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Latency-Robust Adaptive Control for Centralized Advanced Microgrids: Reverse Power Flow Mitigation via Wi-Fi Communication

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ABSTRACT This paper proposes a novel latency-robust adaptive control strategy for regulating active power flow at the point of common coupling (PCC) in centralized grid-connected microgrids (MGs). The proposed strategy dynamically adjusts power management system (PMS) parameters, such as the digital anti-aliasing filter cutoff frequency and packet transmission rate (PTR), to maintain stability and achieve shorter settling times. The strategy is tested in a controller hardware-in-the-loop (CHIL) setup, with the Typhoon HIL 402 simulating the power system and the Raspberry Pi implementing the PMS. The strategy is compared with the typical implementation using fixed PMS parameters. Tests with wired Ethernet communication show that the adaptive control achieves settling times 1.4 to 2.6 times shorter than fixed control, while maintaining stability in scenarios where the fixed control becomes unstable. The proposed strategy is also verified through 24-hour MG operation tests using Wi-Fi, demonstrating stable and accurate power flow control at the PCC while eliminating reverse power flow through self-consumption.

KEYWORDS Centralized control, communication latency, microgrids, stability, Wi-Fi.

I. INTRODUCTION

In recent years, several centralized secondary control strategies have been proposed for low-voltage (LV) advanced microgrids (MGs) to manage distributed energy resources (DERs) [1], [2], thereby improving power quality and hosting capacity [3]. Centralized architectures involve information exchange between a central controller (CC) and the DERs [4]. These architectures have gained adoption due to their significant advantages, such as improved observability, enhanced controllability, and reduced control algorithm complexity [5]. These benefits are enabled by low-bandwidth communication technologies (CTs) available at relatively low cost [6]. Centralized control suffers from a single point of failure, undermining overall system reliability. However, this limitation can be mitigated through redundant CCs, given that their hardware cost is considerably lower than that of other MG components. Communication exhibits non-idealities that affect the performance and stability of MG control, independent of its architecture. Typical issues include latency, data packet loss, and communication link failures [7], [8]. These challenges also affect the proper operation of centralized MGs and must be adequately addressed to mitigate their effects.

Centralized control strategies have been proposed [9]–[16] to address communication non-idealities. The authors of [9] present a coordinated control strategy for damping power oscillations and controlling frequency in grid-connected ac MGs, considering latency and noise. The proposal is verified through simulations; however, the stability limits are not provided. The authors of [10] use a real-time co-simulation platform to assess communication and control interactions in islanded MGs, highlighting the impact of load fluctuations on latency and packet loss without reporting stability limits. In [11], predictive control schemes are designed to restore frequency in islanded MGs, remaining stable up to specific latency thresholds and becoming unstable beyond them. Unlike previous strategies, the approach proposed in this paper monitors the real-time operating latency, disabling the secondary control to preserve MG control stability when a predefined maximum latency limit is exceeded.

The authors of [12] and [13] propose coordinated control for MGs, analyzing stability and improving the point of common coupling (PCC) dynamics under communication latency. In both cases, the centralized control consists of a proportional–integral (PI) controller whose parameters are set in the design stage and remain fixed during operation,

$$\alpha_i = \begin{cases} \frac{P_{b_i}^*}{\sum_{j=1}^{m_i} P_{b_{ij}}^{max}} & \text{if } P_{b_i}^* \geq 0, \\ \frac{P_{b_i}^*}{\sum_{j=1}^{m_i} P_{b_{ij}}^{min}} & \text{if } P_{b_i}^* < 0. \end{cases} \quad (2)$$

$$Q_{b_i}^* = \left(Q_{g_i} + \sum_{k=1}^{m_i} Q_{b_{ik}} \right) - Q_{g_i}^*, \quad (3)$$

$$\beta_i = \frac{Q_{b_i}^*}{\sum_{j=1}^{m_i} Q_{b_{ij}}^{max}}. \quad (4)$$

In the primary control of DER_{ij}, α_i and β_i are multiplied by $P_{b_{ij}}^{max}$ and $Q_{b_{ij}}^{max}$, setting the amount of active ($P_{b_{ij}}^*$) and reactive ($Q_{b_{ij}}^*$) power to be injected by the respective DER into the MG, according to (5) and (6). Based on the current $P_{b_{ij}}$ and the DER nominal apparent power ($A_{b_{ij}}$), a new value for ($Q_{b_{ij}}^{max}$) is computed, and new values of $P_{b_{ij}}$, $Q_{b_{ij}}$, $P_{b_{ij}}^{max}$, $P_{b_{ij}}^{min}$, and $Q_{b_{ij}}^{max}$ are sent to PMS. The PBC cycle restarts aiming to match the power flow supplied by the upstream grid with the power references defined by the PMS (i.e., $P_{g_i} = P_{g_i}^*$ and $Q_{g_i} = Q_{g_i}^*$).

$$P_{b_{ij}}^* = \begin{cases} \alpha_i \times P_{b_{ij}}^{max} & \text{if } \alpha_i \geq 0, \\ \alpha_i \times P_{b_{ij}}^{min} & \text{if } \alpha_i < 0. \end{cases} \quad (5)$$

$$Q_{b_{ij}}^* = \beta_i Q_{b_{ij}}^{max}, \quad Q_{b_{ij}}^{max} = \sqrt{A_{b_{ij}}^2 - P_{b_{ij}}^2} \quad (6)$$

B. THEORETICAL MODEL OF A CENTRALIZED MG

Fig. 2 shows the theoretical model for the i -th phase of a centrally controlled MG with m_i DERs [14]. The MG secondary control level comprises the proposed latency-robust adaptive control and PBC (adaptive PBC). The MG model is a single-input single-output (SISO) system in the Laplace domain, where the active power reference (i.e., $P_{g_i}^*$) is the input, the load active power (i.e., p_{L_i}) is the system disturbance, and the grid active power (i.e., P_{g_i}) is the output. Furthermore, α_{ij} is the active power coefficient received by each DER_{ij} corresponding to α_i , $P_{b_{ij}}'$ is the information received by the PMS corresponding to $P_{b_{ij}}$, P_{b_i}' is the sum of all $P_{b_{ij}}'$, and $\hat{P}_{L_i} = P_{g_i} + P_{b_i}'$ is the estimated average value of the p_{L_i} . The model is divided into four parts: PMS (I), Communication Latency (II), Local Controller (III), and Power System (IV). Table 1 summarizes all transfer functions used in the model along with their parameters.

