Research Article
Iterative Approach for Tuning Multiple Converter-Integrated DER in Microgrids

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This paper proposes an iterative approach to adjust the control parameters of multiple power converters within a microgrid, which operates in grid-connected and grid-islanded modes. The adequate control parameters are determined using an optimisation-based strategy, local measurements, and results obtained in previous algorithm iterations. The proposed objective function is based on the integral time-weighted absolute error (ITAE), modified to improve the microgrid control performance. The proposed approach addresses the control tuning complexity by considering an incremental strategy, starting from adjusting basic microgrids, continuing to the setting of intermediate microgrids, and finalising when the target microgrid control is fine adjusted. The results obtained at the CIGRE LV benchmark microgrid validate the proposal, obtaining during faults, the maximum deviations from rated frequency around 2.2% and 0.3% in grid-islanded or grid-connected cases, respectively. Also, voltage and power references are adequately followed during steady-state regardless of the microgrid operation mode, where the steady voltage profile is below 10% variation. The obtained results demonstrate the proposed approach advantages, which straightforwardly adjust multiple converters integrated into a microgrid. The main contributions are as follows: (a) the microgrid model is not required, and (b) only measurements at the point of common coupling of the distributed energy resource are used; consequently, the proposed tuning approach is especially applicable to complex microgrids. Finally, finely adjusted microgrids are required for further operation or protection studies where complex system configurations are commonly required.

1. Introduction

1.1. Motivation. Distributed energy resources (DER) are integrated into the electric network as these represent technical and economic benefits [1]. Nevertheless, the study of DER integration is an issue considering the compromise between the model detail and the system size; frequently, when detailed representations are considered is at the expense of the microgrid size [2–4].

Power electronic devices such as the voltage source converter (VSC) are generally used to integrate DER into the AC microgrid. The VSC is a nonlinear device that requires several control layers, which are considered by the microgrid hierarchical control [5]. These control schemes are usually based on proportional-integral (PI) strategies, whose parameters are cautiously selected to obtain an adequate microgrid behaviour [3, 6–12].

On the other hand, operation or protection studies require realistic microgrids, including several converter-integrated DER (CIDER), loads, and lines. Such microgrids can be operated in grid-islanded and grid-connected modes, requiring the zero and the primary control layers. The latter is used when the microgrid operates in grid-islanded mode, while the former is required under grid-connected and grid-islanded cases.

As above exposed, the requirement of realistic size microgrids, which must be adequately controlled, is an issue nowadays. Even though adjusting the PI control constants is considered in many proposals, a standard process is not available, which makes the microgrid adjustment from
1.2. State of the Art. Most of the proposed strategies to determine the VSC control parameters aim for optimal tuning. These can be divided into three approaches:

(a) Those that consider the physical model of the controlled system, where the control parameters are obtained using exact techniques or a combination of exact and nonexact techniques.

(b) Those that use a transfer function equivalent model for the controlled system, where exact or nonexact tuning techniques are predominant and mixed techniques are also available.

(c) Those where the controlled system model is not considered and nonexact tuning techniques are usually applied.

A tuning strategy based on the model is usually preferred since the optimal solution is obtained; nonetheless, the determination of VSC and microgrid dynamic models can be challenging in realistic size microgrids. As a consequence, the last two approaches are widely considered.

1.2.1. Tuning Approaches considering the Physical Component Modelling of the Controlled System. In general, the controlled system model has more parameters as the complexity and size increase. In this approach, the models describe the behaviour of the components and consider at least the small-signal system model. Nonetheless, the model complexity is not always the same in microgrids since each of these include different considerations or components. The following paragraphs present some examples. In [2], a small-signal model (SSM) described a microgrid with three VSCs, which included 55 state variables and considered internal model control (IMC) complemented with particle swarm optimisation (PSO). In [14], an eigenvalue analysis defined the PSO objective function and state equations described the main elements of the microgrid; then [14] considers both model and measures of the system. Finally, [15] propose a 2-VSC test microgrid represented by the state-space model; the search space and objective function of a modified whale optimisation (WO) technique were obtained from the eigenvalue analysis. In the two latter references, the optimisation strategy and the objective function definition were as crucial as the modelling process. However, the system size and number of VSCs were small due to model size. Furthermore, strong disturbances as short circuits were not deeply analysed.

Additionally, even though [16, 17] do not consider a tuning technique, these references presented considerations for microgrid and VSC modelling; these are suitable examples of how daunting, a time-consuming and challenging task is the adjusting of an adequate microgrid model. In [17], the VSC model was analysed, and a proposal for VSC 6th order model was validated through the small-signal model and eigenvalue analysis. In [16], the IEEE37 bus system was modified to include 7 VSCs; as a result, the small-signal model of the whole microgrid reached 225th order, which was reduced to a 56-order system model. Finally, in [18], three types of controllers were tuned by using a small-signal model and the gravity centre of a stable area; however, only one VSC was considered in the test system.

