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# Real-Time Optimization-Based Reactive Power Control Strategy for the Lanzarote-Fuerteventura Power System: A Comparative Analysis

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**Abstract.** This paper introduces a centralized reactive power management strategy for the real-time (RT) operation of power systems. The proposed approach reformulates the Optimal Power Flow (OPF) problem to minimize system losses and redispatch costs while ensuring compliance with technical constraints. These include node voltage limits, line capacity, and operational limits of generating units. The strategy has been developed to integrate with the current operation of power systems, which typically relies on market mechanisms or Energy Management Systems (EMS). These solutions calculate the setpoints for dispatchable generation based on day-ahead forecasts, without actively managing reactive power and thus operating in a suboptimal point. To address this, the proposed approach enables continuous, real-time adjustment of plant setpoints within the defined optimization interval, leveraging more accurate forecasts. This aspect becomes increasingly crucial with the growth of renewable energy sources (RES). The method is tested in a real-time hardware-in-the-loop (HIL) simulation environment, evaluating its performance over varying optimization intervals (5, 15, 30, and 60 minutes) for the Lanzarote-Fuerteventura power system. Results from a two-hour real-time experimental simulation demonstrate that the proposed strategy reduces power losses compared to the current power system operation approach, with further reductions as the optimization interval decreases.

**Key words.** Reactive power management, voltage control, optimal control, real-time systems, hardware-in-the loop simulation.

## Nomenclature

*A. Sets*

$\Omega^N$ Set of nodes in the system
$\Omega^{DIS}$ Subset of nodes with dispatchable generation
$\Omega^{REN}$ Subset of nodes with renewable generation

*B. Parameters*

$C_i^{DIS,UP}$ Power increase cost coefficient for dispatchable power plant at node $i$, $\forall i \in \Omega^{DIS}$ [p.u.]
$I_{ik}^{MAX}$ Upper limit of the current in line connecting nodes $(i, k)$, $\forall i, k \in \Omega^N$ [p.u.]
$P_i^{DIS,MAX}/P_i^{DIS,MIN}$ Active power maximum/minimum limit for dispatchable power plant at node $i$, $\forall i \in \Omega^{DIS}$ [p.u.]
$P_i^{DIS,SCH}$ Active power scheduled by an external energy management system or market-clearing mechanism for dispatchable power plant at node $i$, $\forall i \in \Omega^{DIS}$ [p.u.]
$P_i^{LOAD}, Q_i^{LOAD}$ Forecasted active and reactive load at node $i$, $\forall i \in \Omega^N$ [p.u.]
$P_i^{LOAD,REAL}, Q_i^{LOAD,REAL}$ Real active and reactive load profiles at node $i$, $\forall i \in \Omega^N$ [p.u.]
$P_i^{REN}$ Forecasted available renewable energy resource at node $i$, $\forall i \in \Omega^{REN}$ [p.u.]
$P_i^{REN,REAL}$ Real renewable energy resource at node $i$, $\forall i \in \Omega^{REN}$ [p.u.]
$Q_i^{G,MAX}/Q_i^{G,MIN}$ Reactive power maximum/minimum limit for power plant at node $i$, $\forall i \in \Omega^{DIS} \cup \Omega^{REN}$ [p.u.]
$T_{opt}$ Optimization interval [min]
$V_i^{MAX}, V_i^{MIN}$ Maximum and minimum voltage limits at node $i$, $\forall i \in \Omega^N$ [p.u.]
$Y_{ik}, \varphi_{ik}$ Magnitude and angle of element $(i, k)$ of the admittance matrix, $\forall i, k \in \Omega^N$ [p.u., rad]

*C. Variables*

$i_{ik}$ Current in line connecting nodes $(i, k)$, $\forall i, k \in \Omega^N$ [p.u.]
$p_i^{DIS,SP}$ Updated active power setpoint from redispatch for dispatchable power plant at node $i$, $\forall i \in \Omega^{DIS}$ [p.u.]
$p^{LOSS}$ Active power losses in the system [p.u.]
$q_i$ Reactive power setpoint at node $i$, $\forall i \in \Omega^N$ [p.u.]
$v_i$ Voltage magnitude setpoint at node $i$, $\forall i \in \Omega^N$ [p.u.]
$\Delta p_i^{DIS,UP}, \Delta p_i^{DIS,DOWN}$ Active power increase/decrease in dispatchable power plant setpoint at node $i$, $\forall i \in \Omega^{DIS}$ [p.u.]
$\theta_i$ Voltage phase angle at node $i$, $\forall i \in \Omega^N$ [p.u.]

