Frequency Regulation in Isolated Microgrids Through Optimal Droop Gain and Voltage Control

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***Abstract*—This paper presents an adaptive active power droop controller and voltage setpoint control in isolated microgrids for optimal frequency response and stability after disturbances. The control scheme involves an optimal and model predictive control approach that continuously adjusts the active power droop gains and the voltage setpoints of Distributed Energy Resources (DERs) to maintain the frequency of the system within acceptable limits and enhance the primary frequency response of the system, while taking into account the active power sensitivity of the microgrid loads to the system's operating voltage. The proposed control scheme is tested, validated, and compared with previously proposed techniques using time-domain simulations for a test system based on a CIGRE medium voltage benchmark microgrid under different realistic conditions, demonstrating the advantages of the proposed approach.**

***Index Terms*—Droop control, frequency control, frequency stability, microgrid, voltage control, voltage-frequency dependency.**

I. Introduction

RECENTLY, there has been a large-scale deployment of Distributed Energy Resources (DERs) to address both economic and environmental issues associated with conventional power plants located primarily at the transmission level. As a result, Renewable Energy Sources (RESs) are being deployed at both transmission and distribution systems. These intermittent DERs are affecting the characteristics of the grid due to the power electronics used to connect these systems, which can place a significant burden on power systems, since these were not designed to handle such DERs [1].

The proliferation of DERs in distribution feeders is changing the behavior and operation of these systems, with microgrids being formed at these levels [1], [2]. These clusters of DERs and loads may be located at medium and low-voltage levels, and are capable of generating power to meet the local demand, thus supplying these loads autonomously in isolated mode [1], [3], [4]. These systems pose significant technical difficulties to both operators and planners, due to their multi-energy carrier nature, the intermittency of RESs, and the technologies used to interface the latter [3]–[5].

The frequency control of microgrids has been extensively discussed in the literature [2]–[4], [6], [7]. Specifically, the problem of load sharing among DERs has been addressed by employing passive droop controllers to mimic the synchronous generator power-frequency relationship [6]. However, these droop controllers present several drawbacks that could affect microgrid's stability. For instance, the authors in [7] demonstrate that choosing a high droop gain for wind turbines makes the system unstable; furthermore, low droop gains for DERs are shown to result in poor primary frequency response.

There are a few papers that address various issues with passive droop controllers. For example, the authors in [8] present a control scheme to dynamically adjust the droop parameters of derated Doubly Fed Induction Generator (DFIG) wind turbines, to improve both the frequency response of the microgrid and its stability, considering a simplified model where the components of the microgrid are represented by first-order transfer functions. However, this control scheme is limited to the adjustment of the droop gains of wind turbines that have insufficient primary reserves (due to changes in wind speeds) such that the stability of the system is maintained; in addition, it does not coordinate between the various DERs such as diesel generators and Battery Energy Storage Systems (BESS) to improve the primary frequency response of the overall system. A multi-agent based dynamic droop gain adjustment of DERs is presented in [9], where each DER is an agent that interacts with neighboring DERs to adjust the droop parameters to improve the primary frequency response for grid-connected microgrids; such a decentralized scheme presents some challenges for supply-demand balance in isolated microgrids, as discussed in [4], that are not considered in the paper. Another study that proposes adaptive droop control is presented in [10], where the droop gain of a DER is regulated so that its output power follows a setpoint. However, the presented controller does not coordinate the adjustment of multiple DER droop gains for optimal frequency regulation.

Other studies in the literature that involve frequency control in isolated microgrids through voltage control has been reported in [11] and [12]. In these papers, the authors developed a decentralized Voltage Frequency Controller (VFC) for grid forming DERs that indirectly controls the frequency of the microgrid by adjusting the voltage setpoints of DERs, exploiting the loads' sensitivity to the operating voltage of the system. However, the performance of such decentralized voltage controllers is heavily dependent on the load characteristics of the microgrids. In [13], the authors developed a distributed control system to regulate the voltage of a simplified microgrid model, but the proposed controller does not regulate the frequency of the system. In [14], the authors also developed a distributed reactive power control scheme that maintains a desired reactive power distribution among DERs in steady-state. However, this voltage control scheme does not consider the coupling between

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active and reactive power in the system and its effect on the frequency of the system.

Optimal and Model Predictive Control (MPC) based frequency and/or voltage controls in microgrids are presented in [15]–[21]. Thus, in [15], the authors discuss an MPC approach to minimize frequency deviation of an isolated microgrid with electric vehicles; the presented control scheme mainly focuses on adjusting the active power setpoints of DERs to satisfy the objective function and the constraints, but does not consider the impact of voltage and droop control on the system's frequency. Similarly, in [16] and [17], the authors propose an MPC-based secondary controller to improve the transient response of isolated microgrids, but the studies do not consider droop control nor VFC. In [18], a distributed MPC controller is presented to regulate the operating voltage of the system; however, the control scheme does not consider the impact of droop nor VFC control on the system frequency. In [19], the authors propose an MPC approach to adjust the voltage setpoints of DERs, where the controller receives input signals from a conventional droop controller to minimize the difference between the reference and measured DER voltage; however, the proposed technique does not aim to regulate the frequency nor coordinate the DERs to achieve optimal frequency regulation with proper load sharing, and VFC control is not considered either. Similarly, in [20], an MPC technique is used in DERs to improve their voltage dynamic response, but there is no consideration for DER optimal droop, coordination, nor VFC. Finally, in [21], a linear optimization problem to minimize the generation-load power balance is proposed for frequency regulation in microgrids; however, droop and VFC issues are not considered.

Given the aforementioned issues with frequency and voltage controllers in microgrids, the current paper proposes a joint frequency and voltage control approach for isolated microgrids based on a centralized and online nonlinear optimization approach, with and without MPC. The proposed control scheme exploits the sensitivity of the load demand to the operating voltage of the microgrid, and coordinates the various DERs by continuously adjusting both their active power droop parameters and voltage setpoints to obtain an optimal frequency response, while considering the operational limits of the DERs, such as the State of Charge (SOC) of BESS. Therefore, the main contributions of this paper are:

- Develop, test, and demonstrate a new centralized frequency control technique that enhances the frequency response of the system by optimally adjusting the main active power droop parameters to avoid stability issues associated with the improper tuning of DER droop gains. The proposed controllers ensure an optimal trade off between load sharing and frequency regulation by optimally adjusting the droop gains.
- Enhance the robustness of the proposed control by continuously and optimally adjusting the voltage setpoints of the DERs, exploiting the impact of voltage dependent loads on the frequency of the system, as in the case of the VFC.