1.2.2. Tuning Approaches considering the Transfer Function Equivalent Modelling of the Controlled System. This approach is usually applied due to the entire microgrid model complexity; then, simplified transfer functions are considered. Usually, this tuning process does not include microgrid interaction or additional elements besides the VSC. Moreover, the simplifications to obtain TF equivalent make the obtained solutions inadequate for all operating conditions [19].

Therefore, the VSC can be modelled by an equivalent first-order transfer function (TF). This tuning approach is considered in the following papers. In [10], a VSC dominant pole TF and pole placement method were considered. Also, in [20], a zero-level TF for the VSC zero control was complemented with fuzzy logic; then, the system response under small and large signal disturbances was enhanced. In [21], the state-space representation of the microgrid was simplified to a TF, and IMC was applied to obtain adequate VSC behaviour under grid transition. In [22], the grid-forming mode of operation was studied, TFs and restrictions in the frequency domain were applied to define boundaries for the primary control parameters and also explored with different primary control strategies. In [23], the simplified microgrid TFs and eigenvalue analysis was carried away. However, it was remarked that a strict mathematical formulation of the optimisation problem was not acquirable, so the solution was obtained through a genetic algorithm (GA) and validated through eigenvalues. Additionally, even though the control parameters selection was not evident in [24], it considered the microgrid modelling using TFs, analysing stability issues and phase-locked loop (PLL) bandwidth, and it also included multiple-input multiple-output (MIMO) representation and parameters boundaries. Finally, it was usual to validate the proposals using a reduced and simplified test system in the references above.

1.2.3. Tuning Approaches Which Do Not Require the Model of the Controlled System. As described in the two previous tuning approaches (model-based approaches), the microgrid model can differ from one work to another, leading to confusion when implementing and tuning a microgrid from
Therefore, this third approach avoids the modelling stage for the control tuning but requires the definition of an optimisation function (OF). As the microgrid model is not considered or is unknown, OF is based on the error in the signals of interest. Also, nonexact techniques are applied, which means that the obtained solution is the best from all explored solutions. As an advantage, this is a fast and straightforward approach, where OF can be estimated using local measurements.

On the other hand, nonexact techniques are a wide field of research in microgrid applications, especially when the system size conduces to a complex model. Among these techniques, [25] presented a review of the operation cost, concluding that swarm strategies had the best performance. Other proposals, as presented in [26], applied PSO to adjust the primary level control for a simplified microgrid. Additionally, in [12], the grey wolf optimisation (GWO) adjusted the control parameters for a wind turbine generator. In [6], the zero-level control for a simplified wind-battery microgrid was adjusted using GA. In [27], the PSO was applied to train a modified fuzzy controller, where tests were compared to PI controller regarding power-sharing and frequency regulation.

As a result of state of the art, the main characteristics of references with control tuning strategies are summarised in Table 1. This table includes for comparison purposes the system model, the applied tuning technique, the adjusted control, the signals used for control adjustment, commonly power, voltage, and frequency; in some cases, also damping coefficient $\xi$ and the real part of eigenvalues $\Re(\lambda)$ were also used. Table 1 also includes the microgrid operating mode, the test system size, and the proposal scalability.

From the comparison table, small test systems were noticed in most cases. Some approaches, as [28, 29], used large test systems, but the use of communication systems jeopardised the overall microgrid behaviour. This last aspect is not considered in the proposal presented in this paper since primary and zero control layers are decentralised, no communication links are required, constituting an essential advantage by reducing costs and reliability issues.

The comparison in Table 1 allows concluding about the proposal scalability, where qualitative labels, low, medium, or high, are considered. Low scalability means a proposal that was not clearly validated nor presented to be implemented in realistic size microgrids and also a proposal that presents a high dependence of correct microgrid modelling. Medium scalability means a proposal that addressed the tuning problem with a high potentiality for implementation on realistic size microgrids, mainly for the flexibility to partially or totally dismiss the microgrid model, which is complex to obtain in realistic microgrids. High scalability is associated with a proposal that addresses the tuning problem and can be easily implemented in realistic size microgrids. Additionally, the proposal presented in this paper has adequate results with low modelling efforts and can be straightforwardly implemented in several microgrids, regardless of the operating mode.

1.3. Contribution. The paper proposes a straightforward approach to define the control parameters, applied to tune realistic size microgrids with several CIDERs, operating in grid-connected and grid-islanded modes. The considered CIDER representation includes the primary energy resource, the VSC, and the output filter. Additionally, as the microgrid model is not required, the proposed strategy can tune controls of complex microgrids. In the proposal, only measurements at the CIDER point of common coupling (PCC) are considered and compared with a reference signal to calculate OF, minimised through an iterative strategy based on an optimisation technique. These measurements contain information about the CIDER’s behaviour and the remaining part of the microgrid.

The proposed approach allows the tune of the control parameters easily; besides, it can be applied to multiple CIDER microgrids. As the used measurements contain the microgrid response under different disturbances, the obtained control parameters allow the stable behaviour for a wide range of operating conditions. This approach speeds up other studies since an adequately tuned microgrid control is the base of upcoming operation or protection analysis.