Part I shows the PMS embedded with the adaptive PBC to regulate power flow at the PCC. F is the anti-aliasing filter that mitigates aliasing effects on the PMS [17]. A fourth-order Butterworth filter is adopted due to its flat passband response and effective attenuation. The bandwidth of information transmitted by the PMS is limited by the filter F with cutoff frequency f_c^F . D models the PMS firmware processing time (i.e., T_p^{CC}), and Z models the PMS packets transmission through a zero order hold (ZOH), where the PTR is $1/T_{tx}^{CC}$. According to Nyquist's sampling criterion [18], the PMS PTR must be greater than twice the transmitted-information bandwidth, which is limited by

TABLE 1. Transfer functions used in the model proposed in [14].

Transfer function	Parameter	Description
$F(f_c^F)$ is an anti-aliasing filter	f_c^F [Hz]	anti-aliasing cutoff frequency
$D = e^{-sT_p^{CC}}$	T_p^{CC} [s]	PMS algorithm processing time
$Z = \frac{1-e^{-sT_{tx}^{CC}}}{sT_{tx}^{CC}}$	$1/T_{tx}^{CC}$ [pps]	PMS packet transmission rate
$D_{1ij} = e^{-sL_{1ij}}$	L_{1ij} [s]	latency of the 1 _{ij} -th channel
$D_{2ij} = e^{-sL_{2ij}}$	L_{2ij} [s]	latency of the 2 _{ij} -th channel
$D_{ij} = e^{-sT_p^{ij}}$	T_p^{ij} [s]	DER _{ij} algorithm processing time
$H_{ij} = \frac{\omega_c^{ij}}{s + \omega_c^{ij}}$	ω_c^{ij} [rad/s]	low-pass filter cutoff frequency
$M_{ij} = \frac{1-e^{-sT_w^{ij}}}{sT_w^{ij}}$	T_w^{ij} [s]	MAF window length
$Z_{ij} = \frac{1-e^{-sT_{tx}^{ij}}}{sT_{tx}^{ij}}$	$1/T_{tx}^{ij}$ [pps]	DER _{ij} packet transmission rate
$M_{PCC} = \frac{1-e^{-sT_w^{PCC}}}{sT_w^{PCC}}$	T_w^{PCC} [s]	MAF window length
$Z_{PCC} = \frac{1-e^{-sT_{tx}^{PCC}}}{sT_{tx}^{PCC}}$	$1/T_{tx}^{PCC}$ [pps]	PCC packet transmission rate

the f_c^F (i.e., $1/T_{tx}^{CC} > 2f_c^F$). D_{1ij} and D_{2ij} (II) model communication latency (i.e., L_{1ij} and L_{2ij}), which refers to the total time required for information to travel from the source to the destination to a given CT. In part III, D_{ij} models the DER_{ij} firmware processing time (i.e., T_p^{ij}). H_{ij} models local-controller dynamics, where ω_c^{ij} is the cutoff frequency. M_{ij} models power-calculation dynamics through a moving average filter (MAF) [19], whose window length is defined by T_w^{ij} . Z_{ij} models DER_{ij} packet transmission through a ZOH, where $PTR = 1/T_{tx}^{ij}$ and $1/T_{tx}^{ij} \geq 1/T_w^{ij}$ satisfy the Nyquist criterion. Part IV represents the power system, where the active-power balance at the PCC is given by $p_{b_i} + p_{L_i} = p_{g_i}$. This simplified representation is suitable for low-voltage urban residential grids, which are characterized by short cables with resistive features and minimal voltage phase deviation between the DERs and the PCC [13]. M_{PCC} models PCC power-calculation dynamics through an MAF with its window defined by T_w^{PCC} . Z_{PCC} models PCC packet transmission, where $PTR = 1/T_{tx}^{PCC}$ with $1/T_{tx}^{PCC} \geq 1/T_w^{PCC}$. An equivalent reactive-power model is analogous to that shown in Fig. 2. $P_{g_i}/P_{g_i}^*$ (7) describes the relationship between the grid active power (P_{g_i}) and its reference ($P_{g_i}^*$), where X_{ij} (8) is a common term in (7).

$$\frac{P_{g_i}}{P_{g_i}^*} = \frac{\frac{M_{PCC} Z_{PCC} F D Z \sum_{j=1}^{m_i} X_{ij}}{\sum_{j=1}^{m_i} P_{b_{ij}}^{max}}}{\left(\frac{M_{PCC} Z_{PCC} \sum_{j=1}^{m_i} X_{ij} - \sum_{j=1}^{m_i} X_{ij} M_{ij} Z_{ij} D_{2ij}}{(FDZ)^{-1} \cdot \sum_{j=1}^{m_i} P_{b_{ij}}^{max}} + 1 \right)} \quad (7)$$

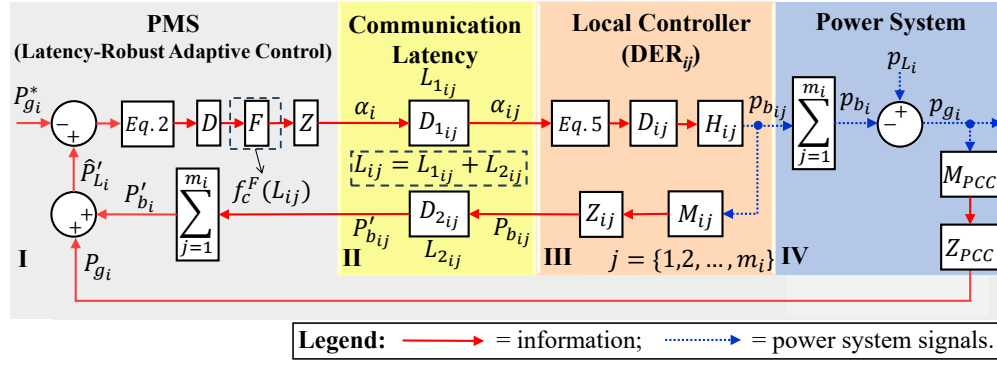


FIGURE 2. Theoretical model for the proposed latency-robust centralized adaptive control [14].

$$X_{ij} = D_{1ij} P_{bij}^{max} D_{ij} H_{ij} \quad (8)$$

III. LATENCY-ROBUST ADAPTIVE CONTROL

Fig. 3 shows the flowchart of the proposed Latency-Robust Adaptive Control algorithm. The proposed strategy requires no knowledge of the MG's physical parameters (e.g., line impedances, electrical loads, etc.). The PMS starts its operation with $f_c^F = f_1$ (lowest operating frequency) and $T_{tx}^{CC} = 1/(rf_1^F)$, where $r > 2$ satisfies the Nyquist sampling criterion. Next, the PMS calculates the total communication latency for each communication (L_{ij}). This latency corresponds to the round-trip communication time required for a data packet to travel from the PMS to a DER and return to the PMS (i.e., $L_{ij} = L_{1ij} + L_{2ij}$). To calculate the total latency, the PMS includes the packet transmission timestamp (E_{ij}) in each transmitted data packet. The DERs, in turn, replicate this information in the data packets sent to the PMS. When the packets arrive at the PMS, the packet arrival timestamp (C_{ij}) is recorded, and each total latency L_{ij} is then computed as $L_{ij} = C_{ij} - E_{ij} - T_p^{ij}$, where T_p^{ij} is the average processing time of each DER's firmware. The adopted approach does not require synchronization between the PMS and the DERs, since both E_{ij} and C_{ij} are obtained from the PMS.