The rest of the paper is organized as follows: Section II briefly discusses the basics of frequency control in microgrids, and the associated modeling of the microgrid components. Section III introduces and explains the proposed optimal control approach. Section IV presents and discusses several time-domain simulations for various studies on a modified CIGRE benchmark microgrid, demonstrating, validating, and comparing the proposed methods to existing techniques. Finally, Section V summarizes and highlights the main conclusions of the presented work.

II. Frequency Control and Component Modeling

The proposed control scheme is designed for isolated microgrids, which present several technical challenges such as large and fast frequency excursions due to supply-demand imbalances associated with RES variability [4]. Frequency control in isolated microgrids is typically done through a centralized, hierarchical control structure, consisting of primary, secondary, and tertiary controls [4]. Primary frequency control, which is the main focus of this paper, is carried out through dispatchable DER units such as synchronous generators and energy storage systems.

A. Synchronous Generators (Diesel Units)

Diesel synchronous generators have been widely used in microgrids since they are readily dispatchable, thus being used as grid forming DERs to support the frequency of the microgrid [4]. The frequency dynamics of these generators are mainly described by the swing equation, which relates the frequency of the microgrid to the power mismatch of the system as follows [22]:

$$M_{DER}\,\frac{\mathrm{d}\omega}{\mathrm{d}t} + D_{DER}\Delta\omega = P_m - P_{DER} \tag{1}$$

where P_m is the mechanical input power into the generator, P_{DER} is the electrical output power, ω is the speed of the rotor (the angular velocity), and M_{DER} and D_{DER} are the inertia and damping coefficients of the diesel generator, respectively. Therefore, primary frequency control is achieved by the governors of the synchronous generators as follows [22]:

$$K_P(f - f_o) = -(P_{DER} - P_{DERo}) \tag{2}$$

where P_{DERo} and f_o are the DER nominal active power and frequency, respectively, while K_P is the droop parameter. Hence, if the frequency of the system deviates due to load, RES, or system disturbances, the primary control will attempt to restore power balance in the system and limit frequency deviations.

The authors in [23] have developed a dynamic model of a diesel generator suitable for time-domain simulations, which have been validated with an actual field model. This model is used here, which includes the governor and exciter models depicted in Fig. 1, with properly tuned gains for the test system used here.

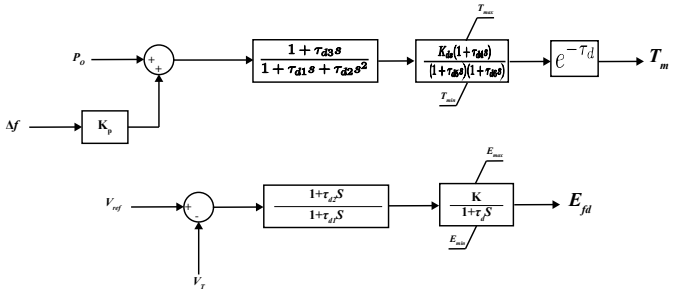


Fig. 1: Governor and exciter models of diesel generator [23].

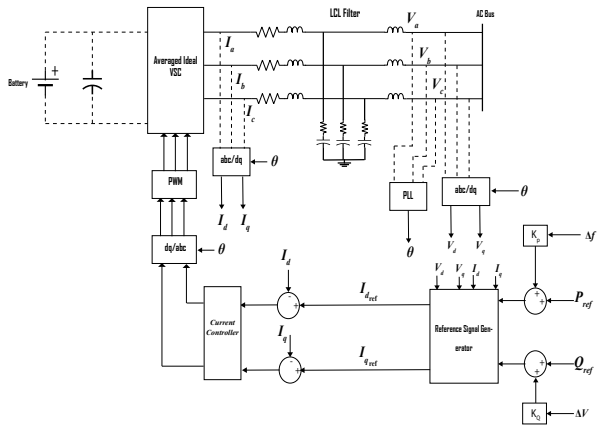


Fig. 2: BESS and WG VSC average model based on [24].

B. BESS Model

BESSs are widely used in microgrids to regulate the frequency of the microgrid, controlling fast changes in the output power of solar and wind generators [4]. These systems are interfaced through a Voltage Source Converter (VSC); therefore, the dynamics of the BESS are much faster than the diesel generator, thus rapidly supplying active power to maintain the frequency of the microgrid. A suitable model of a BESS based on an average model is presented in [24], which is used in this research work, and includes frequency-power and voltage-reactive power droops, as shown in Fig. 2. The LCL filter can be designed based on [25], and the controllers can be properly tuned based on, for example, the techniques proposed in [26], [27], to ensure stable operation over a wide range of operating points. The PLL is tuned to minimize impact of unbalancing and harmonically distorted voltages as proposed in [28], based on small signal analysis of the system obtained through modal estimation approaches for worst operating conditions of the system [29].

C. Wind Generator Model

Wind generators (WGs) are assumed to be Type 4, with full VSC interfaces, as discussed in [11] and [24]. The average model of the WG VSC described in [24] and used here, is similar to the converter of the BESS shown in Fig. 2.

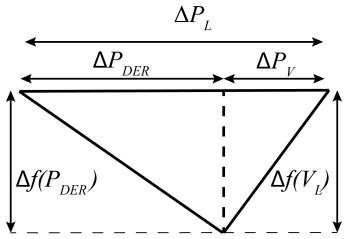


Fig. 3: Frequency deviation after load and generation changes.

D. Load model

An exponential model is used to model every single load in the system as follows [11]:

$$P_{L_l} = K_{LP_l} V_L{}^{\alpha_{pl}} \quad \forall l \tag{3}$$

$$Q_{L_l} = K_{LQ_l} V_L^{\alpha_{ql}} \quad \forall l \tag{4}$$

where V_L is the load voltage, K_{LP_l} and K_{LQ_l} are load scaling factors for load l, and the coefficients α_P and α_Q define the load type, with the values of the coefficients chosen here representing mixed load types. Constant impedance loads represent a significant portion of the loads within microgrids, as reported in [11], resulting in the load demand being sensitive to changes in the voltages, as per (3) and (4); hence, the load demand is affected by the operating voltage of the microgrid.