1.4. Paper Organisation. This document is divided into five sections. In Section 2, the required fundamental theoretical aspects related to the control of CIDERs are exposed, while in Section 3, the proposed approach is described. Later, Section 4 presents the proposed tests, their results, and the corresponding analysis. Finally, Section 5 highlights the conclusions.

2. Control of Converter-Interfaced Distributed Energy Resources

This section briefly introduces the fundamental aspects of microgrid hierarchical control, which comprises four layers known as zero, primary, secondary, and tertiary [4, 5, 30, 31]. Zero layer control is the VSC local control, including the inner and outer loops. The primary level controls the voltage, frequency, and power-sharing. The secondary level improves the quality of voltage and frequency and is in charge of islanding detection. The tertiary level deals with the optimal power flow and the unit commitment in microgrids.

Specifically, this proposal discusses the zero-level control for grid-following CIDERs, while the zero and primary level controls are analysed in the grid-forming CIDERs. The zero-level control for the grid-following CIDERs aims to deliver the reference power imposed by the secondary and tertiary control, while the microgrid is in grid-connected mode. The zero-level control requires proportional and integral parameters $(k_{p1}, k_{i1})$, as depicted in Figure 1. The respective set
of equations for the inner loop is presented in equation (1), while the outer loop is represented by equation set (2).

\[
U_d = u_d - \omega L i_q + \left( k_p + \frac{k_i}{s} \right) (i_{d,ref} - i_d),
\]

\[
U_q = u_q + \omega L i_d + \left( k_p + \frac{k_i}{s} \right) (i_{q,ref} - i_q),
\]

Figur 1: Grid-following controller.

Table 1: Comparison of some referenced microgrid tuning approaches.

| Reference | System model | Tuning technique | Adjusted control level | Signals for adjustment | Microgrid mode | Test system size | Scalability |
|-----------|--------------|------------------|------------------------|------------------------|----------------|-----------------|-------------|
| [2]       | SSM          | IMC and PSO      | Zero and primary       | Q                      | Islanded       | 3 VSC-2 line    | Low         |
| [12]      | None         | GWO              | Zero                   | \( P, U_{ref}, U_{ref,ac} \) and \( V_{dc} \) | Connected      | 2 VSC-1 line    | Low         |
| [10]      | TF           | Pole placement method | Zero                 | None                    | Islanded       | 2 VSC-2 line    | Low         |
| [6]       | None         | GA               | Zero                   | \( \omega_{gen} \)      | Islanded       | 2 VSC-0 line    | Low         |
| [14]      | SSM          | PSO              | Zero                   | \( P \) and \( \text{Re}(\lambda_i) \) | Both           | 3 VSC-2 line    | Medium      |
| [15]      | SSM          | Modified WO      | Zero                   | \( \text{Re}(\lambda_i) \) and \( \xi \) | Islanded       | 2 VSC-1 line    | Low         |
| [20]      | TF           | Fuzzy            | Zero to tertiary       | Q                      | Both           | 4 VSC-3 line    | Medium      |
| [21]      | TF           | IMC              | Zero and primary       | None                    | Both           | 1 VSC-1 line    | Low         |
| [22]      | TF           | Definition of gain margins and parameter ranges | Primary | Not clear | Connected | 2 VSC-3 line | Low |
| [23]      | SSM and TF   | GA               | Zero and primary       | \( P \) and \( Q \)    | Islanded       | 2 VSC-1 line    | Medium      |
| [26]      | None         | Fuzzy and PSO    | Primary                | \( P, Q, U, \text{ and } f \) | Islanded       | 2 VSC-2 line    | Low         |
| [27]      | None         | PSO and fuzzy    | Primary                | \( P \) and \( f \)    | Connected       | 7 VSC-10 line    | Medium      |

| Proposal | None          | Modified ITAE index and metaheuristic optimisation | Zero and primary | \( i_d, i_q, u_d, u_q, \text{ and } f \) | Both           | 5 VSC-10 line    | High        |

where \( U_d \) and \( U_q \) are the \( dq \) voltage references for the VSC, which at the same time are the output of the inner loop. Variables \( u_d, u_q, i_d, \) and \( i_q \) are the \( dq \) voltages and currents measured at VSC PCC, which come from the Park transformation of \( u_{abc} \) and \( i_{abc} \). \( \omega \) is the system frequency while \( \theta \) is the angle reference for the Park transformation. \( L \) is the filter inductance. \( k_p \) and \( k_i \) are the proportional and integral gains, respectively, for the PI controller.
Finally, \( i_{d_1}, i_{d_2}, \) and \( i_{q_1} \) are the \( dq \) currents used as a reference for the inner loop, which are the output of the outer loop in

\[
i_{d_1} = \frac{P_{\text{ref}} u_d + Q_{\text{ref}} u_q}{u_d^2 + u_q^2},
\]

\[
i_{q_1} = \frac{P_{\text{ref}} u_q - Q_{\text{ref}} u_d}{u_d^2 + u_q^2},
\]

where \( i_{d_1}, i_{d_2}, \) and \( i_{q_1} \) are the \( dq \) references for the inner loop and \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) are the references of active and reactive power for the outer loop, respectively. \( u_d \) and \( u_q \) are measurements as described for equation set (1).