Next, the PMS estimates a reference latency for its adaptation (L_{est}) based on the maximum measured total latency ($\max\{L_{ij}\}_{j=1}^{m_i}$). Assuming that the communication link latencies from the PMS to the DERs and vice versa are symmetric (i.e., $L_{1ij} \approx L_{2ij}$), the estimated latency is computed by dividing the maximum average total latency by two (i.e., $L_{est} = \max\{L_{ij}\}_{j=1}^{m_i}/2$).

Next, the PMS dynamically adjusts f_c^F and T_{tx}^{CC} based on L_{est} , according to the flowchart shown in Fig. 3, where n is the number of operating frequencies; f_n , f_{n-1} , and f_1 are the operating frequencies; and $L_{f_n}^{max}$, $L_{f_{n-1}}^{max}$, and $L_{f_1}^{max}$ are the corresponding adaptation thresholds. These thresholds are defined from P_{gi}/P_{gi}^* (7) to ensure that the controller operates stably with the minimum settling time. Details of this definition are shown in Section A. The maximum latency allowed for adaptive control operation (i.e., $L_{f_1}^{max}$) is defined based on the maximum tolerable settling time required for the provision of the most time-critical AS in the MG [14].

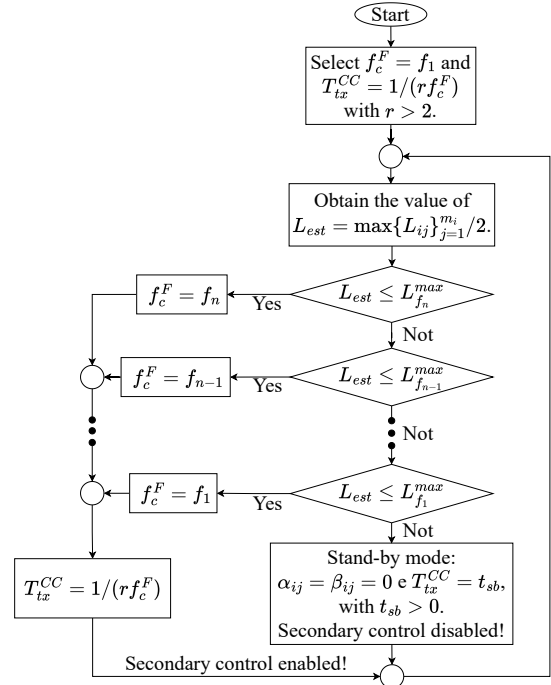


FIGURE 3. Algorithm of the proposed Latency-Robust Adaptive Control.

When $L_{est} > L_{f_1}^{max}$, the PMS disables the secondary control to preserve MG stability and enters stand-by mode. In this mode, the PMS sends $\alpha_{ij} = \beta_{ij} = 0$ to the DERs at intervals of $t_{sb} > 0$, to keep the latency estimation active.

IV. CONTROLLER HARDWARE-IN-THE-LOOP RESULTS

Fig. 4 shows the single-line diagram for the LV MG used in this work, with its features listed in Table 2. It is an advanced MG that incorporates the power dispatchability feature at the MG PCC [2]. The test bench used to validate the proposed control strategy follows a CHIL configuration, where the Typhoon HIL 402 simulates the power system shown in Fig. 4 while the Raspberry Pi 5 is used to implement the CC algorithm, integrating the measurement system, the PMS, and the EMS. While the EMS determines the power references according to the MG operational objectives, such as the provision of AS, the PMS executes the adaptive

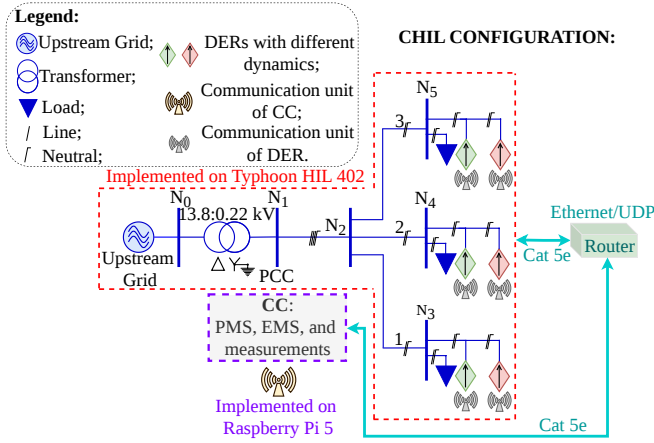


FIGURE 4. Single-line diagram of the low-voltage advanced MG in grid-connected mode with centralized control and CHIL configuration.

TABLE 2. MG Characteristics.

Element	Parameters
Grid	Three-phase, Y with grounded neutral, line voltage = 13.8 kV, symmetrical and 60 Hz.
Transf.	grounded Y-Y, 75 kVA, 60 Hz, V1 = 13.8 kV, V2 = 220 V, R1(pu) = R2(pu) = 0.0073 e L1(pu) = L2(pu) = 0.019.
Lines	R = 0.032 Ω and L = 32.1 μ H.
Load	Constant impedance; nominal frequency: 60 Hz; connection type: grounded Y; balanced 3ph power; nominal 3ph line voltage/power: 220V/15VA; power factor = 1.
PMS	secondary control strategy: PBC; active power reference: $P_{gi}^* = 1$ kW; anti-aliasing filter: fourth-order Butterworth; firmware processing time: $T_P^{CC} = 5$ ms.
DERs	number of DERs: 2 per phase; maximum power availability: 10 kW / 20 kVA; cutoff frequencies: $\omega_c^{i1} = 1$ kHz and $\omega_c^{i2} = 5$ Hz; firmware processing time: $T_P^{i1} = T_P^{i2} = 0$ ms; PTR: $T_{tx}^{ij} = 16.67$ ms.
MAFs	window length: $T_w^{PCC} = T_w^{i1} = T_w^{i2} = 1/60$ s.

