance with the IEEE 1547 standard requirements.

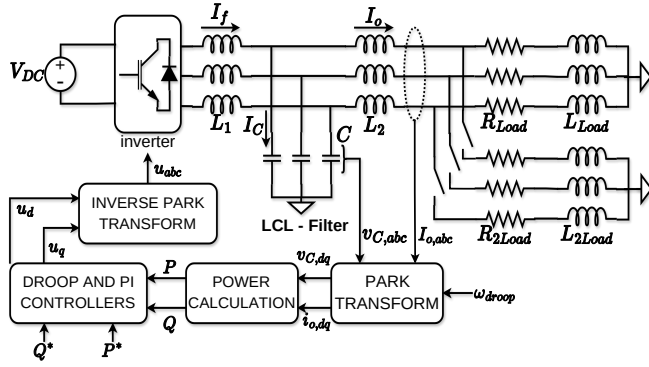


FIGURE 1. GFM inverter connected to the loads through an LCL filter.

The cascaded control strategy is composed of outer and inner loops. The first one regulates system frequency and voltage amplitudes, based on references generated by  $P - \omega$  and  $Q - V$  droop controllers, respectively. These control algorithms allow it to emulate the behavior of a synchronous generator, enabling power-sharing. On the other hand, the internal loop acts to dampen the LCL filter resonance through an active damping technique and is responsible for generating the modulation signal applied to the inverter switches, ensuring stability and power quality.

The isolated system consists of two loads connected in parallel at different instants. Initially, a load of 75 kW and 10 kVar is tied to the formed grid. Next, a second load of 25 kW and 2 kVar is added in parallel, resulting in an increase in the demanded power. The system operates at a nominal voltage of 220 V<sub>RMS</sub> and 60 Hz, while the inverter works with a switching frequency ( $f_{sw}$ ) of 10 kHz. The LCL filter follows the procedure discussed in [22], whose elements resulted in  $L_1 = 0.621$  mH,  $L_2 = 0.017$  mH, and  $C = 91.85$   $\mu$ F. The system dynamics are described by the relationship between the capacitor voltage ( $v_c$ ) and the voltage synthesized by the inverter ( $u_i$ ). The corresponding transfer function is

$$\frac{v_c(s)}{v_i(s)} = \frac{L_2}{CL_1L_2s^2 + L_1 + L_2}. \quad (1)$$

The resonant frequency of the LCL filter is obtained from the denominator of (1) by equaling it to zero and replacing  $s = j\omega$ . Thus, it follows:

$$\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1L_2C}}. \quad (2)$$

Figure 2 shows the Bode diagram of the LCL filter considering the designed elements.

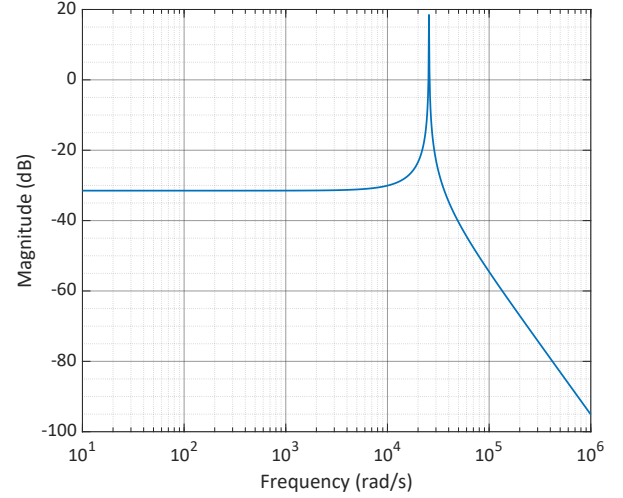


FIGURE 2. Bode diagram of the LCL filter.

A pronounced resonance peak is observed at approximately 4.07 kHz. At this frequency, the resonance peak magnitude is 18.45 dB, indicating a significant amplification that must be overcome using active or passive damping methods to ensure system stability. The filter's attenuation increases relevantly after the frequency where the resonance peak occurs, especially when compared to L and LC filters, allowing for effective filtering of switching harmonics, while it is also more financially viable.

The filter resonance, considering the load, can be calculated as

$$\omega_{res} = \sqrt{\frac{L_1 + L_2 + L_{load}}{L_1(L_2 + L_{load})C}}, \quad (3)$$

where  $L_{load}$  is the load inductance.

Figure 3 shows the Bode diagram considering five different loads (75 kW, 81 kW, 87 kW, 93 kW, and 100 kW). As can be seen, there is a frequency shift where the resonance peak occurs as the power increases. Considering the load of 75 kW, the resonance peak occurs at around 905.43 Hz, while for the load of 100 kW, it shifts to approximately 971.48 Hz. Additionally, the peak amplitude also varies with the load. This feature is a challenge for the control system. Regarding the frequency response analysis, the resistive part of the load is not considered because it contributes positively to controller performance. However, since the load can vary, or the system can even operate without load, it is chosen not to rely on this natural physical damping provided by

the resistive loads when designing the controllers. While this approach makes the controller design process more challenging, the resulting controllers are more robust because they are designed for the worst-case scenario, characterized by the maximum resonance peak.

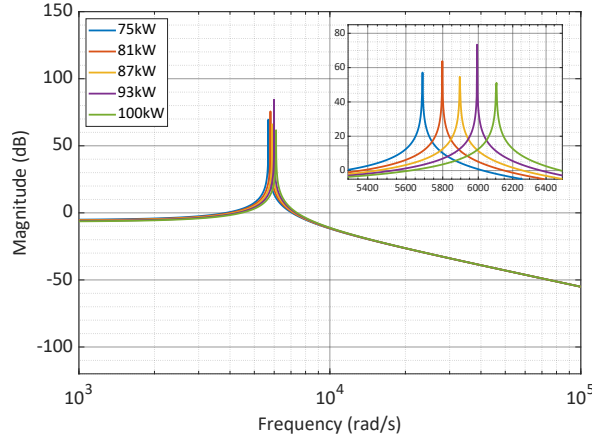


FIGURE 3. Bode diagram of the LCL filter considering different loads.

### III. CONTROLLER STRATEGY AND OPTIMIZED DESIGN

This section presents the implemented control framework and the systematic tuning methodology using a meta-heuristic optimization algorithm.

#### A. Droop control

Unlike the grid-following (GFL) inverter, which exhibits controlled current source characteristics, the GFM inverter behaves as a controlled voltage source. In synchronous machines, the operating frequency is slightly adjusted as a consequence of the imbalance between generation and demand when load varies, allowing the establishment of a new operating point and meeting the required power. This inertia is not inherently present in systems based on renewable energy sources. The simplest strategy to emulate this behavior is through droop control, which is computed as follows [23]:

$$\omega_{droop} = \omega^* - m_p(P^* - P_{LPF}), \quad (4)$$

$$V_{droop} = V^* - n_q(Q^* - Q_{LPF}), \quad (5)$$

where  $\omega^*$ ,  $V^*$ ,  $P^*$ , and  $Q^*$  are the references for frequency, voltage, active power, and reactive power, respectively. Moreover,  $P_{LPF}$  and  $Q_{LPF}$  are the active and reactive power measures at the point of common coupling (PCC) and filtered by a first-order low-pass filter (LPF), respectively. Additionally, the droop coefficients  $m_p$  and  $n_q$  are calculated as

$$m_p = \frac{\Delta\omega}{\Delta P^*} = \frac{376.99 - 380.13}{100000 - 0} = -31.4\mu, \quad (6)$$

$$n_q = \frac{\Delta V}{\Delta Q^*} = \frac{311 - 317}{12000 - 0} = -500\mu, \quad (7)$$

where  $\Delta P^*$  and  $\Delta Q^*$  are the reference range established for obtaining droop gains [24].