The voltage dependency of loads has a significant impact on the microgrid's frequency, thus directly affecting primary frequency control, as discussed in detail and utilized in [11]. This principle is used here in the design of the proposed controller, since, as shown in Fig. 3 based on [30], where the frequency deviations in a microgrid for changes in DER generation and load demand are illustrated. In this figure, ΔP_{DER} represents the change in the total generation of the microgrid, ΔP_L corresponds to the change in the system demand, and ΔP_V represents the change in the voltage-dependent loads. Thus, a deviation in the frequency of the system due to a demand change will force the governors of the diesel generators and the droop controls of the DERs to adjust their output power, while voltage-dependent loads will change with a reverse slope depending on the system voltage. For instance, a frequency drop in the system would result in increased generation from DERs, while a decrease in the DER voltage setpoints of the voltage regulators would decrease the demand of the voltage-dependent loads. Thus, with suitable DER voltage control, the microgrid frequency deviation after a disturbance can be minimized.

E. Primary Frequency Control

To effectively share the load demand among DERs using droop control, a suitable value of the droop constant must be selected [6], which can be defined as:

$$K_P = \frac{\Delta P_{DER}}{\Delta f} \ \frac{\text{pu}}{\text{Hz}} \tag{5}$$

Both diesel units and BESS are considered here to be responsible for regulating the frequency of the system. Thus, the droop control will modulate the output power of DERs as a

function of the frequency deviation, depending on the value of K_P.

Typical values of $\frac{1}{K_P}$ for synchronous generators are between 3% and 6%, as reported in [8]. Generally, the droop parameters of DERs in a microgrid are selected based on its rating, such that the DER with the highest rating would have a droop gain higher than those units with lower ratings, since these units may have more primary reserves and hence would be more capable of regulating the system's frequency; for these units, a small change in the frequency would result in a significant active power injection or reduction.

III. Proposed Droop and Voltage Control for Optimal Frequency Regulation

As previously discussed, both DER primary frequency control and voltage control in isolated microgrids play a significant role in frequency regulation. Since the droop parameters of DER primary frequency controllers significantly affect the system's frequency regulation, choosing suitable droop gains for the DER is important, with low values resulting in a poorly regulated system frequency, while high values could make some DERs unstable [8]. In addition, the operating voltage of the microgrid can significantly affect the load demand and thus, the frequency of the system.

A. Optimization Model

The best approach to overcome the aforementioned issues with primary control in isolated microgrids would be to formulate a control scheme that dynamically and optimally adjusts both the active power droop constant and the voltage setpoints of the DERs, as per Fig. 3, using an optimization approach to minimize the difference between generation and voltage-dependent loads. Therefore, a nonlinear optimization, discrete approach is proposed here, for a given time t, repeating it every Δt.

1) Objective Function: The main objective would be to minimize the power changes at t every Δt in generators and voltage-dependent loads as follows:

$$\min_{K_{DER},V} \Delta P_t = \sum_{i=1}^{N_{DG}} \Delta P_{DG_{i,t}} + \sum_{j=1}^{N_{BESS}} \Delta P_{BESS_{j,t}} - \sum_{l=1}^{N_L} K_{LP_l}(V_t^{\alpha_{pl}} - V_{t-1}^{\alpha_{pl}}) \quad (6)$$

where P_{DG} is the output power of the N_{DG} Diesel Generators (DGs); P_{BESS} is the output power of the N_{BESS} of the BESSs; $K_{DER} = (K_{DG}, K_{BESS})$ are the DER droop gains; and V is the DERs' voltage setpoints and load voltages, as the grid is neglected here as explained below, which should be constrained within limits, i.e., $\underline{V} \leq V \leq \overline{V}$.

2) Droop Constraints: The droop equations for diesel generators, BESSs, and their associated limits can be defined as follows:

$$K_{DG_{i,t}} = \beta_{DG_i} P_{DG_{i,t}} \quad \forall i \quad (7)$$

$$0 \leq K_{DG_{i,t}} \leq \overline{K_{DG_i}} \quad \forall i \quad (8)$$

$$K_{BESS_{j,t}} = \beta_{BESS_j} P_{BESS_{j,t}} \quad \forall j \quad (9)$$

$$0 \leq K_{BESS_{j,t}} \leq \overline{K_{BESS_j}} \quad \forall j \quad (10)$$

where β_{DG_i} and β_{BESS_j} are parameters chosen to have a linear relation between the maximum power of DERs and maximum values of droop constants, as proposed in [31].

3) Power Constraints: The output powers of DGs and BESSs are limited as follows:

$$P_{DG_{i,t}} = P_{DG_{io}+} \Delta P_{DG_{i,t}} \quad \forall i \quad (11)$$

$$\underline{P_{DG_i}} \leq P_{DG_{i,t}} \leq \overline{P_{DG_i}} \ \forall i \quad (12)$$

$$P_{BESS_{j,t}} = P_{BESS_{io}+} \Delta P_{BESS_{j,t}} \quad \forall j \quad (13)$$

$$\underline{P_{BESS_j}} \leq P_{BESS_{j,t}} \leq \overline{P_{BESS_j}} \ \forall j \quad (14)$$

And the power balance between generators and loads should be maintained, considering system loss changes, albeit small, as follows:

$$\sum_{i=1}^{N_{DG}} \Delta P_{DG_{i,t}} + \sum_{j=1}^{N_{BESS}} \Delta P_{BESS_{j,t}} \geq \sum_{l=1}^{N_L} K_{LP_l}(V_t^{\alpha_{pl}} - V_{t-1}^{\alpha_{pl}}) \quad (15)$$

4) BESS Constraints: The BESS SOC and its limits can be defined as [32]:

$$SOC_{j,t} = SOC_{j,t-1} + (P^C_{BESS_{j,t}} \ \eta_{C_j} - P^D_{BESS_{j,t}}/\eta_{D_j})\Delta t \quad \forall j \quad (16)(17)$$

$$P_{BESS_{j,t}} = P^C_{BESS_{j,t}} - P^D_{BESS_{j,t}} \quad \forall j \quad (18)$$

$$P^C_{BESS_{j,t}} P^D_{BESS_{j,t}} = 0 \quad \forall j \quad (19)$$

$$\underline{SOC_j} \leq SOC_{j,t} \leq \overline{SOC_j} \quad \forall j \quad (20)$$

where SOC is the BESS SOC; P^C_{BESS} and P^D_{BESS} are the BESS charge and discharge powers, respectively, with (19) reflecting the fact that the BESS cannot charge and discharge at the same time; and η_C and η_D are the charge and discharge efficiencies, respectively.

5) Discussion: Note that the full optimization problem (6)-(20) ignores power flow equations, since previous studies on isolated microgrids have demonstrated that the grid and its losses are not significant [33], [34]. A detailed justification for this assumption is shown in [33], where the authors show that the losses of a benchmark microgrid system are very small; thus, the system can be represented with a single bus. Similar optimization problems for time-domain simulations of large distribution networks that also ignore the power flow equations are presented in [21], [35]. Furthermore, note that even in large power systems, where transmission lines have a significant impact on the system, power flow equations are usually not considered for frequency regulation, control, studies, and applications [36].