## 1. Introduction

Reactive power control plays a crucial role in ensuring the safe and efficient operation of power systems [1]. As modern grids become increasingly interconnected and extensively monitored [2], centralized control strategies offer advantages over decentralized approaches, which rely solely on local measurements [3], [4].

The growing integration of renewable energy sources (RES)—characterized by their inherent intermittency, variability, and distributed nature—has intensified the need for advanced reactive power management strategies [5]-[7]. In response, various optimization-based methods [8], [9], such as those based on an Optimal Power Flow (OPF) formulation [10], have been extensively explored in the technical literature to address the challenges posed by modern power systems.

However, a critical limitation of many proposed approaches is the lack of thorough validation under realistic operating conditions. To bridge this gap, real-time (RT) simulation, co-simulation, and hardware-in-the-loop (HIL) methodologies [11]-[14] have emerged as essential tools for evaluating the practical feasibility of these control schemes.

In this context, the objective of this paper is twofold: 1) it presents an optimization-based real-time reactive power management strategy; and 2) it evaluates its implementation in the Lanzarote-Fuerteventura power system using a real-time hardware-in-the-loop simulation environment: the Real-Time Optimization Laboratory (RTOLab). The proposed strategy aims to minimize power losses and redispatch costs while ensuring compliance with the system's technical constraints.

The developed framework enables the validation of its execution on real hardware as well as the strategy's behavior in a real-time system model. By accounting for deviations between the predictions considered for the optimization and the real system operating conditions, the framework provides a comprehensive evaluation of the effectiveness of the proposed strategy.

## 2. Methodology

The reactive power control approach proposed in this work is designed considering that the setpoints for dispatchable power plants, $P_i^{DIS,SCH}$, are predetermined. This typically occurs in the actual operation of power systems, in which the generation scheduling is performed either as a result of market clearing mechanisms or as an outcome of a centralized energy management system (EMS), such as unit commitment (UC) algorithms.

The proposed reactive power management strategy is based on an optimization algorithm that is executed periodically in real time, according to a defined optimization interval ($T_{opt}$). For each optimization interval, the predetermined setpoints for dispatchable generation ($P_i^{DIS,SCH}$), as well as the available forecasts for renewable generation ($P_i^{REN}$), and load, ($P_i^{LOAD}$, $Q_i^{LOAD}$)—along with the optimization model parameters—are loaded as inputs. The optimization problem is then solved, which results in the determination of the values of all the defined variables. Therefore, as outputs of the real-time reactive power control strategy, the voltage setpoints ($v_i$) or reactive power setpoints ($q_i$) at the generator nodes (depending on the control type) are determined and transmitted to the power plants.

In this way, the real-time strategy continuously dispatches voltage and reactive power setpoints to the plants, ensuring that the objectives and constraints defined in the optimization formulation are met.

*A. Optimization Problem*

The proposed centralized reactive power management strategy is based on the following Nonlinear Programming (NLP) optimization problem:

$$min\, f\left(\Delta p_i^{DIS,UP}, p^{LOSS}\right) = \sum_{i\in\Omega^{DIS}} C_i^{DIS,UP} \Delta p_i^{DIS,UP} + p^{LOSS} \quad (1)$$

where:

$$p^{LOSS} = \sum_{i\in\Omega^N}\left(p_i^{DIS,SP} + P_i^{REN} - P_i^{LOAD}\right) \quad (2)$$

subject to:

$$p_i^{DIS,SP} + P_i^{REN} - P_i^{LOAD} = v_i \sum_{k\in\Omega^N} Y_{ik} v_k\, cos(\theta_i - \theta_k - \varphi_{ik}), \forall i \in \Omega^N \quad (3)$$

$$q_i - Q_i^{LOAD} = v_i \sum_{k\in\Omega^N} Y_{ik} v_k\, sin(\theta_i - \theta_k - \varphi_{ik}), \forall i \in \Omega^N \quad (4)$$