The grid-forming CIDER regulates frequency and voltage in grid-islanded mode. It requires three pairs of parameters in the zero-level control, namely, \( v \) and \( \theta \) in the droop control to regulate voltage; \( i_{d_1}, i_{d_2}, \) and \( i_{q_1} \) in the outer loop, so the voltage at the PCC is controlled, whereas \( u_{q_1} \) is null. The remaining variables are already defined in the previous set of equations.

\[
\text{Stage 1: Identification of the Target and Definition of the Basic Microgrids.}
\]

This stage is devoted to identifying the target microgrid’s characteristics and defining the two basic microgrids used for the CIDER control adjustment. Thus, instead of initially handling the target microgrid, two basic microgrids presented in Figure 4 are defined in this stage.

The first basic microgrid presented in Figure 4(a) operates in grid-connected mode and includes a single grid-following CIDER. The second operates in grid-islanded mode and considers only one grid-forming CIDER, as depicted in Figure 4(b).

The size of the CIDER, line, and load in the basic microgrids is defined considering the target microgrid rated values. These basic microgrids are initially tuned as presented in stage two; next, these are used to define the intermediate microgrids, as presented in stage three.

\[
\text{Stage 2: Optimisation of the CIDER Control Parameters.}
\]

Stage two focuses on determining the optimal control parameters for the CIDERs within a target microgrid. In this stage, three main processes are proposed: (a) the objective function (OF) is defined, and an improvement criterion is also established to evaluate the control parameters. (b) A control parameter database is used to improve the odds of reaching a proper solution by the optimisation strategy. (c) The required microgrid control parameters are obtained from the execution of an optimisation process.

\[
\text{3. Proposed Iterative and Incremental Approach for CIDER Tuning}
\]

This section presents a three-stage approach to adjust the control parameters of several CIDERs within a target microgrid. Each CIDER uses the control scheme in Figures 1 or 2 for grid-following and grid-forming operating modes, respectively.

The structure of the proposed approach is presented in Figure 3. It starts by identifying the target microgrid and defining the basic microgrids as is presented in stage 1. The target microgrid is defined as the complex system of interest to the network analyst, while the basic microgrids are simplifications that consist of a single CIDER connected to a load through a line, as presented in Figure 4. Next, in Stages 2 and 3, the controls of basic microgrids are optimally adjusted; then, these tuned microgrids are used to obtain intermediate microgrids by adding lines, loads, or CIDERs. These intermediate microgrids are iteratively enlarged and tuned, using an optimisation strategy based on the measurements at the CIDER PCC. Finally, the target microgrid is obtained and tuned as a result of this iterative process.

\[
\text{3.1. Stage 1: Definition of OF.}
\]

This section presents a three-stage approach to adjust the control parameters of several CIDERs within a target microgrid. Each CIDER uses the control scheme in Figures 1 or 2 for grid-following and grid-forming operating modes, respectively.

The structure of the proposed approach is presented in Figure 3. It starts by identifying the target microgrid and defining the basic microgrids as is presented in stage 1. The target microgrid is defined as the complex system of interest to the network analyst, while the basic microgrids are simplifications that consist of a single CIDER connected to a load through a line, as presented in Figure 4. Next, in Stages 2 and 3, the controls of basic microgrids are optimally adjusted; then, these tuned microgrids are used to obtain intermediate microgrids by adding lines, loads, or CIDERs. These intermediate microgrids are iteratively enlarged and tuned, using an optimisation strategy based on the measurements at the CIDER PCC. Finally, the target microgrid is obtained and tuned as a result of this iterative process.
Stage 1: Definition of target and basic microgrids

Start ➔ Target microgrid (complex)

Stage 2: Optimisation of the CIDER control parameters

Grid-connected or grid-islanded basic microgrids

Control parameters database ➔ Optimisation process execution

Variable measurements and OF calculation ➔ Best control parameters

Best OF update ➔ n = n + 1

Stage 3: Enlarging the basic microgrids

n = n + 1

n ≥ 2 ➔ Not ➔ A

Microgrid (n) = microgrid (n-1) + p-type elements

microgrid(n) is the target microgrid

Not ➔ Variable measurements and OF calculation

Final execution of the optimisation process

Target microgrid best control parameters ➔ End

Figure 3: Approach for tuning the CIDERs within a complex microgrid.
case corresponds to the measured and the reference signals [32, 33].

Initially, for a single CIDER and a signal of interest \( x \), the desired time window contains the microgrid response under a single disturbance, for example, short circuit and load change. This window is represented in Figure 5 and has a fixed time length \( T \); an initial time \( t_0 \), corresponding to the first sample of interest \( k = 1 \); and a total of \( K \) samples, which are defined according to the window length and the sampling time \( t_{\text{smpl}} \).