PBC to coordinate the DERs and ensure accurate and stable PCC power regulation despite communication latency. For comparison purposes, the PBC with a fixed anti-aliasing filter cutoff frequency and a fixed packet transmission rate [14] (fixed PBC) is also implemented. Communication between the PMS and the DERs is established through an Ethernet/UDP network [20] with Category 5e cabling and a standard router in Sections A, B, and D. In Section E, a Wi-Fi network [21] is used to evaluate the operation of the proposed control strategy under wireless communication. The theoretical results are obtained in MATLAB.

A. ADAPTATION THRESHOLDS AND STABILITY LIMITS

Fig. 5 shows the settling time curves as a function of $L_{Com} = L_{1ij} = L_{2ij}$, with a cutoff frequency between $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$ and $1/T_{tx}^{CC} = 2.5f_c^F$ obtained from P_{gi}/P_{gi}^* (7). The PTR used by PMS is set to

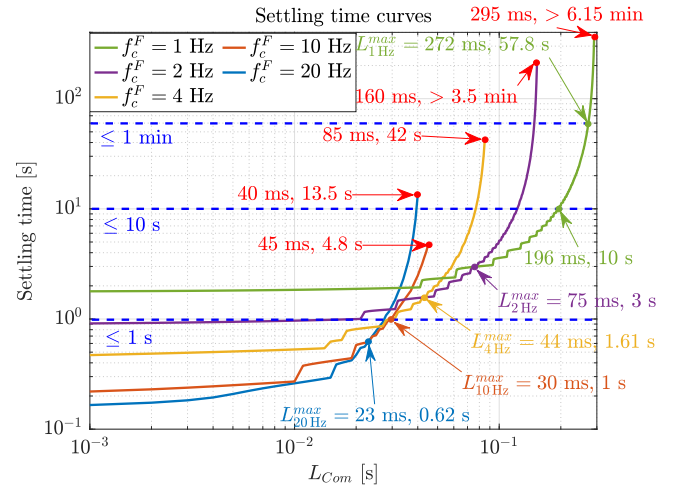


FIGURE 5. Settling time curves for $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$.

$1/T_{tx}^{CC} = 2.5f_c^F$ to satisfy the Nyquist sampling criterion (i.e., $1/T_{tx}^{CC} > 2f_c^F$). For each f_c^F , the red points represent the maximum latencies for stable operation, while the colored points indicate the controller adaptation thresholds (i.e., $L_{20\text{Hz}}^{max} = 23$ ms, $L_{10\text{Hz}}^{max} = 30$ ms, $L_{4\text{Hz}}^{max} = 44$ ms, $L_{2\text{Hz}}^{max} = 75$ ms and $L_{1\text{Hz}}^{max} = 272$ ms). Settling time is defined as the time required for the output variable to remain within a $\pm 2\%$ band around its final value after a step change in the reference.

The adaptation thresholds are defined such that the controller always operates on the f_c^F curve providing the lowest settling time (i.e., the lowest curve) for each operating latency, thereby achieving the best performance. The highest controller latency (i.e., $L_{f_1}^{max}$) defines its maximum settling time. This value must be sufficiently small to ensure the provision of the most time-critical AS in the MG. In Fig. 5, $L_{f_1}^{max} = L_{1\text{Hz}}^{max} = 272$ ms results in a maximum settling time of 57.8 s, which is compatible with AS requiring response times of 1 min or longer [14], such as load-following, load-leveling, and self-consumption [22].

Fig. 6 shows the theoretical and CHIL stability limits for $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$ represented by the intervals $L_{max}^{Theo} \in [x, x + 1 \text{ ms})$ and $L_{max}^{CHIL} \in [y, y + 5 \text{ ms})$, respectively. Here, x is the maximum communication latency identified in MATLAB, with a resolution of 1 ms, for which the transfer function P_{gi}/P_{gi}^* (7) has all its poles in the left-half s -plane. To enable pole-location analysis, the exponential delay terms are approximated using 4th-order Padé approximations. The value of y is obtained from CHIL tests, with a resolution of 5 ms, as the maximum communication latency that ensures stable MG operation. For each f_c^F , the discrepancy range between the theoretical prediction and the CHIL result is indicated by $\epsilon \in (x - y - 5 \text{ ms}, x + 1 \text{ ms} - y)$. The observed differences are attributed to modeling simplifications and experimental effects in the CHIL implementation, with a maximum absolute discrepancy of 10 ms at $f_c^F = 2 \text{ Hz}$. Fig. 6 also highlights the stable operation zone and the adaptation thresholds defined in Fig. 5.

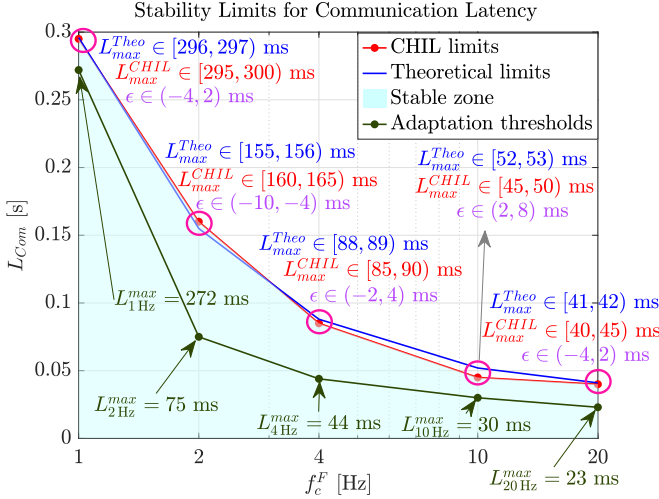


FIGURE 6. CHIL and theoretical stability limits, and controller adaptation thresholds for $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$ and $1/T_{tx}^{CC} = 2.5 f_c^F$.