$$p_i^{DIS,SP} = P_i^{DIS,SCH} + \Delta p_i^{DIS,UP} - \Delta p_i^{DIS,DOWN}, \forall i \in \Omega^{DIS} \quad (5)$$

$$P_i^{DIS,MIN} \le p_i^{DIS,SP} \le P_i^{DIS,MAX}, \forall i \in \Omega^{DIS} \quad (6)$$

$$Q_i^{G,MIN} \le q_i \le Q_i^{G,MAX}, \forall i \in \Omega^{DIS} \cup \Omega^{REN} \quad (7)$$

$$V_i^{MIN} \le v_i \le V_i^{MAX}, \forall i \in \Omega^N \quad (8)$$

$$i_{ik}^2 = Y_{ik}^2 (v_i \cos\theta_i - v_k \cos\theta_k)^2 + Y_{ik}^2 (v_i \sin\theta_i - v_k \sin\theta_k)^2, \ \forall (i,k) \in \Omega^N \quad (9)$$

$$0 \le i_{ik} \le I_{ik}^{MAX}, \forall (i,k) \in \Omega^N \quad (10)$$

$$-\pi \le \theta_i \le \pi, \forall i \in \Omega^N \quad (11)$$

$$\theta_{Reference\ Bus} = 0 \quad (12)$$

The optimization problem formulated in this paper is based on a variant of the Optimal Power Flow algorithm. The objective function (1) minimizes system losses, as defined in (2), while simultaneously minimizing the active power redispatch cost for the dispatchable units. Since the transmission model of the power system is typically not considered in the dispatch performed by market mechanisms or UC algorithms, system losses are generally not accounted for. Therefore, active power redispatch is required to satisfy the power balance of the system.

Constraints (3) and (4) represent the active and reactive power balances of the system according to the power flow formulation. This approach considers the transmission power system model through the admittance matrix. Constraint (5) determines the updated setpoints for dispatchable power plants as a result of the required active power redispatch, while constraint (6) limits the active power output of these units. Constraint (7) imposes limits on the reactive power output of all power plants in the system, while constraint (8) restricts the voltage at the system nodes. Constraints (9) and (10) account for the transmission line capacity limits. Finally, constraint (11) limits the voltage angles, while constraint (12) defines the slack node of the system.

### *B. Real-Time Hardware-in-the-Loop Simulation Environment for Testing Centralized Optimization Control Strategies*

The experimental framework used to validate the implementation of the centralized real-time reactive power control strategy is the RTOLab, developed at the Electrical Engineering Department of Universidad Carlos III de Madrid. As shown in Fig. 1, this setup consists of the following hardware components: an industrial computer (IC), a programmable logic controller (PLC), a real-time digital simulator (RTDS), and a personal computer (PC).

The RTOLab architecture is organized in three levels, which aim to emulate the real-time operation of power systems, allowing the validation of the control strategy under test and its performance in real controllers:

1) Level I is hosted on the industrial computer, where the optimization-based strategy (Section *2.A*) is executed in real-time. The real-time algorithm is implemented in Python, using the Pyomo optimization modeling language. After the setpoints are calculated for each optimization interval, they are transmitted to the next level via the Modbus communication protocol.
2) Level II is implemented on the PLC and is responsible for adjusting and distributing the setpoints to the local controllers of the power plants in the system running in the RTDS. Communication is also carried out using the Modbus protocol.
3) Level III consists of the RTDS and the PC. The power system is modeled in the RTDS using the RSCAD modeling interface, integrating grid models, load models, and generation asset models, along with their low-level control interfaces. The power system runs in real-time, and the setpoints are received by the controls of the power plants, which perform the necessary actions for the dynamic operation of the system.
   The load and renewable generation profiles evolve dynamically following the real measured profiles obtained from the system operator's (SO) information system. The PC is used to feed the model with these profiles via the Modbus protocol.
   The values of the system's real-time variables are recorded by the PC, which also acts as a data logger, using the UDP protocol. In addition, the RTDS presents a human machine interface (HMI) for real-time monitoring.