The ITAE index for the signals in Figure 5 is defined as in equation

\[
\text{ITAE} = \sum_{k=1}^{K} k t_{\text{smpl}} |\Delta x(k)|, \tag{6}
\]

where \( \Delta x(k) = x(k)_{\text{reference}} - x(k)_{\text{measured}} \).

Next, as several disturbances \( d \) are considered, the ITAE in equation (6) becomes

\[
\text{ITAE} = \sum_{d=1}^{D} \sum_{k=1}^{K} k t_{\text{smpl}} |\Delta x(k, d)|, \tag{7}
\]

where \( D \) is the number of considered disturbances.

Additionally, several signals \( s \), such as voltage and current, are considered; then \( \Delta x \) contains a set of signals. Similarly, as the signals of interest differ according to the CIDER operating mode, the average error per signal is preferred. These considerations turn equation (7) into (8), which is obtained for each CIDER \( c \).

\[
\text{ITAE}_c = \frac{1}{S} \sum_{s=1}^{S} \sum_{d=1}^{D} \sum_{k=1}^{K} k t_{\text{smpl}} |\Delta x(k, d, s)|, \tag{8}
\]

where \( S \) is the number of considered signals at each CIDER \( c \).

After that, \( \text{ITAE}_c \) is estimated separately for the grid-forming \( (C_{\text{form}}) \) and grid-following \( (C_{\text{foll}}) \) CIDERs. The evaluation of (9) is therefore performed.

\[
\text{ITAE}_{\text{form}} = \frac{1}{C_{\text{form}}} \sum_{c=1}^{C_{\text{form}}} \text{ITAE}_c; \tag{9}
\]

\[
\text{ITAE}_{\text{foll}} = \frac{1}{C_{\text{foll}}} \sum_{c=1}^{C_{\text{foll}}} \text{ITAE}_c.
\]

Finally, the \( \text{ITAE}_{\text{total}} \) is defined as the OF and presented in (10), which allows comparing CIDERs behaviour.

\[
\text{OF} = \alpha \text{ITAE}_{\text{form}} + (1 - \alpha) \text{ITAE}_{\text{foll}}. \tag{10}
\]

In (10), \( \alpha \) is an adjustable weighting factor that gives relevance to either grid-forming or grid-following CIDERs, considering values from 0 to 1. In the grid-islanded microgrid, the weighting factor emphasises the fine parameter selection of the grid-forming CIDERs, while in the grid-connected microgrid, the importance is focused on the grid-following CIDERs.

### 3.2.2. Definition of the Control Parameter Database.

The purpose of the control parameter database is to initialise the parameters for the CIDERs within the microgrid.

Initially, this database is empty; then, control parameters at first executions of the optimisation process, which consider the basic microgrids, are obtained from empirical tuning methods or reported control parameters for similar applications, as these presented in [10, 12, 34]. After several iterations, this database also contains parameters obtained from the optimisation process, which is iteratively executed due to several intermediate microgrids being considered. It is necessary to execute the optimisation process multiple times since the CIDERs optimal control parameters are not the same in each microgrid. Then, the number of executions of the optimisation process is given by the criteria at stage 3 as
3.2.3. Execution of the Optimisation Process. The considered optimisation problem is oriented to minimise the objective function \( OF \), selecting adequate CIDER control parameters \( \text{par} \), as presented in
\[
\min_{\text{par}} \alpha ITAE_{\text{form}} + (1 - \alpha) ITAE_{\text{fol}},
\]
\[
\text{s.t.} \quad \text{par} \in \text{solutionspace},
\]
\[
\xi \geq 0.
\]

Figure 6 portrays the process to minimise the \( OF \), as proposed in (10). The initial set of parameters \( \{\text{par}\} \) is obtained from the database, as previously described. The \( OF \) is estimated using these parameters at the CIDERs control and the measured signals of interest. The \( OF_i \) estimated in the internal iteration \( i \) is compared to the previous \( OF_{i-1} \) to calculate the tolerance. If the tolerance is lower than the desired value \( \xi \), then the best control parameters for the CIDERs control are obtained \( \{\text{par}_{\text{best}}\} \), which ends the execution of the optimisation process. Otherwise, the optimisation strategy selects a new set of parameters to be evaluated in the CIDER control.

Variable \( \text{par} \) is composed of two or six parameters for each grid-following or grid-forming CIDER, respectively. Additionally, since the number of parameters increases with each CIDER in the microgrid, these are grouped, and each group uses the same control parameters. Thus, the parameters sought by the optimisation strategy are given by (13). The CIDERs are grouped considering this distance to the main grid connection node in the grid-connected case or to the grid-forming CIDER in the grid-islanded case.
\[
\text{par} = 2(Gr_{\text{fol}}) + 6(Gr_{\text{form}}),
\]
where \( Gr_{\text{fol}} \) and \( Gr_{\text{form}} \) are the number of groups for grid-following and grid-forming CIDERs, respectively.

where \( Y \) is a positive integer greater than 1.