Figure 4 summarizes the droop control, where  $\omega_c$  indicates the cutoff frequency of the LPF.

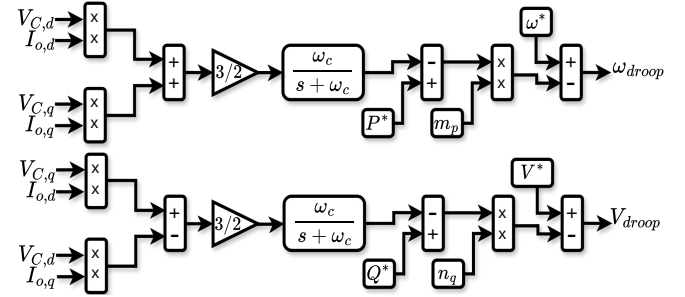


FIGURE 4. Block diagram of the droop control.

The active and reactive power are calculated as

$$P = \frac{3}{2}(v_{C,d}i_{o,d} + v_{C,q}i_{o,q}), \quad (8)$$

$$Q = \frac{3}{2}(v_{C,d}i_{o,q} - v_{C,q}i_{o,d}), \quad (9)$$

where  $i_{o,d}$  and  $i_{o,q}$  are the load currents in the  $d$  and  $q$  coordinates, respectively. Furthermore,  $v_{C,d}$  and  $v_{C,q}$  are the capacitor voltages in the  $d$  and  $q$  coordinates, respectively.

#### IV. OUTER VOLTAGE LOOP

The main purpose of the outer voltage loop is to track the voltage reference from the droop control, ensuring a stable voltage at the inverter output. The output of this loop provides the reference current for the current control loop. A proportional-integral (PI) controller is used to ensure proper steady-state tracking, implemented in  $dq$  reference frame, with feedback obtained from measurements taken at the PCC. Figure 5 illustrates the voltage control loop, where  $I_{lim,d}$  and  $I_{lim,q}$  are the reference currents considering the current limitation.

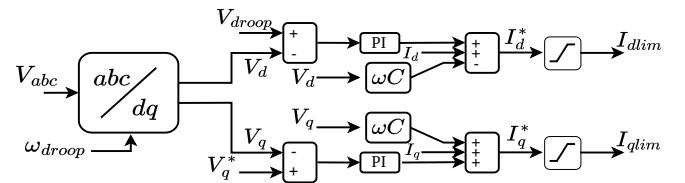


FIGURE 5. Voltage control loop.

#### V. INNER CURRENT LOOP

Differently from approaches implemented in [25], [26], and [27], which control the inverter-side current, this work employs the controller at the load side. Although it brings benefits for harmonic attenuation, it also implies a greater challenge for the control system. Thus, the active damping technique uses capacitor current feedback to mitigate the resonance peak of the LCL filter. This approach allows

for suppressing resonance without the need for resistors, reducing energy losses caused by these passive elements and increasing system efficiency.

Additionally, a current limiter was also incorporated into the controller. The strategy is based on [28]. In this approach, the control prioritizes the active current ( $I_{o,d}^*$ ) to ensure transient stability, resulting in the following saturation logic:

$$|I_{o,d}^*| = \min(I_{max}, |I_{o,d}^*|), \quad (10)$$

$$|I_{o,q}^*| = \max\left(\sqrt{I_{max}^2 - (I_{o,d}^*)^2}, |I_{o,q}^*|\right). \quad (11)$$

However, when a large disturbance occurs and the current  $I_{o,d}$  reaches the limit  $I_{max}$ , the reactive component  $I_{o,q}$  is forced to zero to maintain the total magnitude up to the allowed value, which is  $I_{max} = 230$  A. Since the reactive power is null, the voltage control temporarily loses its regulation capacity, which can excessively raise the voltage after the fault and hinder the inverter's recovery to non-saturated mode. Therefore, it is proposed to use a proportional scaling factor. This strategy preserves the angle of the current vector  $\phi = \arctan(I_{o,q}/I_{o,d})$ , reducing only its magnitude, which is calculated as

$$I_{mag} = \sqrt{(I_{o,d}^*)^2 + (I_{o,q}^*)^2}. \quad (12)$$

If  $I_{mag} > I_{max}$ , then the scaling factor  $k$  is

$$k = \frac{I_{max}}{I_{mag}}. \quad (13)$$

The new limited references are  $I_{lim,d} = kI_{o,d}^*$  and  $I_{lim,q} = kI_{o,q}^*$ . If  $I_{mag} < I_{max}$ , then, the references are  $I_{lim,d} = I_{o,d}^*$  and  $I_{lim,q} = I_{o,q}^*$ . Figure 6 depicts the external current loop.

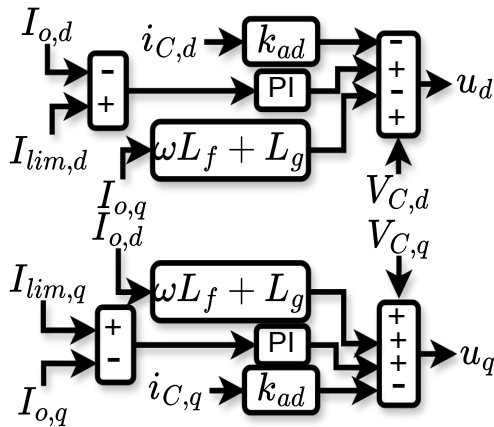


FIGURE 6. Current control loop with active damping.

### A. Meta-heuristic-based controller tuning

Manual adjustment of PI controller gains is often based on classical tuning rules such as the Ziegler-Nichols method, trial and error, performance criteria, and process knowledge,

resulting in suboptimal performance and increased design time. Meta-heuristic optimization algorithms can automate this process by minimizing a fitness function under stability and saturation constraints. These techniques systematically explore the parameter space, converging into a pair of controller gains that balances response time, damping, and steady-state error in accordance with the fitness function minimization. This work employs the hybrid JS-PSO [29] for controller tuning.