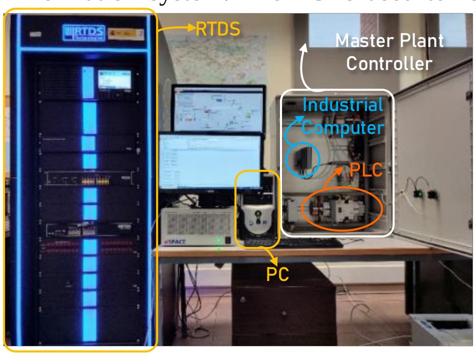


Fig. 1. RTOLab experimental setup

### *C. Implementation of the Strategy in the RTOLab Environment*

Fig. 2 illustrates the implementation of the optimization strategy in the RTOLab environment. The optimizer at Level I receives the external market/UC setpoints, $P_i^{DIS,SCH}$, which are updated hourly. Additionally, it receives forecasts for renewable generation and load ($P_i^{REN}$, $P_i^{LOAD}$, $Q_i^{LOAD}$), which, in contrast, are updated at each optimization interval, $T_{opt}$, to incorporate the most recent predictions. Using these inputs, along with the necessary parameters, the optimization problem is solved at each interval with the Interior Point Optimizer (IPOPT) software library. Consequently, the optimal voltage setpoints, $v_i$, for synchronous generators, and the optimal

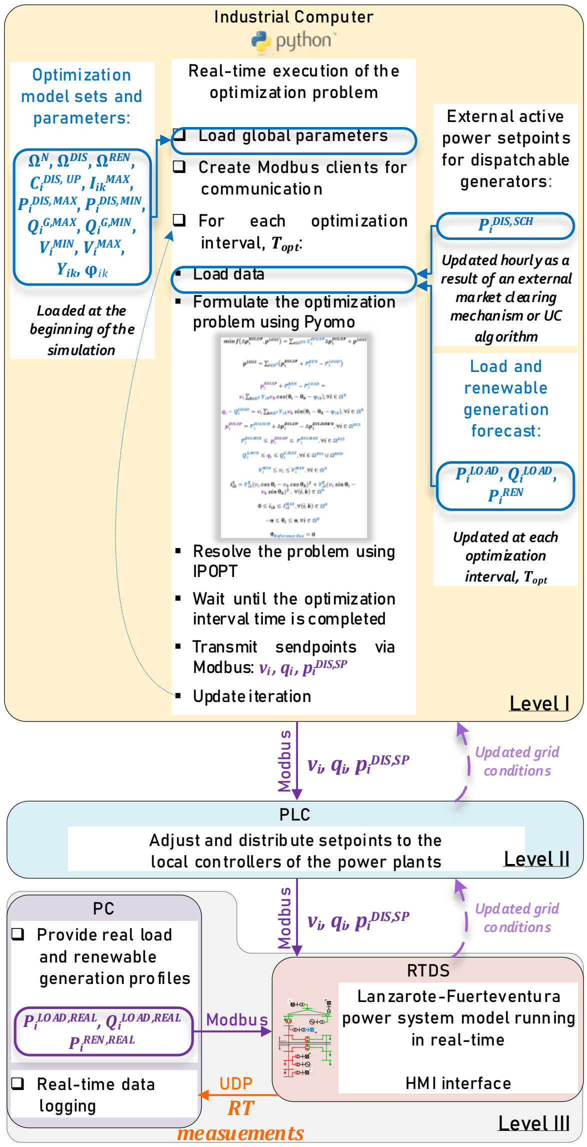


Fig. 2. Implementation of the real-time optimization-based reactive power control strategy in the RTOLab environment

reactive power setpoints, $q_i$, for the remaining power plants, are transmitted. Additionally, dispatchable plants also receive the updated active power setpoints, $p_i^{DIS,SP}$, resulting from the redispatch process at each optimization interval.

## 3. Case Study

*A. Power System Under Analysis: Lanzarote-Fuerteventura Isolated Power Grid*

The optimal real-time reactive power control strategy proposed in this work has been implemented in the RTOLab for the Lanzarote-Fuerteventura power system, located in the Canary Islands (Spain). The single line diagram of this system is shown in Fig. 3. This isolated system includes a thermal power plant on each island, $SG_L$ and $SG_F$, respectively, along with distributed renewable generation. In the implementation presented in this work, renewable generation is represented in an aggregated form, with $WPP_L$ and $WPP_F$ denoting wind power generation, and $PV_L$ and $PV_F$ representing photovoltaic generation. Additionally, although not part of the real system, a 40 MWh battery has been included at Bus 20 to enhance the system flexibility and facilitate the study of management strategies. The rated power values of the power plants are summarized in Table I.