This optimization problem is solved continuously in time t, every Δt, which may be defined to be fractions of a second, depending on the system and its frequency response, as illustrated in Section IV. The proposed model is a Nonlinear Programming Problem (NLP), which can be solved using standard NLP solvers, since the number of optimization variables for a typical microgrid is low, as demonstrated in Section IV.

A Microgrid Central Controller (MGCC) would perform the proposed optimization-based control scheme once the

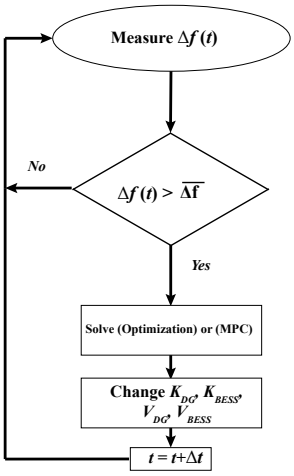


Fig. 4: Implementation of the proposed optimization controls.

frequency of the microgrid deviates by $\overline{\Delta f}$, which is the maximum acceptable frequency deviation. For example, in [37], $\overline{\Delta f}$ is set as low as 0.2 Hz for tripping distributed generators at medium voltage networks within 300 s, and as high as 3 Hz to trip distributed generators within 0.16 s; therefore, the lowest value of 0.2 Hz is used here to force the frequency deviations to be within an acceptable narrow range to avoid generator tripping. The MGCC will then update the droop parameters and the voltage setpoints of the DERs with the ones obtained from the proposed model every Δt, to enhance the performance of primary frequency controllers. The implementation of the proposed optimization is illustrated in Fig. 4. Observe that if the optimization problem fails to converge, the droop and voltage setpoints will remain fixed at their last value.

B. MPC Approach

An MPC version of (6)-(20) is proposed here to improve the optimal frequency control performance, considering the relation between active power deviation and frequency deviation of the microgrid, which can be modeled as a first-order transfer function as follows [9], [22], [36], [38]:

$$G(S) = \frac{Output}{Input} = \frac{\Delta f(S)}{\Delta P(S)} = \frac{1}{Ms + D} \tag{21}$$

where M and D correspond to the microgrid equivalent inertia and damping, estimated with appropriate system identification techniques from the frequency response of the system. The transfer function can then be discretized through a Z transform as follows:

$$Z\left(\mathcal{L}^{-1}\left(\frac{1}{Ms + D}\right)\right) = \frac{1}{D}\,\frac{1 - e^{\frac{-DT}{M}}}{z - e^{\frac{-DT}{M}}} \tag{22}$$

Hence, the predicted frequency deviation per unit power deviation in the time domain can be represented as follows:

$$\Delta f_{t+k+1} = \Delta f_{t+k} e^{\frac{-D\Delta t}{M}} + \frac{\Delta P_{t+k}}{D}\left(1 - e^{\frac{-D\Delta t}{M}}\right) \tag{23}$$

Therefore, the objective function (6) of the proposed optimization approach can be replaced by the following function:

$$\min_{K_{DER},V} \quad \sum_{k=0}^{N_P} |\Delta f_{t+k+1}| = \sum_{k=0}^{N_P} |\Delta f_{t+k} e^{\frac{-D\Delta t}{M}} + \frac{\Delta P_{t+k}}{D}(1 - e^{\frac{-D\Delta t}{M}})| \tag{24}$$

where Δf_{t+k+1} is the predicted frequency deviation of the microgrid, and

$$\Delta P_{t+k} = \sum_{i=1}^{N_{DG}} \Delta P_{DG_{i,t+k}} + \sum_{j=1}^{N_{BESS}} \Delta P_{BESS_{j,t+k}} - \sum_{l=1}^{N_L} K_{LP_l}(V_{t+k}^{\alpha_{pl}} - V_{t+k-1}^{\alpha_{pl}}) \tag{25}$$

with constraints (7)-(20) for each MPC iteration k.

The MPC problem is solved at each control interval k at time t for N_P samples into the future, and defines the droop gains K_{DER} and the voltage setpoints V for only the first control sample. The parameter N_P defines the prediction horizon and should be selected carefully to keep the computational burden reasonable, so that the proposed approach can be applied online, as discussed in the next section. This procedure is implemented as illustrated in Fig. 4.

C. Discussion

The proposed control techniques solve optimization problems with the objective of minimizing the power balance of the system and thus recover the nominal frequency by adjusting the droop gains and the voltage setpoints, hence fulfilling the typically integrated role of frequency regulation controls in microgrids. Note that the proposed frequency controllers do not interact with the microgrid's secondary controls associated with the Energy Management System (EMS), which optimally defines the DER setpoints in longer time frames (e.g., every 5 minutes), as is typically the case in microgrids [4], given the significantly different time frames of the proposed controllers (seconds) and the EMS (minutes). Tertiary control is not applicable here, since being an isolated system, secondary control is the highest control level, as per [4]. Furthermore, the objective of the proposed controllers is to ensure an optimal compromise between load sharing and frequency regulation, which cannot be achieved by a traditional droop frequency control approach, since increasing the droop gain of a specific DER increases its frequency regulation, resulting in less load sharing with the rest of the DERs. On the other hand, the proposed optimization-based techniques allow an optimal trade off between frequency regulation and load sharing.

IV. Case Studies and Results

The proposed optimization-based control schemes using the mathematical model described in Section III-A, referred here as OPT, and its MPC variation explained in Section III-B are tested, validated, and compared here based on a modified version of the CIGRE benchmark microgrid used in several

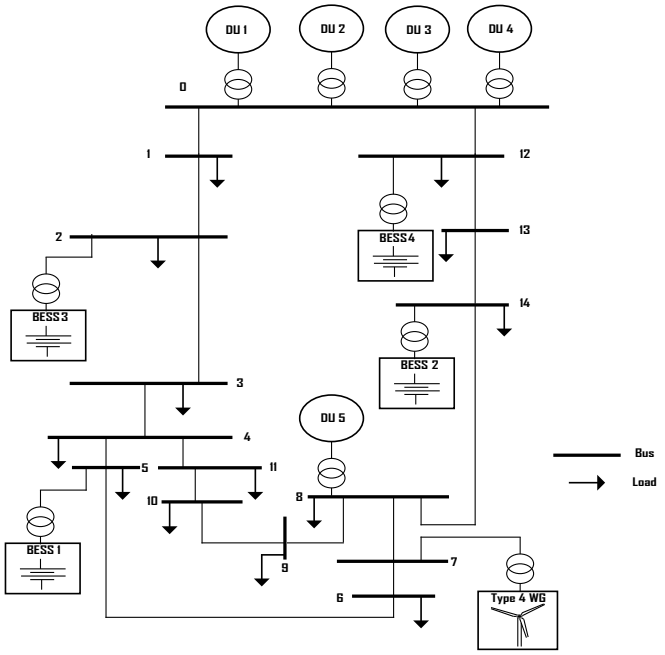


Fig. 5: Modified CIGRE benchmark test microgrid [11].