The fitness function  $J$  designed in this work is a modified version of integral of the time-weighted absolute error (ITAE) criterion. This cost function considers both voltage regulation and current tracking errors, each one with a ponder factor. Mathematically, a weighting factor of 0.2 was adopted to reduce the current loop influence on the fitness function value. Since the control is implemented in a cascade configuration, the current reference is generated by the voltage loop. Consequently, it was chosen to give a greater weight to this control loop. Therefore, the fitness function is

$$J = \int_{t_0}^t (t - t_0) E(t) dt, \quad (14)$$

where

$$e_{vd}(t) = V_{droop}(t) - v_{C,d}(t), \quad (15)$$

$$e_{vq}(t) = V_{C,q}^*(t) - v_{C,q}(t), \quad (16)$$

$$e_{id}(t) = I_{o,d}^*(t) - I_{o,d}(t), \quad (17)$$

$$e_{iq}(t) = I_{o,q}^*(t) - I_{o,q}(t). \quad (18)$$

Moreover, the accumulation of the fitness function is activated only after the initial settling time  $t_0 = 0.2$  s. Excluding the initialization window ( $0 \leq t < 0.2$  s) prevents the objective function from being disproportionately increased by the startup error peak. This ensures the optimization algorithm converges on robust control gains optimized for tracking performance and disturbance rejection, rather than being biased by the initial transient. Additionally, a fitness penalty strategy was implemented to ensure that the algorithm converges only to dynamically stable solutions. In this sense, if the optimization results in a set of controller gains that cause overcurrent in the inductors or overvoltage in the capacitors (exceeding 1000 A and 1000 V, respectively), the fitness function receives a high penalty value. That is,  $J = 10^3$ , immediately eliminating solutions that are unfeasible for practical implementation.

The parameters that JS-PSO aims to tune are the gains of the multi-loop control system, which are the proportional and integral gains for both external voltage loop ( $k_{pv}$  and  $k_{iv}$ ) and internal current loop ( $k_{pi}$  and  $k_{ii}$ ), as well as the gain associated with the active damping strategy ( $k_{ad}$ ). Therefore, the variables of interest are:

$$S = [k_{pv} \ k_{iv} \ k_{pi} \ k_{ii} \ k_{ad}], \quad (19)$$

whose search space for each variable of interest is delimited by a lower bound ( $L_b$ ) and upper bound ( $U_b$ ), which is

$$L_b = [0.1 \ 50 \ 1 \ 500 \ 1], \quad (20)$$

$$U_b = [0.4 \ 100 \ 4 \ 10000 \ 4]. \quad (21)$$

The search space was defined to account for the dynamic characteristics of each control loop, establishing limits compatible with the response speed and the specific tuning range of each controller. Values presented in [24] and [30] were also used as the basis. The optimizer was configured with a population size of 10 search agents and 25 iterations.

## VI. VIRTUAL HIL RESULTS

Typhoon HIL simulator, in its virtual version, was used to validate the control design and closed-loop operation of the proposed system, allowing for a detailed analysis of the inverter's dynamic behavior under different operating conditions. Table 1 presents the system parameters and the optimized controller gains.

TABLE 1. System parameters and controller gains.

| Parameter   | Value         | Parameter  | Value       | Gain     | Value   |
|-------------|---------------|------------|-------------|----------|---------|
| $L_{Load}$  | 0.668 mH      | $n_p$      | -500 $\mu$  | $k_{pv}$ | 0.358   |
| $L_{2Load}$ | 1.21 mH       | $m_p$      | -31.4 $\mu$ | $k_{iv}$ | 68.171  |
| $R_{Load}$  | 1.89 $\Omega$ | $\omega_c$ | 3 Hz        | $k_{pi}$ | 3.79    |
| $R_{2Load}$ | 5.73 $\Omega$ | $f_s$      | 10 kHz      | $k_{ii}$ | 828.559 |
|             |               |            |             | $k_{ad}$ | 3.74    |

### A. Operation with load variation

In the initial interval, for  $t < 0.1$  s, only load 1 is connected to the inverter. As illustrated in Figs. 7 and 8, the system operates below its nominal power. Even so, satisfactory performance is observed, with the effective voltage maintained close to 220  $V_{RMS}$  and the frequency with a maximum variation of 0.0083% in relation to the nominal value of 60 Hz. This behavior demonstrates good system regulation and the controller effectiveness in grid formation, even under partial load conditions.

At time  $t > 0.1$  s, load 2 is connected, bringing the system to its nominal operating condition. In this situation, both voltage and frequency remain within the limits specified in the design, without significant oscillations or temporary instabilities, which demonstrates the controller's adequate responsiveness to load variations.

Table 2 presents quantitative performance metrics: mean absolute error (MAE), mean squared error (MSE), and root mean squared error (RMSE).

The analysis of these performance indexes reveals low steady state error values, indicating high accuracy in tracking voltage and frequency references. The reduced MAE confirms the overall system stability, with low tracking error,

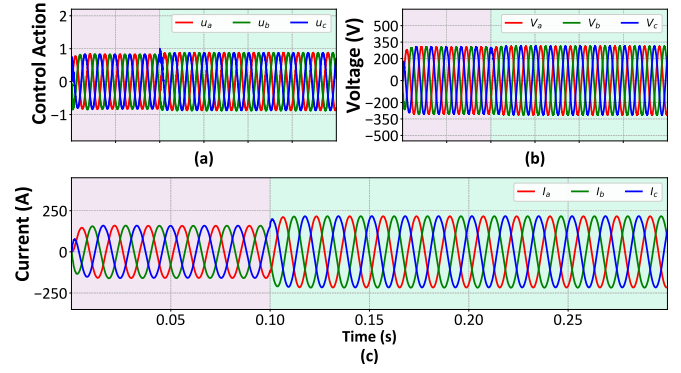


FIGURE 7. Closed-loop system response considering load variation: a) Control actions, b) Voltages at PCC, and c) Currents at PCC.

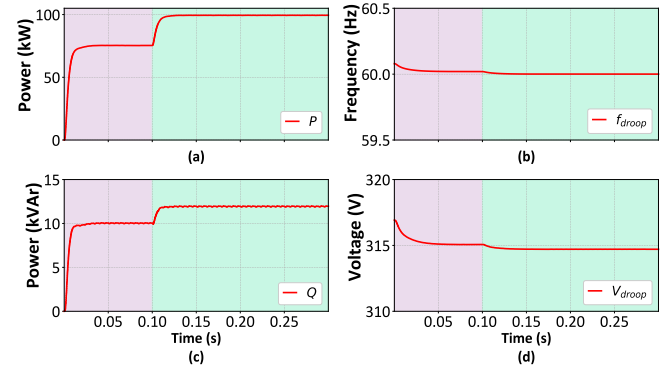


FIGURE 8. Closed-loop system response considering load variation: a) Active power, b) Reactive power, c) Frequency droop, and d) Voltage droop.

TABLE 2. Quantitative performance metrics.

| Metric | Power (W)  | Power (VAr) | Voltage (V) | Frequency (Hz) |
|--------|------------|-------------|-------------|----------------|
| MAE    | 350.132    | 42.020      | 0.557       | 0.000281       |
| MSE    | 123985.792 | 2160.977    | 0.481       | 0.00000008     |
| RMSE   | 352.116    | 46.486      | 0.694       | 0.000281       |

while the RMSE shows a good transient response, without relevant deviations. These results corroborate the effectiveness of the implemented control system. A comparison against a benchmark case is presented in the Appendix, where the superiority of the proposed controller can be verified.