According to Section 2.*B*, this system has been modeled in Level III of the RTOLab using electromagnetic transient (EMT) models within the RSCAD interface. For thermal generation, the models include 6th-order synchronous generator models with their corresponding turbine-governor and excitation systems. Additionally, $SG_L$ includes a

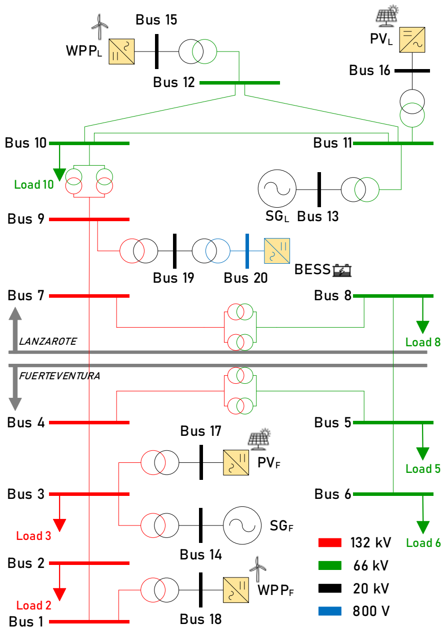

Fig. 3. Lanzarote-Fuerteventura power grid

Table I. - Rated Power of Power Plants in the Lanzarote-Fuerteventura Power System

| Power Plant | $SG_L$ | $SG_F$ | $WPP_L$ | $PV_L$ | $WPP_F$ | $PV_F$ | BESS |
|---|---|---|---|---|---|---|---|
| Rated Power (MW) | 204.82 | 159.27 | 32.63 | 7.01 | 66.03 | 17.85 | 30.00 |

secondary control loop to maintain the system frequency at its reference value and to account for deviations between generation and demand. Power-electronics-based generation is modeled using average-value voltage source converter (VSC) models, which enable the implementation of different controls. In the present study, active and reactive power control (P/Q control) is employed. Dynamic load models are used for load nodes, and a lithium battery model represents the energy storage system.

The power grid model is based on the 2026 planning horizon, which includes two submarine interconnections (66 kV and 132 kV cables) and a 132 kV double circuit corridor. These additions aim to enhance transmission capacity and facilitate the integration of the expected near-term growth in renewable energy generation.

*B. Experimental Case Studies*

In order to evaluate the feasibility and effectiveness of the strategy presented in this paper, two-hour real-time experimental case studies were conducted under different operating conditions. A total of five cases were evaluated, comparing a base case with four scenarios using the proposed strategy, in which the optimization interval, $T_{opt}$, varies:

1) *Base case.* This scenario aims to represent the actual power system operation, in which power plants adhere to predetermined voltage/reactive power setpoints. Specifically, synchronous generation is assigned a voltage setpoint of 1.02 p.u., while converter-based plants are set to operate at unit power factor (zero reactive power). Dispatchable units, including thermal units and the battery, receive the market/UC active power setpoints directly, $P_i^{DIS,SCH}$, without undergoing the optimal redispatch process. These setpoints are updated hourly. Renewables, on the other hand, operate in Maximum Power Point Tracking (MPPT) mode to extract the maximum amount of energy from the available resource.
   Power plant controllers running in real time in the RTDS are responsible for maintaining system balance.
2) *Optimization-based scenarios*. Four case studies are considered, varying the optimization interval, $T_{opt}$, to 5, 15, 30, and 60 minutes. Since these setpoints are generated taking into account the system's transmission model and more accurate forecasts, the deviations that need to be compensated by the low-level controllers in the real-time simulation are smaller. Renewable power plants also operate according to the available resource, adjusting their output based on real-time conditions

In all simulations conducted, both for case *1)* and cases *2)*, the real profiles for renewable generation, $P_i^{REN,REAL}$, and load, $P_i^{LOAD,REAL}$, $Q_i^{LOAD,REAL}$, provided by the PC to the RTDS, are the same. These profiles were obtained through interpolation of real data supplied by the SO, with the data being interpolated every 15 seconds for the period from 12:00 to 14:00 on August 13, 2023. This timeframe includes several 5-minute periods coinciding with peak monthly PV production.