B. TIME-VARYING STABILITY

Fig. 7 shows the active power injected by the upstream grid into each of the three PCC phases (P_{g1}, P_{g2}, P_{g3}) obtained by the CHIL for: (a) fixed control with $f_c^F = 4 \text{ Hz}$ and $T_{tx}^{CC} = 0.1 \text{ s}$, and (b) adaptive control with $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$, $T_{tx}^{CC} = 1/(2.5 f_c^F)$, and adaptation thresholds defined in Fig. 6. Fig. 7 (c) shows the estimated latency (L_{est}) for both fixed and adaptive control with $L_{1ij} \approx L_{2ij}$, and Fig. 7 (d) shows the corresponding f_c^F and T_{tx}^{CC} values for the adaptive control. In fixed control (Fig. 7 (a)), it is observed that instability occurs when the latency reaches 100 ms (between 180 and 240 s), exceeding the stability limit for $f_c^F = 4 \text{ Hz}$ (90 ms), as shown in Fig. 6. The system returns to stability at 360 s when the latency drops to 70 ms. It becomes unstable again at 480 s with a latency of 320 ms. Stability is restored at 540 s when the latency drops to zero, and the system remains stable until the end of the experiment. Fig. 8 shows a zoomed-in view covering the 480–540 s interval of Fig. 7 (a), highlighting the oscillatory behavior associated with the MG unstable operation. Fig. 7 (b) demonstrates the effectiveness of the proposed adaptive control, maintaining stable MG operation throughout the entire experiment. The secondary control remains active as long as the latency remains below 272 ms, adjusting the PMS parameters (i.e., f_c^F and T_{tx}^{CC}) to maintain stable MG operation with the shortest possible settling time, as shown in Fig. 7 (d). When latency exceeds 272 ms (during the intervals from 300 to 360 s and from 480 to 540 s), the PMS disables the secondary control to avoid MG instability, sending zero coefficients to the DERs (i.e., $\alpha_{1,2,3} = \beta_{1,2,3} = 0$) at a PTR of 2 s. Thus, the DERs operate with only the primary control, and the MG loses its power dispatch functionality.

C. PACKET LOSS AND COMMUNICATION FAILURES

Packet loss and communication failures are treated as latency-related issues. While packet loss increases communication latency due to packet retransmission, communication

failures are characterized by the unavailability of the link between the PMS and the DERs. For example, with a PTR of 10 pps, the retransmission delay is at least 0.1 s. This latency is sufficient to destabilize the MG operating with the fixed controller operating at $f_c^F = 4 \text{ Hz}$ and a PTR of 10 pps (i.e., $T_{tx}^{CC} = 0.1 \text{ s}$), as shown in Fig. 7(a) during the 180–240 s interval. In contrast, the adaptive controller maintains system stability by reducing f_c^F to 1 Hz and adjusting the PTR to 2.5 pps (i.e., $T_{tx}^{CC} = 0.4 \text{ s}$), as shown in Fig. 7(b) over the same time period. The adaptive PBC effectiveness under communication failures is verified in [4], where the control remains precise and stable as long as at least one DER remains connected to the PMS.

D. TIME-VARYING SETTLING TIME PERFORMANCE

Figs. 9 (a) and 9 (b) show P_{g1}, P_{g2}, P_{g3} for the fixed and adaptive controls under the same configurations as in the previous case (Fig. 7). Fig. 9 (c) shows the estimated latency, and Fig. 9 (d) shows the f_c^F and T_{tx}^{CC} for the adaptive control. The settling times associated with reference power changes and load input/output events under fixed control are shown in Figs. 9 (a.i)–(a.iv), with values of 0.7, 0.9, 3.8, and 5.8 s, respectively. In contrast, Figs. 9 (b.i)–(b.iv) show the settling times under adaptive control, equal to 0.27, 0.43, 2.42, and 3.98 s, respectively, highlighting the superior performance of the adaptive control by achieving shorter settling times under identical operating conditions.

E. EVALUATION OF ANCILLARY SERVICE PROVISION IN A MG UNDER WIRELESS COMMUNICATION

To evaluate the effectiveness of the adaptive PBC in providing AS in a MG [4], CHIL tests are conducted over a 24-hour MG operation. Fig. 10 shows the test configuration, including single-phase variable loads at N_6, N_7 , and N_8 , as well as autonomous DERs at N_3, N_4 , and N_5 , all rated at 5 kW and operating at unit power factor. The autonomous DERs operate only with primary control and are considered in this test to verify the proposed strategy under a realistic scenario in which not all DERs participate in secondary control. Communication between the PMS and the DERs is established through a shared wireless Wi-Fi/UDP local area network (LAN) [21]. Although Wi-Fi introduces higher and more variable latency than wired Ethernet, it offers greater flexibility and scalability for DER integration.

Fig. 11 shows MG operation without secondary control (i.e., without communication), where the phase-1 grid active and reactive power (P_{g1} and Q_{g1}) are shown in (a), and the autonomous DER and load power profiles (P_{aut1} and P_{load1}) are shown in (b). Load and generation profiles shown in Fig. 11(b) are updated every minute. Note that the power generation (P_{aut1}) between 6 h and 18 h exceeds the MG load demand (P_{load1}), and the surplus ($P_{aut1} - P_{load1}$) is injected back into the main grid ($P_{g1} = P_{aut1} - P_{load1}$). To eliminate reverse active power flow in the electrical grid, self-consumption can be performed by the EMS [22]. Self-