### 1) Repeatability analysis

Five independent runs of the optimizer were performed to evaluate the consistency and performance of the optimization procedure across different runs. Table 1 shows the optimized gains. Figure 9 presents the convergence curves of the fitness in these five runs, where it can be observed that all solutions converge to a small value, close to zero, indicating irrelevant tracking errors. Additionally, Table 3 presents the error metrics for each variable, enabling an analysis of the results across the different runs. Note that there is consistency of the results obtained with all optimized controllers.

| Run | $k_{pv}$ | $k_{iv}$ | $k_{pi}$ | $k_{ii}$ | $k_{ad}$ |
|-----|----------|----------|----------|----------|----------|
| 1   | 0.308    | 77.467   | 3.78     | 962.243  | 3.93     |
| 2   | 0.360    | 80.885   | 3.50     | 1780.381 | 3.81     |
| 3   | 0.330    | 70.229   | 3.13     | 708.838  | 3.62     |
| 4   | 0.358    | 68.171   | 3.79     | 828.559  | 3.92     |
| 5   | 0.368    | 63.605   | 3.10     | 1113.216 | 3.74     |

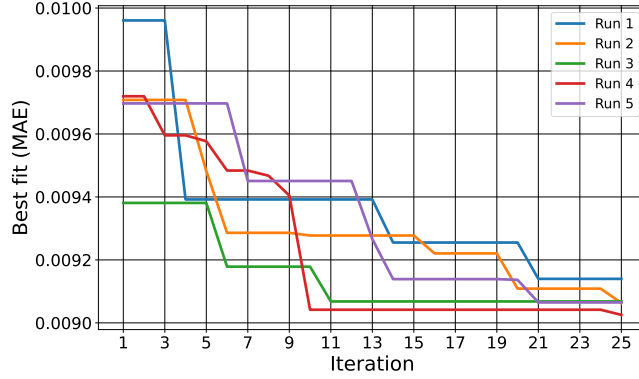


FIGURE 9. Fitness convergence curves.

### B. GFM inverters operating in parallel

To validate the droop-based control strategy, a second inverter was incorporated into the system, which operates in parallel with the first device. The specifications of both GFM inverters are identical. Figure 10 shows the active and reactive power-sharing between both units. It allows evaluating the control strategy performance by providing adequate power between inverters. As can be observed, each inverter is at half of the total load, which is 100 kW and 12 kVar.

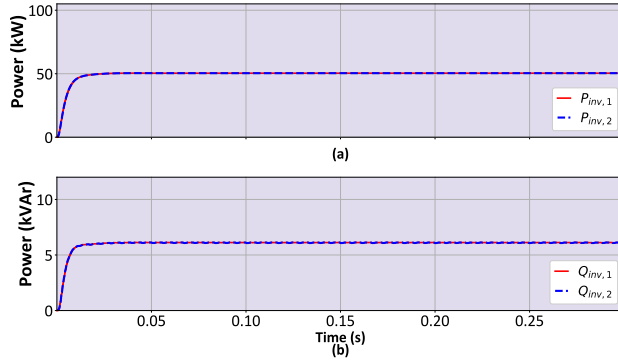


FIGURE 10. Power sharing: a) Active power with two inverters, and b) Reactive power with two inverters.

### C. No-load operation, black start, and RL load

The GFM inverter was subjected to a no-load test. During the time interval  $t < 0.1$  s, the equipment remained disconnected from the load. At  $t = 0.1$  s, an RL load corresponding to 50% of the inverter's rated capacity was connected, comprising a resistance of  $R = 2.62 \Omega$  and inductance of

$L = 2.29$  mH, resulting in an active power of 50 kW and reactive power of 16 kVar. Subsequently, the remainder of the load was connected with identical electrical parameters, bringing the total load to 100 kW and 32 kVar, equivalent to 100% of the inverter's rated capacity. Given the power factor setting in 0.95 and the change in the total reactive power reference to 32 kVar, the droop gains were adjusted to

$$m_p = \frac{\Delta f}{\Delta P^*} = \frac{60 - 60.5}{100000 - 0} = \frac{-0.5}{100000} = -5\mu, \quad (22)$$

$$n_q = \frac{\Delta V}{\Delta Q^*} = \frac{311 - 317}{32000 - 0} = \frac{-7}{32000} = -185.5\mu. \quad (23)$$

These gains were used exclusively to do the no-load test, aiming to prevent excessive voltage or frequency deviations. Figure 11 illustrates this test, showing that the GFM inverter successfully established the output voltage and frequency under no-load conditions, demonstrating the correct operation of the control system. Besides, it responded smoothly to the two load steps. Figures 11 and 12 complemented this analysis, where it can be observed that the system was able to operate adequately under all evaluated conditions. During switching operations, the inverter maintained output voltage, frequency, and currents within expected values, even following successive load connections, demonstrating stable performance and satisfactory dynamic response.

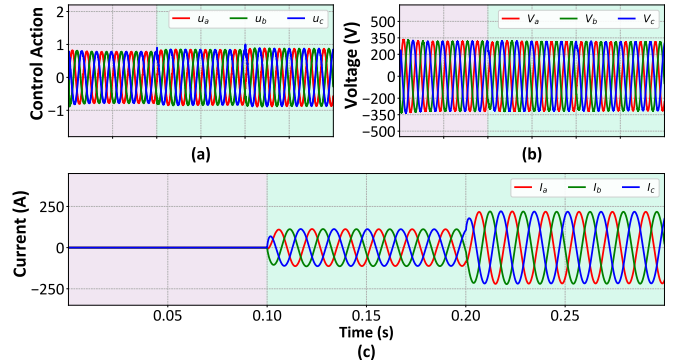


FIGURE 11. Closed-loop system response considering black start and RL load: a) Control actions, b) Voltages, and c) Currents.

### D. No-load operation, black start, and RLC load

A second no-load test was also conducted using an RLC load. Again, the inverter operates at no-load until  $t = 0.1$  s. At this instant, a switching operation was performed, connecting the inverter to an RL load with values of  $R = 2.62 \Omega$  and  $L = 2.29$  mH. Subsequently, at  $t = 0.2$  s, an RLC load was connected to the circuit with the following values:  $R = 2.62 \Omega$ ,  $L = 5.3$  mH, and  $C = 2330 \mu\text{F}$ , bringing the load to the inverter's performance with these loads. Figures 13 and 14 illustrate the inverter's performance with these loads. Again, the GFM controller presented adequate voltage and frequency regulation.