Additionally, the accuracy of the forecasts that feed the optimizer improves as $T_{opt}$ is reduced. This was achieved by applying an error function to the predictions, which was adapted according to the specific case.

## 4. Results and discussion

The five case studies presented earlier were executed over a two-hour period in the RTOLab environment. Fig. 4 illustrates the system's active power losses, measured in the Lanzarote-Fuerteventura power system model running in real time in the RTDS. The results demonstrate that the optimization-based strategy consistently reduces system losses compared to the base case. Among the tested intervals, shorter $T_{opt}$ values generally result in lower losses, highlighting the benefits of more frequent optimization updates. However, the differences between the optimization cases remain moderate. Table II presents the total system losses over the two-hour simulation, demonstrating that the proposed strategy achieves up to an 18.66% reduction in losses for $T_{opt}$ = 5 min compared to the base case.

The power plants receive the optimal voltage/reactive power setpoints and adjust their output through a brief transient, as shown in Fig. 5 for WPP$_F$. Additionally, Fig. 6 illustrates the voltage profile for all buses in the system for the optimal case of $T_{opt}$ = 5 min, as measured during the two-hour simulation with the system operating in real time. This demonstrates that the voltages remain within the established limits and exhibit acceptable dynamics.

Fig. 7 shows, for the Lanzarote synchronous generator, the external market/UC active power setpoint, $P_{SG_L}^{DIS,SCH}$, alongside the updated setpoint, $p_{SG_L}^{DIS,SP}$, obtained as a result of the optimization process. Additionally, its power output, $p_{SG_L}^{out}$, is also presented, representing the adaptation of its controls to real-time operating conditions. Due to its fast secondary control loop, this generator is primarily responsible for balancing generation and demand in the system.

In the redispatch process, the results show that this is the only generating unit whose scheduled setpoint is modified. This is because it is the dispatchable generator with the

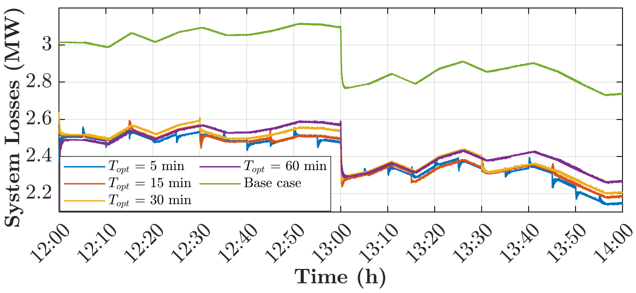


Fig. 4. Active power losses of the system measured in the RT system running in the RTDS for the different case studies

Table II. - Comparison of System Losses for Different Case Studies Measured in the Real-Time System

| Case Study | $T_{opt}$ = 5 min | $T_{opt}$ = 15 min | $T_{opt}$ = 30 min | $T_{opt}$ = 60 min | Base Case Scenario |
|---|---|---|---|---|---|
| Two-Hour System Losses (MWh) | 4.7914 | 4.8121 | 4.8594 | 4.8886 | 5.8917 |
| Loss Reduction Relative to Base Case Scenario (%) | 18.66% | 18.32% | 17.47% | 17.02% | - |

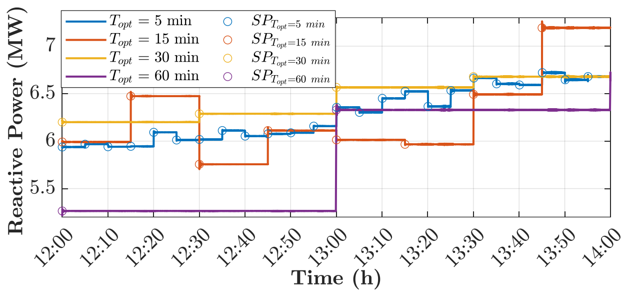


Fig. 5. WPP$_F$ reactive power output and setpoint for different optimization intervals in the two-hour real-time simulations

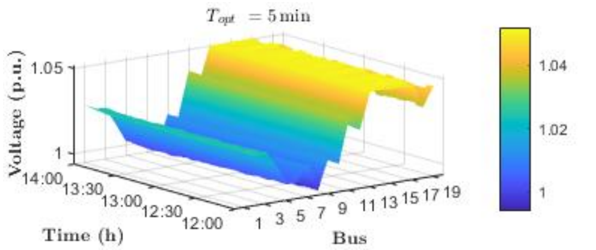


Fig. 6. Voltage profile for all buses in the system, measured in the RTDS for $T_{opt}$ = 5 min

lowest redispatch cost associated, according to the objective function (1). This modification is shown in Fig. 7 for the different $T_{opt}$ values (orange dashed line: scheduled setpoint vs. black line: optimized setpoint).