Finally, the parameters in the database are inputs for the optimisation strategy; then, as the information of previous solutions is available, the optimiser is more likely to find a proper solution in the actual iteration.

\[
OF_{(a)}
\]
\[
OF_{\text{best}} = \psi \Rightarrow \begin{cases} 
\text{Continue to the optimisation process execution,} & \forall \psi \geq Y, \\
\text{Enlarge the intermediate microgrid,} & \forall \psi < Y,
\end{cases}
\]

4. Tests and Discussion

This section presents the test results that validate the proposed approach, aiming to adjust the CIDER control parameters within a complex microgrid. Measurements at the CIDERs PCC and PSO are used in this paper considering previous satisfactory results [35], although the proposed approach allows other techniques as those presented in [25].

Initially, the target and the basic microgrids are presented; next, the results for the basic microgrid considering two testing scenarios. After, the analysis of one of the intermediate microgrids is presented, and finally, the last part presents the result analysis of the target microgrid tuned using the proposed approach.

4.1. Test System. The target microgrid selected for tests is based on the CIGRE LV benchmark [36] and has 170 kVA maximum load, operating in islanded or connected modes as presented in Figure 7. The basic microgrids have a single 100 kW CIDER (as CIDER 5), 2/0 AWG conductor, 100 m line, and 80 kVA load.

4.2. Analysis of the Basic Microgrids

4.2.1. Testing Operating Conditions for the Basic Microgrids. The adequate signals used in evaluating the \( OF \) defined in (10) consider two testing scenarios in the case of basic microgrids. The first testing scenario is oriented to evaluate the \( dq \) currents or voltages, considering the CIDER control based on the \( dq \) frame. On the other hand, as the measurements are in the \( abc \) frame, the second scenario considers the active and reactive power signals and the RMS voltage to evaluate the \( OF \). Frequency is considered in both scenarios. Finally, the testing operating condition for basic microgrids considers disturbances, including a three-phase fault \( (R_f = 1.0 \Omega) \) at 0.20 s, and load changes of 15% and
50% of the CIDER rated value at 0.56 s for grid-islanded and grid-connected cases, respectively.

4.2.2. Results for Grid-Following CIDER in the Basic Grid-Connected Microgrid. In this case, both scenarios behave alike in the measured signals (id, iq, P, and Q), which have a stable and flawless response after the load change and the fault clearance; then, no advantage of the dq frame scenario over the abc frame scenario is noticed. For comparison purposes, in the dq frame scenario, the OF best value is 5.13 when estimated using id and iq, whereas it is 208.4 when P and Q are used. In the abc frame scenario, the OF is 5.91 when using id and iq, whereas it is 208.1 with P and Q. Then, the dq frame scenario is, on average, slightly better.

Despite both scenarios being similar and valid to obtain control parameters, the dq frame scenario is selected. Still, the best parameters obtained in both scenarios are used as nourishment for the control parameter database. The best control parameters for the CIDER in the basic grid-connected microgrid are \([k_{p1}, k_{i1}] = [10.352 421.962]\).

4.2.3. Results for Grid-Forming CIDER in the Basic Grid-Islanded Microgrid. The differences between scenarios in the grid-forming CIDER are bigger than in the grid-following case. Therefore, in the dq frame scenario, the OF is 17.65 with ud, uq, and f, whereas it is 28.34 when urms and f are used; on the other hand, the abc frame scenario has an OF of 40.13 with ud, uq, and f, whereas it is 11.90 with urms and f. As a consequence, the dq frame scenario has slightly better performance, as is presented in Figure 8. Also, it is shown that the smaller difference is obtained for the id signal, which under fault has a slightly higher overshoot in the dq frame scenario; however, it also recovers faster than the abc frame scenario. Still, results from both scenarios enrich the control parameter database. Finally, the best control parameters for the CIDER in the basic grid-islanded microgrid are \([k_{p2}, k_{i2}] = [0.082, 0.], \ [k_{p3}, k_{i3}] = [8.657, 6361.07], \) and \([m_p, m_q] = [4.291 \times 10^{-4}, 3.173 \times 10^{-5}].\)

4.3. Analysis of the Intermediate Microgrids. The evolution of the two basic microgrids towards the target microgrid is achieved at stage three of the proposed methodology. This
stage is the most complex since it handles the microgrid enlarging by adding a line, load, and CIDER-type elements.

Adding elements raises the microgrid’s complexity, whose behaviour is mainly jeopardised by the CIDER-type elements due to their nonlinear behaviour. As these elements cause significant increments in the $\text{OF}$, then one of the intermediate microgrids obtained by adding line and load-type elements and only the CIDER 5 to the basic grid-connected, resulting in the same topology presented in Figure 7, is here analysed as an example of the tuning process. In this case and using the same control parameters as in the basic microgrid, the obtained $\text{OF}$ value is 6.37. The $\text{OF}$ is severely varied when changing the location, rated power, and the number of CIDER-type elements; for example, changing the CIDER location from N6 to N5 causes an $\text{OF}$ value of 9.06, while it rises to 94.85 or 268.11 when the CIDER rated power is reduced to 50 kW or 20 kW, respectively. Similar results are obtained from the intermediate microgrids based on the grid-islanded basic microgrid. A high $\text{OF}$ is related to strong and fast signal oscillations in both grid-islanded and grid-connected cases.