TABLE 3. Error metrics for the five optimized controllers.

| Run | Metric | Active power (W) | Reactive power (VAr) | Voltage (V) | Frequency (Hz) |
|-----|--------|------------------|----------------------|-------------|----------------|
| 1   | MAE    | 350.031          | 42.548               | 0.621       | 0.000281       |
|     | MSE    | 124748.950       | 2228.852             | 0.578       | 0.00000008     |
|     | RMSE   | 353.198          | 47.210               | 0.760       | 0.000281       |
| 2   | MAE    | 349.705          | 42.838               | 0.605       | 0.000281       |
|     | MSE    | 124459.645       | 2229.772             | 0.574       | 0.00000008     |
|     | RMSE   | 352.788          | 47.220               | 0.757       | 0.000281       |
| 3   | MAE    | 349.990          | 42.760               | 0.646       | 0.000281       |
|     | MSE    | 125443.522       | 2272.376             | 0.628       | 0.00000008     |
|     | RMSE   | 354.180          | 47.669               | 0.792       | 0.000281       |
| 4   | MAE    | 350.132          | 42.020               | 0.557       | 0.000281       |
|     | MSE    | 123985.792       | 2160.977             | 0.481       | 0.00000008     |
|     | RMSE   | 352.116          | 46.486               | 0.694       | 0.000281       |
| 5   | MAE    | 349.976          | 42.625               | 0.614       | 0.000281       |
|     | MSE    | 124721.464       | 2231.901             | 0.578       | 0.00000008     |
|     | RMSE   | 353.159          | 47.243               | 0.760       | 0.000281       |

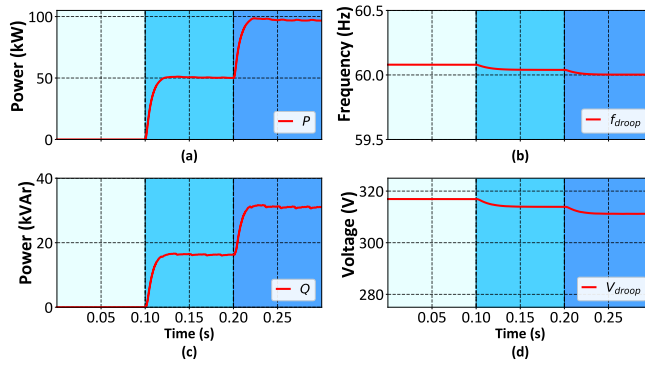


FIGURE 12. Closed-loop system response considering black start and RL load: a) Active power, b) Frequency, c) Reactive power, and d) Voltage.

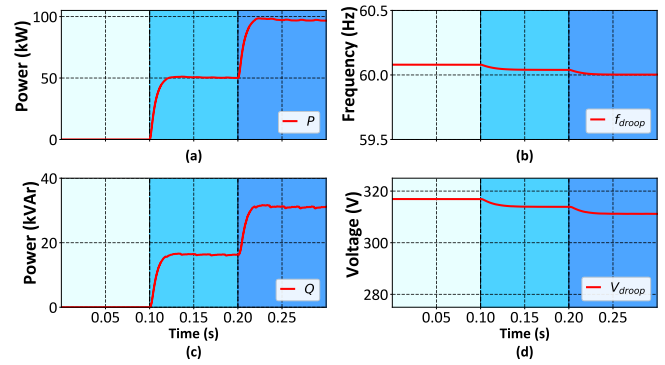


FIGURE 14. Closed-loop system response considering black start and RLC load: a) Active power, b) Frequency, c) Reactive power, and d) Voltage.

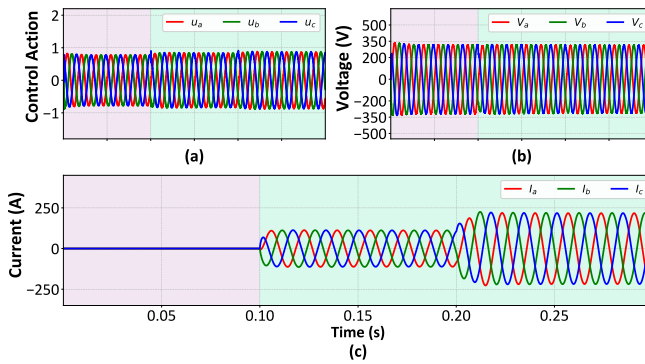


FIGURE 13. Closed-loop system response considering black start and RLC load: a) Control actions, b) Voltages, and c) Currents.

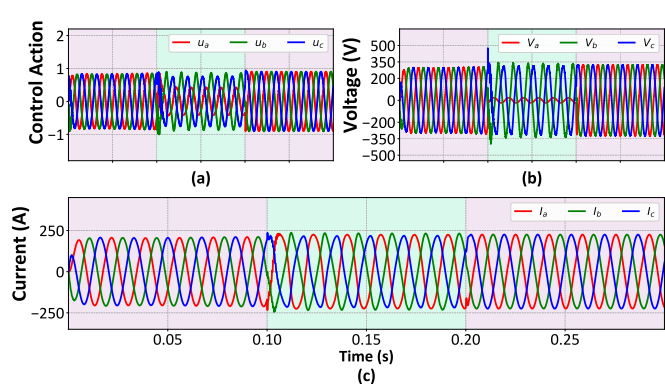


FIGURE 15. Closed-loop system response considering short-circuit event between phase A and the ground: a) Control actions, b) Voltages at PCC, and c) Currents at PCC.

### E. Operation under faults

Figure 15 presents the results for phase-to-ground short-circuit events. As can be observed, the system demonstrated recovery capability. None concerning behavior was observed during the fault occurrence, and the voltage is completely reestablished in the post-fault clearance.

Figure 16 shows the result for the imbalance test applied individually to each phase. This test was performed by inserting a resistor in phase A to validate the controller's responsiveness under adverse load conditions during grid formation. As can be seen, despite the system disturbance, it

acts efficiently to restore balance and ensure operational stability, confirming its resilience and rapid recovery provided by the optimized control system.

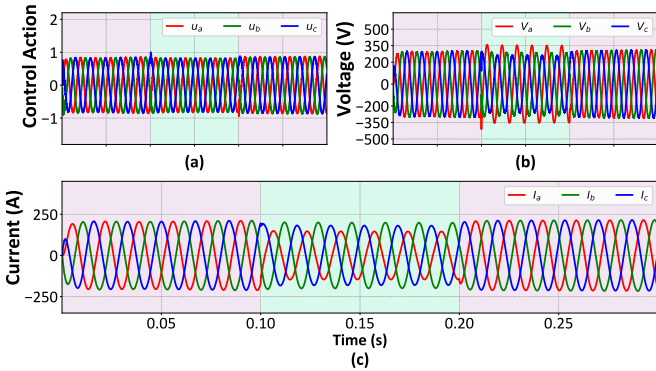


FIGURE 16. Closed-loop system response considering imbalance test in phase A: a) Control actions, b) Voltages at PCC, and c) Currents at PCC.

Figure 17 presents the harmonic analysis. The total harmonic distortion (THD) is concentrated in low-order harmonics, with magnitude less than 2% of the fundamental. The rapid decay of the higher harmonic components and the symmetry between the phases indicate stable operation and properly filtered loads, fully complying with current normative standards.

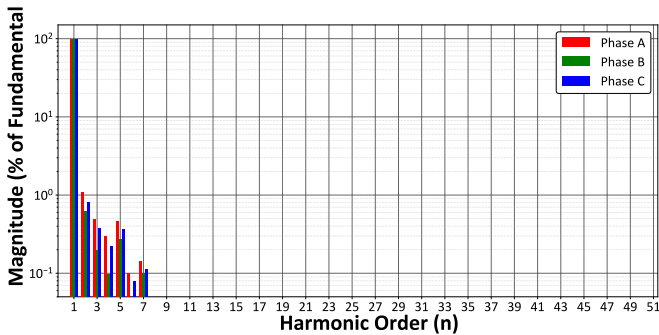


FIGURE 17. Total harmonic distortion.