Based on the most recent forecasts available at each optimization interval, the resulting reactive power sharing, along with this active power setpoint modification, would lead the system toward the operating point with the lowest possible losses. This is achieved while ensuring compliance with the technical limits. However, since the optimization forecasts differ from the actual real-time load and renewable generation profiles, power plant controllers must dynamically adjust their output to account for these deviations. As shown in Fig. 7, for $T_{opt}$ = 5 min, which considers the shortest-term and therefore more accurate forecasts, the optimal setpoint is closer to the generator's actual output, reducing the effort required from the secondary regulation. However, this effort increases as $T_{opt}$ grows.

## 5. Conclusion

This paper proposes a centralized real-time reactive power management strategy based on a variant of the OPF formulation. The strategy aims to minimize system losses and redispatch costs while ensuring compliance with steady-state technical constraints, including generator limits, node voltage constraints, and line capacity limits.

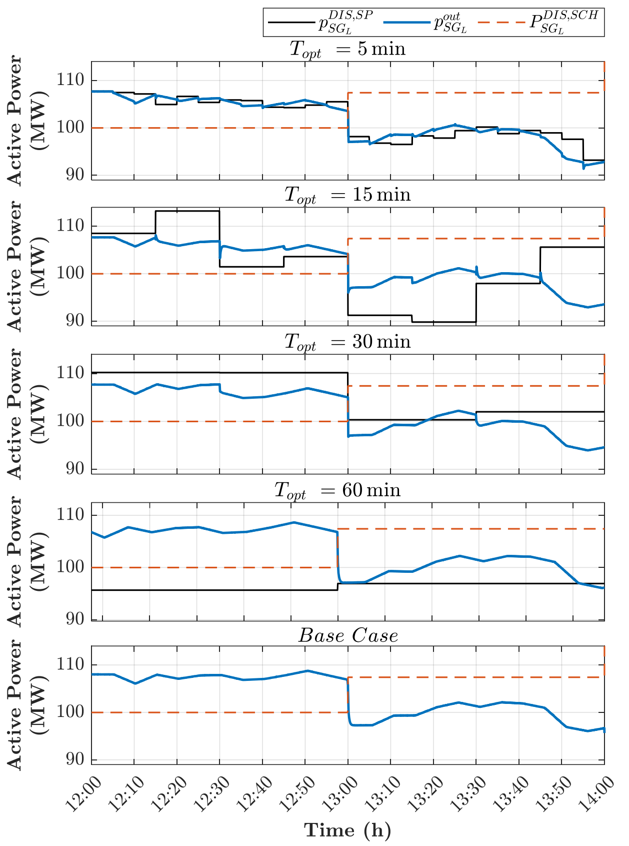


Fig. 7. Scheduled active power setpoint, updated setpoint, and measured output in the real-time experimental case studies for $SG_L$

The strategy's performance is evaluated on the Lanzarote-Fuerteventura Power System using a real-time HIL simulation environment, the RTOLab, over a two-hour RT simulation. This setup allows for the assessment of the strategy's effectiveness under different optimization intervals in realistic conditions. Among the tested intervals, shorter $T_{opt}$ values result in lower losses, highlighting the benefits of frequent optimization updates. These updates leverage more accurate forecasts, bringing the system closer to its optimal operating point. Additionally, it is worth nothing that the proposed strategy reduces the required effort from the secondary regulation. The differences between optimization cases remain moderate, although the improvement over the non-optimized base case scenario is significant.

The implementation in RTOLab validates the strategy's applicability to real-world systems and hardware, demonstrating timely convergence and adequate system response. Future work will focus on incorporating additional constraints, such as stability constraints, which will introduce greater computational complexity that must be assessed for real-time applications.

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