The aspects mentioned above allow determining $Y$ value. This is greater than 1, but not too small, never to stop the iteration process, and not too big that an intermediate microgrid with lousy behaviour (high oscillations or low-quality voltage or frequency signals) misses the optimisation process. A value of $Y = 5$ is considered.

Finally, the addition of CIDER-type elements causes drastic changes in $\text{OF}$ that usually activate the optimisation process execution; that is, the associated $\text{OF}$ is higher than 5 times $\text{OF}_{\text{best}}$. For instance, in the intermediate microgrid, a second CIDER at N8 produces $\text{OF} = 138.43$, which is around 27 times larger than the $\text{OF}_{\text{best}}$ until now results from the grid-connected basic microgrid and is 5.13, activating the optimisation process. The sequence mentioned above for intermediate microgrid definition and performance evaluation is executed until the target microgrid is obtained.

4.4. Analysis of Target Microgrid. This section summarises the optimisation process results for the CIDER control parameters and the target microgrid overall behaviour.

4.4.1. Control Parameters Obtained by the Optimisation Process. The target microgrid in Figure 7 operates in grid-connected or grid-islanded modes. During grid-connected, all CIDERS are grid-followers, while in grid-islanded, it has a single grid-forming at node N6.

The best CIDER parameters for both microgrid operating modes are different, as presented in Tables 2 and 3. Additionally, $Gr_{\text{poll}} = 2$ and $Gr_{\text{form}} = 1$, and the criteria for assigning a CIDER to a certain group are related to the distance from the slack node (N1 in grid-connected mode or N6 in grid-islanded mode).

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**Figure 8:** Comparison of the optimisation scenarios for the basic grid-islanded microgrid. (a) Basic microgrid frequency. (b) RMS voltage in the PCC. (c) Voltage in direct and quadrature axis at the PCC.
Table 2: Best control parameters in the grid-islanded microgrid.

| Group | CIDER | Parameters                  | OF  |
|-------|-------|-----------------------------|-----|
| 1     | 5     | $m_p = 3.35 \times 10^{-5}$ |     |
|       |       | $m_q = 2.167 \times 10^{-6}$|     |
|       |       | $k_{p3}, k_{i3} = 10.896, 0$|     |
|       |       | $k_{p2}, k_{i2} = 2.012, 0$|     |
| 2     | 1     | $k_{p2}, k_{i2} = 1.055, 1053$| 23.795 |
| 3     | 2, 3, and 4 | $k_{p1}, k_{i1} = 0.241, 1742.6$ | 1.66 |

Table 3: Best control parameters in the grid-connected microgrid.

| Group | CIDER | Parameters                  | OF  |
|-------|-------|-----------------------------|-----|
| 1     | 1, 3, and 5 | $k_{p1}, k_{i1} = 1.223, 3683.8$ |     |
| 2     | 2 and 4  | $k_{p1}, k_{i1} = 1.145, 3467$ | 1.66 |

Figure 9: Continued.
4.4.2. Testing Operating Conditions for Target Microgrid. Target microgrid contains intentional grid transition; then, CIDER 5 is selected to operate in grid-forming and grid-following modes according to the $t_{sw}$ state, while the remaining CIDERs only operate in grid-following mode. The best control parameters for grid-islanded and grid-connected modes are used while considering grid transition.

Figures 9(a)–9(c) present the active power ($P$), voltage ($v$), and frequency ($f$) for each CIDER. The considered operating conditions for tests include (a) operation starts in grid-islanded mode, and grid-following CIDERs are compelled to deliver constant power; (b) two load increments of 15 kVA in node N8 at 1.2 s and 10 kVA in node N6 at 1.4 s; (c) three-phase fault at node N4 with $R_f = 1.01 \Omega$ and duration of 0.3 s at 1.8 s and 3.1 s3.1 s; then disturbances are included within the two microgrid operating modes; and (d) intentional grid transition at 2.6 s.

As presented in Figure 9, the initial time instant of interest is 1 s. This is because at any time earlier, the considered CIDERs are in a start-up state, where grid-forming CIDER starts first, and grid-following CIDERs start sequentially to reduce stability issues. The aforementioned start-up sequence is similar to a plug and plays capability in the grid-following CIDERs.

As presented, the proposed approach is successfully applied and validated to adjust the control parameters of several CIDERs within a complex microgrid and tested under several disturbances, including intentional grid transition.

5. Conclusions

Nowadays, the modelling of realistic size microgrids requires several studies. Nevertheless, the study of DER integration is an issue considering the compromise between the model detail and the system size; frequently, the microgrid size is reduced when detailed representations are considered.

The proposed approach considers two basic microgrids used to iteratively enlarge the system towards the desired target microgrid. The approach helps to obtain an adequate microgrid behaviour because lines, loads, and CIDERs are sequentially added; then, the control parameters are updated considering the settings in the previous iterations and a parameter database.