studies [11], [24], [33], [39]. The topology of the microgrid is shown in Fig. 5, which has been implemented for time-domain simulations in PSCAD, using MATLAB to solve both OPT and MPC models. To test the presented approaches using a large number of DERs for typical microgrid, the test system is modified to include: 5 Diesel Units (DUs), with DUs 1-4 having a total rating of 5.5 MVA, and DU 5 being rated at 2.25 MVA to be used for frequency disturbances; one aggregated Type 4 WG rated at 4 MW; four BESSs rated at 2.2 MVA combined; and a total load of 9.55 MVA. The composition of the loads is assumed to be a realistic combination, for microgrids, of 10% constant power, 30% constant current, and 60% constant impedance, with the same unbalancing as in [12]. For these operating conditions, the losses are determined to be only 1% of the total power generated, thus confirming the small impact of the grid in typical microgrids.

The DUs and BESSs are responsible for regulating the frequency of the microgrid and providing primary frequency and voltage control, while the aggregated WG is operated in unity power factor mode [11], [12]. The WG output power variation and its impact on the system frequency are illustrated in Fig. 6, considering that WGs do not regulate frequency through deloading or virtual inertia techniques, as such controls techniques are not common in microgrids [4], thus presenting a more challenging condition for frequency regulation and control; the generation profile of the wind turbines is based on actual data from [11]. The initial droop gains of the primary frequency controllers of the DUs and BESSs are selected to ensure that the frequency of the microgrid does not deviate beyond $\overline{\Delta f} = 0.2$ Hz for the base system, due to the variability of the output power of the wind turbines, as observed in Fig. 6.

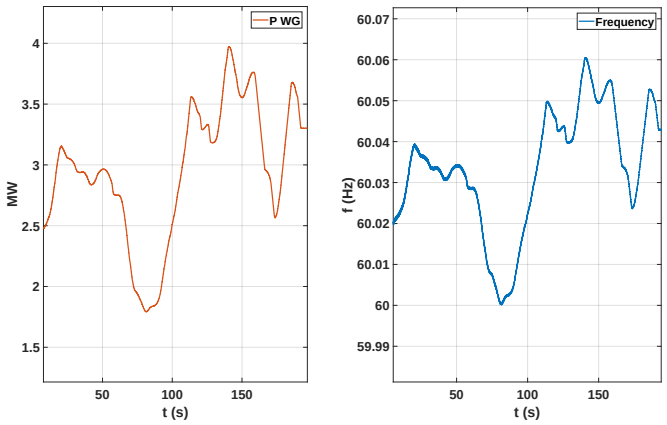


Fig. 6: WG power variations and frequency of the test microgrid for the base case.

A. Validation and Comparisons

The proposed control OPT and MPC schemes are compared here with respect to the VFC controller presented in [11], for a sudden trips of BESS 2-4, which is a manageable contingency from the frequency stability point of view, and for a trip of DU 5. The contingencies occur at $t = 80$ s, which is the worst possible frequency stability scenario, since the reserves of the system are at its lowest at this time. Thus, in Fig. 4, the sample time is defined as $\Delta t = 0.5$ s, with an acceptable maximum frequency deviation range of $\overline{\Delta f} = 0.2$ Hz, as previously explained, so that the proposed control schemes are activated when the frequency of the microgrid is below 59.8 Hz, and continues until the frequency of the system stabilizes within ± 0.2 Hz.

In this scenario, the disconnection of DU 5 results in a reduction of the estimated values of M from 1.96 to 0.78 s^2, and for D from 36 to 30.21 s, using the Steiglitz-McBride system identification technique [24]; all BESSs are fully charged in this case. The choice of the prediction horizon for the MPC approach depends on the dynamics of the system; hence, a low value of $N_P = 2$ should be sufficient to obtain optimal results due to the fast dynamics of the microgrid, thus minimizing computation times. This simulation allows evaluating the effect of the proposed control scheme on the frequency of the system during disturbances.

Fig. 7 shows the microgrid frequency response for the trips of BESS 2-4. Observe that the fixed droop control is able to regulate the frequency, albeit slowly and remaining below its nominal value, as an integral frequency controller was not implemented in this case to highlight the fact that the proposed methods do not need such a controller to recover the nominal frequency. On the other hand, both proposed techniques quickly recover the frequency to its nominal value, without the need for additional integral control.

The simulation results for the DU 5 trip are shown in Fig. 8. Observe that the frequency of the system with fixed droops is unstable after the generator trip, which results in a system blackout [37]; on the other hand, with the proposed optimization approaches, the frequency recovers quickly to the

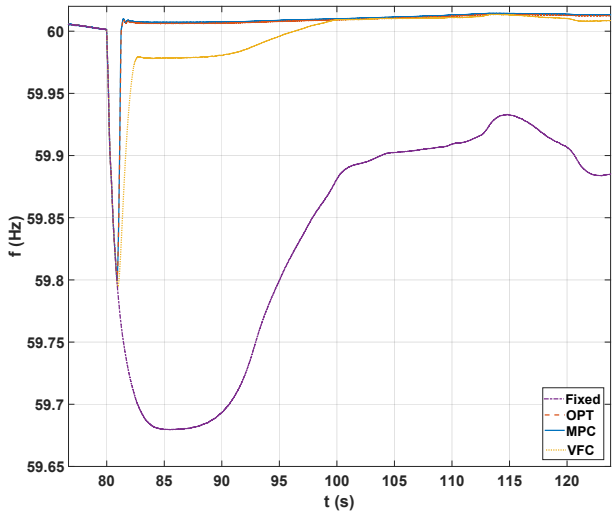


Fig. 7: Microgrid frequency for various control schemes for BESS 2-4 trips.