## VII. CONCLUSION

This work presented an improved control system for GFM inverters operating in off-grid systems. The developed control strategy incorporated cascaded PI controllers with a current limiter with a scaling strategy, which works to preserve the current angle and reduce only its magnitude in the event of a large disturbance. Additionally, a secondary contribution is a parametrization methodology based on the JS-PSO algorithm, which tunes simultaneously the multi-loop controllers and the active damping technique. The proposed control solution was validated in a virtual HIL environment. The robustness and effectiveness of the inverter were validated under various operating conditions through a series of dynamic tests. In the no-load startup test, the inverter demonstrated the ability to satisfactorily establish output voltage and frequency before being subjected to

successive RL and RLC load connections. The system maintained stability and the expected dynamic behavior even in the face of power factor variations and abrupt transitions, up to the inverter's rated capacity. Faced with severe short-circuit and phase-to-ground events, as well as individual phase imbalances, the optimized controllers proved to be resilient, maintaining operational stability and rapidly restoring normal voltage levels following the fault. Additionally, the THD analysis confirmed the satisfactory quality of the generated power, maintaining magnitudes below 2% relative to the fundamental component and ensuring full compliance with current technical standards. Therefore, the proposed tuning methodology provided an optimal parametrization for the developed enhanced droop-controlled system, ensuring stability and satisfactory performance in transient events and steady state.

## REFERENCES

- [1] P. J. D. O. Evald, L. Schmitz, J. M. de Andrade, F. J. Viglus, T. B. Lazzarin, "Towards the future low-inertia power systems: A review on grid-forming inverter control-advances, challenges, and opportunities", *Renewable and Sustainable Energy Reviews*, vol. 235, p. 116948, Jul, 2026, doi:10.1016/j.rser.2026.116948.
- [2] G. V. Hollweg, P. J. D. O. Evald, R. V. Tambara, R. Z. Azzolin, H. A. Gründling, M. L. Martins, "Inversor Quasi-Z-Source Fotovoltaico Conectado à Rede com Filtro LCL Utilizando uma Estrutura MRAC-SM Cascata com Modelo Reduzido para Aplicações em Redes Fracas", *Eletrônica de Potência*, vol. 26, no. 2, pp. 205–216, Jun, 2021, doi:10.18618/REP.2021.2.0069.
- [3] P. J. D. O. Evald, M. S. Dall'asta, J. M. de Andrade, L. Schmitz, T. B. Lazzarin, "Um Controle Orientado a Campo Aprimorado para Sistemas de Conversão de Energia Eólica Usando Grasshopper Optimizer", *Eletrônica de Potência*, vol. 29, pp. e20248–e20248, Nov, 2024, doi:10.18618/REP.2024.11.0048.
- [4] V. Joddumahanthi, Ł. Knypinski, Y. Gopal, K. Kasprzak, "Review of power electronics technologies in the integration of renewable energy systems", *Applied Sciences*, vol. 15, no. 8, p. 4523, Apr, 2025, doi:10.3390/app15084523.
- [5] M. Alizadeh, W. Sun, "Dynamic Issues in Power System Restoration With Synchronous Generators and Grid-Forming Inverters", *IEEE Access*, vol. 13, pp. 151850–151865, Aug, 2025, doi:10.1109/ACCESS.2025.3603566.
- [6] A. Q. Al-Shetwi, I. E. Atawi, A. Abuelrub, M. Hannan, "The role of grid-forming inverters in enabling high penetration of renewable energy in power systems: standards, ancillary services, current deployment, and future perspectives", *Progress in Energy*, vol. 8, no. 2, p. 022002, Mar, 2026, doi:10.1088/2516-1083/ae4e79.
- [7] G. V. Hollweg, P. J. D. O. Evald, G. G. Koch, E. Mattos, R. V. Tambara, H. A. Gründling, "Controlador Robusto Adaptativo Super-Twisting Sliding Mode por Modelo de Referência para Regulação das Correntes Injetadas em Redes Fracas por Inversores Trifásicos com Filtro LCL", *Eletrônica de Potência*, vol. 26, no. 2, pp. 147–158, Jun, 2021, doi:10.18618/REP.2021.2.0001.
- [8] P. J. D. O. Evald, G. V. Hollweg, R. V. Tambara, H. A. Gründling, "A discrete-time robust adaptive PI controller for grid-connected voltage source converter with LCL filter", *Eletrônica de Potência*, vol. 26, no. 1, pp. 19–30, Mar, 2021, doi:10.18618/REP.2021.1.0053.
- [9] E. Mattos, L. C. Borin, J. D. O. Paulo, G. V. Hollweg, V. F. Montagner, "Comparação Entre Controladores por Realimentação Parcial e Total de Estados Otimizados para Conversores Conectados à Rede Sujeitos a Incertezas Paramétricas", *Eletrônica de Potência*, vol. 28, no. 1, pp. 7–16, Jan, 2023, doi:10.18618/REP.2023.1.0044.
- [10] M. Alharbi, "The dual role of grid-forming inverters: Power electronics innovations and power system stability", *Electronics*, vol. 15, no. 5, p. 1115, Mar, 2026, doi:10.3390/electronics15051115.
- [11] Y. Abudyak, M. H. Rezaei, A. A. B. Abdelnabi, H. S. Rizzi, I. Batarseh, A. Q. Hung, "Grid-Forming Inverters Review: Control, Stability, and the Next Stage with Artificial Intelligence and Digital Twins", *IEEE*