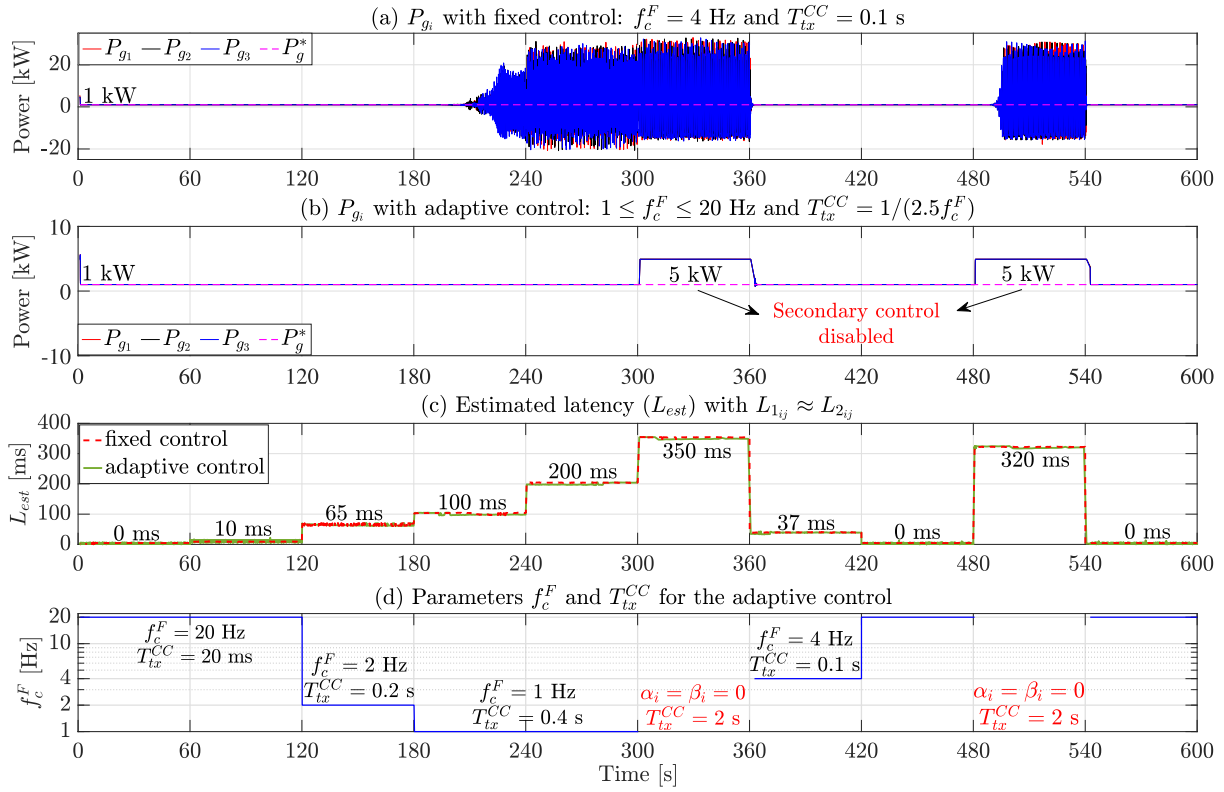


FIGURE 7. Grid active power with (a) fixed control with $f_c^F = 4$ Hz and $T_{tx}^{CC} = 0.1$ s, and (b) adaptive control with $1 \text{ Hz} \leq f_c^F \leq 20 \text{ Hz}$, $T_{tx}^{CC} = 1/(2.5 f_c^F)$, and adaptation thresholds defined in Fig. 6. (c) Estimated latency (L_{est}) with $L_{1ij} \approx L_{2ij}$. (d) Parameters f_c^F and T_{tx}^{CC} .

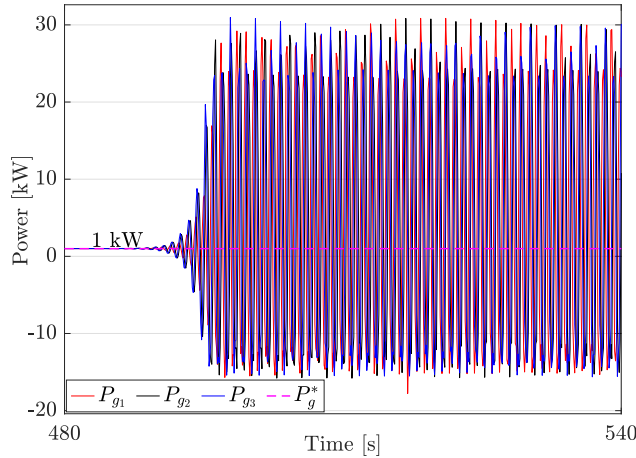


FIGURE 8. Zoom-in view of the 480–540 s interval in Fig. 7(a).

consumption with a 1-minute update rate can be achieved by the adaptive PBC with $f_c^F \geq 1$ Hz and latencies below 272 ms (see Fig. 6). This latency limit is compatible with typical Wi-Fi latencies (< 100 ms) [21].

Fig. 12 shows the results of MG self-consumption using the fixed PBC with $f_c^F = 10$ Hz and $T_{tx}^{CC} = 0.04$ s, where (a) presents the P_{g1} and Q_{g1} , (b) presents the autonomous DER and load power profiles (P_{aut1} and P_{load1}), (c) shows the estimated latency (L_{est}) with $L_{1ij} \approx L_{2ij}$, and (d) shows the PMS parameters (f_c^F and T_{tx}^{CC}). Self-consumption is

applied between 6 h and 18 h, corresponding to the daytime period when reverse power flow occurs in the electrical grid, as shown in Fig. 11. During this interval, all MG surplus generation is absorbed locally, thereby eliminating reverse power flow in the electrical grid ($P_{g1} = Q_{g1} = 0$). The latency levels of 45 ms, 200 ms, and 300 ms are intentionally imposed with $L_{1ij} = L_{2ij}$ to ensure the symmetry condition. The fast latency variations, in turn, represent a form of experimentally induced jitter caused by physical obstruction of the Wi-Fi signal from the Raspberry Pi hosting the PMS. Since this interference acts directly on the shared radio link common to both the PMS-to-DER and DER-to-PMS transmissions, its effect impacts both directions simultaneously, supporting the symmetry assumption. Observe in Fig. 12(a) that the fixed PBC loses PCC power-flow control during the intervals from 4 h to 8 h, from 16 h to 20 h, as well as at several moments of fast latency variations (jitter), leading the MG to unstable conditions. This occurs because both L_{1ij} and L_{2ij} exceed the stability limit of 45 ms (Fig. 6).

Fig. 13(a) shows the MG self-consumption results achieved using the adaptive PBC. The proposed strategy maintains effective secondary control for latencies below 272 ms, which corresponds to the maximum operating limit of the adaptive controller (Fig. 6). Above 272 ms latency (16:00–20:00), secondary control is disabled to maintain MG stability, precluding self-consumption. Fig. 13(d) shows how f_c^F and T_{tx}^{CC} are adaptively adjusted based on L_{est} .