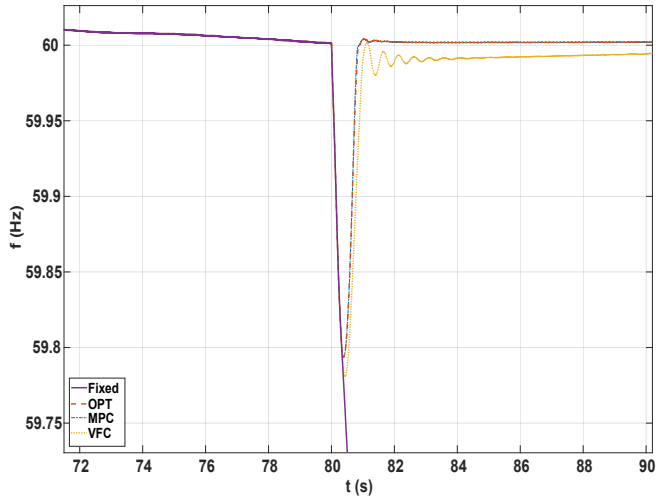


Fig. 8: Microgrid frequency for various control schemes for a DU 5 trip.

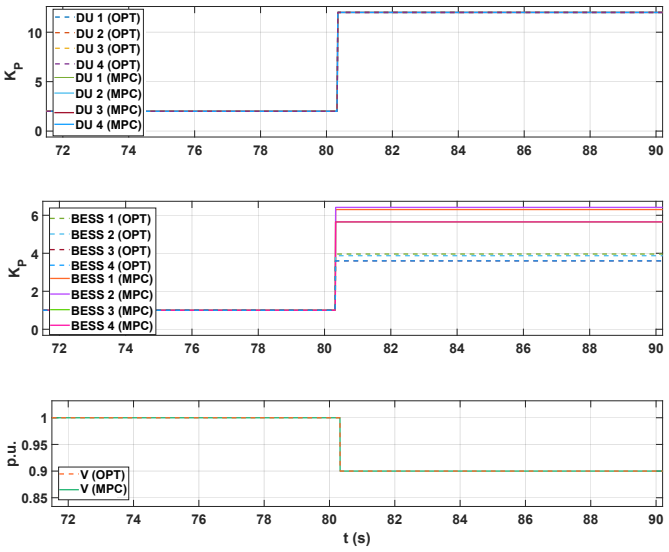


Fig. 9: Droop gains from the proposed methods for a DU 5 trip.

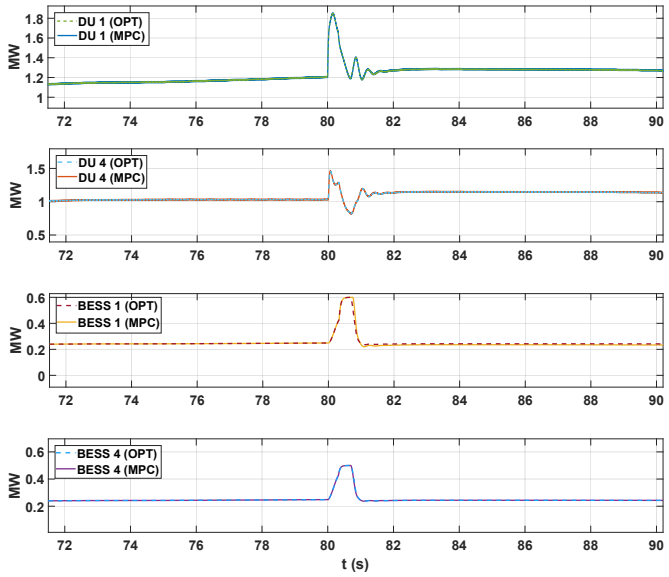


Fig. 10: Active power outputs of DERs for a DU 5 trip. The smaller droop gains of the BESSs with respect to the DUs, due to their smaller ratings, limit their response to frequency variations.

required range. Furthermore, note that both OPT and MPC approaches recover to the same frequency, showing better frequency recovery than the VFC technique proposed in [11].

The droop gains and voltage setpoints obtained from the optimization are shown in Fig. 9. Observe that the proposed optimization approach dynamically adjusts the droop gains and the voltage setpoints of the DERs to stabilize the frequency of the system. Fig. 10 depicts the DERs' active output powers during the optimization period. Fig. 11 illustrates the voltages at two of the farthest load buses in the test microgrid, showing the little impact of the grid, as the load voltages follow closely the reference voltage set point from the controller and are practically the same, despite the significant voltage variations allowed in this case.

B. Sensitivity Analysis of Optimization Parameter

The following parameters need to be carefully selected to obtain adequate results: the sample time, i.e., Δt; the maximum limit of the DER droop gains; and the limits of the voltage setpoints. For the results depicted in Figs. 7 to 11, the optimization problem is solved every $\Delta t = 0.5$ s. The maximum limits of the droop gains were determined through small-signal stability of the system, by increasing the droop gains until the maximum droop gain is found for the worst operating condition with the system remaining stable, thus resulting in $\overline{K_{DU}} = 12$, and $\overline{K_{BESS}} = 8$ for all DUs and BESSs, respectively.

To investigate the impact of the sample time and the voltage limits on the proposed control techniques, trips for DU 5 and BESS 4 at $t = 80$ s and $t = 80.4$ s, respectively, are simulated.

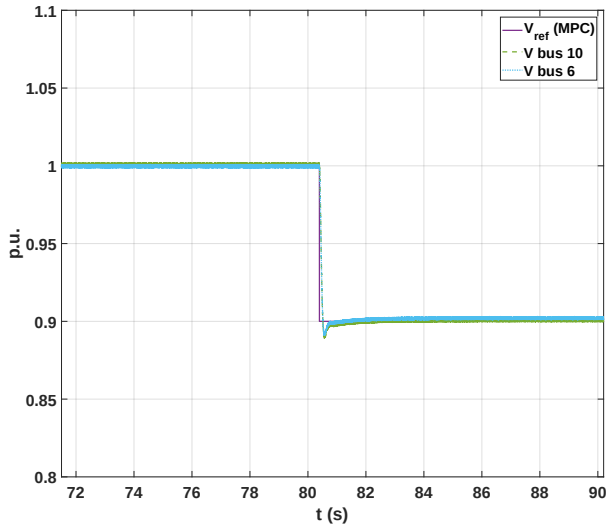


Fig. 11: DER voltage setpoints and voltages at two of the farthest load buses.

TABLE I: Microgrid frequency for different Δt and N_P values for DU 5 and BESS 4 trips.