- Open Journal of Power Electronics*, vol. 7, pp. 351–387, Jan, 2026, doi:10.1109/OJPEL.2026.3654526.
- [12] S. Fazal, M. E. Haque, M. T. Arif, A. Gargoom, “Droop control techniques for grid forming inverter”, in *14th Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 1–6, IEEE, Mar, 2022, doi:10.1109/APPEEC53445.2022.10072251.
- [13] G. Shahgholian, M. Moradian, A. Fathollahi, “Droop control strategy in inverter-based microgrids: A brief review on analysis and application in islanded mode of operation”, *IET Renewable Power Generation*, vol. 19, no. 1, p. e13186, Jan, 2025, doi:10.1049/rpg2.13186.
- [14] K. Y. Saimadhuri, M. Janaki, “Advanced control strategies for microgrids: A review of droop control and virtual impedance techniques”, *Results in Engineering*, vol. 25, p. 103799, Mar, 2025, doi:10.1016/j.rineng.2024.103799.
- [15] K. M. Cheema, “A comprehensive review of virtual synchronous generator”, *International Journal of Electrical Power & Energy Systems*, vol. 120, p. 106006, Sep, 2020, doi:10.1016/j.ijepes.2020.106006.
- [16] W. Sang, W. Guo, S. Dai, C. Tian, S. Yu, Y. Teng, “Virtual synchronous generator, a comprehensive overview”, *Energies*, vol. 15, no. 17, p. 6148, Aug, 2022, doi:10.3390/en15176148.
- [17] M. Shadoul, R. Ahshan, R. S. Alabri, A. Al-Badi, M. Albadi, M. Jamil, “A comprehensive review on a virtual-synchronous generator: Topologies, control orders and techniques, energy storages, and applications”, *Energies*, vol. 15, no. 22, p. 8406, Nov, 2022, doi:10.3390/en15228406.
- [18] S. Azizi Aghdam, M. Agamy, “Virtual oscillator-based methods for grid-forming inverter control: A review”, *IET Renewable Power Generation*, vol. 16, no. 5, pp. 835–855, Feb, 2022, doi:10.1049/rpg2.12398.
- [19] M. Lu, “Virtual oscillator grid-forming inverters: State of the art, modeling, and stability”, *IEEE Transactions on Power Electronics*, vol. 37, no. 10, pp. 11579–11591, Mar, 2022, doi:10.1109/TPEL.2022.3163377.
- [20] H. Rezazadeh, M. Monfared, M. Fazeli, S. Golestan, “Virtual Oscillator Control for Grid-Forming Inverters: Recent Advances, Comparative Evaluation, and Small-Signal Analysis”, *Energies*, vol. 18, no. 22, p. 5981, Nov, 2025, doi:10.3390/en18225981.
- [21] P. Arévalo, C. Ramos, A. Rocha, “A systematic review of grid-forming control techniques for modern power systems and microgrids”, *Energies*, vol. 18, no. 14, p. 3888, Jul, 2025, doi:10.3390/en18143888.
- [22] M. Dursun, M. K. Döşoğlu, “LCL filter design for grid connected three-phase inverter”, in *2018 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, pp. 1–4, IEEE, Dec, 2018, doi:10.1109/ISMSIT.2018.8567054.
- [23] M. Habibullah, F. Gonzalez-Longatt, M. N. A. Montalvo, H. R. Chamorro, J. L. Rueda, P. Palensky, “On short circuit of grid-forming converters controllers: A glance of the dynamic behaviour”, in *2021 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America)*, pp. 1–5, IEEE, Oct, 2021, doi:10.1109/ISGTLatinAmerica52371.2021.9543017.
- [24] Q. Salem, R. Aljarrah, M. Karimi, A. Al-Quraan, “Grid-forming inverter control for power sharing in microgrids based on P/f and Q/V droop characteristics”, *Sustainability*, vol. 15, no. 15, p. 11712, Jul, 2023, doi:10.3390/su151511712.
- [25] S. Eberlein, K. Rudion, “Small-signal stability modelling, sensitivity analysis and optimization of droop controlled inverters in LV microgrids”, *International Journal of Electrical Power & Energy Systems*, vol. 125, p. 106404, Feb, 2021, doi:10.1016/j.ijepes.2020.106404.
- [26] M. Mirmohammad, S. P. Azad, “Control and stability of grid-forming inverters: A comprehensive review”, *Energies*, vol. 17, no. 13, p. 3186, Jun, 2024, doi:10.3390/en17133186.
- [27] B. Vega, C. Rahmann, R. Álvarez, V. Vittal, “Determination of control requirements to impose on CIG for ensuring frequency stability of low inertia power systems”, *IEEE Access*, vol. 10, pp. 44891–44908, Apr, 2022, doi:10.1109/ACCESS.2022.3169489.
- [28] K. Zhuang, H. Xin, P. Hu, Z. Wang, “Current saturation analysis and anti-windup control design of grid-forming voltage source converter”, *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2790–2802, Sep, 2022, doi:10.1109/TEC.2022.3208060.
- [29] H. M. Nayyef, A. A. Ibrahim, M. A. A. Mohd Zainuri, M. A. Zulkifley, H. Shareef, “A novel hybrid algorithm based on jellyfish search and particle swarm optimization”, *Mathematics*, vol. 11, no. 14, p. 3210, Jul, 2023, doi:10.3390/math11143210.
- [30] N. Pogaku, M. Prodanovic, T. C. Green, “Modeling, analysis and testing of autonomous operation of an inverter-based microgrid”, *IEEE Transactions on power electronics*, vol. 22, no. 2, pp. 613–625, Mar, 2007, doi:10.1109/TPEL.2006.890003.

## ACKNOWLEDGEMENT

The authors thank the National Institute of Science and Technology in Power Electronics: Developing Technologies for a Sustainable Energy Transition (INCT EPTech). This work was financed by the National Council for Scientific and Technological Development (CNPq) under grant 408822/2024-4.

## APPENDIX - COMPARISON AGAINST BENCHMARK CASE

The pole-placement technique was used as a comparison criterion for the controller design. For the voltage controller, Kirchhoff’s current law was applied to the single-phase equivalent circuit of the LCL filter, resulting in

$$i_f \approx i_o + C \frac{dv_C}{dt}. \quad (24)$$

Since the PI controller is not recommended for sinusoidal signals, the  $dq$  reference frame is used:

$$C \frac{dv_{C,d}}{dt} - \omega C v_{C,q} = i_{f,d} - i_{o,d}, \quad (25)$$

$$C \frac{dv_{C,q}}{dt} - \omega C v_{C,d} = i_{f,q} - i_{o,q}. \quad (26)$$

Transforming to the frequency domain:

$$v_{C,d} = \frac{1}{sC} (i_{f,d} - i_{o,d} + \omega C v_{C,q}), \quad (27)$$

$$v_{C,q} = \frac{1}{sC} (i_{f,q} - i_{o,q} + \omega C v_{C,d}). \quad (28)$$

Taking into account the feedforward of the currents  $i_{o,d}$  and  $i_{o,q}$  and assuming perfect decoupling:

$$G_{OL_v}(s) = G_{PI}(s)G_v(s), \quad (29)$$

where  $G_{OL_v}(s)$  is the open-loop transfer function,  $G_{PI}(s)$  is the PI controller transfer function, and  $G_v(s)$  is the system transfer function. Therefore,

$$G_{OL_v}(s) = \left( k_{pv} + \frac{k_{iv}}{s} \right) \frac{1}{sC}. \quad (30)$$

The second-order characteristic polynomial is used to obtain the gain parameters,

$$C(s) = s^2 + 2\xi\omega_n s + \omega_n^2, \quad (31)$$

where  $\xi$  is the system’s damping factor and  $\omega_n$  is the natural frequency. Taking the closed-loop transfer function results in

$$G_{CL,v}(s) = \frac{G_{OL,v}(s)}{1 + G_{OL,v}(s)}. \quad (32)$$

From (31) and (32), it follows:

$$k_{pv} = 2\xi\omega_{n,v}C, \quad (33)$$

$$k_{iv} = \omega_{n,v}^2 C. \quad (34)$$

Similarly, approximating the low-frequency model, the open-loop equation for the PI current controller is

$$G_{OL,i}(s) = \left( k_{pv} + \frac{k_{iv}}{s} \frac{1/L_{eq}}{s + r_{eq}/L_{eq}} \right), \quad (35)$$

where  $r_{eq} = r_1 + r_2$  is the parasitic resistance of the inductor, and  $L_{eq} = L_1 + L_2$ . Therefore, the closed-loop transfer function is

$$G_{CL,i}(s) = \frac{G_{OL,i}(s)}{1 + G_{OL,i}(s)}. \quad (36)$$

and comparing with (31),

$$k_{pi} = 2\xi\omega_{n,i}L_{eq} - r_{eq}, \quad (37)$$

$$k_{ii} = \omega_{n,i}^2 L_{eq}, \quad (38)$$

where  $\xi = 0.89$ ,  $\omega_{n,i} = 2\pi f_{sw}/10$  so that the switching does not affect the dynamics of the control, and  $\omega_{n,v} = \omega_{n,i}/10$  so that one control loop does not affect the other. The resulting gains are  $k_{pv} = 0.171$ ,  $k_{iv} = 100$ ,  $k_{pi} = 3.512$ ,  $k_{ii} = 6280$ , and  $k_{ad} = 4$ . The same load variation test presented in Subsection IV.A was performed, considering the same switch transition times. Figure 18 shows the system dynamics under load variation.