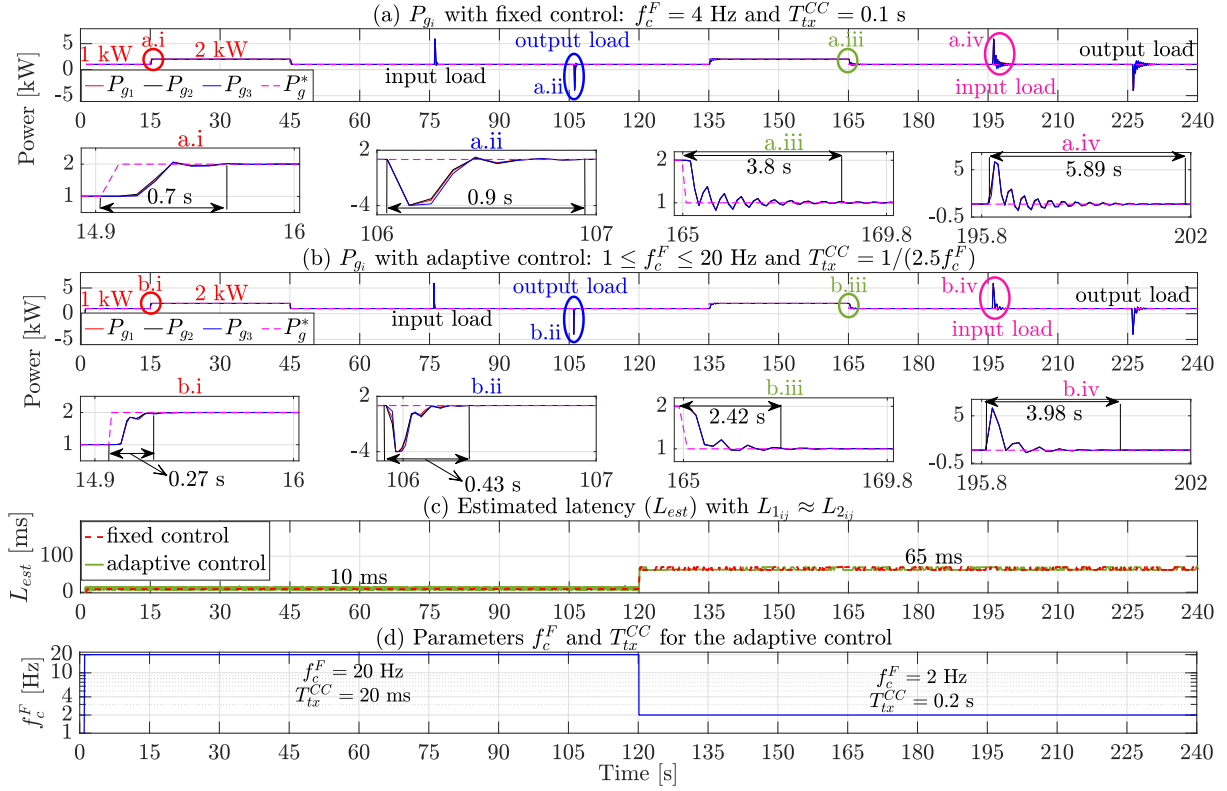


FIGURE 9. (a) and (b) show P_{g_1} , P_{g_2} , P_{g_3} for the fixed and adaptive controls under the same configurations as in the previous case (Fig. 7). (c) Estimated latency. (d) f_c^F and T_{tx}^{CC} . The settling times are shown in (a.i)–(a.iv) for the fixed control and in (b.i)–(b.iv) for the adaptive control.

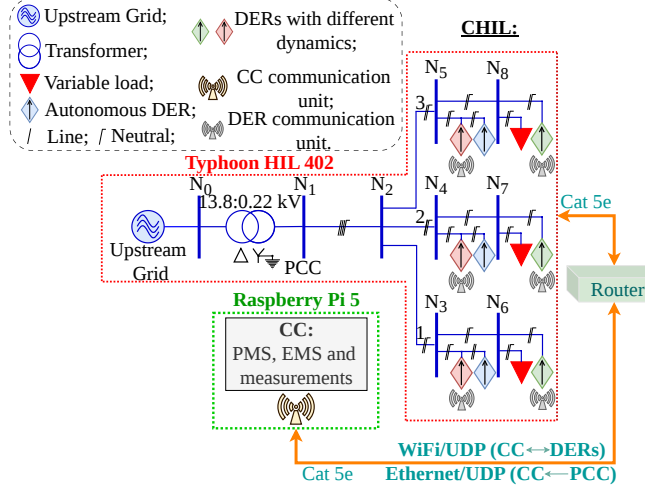


FIGURE 10. CHIL and MG in the adaptive PBC long-duration tests.

V. CONCLUSIONS

This paper proposed a latency-robust adaptive control strategy for power control in advanced MGs with centralized control. CHIL tests demonstrated that the proposed strategy achieves shorter settling times than fixed-dynamics strategies (1.4 and 2.6 times faster) for both reference and load variations under the same latency conditions. Moreover, the proposed strategy maintains stability in scenarios where fixed control becomes unstable. CHIL tests also were conducted considering load/generation power variations and the use of

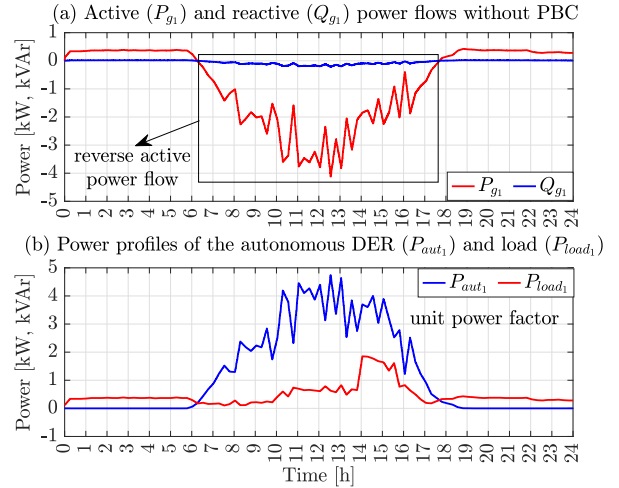


FIGURE 11. (a) Phase-1 grid active (P_{g_1}) and reactive (Q_{g_1}) power obtained by CHIL without secondary control and (b) autonomous DER and load power profiles (P_{aut_1} and P_{load_1}).

a shared Wi-Fi network. In these tests, MG self-consumption was implemented to eliminate reverse power flow in the main grid. The results confirmed the applicability of the latency-robust adaptive PBC and its superiority over the fixed PBC, effectively achieving self-consumption while maintaining MG stability throughout the entire operating period. Notably, the adaptive PBC allows the maximum latency and settling time to be adjusted through the minimum f_c^F and PTR