Control	f [Hz]	Δt				
		1 s	0.5 s	0.2 s	0.015 s	0.015 s $N_P = 5$
MPC	59.79	80.46 s	80.46 s	80.46 s	80.46 s	80.46 s
	60	80.96 s	80.93 s	80.93 s	80.92 s	80.92 s
OPT	59.79	80.46 s	80.46 s	80.46 s	Unstable	–
	60	81 s	80.93 s	80.93 s	Unstable	

The sample time Δt needs to be selected carefully, because if OPT is solved too often, the rapid changes in the droop gains and the voltage setpoints, especially for DUs, would cause the system to become unstable, as illustrated in Table I. On the other hand, the MPC method is not significantly affected by faster sample times, as shown in Table I, due to the fact that this technique estimates the frequency response of the system and reacts accordingly. Furthermore, observe that the faster the sample time, the faster frequency recovers; however, the computational burden is an issue in this case, since if the sample time is too short, the model will not be solvable online. Also, increasing the prediction horizon N_P does not result in a noticeable improvement in the frequency response of the system, mainly due to the fast dynamics of the system associated with the diesel generator trip, which resulted in a significant decrease in the equivalent values of M and D, as mentioned earlier.

In the previous studies, the limits on the DER voltage setpoints are 0.9 and 1.1. Simulation results for more restrictive voltage limits are shown in Fig. 12, observing that the microgrid frequency recovery decreases as the limits become more restrictive, as expected; however, the proposed control technique is robust against restrictive voltage limits. Note that the proposed MPC performs better than the VFC as the voltage setpoints limit decreases.

The proposed approaches are compared with previously presented MPC and optimal techniques for frequency regulation

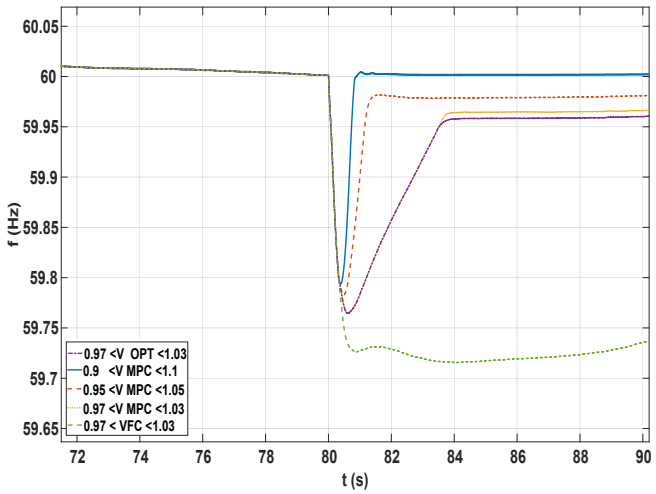


Fig. 12: Microgrid frequency for different limits on DER voltage setpoints for a DU 5 trip and $\Delta t = 0.5$ s.

TABLE II: Computational performance comparison

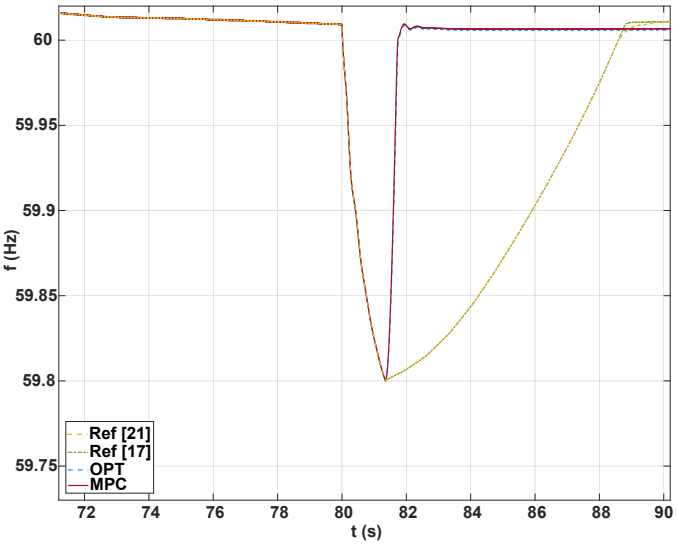
Technique	MPC	OPT	Ref [17]	Ref [21]
CPU Time (ms)	11	8	5	4

described in [17] and [21], respectively, for the first (BESS 2-4 trips) and second (DU 5 trip) contingencies. The obtained results are illustrated in Fig. 13, where it can be observed that for the first contingency in Fig. 13a, the dynamic response of the proposed techniques is better than the one obtained with the methods described in [17] and [21], whereas for the second contingency in Fig. 13b, the system becomes unstable with the existing techniques. The computational performance of the techniques is illustrated and compared in Table II, where it can be observed that even though the proposed techniques are slower compared to existing ones, the computational cost is such that their application to real-time frequency regulation is feasible, as per [40].

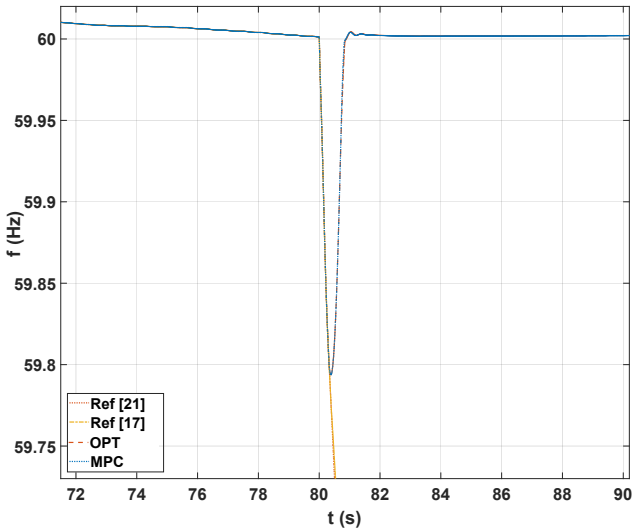
It is important to highlight the fact that the OPT and MPC models are non-convex, nonlinear mathematical models, i.e., Nonlinear Programming (NLP) problems. However, the constraints are at most quadratic, and hence do not present a significant challenge for existing NLP solvers, especially considering the reasonable size of the problem. Thus, for example, for the complex CIGRE benchmark microgrid system used here, which includes a significant number of DERs, both OPT and MPC models can be solved in less than 0.02 seconds at most, using the CONOPT solver in MATLAB for all cases.

C. Severe Disturbance

The proposed controls are tested here for an even larger disturbance in the system; thus, DU 5 and BESS 2-4 are tripped at $t = 80$ s. The results are shown in Fig. 14, where it can be observed that the proposed control schemes OPT and MPC successfully maintain the frequency stable and within the 0.2 Hz steady-state limit compared to the system without controls, which is unstable, and to the VFC. Note also that



(a) BESS 2-4 Disturbance



(b) DU 5 Disturbance

Fig. 13: Comparison with respect to existing techniques.