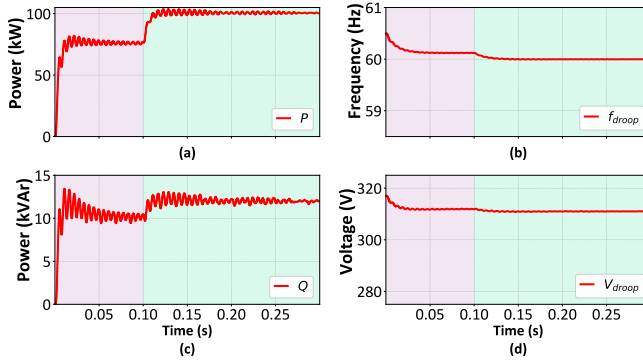


FIGURE 18. Closed-loop system response considering load variation: a) Active power, b) Frequency droop, c) Reactive power, and d) Voltage droop.

Table 4 presents the results of the benchmark case along with the proposed solution, detailing the reduction in error metrics for each system variable when tuning the control system using the developed procedure. The data demonstrate that the use of optimized parameters resulted in a consistent reduction of errors across all evaluated variables. The most significant gains were observed in frequency estimation, where reductions reached approximately 93.29% for MAE, 99.58% for MSE, and 93.53% for RMSE, indicating a substantial improvement in the optimizer's ability

to reproduce this quantity. Substantial reductions were also achieved for voltage (ranging from 86.93% to 98.29%) and reactive power (ranging from 72.56% for MAE to 94.07% for MSE). Regarding active power, although the percentage gains were more moderate (ranging from 58.92% for MAE to 87.44% for MSE), this was expected given that the baseline model already exhibited relatively low initial error levels for this variable. Overall, the results demonstrate that the parameter optimization procedure contributed to reduce estimation errors across all evaluated quantities, highlighting the effectiveness of the proposed methodology.

TABLE 4. Comparison of performance metrics.

| Metric | Variable       | Benchmark  | Optimized  | Reduction |
|--------|----------------|------------|------------|-----------|
| MAE    | Power (W)      | 852.162    | 350.133    | 58.92%    |
|        | Power (VAr)    | 153.126    | 42.021     | 72.56%    |
|        | Voltage (V)    | 4.325      | 0.558      | 87.10%    |
|        | Frequency (Hz) | 0.00419    | 0.000281   | 93.29%    |
| MSE    | Power (W)      | 986780.795 | 123985.792 | 87.44%    |
|        | Power (VAr)    | 36440.128  | 2160.978   | 94.07%    |
|        | Voltage (V)    | 28.231     | 0.482      | 98.29%    |
|        | Frequency (Hz) | 0.000019   | 0.00000008 | 99.58%    |
| RMSE   | Power (W)      | 993.368    | 352.116    | 64.56%    |
|        | Power (VAr)    | 190.892    | 46.486     | 75.65%    |
|        | Voltage (V)    | 5.313      | 0.694      | 86.93%    |
|        | Frequency (Hz) | 0.00434    | 0.000281   | 93.53%    |

The comparison between conventional pole placement and the proposed meta-heuristic optimizer demonstrates a clear advantage across all analyzed error parameters. In addition to reducing output ripple, the proposed method improves the waveform delivered to the load, providing greater stability and an optimized transient response, thereby overcoming the limitations of the traditional approach.

## AUTHOR'S CONTRIBUTIONS

**S.C.SCHÜLER:** Conceptualization, Investigation, Software, Visualization, Writing – Original Draft. **M.RADKE:** Conceptualization, Investigation, Software, Visualization, Writing – Original Draft. **P.J.D.O.EVALD:** Methodology, Supervision, Writing – Review & Editing. **T.B.LAZZARIN:** Funding acquisition, Project Administration, Writing – Review & Editing.

## PLAGIARISM POLICY

This article was submitted to the similarity system provided by Crossref and powered by iThenticate – Similarity Check.

## DATA AVAILABILITY

The data used in this research is available in the body of the document.

## BIOGRAPHIES

**Samuel Costa Schüler** He is currently pursuing a bachelor's degree in Electronic Engineering at the Federal University of Pelotas (UFPEL). He is an

undergraduate researcher with the Group of Intelligent Systems and Control (GSIC) at UFPel. His work focuses on the development of control solutions for renewable energy systems. His research interests include control theory, renewable energy systems, and intelligent control.

**Mateus Radke** He is currently pursuing a bachelor's degree in Electronic Engineering at the UFPel. He received a Technologist degree in Internet Systems in 2024 from Anhanguera Educacional. He is an undergraduate researcher with the GSIC. His research interests include power electronics, renewable energy systems, embedded systems, and software development.

**Paulo Jefferson Dias de Oliveira Evald** holds a bachelor's degree in Automation Engineer (2016) and a Master's degree in Computer Engineering (2018), both from the Federal University of Rio Grande (FURG), and a PhD in Electrical Engineering (2021) from the Federal University of Santa Maria (UFSM). He was a post-doctoral researcher at Intelligent Automation and Robotics Research Group (NAUTEC/FURG) from 2022 to 2023. Currently, he is a post-doctoral researcher at the Institute of Power Electronics (INEP) at Federal University of Santa Catarina (UFSC). Since 2022, he has been a Professor at the Federal University of Pelotas (UFPel) in the Engineering Center. He is the leader of the GSIC, and a member of the Group of

Power Electronics and Control (GEPOC) from UFSM, INEP/UFSC, the Brazilian Society of Power Electronics (SOBRAEP), and National Institute of Science and Technology in Power Electronics: Developing Technologies for a Sustainable Energy Transition (INCT EPTech). His main research areas are renewable energy, power electronics control applications, biomedical system control, and meta-heuristic optimization of controllers.

**Telles Brunelli Lazzarin** holds a bachelor's degree (2004), a master's degree (2006), a doctorate (2010), and a postdoctorate (2011) in Electrical Engineering from UFSC. He was a visiting researcher at Northeastern University in Boston from 2017 to 2018. Since 2013, he has been a Professor at UFSC in the Department of Electrical and Electronic Engineering. Currently, he is Visiting Professor at Laboratoire de Génie électrique et électronique de Paris (GeePs) at France, coordinator of INCT EPTech, president of SOBRAEP, and Associate Editor of the IEEE Open Journal of Power Electronics (OJ-PEL) and the Open Journal of Power Electronics. His main research interests include switched-capacitor converters, switched-capacitor hybrid converters, single-phase rectifiers, voltage inverters, converters for small wind generators, and high-gain DC-DC converters.