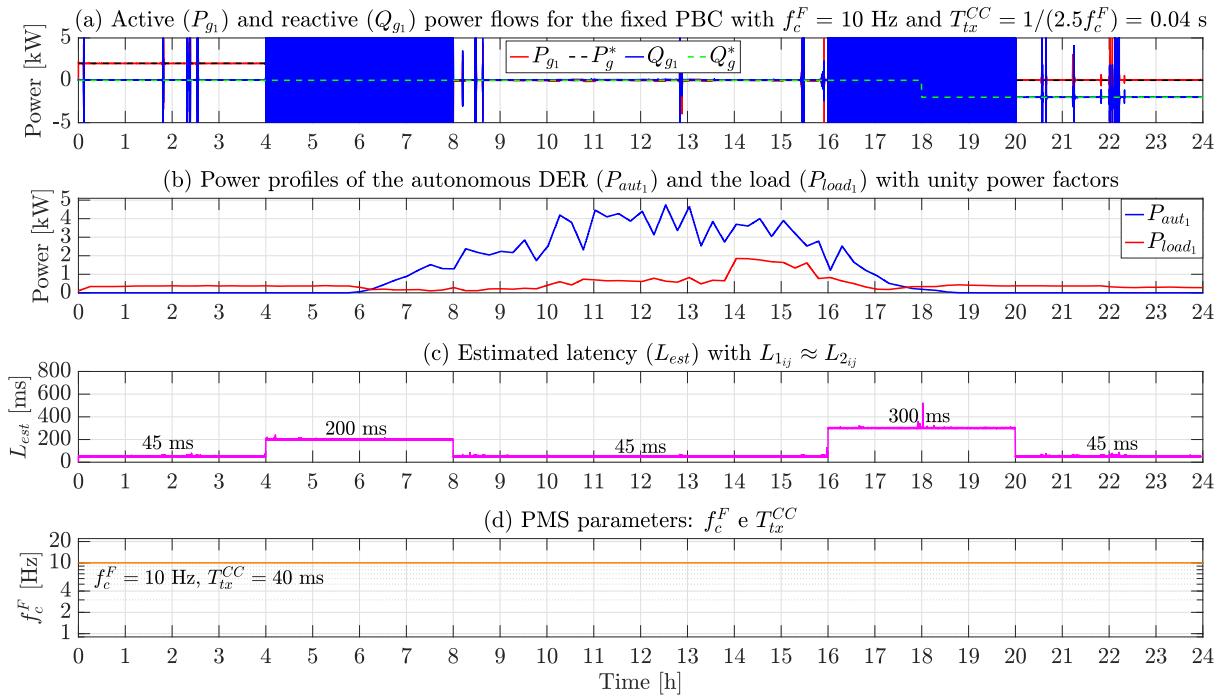


FIGURE 12. Fixed PBC: (a) phase-1 grid active (P_{g1}) and reactive (Q_{g1}) power using CHIL with $f_c^F = 10$ Hz and $T_{tx}^{CC} = 0.04$ s; (b) autonomous DER and load power profiles (P_{aut1} and P_{load1}); (c) estimated latency (L_{est}) with $L_{1ij} \approx L_{2ij}$; and (d) PMS parameters f_c^F and T_{tx}^{CC} . The system becomes unstable, compromising the MG self-consumption operation.

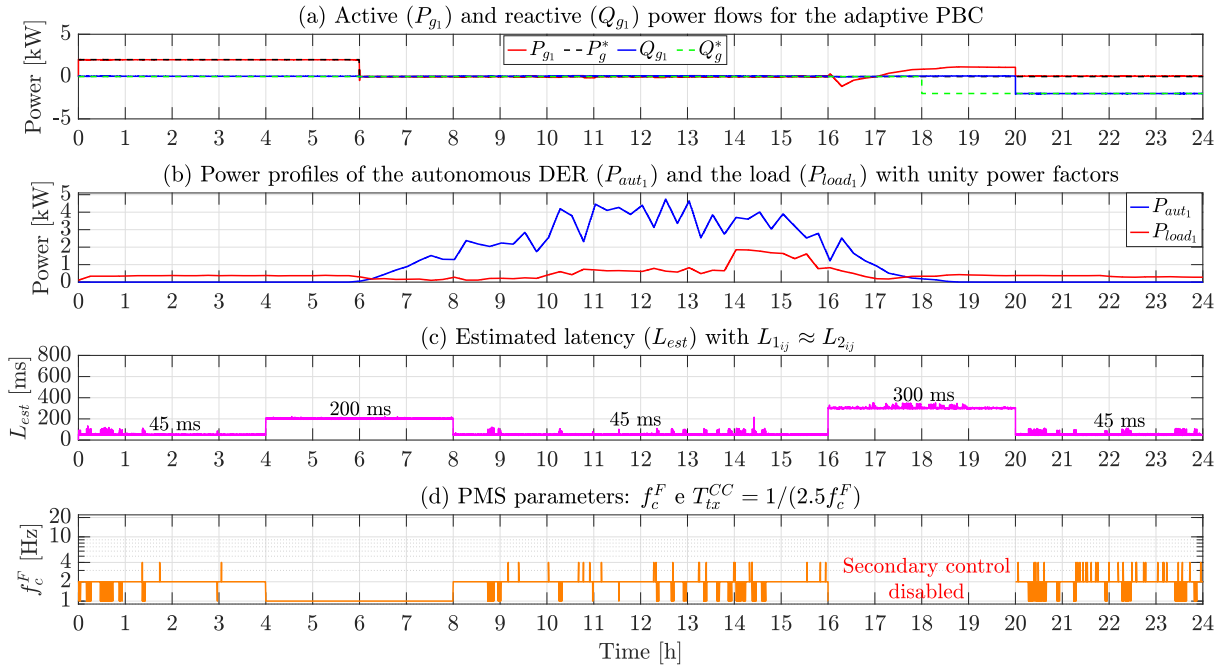


FIGURE 13. Adaptive PBC: (a) phase-1 grid active (P_{g1}) and reactive (Q_{g1}) power obtained using CHIL. (b) autonomous DER and load power profiles (P_{aut1} and P_{load1}); (c) estimated latency (L_{est}) with $L_{1ij} \approx L_{2ij}$. (d) PMS parameters f_c^F and T_{tx}^{CC} . MG self-consumption is achieved.

values, enabling compatibility with different CTs and MG AS requirements. As future work, the authors intend to generalize the proposed method to be robust to asymmetric latency ($L_{1ij} \neq L_{2ij}$), as well as to validate the strategy in a complete physical MG with real DERs and power system.

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AUTHOR'S CONTRIBUTIONS

L.S.CHAVES: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. **J.M.S.CALLEGARI:** Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Visualization, Writing – Review & Editing. **L.S.ARAUJO:** Conceptualization, Formal Analysis, Methodology, Visualization, Writing – Review & Editing. **D.I.BRANDAO:** Conceptualization, Funding Acquisition, Methodology, Project Administration, Resources, Software, Supervision, Visualization, 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.

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