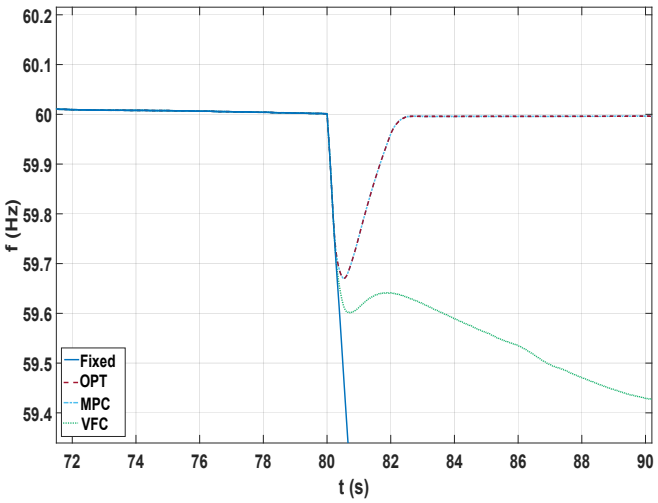


Fig. 14: Microgrid frequency for DU 5 and BESS 2-4 trips and $\Delta t = 0.5$ s.

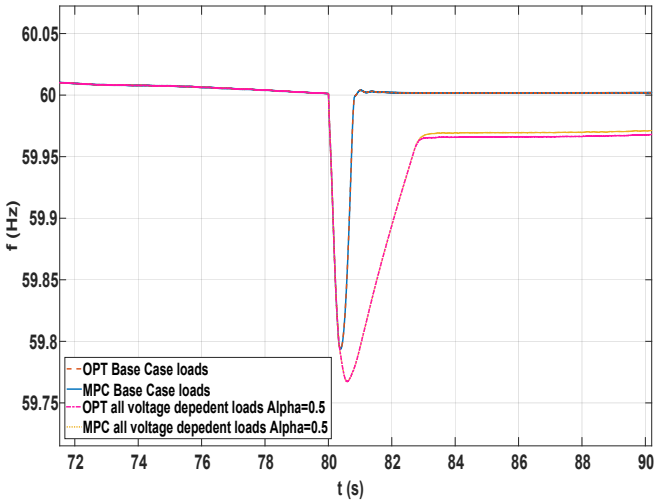


Fig. 15: Impact of uncertainty on the load parameters for the proposed control techniques for a DU 5 trip.

proposed control techniques show better frequency recovery compared to the VFC, with the latter exceeding the frequency range limits of 0.2 Hz, which could trigger DU protections as per [37]. The instability of the frequency for the fixed control in Figs. 8 and 14 can be associated with a system eigenvalue crossing onto the right-half plane due to the severe disturbance.

D. Parameter Uncertainty

The impact of uncertainty of the load parameters, as well as the estimated system's M and D values, are studied in this section to test the robustness of the proposed techniques. Thus, note that the significant reduction on the M and D values due to the DU 5 trip does not have a noticeable impact on the proposed MPC technique, as seen in Fig. 8; hence, the MPC is shown to be not very sensitive to variations in the dynamics of the system due to disturbances. Furthermore, Fig. 15 depicts the results of assuming load exponents $\alpha = 0.5$ for all voltage dependent loads, which are significantly different from the α values used in the previous simulations, thus introducing a significant error in the estimated load model used in the proposed control approach. Observe that the frequency still recovers to a reasonable value within the allowable range, demonstrating that both OPT and MPC approaches are robust against uncertainties in the load models.

E. Impact of Communication Delay

The impact of communication delay on the performance of the proposed controllers is studied in this section. Thus, a time delay transfer function $G_d(s) = e^{-s\tau}$, where τ is the time delay, is added between the proposed optimal controls' outputs and the corresponding system setpoints. The following time delays were then studied: 100 ms, 250 ms, 500 ms, which are typical time delays used in [41], for which instabilities

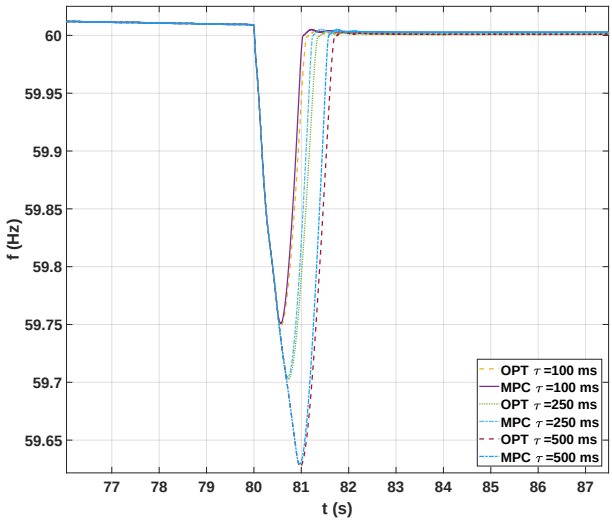


Fig. 16: Impact of communication delays on the proposed controllers.

were observed. The simulation results are shown in Fig. 16, where it can be observed that longer time delays result in lower frequency nadirs. However, in all cases, the system frequency properly recovers, thus demonstrating the robustness of the proposed controllers against time delays.

V. Conclusions

Adaptive optimization-based frequency controllers through droop and voltage control for isolated microgrids have been developed and discussed here, to improve the frequency response of the microgrid and enhance the system's stability and robustness against severe disturbances. The proposed control scheme has been designed to optimally and dynamically change active power droop gains and voltage setpoints of DERs, adjusting their values based on an optimization approach that takes into account several factors, such as generation-demand balance, BESS SOC, and the voltage sensitivity of the microgrid loads. The proposed approaches were tested on a benchmark microgrid with multiple DERs, showing that both maintain the frequency stability of the system during severe disturbances, even in the presence of uncertainties and communication delays, performing better than the state-of-art VFC. Overall, the MPC technique performed slightly better compared to the OPT method, being more appropriate if faster sample times are required.

The main factors that could adversely affect the performance of the proposed techniques are the droop gain and voltage setpoint limits of DERs, which should be carefully selected to avoid large system voltage variations. The sample time should also be appropriately chosen so that the proposed models are not solved too often, while still properly regulating frequency; furthermore, since the developed control methods would be implemented in an MGCC with an existing microgrid communication infrastructure, communication delays should be taken into consideration when defining the sample time.

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