The application of the proposed approach is straightforward, as it avoids detailed modelling of the microgrid and the CIDER. As a consequence of simplifying the modelling efforts and reducing the computational burden, suitable solutions for larger systems, including several CIDERs, are obtained, which constitute relevant advantages of the proposal over those approaches usually addressed by the cited references. Moreover, the proposed objective function considers measurements under different system states; transient and small-signal stability is also addressed.

As demonstrated in the testing section, the proposal is validated and successfully applied to adjust the control parameters of several CIDERs in a complex microgrid, whose behaviour is analysed under small and strong disturbances, including load changes, faults, and intentional grid transition. Moreover, the proposed approach optimally adjusts CIDERs for operating under grid-connected or grid-islanded microgrid modes; consequently, considering the observed results, the obtained microgrid and CIDER parameters configuration adequately supports grid transition.
This corroborates the suitability of the proposed iterative and optimisation-driven approach. This proposal is also an integrated approach since it iteratively considers several systems prior to the target microgrid study. Also, the proposal considers parameter results from other works or systems, which enables the proposal to embrace many other proposals as an initial point database.

Additionally, the fine selection of the CIDER control parameters in a target microgrid influences the system stability since, in the case of a deficient adjustment process, high oscillations and time responses may lead to issues. In the performed tests, disturbances affecting small-signal and transient stability are indirectly considered by including the measured signals at the optimisation process. These stability studies are challenging to consider in other approaches due to the complexity of the system modelling; then, this fact validates an additional demonstrated proposal advantage.

Finally, the main contribution is to propose and validate an off-line approach to optimally adjust the control parameters of a multiple CIDER microgrid, considering only local measurements at the objective function. This function is evaluated considering several microgrid operating conditions such as grid transition, power system faults, and load changes. The proposed approach accelerates microgrid studies since fine control adjustment is mandatory to obtain adequate test systems for studying further operation or protection issues.

### Abbreviations

- **AC**: Alternating current
- **CIDER**: Converter-integrated distributed energy resource
- **DER**: Distributed energy resource
- **GA**: Genetic algorithm
- **GWO**: Grey wolf optimisation
- **IMC**: Internal model control
- **ITAE**: Integral of time-weighted absolute error
- **MIMO**: Multiple-input multiple-output
- **OF**: Objective function
- **PCC**: Point of common coupling
- **PI**: Proportional-integral
- **PLL**: Phase-locked loop
- **PSO**: Particle swarm optimisation
- **SSM**: Small-signal model
- **TF**: Transfer function
- **VSC**: Voltage source converter
- **WO**: Whale optimisation.

### Symbols

- **C**: Filter capacitance
- $C_{\text{foll}}$: Number of grid-following CIDERs
- $C_{\text{form}}$: Number of grid-forming CIDERs
- $D$: Considered disturbances
- $f$: Frequency measurement
- $G_{\text{foll}}$: Groups of grid-following CIDERs
- $G_{\text{form}}$: Groups of grid-forming CIDERs
- $i_{\text{abc}}$: abc currents at VSC PCC
- $i_d$, $i_q$: dq currents measured at VSC PCC
- $i_{d\text{ref}}$, $i_{q\text{ref}}$: dq reference currents for inner loop
- $K$: Total of samples of the window to analyse
- $k_{p1}$: Proportional gain for grid-following inner loop control
- $k_{p2}$: Proportional gain for grid-forming inner loop control
- $k_{p3}$: Proportional gain for grid-forming outer loop control
- $k_{I1}$: Integral gain for grid-following inner loop control
- $k_{I2}$: Integral gain for grid-forming inner loop control
- $k_{I3}$: Integral gain for grid-forming outer loop control
- $L$: Filter inductance
- $m_p$, $m_q$: Active and reactive gains for droop control
- $P$, $Q$: Active and reactive power measures at PCC
- $P_{\text{ref}}$: Reference of active power for VSC
- $Q_{\text{ref}}$: Reference of reactive power for VSC
- $S$: Number of considered signals at each CIDER $c$
- $T$: Time length of window to analyse
- $t_0$: Initial time of window to analyse
- $t_{\text{sampl}}$: Sampling time for $x$ signal
- $u_{\text{abc}}$: abc voltages at VSC PCC
- $u_d$, $u_q$: dq voltages measured at VSC PCC
- $u_{d\text{ref}}$, $u_{q\text{ref}}$: dq voltage references for grid-forming outer loop
- $U_d$, $U_q$: dq voltage references for the VSC
- $Y$: Limit value to compare the best objective function at the optimisation process
- $\alpha$: Relevance factor for grid-forming or grid-following CIDER ITAE
- $\Delta x$: Error between signal $x$ reference and measure
- $\theta$: Angle reference for the Park transformation
- $\xi$: Tolerance for the optimisation strategy
- $\omega$: System angular frequency
- $\omega_{\text{ref}}$: Frequency reference for the VSC.

### Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Conflicts of Interest

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

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